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IUPAC Technical Report

Norman E. Holden, Tyler B. Coplen, John K. Böhlke, Lauren V. Tarbox*, Jacqueline Benefield, John R. de Laeter[a], Peter G. Mahaffy, Glenda O'Connor[b], Etienne Roth[a], Dorothy H. Tepper, Thomas Walczyk, Michael E. Wieser and Shigekazu Yoneda

IUPAC Periodic Table of the Elements and Isotopes (IPTEI) for the Education Community (IUPAC Technical Report)

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Abstract: The IUPAC (International Union of Pure and Applied Chemistry) Periodic Table of the Elements and Isotopes (IPTEI) was created to familiarize students, teachers, and non-professionals with the existence and importance of isotopes of the chemical elements. The IPTEI is modeled on the familiar Periodic Table of the Chemical Elements. The IPTEI is intended to hang on the walls of chemistry laboratories and classrooms. Each cell of the IPTEI provides the chemical name, symbol, atomic number, and standard atomic weight of an element. Color-coded pie charts in each element cell display the stable isotopes and the relatively long-lived radioactive isotopes having characteristic terrestrial isotopic compositions that determine the standard atomic weight of each element. The background color scheme of cells categorizes the 118 elements into four groups: (1) white indicates the element has no standard atomic weight, (2) blue indicates the element has only one isotope that is used to determine its standard atomic weight, which is given as a single value with an uncertainty, (3) yellow indicates the element has two or more isotopes that are used to determine its standard atomic weight, which is given as a single value with an uncertainty, and (4) pink indicates the element has a well-documented variation in its atomic weight, and the standard atomic weight is expressed as an interval. An element-by-element review accompanies the IPTEI and includes a chart of all known stable and radioactive isotopes for each element. Practical applications of isotopic measurements and technologies are included for the following fields: forensic science, geochronology, Earth-system sciences, environmental science, and human health sciences, including medical diagnosis and treatment.

Keywords: chart of nuclides; IPTEI; IUPAC Inorganic Chemistry Division; radioactive isotopes; stable isotopes.

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[a] Deceased.

[b] Glenda O'Connor née Singleton.

***Corresponding author: Lauren V. Tarbox,** U.S. Geological Survey, Reston, VA, USA, e-mail: lvtarbox@gmail.com
Norman E. Holden: National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, USA
Tyler B. Coplen, John K. Böhlke, Jacqueline Benefield, Glenda O'Connor and Dorothy H. Tepper: U.S. Geological Survey, Reston, VA, USA
John R. de Laeter: Curtin University, Perth, Australia
Peter G. Mahaffy: King's University, Edmonton, Canada
Etienne Roth: Commissariat à l'énergie atomique (CEA), Gif-sur-Yvette, France
Thomas Walczyk: Department of Chemistry, National University of Singapore, Singapore, Singapore
Michael E. Wieser: Department of Physics and Astronomy, University of Calgary, Calgary, Canada
Shigekazu Yoneda: National Museum of Nature and Science, Tokyo, Japan

1 Introduction

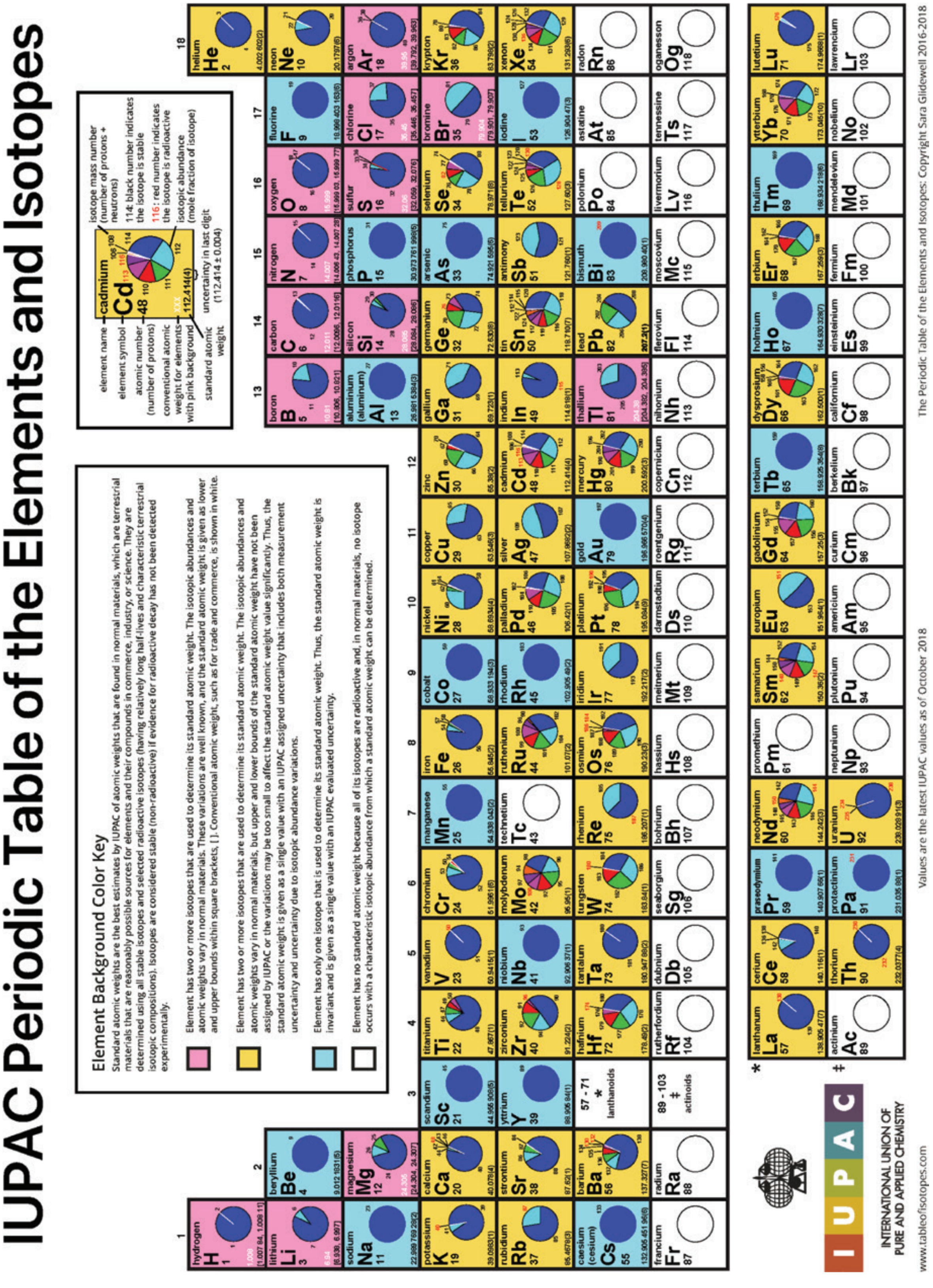
The IUPAC Periodic Table of the Elements and Isotopes (**IPTEI**), shown in Fig. 1.1, is modeled on the familiar Periodic Table of the Chemical Elements. The IPTEI effort was launched during the 2011 International Year of Chemistry (**IYC**-2011) [1, 2]. While the familiar Periodic Table indicated similarities of chemical **element** properties (terms that appear in the text in bold font appear in a glossary in Section 5), the IPTEI emphasizes some of the unique properties of each element. It is intended to familiarize students, teachers, and non-professionals with the nature and properties of **isotopes** of the chemical elements. A large-format IPTEI is intended to hang on the walls of chemistry laboratories and classrooms, just as the Periodic Table of the Chemical Elements is commonly displayed.

Atoms of all chemical elements are composed of positively charged particles called **protons**, an equal number of negatively charged particles called **electrons**, and electrically neutral particles called **neutrons**. The number of protons in each atom is its **atomic number**, symbol Z, and determines the chemical element; for example, for hydrogen atoms $Z=1$ and for gold atoms $Z=79$. The number of neutrons, symbol N, in an atom of a given element may vary. The total number of protons and neutrons ($Z+N$) in a specific atom is the **mass number**, symbol A, where $A=Z+N$. A nuclide is an atom with a specific number of protons and a specific number of neutrons; that is, a specific atomic number and mass number. The terms Nickel-64 and ^{64}Ni both refer to a nuclide of the element nickel with a mass number of 64. Nuclides of a given element that have different numbers of neutrons, but the same number of protons, are called isotopic nuclides or isotopes. The term “isotope” is commonly used in discussions of atomic properties of an atom and “nuclide” is used for discussions of nuclear properties. For any particular element, only certain isotopes are stable. ^{64}Ni, with 28 protons and 36 neutrons, is stable, whereas ^{65}Ni, with 37 neutrons, is unstable. A **stable isotope** is defined as an isotope for which no **radioactive decay** has been experimentally detected [3]. An unstable isotope (also called a **radioactive isotope** or **radioisotope**) is energetically unstable and will decay (disintegrate) over time to another isotope of the same element or to a nuclide of a different element. The time it takes for one half of the atoms of a given isotope in a sample to decay is called the **half-life**, symbol $t_{1/2}$, of that isotope. The term isotope applies to both stable and radioactive isotopes.

The world surrounding us, including the water we drink and the air we breathe, is made up of substances comprised of isotopes of the elements, *e.g.* hydrogen, oxygen, and nitrogen. The fraction of the amount of a specified isotope in a substance (**amount fraction**) is also called the **mole fraction**, the atom fraction, and the **isotopic abundance**. Many isotopes that occur naturally are radioactive and have half-lives ranging from a fraction of a second to much greater than 10^{10} years, which is greater than the age of the Earth. In natural terrestrial substances, a radioactive isotope with a sufficiently long half-life is said to have a characteristic terrestrial **isotopic composition**, *e.g.* xenon-136 and potassium-40. Considering all chemical elements that have been discovered in nature (in contrast to elements that have been synthesized or produced by humans), natural terrestrial samples contain a total of 289 different isotopes that have characteristic terrestrial isotopic compositions that are listed in **IUPAC’**s Table of Isotopic Compositions of the Elements [4]. Of these isotopes, 253 are stable and 36 are radioactive with long half-lives (greater than 3.25×10^4 years, *e.g.* for protactinium). In addition to these 289 isotopes, more than 3000 other natural and artificial isotopes are known, corresponding to the radioactive isotopes of all elements, most with short half-lives (less than 1 month).

The **relative atomic mass** which, for historical reasons, is called **atomic weight** (and is used in this document throughout), of an element E in any particular sample, A_r(E), is calculated from the sum of the products of the relative atomic mass and isotopic abundances of each stable isotope and each radioactive isotope having a sufficiently long half-life and sufficiently large isotopic abundance that a characteristic terrestrial isotopic composition can be listed in IUPAC’s Table of Isotopic Compositions of the Elements [5] of that element in a given sample. In contrast to the atomic weight of an element in any given material, the **standard atomic weight** (standard relative atomic mass) is a quantity that represents the atomic weight of an element in normal terrestrial materials.

Each element cell of the IUPAC Periodic Table of the Elements and Isotopes (Fig. 1.1) provides the chemical name, chemical symbol, atomic number, and standard atomic weight of that element, as is shown in



IUPAC Periodic Table of the Elements and Isotopes

Element Background Color Key

Standard atomic weights are the best estimates by IUPAC of atomic weights that are found in normal materials, which are terrestrial materials that are reasonably possible sources for elements and their compounds in commerce, industry, or science. They are determined using all stable isotopes and selected radioactive isotopes (having relatively long half-lives and characteristic terrestrial isotopic compositions). Isotopes are considered stable (non-radioactive) if evidence for radioactive decay has not been detected experimentally.

🟥 Element has two or more isotopes that are used to determine its standard atomic weight. The isotopic abundances and atomic weights vary in normal materials. These variations are well known, and the standard atomic weight is given as lower and upper bounds within square brackets, [ ]. Conventional atomic weight, such as for trade and commerce, is shown in white.

🟨 Element has two or more isotopes that are used to determine its standard atomic weight. The isotopic abundances and atomic weights vary in normal materials, but upper and lower bounds of the standard atomic weight have not been assigned by IUPAC or the variations may be too small to affect the standard atomic weight value significantly. Thus, the standard atomic weight is given as a single value with an IUPAC assigned uncertainty that includes both measurement uncertainty and uncertainty due to isotopic abundance variations.

🟦 Element has only one isotope that is used to determine its standard atomic weight. Thus, the standard atomic weight is invariant and is given as a single value with an IUPAC evaluated uncertainty.

☐ Element has no standard atomic weight because all of its isotopes are radioactive and, in normal materials, no isotope occurs with a characteristic isotopic abundance from which a standard atomic weight can be determined.

Values are the latest IUPAC values as of October 2018

The Periodic Table of the Elements and Isotopes: Copyright Sara Glidewell 2016-2018

www.tableofisotopes.com

Fig. 1.1: IUPAC Periodic Table of the Elements and Isotopes [modified by Sara Glidewell from The Periodic Table of Elements and Isotopes©, copyright by Sara Glidewell (www.tableofisotopes.com), and used with permission].

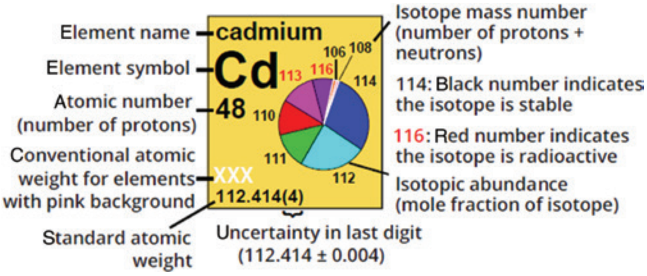


Fig. 1.2: Legend of the IUPAC Periodic Table of the Elements and Isotopes (prepared by and used with permission of Sara Glidewell).

the cadmium legend in Fig. 1.2. Each cell displays the current standard atomic weight [4] for each element with its estimated uncertainty in the last digit. For the 13 elements with **standard atomic-weight intervals** (hydrogen, lithium, boron, carbon, nitrogen, oxygen, magnesium, silicon, sulfur, chlorine, argon, bromine, and thallium), the standard atomic weight is given as an interval to stress that standard atomic weights are not constants of nature [6]. Each is shown as lower and upper bounds (limits) (Figs. 1.1 and 1.2). Some users of atomic-weight data need a value that is not an interval, such as for purposes of trade and commerce. For these users, a **conventional atomic-weight value** [4] is provided for each of these 13 elements and is shown in white (Figs. 1.1 and 1.2). A color-coded pie chart displays all of the stable isotopes and radioactive isotopes having characteristic terrestrial isotopic compositions that determine the standard atomic weight of that element, *e.g.* eight isotopes for cadmium. The mole fraction (isotopic abundance) of each of these isotopes is indicated by the relative size of the pie slice associated with that isotope. The mass numbers of each of these isotopes appear around the outside of the pie chart. Mass numbers are shown in black for stable isotopes (*e.g.* ^{112}Cd) and in red for radioactive isotopes (*e.g.* ^{113}Cd). More than 3000 radioactive isotopes with half-life values too short or isotopic abundances too low to impact the standard atomic weights are excluded from the IUPAC Periodic Table of the Elements and Isotopes, but they are included in the accompanying element-by-element review (Section 4).

In the following element-by-element review, there are often expressions in the textual material of nuclear reactions, which are listed in the form A(a,b)B, where A is a target that reacts with an incoming projectile, a, and forms the residual, B, and emits the outgoing projectile, b. In many cases, there may be a subsequent radioactive decay reaction associated in a two-step reaction process, with the notation $B \rightarrow C + c$. This secondary decay reaction indicates that the residual, B, is unstable and decays with a characteristic half-life to another residual, C, *via* the c decay. The c could be a negatively charged beta particle (electron), a positively charged beta particle (**positron**), or a positively charged **alpha particle**, α. It could indicate a negatively charged electron capture reaction, ec, or a neutral particle, a neutron (see Section 2.10.1 (ii), page 50 of ref [7]).

2 Background color scheme for an element cell

The background color scheme for an **element** cell in the **IPTEI** (Fig. 1.1) depends in part on the number of **isotopes** that are used to determine the **standard atomic weight** of the element:

- Yellow is the background color if an element has two or more isotopes that are used to determine its **atomic weight**. The standard atomic weight is given as a single value with an uncertainty that includes both **measurement uncertainty** and uncertainty due to **isotopic abundance** variations. The variations in **isotopic abundances** may be too small to exceed the measurement uncertainty and affect the atomic weight value. An example is cadmium, shown in Fig. 1.2, with a standard atomic weight of 112.414(4).
- Blue is the background color if only one isotope is used to determine the standard atomic weight. The standard atomic weight is invariant and is given as a single value with an **IUPAC**-evaluated measurement uncertainty. An example is arsenic, with a standard atomic weight of 74.921 595(6), where the uncertainty in the last digit, 5, is indicated by the value, 6, in parentheses (Fig. 1.1).

- White is the background color if an element has no standard atomic weight because all of its isotopes are radioactive and no isotope occurs in **normal materials** with a characteristic terrestrial isotopic composition from which a standard atomic weight can be determined. An example is americium, for which no standard atomic weight is listed (Fig. 1.1).
- Pink is the background color if an element has two or more isotopes that are used to determine its **atomic weight** and the variation in isotopic abundances and atomic weights in normal materials is large and well known. The standard atomic weight is given as lower and upper bounds within square brackets, [ ]. An example is boron, with a standard atomic weight of [10.806, 10.821] (Fig. 1.1). In this case, the standard atomic-weight value indicates that known boron atomic-weight values, found in normal materials, are as low as 10.806 and as high as 10.821. The standard atomic weight should not be expressed as the average of the lower and upper bounds. These elements do not have an IUPAC-assigned uncertainty.

3 Electronic, interactive version of the IUPAC Periodic Table of the Elements and Isotopes

The printed version of the **IPTEI** is accompanied by an electronic interactive version, which runs on a variety of platforms and devices. The global launch of the electronic, interactive version of the IPTEI took place in August 2016 at the 24th IUPAC Conference on Chemistry Education, held in Kuching, Malaysia. This electronic, interactive version, developed by the King's Centre for Visualization in Science (KCVS), can be found at www.isotopesmatter.com. A click on a **chemical element** cell in Fig. 1.1 on that site will display additional information from the element-by-element review (Section 4) about the **isotopes** of that element, including a table of the naturally occurring isotopes for each element, their atomic masses, and their **isotopic abundances** (**mole fractions**). There is a list of all **radioactive isotopes** and an indication of their **half-life** value within one of three half-life ranges. This electronic, interactive IPTEI has been designed to be used both as a stand-alone digital learning object and as an object to be embedded in a set of electronic learning resources that will (a) stress the importance of isotopes in everyday life, (b) connect the knowledge of isotopes to core concepts in chemistry and physics curricula, and (c) help students and teachers understand the evidential basis for our knowledge of isotopes through the use of tools such as **mass spectrometry**.

4 Element-by-element review

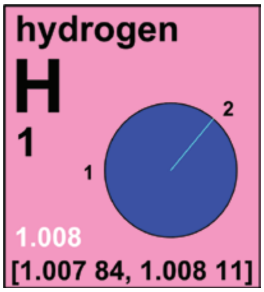
For each of the 118 **elements**, the following is presented:

- The element cell from the IUPAC Periodic Table of Elements and Isotopes.
- A table of **stable isotopes** or long-lived **isotopes** that have a characteristic terrestrial **isotopic composition** and contribute to the value of a **standard atomic weight**. For each isotope the **relative atomic mass**, abridged from Wang *et al.* [8], is listed. The **mole fraction** of each isotope is listed and is taken from column 9 of the Table of Isotopic Compositions of the Elements 2013 [5], except for ytterbium, whose standard atomic weight and **isotopic abundances** were updated in 2015 [9, 10], and for iridium, whose standard atomic weight and isotopic abundances were updated in 2018 [11, 12]. For the 13 elements having an interval for the standard atomic weight (hydrogen, lithium, boron, carbon, nitrogen, oxygen, magnesium, silicon, sulfur, chlorine, argon, bromine and thallium) the isotopic abundance of each stable isotope is given as an interval to denote the set of isotopic-abundance values in normal materials.
- A chart of all known isotopes of each element. **Mass numbers** of **radioactive isotopes** are red and the cell background categorizes the **half-life** range. Mass numbers of stable isotopes are black and the background colors are from the pie diagram sections of the isotopic abundances of the element.
- Selected applications of stable and/or radioactive isotopes in one or more of the following categories:

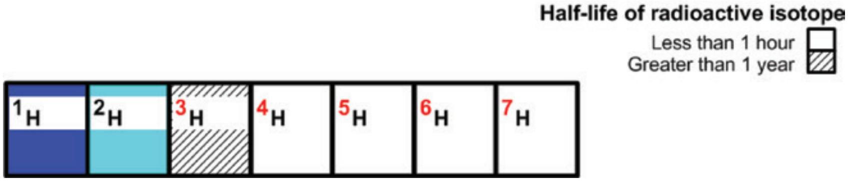
(i) Isotopes in biology
(ii) Isotopes in Earth/planetary science
(iii) Isotopes in forensic science and anthropology
(iv) Isotopes in **geochronology**, which encompasses **isotopic dating**
(v) Isotopes in industry
(vi) Isotopes in medicine
(vii) Isotopes used as a source for radioactive isotopes

The applications provided are only examples and are not intended to encompass all isotope applications of an element.

4.1 Hydrogen



Stable isotope	Relative atomic mass	Mole fraction
^{1}H	1.007 825 0322	[0.999 72, 0.999 99]
^{2}H	2.014 101 7781	[0.000 01, 0.000 28]



4.1.1 Hydrogen isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of hydrogen possess slightly different physical and chemical properties and they are commonly fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights** (Fig. 4.1.1). Hydrogen has the largest relative mass difference among its **isotopes** and consequently exhibits the largest variation in **isotopic composition** of any **element** that does not have radioactive or **radiogenic** isotopes. Ranges in the stable isotopic composition of naturally occurring hydrogen-bearing materials are shown in Fig. 4.1.1. These variations enable hydrogen isotopes to be used as **tracers** in environmental studies [13].

A primary use of stable hydrogen isotopes is in isotope hydrology. Although the evolution of the stable hydrogen and oxygen isotopic composition of precipitation begins with the evaporation of water from the oceans, their local and global relationship arises primarily from equilibrium **isotopic fractionation** of heavier (^{2}H and ^{18}O) and lighter (^{1}H and ^{16}O) isotopes of hydrogen and oxygen during condensation as a **tropospheric** vapor mass follows a trajectory to higher latitudes and over continents [14, 15]. As a consequence, the hydrogen isotopic composition of precipitation, rivers, and tap waters varies with elevation, season, and distance from the ocean-continent boundary. Figure 4.1.2 shows the variation in the atomic weight of hydrogen in water from rivers across the United States. These variations in the hydrogen isotopic composition of environmental water are often combined with stable oxygen isotopic compositions and have been used to identify the origin of water samples and to investigate the interaction between groundwater and surface water (*e.g.* lakes, streams, and rivers) [16].

4.1.2 Hydrogen isotopes in forensic science and anthropology

Measurements of relative ^{2}H abundances are used to determine the breeding grounds of many species of migrant songbirds. These species of songbirds only grow their feathers before migration, and they grow them on or close to their breeding grounds. Therefore, the isotopic composition of a bird's feathers correlates to the isotopic composition of the growing season's precipitation [18–20].

Measurements of relative ^{2}H abundances of human hair samples collected at archeological sites are used to determine the geographic region in which a subject lived based on the hydrogen isotopic composition of the water they drank. This is possible because hair stores a daily record of the hydrogen isotopic composition of intake water, which correlates to local **meteoric water** [18, 21].

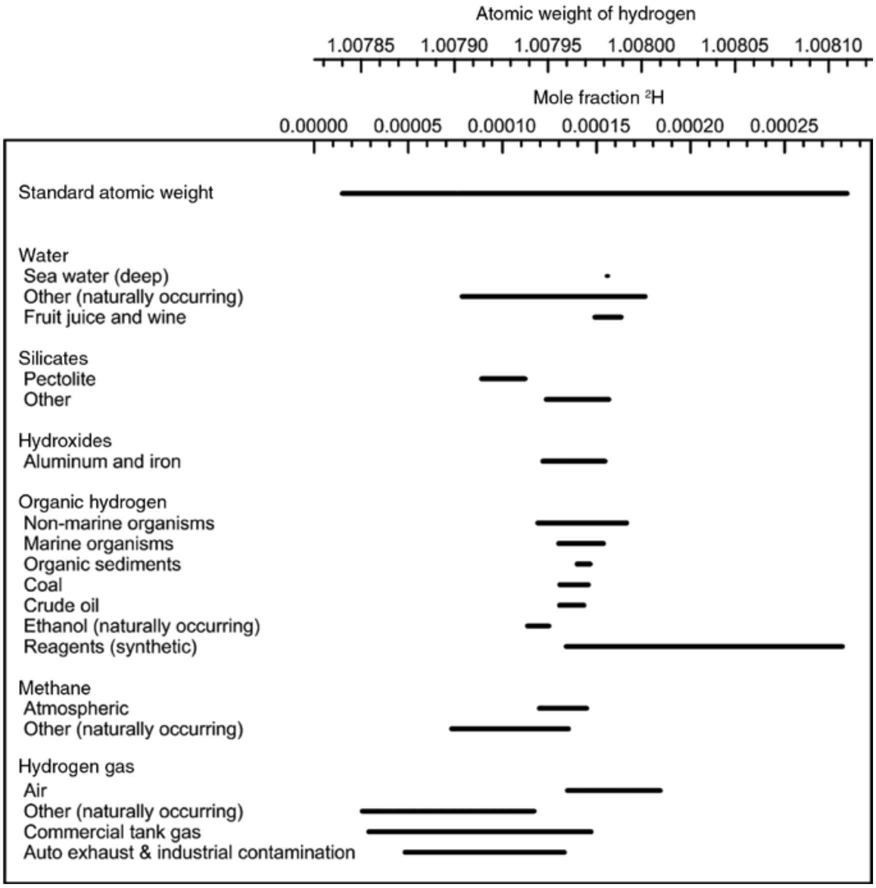


Fig. 4.1.1: Variation in **atomic weight** with **isotopic composition** of selected hydrogen-bearing materials (modified from [13, 17]).

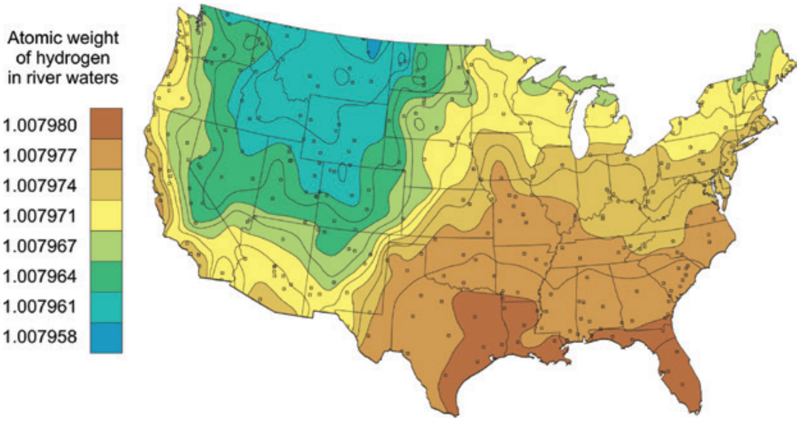


Fig. 4.1.2: Variation in **atomic weight** of hydrogen in river waters across the continental United States (modified from [16]). Blue color indicates waters most depleted in ^{2}H (resulting in lower atomic weight of hydrogen) and brown color indicates those most enriched in ^{2}H (resulting in higher atomic weight of hydrogen).

4.1.3 Hydrogen isotopes in geochronology

^{3}H (tritium), with a **half-life** of 12.31 years, decays to ^{3}He. The relative variations in $n(^{3}\mathrm{He})/n(^{3}\mathrm{H})$ ratios can be interpreted in terms of elapsed time for dating purposes. The dates of groundwater recharge (water moving downward from the surface), where large amounts of ^{3}H were received from precipitation following **thermonuclear bomb** test periods, come from the elapsed time since a water mass became isolated from the atmosphere in the time range from the mid-1950s to the present [15].

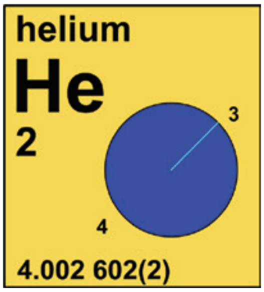
4.1.4 Hydrogen isotopes in industry

^{3}H is used for self-**luminous** exit signs in aircraft and commercial buildings. It is found in luminous dials, gauges, wristwatches, and luminous paints [22]. ^{2}H, in the form of **heavy water**, is used in CANDU (**CAN**ada **D**euterium **U**ranium) nuclear reactors as a moderator and coolant [23].

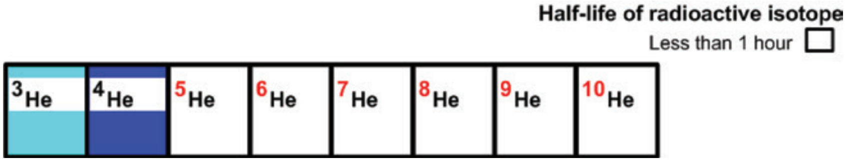
4.1.5 Hydrogen isotopes in medicine

^{2}H is used for the isotopic labeling of drugs and nutrients to trace their uptake and **metabolism** in the human body [24, 25]. ^{2}H, in the form of heavy water, is used to study human metabolism. For example, ^{2}H is used in combination with ^{18}O (double labeled water) to measure energy expenditure [26].

4.2 Helium



Stable isotope	Relative atomic mass	Mole fraction
^{3}He	3.016 029 322	0.000 002
^{4}He	4.002 603 2545	0.999 998



4.2.1 Helium isotopes in geochronology

^{3}He is a product of the **radioactive decay** of ^{3}H (**half-life** of 12.31 years). The relative variations in the **amount ratio** $n(^{3}\text{He})/n(^{3}\text{H})$ can be interpreted in terms of elapsed time. This has been especially useful in aquatic systems, including oceans, lakes, and aquifers, that received large inputs of ^{3}H from precipitation following **thermonuclear bomb** test periods. ^{3}H-^{3}He dating provides the elapsed time since a water mass became isolated from the atmosphere in the time range from the mid-1950s to the present. Such studies are important for establishing the sustainability of groundwater resources in shallow aquifers [27, 28].

^{4}He is a product of radioactive decay in the uranium and thorium decay series. As a result, ^{4}He concentration is used to estimate the relative ages of minerals and groundwater. In closed systems (systems that do not exchange matter with their surroundings), relative variations in the amount ratio $n(^{4}\text{He})/n(\text{U})$ can be interpreted in terms of elapsed time, although other processes can alter the distribution of helium, which is highly mobile in terrestrial environments [29, 30].

^{4}He concentrations commonly increase along groundwater flow paths through a cumulative release from aquifer materials. This rate of accumulation is used to estimate the time since the groundwater was recharged at the surface. The ^{4}He accumulation method of groundwater dating is typically used in deeper aquifers, where groundwater is relatively old and the ^{3}H-^{3}He method cannot be used because of the relatively short half-life of 12.31 years for ^{3}H [30].

4.2.2 Helium isotopes in industry

^{3}He has a large **absorption cross section** for **neutrons**, which makes it especially useful for radioactivity detection [31, 32]. In this application, neutrons produced by the radioactive decay of **elements**, such as uranium and plutonium, enter the detector, where the reaction ^{3}He (n, p) ^{3}H produces ^{1}H and ^{3}H atoms. This induces further collisions and the release of **electrons**, which interact with charged surfaces to generate an electric current. Large amounts of ^{3}He are used to produce neutron detectors in portal monitors for detecting illicit radioactive materials at ports, border crossings, and airports (Fig. 4.2.1). Unfortunately, the **isotope** ^{3}He is rare and there is a need to incorporate alternative gases for use in neutron detectors. ^{3}He neutron detectors are also used in devices that determine the proportions of water, oil, and gas in wells drilled for energy production. Other important uses of ^{3}He include lasers, gyroscopes used for missile stability and guidance, and cryogenic research (ultra-low temperature, less than 1 K).

The global supply of ^{3}He available for research and practical applications has become severely limited in recent years, such that prices have increased substantially and some uses have been curtailed [31, 32]. A major source of ^{3}He is from nuclear weapons containing ^{3}H, recovered when the warheads are reconditioned

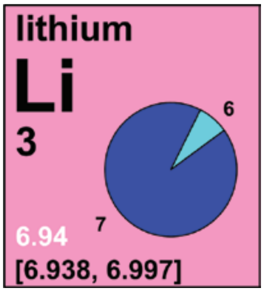
Fig. 4.2.1: Radiation detectors are installed in many areas to screen people, vehicles, and cargo for radioactive materials. ^{3}He detectors are sensitive to **thermal neutrons** and are used to detect isotopes of uranium and plutonium that might be used in nuclear weapons, along with other sources that produce **neutrons** by **radioactive decay**. (Image Source: U.S. Government Accountability Office) [33].

or dismantled. ^{3}He accumulates in such devices as a **radiogenic** product of ^{3}H decay. The annual supply of new ^{3}He has decreased with reductions in nuclear arsenals.

4.2.3 Helium isotopes in medicine

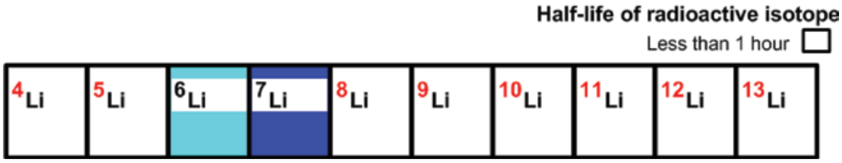
^{3}He is used as an inhalant to improve **magnetic resonance imaging** (MRI) of the lungs [34].

4.3 Lithium



Stable isotope	Relative atomic mass	Mole fraction
^{6}Li	6.015 122 887	[0.019, 0.078][†]
^{7}Li	7.016 003 44	[0.922, 0.981][†]

[†] Materials depleted in lithium-6 are common sources of commercial laboratory shelf reagents, which is the reason for the wide interval of **isotopic abundances** given.



4.3.1 Lithium isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of lithium possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. Natural terrestrial materials show a substantial variation in lithium isotopic abundance (Fig. 4.3.1), and these natural isotopic abundances have been used to determine sources of dissolved lithium and to investigate environmental processes [13, 35].

Variations in **isotope-amount ratios** $n(^{7}\text{Li})/n(^{6}\text{Li})$ can help determine the source of some water. Because the relative abundances of lithium **isotopes** can change during hydrothermal processes, isotopic analysis of lithium in water can help distinguish water derived from marine sedimentary rocks from water derived from hydrothermally altered **igneous** rocks (Fig. 4.3.2) [36, 37].

4.3.2 Lithium isotopes in industry

^{7}Li, as hydroxide monohydrate ($^{7}\text{LiOH}\bullet\text{H}_2\text{O}$), is used to maintain the pH level of the coolant used in pressurized water reactors in the nuclear power industry [39, 40]. Lithium plays a role in the construction of a **thermonuclear bomb**, which differs from a **fission** weapon in that it uses the energy released when two light atomic nuclei (*i.e.* deuterium (^{2}H) and tritium (^{3}H)) fuse to form helium and a high energy **neutron** *via* this DT reaction. ^{6}Li is used, in the form of ^{6}Li deuteride ($^{6}\text{Li}^{2}\text{H}$), as fusion fuel capable of producing tritium when bombarded with neutrons within the weapon *via* the reaction $^{6}\text{Li (n, }^{3}\text{H) }^{4}\text{He}$ [41].

Li-based laboratory reagents have found their way into surface water and can be easily identified. Although a military secret in the 1950s, it is now known that substantial amounts of ^{6}Li (normally having an isotopic abundance of 0.076) were removed from chemical reagents to be used in nuclear weapon development. Reagents containing the remaining lithium depleted in ^{6}Li (having an isotopic abundance as low as 0.025) were sold to both chemical manufacturers and to laboratory chemists for their use [42]. The distinctive isotopic signature of depleted ^{6}Li, having a $n(^{7}\text{Li})/n(^{6}\text{Li})$ ratio of 39, compared to a ratio of 12 in naturally occurring terrestrial materials, enables easier detection of this lithium source in polluted waterways and the environment [35, 37].

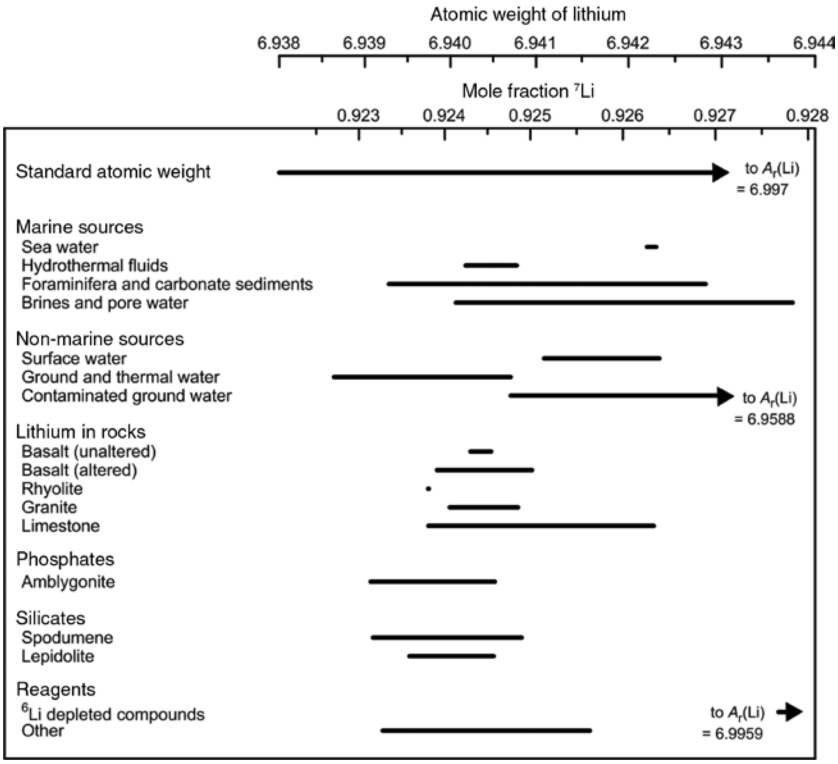


Fig. 4.3.1: Variation in **atomic weight** with **isotopic composition** of selected lithium-bearing materials (modified from [13, 17]).

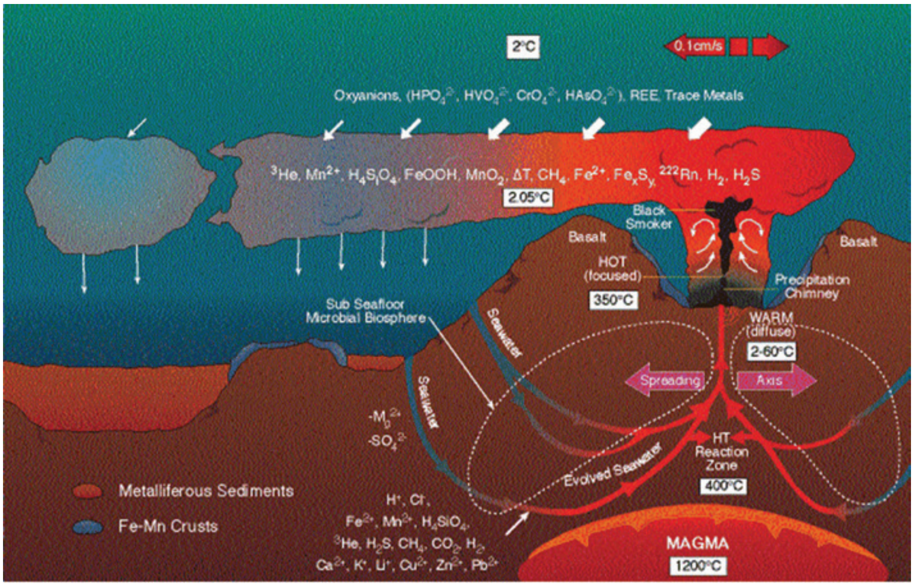


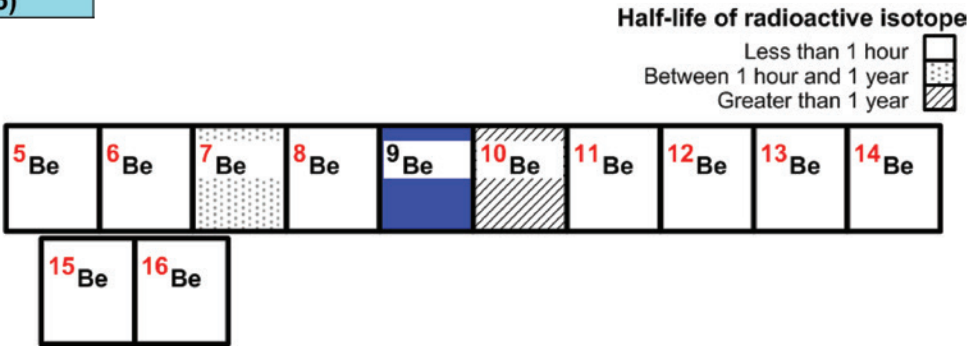
Fig. 4.3.2: Diagram of submarine hydrothermal vent processes. (Image Source: Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration) [38].

4.3.3 Lithium isotopes in medicine

^{7}Li is a **decay product** of the ^{10}B (neutron, alpha) ^{7}Li reaction, which has a peak value for room temperature neutrons. Brain tumor cells are typically found some 5 to 7 cm below the surface of the skull. After ^{10}B has been introduced to or entered the tumor cells, a beam of neutrons of energy slightly above room temperature is introduced to the affected areas. The energy of these neutrons is reduced to room temperature by the time they react with the ^{10}B, which then disintegrates into high energy charged particles (^{7}Li and ^{4}He), which deposit their kinetic energy in nearby (predominately cancerous) cells and destroys them. Any adjacent normal cells are unaffected [43].

4.4 Beryllium

Stable isotope	Relative atomic mass	Mole fraction
^{9}Be	9.012 1831	1



4.4.1 Beryllium isotopes in geochronology

Cosmogenic ^{10}Be and ^{7}Be **isotopes** are produced in the atmosphere, largely by **cosmic-ray spallation** of nitrogen and oxygen. Because of its relatively short **half-life** (^{7}Be, half-life $t_{1/2} = 53$ d, compared to that of ^{10}Be, half-life $t_{1/2} = 1.39 \times 10^{6}$ a, where the unit symbol “d” stands for day and “a” stands for year), measurements of cosmogenic ^{7}Be, and especially the **isotope-amount ratio** $n(^{7}\text{Be})/n(^{10}\text{Be})$, have been used to study rates of atmospheric circulation, mixing, formation of aerosols (fine solids or liquids suspended in a gas; *e.g.* smoke and mist are aerosols), and particle deposition [44]. Cosmogenic atmospheric beryllium isotopes (^{7}Be and ^{10}Be) are deposited on the Earth’s surface, where they accumulate in soils, sediments, and snow while decaying away. Measurements of cosmogenic beryllium isotopes in such deposits are used to explore rates of soil formation, erosion, sedimentation, and snow accumulation on time scales ranging from months (^{7}Be)

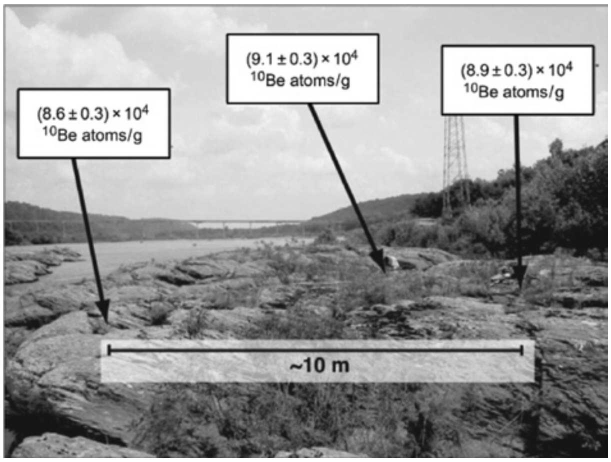
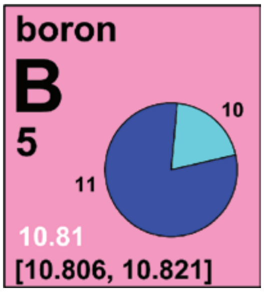


Fig. 4.4.1: Variability in ^{10}Be production as a result of the interaction of **cosmic rays** with exposed rocks at three sites on the Level 2 terrace in upper Holtwood Gorge, Pennsylvania, approximately 50 km upstream of Chesapeake Bay [49].

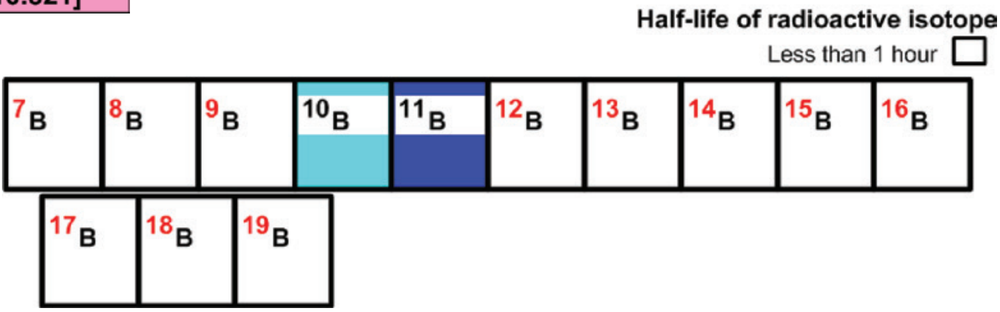
to millions of years (^{10}Be) [45, 46]. The minerals in rocks at the Earth's surface interact with cosmic rays and form substantial quantities of ^{10}Be and ^{7}Be, thus providing a tool to determine the ages of geologic processes. In some situations, it is possible to estimate "exposure ages" for rocks in eroding terrains [47–49]. By comparing measured ^{10}Be concentrations with estimated rates of *in situ* cosmogenic ^{10}Be production, the rate of rock erosion and formation of canyons and other geologic features can be determined (Fig. 4.4.1).

Anthropogenic ^{10}Be was produced by nuclear bomb explosions largely through the reaction of fast **neutrons** (neutrons produced by nuclear **fission** having high kinetic energy) with ^{13}C *via* the ^{13}C (n, alpha) ^{10}Be reaction in atmospheric CO_2. Although the quantity of ^{10}Be produced in this way is small, its presence above natural background concentrations in some environmental samples can potentially provide information about bomb-related processes and contamination [50].

4.5 Boron



Stable isotope	Relative atomic mass	Mole fraction
^{10}B	10.012 9369	[0.189, 0.204]
^{11}B	11.009 305 17	[0.796, 0.811]



4.5.1 Boron isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of boron possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. Natural terrestrial materials show a substantial variation in boron isotopic abundance (Fig. 4.5.1). The relative abundances of ^{10}B and ^{11}B have been used in a variety of environmental **tracer** applications [51, 52]. The **isotope-amount ratio** $n(^{11}\mathrm{B})/n(^{10}\mathrm{B})$ of boron in a water sample depends on the source of the water and region through which the water flows,

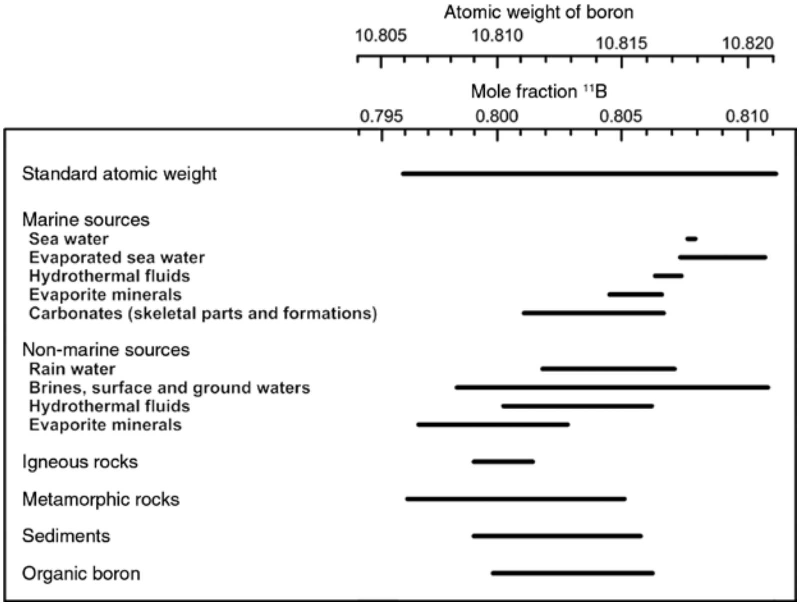


Fig. 4.5.1: Variations in **atomic weight** with **isotopic composition** of selected boron-bearing materials (modified from [13]).

and it may also be affected by some types of contamination, such as dissolved borate in domestic wastewater. Different water sources may have their own distinct boron isotopic composition, *e.g.* seawater *versus* water from continental sources (Fig. 4.5.1).

4.5.2 Boron isotopes in industry

The large value of the **absorption cross section** of ^{10}B for **thermal neutrons** makes this **isotope** useful for counting **neutrons**. ^{10}B is being studied as a potential replacement for ^{3}He in radiation detectors [32, 53, 54]. The large thermal absorption cross section of ^{10}B makes the isotope useful in **control rods** (Fig. 4.5.2) [55].

4.5.3 Boron isotopes in medicine

^{10}B has a high thermal neutron absorption cross section and can readily absorb neutrons *via* the reaction $^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{7}\mathrm{Li} + \alpha$. The **alpha particles** resulting from this reaction carry away a relatively large kinetic energy and are useful for the treatment of **malignant** tumors in cancer patients [56–58].

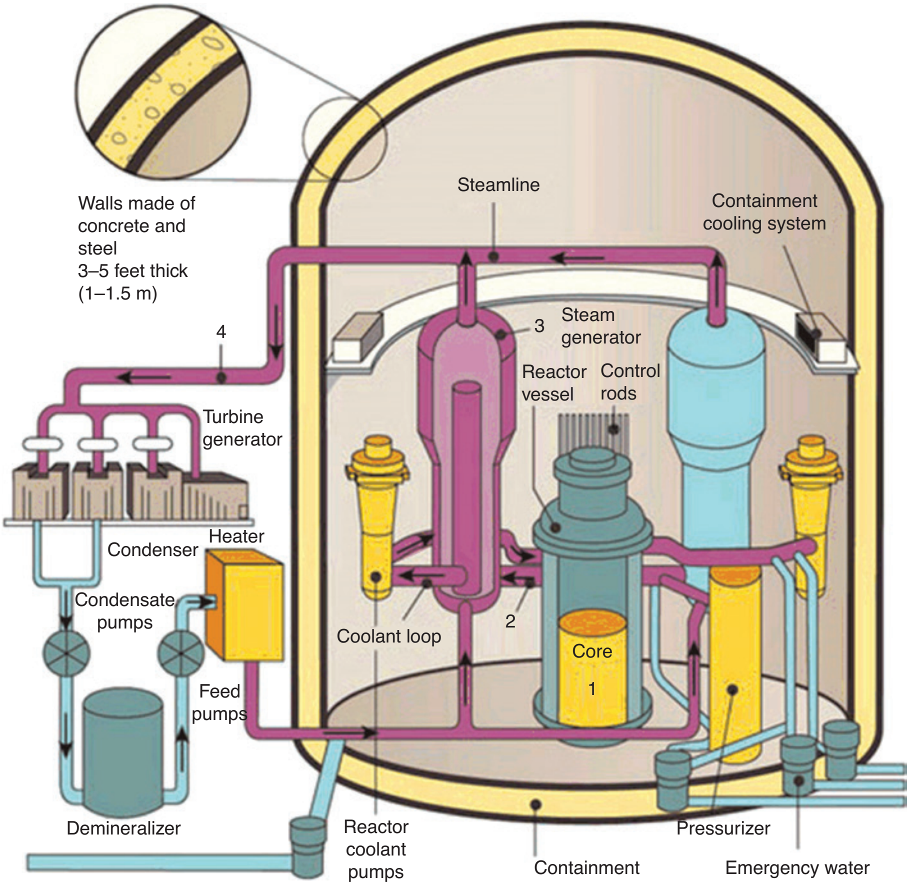
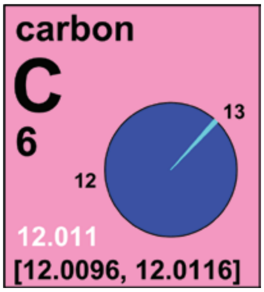
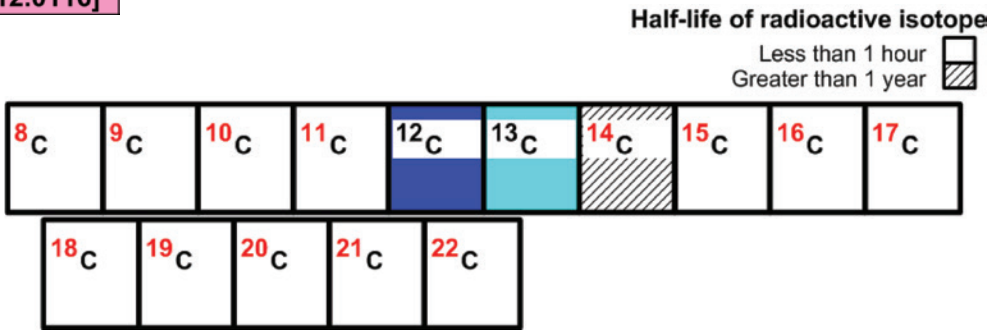


Fig. 4.5.2: Diagram of a typical pressurized water reactor, which shows where the boron **control rods** can be inserted or withdrawn from the core (1). (Diagram Source: U.S. Nuclear Regulatory Commission) [55].

4.6 Carbon



Stable isotope	Relative atomic mass	Mole fraction
$^{12}\mathrm{C}$	12	[0.9884, 0.9904]
$^{13}\mathrm{C}$	13.003 354 835	[0.0096, 0.0116]



4.6.1 Carbon isotopes in biology

Because of above-ground nuclear bomb testing, the **neutrons** released reacted with CO_2 to increase atmospheric $^{14}\mathrm{C}$ *via* the $^{14}\mathrm{N}$ (n, p) $^{14}\mathrm{C}$ reaction, and $^{14}\mathrm{C}$ started rising in about 1955 (Fig. 4.6.1) and reached a peak in the mid-1960s [59]. With the curtailment of above-ground nuclear testing in the 1960s, the atmospheric $^{14}\mathrm{C}$ concentration has since been decreasing exponentially (Fig. 4.6.1). This variation in $^{14}\mathrm{C}$ concentration is used to establish when cells in biology were born and how quickly they are renewed [60]. This technique is commonly called carbon-14 bomb pulse biology and it has provided information on the age of cells and their regeneration. Figure 4.6.2 shows the average age of selected cells in a 30-year-old human.

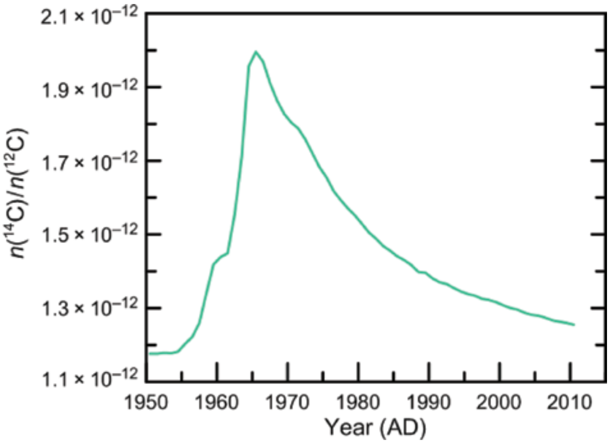


Fig. 4.6.1: Global relative average atmospheric $^{14}\mathrm{C}$ concentration (**isotope-amount ratio** $n(^{14}\mathrm{C})/n(^{12}\mathrm{C})$) between 1950 and 2010 (modified from [59]).

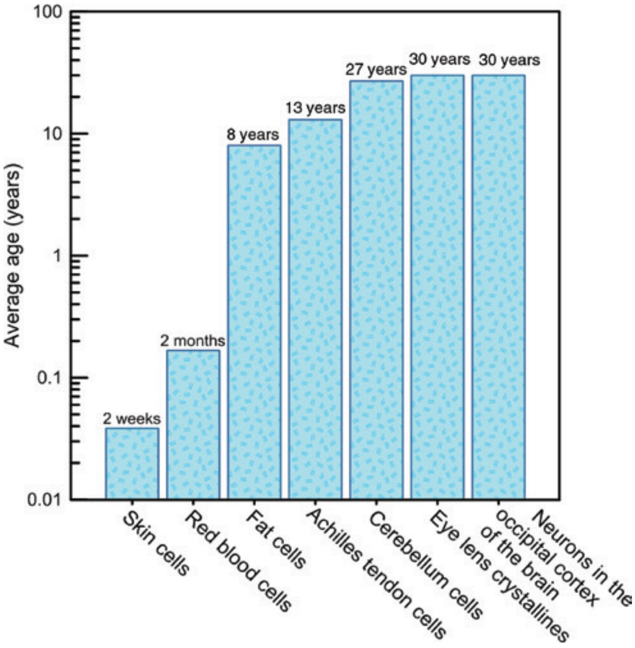


Fig. 4.6.2: Average age of selected cells in a 30-year-old human, determined with ^{14}C produced primarily in the 1960s as a result of above-ground, nuclear-weapons testing (figure compiled from published data [60–65]). This technique commonly is called carbon-14 bomb pulse biology. Occipital neurons in the cortex of the adult human brain are as old as the individual [60]. Lens crystallines are special proteins in the eye lens and are formed almost exclusively at birth with a very small, and decreasing, continuous formation throughout life [65]. Achilles tendon cells do not regenerate after the first 17 years of life [61]. Half of human fat cells are replaced about every 8 years [63].

4.6.2 Carbon isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of carbon possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. Carbon in natural terrestrial materials shows a substantial variation in isotopic abundance (Fig. 4.6.3), providing many different ways of distinguishing sources of materials and processes affecting them [13]. Variations in the **isotope-amount ratio** $n(^{13}C)/n(^{12}C)$ in tree rings and in CO_2 trapped in ice cores have been used to study causes of variations in atmospheric CO_2 levels [66]. Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ and in the ^{14}C concentration of surface ocean waters have been used to trace the incorporation and movement of atmospheric CO_2 in the ocean [66].

4.6.3 Carbon isotopes in forensic science and anthropology

Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of biological products can be observed using **isotope-ratio mass spectrometry** (**IRMS**) to detect adulteration (the addition of inferior ingredients) in honey and other food products.

The isotope-amount ratio $n(^{13}C)/n(^{12}C)$ can fluctuate between carbon sources, for example C_3 plants (found in temperate climates and which use atmospheric carbon dioxide to make a 3-carbon molecule during photosynthesis — examples include rice, potatoes, tomatoes, and sugar beets), C_4 plants (found in hot climates and which use atmospheric carbon dioxide to make a 4-carbon molecule during photosynthesis — examples include corn and sugar cane), animal carbon, atmospheric CO_2, *etc*. This commonly makes it possible to detect whether these different carbon sources have been mixed by using **isotope** or mass balance to

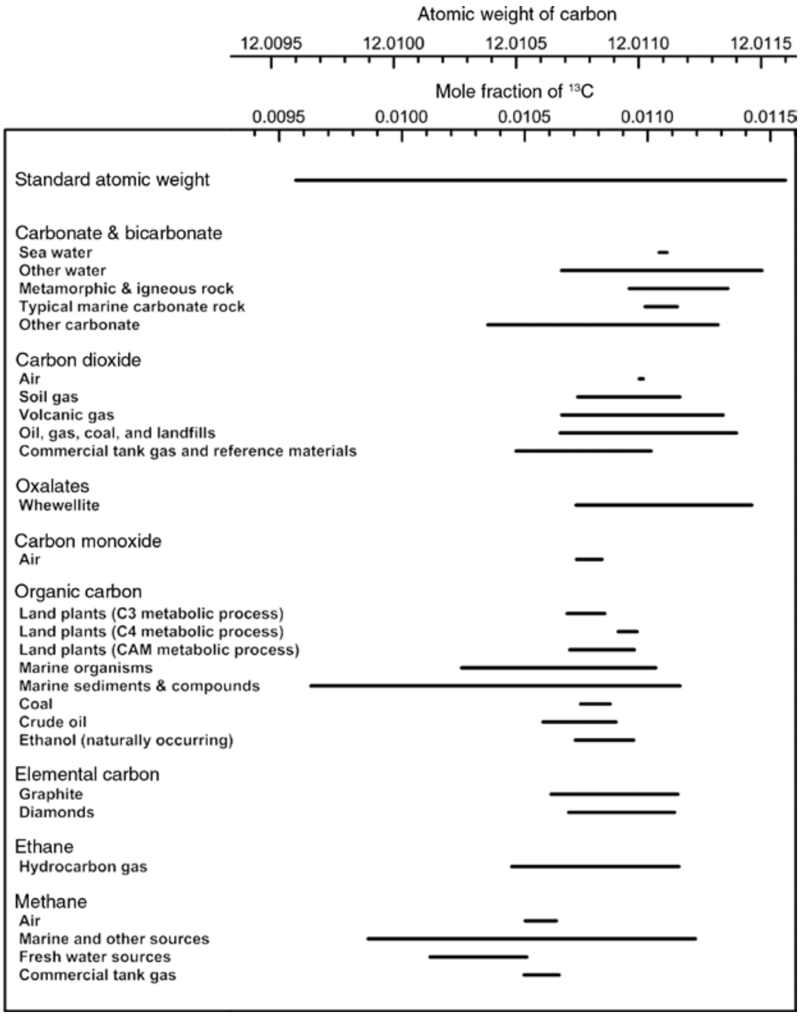


Fig. 4.6.3: Variation in **atomic weight** with **isotopic composition** of selected carbon-bearing materials (modified from [13, 17]).

distinguish, for example, between beet sugar and cane sugar. Complications in source identification can arise with plants that open stomata at night to collect carbon dioxide to use a third mechanism to fix atmospheric carbon dioxide (CAM or crassulacean acid **metabolism**). The isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of CAM plants overlaps that of C_3 or C_4 plants — examples include pineapples and jade plants. The following adulterations are commonly detected using stable carbon isotope IRMS:

- Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of honey are used to detect the addition (and potential adulteration) of high fructose corn syrup, corn, or sugar cane [67].
- Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of fruit juice have been used to detect the addition of a sugar [67].
- Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of natural vanilla extract have been used to detect the addition of artificial vanillin or p-hydroxybenzaldehyde [67].
- Variations in the isotope-amount ratio $n(^{13}C)/n(^{12}C)$ of beer are used to detect C_4 carbon, which would indicate that a beer company may have added ingredients that are not traditionally used in brewing beer. Therefore, this ratio is used to detect the misrepresentation of a product as being pure [67, 68].

Stable carbon IRMS has been used to determine if the botanical origin of an alcoholic spirit has been mislabeled and if chaptalization (the process of adding sugar to increase the alcoholic content) of wine has occurred [67, 68]. ^{14}C **scintillation counting** has been used to determine the age of wine and alcoholic

Fig. 4.6.4: Variations in the **isotope-amount ratio** $n(^{13}\mathrm{C})/n(^{12}\mathrm{C})$ of marijuana have been used to determine if the plants were grown inside a building or greenhouse or were "open grown." (Image Source: U.S. Drug Enforcement Administration and U.S. Department of Justice) [74].

spirits [67, 68]. Variations in the isotope-amount ratio $n(^{13}\mathrm{C})/n(^{12}\mathrm{C})$ of urine has been used to determine if steroids in urine are natural or of synthetic origin. These measurements enable anti-doping laboratories to perfect their methods for detecting steroid doping in athletes [69–71]. Variations in the isotope-amount ratio $n(^{13}\mathrm{C})/n(^{12}\mathrm{C})$ of marijuana can provide information to determine if the plants were grown "inside" a building or greenhouse or were "open grown" (Fig. 4.6.4). Plant carbon **isotopic compositions** are controlled by atmospheric CO_2 and the supply and demand of CO_2 in photosynthesis (the process used by plants to convert light energy from the sun into chemical energy). "Open grown" plants are grown in an area that is well ventilated and receives natural CO_2. In contrast, plants grown "inside" receive supplemented CO_2 and the photosynthesis process is more confined. Additionally, CO_2 from a tank of compressed gas used to augment atmospheric CO_2 to increase the growth of marijuana plants is commonly highly depleted in ^{13}C as a refinery by-product. These differences change the carbon **isotope ratios** of the plants and the ratios vary enough to enable the determination of the growing and cultivation process of marijuana [72, 73].

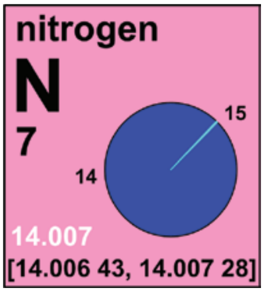
4.6.4 Carbon isotopes in geochronology

Radioactive ^{14}C is the basis for the radiocarbon dating method to determine the ages of carbon-bearing materials. ^{14}C is formed naturally in the atmosphere by **cosmic-ray** interactions and was also released by above-ground, nuclear weapons testing (Fig. 4.6.1). Atmospheric ^{14}C is incorporated into plants, animals, soils, groundwater, and ocean water, and it decays with a **half-life** of ~5700 years. This makes it useful for dating objects, such as archaeological remains and water masses in oceans and aquifers, on time scales ranging from hundreds of years to tens of thousands of years [15]. Plants and animals living since the 1950s can be identified by bomb-peak ^{14}C in their cells (see Section 4.6.1).

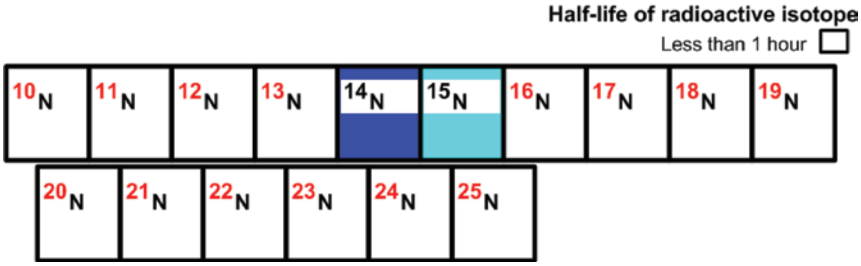
4.6.5 Carbon isotopes in medicine

^{14}C is used to create **isotopically labeled** drugs to study their uptake and metabolism in humans [75–77]. ^{13}C is used in breath tests to detect *Helicobacter pylori* bacteria (bacteria in the stomach linked to ulcers), which can cause cancers [78].

4.7 Nitrogen



Stable isotope	Relative atomic mass	Mole fraction
^{14}N	14.003 074 004	[0.995 78, 0.996 63]
^{15}N	15.000 108 899	[0.003 37, 0.004 22]



4.7.1 Nitrogen isotopes in biology

Isotopic fractionation can cause the **isotope-amount ratio** $n(^{15}\text{N})/n(^{14}\text{N})$ to increase systematically through food chains through assimilation of nitrogen compounds in biomolecules such as proteins. When lower-order organisms are ingested by higher-order organisms, ^{15}N may be selectively retained and ^{14}N may be selectively excreted such that higher-order organisms tend to have higher $n(^{15}\text{N})/n(^{14}\text{N})$ ratios than their food sources. Isotopic fractionation occurs as a result of assimilation, storage, and **excretion** of proteins and other nitrogen compounds. Biologists can use isotope-amount ratio $n(^{15}\text{N})/n(^{14}\text{N})$ measurements to test hypotheses

Fig. 4.7.1: Variation in nitrogen **stable isotopes** has been used to track fertilizer nitrogen into plants, soils, and infiltrating groundwater in experiments to improve agricultural efficiency and reduce impacts on the environment. This aerial photograph shows experimental agricultural fields where different amounts of excess nitrogen from fertilizer and plant residues can be found in groundwater. (Photo Source: Böhlke, J.K., U.S. Geological Survey).

Fig. 4.7.2: **Tracer** experiments with the **stable isotope** ^{15}N have been used to track excess dissolved nitrate in groundwater and streams and to determine to what extent the dissolved nitrate is removed by natural processes, such as conversion to harmless N_2 gas before entering nitrogen-sensitive ecosystems [83]. (Photo Source: Böhlke, J.K., U.S. Geological Survey).

about predator-prey relations and detect disruptions to trophic structure of ecosystems that might be caused by toxic contaminants, invasive species, or harvesting of organisms. Similar principles are used to detect differences in diets among animals, including humans, both today and in the distant past [79–81].

Artificially enriched ^{15}N **tracers** are used to study movement and transformation of nitrogen in biological and environmental systems, such as the uptake and loss of nitrogen fertilizers by crops (Fig. 4.7.1). A common experiment involves introducing an **isotopically labeled compound** into the environment and then analyzing various samples taken from the environment for the presence of the enriched **isotope** to determine where the labeled compound moved and whether it transformed into other compounds (Fig. 4.7.2). Artificially enriched ^{15}N is used to study uptake and dispersal of nitrogen in feed supplies used in food production industries such as aquaculture [82].

4.7.2 Nitrogen isotopes in Earth/planetary science

The **stable isotopes** of nitrogen are subject to isotopic fractionation by physical, chemical, and biological processes. Variations in the isotope-amount ratio $n(^{15}\mathrm{N})/n(^{14}\mathrm{N})$ are substantial (Fig. 4.7.3) and commonly are used to study Earth-system processes, especially those related to biology because nitrogen is a major nutrient for growth [84]. For example, isotope fractionation occurs when dissolved solutes, such as nitrate (NO_3^-), are transformed to more reduced compounds (*i.e.* nitrogen gas) because nitrate with higher ^{14}N abundances tends to be more readily broken down. This leaves the residual unreacted nitrate with a higher $n(^{15}\mathrm{N})/n(^{14}\mathrm{N})$ ratio than the initial ratio prior to reaction. Changes in the **isotopic composition** of biologically reactive compounds can be used to detect such reactions in aquatic environments, which are important mechanisms for removing reactive contaminants like nitrate [85, 86].

Variations in the isotope-amount ratio $n(^{15}\mathrm{N})/n(^{14}\mathrm{N})$ are used to determine sources of nitrogen contamination in the atmosphere, oceans, groundwater, and rivers, where the isotopic composition of a contaminant molecule preserves evidence of the nitrogen sources and processes involved in its creation. An example is nitrate derived from artificial fertilizer, manure, power-plant emissions, or natural sources [87–89].

Artificially enriched ^{15}N tracers have been used to determine rates of movement and natural remediation of nitrogen-bearing contaminants in aquifers and rivers [83, 90].

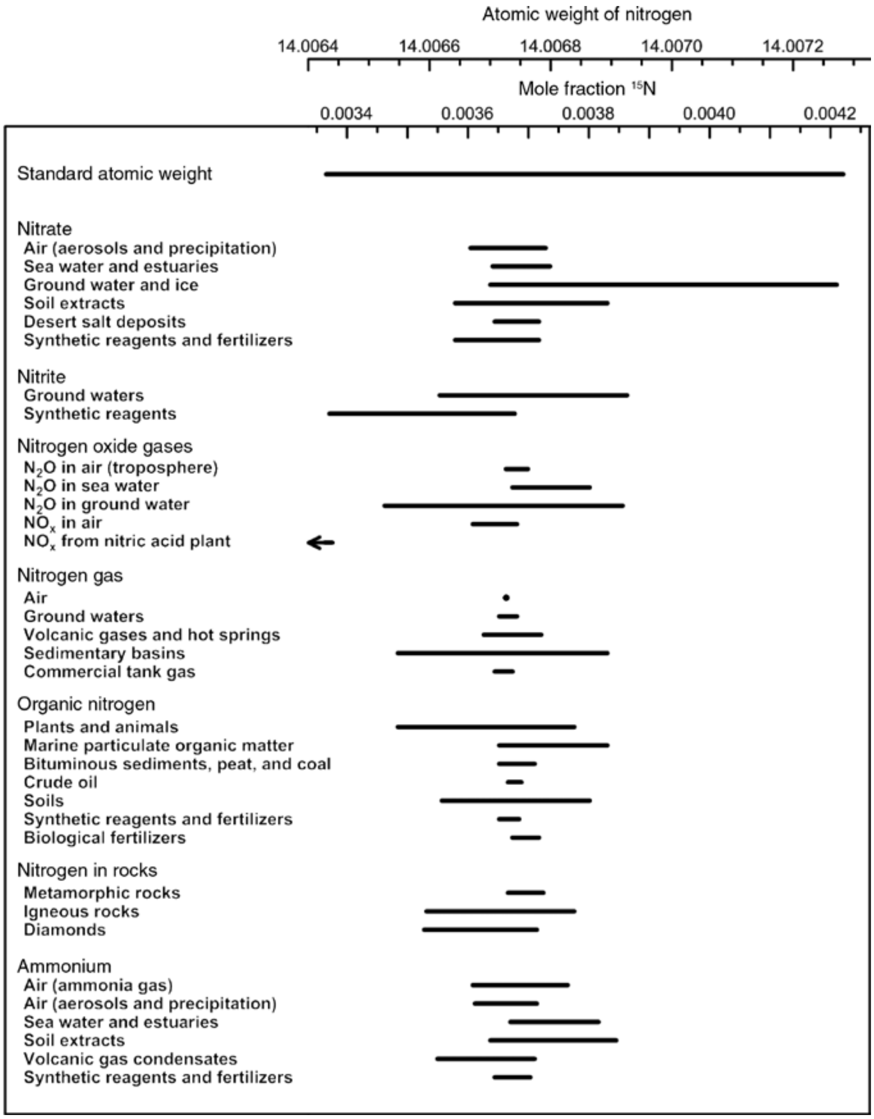
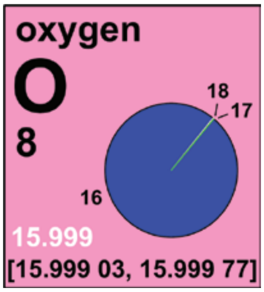


Fig. 4.7.3: Variation in **atomic weight** with **isotopic composition** of selected nitrogen-bearing materials (modified from [13, 17]).

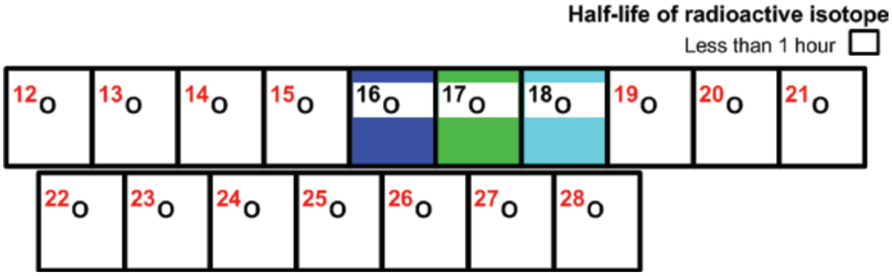
4.7.3 Nitrogen isotopes in forensic science and anthropology

Stable hydrogen, carbon, and nitrogen isotopic compositions are used to determine the origin of pseudoephedrine from seized methyl-amphetamine made from the pseudoephedrine (drug used as a nasal decongestant or as a stimulant) [91].

4.8 Oxygen



Stable isotope	Relative atomic mass	Mole fraction
^{16}O	15.994 914 619	[0.997 38, 0.997 76]
^{17}O	16.999 131 757	[0.000 367, 0.000 400]
^{18}O	17.999 159 613	[0.001 87, 0.002 22]



4.8.1 Oxygen isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of oxygen possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of oxygen in natural terrestrial materials (Fig. 4.8.1). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [13].

A primary use of stable oxygen **isotopes** is in isotope hydrology. Although the evolution of the stable hydrogen and oxygen **isotopic composition** of precipitation begins with the evaporation of water from the oceans, their local and global relationship arises primarily from equilibrium **isotopic fractionation** of heavier (^{2}H and ^{18}O) and lighter isotopes (^{1}H and ^{16}O) of hydrogen and oxygen during condensation as a **tropospheric** vapor mass follows a trajectory to higher latitudes and over continents [14, 15]. As a consequence, the isotopic composition and atomic weight of oxygen in precipitation, rivers, and tap waters varies with elevation, season, and distance from the ocean-continent boundary. Figure 4.8.2 shows the variation in stable oxygen isotopic composition of water from rivers across the United States. These variations in oxygen isotopic composition of environmental water are often combined with hydrogen isotopic compositions and have been used to identify the origin of water and to investigate the interaction between groundwater and surface water (*e.g.* lakes, streams, and rivers) [16].

4.8.2 Oxygen isotopes in forensic science and anthropology

Measurements of relative ^{18}O abundances have been used to determine the breeding grounds of many species of migrant songbirds. These species of songbirds only grow their feathers before migration, and they grow them on or close to their breeding grounds. Therefore, the isotopic composition of a bird's feathers correlates to the isotopic signature of the growing season's precipitation [19, 20].

Measurements of relative ^{18}O abundances of human hair or nail samples collected at archeological sites have been used to determine the geographic region in which a subject lived based on the oxygen isotopic

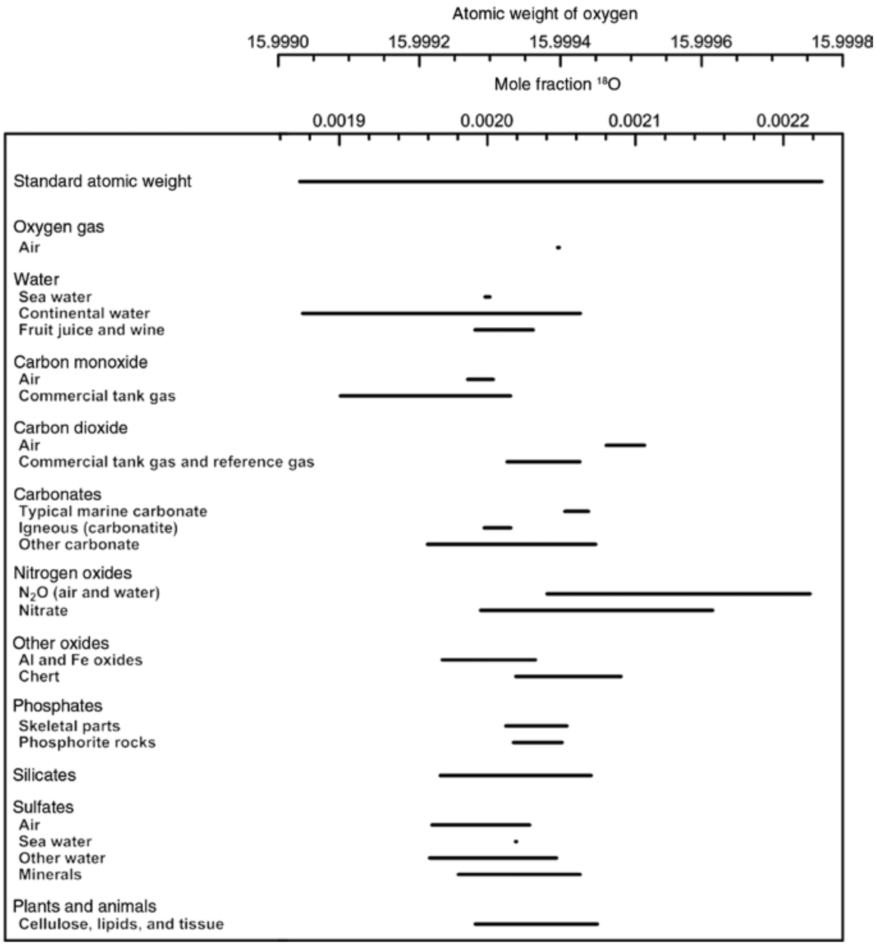


Fig. 4.8.1: Variation in **atomic weight** with **isotopic composition** of selected oxygen-bearing materials (modified from [13, 17]).

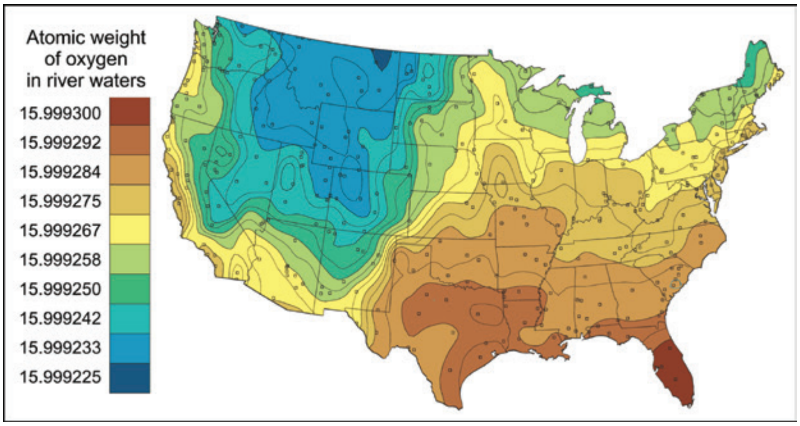


Fig. 4.8.2: Variation in **atomic weight** of oxygen in river waters across the continental United States (modified from [16]). Blue color indicates waters most depleted in ^{18}O (resulting in lower atomic weight of oxygen) and brown color indicates those most enriched in ^{18}O (resulting in higher atomic weight of oxygen).

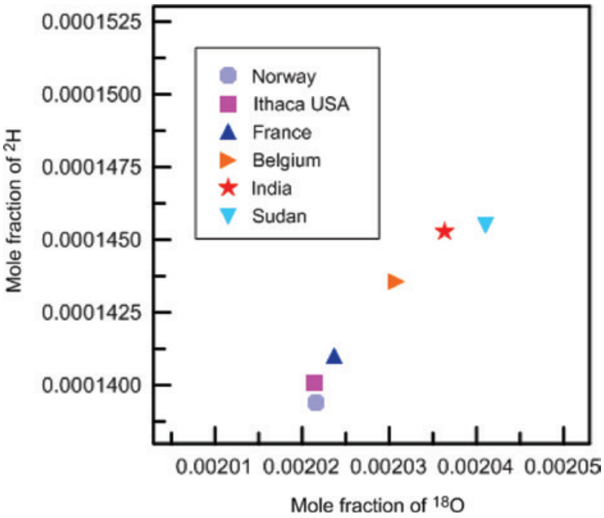


Fig. 4.8.3: Cross plot of **mole fractions** of ^{2}H and ^{18}O of human nail samples from a variety of global sites (modified from [93]). The hydrogen and oxygen **isotopic compositions** reflect the oxygen and hydrogen isotopic compositions of water consumed, and generally they decrease with increasing latitude, increasing elevation, and distance inland from the ocean-continent boundary [14, 15].

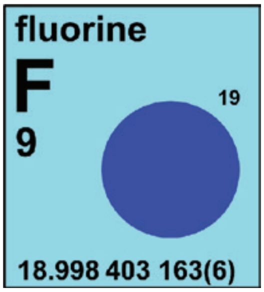
composition of the water they drank (Fig. 4.8.3). This is possible because hair stores a daily record of oxygen isotopic composition of intake water, which correlates to local **meteoric water** [92].

4.8.3 Oxygen isotopes in medicine

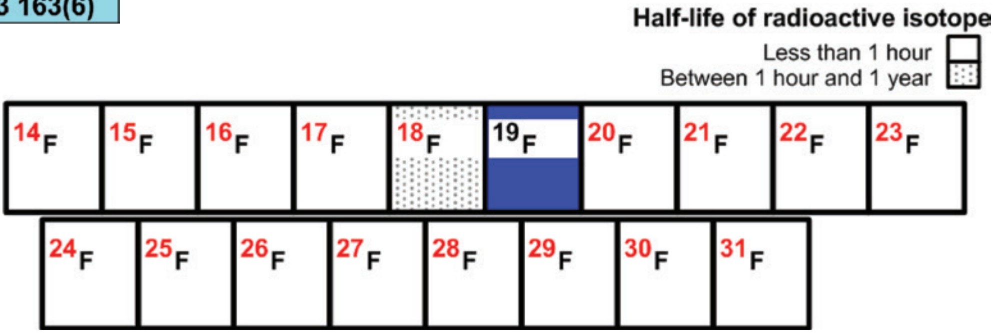
^{16}O is used to produce radioactive ^{13}N *via* the ^{16}O (p, ^{4}He) ^{13}N reaction for imaging in **positron emission tomography** (**PET**) and to study blood flow through the heart (myocardial perfusion) [94, 95].

^{17}O has been used as a **tracer** to study cerebral oxygen utilization [96]. Variations in stable oxygen and hydrogen isotopes are used in energy expenditure studies in animals and humans. The subject is administered a dose of doubly labeled water (water enriched in both ^{2}H and ^{18}O). Measurements of the elimination rates of ^{2}H and ^{18}O in the subject over time through regular sampling of body water (by sampling saliva, urine, or blood) provide information on energy expenditure because the hydrogen isotopic composition of body water is affected primarily by water loss (mainly urination), but the oxygen isotopic composition is affected by both respiration and water loss [97].

4.9 Fluorine



Stable isotope	Relative atomic mass	Mole fraction
^{19}F	18.998 403 163	1



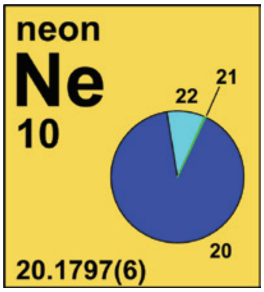
4.9.1 Fluorine isotopes in medicine

^{18}F is a radioactive fluorine **isotope** that is used in an ^{18}F-FDG compound (^{18}F-labeled, fluoro-deoxy glucose) for imaging the organs, bones, tissues, and brain of the body with a technique called **positron emission topography** (**PET**). The ^{18}F-FDG compound is injected and the **isotopically labeled** glucose is consumed by any cell requiring glucose as a source of energy [98, 99].

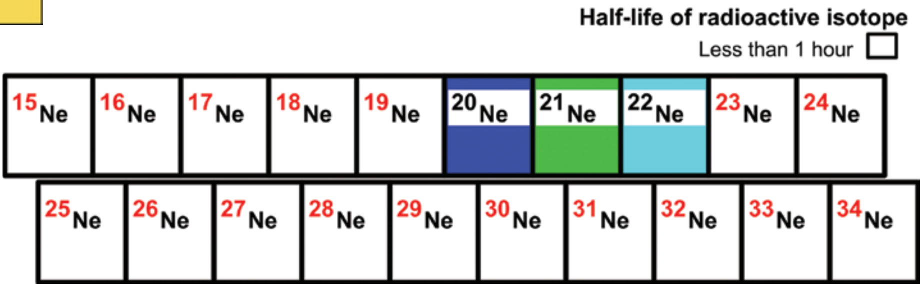
- ^{18}F emits **positrons** that collect in tissue and interact with regular negative **electrons** when injected into the body. The positrons and electrons annihilate each other, producing two **gamma rays** that are emitted in opposite directions. The radiation is detected on a PET camera, which generates a picture of the body part being examined (Fig. 4.9.1).
- Because ^{18}F has a short **half-life** of about 110 min, there is little chance of radiation damage to the patient.

Fig. 4.9.1: An ^{18}F-FDG **PET** scan is used to observe the differences in brain activity between a sober and an intoxicated brain. (Image Source: National Institute on Alcohol Abuse and Alcoholism (NIAAA)) [100].

4.10 Neon



Stable isotope	Relative atomic mass	Mole fraction
^{20}Ne	19.992 440 18	0.9048
^{21}Ne	20.993 8467	0.0027
^{22}Ne	21.991 3851	0.0925



4.10.1 Neon isotopes in Earth/planetary science

Neon is subject to stable **isotopic fractionation** by physical processes, such as exchange between gas, liquid, and solid phases. Small variations in the **isotope-amount ratio** $n(^{22}\mathrm{Ne})/n(^{20}\mathrm{Ne})$ have been used to examine gas-liquid exchange processes during groundwater recharge (water moving downward from the surface) and discharge [29, 101, 102].

4.10.2 Neon isotopes in geochronology

Some ^{21}Ne and ^{22}Ne form naturally in the Earth's crust largely by reactions of ^{18}O and ^{19}F in minerals with **neutrons** and **alpha particles** emitted from uranium and thorium decay, called nucleogenic neon **isotopes** [29, 101]. In addition, neon isotopes can form at the surface of the Earth and in extraterrestrial bodies by **cosmic-ray**-induced **spallation** reactions on magnesium, silicon, aluminum, and sodium [103, 104]. Analyses of all three stable neon isotopes may be used to distinguish these sources from **primordial** neon. The relative amounts of atmospheric neon and crustal nucleogenic neon isotopes in deep groundwaters and natural gases have been used in studies of solid-water-gas interactions and migration (Fig. 4.10.1). The **cosmogenic** component is mainly detected in ^{21}Ne and can be used to determine cosmic-ray exposure ages of rock samples, including **meteorites** exposed during travel through space and boulders exposed by melting of glacial ice (Fig. 4.10.1).

4.10.3 Neon isotopes in industry

Masers (Microwave Amplification by Stimulated Emission of Radiation) containing ^{20}Ne have been used to study quantum physics. ^{21}Ne may also play a role in maser studies of quantum physics [106].

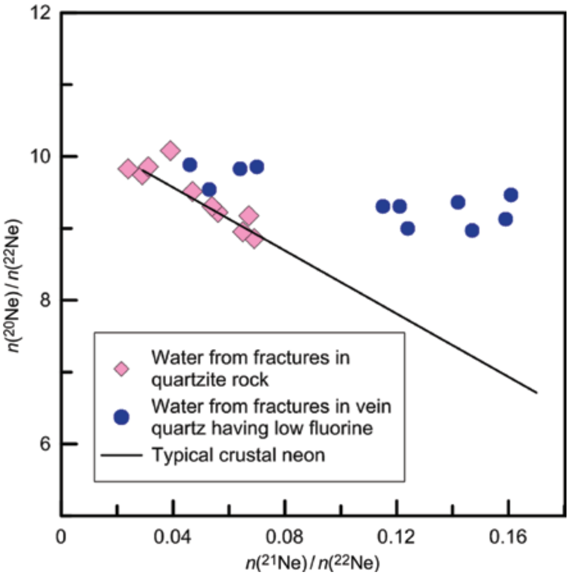
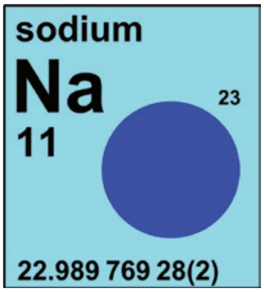


Fig. 4.10.1: Neon-**isotope ratios** of water from fractures in quartzite (open diamonds) and water from fractures in vein quartz (solid circles) from the deep gold mines of the Witwatersrand Basin, South Africa [105]. The **isotope-amount ratio** $n(^{21}Ne)/n(^{22}Ne)$ depends upon the **amount ratio** of oxygen to fluorine in the ~40-µm reaction range of **alpha particles** from uranium and thorium. Lippmann-Pipke *et al.* [105] show that the neon end-member represents a fluorine-depleted fluid component that was trapped in fluid inclusions in vein quartz more than 2×10^9 years ago.

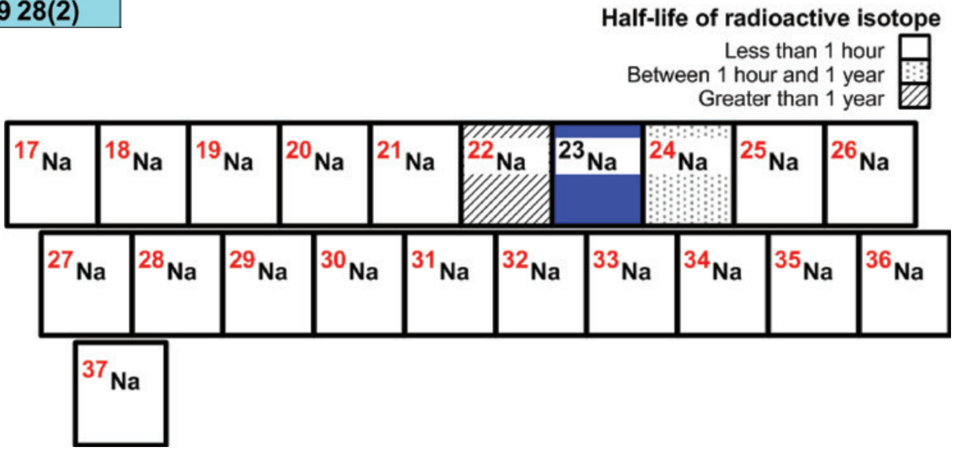
4.10.4 Neon isotopes used as a source of radioactive isotope(s)

^{22}Ne is used to produce the **radioisotope** ^{22}Na *via* the reaction ^{22}Ne (p, n) ^{22}Na [107]. ^{20}Ne has been used to produce the radioisotope ^{18}F *via* the reaction ^{20}Ne (d, ^{4}He) ^{18}F [107].

4.11 Sodium



Stable isotope	Relative atomic mass	Mole fraction
^{23}Na	22.989 769 28	1



4.11.1 Sodium isotopes in biology

Both ^{22}Na and ^{24}Na have been used as radioactive **tracers** to study electrolytes in the human body [108–110].

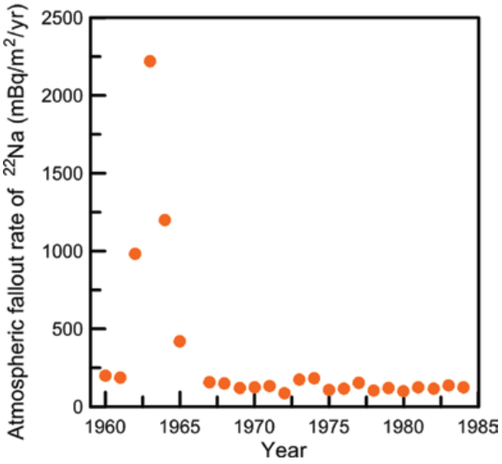


Fig. 4.11.1: Variation of ^{22}Na atmospheric fallout rate at St. Petersburg, Russia (modified from [111]); note that an abbreviation “yr” is used instead of the unit symbol “a” for year. This variation makes ^{22}Na useful for determining **residence time** of lakes and other surface water bodies.

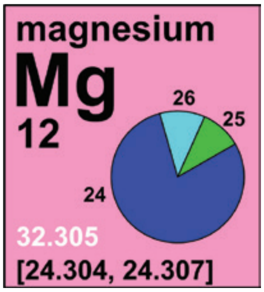
4.11.2 Sodium isotopes in geochronology

^{22}Na is a **cosmogenic isotope** with a **half-life** of 2.6 years that has been used to study the **residence time** of water in freshwater basins. It has been used for dating of young (up to a few decades old) surface water and groundwater (Fig. 4.11.1) [111].

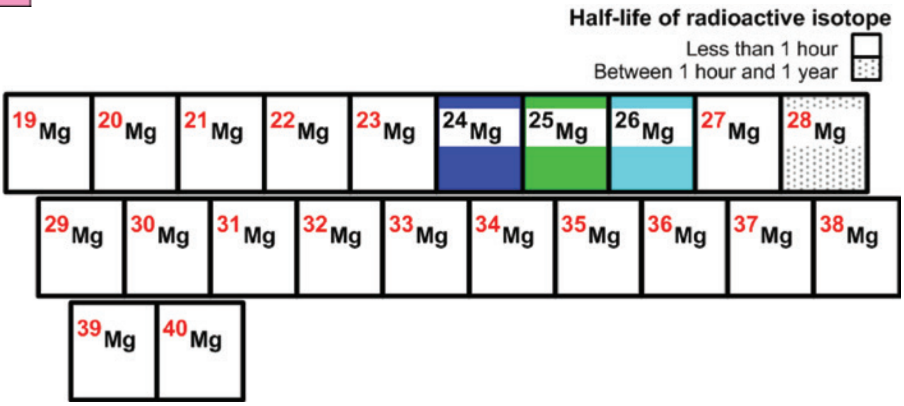
4.11.3 Sodium isotopes in medicine

^{22}Na is used as a source to calibrate **positron emission tomography** (**PET**) imaging scanners to check that the instruments are functioning properly [112].

4.12 Magnesium



Stable isotope	Relative atomic mass	Mole fraction
^{24}Mg	23.985 041 70	[0.7888, 0.7905]
^{25}Mg	24.985 8370	[0.099 88, 0.100 34]
^{26}Mg	25.982 5930	[0.1096, 0.1109]



4.12.1 Magnesium isotopes in biology

Natural magnesium enriched in the **stable isotopes** ^{25}Mg and ^{26}Mg has been used as **tracers** in human studies to assess absorption, **excretion**, distribution, and utilization of magnesium in basic and applied research [108, 113, 114].

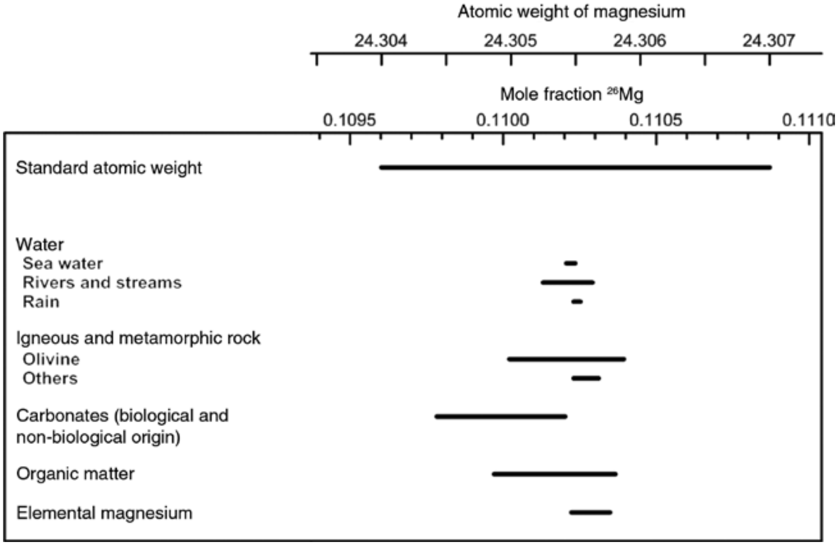


Fig. 4.12.1: Variation in **atomic weight** with **isotopic composition** of selected magnesium-bearing materials (modified from [13, 17]).

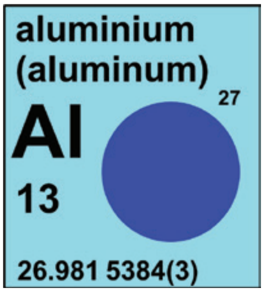
4.12.2 Magnesium isotopes in Earth/planetary science

Molecules, atoms, and ions of the stable isotopes of magnesium possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of magnesium in natural terrestrial materials (Fig. 4.12.1). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [13, 17, 115].

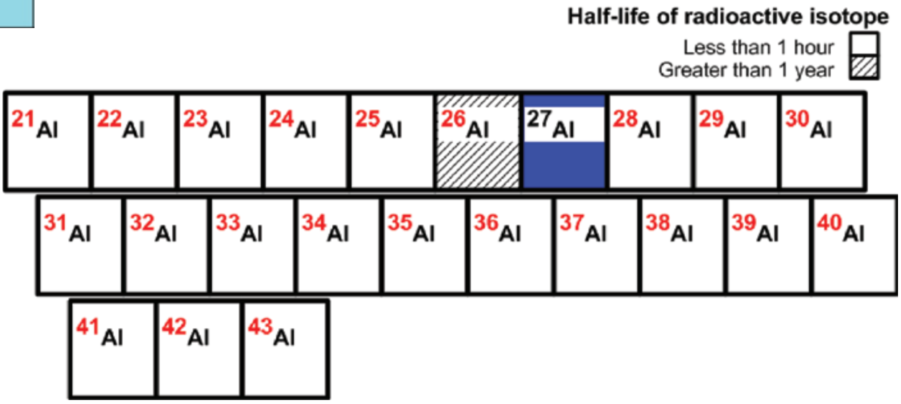
4.12.3 Magnesium isotopes in geochronology

^{26}Mg is a stable isotope and is the **radiogenic** product of ^{26}Al decay. ^{26}Al is produced by **cosmic rays** in space and in the atmosphere, and it was present in the **primordial solar nebula**. The anomalous abundance of ^{26}Mg in **meteorite** inclusions indicate that this material must have been formed early in the development of the Solar System before all primordial ^{26}Al (with **half-life** of 7.1×10^5 years) had decayed [116].

4.13 Aluminium (aluminum)



Stable isotope	Relative atomic mass	Mole fraction
^{27}Al	26.981 5384	1



4.13.1 Aluminium isotopes in biology

^{26}Al is a **radioactive isotope** (**half-life** of 7.1×10^5 years) that can be detected at the ultra-trace level (attogram range; 10^{-18} g levels) using **accelerator mass spectrometry**. ^{26}Al is used as a **tracer** to study the uptake, distribution, and retention of aluminium in plants, animals, and humans under different physiological conditions [117, 118].

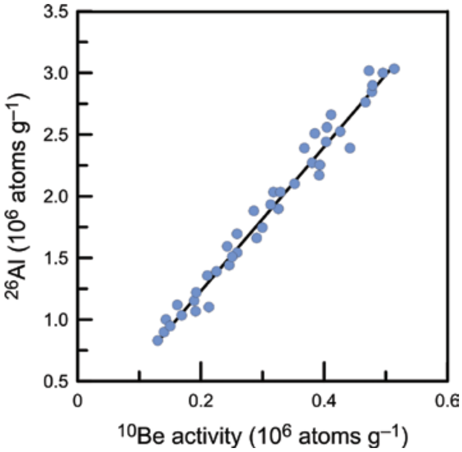


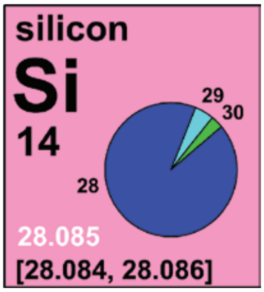
Fig. 4.13.1: ^{26}Al and ^{10}Be content in forty sediment samples from eastern Mojave Desert, California (modified from [121]). These results enabled investigators to determine that sediment moves down the piedmont in an active transport layer, which is 20 to 30 cm thick.

4.13.2 Aluminium isotopes in geochronology

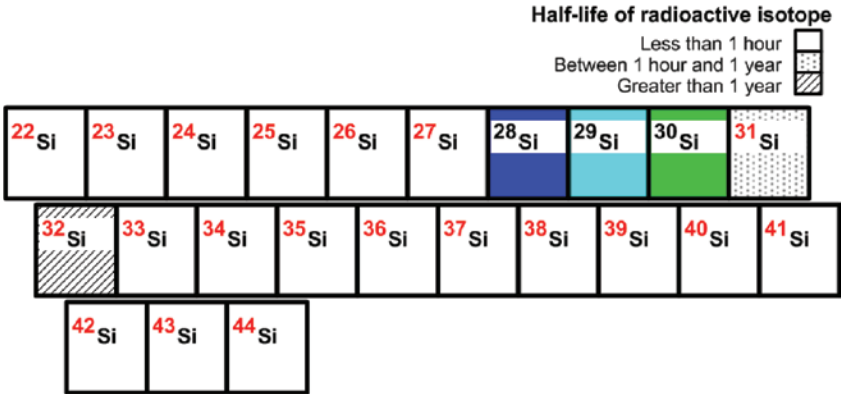
^{26}Al is produced from **spallation** reactions of **protons**, produced by **cosmic rays**, on argon. ^{26}Al has been used for dating geological samples, such as **marine** sediments, manganese nodules, rocks, and **meteorites** [119, 120]. The abundances of ^{26}Al to ^{10}Be have been used to study erosion and transport of soil and sediments on a thousand- to million-year time scale, because production rates of ^{26}Al to ^{10}Be are greatest at the surface and decrease exponentially with depth (Fig. 4.13.1) [121, 122].

Intense cosmic-ray bombardment in space produces ^{26}Al in meteorites and other bodies, such as the Moon. After a meteorite falls to Earth, ^{26}Al production ceases due to atmospheric shielding; the decay of ^{26}Al to ^{26}Mg has been used to determine the terrestrial age of a meteorite (*i.e.* the time elapsed since the meteorite fell to Earth) [119].

4.14 Silicon



Stable isotope	Relative atomic mass	Mole fraction
^{28}Si	27.976 926 535	[0.921 91, 0.923 18]
^{29}Si	28.976 494 665	[0.046 45, 0.046 99]
^{30}Si	29.973 7701	[0.030 37, 0.031 10]



4.14.1 Silicon isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of silicon possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of silicon in natural terrestrial materials (Fig. 4.14.1). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [13, 17]. Diatoms, a major group of algae, need silicon to build up their opaline shells and prefer ^{28}Si while

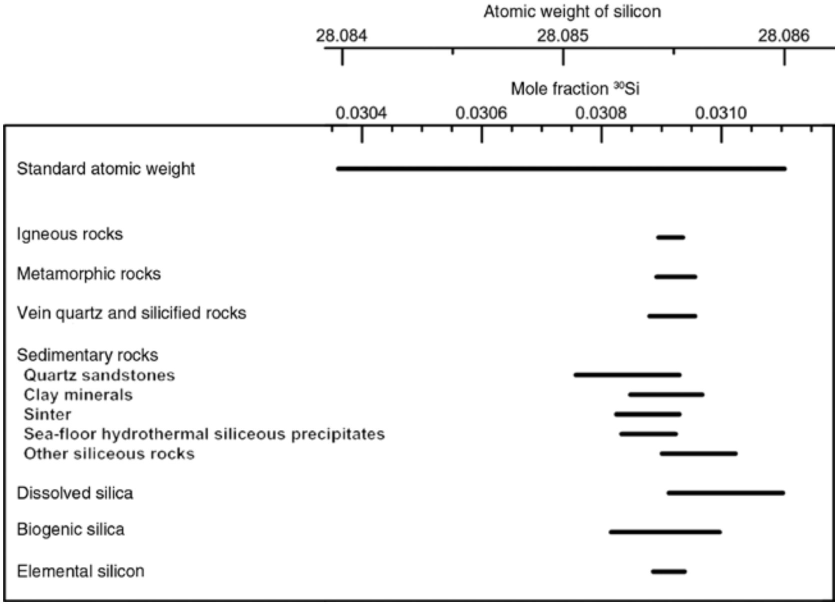


Fig. 4.14.1: Variation in **atomic weight** with **isotopic composition** of selected silicon-bearing materials (modified from [13, 17]).

taking up $Si(OH)_4$, which is the biologically available form of silicon in the marine environment. This progressively enriches surface waters with ^{29}Si and ^{30}Si [123]. ^{32}Si-labeled silicic acid of high specific radioactivity is used to measure uptake rates of Si and estimate marine sedimentation of biogenic (created by living organisms) silica (by diatoms and sea shells). By performing uptake kinetic experiments, the ^{32}Si **activity** can be measured as ^{32}P using counting of Cherenkov radiation (radiation produced by charged particles passing through a medium at a speed greater than that of light through the same medium — after Soviet physicist Pavel A. Cherenkov) with a liquid scintillation analyzer (measuring **ionizing** radiation using the interaction of radiation on a material and counting the resulting **photon** emissions).

4.14.2 Silicon isotopes in geochronology

Cosmogenic ^{32}Si has a **half-life** of about 150 years and is produced by **cosmic-ray spallation** of argon in the stratosphere and **troposphere** [124]. ^{32}Si in dust is precipitated in snow, making it possible to date dust in snow and glacial ice (Fig. 4.14.2). Glaciers are archives for global climate history because they contain a variety of proxies (imprints of past environmental conditions used to interpret paleoclimate) for climate forcing and climate response. Cosmogenic ^{32}Si that is stored in glaciers and ice-core samples can be analyzed using **accelerator mass spectrometry** to date when sections of glaciers formed [125, 126].

4.14.3 Silicon isotopes in industry

At Keio University in Japan, the Itoh Research Group has developed a method that utilizes ^{29}Si to store and process information. The Itoh Research Group focused on manipulating the nanostructure of materials at an atomic level, especially with **semiconductors** such as silicon. Their manipulations and observations demonstrate that differences in the nuclear spin and mass of an **isotope** affects the ease of further manipulation of the isotope [128, 129].

Silicon crystals enriched to higher than 99.99 percent purity of ^{28}Si are being used in the Avogadro Project. This project is intended to remeasure the **Avogadro constant** (N_A), which is the proportionality factor between the amount of substance and number of elementary entities [130].

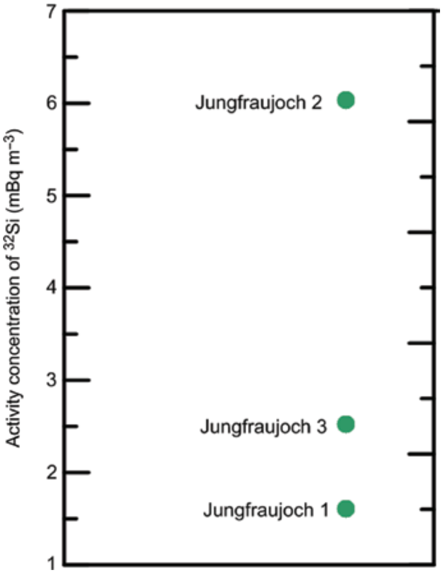
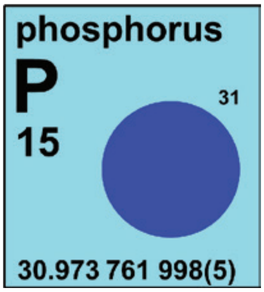
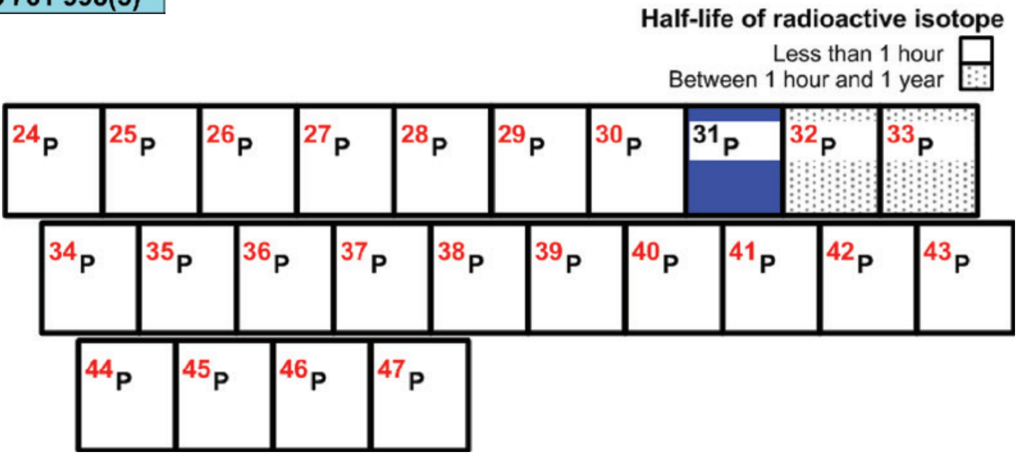


Fig. 4.14.2: ^{32}Si activity concentrations in three snow samples from Jungfraujoch, a glacial pass in the Bernese Alps at an elevation of approximately 3.5 km above sea level (modified from [127]). Sample Jungfraujoch 2 contains Saharan dust and has a substantially higher concentration of ^{32}Si than snow samples not containing Saharan dust.

4.15 Phosphorus



Stable isotope	Relative atomic mass	Mole fraction
^{31}P	30.973 761 999	1



4.15.1 Phosphorus isotopes in biology

^{32}P (**half-life** of 14.3 days) is a **radioactive isotope** of phosphorus that is used to help understand the biological and chemical processes in plants. It is chemically identical to other **isotopes** of phosphorous and can be substituted in biological and chemical reactions. For example, a phosphate solution containing ^{32}P (which has the identical behavior of non-radioactive ^{31}P) can be inserted into the roots of a plant and its movement can then be tracked throughout the plant with the use of a **Geiger counter**. This movement detection study helps scientists to better understand how plants use phosphorous to reproduce and grow [131, 132].

At the molecular level, ^{32}P can substitute for ^{31}P in nucleotides of **DNA** or RNA (ribonucleic acid, a single stranded molecule that regulates genes). Radioactive probes can be created to help identify the presence, absence, and quantity of genes in a system [133, 134].

4.15.2 Phosphorus isotopes in Earth/planetary science

^{32}P has been used as a **tracer** to help determine phosphorus nutrient cycling in eutrophied lakes (lakes rich in organic and mineral nutrients commonly leading to the excessive growth of phytoplankton, a self-feeding water organism) (Fig. 4.15.1). In one experiment, phosphoric acid labeled with ^{32}P was added to a lake that had been experimentally eutrophied. ^{32}P was measured in microphytoplankton (plankton visible only with a microscope), phytoplankton, and zooplankton (tiny animals that live suspended in fresh or salt water), and the amount of incorporated ^{32}P was determined [132].

^{33}P has been used to better understand phosphorus dynamics in the environment at the sediment-surface level. Phosphorus is a necessary nutrient for many biota (the plant and animal life of a particular habitat, region, or geological period). Understanding bioavailability and sorption (bonding) of this nutrient

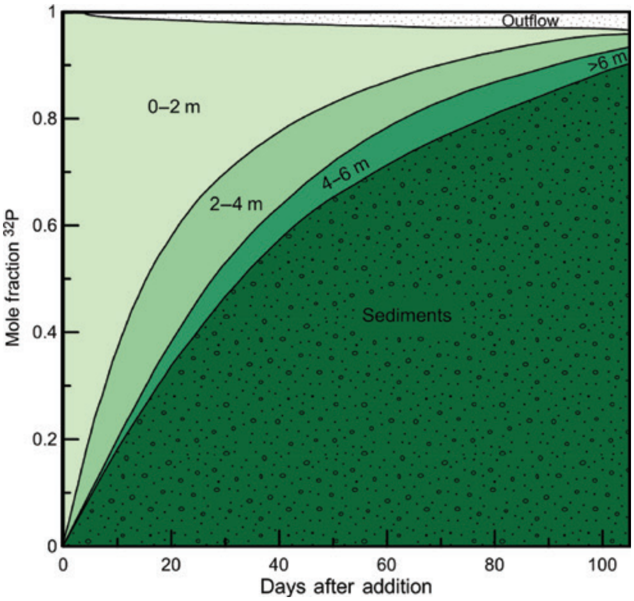


Fig. 4.15.1: Partitioning of ^{32}P among water layers, the sediments, and outflow during the 105 days following addition of ^{32}P to the upper layer of stratified Lake 227 (northwestern Ontario) to trace the lake's phosphorus cycle during lake stratification and fall overturn (modified from [132]).

to particles in soil is important for understanding ecosystem health. Organic and inorganic phosphorus **substrates isotopically labeled** with ^{33}P can be tracked within a sediment system to determine their transport properties and availability to biota [135].

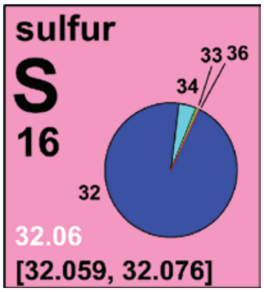
4.15.3 Phosphorus isotopes in industry

^{32}P was added to tires in the 1950s by Goodrich Laboratories to help determine the location and depth of tire wear in performance tests [136].

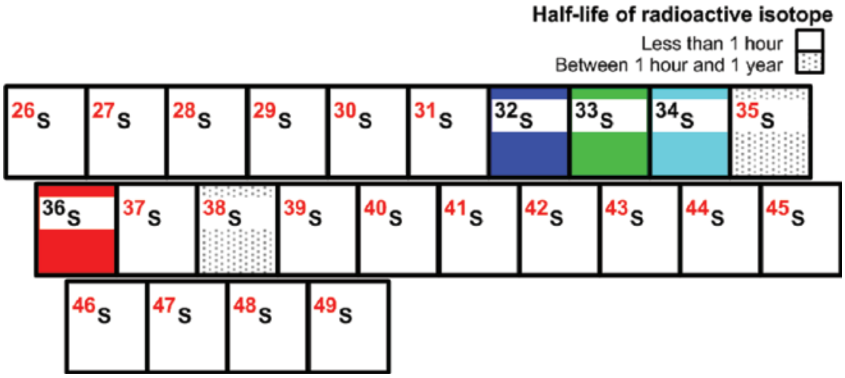
4.15.4 Phosphorus isotopes in medicine

Beta emissions from the radioactive isotope ^{32}P can be used in drug therapy of cancerous bone masses. By injecting a patient with a ^{32}P pharmaceutical, tumors and other cells can be targeted for cell death, which also helps to alleviate pain [137, 138]. For example, *Polycythemia vera* is the condition of having excess red blood cells in the bone marrow: ^{32}P can be used to treat this condition by reducing the number of red blood cells. However, there is no cure for this condition [139]. Using a ^{32}P labeled bio-silicone product, ^{32}P has been used as the radioactive target in **brachytherapy** of solid tumors in the lung [140]. Depending on the type of ^{32}P-labeled compound (antibody or pharmaceutical drug), when it is ingested or injected into the body, specific body parts (blood, tumors, joints, or bones) can be targeted for visualization and imaged using a **gamma camera**. This is useful for imaging cancer sites and for treatment monitoring of oncologic patients [133, 134, 138].

4.16 Sulfur



Stable isotope	Relative atomic mass	Mole fraction
^{32}S	31.972 071 174	[0.9441, 0.9529]
^{33}S	32.971 458 910	[0.007 29, 0.007 97]
^{34}S	33.967 8670	[0.0396, 0.0477]
^{36}S	35.967 081	[0.000 129, 0.000 187]



4.16.1 Sulfur isotopes in biology

The stable sulfur **isotope-amount ratio** $n(^{34}\mathrm{S})/n(^{32}\mathrm{S})$ has been used to distinguish whether animal tissues grew in freshwater or in marine ecosystems. The **isotopes** do not fractionate (separate) substantially with trophic influences (the movement of sulfur through and into plant and animal systems), and the isotope-amount ratio $n(^{34}\mathrm{S})/n(^{32}\mathrm{S})$ is usually substantially different between freshwater and marine environments. As an example, by analyzing sulfur isotope-amount ratios in bird feathers, the environment in which the bird was living when these feathers developed can be determined. This enables one to track bird habitats and migration patterns throughout the year (Fig. 4.16.1) [141].

4.16.2 Sulfur isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of sulfur possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of sulfur in natural terrestrial materials (Fig. 4.16.2). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [13, 17]. The isotope-amount ratio $n(^{34}\mathrm{S})/n(^{32}\mathrm{S})$ can be used to trace natural and **anthropogenic** sources of sulfur. Examples include studies of acid mine drainage, the cycling of sulfur in agricultural watersheds, groundwater contamination from landfills, and sources of salinity in coastal aquifers [142–144].

4.16.3 Sulfur isotopes in forensic science and anthropology

The isotope-amount ratio $n(^{34}\mathrm{S})/n(^{32}\mathrm{S})$ can be used to authenticate the dietary source of cattle. First, stable isotopes are measured to infer the dietary source of the cattle. Once the source of the diet is found, the **isotopic**

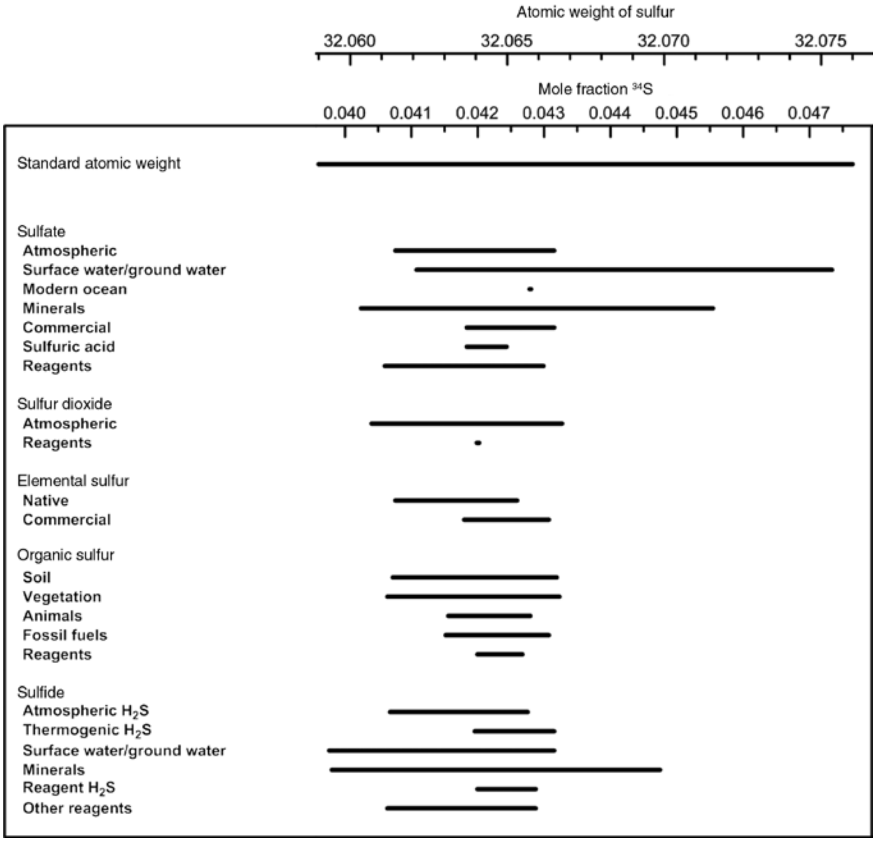


Fig. 4.16.1: Variation in **atomic weight** with **isotopic composition** of selected sulfur-bearing materials (modified from [13, 17]).

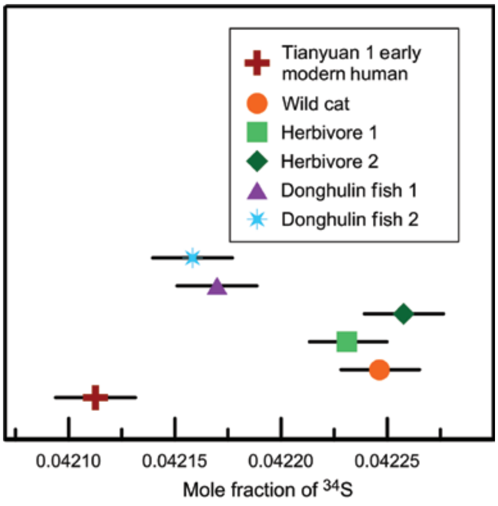


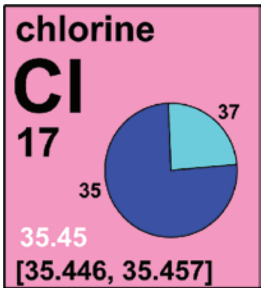
Fig. 4.16.2: Sulfur **isotopic abundances** of Tianyuan 1 early modern human found in Eurasia, three terrestrial animals from Tianyuan Cave (Tianyuandong) in the Zhoukoudian region of China, and two fish from Donghulin (modified from [146]). Based on sulfur, carbon, and nitrogen isotopic analyses of bones from the early modern human and the associated animals in Tianyuan Cave and the Donghulin site, Hu *et al.* [146] conclude that the human most likely obtained a substantial portion of its protein from a freshwater ecosystem, probably from freshwater fish.

compositions can be traced in certain muscle groups of the cattle and can be used to determine if the diet of the animal has been changed or if the feed is consistent with what the animal has been claimed to have been fed [145].

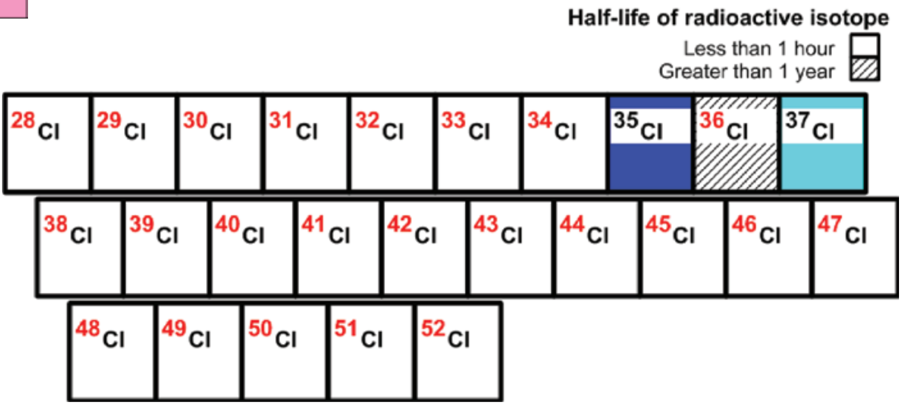
4.16.4 Sulfur isotopes in geochronology

^{35}S has a **half-life** of 87 days, which is an ideal duration for use as a conservative **tracer** in atmospheric processes. $^{35}SO_2$ gas is produced as a natural product of argon exposure to **cosmic rays** in the atmosphere. Because $^{35}SO_2$ gas is present in the atmosphere and then precipitates and falls as moisture in the form of $^{35}SO_4^{2-}$, ^{35}S can act as a tracer to study air mass transport dynamics and atmospheric oxidation capacity [147]. Analyses of ^{35}S in lake water and precipitation can also be used as a tracer to monitor contributions of sulfur that originated in precipitation to surface waters. If a water tests positive for the isotope ^{35}S, it provides evidence that the water had been affected by recent (<~ 1 year) precipitation [148–150]. ^{35}S is used in direct labeling of elemental sulfur or sulfate sources to trace the fate of sulfur in fertilizers [142].

4.17 Chlorine



Stable isotope	Relative atomic mass	Mole fraction
^{35}Cl	34.968 8527	[0.755, 0.761]
^{37}Cl	36.965 9026	[0.239, 0.245]



4.17.1 Chlorine isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of chlorine possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of chlorine in natural terrestrial materials (Fig. 4.17.1). These variations are useful for investigating the origin of substances and studying environmental, hydrological, and geological processes.

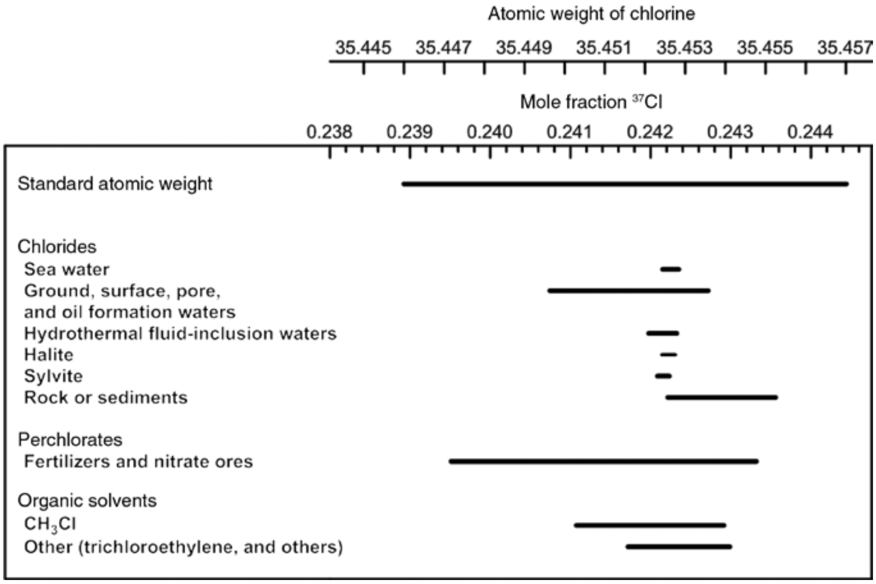


Fig. 4.17.1: Variation in **atomic weight** with **isotopic composition** of selected chlorine-bearing materials (modified from [13, 17]).

Chlorine is subject to **isotopic fractionation** by physical and chemical processes. Variations in **isotopic compositions** of stable chlorine **isotopes** provide evidence for ultrafiltration and crystallization of brines and indicate sources of chlorine-bearing contaminants, such as solvents and rocket fuels, in the environment [151, 152].

4.17.2 Chlorine isotopes in forensic science and anthropology

Analyses of chlorine isotopes and other environmental **tracers** can help to identify whether an environmental contaminant is of **anthropogenic** origin or naturally occurring. For example, perchlorate (ClO_4^-) can be of anthropogenic origin and is also found naturally. Perchlorate is a widespread groundwater contaminant that can interfere with hormone production in the thyroid gland by displacing iodide. Both the stable chlorine **isotope-amount ratio** $n(^{37}\mathrm{Cl})/n(^{35}\mathrm{Cl})$ and the **mole fraction** of ^{36}Cl, $n(^{36}\mathrm{Cl})/n(\mathrm{Cl})$, can provide useful information about origins of perchlorate in the environment (Fig. 4.17.2). Such information may be important for legal reasons and for remediation of contaminated areas [152, 153].

4.17.3 Chlorine isotopes in geochronology

Radioactive ^{36}Cl provides a useful tool to determine ages in geology and hydrology. Some radioactive ^{36}Cl is **cosmogenic** and enters the terrestrial environment in precipitation. Because of its long **half-life** of 3.01×10^5 years, the level of ^{36}Cl in aquifers can be measured and used to estimate ages (on the order of 10^5 to 10^6 years) of old meteoric groundwater (water that was originally precipitation) [155].

Thermonuclear bomb tests in the ocean produced large amounts of ^{36}Cl by **neutron** reactions with ^{35}Cl in seawater. This was especially prevalent in the late 1950s. Large amounts of this anthropogenic ^{36}Cl were distributed throughout the atmosphere, deposited with precipitation, and incorporated into terrestrial soils and groundwater. This enriched ^{36}Cl has been used as a tracer of **meteoric water** from that era [156].

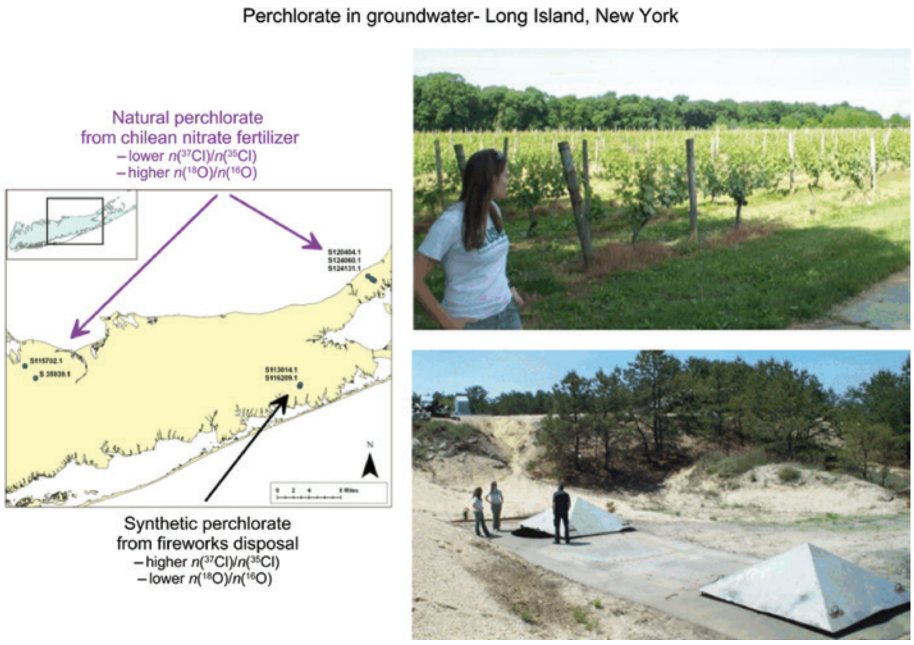
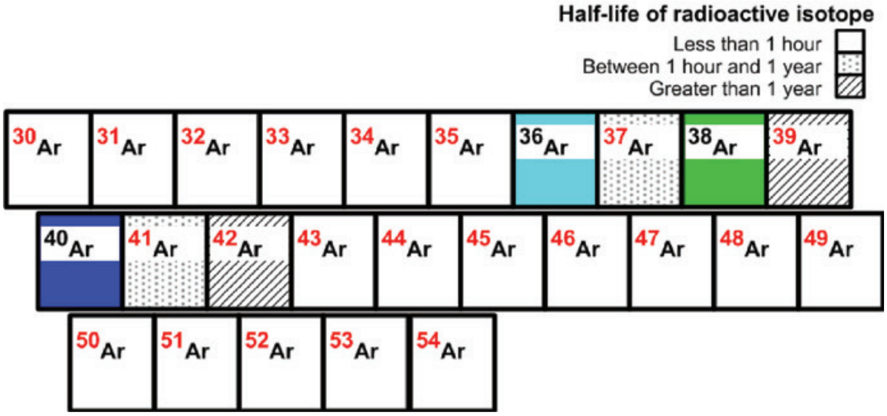


Fig. 4.17.2: By analyzing the **isotopic composition** of chlorine and oxygen in perchlorate in groundwaters of Long Island, NY, sources of perchlorate contamination could be identified [154]. Isotopic compositions indicate that wells in different parts of Long Island were contaminated by different sources. The agriculture source of perchlorate (upper photo) is identified as nitrate fertilizer from Chile, where natural perchlorate-bearing nitrate salt deposits were mined and processed for export. The synthetic source is attributed to contamination from a fireworks disposal area (lower photo). (Image Source: J.K. Böhlke, U.S. Geological Survey).

4.18 Argon

Stable isotope	Relative atomic mass	Mole fraction
^{36}Ar	35.967 5451	[0.0000, 0.0208]
^{38}Ar	37.962 732	[0.0000, 0.0433]
^{40}Ar	39.962 3831	[0.936, 1.000]



4.18.1 Argon isotopes in Earth/planetary science

Argon's chemically inert properties and three **stable isotopes** make it an ideal **tracer** of Earth processes [101, 157–167]. Measurements and models of the **isotope-amount ratio** $n(^{40}\text{Ar})/n(^{36}\text{Ar})$ can provide insights about the evolution of the atmosphere and orogenic (mountain-building) history of the Earth. The comparison of results from potassium-argon and $n(^{40}\text{Ar})/n(^{39}\text{Ar})$ isotope-amount-ratio dating methods with results from other dating methods has been used to study temperature histories of rocks through differences in apparent ages caused by excess argon or partial argon gas loss. The isotope-amount ratio $n(^{40}\text{Ar})/n(^{36}\text{Ar})$ of dissolved argon in groundwater can provide hydrologic information, such as rates of crustal degassing and relative groundwater age. ^{38}Ar produced by **cosmic-ray** bombardment of rocks and soils at Earth's surface can provide information about surface exposure history and erosion rate.

4.18.2 Argon isotopes in geochronology

Argon **isotopes** are used to date rock samples, especially volcanic rocks, using two related techniques (Fig. 4.18.1) [101, 168–170].

- The first technique is potassium-argon dating (K-Ar), which is based on the decay of radioactive ^{40}K to stable ^{40}Ar. By comparing the concentrations of potassium and ^{40}Ar in a sample, it is possible to determine how long the sample has been accumulating **radiogenic** ^{40}Ar to determine the "age" of the sample. The **half-life** of ^{40}K is approximately 1.25×10^9 years, making this a useful tool for dating rocks range in age from about 10^6 to 10^9 years.
- A modification of the potassium-argon dating technique is the $n(^{40}\text{Ar})/n(^{39}\text{Ar})$ isotope-amount-ratio technique, in which a sample is irradiated in a nuclear reactor to produce ^{39}Ar from ^{39}K. The isotope-amount ratio $n(^{40}\text{Ar})/n(^{39}\text{Ar})$ is then determined, and from this, the approximate age of the rock can be calculated (Fig. 4.18.2).

Fig. 4.18.1: Studying the ratios of argon **isotopes** can provide insight into the origins and movement of magma and the ages of volcanic rock. ^{40}Ar begins increasing in concentration once lava has solidified. (Image Source: U.S. Geological Survey Hawaiian Volcano Observatory, Kilauea) [174].

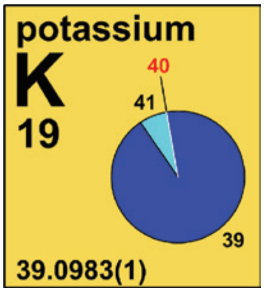
Fig. 4.18.2: The U.S. Geological Survey ^{40}Ar/^{39}Ar **geochronology** laboratory in Denver, Colorado uses a custom-built argon extraction line connected to a Mass Analyzer Products (MAP) 215-50 **mass spectrometer** with a differentially pumped dual laser setup. (U.S. Geological Survey ^{40}Ar/^{39}Ar Geochronology Laboratory) [175].

The study of ^{37}Ar (half-life of 35 days), ^{39}Ar (half-life of 268 years), and ^{40}Ar concentrations in groundwater can provide information about the production and release of these isotopes from rocks and other sources into groundwater and the relative ages of different groundwaters [159, 164, 165, 171–173].

4.18.3 Argon isotopes in industry

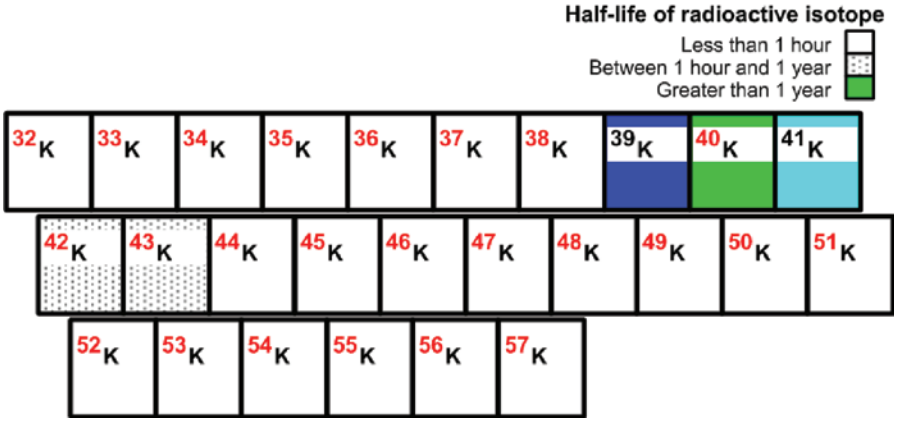
^{38}K (half-life of 7.6 min), which is produced by the reactions ^{38}Ar (p, n) ^{38}K and ^{40}Ar (n, 3n) ^{38}K, is a widely used blood-flow tracer. Because ^{38}Ar is more expensive, ^{40}Ar, which also offers many additional advantages as a target, is more commonly used to produce ^{38}K for medical purposes [176, 177]. ^{41}Ar (half-life of 1.82 h) is used as an industrial gas-flow tracer to help track the movement of gases because its inert properties, half-life, and **gamma radiation** make it well suited for this purpose [177].

4.19 Potassium



Stable isotope	Relative atomic mass	Mole fraction
^{39}K	38.963 706 49	0.932 581
^{40}K†	39.963 9982	0.000 117
^{41}K	40.961 825 26	0.067 302

† **Radioactive isotope** having a relatively long **half-life** (1.248×10^9 years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.19.1 Potassium isotopes in biology

The **mole fraction** of ^{40}K, $n(^{40}\mathrm{K})/n(\mathrm{K})$, is used to study the effects of potassium in soil on the growth of plants. Plants need potassium to promote growth and reproduction, and potassium also helps plants resist drought and diseases. The mole fraction of ^{40}K is being studied at different depths in several soil types to determine how soil properties affect the fractionation of ^{40}K [178].

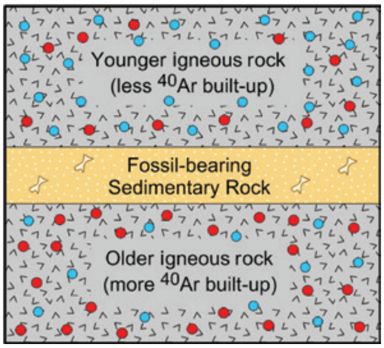


Fig. 4.19.1: Deeper, older **igneous** rocks will have a higher ^{40}Ar concentration than younger igneous rock, and this technique requires rocks older than 1×10^5 years in order that sufficient ^{40}Ar has accumulated.

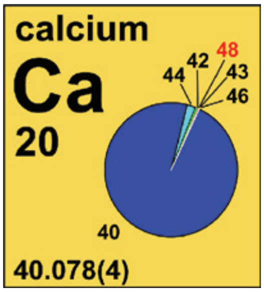
4.19.2 Potassium isotopes in geochronology

The **amount ratio** $n(^{40}\mathrm{K})/n(^{40}\mathrm{Ar})$ is used in potassium-argon dating by geologists, archaeologists, and paleoanthropologists to determine the age of rocks. This dating method is based on the **radioactive decay** of ^{40}K, having a **half-life** of 1.248×10^9 years, to ^{40}Ar. When lava crystalizes, ^{40}Ar can no longer escape and begins increasing in concentration in a rock (Fig. 4.19.1) [179, 180].

4.19.3 Potassium isotopes in medicine

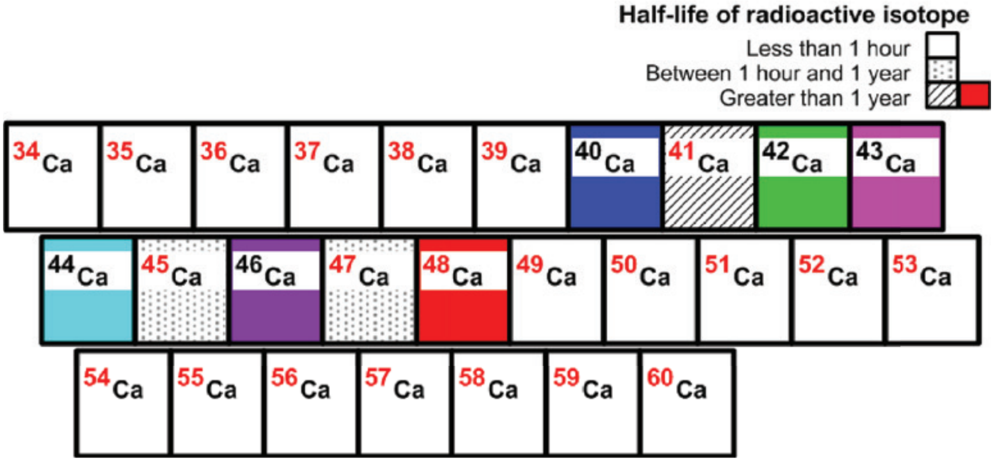
^{38}K, which has a half-life of 7.6 min and is produced by a nuclear reaction involving ^{38}Ar and ^{40}Ar as targets, is a widely used blood-flow **tracer**. Because ^{38}Ar is more expensive, ^{40}Ar, which also offers many additional advantages as a target, is more commonly used to produce ^{38}K for medical purposes [75, 176, 181].

4.20 Calcium



Stable isotope	Relative atomic mass	Mole fraction
^{40}Ca	39.962 5909	0.969 41
^{42}Ca	41.958 618	0.006 47
^{43}Ca	42.958 766	0.001 35
^{44}Ca	43.955 482	0.020 86
^{46}Ca	45.953 69	0.000 04
^{48}Ca†	47.952 5229	0.001 87

† **Radioactive isotope** having a very long **half-life** (4 × 10^{19} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.20.1 Calcium isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of calcium possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights** (Fig. 4.20.1). The **isotope-amount ratio** $n(^{44}\mathrm{Ca})/n(^{40}\mathrm{Ca})$ is used to quantify the calcium cycle (sources and sinks of calcium) in the ocean. Calcium **isotopes** fractionate (separate) in terrestrial and marine environments owing to biological and inorganic processes, which discriminate against heavy calcium **isotopes**. The calcification process controls the removal of calcium from the ocean, which is mostly balanced by hydrothermal and riverine calcium input. Calcium has a long **residence time**, symbol τ, in seawater (τ_{Ca} about 1 to 2 million years) relative to the short mixing time of the global ocean (about 1000 years), which has allowed the calcium **isotopic composition** of modern seawater to homogenize globally. This was likely the case in the geological past as well, which makes the $n(^{44}\mathrm{Ca})/n(^{40}\mathrm{Ca})$ ratio useful when quantifying the oceanic calcium cycle [182, 183]. The isotope-amount ratio $n(^{44}\mathrm{Ca})/n(^{40}\mathrm{Ca})$ has been used to trace sources of calcium in soil and river water [184]. The isotope-amount ratio $n(^{44}\mathrm{Ca})/n(^{40}\mathrm{Ca})$ ratio of calcium carbonate may serve as a paleothermometer to determine seawater temperatures in the past, making use of the temperature-dependent **isotopic fractionation** between ^{40}Ca and ^{44}Ca [185, 186].

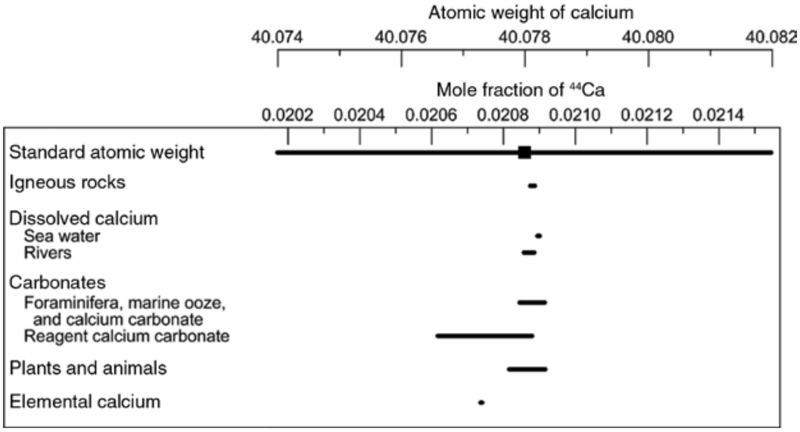


Fig. 4.20.1: Variation in **atomic weight** with **isotopic composition** of selected calcium-bearing materials (modified from [17]).

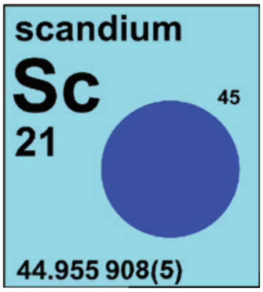
The **radioactive isotope** ^{45}Ca (**half-life** of 163 days) is used to study calcium behavior in soils, detergents, water-purification systems, and glassy materials. ^{45}Ca is introduced into a system and monitored to measure various types of calcium responses within the system and to investigate how calcium of one matrix may interact with another (*i.e.* calcium of soil mixing with that of fertilizers). ^{45}Ca has been used to investigate the transport of contaminants in groundwater through the unsaturated zone [187].

4.20.2 Calcium isotopes in medicine

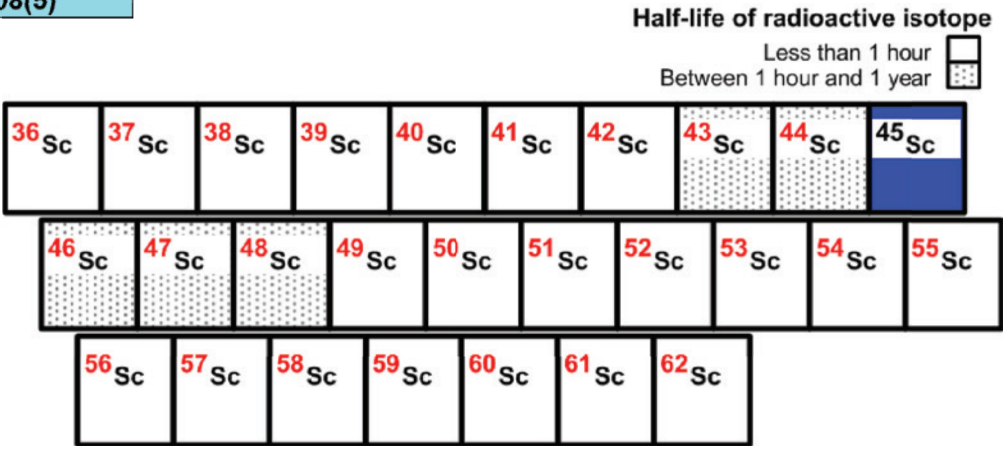
Stable isotopes of calcium (^{42}Ca, ^{44}Ca, ^{46}Ca, and ^{48}Ca) and **radioisotopes** of calcium (^{45}Ca and ^{47}Ca, with a half-life of 109 h) can be used for tracing calcium uptake, utilization, and **excretion** in the body. For example, most of our knowledge on the efficiency by which calcium is absorbed in the intestine (bioavailability) comes from studies in which calcium in the diet was labeled with stable or radioactive isotopes. In such studies, the isotope-labeled food is ingested and fecal matter tested for the presence and quantity of unabsorbed isotope. When coupling oral ingestion of food labeled with one calcium isotope with an **intravenous** injection of a second calcium isotope, this technique can be used as a means to measure calcium absorption within the body by measuring excretion of both **tracers** in the urine. In a similar fashion, dietary absorption of magnesium and zinc can be studied [184, 188].

Stable and radioactive isotopes are used in biomedical research and clinical practice to study disorders associated with calcium **metabolism**, in particular in relation to bone health and calcium accumulation in body tissues (vascular calcification, kidney stone formation). Stable isotope tracers have been used successfully to study bone calcium balance during space-flight and in-bed-rest studies. A long-living calcium radioisotope (^{41}Ca), with a half-life of 9.9×10^4 years, has been used successfully for labeling of bone calcium to measure bone calcium turnover *via* urinary excretion of the tracer [189].

4.21 Scandium



Stable isotope	Relative atomic mass	Mole fraction
^{45}Sc	44.955 908	1



4.21.1 Scandium isotopes in biology

Radioactive ^{46}Sc is used as a non-absorbed **isotopic reference material** for determining digestibility, absorption in the gut, and secretion sites for nutrients associated with feed residues in ruminating animals (animals that chew their food repeatedly for an extended period of time) [190].

4.21.2 Scandium isotopes in Earth/planetary science

The **radioactive isotope** ^{46}Sc has been used for sediment labeling to determine the transportation of sediments by water flow in rivers, estuaries, harbors, and seas. The **half-life** of ^{46}Sc is about 84 days and when released into an estuary with similar grain density and grain size, a gamma spectrometer (instrument for measuring the intensity of **gamma radiation** versus the energy of each **photon**) can be used to measure the intensities of ^{46}Sc in the sediments and the movement of the sediments can be determined [191–193].

4.21.3 Scandium isotopes in industry

^{46}Sc is a beta emitter and has been used as a **tracer** in oil refinery crackers for crude oil (converting crude oil into gasoline and other lower-molecular weight hydrocarbon fractions). Its beta radiation enables the substance to be tracked as the oil travels [194]. Due to its easily traceable properties, coastal engineers use ^{46}Sc to develop dredging strategies and to design navigation channels based on silt movement [192].

4.21.4 Scandium isotopes in medicine

^{46}Sc is used in **isotope**-carrying antibodies for bonding with tumor-associated cell surface antigens (substances that causes the production of an antibody when introduced into the body, *e.g.* toxins, bacteria, and viruses). ^{46}Sc is added to **DTPA**-derivatized (process by which a compound is chemically changed, producing a new compound that has properties more amenable to a particular analytical method) **monoclonal antibodies** and has been shown to target tumor cells, specifically ***in vivo***, where it accumulates to high levels in the tumor (Fig. 4.21.1) [195, 196].

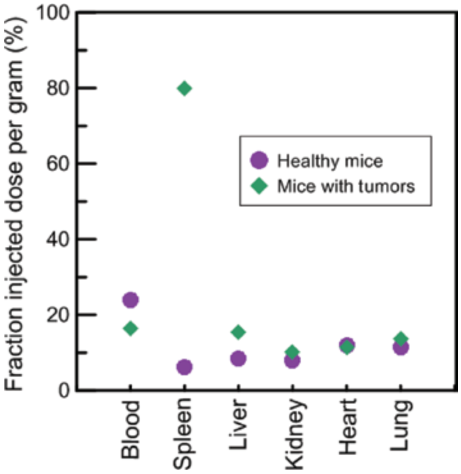
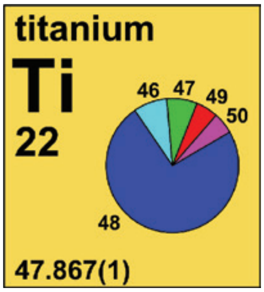
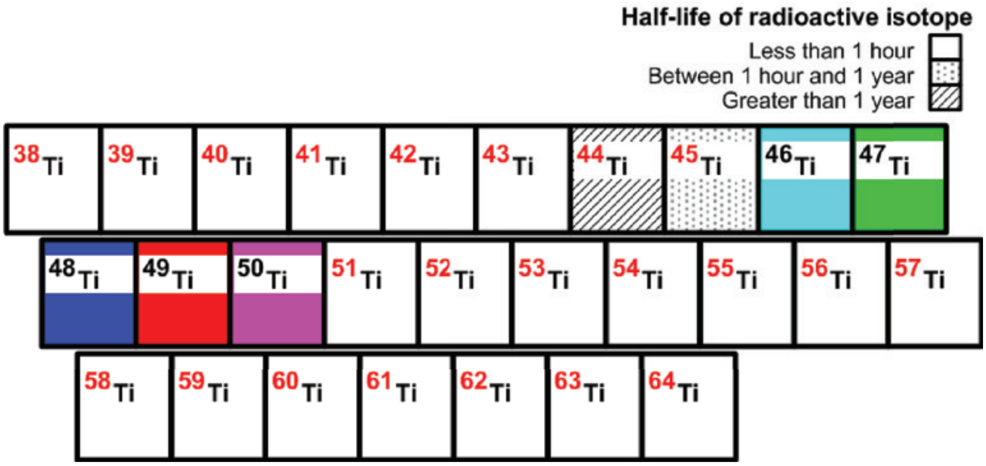


Fig. 4.21.1: Comparison of biodistribution of ^{46}Sc citrate and ^{46}Sc-labeled ca**DTPA**-antibody conjugates in healthy mice (circles) and leukemic mice (diamonds) 1 h after injection in tail vein (modified from [195, 196]).

4.22 Titanium



Stable isotope	Relative atomic mass	Mole fraction
^{46}Ti	45.952 627	0.0825
^{47}Ti	46.951 7578	0.0744
^{48}Ti	47.947 9409	0.7372
^{49}Ti	48.947 8646	0.0541
^{50}Ti	49.944 7858	0.0518



4.22.1 Titanium isotopes in Earth/planetary science

The **isotope-amount ratio** $n(^{50}\text{Ti})/n(^{46}\text{Ti})$ is used to study the early history of the Solar System. The value of the ratio can help determine whether the Solar System was created from a well-homogenized source [197, 198]. For example, variations in titanium **isotopic compositions** of various groups of **meteorites** can be observed (Fig. 4.22.1) [199].

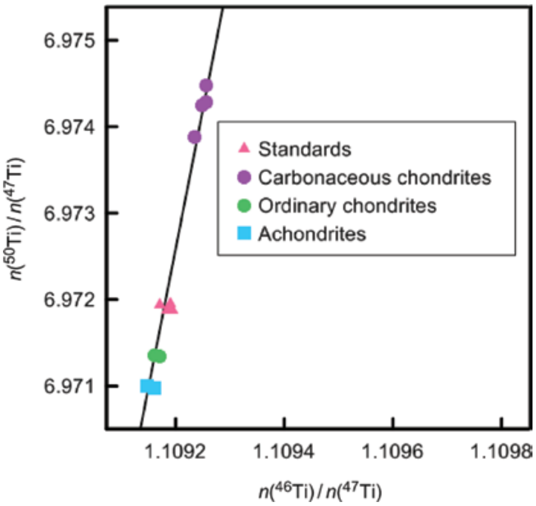
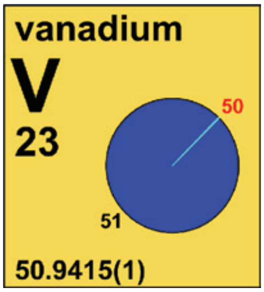


Fig. 4.22.1: Cross plot of the **isotope-amount ratio** $n(^{50}\mathrm{Ti})/n(^{47}\mathrm{Ti})$ and the isotope-amount ratio $n(^{46}\mathrm{Ti})/n(^{47}\mathrm{Ti})$ of selected groups of **meteorites** (modified from [199]), assuming measured $n(^{50}\mathrm{Ti})/n(^{47}\mathrm{Ti})$ and $n(^{46}\mathrm{Ti})/n(^{47}\mathrm{Ti})$ isotope-amount ratios of 0.697 19 and 1.109 18, respectively [200]. Normal titanium **isotopic compositions** were observed in standards, but ^{46}Ti and ^{50}Ti **isotope** anomalies were resolved among different meteorite groups.

4.22.2 Titanium isotopes in industry

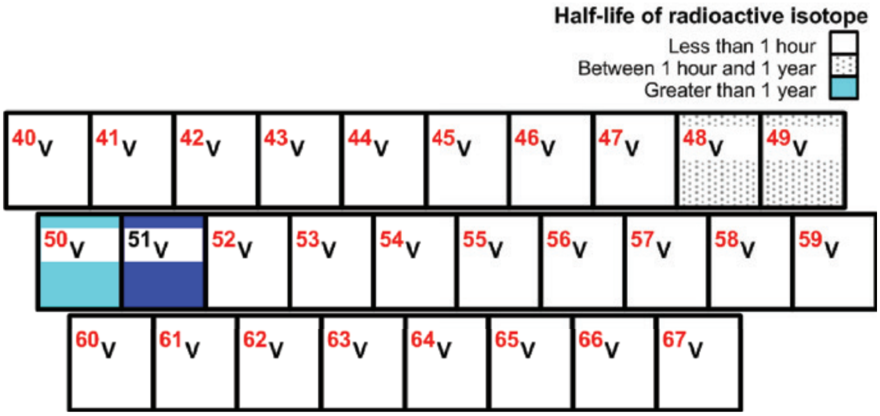
The isotope-amount ratio $n(^{48}\mathrm{Ti})/n(^{49}\mathrm{Ti})$ has been used in Isotope Ratio Method (IRM) analysis (initial titanium ratio/final titanium ratio) to estimate the energy production of nuclear reactors. This ratio can also be used to confirm that a reactor is being used for non-proliferation purposes (purposes other than to assist in the formation of nuclear weapon grade materials) [201].

4.23 Vanadium



Stable isotope	Relative atomic mass	Mole fraction
^{50}V†	49.947 156	0.002 50
^{51}V	50.943 957	0.997 50

† **Radioactive isotope** having a relatively long **half-life** (2×10^{17} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.23.1 Vanadium isotopes in Earth/planetary science

The **isotopic abundances** of ^{50}V and ^{51}V have been used as an indicator of planetary core formation processes (Fig. 4.23.1). Vanadium is greatly depleted in the Earth's mantle compared with that in **chondritic meteorites** (**chondrites**). It is assumed that the deficit of vanadium in the Earth's crust is accounted for by its partitioning into the core [202]. The ratios of ^{50}V and ^{51}V have been used as a test of the X-wind model, which accounts

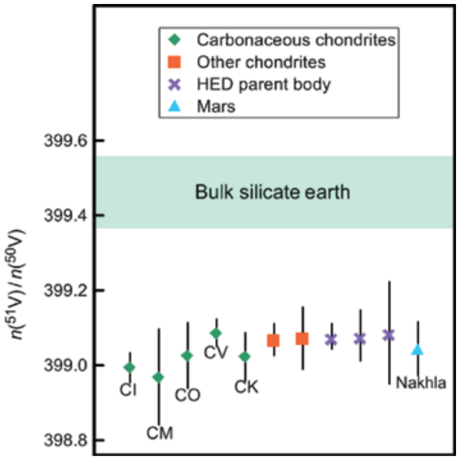


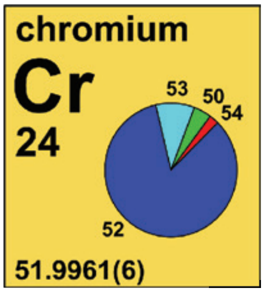
Fig. 4.23.1: Variation in the **isotope-amount ratio** $n(^{51}\text{V})/n(^{50}\text{V})$ of selected **meteorites** and that of bulk silicate Earth (modified from [203]), assuming a measured $n(^{51}\text{V})/n(^{50}\text{V})$ isotope-amount ratio of 399.5 [204].

for a portion of the extinct radioactive nuclides present in the early Solar System by radiation from the young Sun [202]. ^{51}V is depleted in meteorites compared to Earth [203].

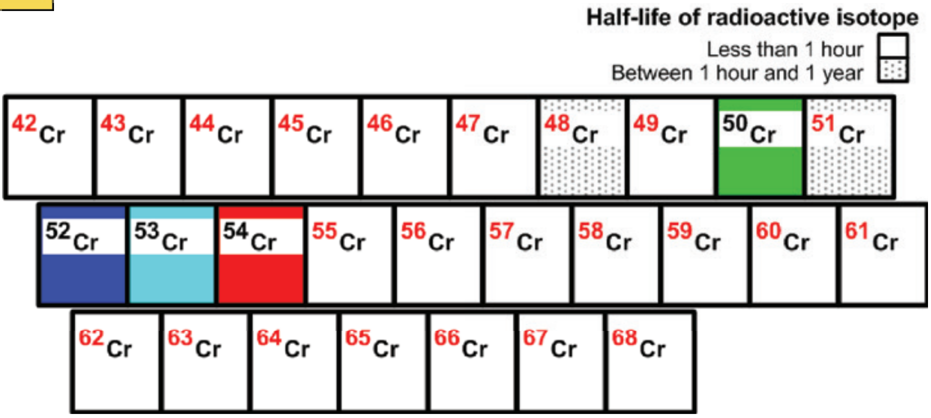
4.23.2 Vanadium isotopes in industry

^{51}V is used in solid state **Nuclear Magnetic Resonance** (**NMR**) to provide information to material scientists about surface species of vanadium oxide catalysts (substances that increase the rate of chemical reactions without themselves undergoing any permanent chemical change), their interaction with the supporting material, and their reactions during catalytic processes [205].

4.24 Chromium



Stable isotope	Relative atomic mass	Mole fraction
^{50}Cr	49.946 041	0.043 45
^{52}Cr	51.940 505	0.837 89
^{53}Cr	52.940 647	0.095 01
^{54}Cr	53.938 878	0.023 65



4.24.1 Chromium isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of chromium possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of chromium in natural terrestrial materials (Fig. 4.24.1).

SiC grains are formed in very high-temperature events that occurred before the formation of the Solar System. The chemical and **isotopic composition** of certain **elements** in these grains, such as chromium, provides insights into the origin of the Solar System. The ^{54}Cr nucleus is only produced by **supernovae**. Excess amounts of this **isotope** in the SiC grains (relative to terrestrial isotopic composition) in primitive **meteorites** suggest a heterogeneous distribution of ^{54}Cr in the early Solar System and different sources of material to our Solar System [206]. The early **solar nebula** was divided into two components. One contained chromium depleted in the lighter isotopes and the other contained heavier chromium isotopes. Isotopic studies indicate

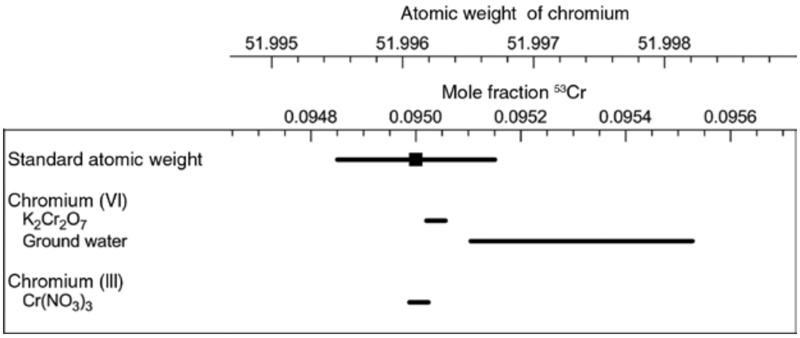


Fig. 4.24.1: Variation in **atomic weight** with **isotopic composition** of selected chromium-bearing materials (modified from [17]).

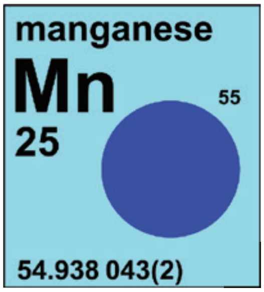
these components formed a homogeneous mixture in the early Earth, but they separated during partitioning of the Earth's core (Fig. 4.24.1) [207, 208].

Mobility and toxicity of chromium metal depend largely on the oxidation state of the element. Isotopes of chromium are fractionated by **reduction-oxidation (redox)** chemical reactions. The isotopic composition has been used to trace the origin of the element in the environment and provide information on reduction-oxidation chemical processes [209].

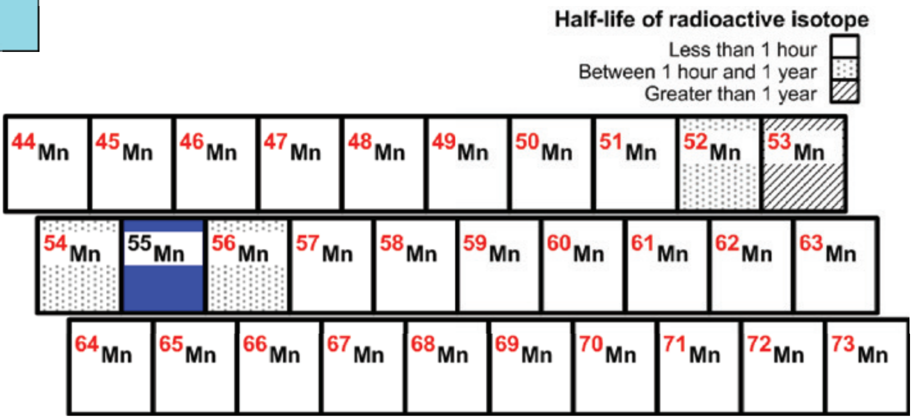
4.24.2 Chromium isotopes in medicine

Stable isotopes of chromium are used to investigate the **metabolism** of chromium (III), which is an essential nutrient. Chromium stable isotopes (^{53}Cr and ^{54}Cr) have been administered to patients and the relative metabolic activity of each isotope is measured to study insulin function in patients suffering from diabetes (a disease in which the body is unable to produce any or enough insulin, and/or is not able to properly use the insulin that it does produce, resulting in elevated levels of glucose in the blood) [210]. ^{51}Cr and ^{53}Cr have been used to label red blood cells to determine blood volume and life-time of red blood cells in the body [210].

4.25 Manganese



Stable isotope	Relative atomic mass	Mole fraction
^{55}Mn	54.938 043	1



4.25.1 Manganese isotopes in Earth/planetary science

Radioactive ^{54}Mn (**half-life** of 312 days) has been used as a **tracer** to study migration of heavy metals in effluents (flowing out) from mining waste [109, 110].

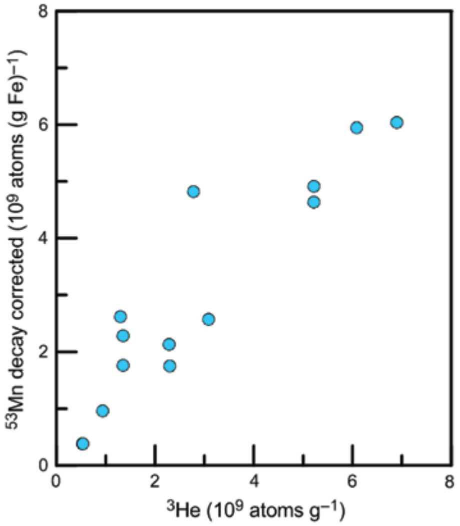


Fig. 4.25.1: Cross plot of **cosmic-ray** produced radioactive ^{53}Mn and ^{3}He from 13 **igneous**-rock samples collected from land surface at the Dry Valleys, Antarctica (modified from [211]). The correlation between ^{53}Mn and ^{3}He indicates that ^{53}Mn is produced continuously in place and has been used to monitor Earth-surface processes.

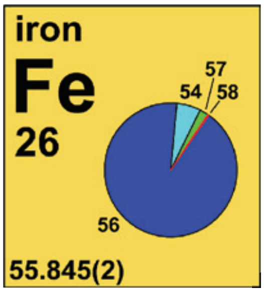
4.25.2 Manganese isotopes in geochronology

The **radioactive isotope** ^{53}Mn is formed by the interaction of **protons**, produced by **cosmic rays**, on iron in rocks. The accumulation of ^{53}Mn, having a **half-life** of 3.7×10^6 years, at the Earth's surface enables determination of exposure ages of landforms to cosmic rays and quantification of erosion rates. For example, Schaefer *et al.* [211] measured 13 samples from nine dolerite (**igneous** rock containing plagioclase, pyroxene, and olivine) surfaces in the Dry Valleys, Antarctica. They found that the terrestrial ^{53}Mn concentrations correlate well with cosmic-ray-produced ^{3}He and ^{21}Ne concentrations in the same samples (Fig. 4.25.1), which suggests that ^{53}Mn is produced continuously in place and retained over millions of years without loss. Their results suggest that ^{53}Mn concentrations in rocks can be used to monitor Earth-surface processes on time scales exceeding 10×10^6 years.

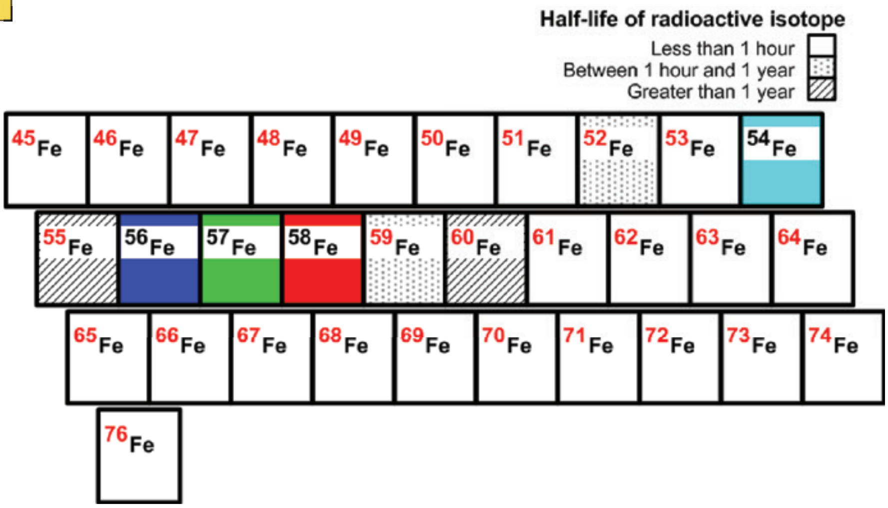
4.25.3 Manganese isotopes in medicine

^{51}Mn, ^{52}Mn and ^{52m}Mn (with half-lives of 46 min, 5.6 days, and 21 min, respectively) are radioactive isotopes that emit **positrons** that are used in **positron emission tomography** (**PET**) imaging [212, 213]. The m in the superscript of ^{52m}Mn indicates a **metastable state** of the **isotope**.

4.26 Iron



Stable isotope	Relative atomic mass	Mole fraction
^{54}Fe	53.939 608	0.058 45
^{56}Fe	55.934 936	0.917 54
^{57}Fe	56.935 392	0.021 19
^{58}Fe	57.933 274	0.002 82



4.26.1 Iron isotopes in biology

Natural iron enriched in its least abundant **stable isotopes**, ^{57}Fe and ^{58}Fe, are used as a **tracer** in human studies to assess absorption, **excretion**, distribution, and utilization of iron in basic and applied research [108–110, 214–216]. The two **radioisotopes**, ^{55}Fe and ^{59}Fe, have sufficiently long **half-lives** of 2.75 years and 44.5 days, respectively, to be used as tracers, but potential health and environmental hazards limit their use to diagnostic applications in patient care (*i.e.* disorders of blood and of iron **metabolism**) [110, 215, 216].

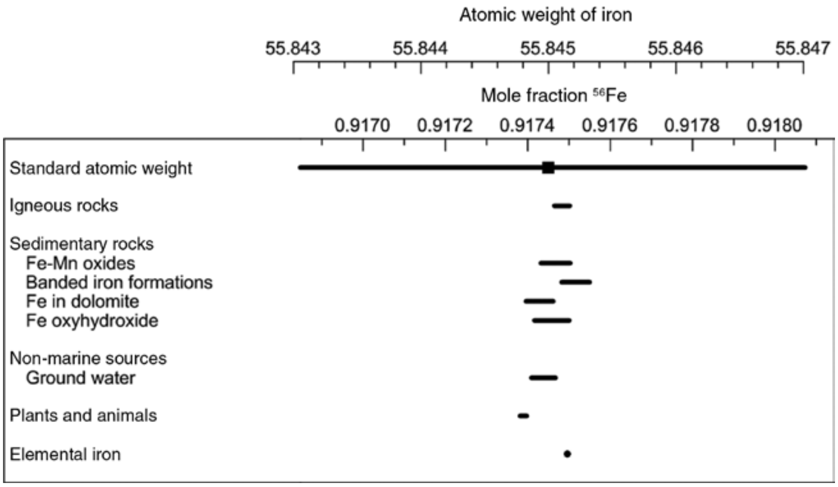


Fig. 4.26.1: Variation in **atomic weight** with **isotopic composition** of selected iron-bearing materials (modified from [17]).

4.26.2 Iron isotopes in Earth/planetary science

^{60}Fe is an extinct **radionuclide** with a half-life of 2.6×10^6 years that has fully decayed to ^{60}Ni since formation of the Solar System. The distribution of the product (**radiogenic**) ^{60}Ni in extraterrestrial material, such as **meteorites**, has been used to gain insight into the early history of the Solar System [216]. Because molecules, atoms, and ions of the stable isotopes of iron possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of iron in natural terrestrial materials (Fig. 4.26.1). Small variations in stable iron **isotopic compositions** caused by physical and chemical **isotopic fractionation** processes have been used to study mass transfer processes in nature and chemical equilibria [17, 216, 217].

4.26.3 Iron isotopes in industry

^{55}Fe is a beta emitting nuclide that serves as an **electron** source together with ^{63}Ni (with a half-life of 99 years) in **electron-capture detectors**. Electron-capture detectors are used as thickness gauges or as detectors for organic **analytes** in **gas chromatography** [218].

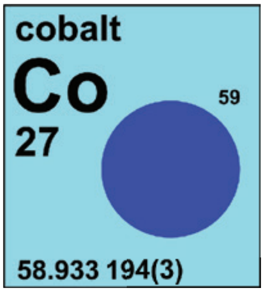
4.26.4 Iron isotopes in medicine

^{52}Fe, with a half-life of 8.3 h, emits **positrons** and is used in **positron emission tomography** (**PET**) studies. It can be produced in a **cyclotron** from stable ^{50}Cr by **alpha particle capture** [99, 219, 220].

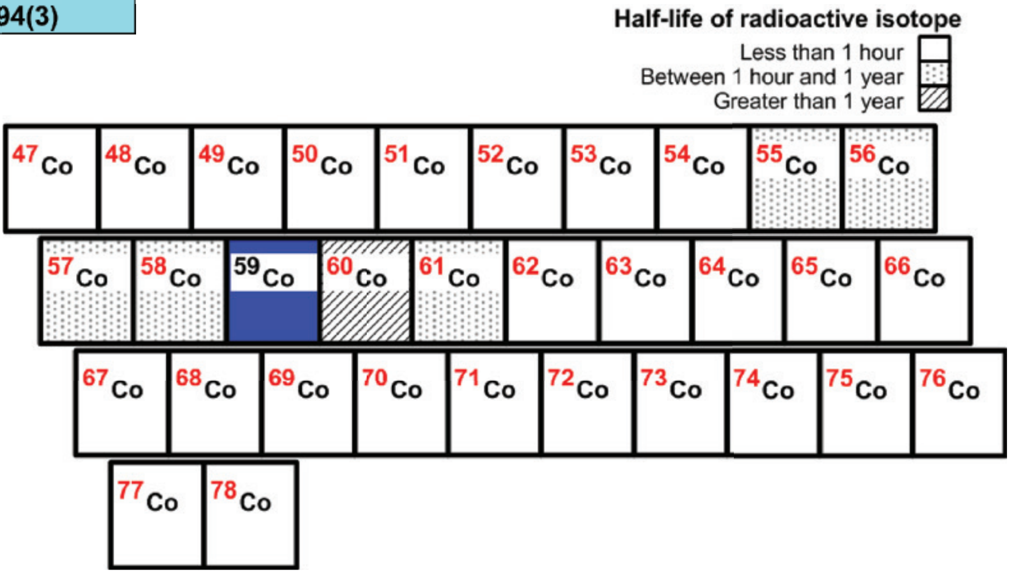
4.26.5 Iron isotopes used as a source of radioactive isotope(s)

Stable ^{56}Fe is used for production of radioactive ^{55}Co (with a half-life of about 18 h), as an emitter of positrons for PET applications using the reaction ^{56}Fe (p, 2n) ^{55}Co [221, 222].

4.27 Cobalt



Stable isotope	Relative atomic mass	Mole fraction
^{59}Co	58.933 194	1



4.27.1 Cobalt isotopes in industry

^{60}Co (with a **half-life** of 5.27 years) is used to irradiate food sources as a method of preserving food (Fig. 4.27.1). The **gamma radiation** from ^{60}Co kills bacteria and other organisms that cause disease and spoilage of food (see Fig. 4.27.1). The use of radioactive compounds for preserving food is not always viewed

Fig. 4.27.1: Plants growing in the gamma greenhouse at Brookhaven National Laboratory. The plants are arranged in concentric rings around the radioactive ^{60}Co source, which is in the pipe extending into the floor (circa 1959) [223]. (Photo Source: Life Sciences Foundation (LSF) Magazine).

positively. Some individuals are concerned that harmful compounds will be produced during the irradiation process. However, there is no evidence to support the claim that irradiation is dangerous for food preservation [108]. Many medical products today are sterilized using **gamma rays** from a ^{60}Co source. This technique of sterilization is generally much cheaper and more effective than steam-heat sterilization because it is a cold process. For example, it can be performed on packaged items, such as disposable syringes. This sterilization technique is applicable to a wide range of heat-sensitive items, such as powders, ointments, and solutions, as well as biological preparations, such as bone, nerve, skin, *etc.*, used in tissue grafts [108].

^{60}Co is also used in industrial **radiography** to detect structural flaws in metal parts. The radiation can penetrate metals and the **X-ray** pattern produced by the radiating material can provide information on its strength, composition, and other properties [108]. Because of the above property, ^{60}Co is also used in leveling devices and thickness gauges used to test welds and castings [108].

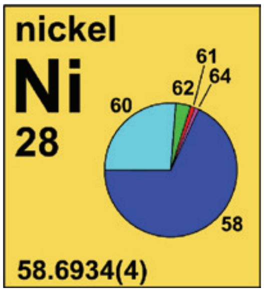
4.27.2 Cobalt isotopes in medicine

^{60}Co is a radioactive metal **isotope** that is used in cancer treatments by **radiotherapy**. When ^{60}Co undergoes **radioactive decay**, high-energy gamma rays (energies of 1.17 MeV and 1.33 MeV) are emitted and have been used in **brachytherapy** to treat various types of cancer. Brachytherapy (brachy is Greek meaning "short distance") is a method of radiation treatment in which sealed sources are used to deliver a radiation dose at a distance of up to a few centimeters by surface, intracavitary (insertion of the **radioactive isotope** in a body cavity), or interstitial (between cells) application [75]. ^{60}Co is used as a source of high-energy **ionizing** gamma radiation that can be directed to cancer cells from a device outside the body (external radiotherapy).

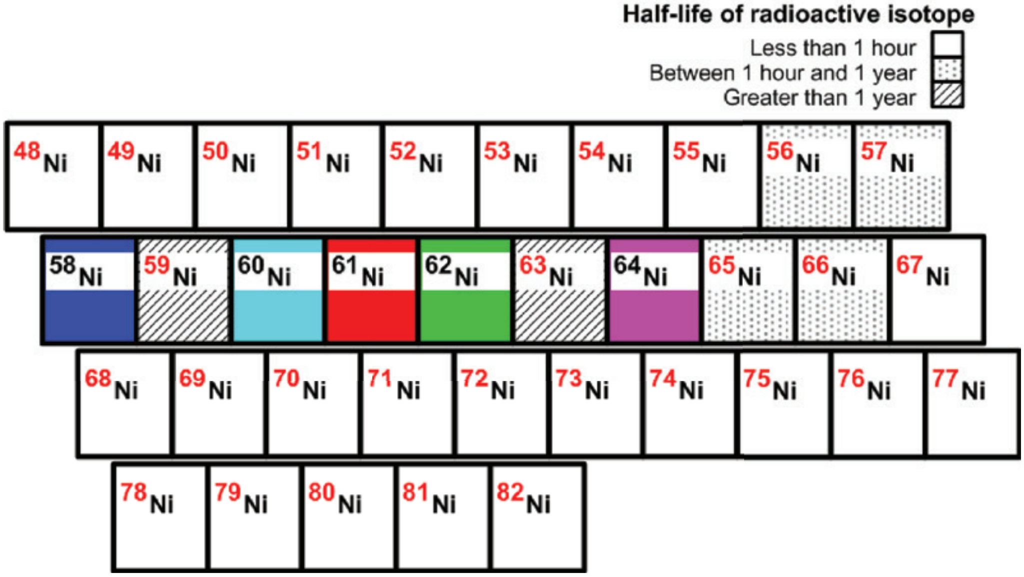
^{60}Co (and sometimes ^{57}Co and ^{58}Co, with half-lives of 0.75 year and 71 days, respectively) is the key component of the Schilling test, which is a method for determining whether a patient's body is making and using vitamin B12 properly. The cobalt isotope is used to label cobalt in vitamin B12 to monitor how the body processes this essential vitamin [224].

^{57}Co delivers the smallest radiation dose of all the cobalt isotopes. As a result, it has been used in the past for imaging and estimating organ size and location and in evaluating tumors of the head and neck [75, 99, 225–227].

4.28 Nickel



Stable isotope	Relative atomic mass	Mole fraction
^{58}Ni	57.935 342	0.680 769
^{60}Ni	59.930 785	0.262 231
^{61}Ni	60.931 055	0.011 399
^{62}Ni	61.928 345	0.036 345
^{64}Ni	63.927 966	0.009 256



4.28.1 Nickel isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of nickel possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of nickel in terrestrial silicate rocks (Fig. 4.28.1) [228].

4.28.2 Nickel isotopes in geochronology

Anomalies in ^{60}Ni abundance caused by decay of now extinct ^{60}Fe have been used to study the early history of our Solar System (see section 4.26.2). ^{59}Ni is a **cosmogenic radionuclide** with a **half-life** of 7.6×10^4 years. Decay of ^{59}Ni has been used to assess the terrestrial age of **meteorites** and to determine abundances of extra-terrestrial dust in ice and sediment [230].

4.28.3 Nickel isotopes in industry

^{63}Ni (with a half-life of 99 years) is produced from stable ^{62}Ni and is a beta-emitting radionuclide that serves as an **electron** source together with ^{55}Fe in **electron-capture detectors**. Electron-capture detectors are used as thickness gauges or as detectors for organic **analytes** in **gas chromatography** (Fig. 4.28.2) [108]. ^{63}Ni is also

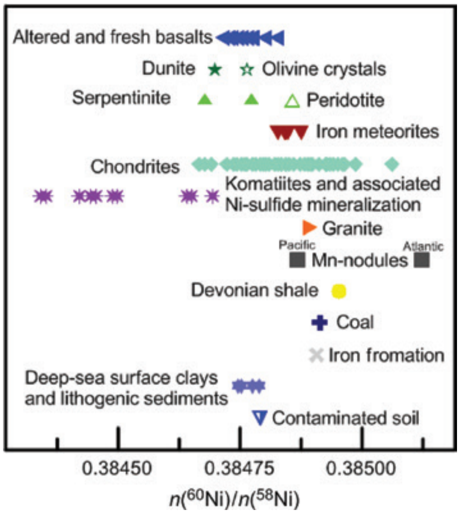


Fig. 4.28.1: Variation in **isotope-amount ratio** $n(^{60}\mathrm{Ni})/n(^{58}\mathrm{Ni})$ of terrestrial nickel-bearing silicate rocks (modified from [228]), assuming a measured $n(^{60}\mathrm{Ni})/n(^{58}\mathrm{Ni})$ isotope-amount ratio of 0.385 198 [229].

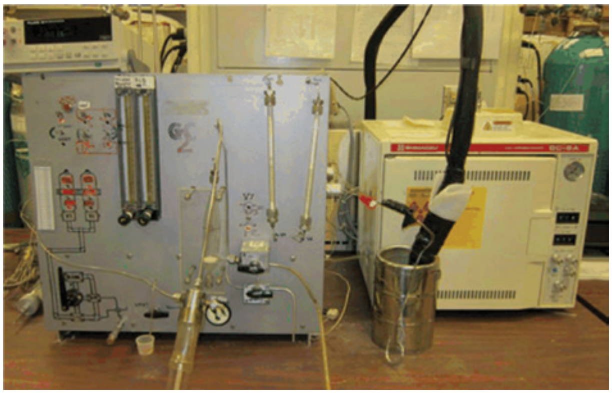


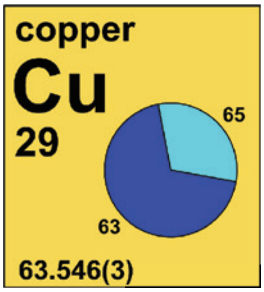
Fig. 4.28.2: Shimadzu GC-8A **Gas Chromatograph** (GC) with an **Electron-Capture Detector** (ECD). (Image Source: The Reston Chlorofluorocarbon Laboratory, U.S. Geological Survey) [233, 234].

used to ionize substances in ion mobility spectrometry–the basis of the instrument used in airports to screen passengers for drugs and bombs [231]. ^{63}Ni is also used as a fluorescence-inducing source in elemental analysis by **X-ray fluorescence spectroscopy** and in miniaturized long-lived **nuclear batteries** [108]. Until the mid-1980s, nuclear batteries were used in pacemakers, but then they were replaced by long-lasting lithium batteries [232].

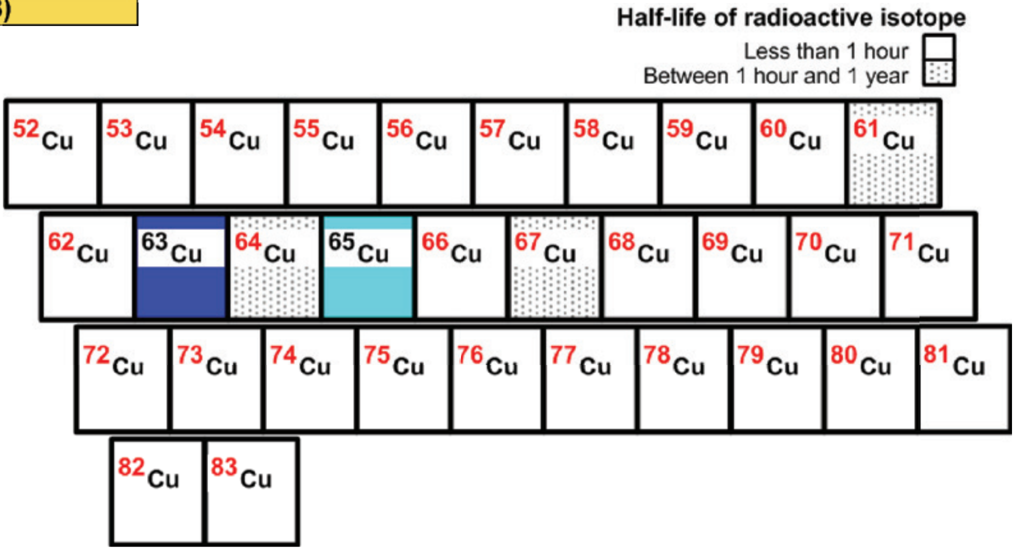
4.28.4 Nickel isotopes used as a source of radioactive isotope(s)

^{61}Ni is used as a radiation target for production of the **radioactive isotope** ^{61}Cu (with a half-life of 3.3 h), which emits **positrons** for **positron emission tomography** (**PET**) applications using the ^{61}Ni (p, n) ^{61}Cu reaction. ^{64}Ni is used as a radiation target for production of ^{64}Cu (with a half-life of 12.7 h), which is used in **radioimmunotherapy** by attaching it to an antibody for delivery of cytotoxic radiation (toxic to living cells) to a target cell *via* the ^{64}Ni (p, n) ^{64}Cu reaction [235]. ^{60}Ni is used for the production of ^{57}Co (with a half-life of 0.75 year), which is used as a reference source for **gamma cameras** that are used in **nuclear medicine** *via* the ^{60}Ni (p, ^{4}He) ^{57}Co reaction [235].

4.29 Copper



Stable isotope	Relative atomic mass	Mole fraction
^{63}Cu	62.929 597	0.6915
^{65}Cu	64.927 790	0.3085



4.29.1 Copper isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of copper possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of copper in natural terrestrial materials (Fig. 4.29.1). ^{63}Cu and ^{65}Cu have been used to study copper **isotope** science of supergene (formed by descending solutions) copper minerals for potential use as an indicator of the paleohydraulic (ancient hydraulic) gradient, and for potential to provide a vector toward unrecognized copper source regions [236]. Copper **isotope ratios** of iron oxides and supergene copper sulfides in surface samples or fossil leached caps of ore deposits are being used in prospecting to rank prospects and focus on drilling areas that have the greatest potential for mature enrichment profiles [236].

4.29.2 Copper isotopes in forensic science and anthropology

The copper **isotope-amount ratio** $n(^{65}\text{Cu})/n(^{63}\text{Cu})$ along with the silver isotope-amount ratio $n(^{109}\text{Ag})/n(^{107}\text{Ag})$ and lead isotope-amount ratios $n(^{206}\text{Pb})/n(^{204}\text{Pb})$, $n(^{207}\text{Pb})/n(^{204}\text{Pb})$, and $n(^{208}\text{Pb})/n(^{204}\text{Pb})$ have been used to determine the origin of European coins and the flow of goods in the historical world market. Metals from Peru and Mexico and those from European mining sites have distinct isotopic signatures that enable the origin of the metal to be determined based on the **isotopic compositions** of silver, copper, and lead in the coins. Silver

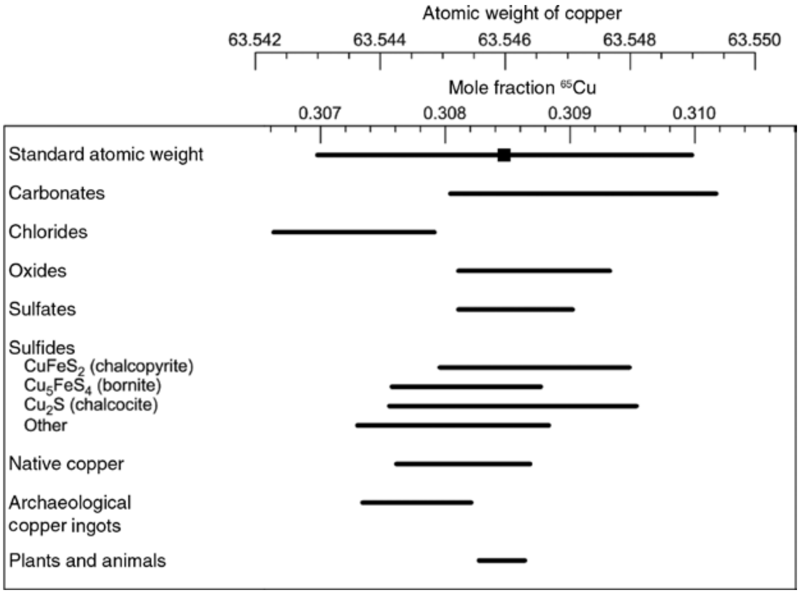


Fig. 4.29.1: Variation in **atomic weight** with **isotopic composition** of selected copper-bearing materials (modified from [17]).

from mines in Mexico and Peru in the 16th century was used to mint coins but did not influence the European coin market until the 18th century [237].

4.29.3 Copper isotopes in medicine

The **radiopharmaceutical** ^{62}Cu-PTSM, which contains radioactive ^{62}Cu (with a **half-life** of 9.7 min), is used as a **tracer** in **positron emission tomography** (**PET**) to quantify myocardial perfusion (heart blood-flow measurements) [238, 239]. The **radioisotope** ^{64}Cu (with a half-life of 12.7 h) is used for PET imaging and **radiotherapy** to diagnose, understand, and monitor disease (Fig. 4.29.2) [238, 240]. The stable isotope ^{65}Cu has been used as a tracer to study copper absorption, utilization, and **excretion** in humans [241, 242].

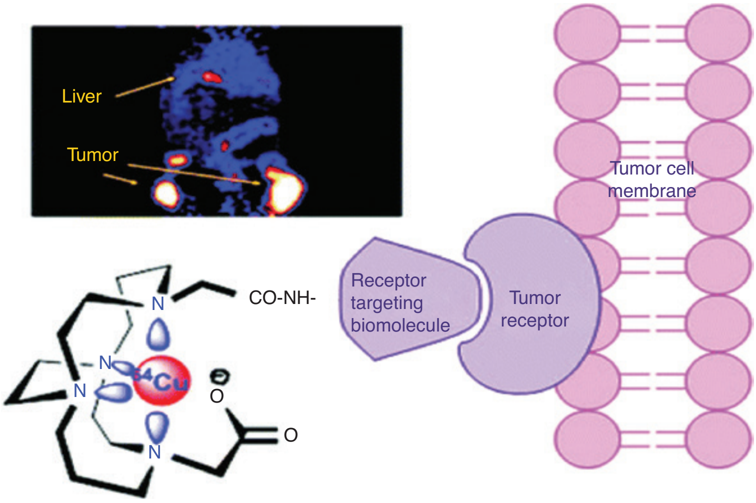
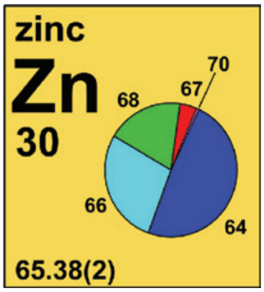
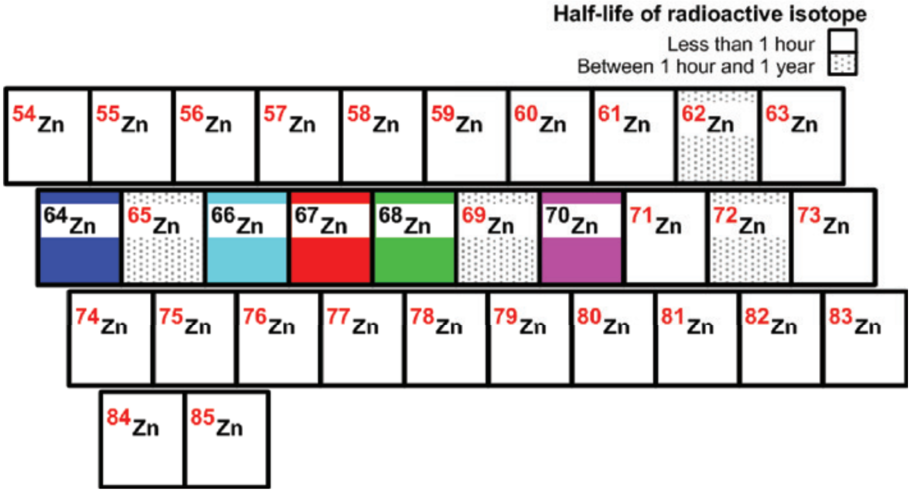


Fig. 4.29.2: An illustration of a small-animal **positron emission tomography** (**PET**) system that uses the ^{64}Cu **radioisotope** to generate a reconstructed image of the animal in a noninvasive manner. (Reprinted with permission from Monica, S. & Anderson, C.J., 2009 [240]. Copyright © 2009 American Chemical Society).

4.30 Zinc



Stable isotope	Relative atomic mass	Mole fraction
^{64}Zn	63.929 142	0.4917
^{66}Zn	65.926 034	0.2773
^{67}Zn	66.927 128	0.0404
^{68}Zn	67.924 844	0.1845
^{70}Zn	69.925 32	0.0061



4.30.1 Zinc isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of zinc possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of zinc in natural terrestrial materials (Fig. 4.30.1). Stable zinc **isotopes** have been used as **tracers** to investigate biogeochemical and chemical processes in environmental contamination sites [243]. The **isotope-amount ratio** $n(^{66}\mathrm{Zn})/n(^{64}\mathrm{Zn})$ can be used as an environmental tracer for detecting the pathways of **anthropogenic** zinc [244–246].

4.30.2 Zinc isotopes in medicine

Oral tracers of enriched ^{67}Zn and **intravenous**ly injected stable isotopic tracers with enriched ^{70}Zn are used simultaneously to determine the fraction of dietary zinc absorbed in humans, maintaining the amount or concentration of a nutrient or biomolecule in organs and body fluids. For example, zinc-isotope tracers can be administered to humans to determine if zinc absorption in their bodies may be impaired by ingestion of certain foods, food components, or dietary supplements. One such study conducted with Peruvian women showed that prenatal iron supplements affected the absorption of zinc during pregnancy. Another isotope tracer study investigated zinc deficiency in children with Crohn's disease (an inflammatory disease of the intestines, especially the colon and ileum) [249, 250]. Zinc **radioisotopes** (*e.g.* ^{65}Zn, with a **half-life** of 244 days) can also be used for determining zinc absorption in humans, but they are now used rarely because

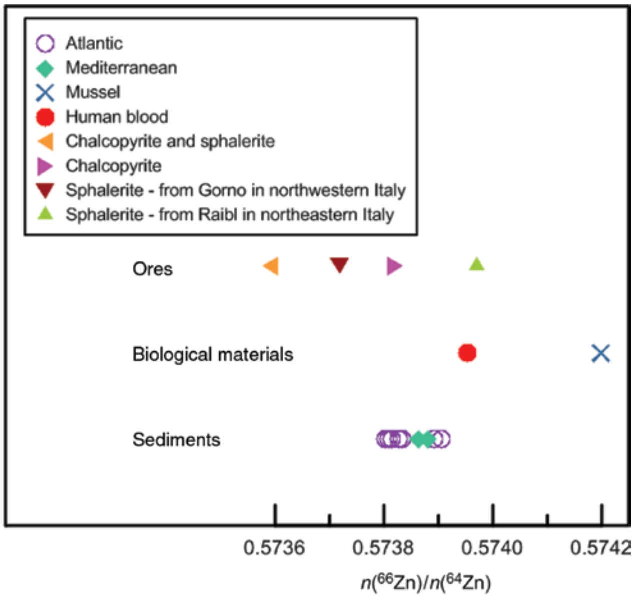


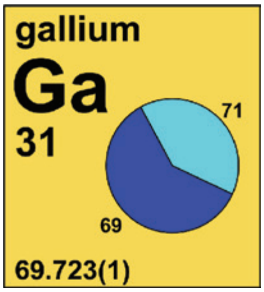
Fig. 4.30.1: Variation in the **isotope-amount ratio** $n(^{66}\text{Zn})/n(^{64}\text{Zn})$ of selected zinc-bearing materials (modified from [247], assuming a $n(^{66}\text{Zn})/n(^{64}\text{Zn})$ value of 0.57372 for a Johnson–Mattey zinc solution [248]).

of radiation hazards [251, 252]. ZnO nanoparticles enriched with ^{67}Zn have been used as biological/environmental nanotoxicity tracers [253].

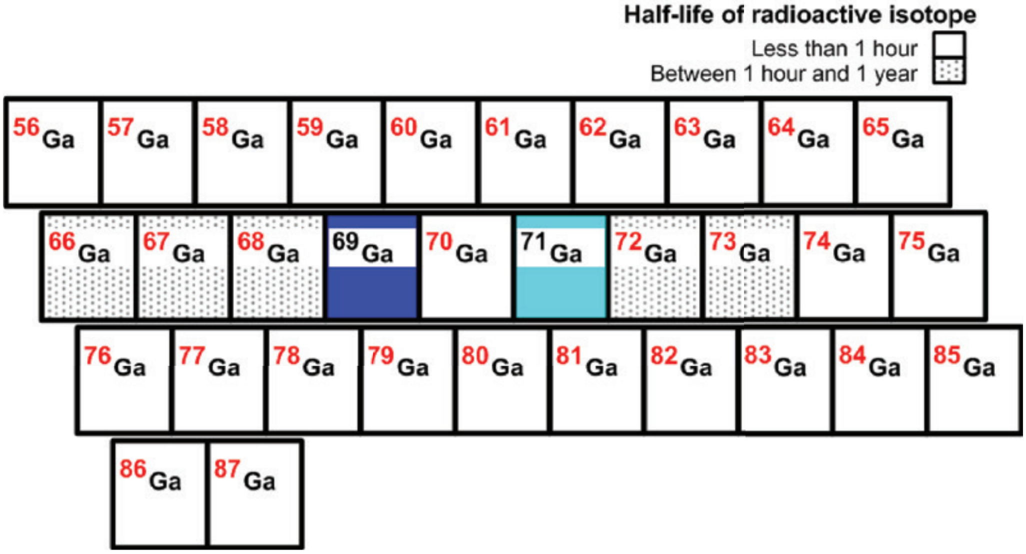
4.30.3 Zinc isotopes used as a source of radioactive isotope(s)

The ^{68}Zn (p, 2p) ^{67}Cu (with a half-life of 62 h) reaction in which targets with zinc enriched in ^{68}Zn are irradiated and the **neutron** induced reaction ^{67}Zn (n, p) ^{67}Cu are both processes for producing ^{67}Cu for **radiotherapy** [254]. Irradiation of ^{64}Zn with a deuteron (the nucleus of ^{2}H, consisting of a **proton** and a neutron) in a **cyclotron** will produce the radioisotope ^{64}Cu (with a half-life of 12.7 h), which can be used for therapeutic applications and diagnosis with **positron emission tomography** (**PET**) *via* the ^{64}Zn (d, 2p) ^{64}Cu reaction [255].

4.31 Gallium



Stable isotope	Relative atomic mass	Mole fraction
^{69}Ga	68.925 574	0.601 08
^{71}Ga	70.924 703	0.398 92

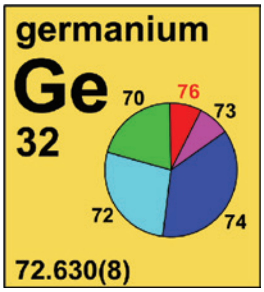


4.31.1 Gallium isotopes in medicine

^{68}Ga (with a **half-life** of 68 min) is a **radioactive isotope** that emits **positrons**, which are used to produce high-resolution imaging with **positron emission tomography** (**PET**). Unlike ^{18}F, which is most commonly used, ^{68}Ga is more easily produced using a cost-effective generator with the **parent radionuclide** ^{68}Ge (with a half-life of 271 days) (Fig. 4.31.1). Once produced, ^{68}Ga easily couples to biomolecules (most commonly **peptides**) that target **G-protein coupled receptors**, which are **over-expressed** on human tumor cells. The labeled protein acts as a radioactive **tracer** for cancer diagnostics. PET images are often coupled with CT images to get a more complete picture of the body [256–262]. **Radiopharmaceutical** ^{67}Ga (with a half-life of 78 h) is a gamma-emitting **isotope** used in **scintigraphy** for medical imaging [263–265].

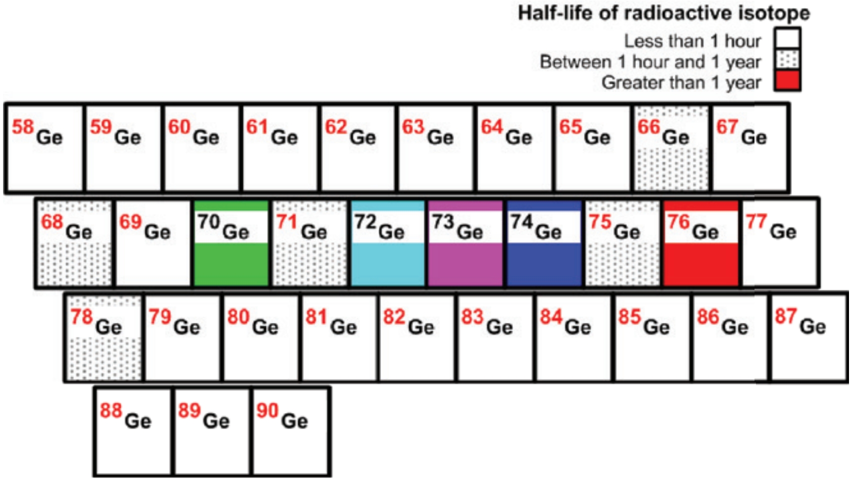
Fig. 4.31.1: Gallium-68 generator used to provide medical therapy with the **positron**-emitting **radionuclide** ^{68}Ga. The **parent radionuclide**, ^{68}Ge, has a **half-life** of 271 days and has been used as the source of ^{68}Ga, which has a half-life of only 68 min. Image kindly provided by Dr. Anatolii Razbash, Cyclotron Co. Ltd., Obninsk, Russia.

4.32 Germanium



Stable isotope	Relative atomic mass	Mole fraction
^{70}Ge	69.924 249	0.2052
^{72}Ge	71.922 0758	0.2745
^{73}Ge	72.923 4590	0.0776
^{74}Ge	73.921 177 76	0.3652
^{76}Ge†	75.921 4027	0.0775

† **Radioactive isotope** having a relatively long **half-life** (1.5×10^{21} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.32.1 Germanium isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of germanium possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of germanium in terrestrial materials (Fig. 4.32.1).

4.32.2 Germanium isotopes in medicine

^{68}Ge is used to calibrate **positron emission tomography** (**PET**) scanners, which have been used for medical diagnostic procedures [268].

4.32.3 Germanium isotopes used as a source of radioactive isotope(s)

^{72}Ge and ^{74}Ge are used to produce the **radioactive isotopes** ^{72}As and ^{74}As, with **half-lives** of 26 h and 17.8 days, respectively. The arsenic nuclei can attach to tumors and the decay of these **isotopes** is used to image the location of cancerous tumors ***in vivo*** *via* the ^{72}Ge (n, p) ^{72}As reaction and the ^{74}Ge (n, p) ^{74}As reaction [269]. ^{70}Ge,

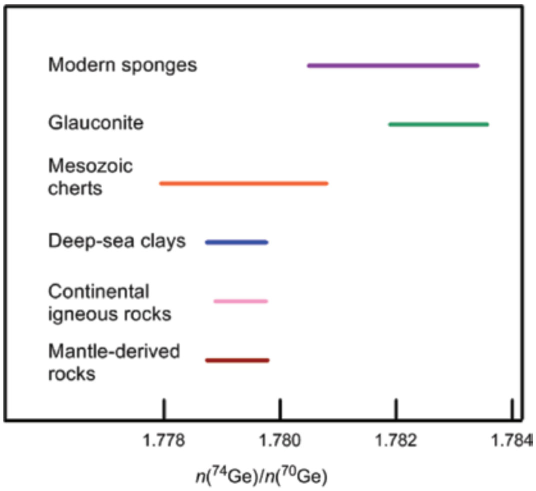
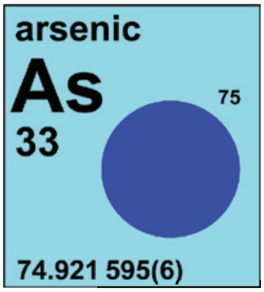


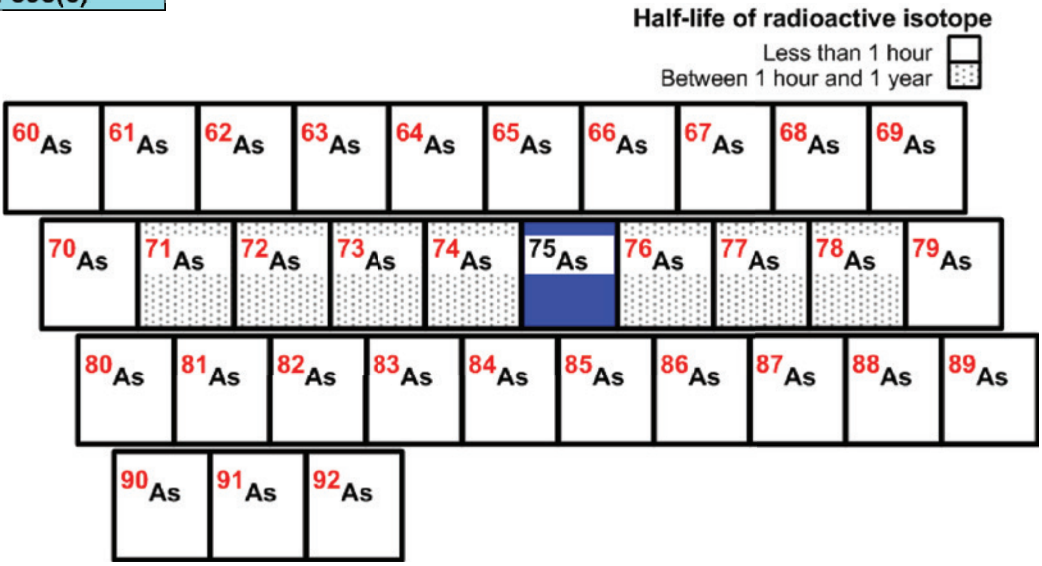
Fig. 4.32.1: Variation in the **isotope-amount ratio** $n(^{74}\mathrm{Ge})/n(^{70}\mathrm{Ge})$ of selected geranium-bearing rocks and marine precipitates (modified from [266]), assuming a measured $n(^{74}\mathrm{Ge})/n(^{70}\mathrm{Ge})$ isotope-amount ratio of 1.7794 [267].

^{72}Ge, and ^{74}Ge have all been used to produce the medical **radioisotope** ^{73}Se *via* the ^{70}Ge (^{4}He, n) ^{73}Se reaction, *via* the ^{72}Ge (^{4}He, 3n) ^{73}Se reaction and *via* the reaction ^{74}Ge (^{4}He, 5n) ^{73}Se, respectively [269].

4.33 Arsenic



Stable isotope	Relative atomic mass	Mole fraction
^{75}As	74.921 595	1



4.33.1 Arsenic isotopes in biology

^{73}As and ^{76}As (with **half-lives** of 80.3 days and 1.1 days, respectively) are important radioactive **tracers** used in environmental and biomedical studies to quantify arsenic uptake [270]. ^{74}As (with a half-life of 17.8 days) has been used to investigate the biotransformation (modification of a chemical compound by an organism) of arsenate by mammals. In one study rabbits were injected with ^{74}As-labeled arsenate. After a given amount of time, blood and blood products were sampled and tested for the presence and quantity of labeled arsenate metabolites [270]. Inhalation of dust or smoke containing ^{74}As is thought to be a causal agent of lung cancer. In one study [271], the “absorption rate from the bronchial tree (a respiratory tract, which conducts air into the lungs) was rapid for the first several days and then tapered off slowly. In three patients an average of 45 percent of the inhaled arsenic was eliminated in the urine in 10 days and about 0.5 percent in the stools. The remainder must be assumed to have been deposited in the body, exhaled, and/or eliminated in body secretions and excreta over a long period of time.” See Fig. 4.33.1.

4.33.2 Arsenic isotopes in medicine

^{72}As (with a half-life of 26 h) and ^{74}As are useful in molecular imaging because they are **radioactive isotopes** that emit **positrons** that can be designed to bind to **monoclonal antibodies** (moAb), which accumulate in tumors and then ^{72}As- or ^{74}As-labeled **ligands** will bind to the moAbs. Once the ^{72}As- or ^{74}As-labeled ligand binds to the moAb, **positron emission tomography** (**PET**) is used to visualize the exact location of the tumor

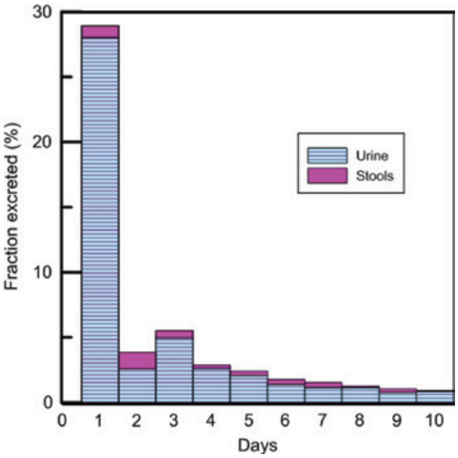
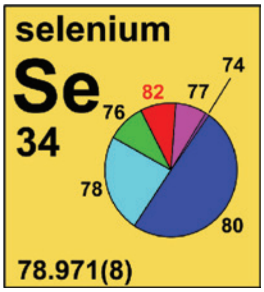


Fig. 4.33.1: Combined urine and fecal elimination of inhaled ^{74}As over a 10-day period. The ratio of urine to fecal elimination was approximately 30 to 1 (modified from [271]).

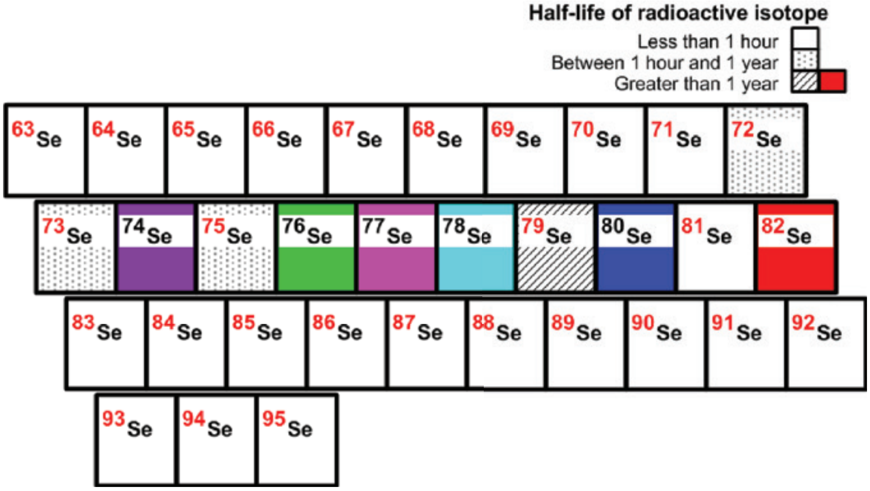
[272]. A specific example of using **radiolabeled** antibodies for better imaging of tumors is the combination of ^{74}As with bavituximab, which is an antibody that binds strongly to unique lipids on the surface of tumors. When a **thiol** group is introduced to bavituximab, arsenic is able to bind **covalently**, creating a simple and elegant radio-label for targeting cancerous tumors [269].

4.34 Selenium



Stable isotope	Relative atomic mass	Mole fraction
^{74}Se	73.922 4759	0.0086
^{76}Se	75.919 2137	0.0923
^{77}Se	76.919 9142	0.0760
^{78}Se	77.917 309	0.2369
^{80}Se	79.916 522	0.4980
^{82}Se†	81.916 700	0.0882

† **Radioactive isotope** having a relatively long **half-life** (9×10^{19} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.34.1 Selenium isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of selenium possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of selenium in natural terrestrial materials (Fig. 4.34.1).

4.34.2 Selenium isotopes in industry

^{75}Se (with a **half-life** of 120 days) is used for **X-ray radiography** of welds to visualize welds and ensure that each weld is appropriate for its purpose [274].

4.34.3 Selenium isotopes in medicine

^{75}Se-selenomethionine (organic compound that combines to form proteins, found in Brazil nuts and soybeans) has been used to study the production of digestive enzymes (biological catalysts that accelerates

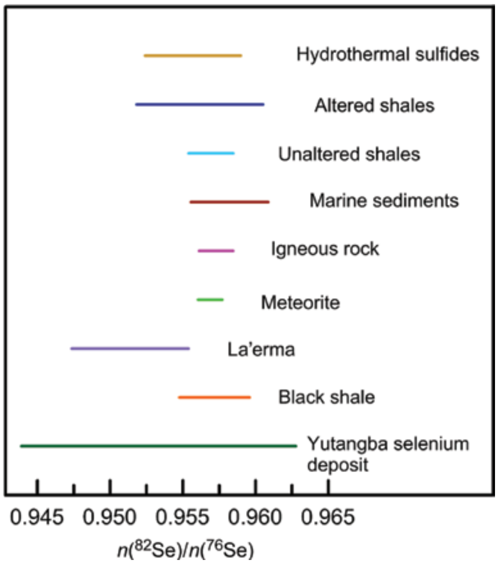


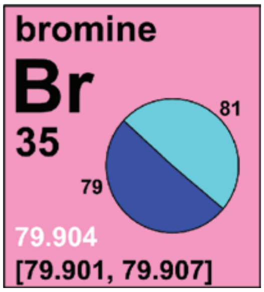
Fig. 4.34.1: Variation in the **isotope-amount ratio** $n(^{82}\mathrm{Se})/n(^{76}\mathrm{Se})$ of selected selenium-bearing materials (modified from [273]).

chemical reactions) [275]. Selenium stable isotopes are used in metabolic studies to monitor selenium intake and output [276, 277].

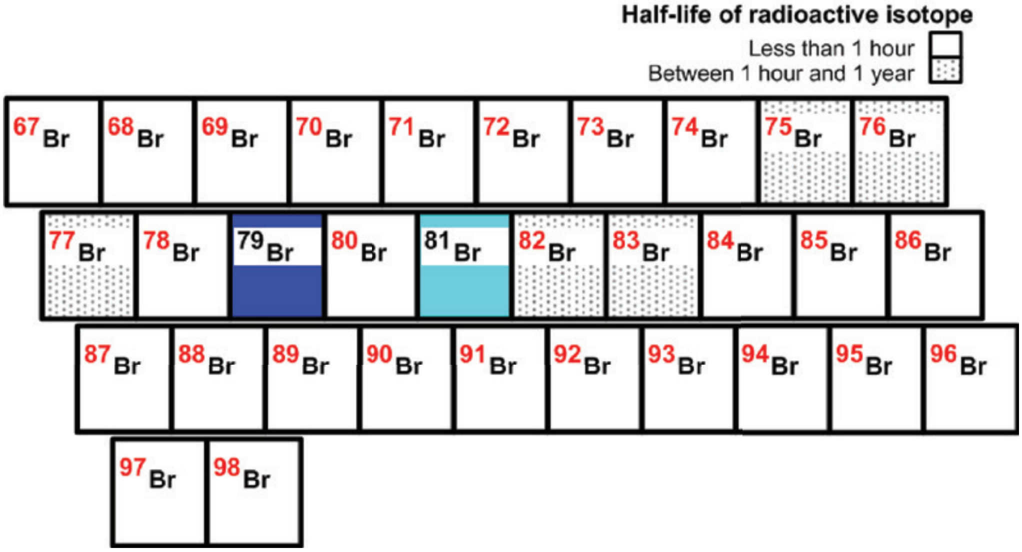
4.34.4 Selenium isotopes used as a source of radioactive isotope(s)

^{77}Se and ^{78}Se are used to produce the therapeutic **radioisotope** ^{77}Br *via* the ^{77}Se (n, p) ^{77}Br and the ^{78}Se (n, 2p) ^{77}Br reactions, respectively. ^{80}Se is used to produce $^{80\mathrm{m}}$Br *via* the reaction ^{80}Se (n, p) $^{80\mathrm{m}}$Br. The m the superscript of $^{80\mathrm{m}}$Br indicates a **metastable state** of the **isotope**.

4.35 Bromine



Stable isotope	Relative atomic mass	Mole fraction
^{79}Br	78.918 338	[0.505, 0.508]
^{81}Br	80.916 288	[0.492, 0.495]



4.35.1 Bromine isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of bromine possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of bromine in natural terrestrial materials (Fig. 4.35.1). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [13, 278]. ^{79}Br has been used as a groundwater **tracer** (Fig. 4.35.2). Introduction of a solution spiked with ^{79}Br

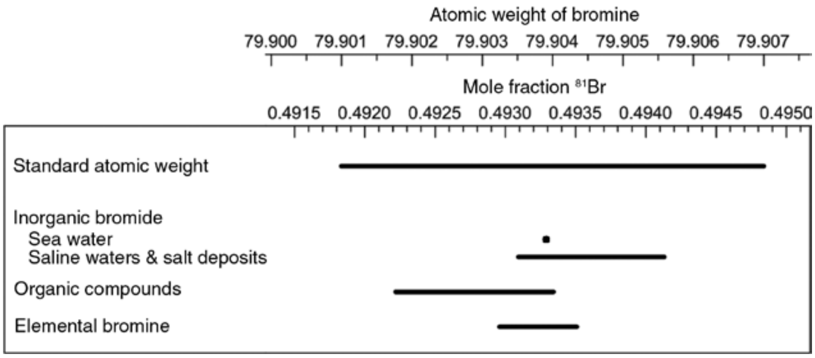


Fig. 4.35.1: Variation in **atomic weight** with **isotopic composition** of selected bromine-bearing materials (modified from [13]).

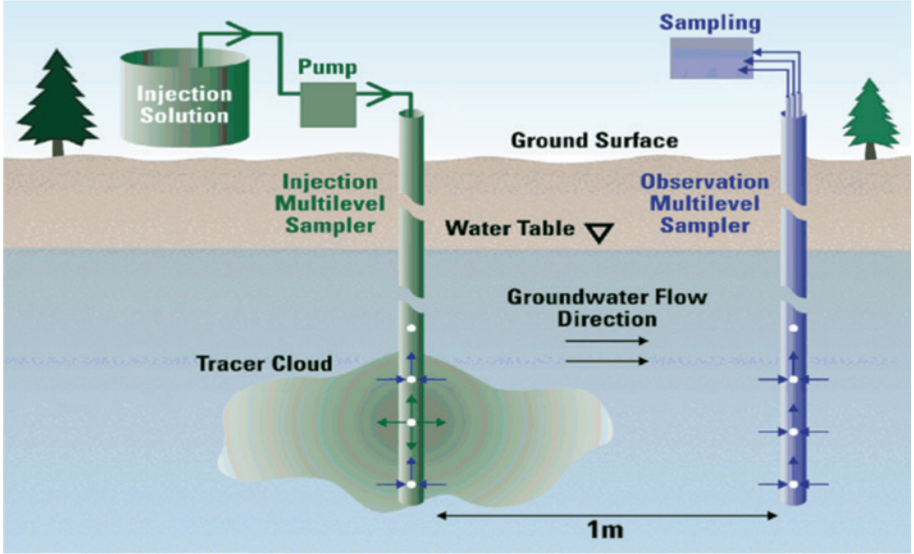


Fig. 4.35.2: Depiction of a hypothetical subsurface/groundwater **tracer** test with ^{79}Br. The tracer cloud identifies the location of the dissolved ^{79}Br spike. ^{79}Br concentration in water of the tracer cloud is compared to ^{79}Br concentration in groundwater samples in the neighboring sample site. (Diagram Source: U.S. Geological Survey, 2009) [280].

to groundwater and measurement of the change in the **isotope-amount ratio** $n(^{79}\text{Br})/n(^{81}\text{Br})$ over time has been used to monitor tracer breakthrough and to calculate bromide travel time [279].

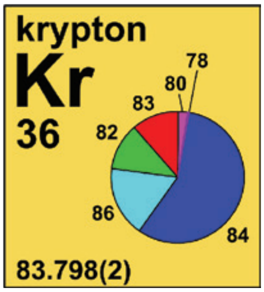
4.35.2 Bromine isotopes in medicine

^{77}Br (with a **half-life** of 57 h) is used to label **radiopharmaceuticals** that bind to estrogen receptors for tumor imaging. ^{75}Br (with a half-life of 97 min) is being used with **positron emission tomography** (**PET**) imaging [281].

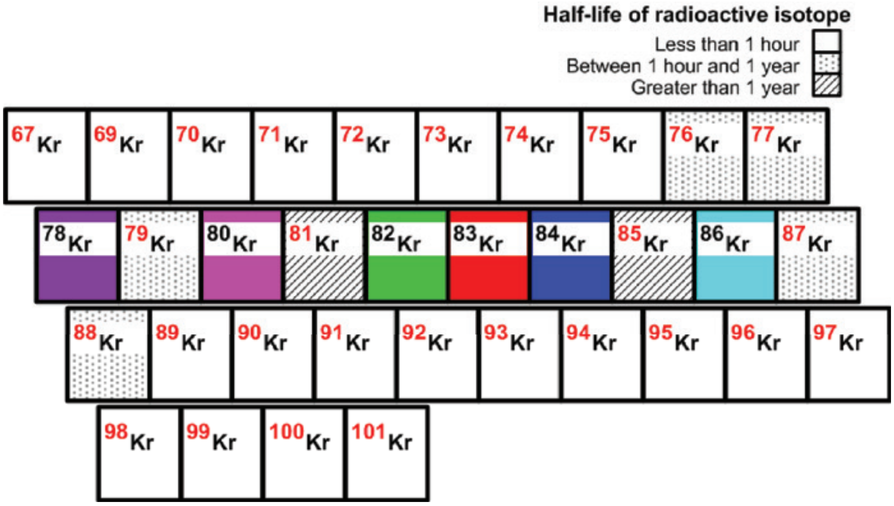
4.35.3 Bromine isotopes used as a source of radioactive isotope(s)

^{79}Br is used in the **proton cyclotron** to produce ^{77}Kr, which decays to ^{77}Br *via* the reaction ^{79}Br (p, 3n) ^{77}Kr, which decays into ^{77}Br [282].

4.36 Krypton



Stable isotope	Relative atomic mass	Mole fraction
^{78}Kr	77.920 366	0.003 55
^{80}Kr	79.916 378	0.022 86
^{82}Kr	81.913 481 16	0.115 93
^{83}Kr	82.914 126 52	0.115 00
^{84}Kr	83.911 497 73	0.569 87
^{86}Kr	85.910 610 63	0.172 79



4.36.1 Krypton isotopes in forensic science and anthropology

^{85}Kr (with a **half-life** of 10.7 years) has been used in atmospheric monitoring programs to track the effect of atomic facilities on the surrounding environment. ^{85}Kr is co-generated with plutonium in the fuel elements of nuclear **fission** reactors and can be monitored at short distances (*i.e.* 1 to 5 km) from an area of clandestine plutonium separation from spent fuel from the nuclear reactor. The differences in ^{85}Kr levels in the atmosphere have been used to estimate the amount of plutonium separated at weekly intervals. The production of plutonium for nuclear weapons and the output from commercial reprocessing plants have released large amounts of ^{85}Kr into the atmosphere [283].

4.36.2 Krypton isotopes in geochronology

^{85}Kr has minimal natural production in the Earth, but its concentration in the atmosphere has increased steadily because of human activities related to the nuclear industry. ^{85}Kr enters oceans, lakes, and groundwater through equilibration of the water with air. ^{85}Kr is produced terrestrially as a **fission** product of nuclear reactors and released into the atmosphere with the noble gases. It is also produced in the atmosphere *via* the **cosmic ray neutron**-activation reaction, ^{84}Kr (n, γ) ^{85}Kr. Thus, the ^{85}Kr specific **activity** can be used to determine the time since water was isolated from the atmosphere (Fig. 4.36.1). This approach provides a valuable addition to the use of tritium (^{3}H) as an indicator of ocean circulation and groundwater age on decadal (a period of 10 consecutive years) time scales [284, 285].

Fig. 4.36.1: ^{81}Kr has been used to date the groundwater being discharged from springs and wells. The photo shows collection of a ^{81}Kr sample from an artesian well in Farafra Oasis, Egypt [289]. (Photo Source: N. C. Sturchio, University of Delaware, Delaware, USA).

Krypton **stable isotopes** react in the upper atmosphere by cosmic-ray-induced **spallation** and neutron activation to produce radioactive ^{81}Kr, with a half-life of approximately 2.1×10^5 years. In the atmosphere, ^{81}Kr is chemically inert and has a long **residence time**; because of these characteristics, it is expected that ^{81}Kr has a relatively constant and well-constrained atmospheric source. Natural **cosmogenic** ^{81}Kr is incorporated from air into infiltrating groundwater and has been used to determine the age of groundwater over time scales ranging to over 10^6 years [286–289].

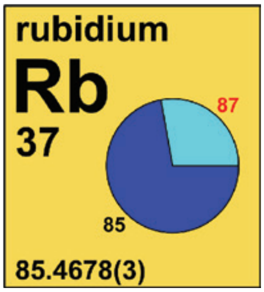
4.36.3 Krypton isotopes in industry

^{85}Kr has been used as the illumination element of indicator lights of appliances and can be combined with phosphors to create materials that glow in the dark. Light is created when radiation from ^{85}Kr strikes the phosphor [98]. ^{85}Kr can be used to detect container leaks by placing the radioactive gas inside a container and measuring (with a radiation detecting device) the amount of radioactive ^{85}Kr that escapes. Because the gas is inert, Kr will not react with anything else in the container [98].

4.36.4 Krypton isotopes in medicine

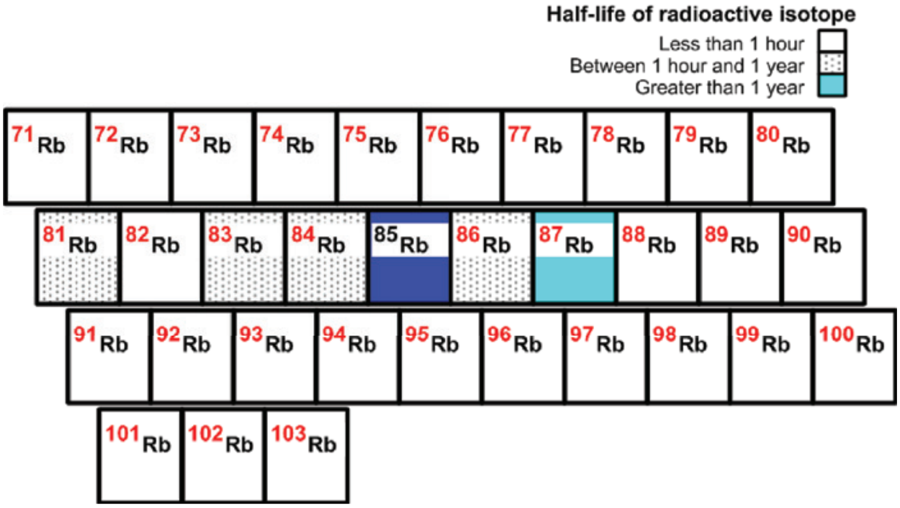
A patient can inhale gaseous radioactive ^{85}Kr, which is then absorbed in the bloodstream, enabling the blood flow of the patient to be studied. Movement of the ^{85}Kr can be tracked with a radiation detector to reveal pathways followed by the blood and to quantify blood velocity [99, 284, 290].

4.37 Rubidium



Stable isotope	Relative atomic mass	Mole fraction
^{85}Rb	84.911 789 74	0.7217
^{87}Rb†	86.909 180 53	0.2783

† **Radioactive isotope** having a relatively long **half-life** (4.97×10^{10} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.37.1 Rubidium isotopes in biology

Due to biological similarities between rubidium and potassium, the **radionuclide** ^{86}Rb (with a **half-life** of 18.7 days) is used as a **tracer** in biological or medical investigations for applications where the half-life of the **radioactive-tracer** ^{42}K (half-life of 0.5 day) is too short [110]. ^{86}Rb (with a half-life of 18.7 days) has been used measure the **metabolism** in small vertebrates (Fig. 4.37.1), such as dunnarts (furry, narrow-footed marsupials about the size of a mouse) [291]. The advantage of this technique over the standard doubly labelled water

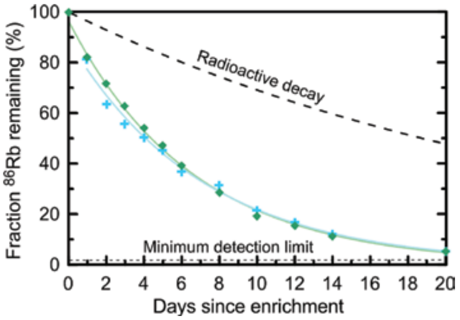


Fig. 4.37.1: Exponential decay of ^{86}Rb for *Sminthopsis macroura* (striped-faced dunnart; an Australian marsupial that weighs between 15 and 25 g; turquoise crosses) and *Sminthopsis ooldea* (an Australian marsupial called the Troughton's dunnart that weighs between 10 and 18 g; green diamonds) in **thermoneutrality** (after [291]). The solid lines are the best fit of the fraction of initial enrichment remaining, taking into account both **radioactive decay** and biological elimination of ^{86}Rb.

method, using water enriched in ^{2}H and ^{18}O, include lower equipment requirements, lower technical expertise, and longer time spans over which measurements can be made. This technique could be very useful for measuring the metabolism of amphibians and insects.

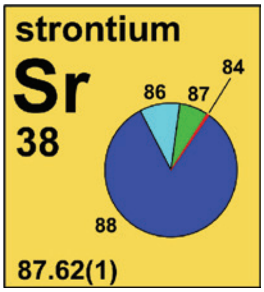
4.37.2 Rubidium isotopes in geochronology

^{87}Rb (with a half-life of 4.97×10^{10} years) is a long-lived **radioisotope** that is transformed into ^{87}Sr by emission of a beta-minus particle (an **electron**) and an **antineutrino**. From the abundance of ^{87}Sr and the Rb/Sr **amount ratio** in a rock, its age of crystallization can be calculated. Rb/Sr dating is one of the most widely employed techniques for dating geological samples [292].

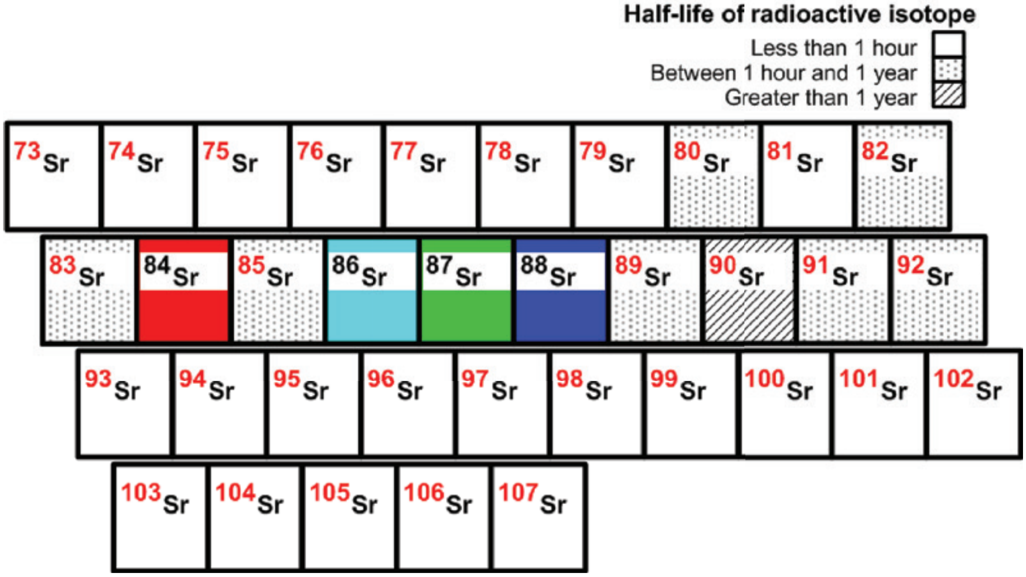
4.37.3 Rubidium isotopes in medicine

^{82}Rb (with a half-life of 75 s) acts similarly to potassium and is used for imaging of the heart to better assess heart muscle function as a radioactive analog to potassium [293, 294]. ^{82}Rb is being considered as an alternative to highly-enriched uranium for producing medically important radioisotopes [293].

4.38 Strontium



Stable isotope	Relative atomic mass	Mole fraction
^{84}Sr	83.913 419	0.0056
^{86}Sr	85.909 260 73	0.0986
^{87}Sr	86.908 877 50	0.0700
^{88}Sr	87.905 612 26	0.8258



4.38.1 Strontium isotopes in Earth/planetary science

Stable **isotopic fractionation** of strontium is small because the relative differences between the masses of strontium **stable isotopes** are small (**mass numbers** are 86, 87, and 88 for the most abundant stable isotopes). Also, strontium is not subject to **reduction-oxidation** reactions in normal terrestrial environments, which would cause isotopic fractionation to be more evident. Nevertheless, current studies are exploring

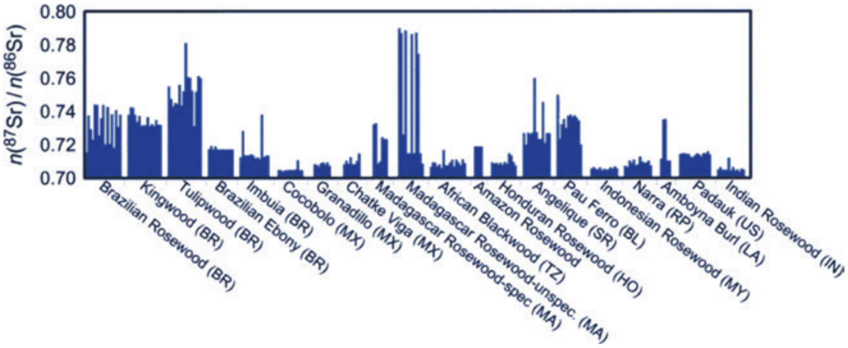


Fig. 4.38.1: Variation in strontium **isotope-amount ratios** of twenty species of exotic wood from thirteen countries (modified from [300]).

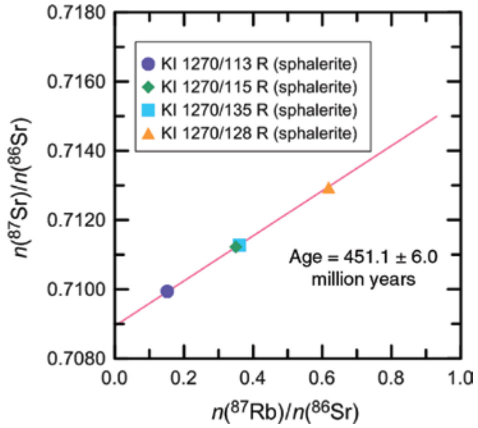


Fig. 4.38.2: Cross plot of $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ **isotope-amount ratio** and $n(^{87}\mathrm{Rb})/n(^{86}\mathrm{Sr})$ **amount ratio** of sphalerites (zinc sulfide mineral) from the Kipushi base metal deposit, Democratic Republic of Congo (modified from [302]). ^{87}Sr is produced by decay of radioactive ^{87}Rb. Rock containing higher amounts of ^{87}Rb will over time produce higher amounts of ^{87}Sr, for example sample KI 1270/128 R. Rock containing lower amounts of ^{87}Rb will over time produce smaller amounts of ^{87}Sr, for example sample KI 1270/113 R. Assuming all the sphalerites in this figure were formed at the same time, one can determine the age of formation of the sulfides from the slope of the line through the data points, here $(451.1 \pm 6.0) \times 10^6$ a, and this line is called an **isochron**.

potential applications of stable strontium isotopic fractionation; for example, it has been used as a **proxy** for temperature during coral growth and for insights into the diets of ancient populations [295, 296].

The relative abundance of natural **radiogenic** ^{87}Sr in seawater is related to the relative rates of processes that add or remove strontium in the ocean (seafloor spreading, mid-ocean-ridge hydrothermal activity, and continental weathering). Over geologic time, these processes have fluctuated and the **isotope-amount ratio** $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ has changed systematically. By measuring the $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ ratio in marine fossils of known age, it is possible to identify when such environmental changes occurred. Conversely, it is possible to estimate the ages of marine deposits by comparing measured $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ ratios with the global time chart; this process is known as strontium **isotope** stratigraphy [297].

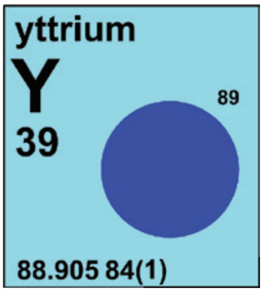
4.38.2 Strontium isotopes in forensic science and anthropology

The isotope-amount ratio $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ is highly variable in rocks, minerals, soils, and waters, and it can be transmitted to plants (Fig. 4.38.1), animals, and manufactured materials. Measurements of $n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr})$ ratios are used for forensic applications in food authentication (determining where food came from), archaeology, crime-scene investigation, and human migration [298, 299].

4.38.3 Strontium isotopes in geochronology

The ^{87}Rb-^{87}Sr dating technique utilizes the fact that ^{87}Sr is a product of radioactive ^{87}Rb decay (**half-life** of 4.97×10^{10} years) and is a useful tool for determining ages of rocks and minerals spanning the age of the Earth (Fig. 4.38.2) [301].

4.39 Yttrium



Stable isotope	Relative atomic mass	Mole fraction
^{89}Y	88.905 84	1

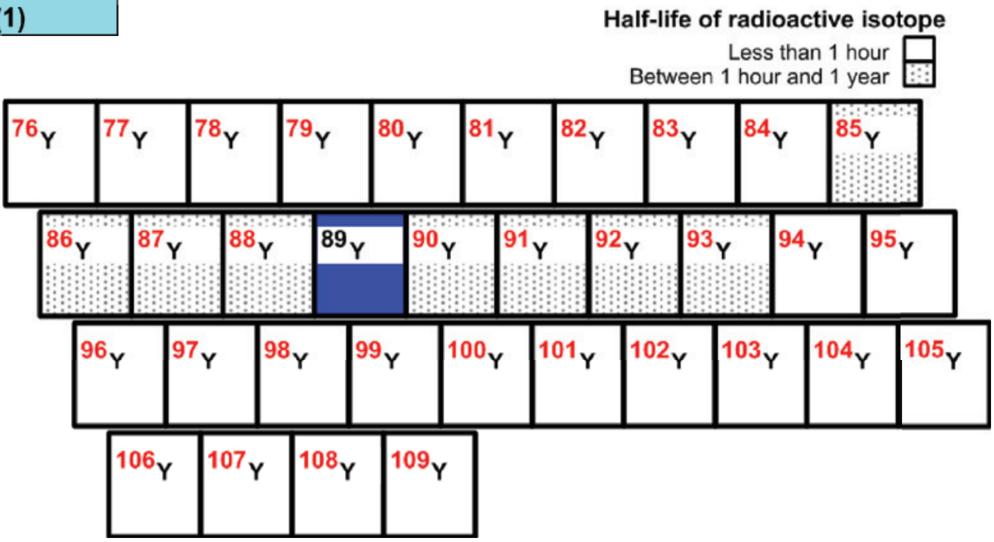
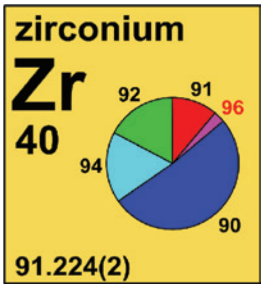


Fig. 4.39.1: Ultrapure ^{90}Y. (Photo Source: Pacific Northwest National Laboratory) [306].

4.39.1 Yttrium isotopes in medicine

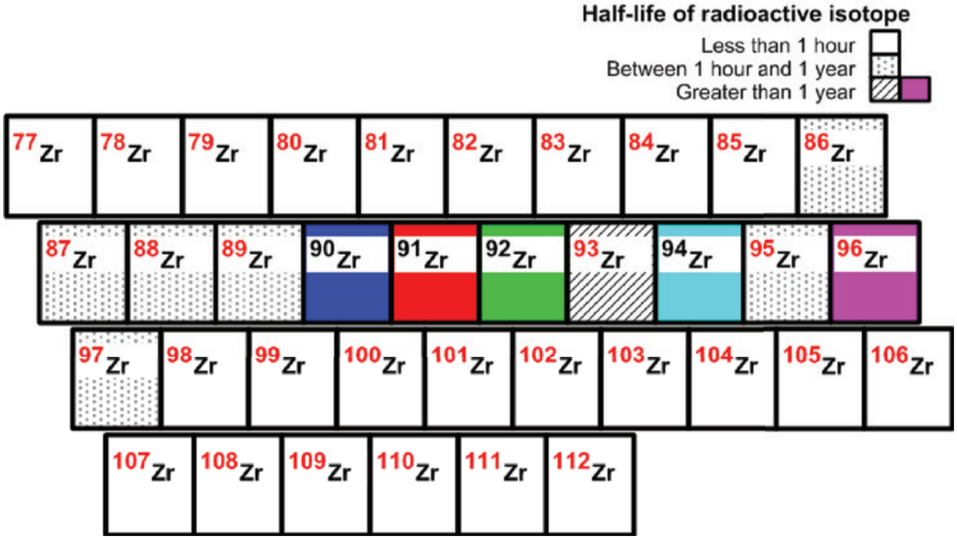
Carbon nanotubes (CNT), which are nano-scaled carbon tubes, are being examined in nanobiotechnology research studies because it has been discovered that CNTs labeled with ^{86}Y (with a **half-life** of 0.6 day) are soluble when they are injected into mice. This discovery was made after mice were given an **intravenous** or intraperitoneal (directly into a body cavity) injection with the ^{86}Y CNT and then were examined using **positron emission tomography** (**PET**) scans to observe whether the ^{86}Y had been flushed from their systems. The PET scan determined that accumulation of ^{86}Y occurred in the liver, kidney, and spleen with very rapid blood clearance. This has broad implications for developing drug treatments [303]. Radiomicrosphere therapy (RT) that uses ^{90}Y (with a half-life of 64 h) microspheres is a proven therapy that helps treat hepatic (liver) cancer (Fig. 4.39.1) [304]. ^{90}Y is also used in **radiosynovectomy** to reduce joint pain [305].

4.40 Zirconium



Stable isotope	Relative atomic mass	Mole fraction
^{90}Zr	89.904 6988	0.5145
^{91}Zr	90.905 6402	0.1122
^{92}Zr	91.905 0353	0.1715
^{94}Zr	93.906 313	0.1738
^{96}Zr†	95.908 2776	0.0280

† **Radioactive isotope** having a relatively long **half-life** (2.3 × 10^{19} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.40.1 Zirconium isotopes in industry

Zirconium enriched in ^{90}Zr has been proposed for the cladding (covering) of reactor fuel elements (Fig. 4.40.1) because it has a lower **neutron absorption cross section** than natural abundances of zirconium and is well suited for coverage of metal parts without absorbing neutrons [307].

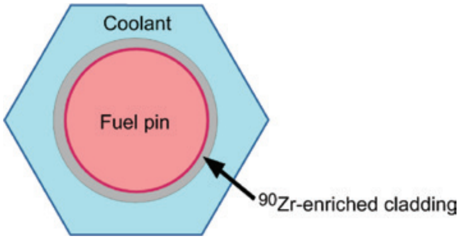
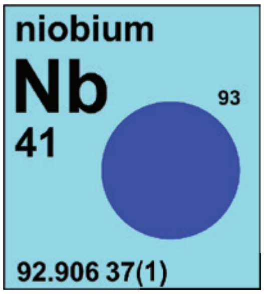
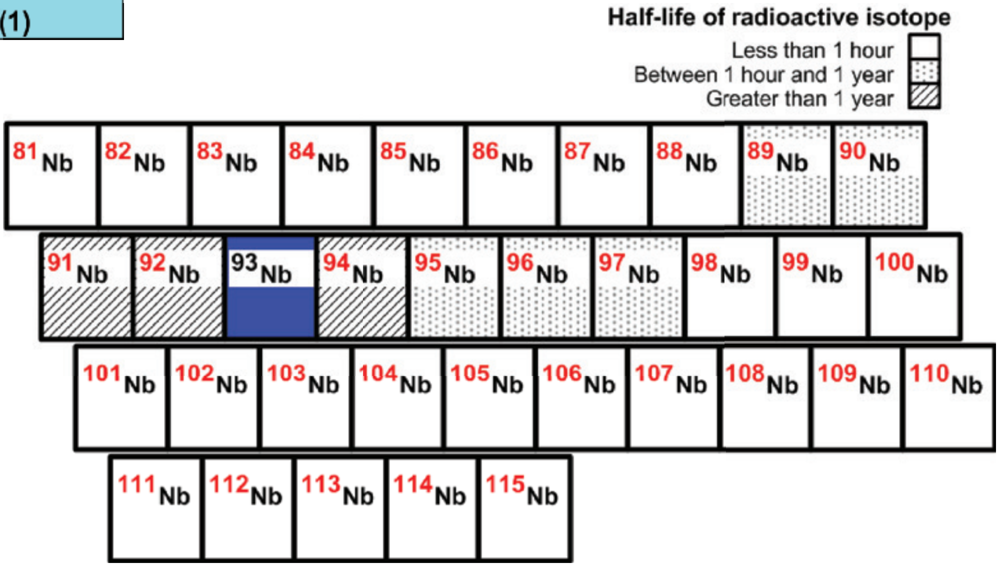


Fig. 4.40.1: The cores of nuclear reactors have fuel pins that are typically made of uranium-oxide. To keep **fission** products from escaping into the coolant, these pins are surrounded by zirconium cladding. (Modified from [308]).

4.41 Niobium



Stable isotope	Relative atomic mass	Mole fraction
^{93}Nb	92.906 37	1



4.41.1 Niobium isotopes in biology

^{95}Nb (with a **half-life** of 35 days) and ^{95}Nb-oxalates have been used to study the absorption, retention and distribution of niobium in the body [309, 310].

4.41.2 Niobium isotopes in Earth/planetary science

Nuclear physicists are trying to study the generation of new **isotopes** and their **elements** in stars (astrophysical **nucleosynthesis**) *via* the rapid **neutron** capture process (**r-process**). Physicists at the Radioactive Isotope Beam Facility (RIBF) of the RIKEN Nishina Center for Accelerator-Based Science in Wako, Japan, have begun creating and studying highly neutron-rich isotopes that are thought to only be produced by the r-process. The data for many neutron-rich isotopes is incomplete, and the RIKEN team is filling in key missing information that is needed to simulate the r-process (including information on the half-lives of the neutron-rich isotopes). So far, the half-lives of 38 neutron-rich isotopes have been measured from krypton to technetium, including ^{111}Nb and ^{112}Nb. When the missing information has been obtained, physicists will have a better understanding of the r-process and how elements are created [311, 312].

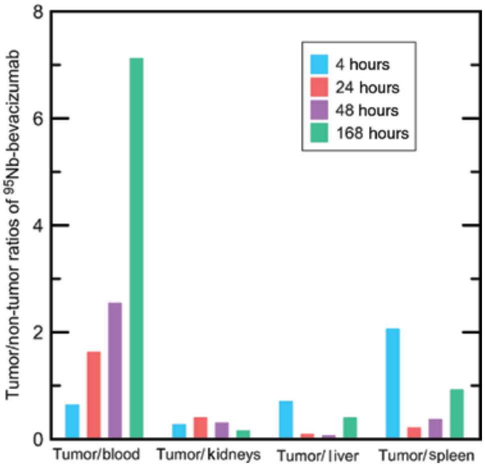
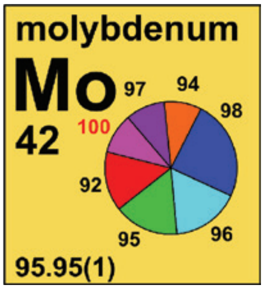


Fig. 4.41.1: Tumor/Non-tumor ratios of ^{95}Nb-bevacizumab at 4, 24, 48 and 168 h post injection (modified from [315]). Bevacizumab, sold under the trade name Avastin, is a drug that slows the growth of new blood vessels and was approved by the U.S. Food and Drug Administration for selected metastatic cancers, including colon cancer. This *in vivo* biodistribution study (a distribution of compounds within a biological system or organism) shows increased tumor uptake of ^{95}Nb-bevacizumab and a satisfactory tumor/blood ratio.

4.41.3 Niobium isotopes in medicine

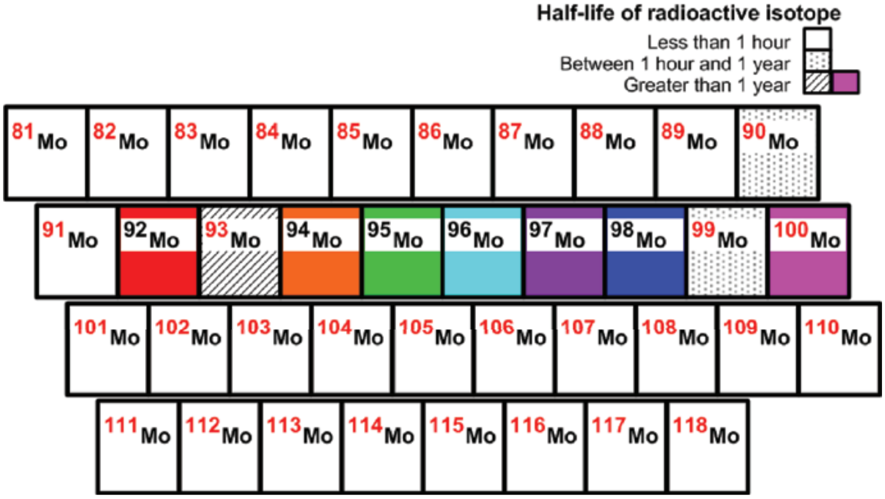
^{95}Nb and ^{95m}Nb (with a half-life of 3.6 days) have been used in tumor research and tumor imaging studies (Fig. 4.41.1) [313–315]. The m in the superscript of ^{95m}Nb indicates a **metastable state** of the isotope.

4.42 Molybdenum



Stable isotope	Relative atomic mass	Mole fraction
^{92}Mo	91.906 807	0.146 49
^{94}Mo	93.905 0836	0.091 87
^{95}Mo	94.905 8374	0.158 73
^{96}Mo	95.904 6748	0.166 73
^{97}Mo	96.906 017	0.095 82
^{98}Mo	97.905 404	0.242 92
^{100}Mo†	99.907 468	0.097 44

† **Radioactive isotope** having a relatively long **half-life** (7.1 × 10^{18} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.42.1 Molybdenum isotopes in Earth/planetary science

Molybdenites display a variation in **isotopic composition** (Fig. 4.42.1) [316]. The isotopic composition of molybdenum in ocean sediments depends on oxygen levels in the ocean. When oxygen levels are high, the lighter **isotopes** of molybdenum are scavenged by iron and manganese oxides into sediments. However, when oxygen levels are low, the mechanism for molybdenum removal becomes more efficient and more of the heavier isotopes of molybdenum are found in iron and manganese oxides. Thus, the molybdenum isotopic composition of these sediments can be used as a **proxy** for oxygen levels in the paleo oceans (history of the oceans in the geological past) to gain insights into mechanisms that may have been responsible for mass-extinction events in the Earth's history [317].

4.42.2 Molybdenum isotopes in industry

Depleted ^{95}Mo has been used in the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (Tennessee, USA). The use of U-10Mo fuel elements (90 percent uranium, 10 percent molybdenum) would

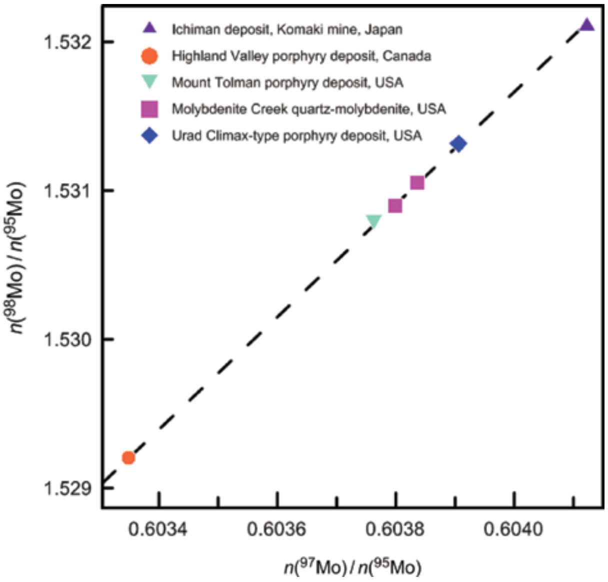


Fig. 4.42.1: Cross plot of $n(^{98}\text{Mo})/n(^{95}\text{Mo})$ **isotope-amount ratio** and $n(^{97}\text{Mo})/n(^{95}\text{Mo})$ isotope-amount ratio of selected molybdenum-bearing materials (modified from [316]), assuming a measured $n(^{98}\text{Mo})/n(^{95}\text{Mo})$ isotope-amount ratio of 1.530 40 and a measured $n(^{97}\text{Mo})/n(^{95}\text{Mo})$ isotope-amount ratio of 0.603 67 [318].

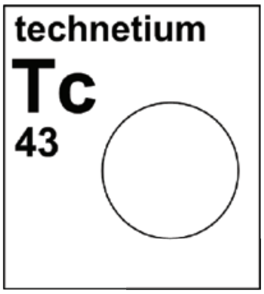
Fig. 4.42.2: Pictured above is Brookhaven National Laboratory where the $n(^{99}\text{Mo})/n(^{99\text{m}}\text{Tc})$ **amount-ratio** generator was originally developed in the early 1960s. (Picture Source: Brookhaven National Laboratory) [321].

allow the conversion from high-enrichment uranium (HEU) fuel, 92 percent, to low-enrichment uranium (LEU) fuel, below 20 percent, for nuclear non-proliferation purposes [319].

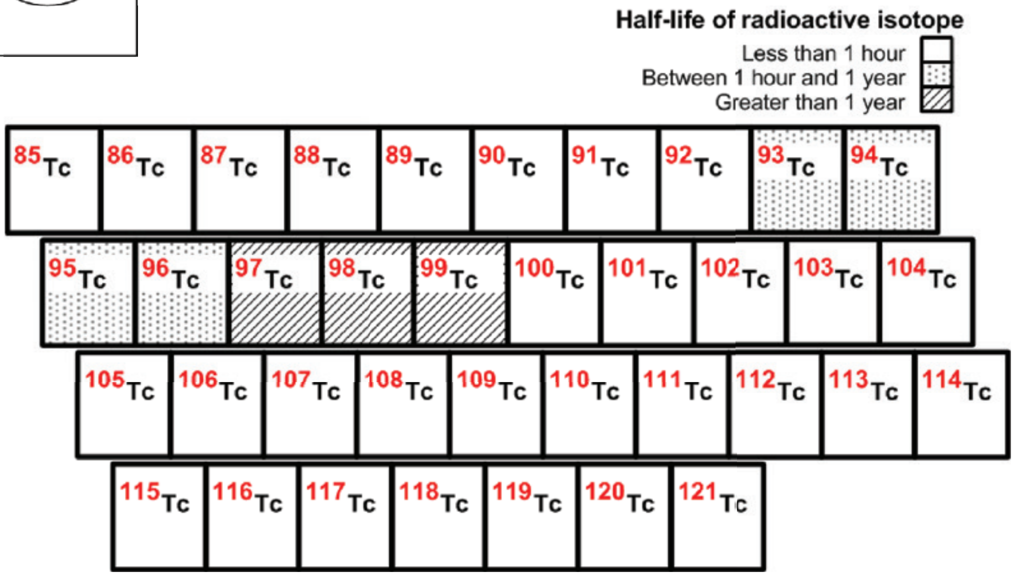
4.42.3 Molybdenum isotopes used as a source of radioactive isotope(s)

^{95}Mo is used to produce medical **radioisotope** ^{97}Ru *via* the ^{95}Mo (^{4}He, 2n) ^{97}Ru reaction. The isotope ^{99}Mo is commercially produced by the **fission** of ^{235}U and is the **parent radionuclide** of $^{99\text{m}}$Tc, which is the most widely used **radiopharmaceutical** in the world. The much longer **half-life** of ^{99}Mo (about 66 h) enables the **radionuclide** to be transported more easily than the short-lived (6 h half-life) $^{99\text{m}}$Tc. The $n(^{99}\text{Mo})/n(^{99\text{m}}\text{Tc})$ amount-ratio generator was originally developed at Brookhaven National Laboratory (Fig. 4.42.2) in the early 1960s and is now a patented system [320].

4.43 Technetium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.43.1 Technetium isotopes in medicine

^{99m}Tc is an **isomer** of ^{99}Tc with a **half-life** of approximately 6 h that is used to label **peptides** for morphologic (the form and structure of an organism) and dynamic modeling of renal (kidney), hepatic (liver), bone, and cardiac imaging [320, 322]. ^{99m}Tc **radiopharmaceuticals** absorb to a variety of tumors. These tumors can be imaged using **single-photon emission computed tomography** (SPECT) coupled with non-invasive computed tomography (**CT scan**), which provides a high level of functional and anatomical information in a

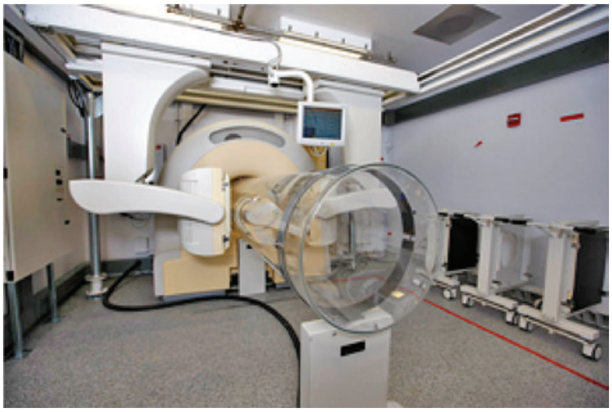
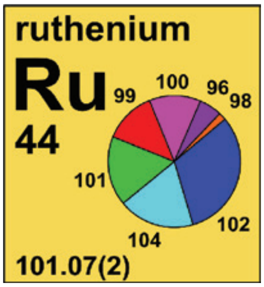


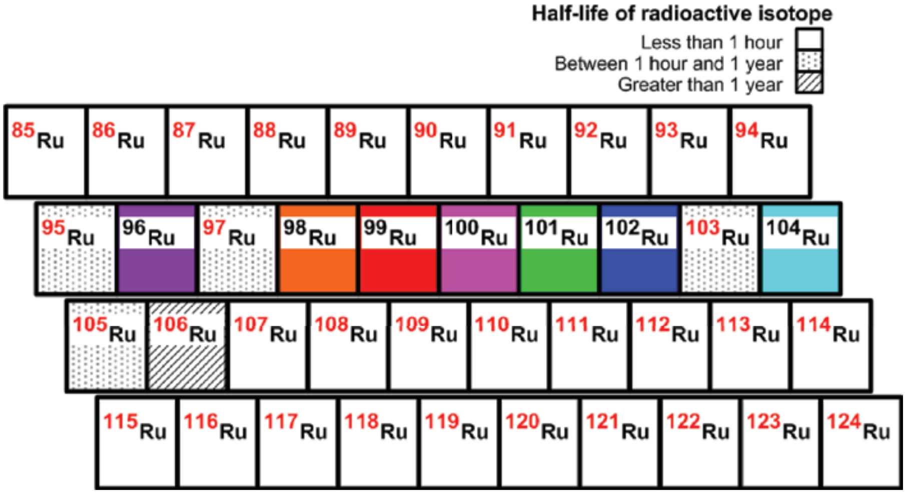
Fig. 4.43.1: Single-photon emission computed tomography (SPECT CT) machine. (Image Source National Institute of Allergy and Infectious Diseases (NIAID) and National Institutes of Health) [325].

three-dimensional image (Fig. 4.43.1) [323, 324]. Medronate is a radioactive pharmaceutical, which has been used to find, treat, or study certain diseases or body functions. ^{99m}Tc-labeled medronate (^{99m}Tc-MDP) is used in a diagnostic test to detect **metastases** from prostate, lung or thyroid cancer, making use of a **gamma camera** to record the distribution of ^{99m}Tc-MDP within the body. A two-dimensional image of the affected areas is produced.

4.44 Ruthenium



Stable isotope	Relative atomic mass	Mole fraction
^{96}Ru	95.907 589	0.0554
^{98}Ru	97.905 29	0.0187
^{99}Ru	98.905 930	0.1276
^{100}Ru	99.904 211	0.1260
^{101}Ru	100.905 573	0.1706
^{102}Ru	101.904 340	0.3155
^{104}Ru	103.905 43	0.1862



4.44.1 Ruthenium isotopes in Earth/planetary science

^{100}Ru is the product of a rare (and hence very long-lived) nuclear decay process from the **double beta decay** of ^{100}Mo. A careful measurement of the **half-life** for this decay, which is 7.1×10^{18} years, can be used to place an upper limit on the mass of the **electron neutrino**, which is a neutral and weakly interacting subatomic particle first postulated by Wolfgang Pauli in 1930 [326].

Ruthenium and molybdenum share many similarities. They both have seven **isotopes** (96, 98, 99, 100, 101, 102, and 104 for ruthenium and 92, 94, 95, 96, 97, 98, and 100 for molybdenum), and their isotopes are formed by the same **nucleosynthesis p-processes**, **r-processes**, and **s-processes**, namely, p, r, s and r, s only, s and r, s and r, and r, respectively. The molybdenum and ruthenium **isotopic composition** of most **meteorites** lie along a mixing line (Fig. 4.44.1). The ruthenium and molybdenum of silicates in the Earth also lie on this line, which supports the hypothesis that the Earth **accreted** homogeneously. That is, the feeding zone of the Earth did not change substantially over time as both the bulk of the Earth and the late veneer accreted from material having the same ruthenium-molybdenum isotopic reservoir [327].

4.44.2 Ruthenium isotopes in medicine

^{106}Ru plaque **brachytherapy** has been used for eye preservation and tumor control of uveal (the middle layer of the wall of the eye) melanoma [333]. The half-life of ^{106}Ru is 373 days.

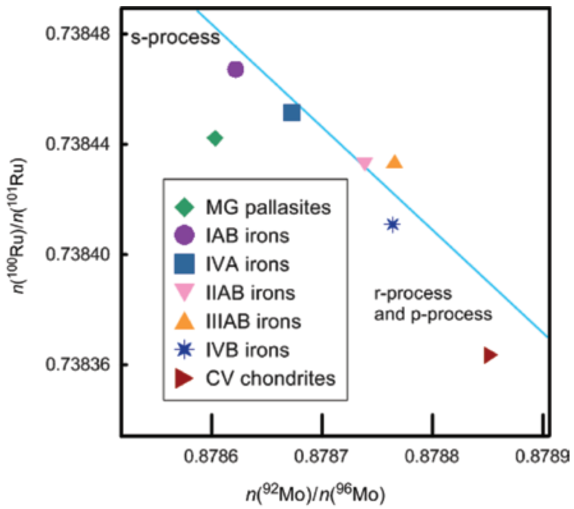


Fig. 4.44.1: Cross plot of $n(^{100}Ru)/n(^{101}Ru)$ **isotope-amount ratio** [328, 329] and $n(^{92}Mo)/n(^{96}Mo)$ isotope-amount ratio [330, 331] of selected **meteorite** groups (modified from [327]), assuming a measured $n(^{100}Ru)/n(^{101}Ru)$ isotope-amount ratio of 0.738 48 [332] and a measured $n(^{92}Mo)/n(^{96}Mo)$ isotope-amount ratio of 0.878 61 [318].

4.44.3 Ruthenium isotopes used as a source of radioactive isotope(s)

^{96}Ru is used to produce **radioisotopes** ^{94}Ru (with a half-life of 52 min) and ^{95}Ru (with half-life of about 1.64 h) *via* the reactions ^{96}Ru (n, 3n) ^{94}Ru and ^{96}Ru (n, 2n) ^{95}Ru, respectively (Fig. 4.44.2) [334, 335]. ^{104}Ru is used to produce the radioisotope ^{105}Rh (with a half-life of about 35 h) *via* the reaction ^{104}Ru (p, γ) ^{105}Rh. ^{105}Rh has been used in the treatment of bone pain [334].

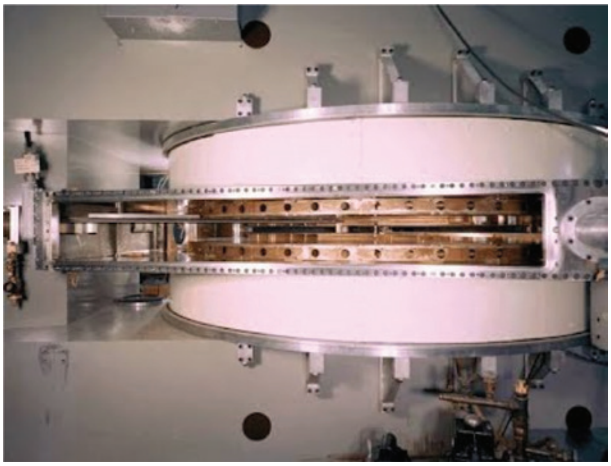
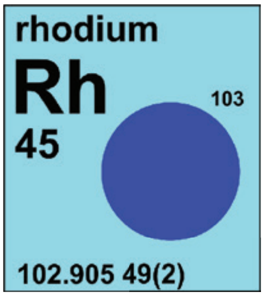
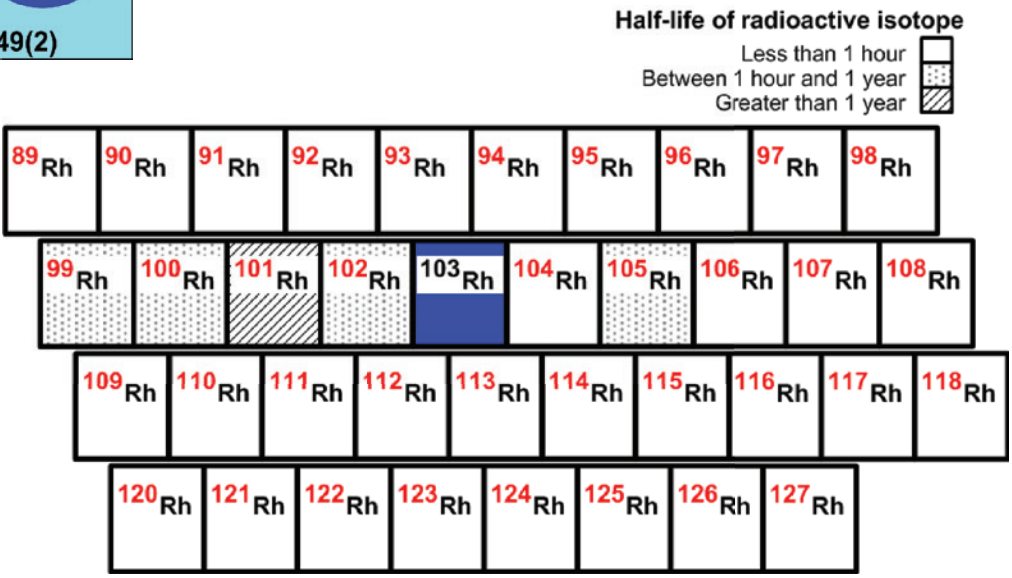


Fig. 4.44.2: The 88-Inch **cyclotron** was used to produce both light and heavy ions, including ^{94}Ru and ^{95}Ru. (Photo Source: Lawrence Berkeley National Laboratory) [336].

4.45 Rhodium



Stable isotope	Relative atomic mass	Mole fraction
^{103}Rh	102.905 49	1



4.45.1 Rhodium isotopes in medicine

The beta particles of ^{105}Rh (with a **half-life** of about 35 h) are used in target **radiotherapy** to kill cancer cells or cause cancer cell sterilization [334]. The **gamma rays** from ^{105}Rh enable *in vivo* tracking during radiotherapy [334]. ^{105}Rh has been used in the treatment of bone pain (Fig. 4.45.1) [334, 337].

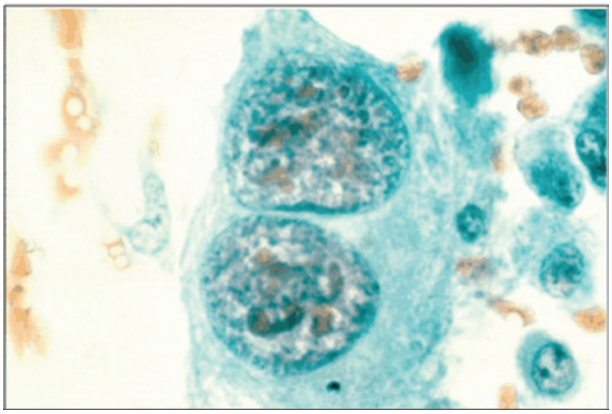


Fig. 4.45.1: Bone cancer cells that have been pap stained and magnified to 400 times. The beta particles and **gamma rays** of ^{105}Rh are used, respectively, in **radiotherapy** to kill cancer cells and for *in vivo* tracking during radiotherapy [339]. (Photo Source: National Cancer Institute at the National Institutes of Health).

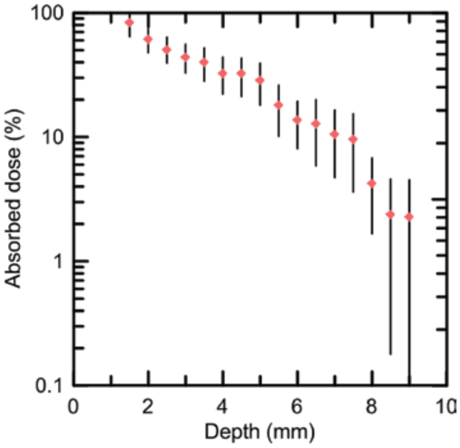
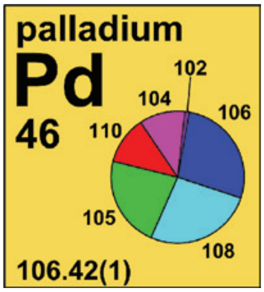


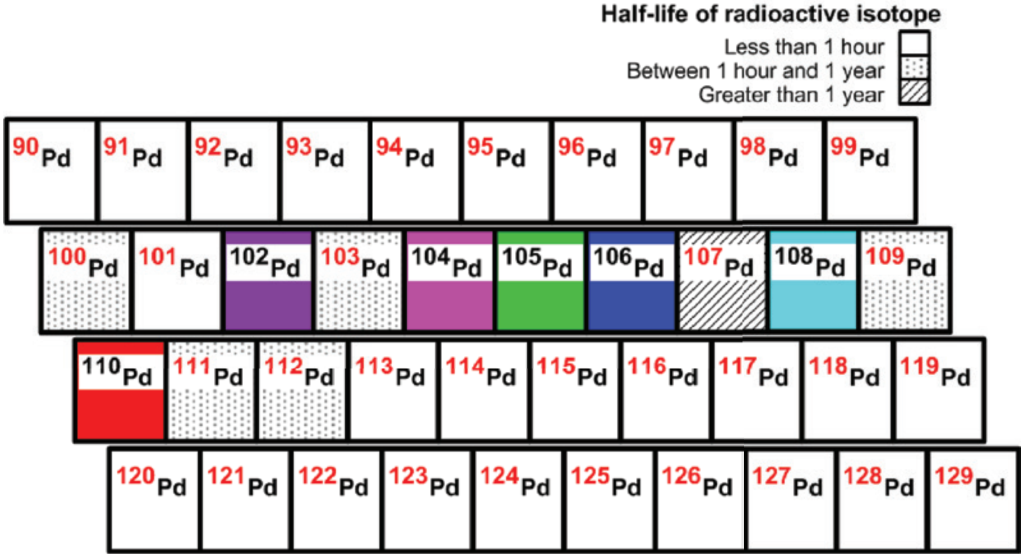
Fig. 4.45.2: Variation in absorbed dose of ^{106}Rh as a function of tissue depth in **ocular brachytherapy** (modified from [338]).

Ocular brachytherapy currently is performed using ^{125}I (with a half-life of about 59 days) or ^{106}Rh (with a half-life of about 30 s) seeds [338]. Brachytherapy can allow a good spatial dose distribution over the ocular tumor with lower radiation on adjacent tissues. In the case of irradiation of the eyeball with ^{106}Rh, 80 percent of the dose has been absorbed within a depth of 5.2 mm and 90 percent has been absorbed within 7.2 mm (Fig. 4.45.2). This limits the application of ^{106}Rh; however, when ^{106}Rh can be used, the radiation dose can be lower, which is preferred.

4.46 Palladium



Stable isotope	Relative atomic mass	Mole fraction
^{102}Pd	101.905 632	0.0102
^{104}Pd	103.904 030	0.1114
^{105}Pd	104.905 080	0.2233
^{106}Pd	105.903 480	0.2733
^{108}Pd	107.903 892	0.2646
^{110}Pd	109.905 173	0.1172



4.46.1 Palladium isotopes in Earth/planetary science

Small palladium **nucleosynthetic** anomalies in **isotopic composition** (related to **s-process** variability) were identified in type IVB iron **meteorites** [340]. These nucleosynthetic **isotope** anomalies may represent spatial and/or temporal heterogeneity in the early **solar nebula** or may be due to chemical processing within the solar nebula [327, 341]. Palladium and molybdenum isotopic compositions on selected iron meteorites are correlated (Fig. 4.46.1). One possible conclusion is that "a common presolar carrier must have been thermally processed on which the more volatile (a measure of the tendency of a substance to vaporize) Pd was lost and homogenized in the solar nebula, resulting in the deviation from the s-process" variability [342]. Because these palladium (and other **element**) anomalies are persistent throughout the measured iron meteorites, the thermal processing must have occurred prior to the formation of the parent body that produced iron meteorites [342].

4.46.2 Palladium isotopes in geochronology

The **isotope-amount ratio** $n(^{107}\text{Pd})/n(^{107}\text{Ag})$ is used in **geochronology** to help date major thermal events in the Solar System. Although ^{107}Ag is naturally occurring, ^{107}Ag is also the **daughter product** of the **beta decay** of ^{107}Pd. If both excess ^{107}Ag and ^{107}Pd (with a **half-life** of 6.5×10^6 years) are present in a sample of extraterrestrial

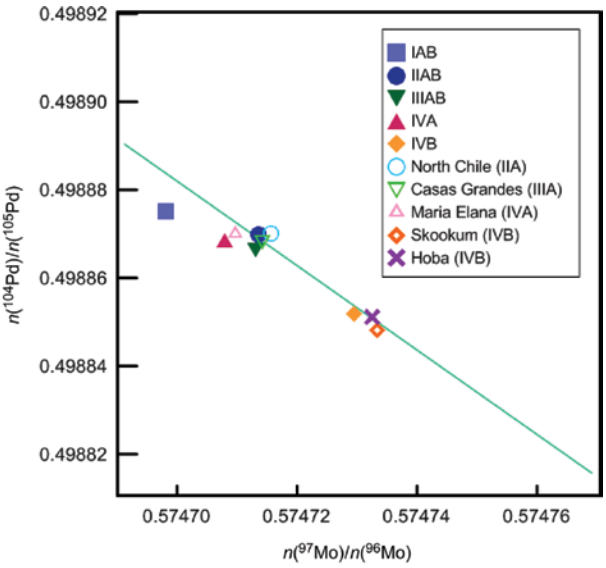


Fig. 4.46.1: Cross plot of $n(^{104}\text{Pd})/n(^{105}\text{Pd})$ and $n(^{97}\text{Mo})/n(^{96}\text{Mo})$ **isotope-amount ratios** of selected **meteorites** (modified from [342]), assuming a measured $n(^{104}\text{Pd})/n(^{105}\text{Pd})$ isotope-amount ratio of 0.498 88 in terrestrial material [343] and a measured $n(^{97}\text{Mo})/n(^{96}\text{Mo})$ isotope-amount ratio of 0.574 70 in terrestrial material [318].

origin, then the material would have formed sometime after ^{107}Pd decayed. The $n(^{107}\text{Pd})/n(^{107}\text{Ag})$ **amount ratio** can be measured to help determine when the ^{107}Pd decay process began and how much time has elapsed since the material was formed [344–348].

4.46.3 Palladium isotopes in medicine

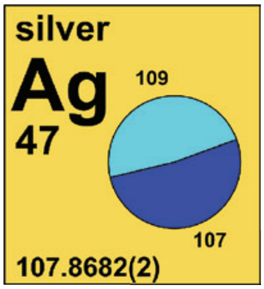
Seeds of the **radioactive isotope** ^{103}Pd are internally placed in the body to fight prostate and other cancers locally. ^{103}Pd has a half-life of 16.99 days and releases energy at about 80 **X-rays** and 186 **Auger electrons** per 100 decays of ^{103}Pd. Therefore, this makes this isotope an ideal candidate for internal **radiotherapy** for the treatment of cancers [349].

The **radioisotope** ^{109}Pd (with a half-life of 13.5 h) can be used as a form of cancer therapy. For example, ^{109}Pd-labeled **porphyrins** or porphyrin-like substances are used as diagnostic and therapeutic techniques to help locate and address areas of tumorous growth. Porphyrins accumulate in tumors of the body and when **radiolabeled** porphyrins are introduced to the body, the X-rays and energy released can help determine the location and even treat the cancerous tumors [350].

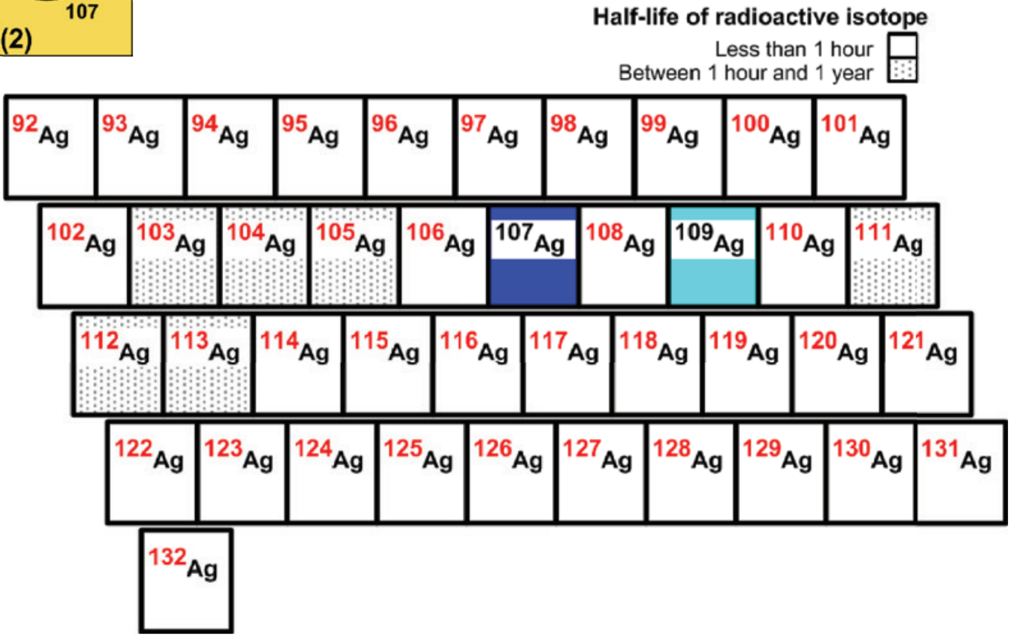
4.46.4 Palladium isotopes used as a source of radioactive isotope(s)

^{104}Pd is the major target used for **cyclotron** production of the medically important radioactive isotope ^{103}Pd *via* the reaction ^{104}Pd (p, p n) ^{103}Pd [349].

4.47 Silver



Stable isotope	Relative atomic mass	Mole fraction
^{107}Ag	106.905 09	0.518 39
^{109}Ag	108.904 76	0.481 61



4.47.1 Silver isotopes in Earth/planetary science

The measurement of relative amounts of ^{107}Ag and ^{109}Ag is used to study the processes responsible for the **isotopic fractionation** of silver **isotopes** in ore deposits, which depends on the specific minerals and environmental conditions. This is currently an area of active research and it is thought that the relative amounts of the isotopes of silver are altered during the formation of the ore [351, 352].

4.47.2 Silver isotopes in forensic science and anthropology

Silver **isotope-amount ratios** $n(^{107}\text{Ag})/n(^{109}\text{Ag})$ along with isotope-amount ratios of copper $n(^{65}\text{Cu})/n(^{63}\text{Cu})$, and isotope-amount ratios of lead ($n(^{206}\text{Pb})/n(^{204}\text{Pb})$, $n(^{207}\text{Pb})/n(^{204}\text{Pb})$ and $n(^{208}\text{Pb})/n(^{204}\text{Pb})$) have been used to determine origins of European coins and information on the flow of goods in the world market over time (Fig. 4.47.1). Metals from Peru and Mexico and those from European mining have distinct isotopic signatures that enable the origin of the metal to be determined by examining the **isotopic compositions** of silver, copper, and lead in the coins. Abundant silver sources, mined in Mexico and Peru in the 16th century, were used to mint coins, but they were not a major influence in the European coin market until the 18th century (Fig. 4.47.1) [237].

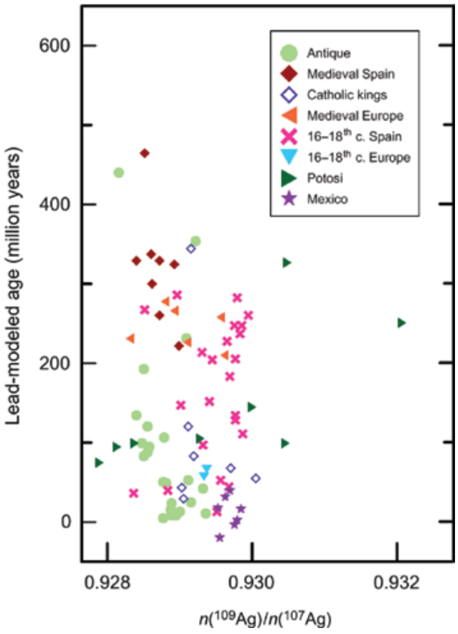


Fig. 4.47.1: Cross plot of lead model age and $n(^{109}\text{Ag})/n(^{107}\text{Ag})$ **isotope-amount ratio** of *selected* coins (modified from [237]) assuming a $n(^{109}\text{Ag})/n(^{107}\text{Ag})$ value of 0.929 04 for the **isotopic reference material** SRM 981a silver nitrate [237]. The isotopic signatures of the silver, copper, and lead in the metals used to make Spanish coins have been used to trace (see **tracer**) the origin of the metals to help determine the flow of metal in the global market during the 16th century. The Mexico coins show little variation in the silver **mole fraction,** although the observed range of isotopic variation is about 30 times the analytical uncertainty. The antique coins have two groups, the oldest on the right and the younger on the left. They are statistically different at the 99-percent confidence level. The Catholic Kings coins are distinct from the rest of the medieval coins.

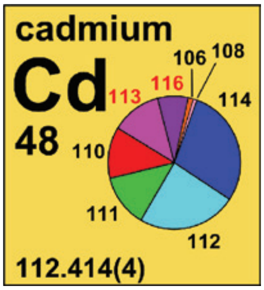
4.47.3 Silver isotopes in geochronology

The **amount ratio** $n(^{107}\text{Pd})/n(^{107}\text{Ag})$ is used in **geochronology** to date major events in the Solar System [344–348, 353]. Although ^{107}Ag is naturally occurring, it is also the **daughter product** by **beta decay** of ^{107}Pd. If both excess ^{107}Ag and ^{107}Pd are present in a sample of extraterrestrial origin, then the material would have formed sometime after ^{107}Pd decayed (*i.e.* sometime after the 6.5-million-year **half-life** of ^{107}Pd). The $n(^{107}\text{Pd})/n(^{107}\text{Ag})$ amount ratio can be measured to help determine when the ^{107}Pd decay process began and determine how much time has elapsed since the material was formed.

4.47.4 Silver isotopes in industry

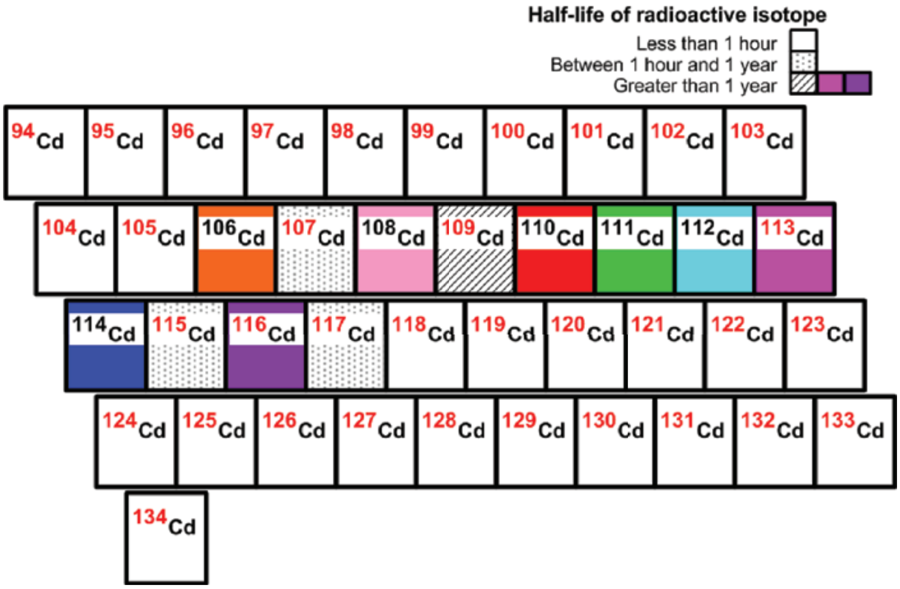
^{107}Ag is being studied as a possible target for **cyclotron** production of ^{103}Pd (with a half-life of 17 days) *via* the ^{107}Ag (p, α n) ^{103}Pd reaction. ^{103}Pd releases **X-rays** and **Auger electrons** at the rate of about 80 X-rays and 186 Auger electrons per 100 decays of ^{103}Pd, which makes this isotope an ideal candidate for internal **radiotherapy** for the treatment of cancers. The production of this isotope in a no-carrier form (not formed in another solution) is important for its medical uses. By using **neutrons**, **photons**, and charged particles to force reactions with isotopes of a higher **mass number** than 103, ^{103}Pd will occur in a fraction of those reactions. The most common methods of ^{103}Pd production use targets of rhodium or other isotopes of palladium. However, ^{107}Ag has also been studied as a feasible option [349, 354]. ^{109}Ag is used to produce the gamma reference source $^{110\text{m}}$Ag to help calibrate gamma detectors [349, 354].

4.48 Cadmium



Stable isotope	Relative atomic mass	Mole fraction
^{106}Cd	105.906 460	0.012 45
^{108}Cd	107.904 184	0.008 88
^{110}Cd	109.903 008	0.124 70
^{111}Cd	110.904 184	0.127 95
^{112}Cd	111.902 764	0.241 09
^{113}Cd†	112.904 408	0.122 27
^{114}Cd	113.903 365	0.287 54
^{116}Cd†	115.904 763	0.075 12

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. Half-lives of ^{113}Cd and ^{116}Cd are 8.04 × 10^{15} years and 3 × 10^{19} years, respectively.



4.48.1 Cadmium isotopes in biology

Metal accumulation is a threat to our world's water systems and wildlife. As a way to measure the influence of heavy metals on wildlife utilizing mass spectrometric techniques, some researchers use animal food enriched in specific cadmium **isotopes**. These experiments work by exposing the animals to a diet enriched in ^{106}Cd and/or other **stable isotopes** of metals (for example, ^{65}Cu and/or ^{62}Ni) for a period of time. Depending on the purpose of the experiment, the **residence time** of the food in the gut is determined and **isotopic compositions** of the gut and/or feces are measured *via* **inductively coupled plasma mass spectrometry** (ICP-MS). This information is used to measure bio-uptake (absorption and incorporation of a substance by living tissue) and accumulation rates of metals in an exposed animal [355, 356].

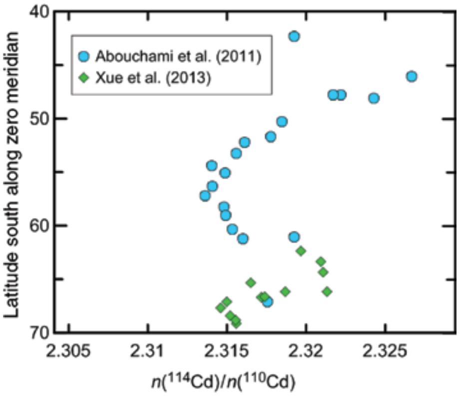


Fig. 4.48.1: Variations in the **isotope-amount ratio** $n(^{114}\mathrm{Cd})/n(^{110}\mathrm{Cd})$ of dissolved ocean cadmium as a function of latitude south for Zero Meridian surface water samples (modified from Xue *et al.* [359], with data from Abouchami *et al.* [358] assuming a $n(^{114}\mathrm{Cd})/n(^{110}\mathrm{Cd})$ value of **isotopic reference material** SRM 3108 of 2.304 07 [360]).

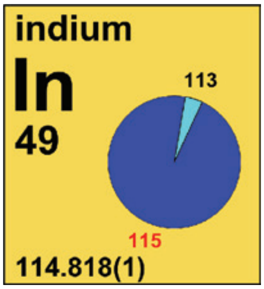
4.48.2 Cadmium isotopes in Earth/planetary science

Molecules, atoms, and ions of the stable isotopes of cadmium possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are small but measureable variations in the isotopic abundances of dissolved cadmium in ocean water, which are a consequence of **isotopic fractionation** associated with biological uptake (Fig. 4.48.1) [357–359].

4.48.3 Cadmium isotopes used as a source of radioactive isotope(s)

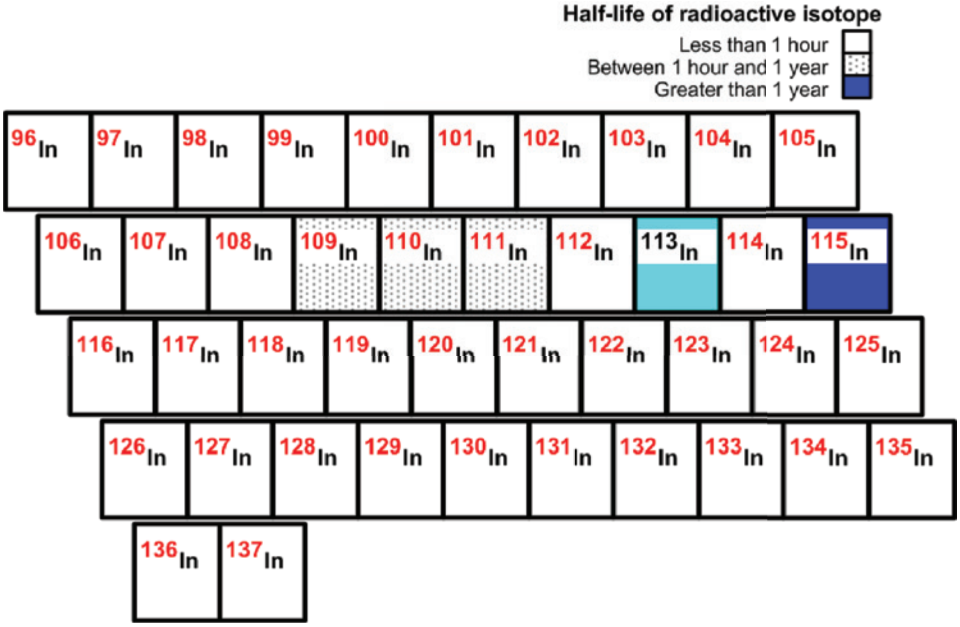
^{112}Cd is used to produce the diagnostic **radioisotope** ^{111}In (with a **half-life** of 2.8 days) *via* the reaction ^{112}Cd (p, 2n) ^{111}In [94].

4.49 Indium



Stable isotope	Relative atomic mass	Mole fraction
^{113}In	112.904 060	0.042 81
^{115}In†	114.903 878 77	0.957 19

† **Radioactive isotope** having a relatively long **half-life** (4.4 × 10^{14} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.49.1 Indium isotopes in medicine

^{111}In (with a **half-life** of 2.8 days) is used in indium leukocyte imaging (Fig. 4.49.1), in which white blood cells that are abundant at sites of infection are labeled with ^{111}In to help locate the source of the infection [361–363].

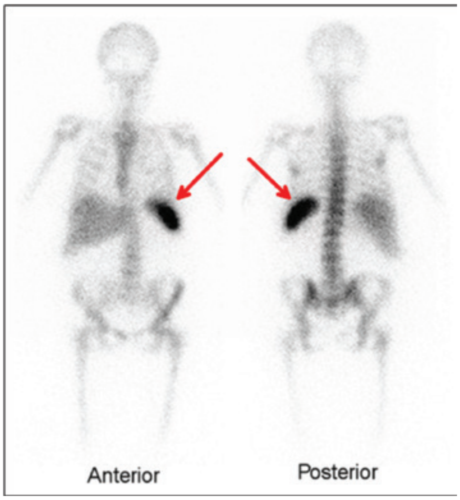
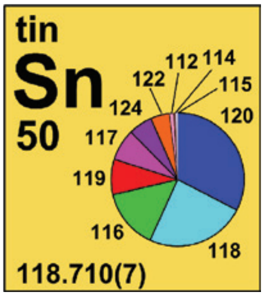


Fig. 4.49.1: **Radionuclide** imaging of infection. Leukocytes are white blood cells in the body that protect the body from infection and can be dyed with ^{111}In to locate the site of an infection in the body. (Image Source: Love, Charito MD and Palestro, Christopher J. MD., 2004) [363].

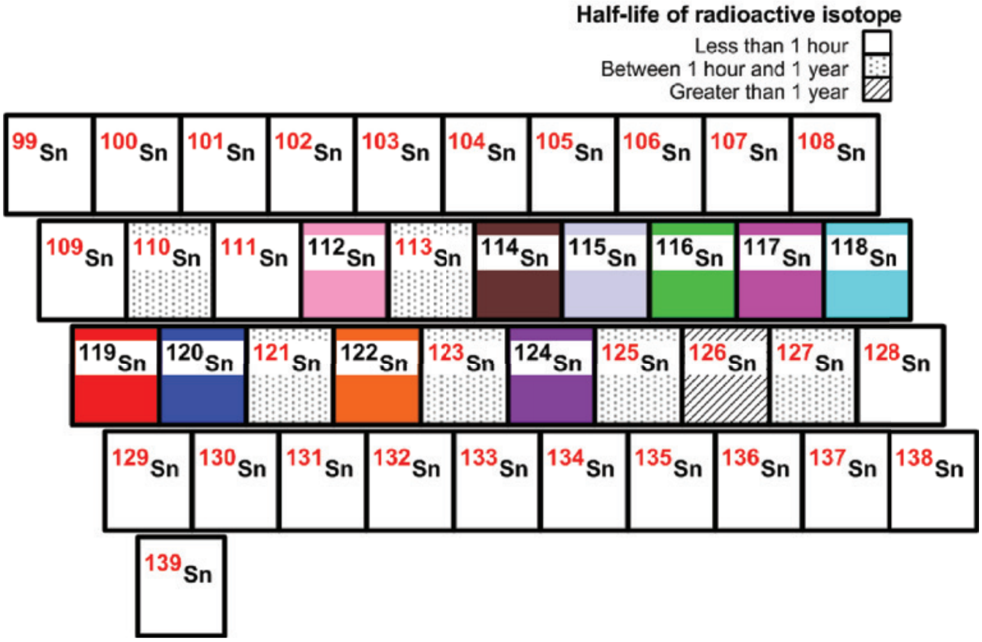
4.49.2 Indium isotopes used as a source of radioactive isotope(s)

^{113}In is used to produce ^{113}Sn (with a half-life of 115 days) *via* the reaction ^{113}In (p, n) ^{113}Sn, and ^{113}In is used to produce the **radioisotope** ^{110}In (with a half-life of 1.15 h) [364, 365].

4.50 Tin



Stable isotope	Relative atomic mass	Mole fraction
^{112}Sn	111.904 825	0.0097
^{114}Sn	113.902 7801	0.0066
^{115}Sn	114.903 3447	0.0034
^{116}Sn	115.901 7428	0.1454
^{117}Sn	116.902 954	0.0768
^{118}Sn	117.901 607	0.2422
^{119}Sn	118.903 311	0.0859
^{120}Sn	119.902 202	0.3258
^{122}Sn	121.903 44	0.0463
^{124}Sn	123.905 277	0.0579



4.50.1 Tin isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of tin possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of tin in natural terrestrial materials (Fig. 4.50.1) [366].

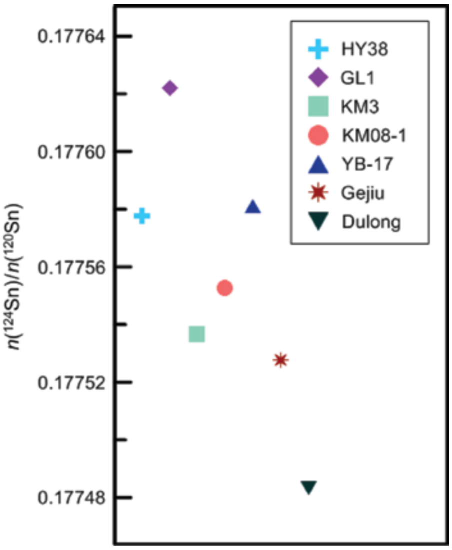


Fig. 4.50.1: Variation of the **isotope amount ratio** $n(^{124}Sn)/n(^{120}Sn)$ of selected cassiterite samples from China (modified after [366]).

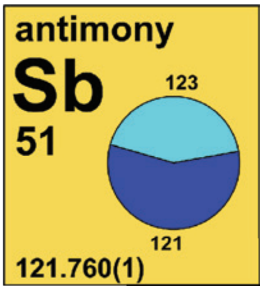
4.50.2 Tin isotopes in medicine

^{117m}Sn (with a **half-life** of 14 days) **DTPA** is routinely used for diagnostic bone imaging and for the treatment of bone pain caused by the spread of cancer to bones. The m in the superscript of ^{117m}Sn indicates a **metastable state** of the **isotope**. By using ^{117m}Sn DTPA, marrow toxicity can be reduced, and the therapeutic efficacy of using **radionuclides** is maintained [367]. ^{117m}Sn is a promising radionuclide for therapeutic applications because the radionuclide decays in a way that causes less damage to healthy tissues and bone marrow than other available treatments. These properties of ^{117m}Sn make it useful for the treatment of inflammatory synovial disease (*i.e.* rheumatoid arthritis) [368].

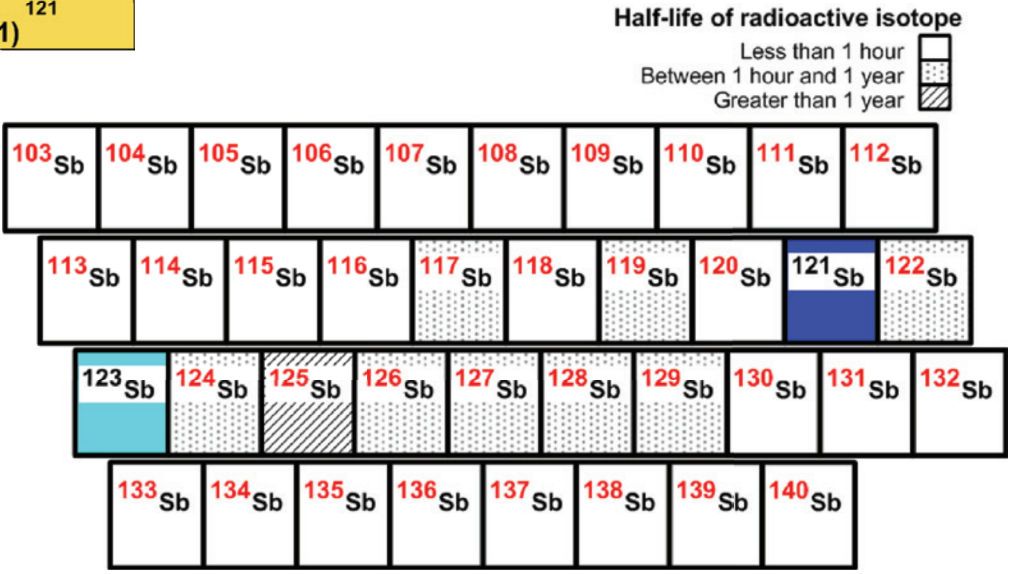
4.50.3 Tin isotopes used as a source of radioactive isotope(s)

^{112}Sn is used to produce the **radioisotope** ^{113}Sn (with a half-life of 115 days) *via* the reaction $^{112}Sn(n, \gamma)\,^{113}Sn$. This is used for $n(^{113}Sn)/n(^{113m}In)$ generators for the elution (extracting one material from another) of ^{113m}In (with a half-life of 1.66 h) as chloride for blood pool imaging. The m the superscript of ^{113m}In indicates a metastable state of the isotope. ^{117m}Sn is a medical radioisotope that can be produced using ^{116}Sn and ^{117}Sn [369].

4.51 Antimony



Stable isotope	Relative atomic mass	Mole fraction
^{121}Sb	120.903 81	0.5721
^{123}Sb	122.904 21	0.4279



4.51.1 Antimony isotopes in Earth/planetary science

Molecules, atoms, and ions of the **stable isotopes** of antimony possess slightly different physical and chemical properties, and they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable substantial variations in the isotopic abundances of antimony in natural terrestrial materials (Fig. 4.51.1) [370]. The stable isotopes ^{121}Sb and ^{123}Sb have been used to measure movement of sediments and rocks originating from locations high in antimony. ^{121}Sb and ^{123}Sb move with the sediments and have been used as **tracers** in areas low in antimony to determine the originating location of certain metal/metalloid contaminants in streams [371–373].

4.51.2 Antimony isotopes in industry

In the 1950s, ^{124}Sb and ^{125}Sb (with **half-lives** of 60 days and about 1000 days, respectively) were used commercially as tracers. They were injected into oil pipelines as a way to detect the **residence time** and flow rate of the substance through the pipeline. The presence of these **isotopes** could be detected by means of a **Geiger counter** held above the pipeline. If the pipeline had a leak, the tracer would escape and its contamination and movement could be detected in the soil. ^{124}Sb and ^{125}Sb are now both treated as environmental contaminants [375].

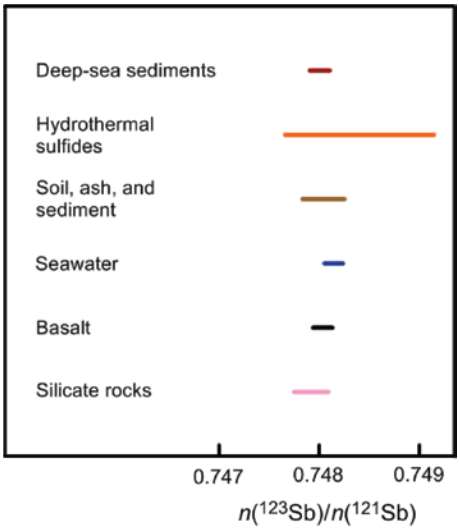
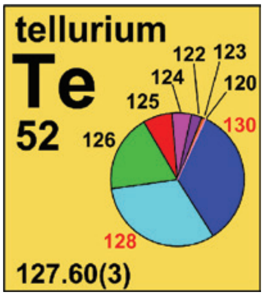


Fig. 4.51.1: Variation in **isotope-amount ratio** $n(^{123}Sb)/n(^{121}Sb)$ of antimony in terrestrial materials (modified from [370]), assuming a measured isotope-amount ratio $n(^{123}Sb)/n(^{121}Sb)$ of 0.747 85 [374].

4.51.3 Antimony isotopes used as a source of radioactive isotope(s)

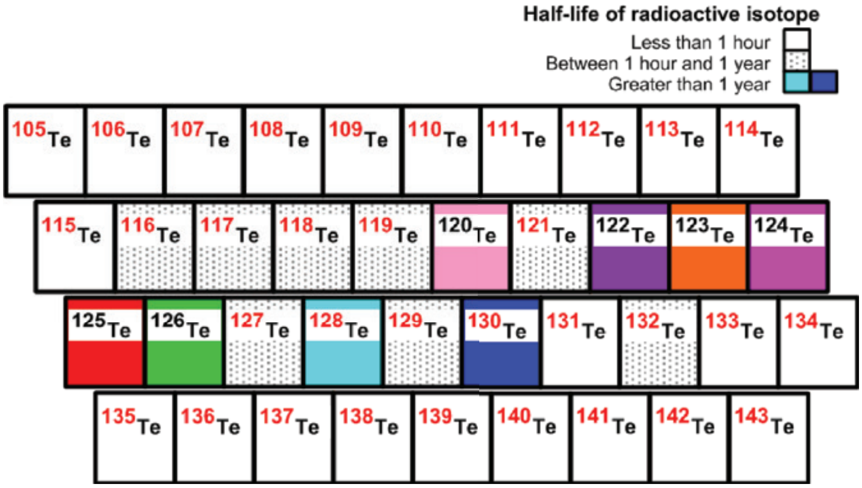
^{123}Sb is used to produce ^{124}I (with a half-life of 100 h), which is used in **radioimmunotherapy** and also in **positron emission tomography**. It can be produced from the ^{123}Sb (^{3}He, 2n) ^{124}I reaction [376]. ^{121}Sb and ^{123}Sb can both be used for the production of ^{123}I (with a half-life of 13.2 h) *via* ^{3}He and **alpha particle**-induced reactions with ^{121}Sb and ^{123}Sb, although the most common production route is *via* ^{124}Xe or ^{123}Te [377].

4.52 Tellurium



Stable isotope	Relative atomic mass	Mole fraction
^{120}Te	119.904 06	0.0009
^{122}Te	121.903 04	0.0255
^{123}Te	122.904 27	0.0089
^{124}Te	123.902 82	0.0474
^{125}Te	124.904 43	0.0707
^{126}Te	125.903 31	0.1884
^{128}Te†	127.904 461	0.3174
^{130}Te†	129.906 222 75	0.3408

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. The half-lives of ^{128}Te and ^{130}Te are 2.5×10^{24} and 7×10^{20} years, respectively.



4.52.1 Tellurium isotopes in Earth/planetary science

Tellurium **isotopes** are a mixture of **r-process**, **s-process**, and **p-process nucleosynthesis** products, making them useful for studying the contribution of stellar products to the molecular cloud from which the Sun and planets were formed (Fig. 4.52.1) [378–380].

4.52.2 Tellurium isotopes in geochronology

The **double beta decay** of ^{130}Te (with a **half-life** of 7×10^{20} years) has been used for the determination of gas-retention ages of tellurium minerals [382].

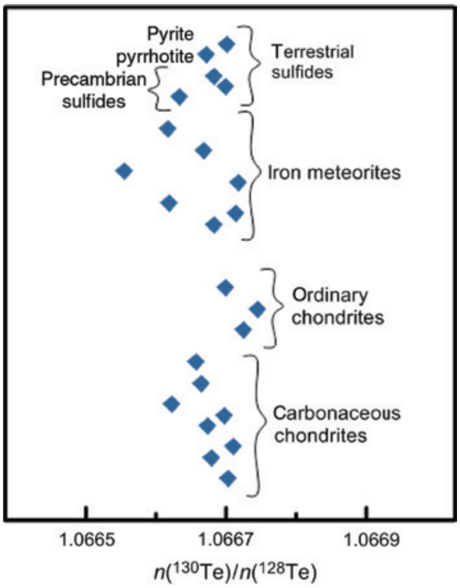
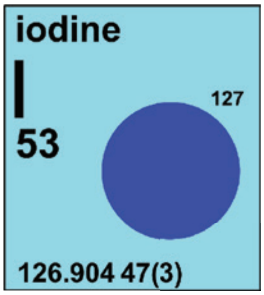


Fig. 4.52.1: Variation in **isotope-amount ratio** $n(^{130}\text{Te})/n(^{128}\text{Te})$ of tellurium in selected **meteorites** and terrestrial materials (modified from [380]), assuming a measured isotope-amount ratio $n(^{130}\text{Te})/n(^{128}\text{Te})$ of 1.066 65 [381]. Based on these data, Fehr *et al.* [380] conclude that the regions of the solar disk that were sampled during accretion of meteorite parent bodies were well mixed and homogeneous on a large scale, with respect to tellurium **isotopes**.

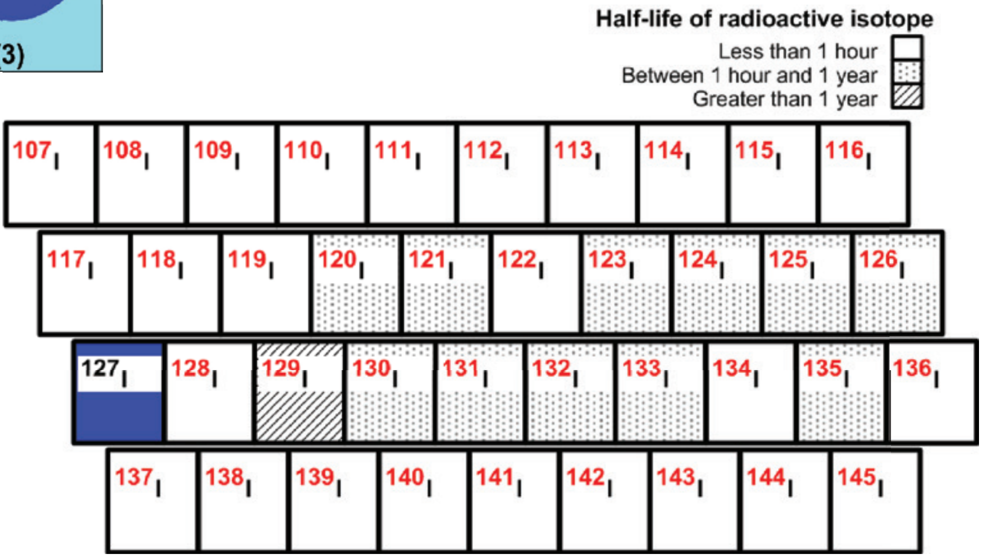
4.52.3 Tellurium isotopes used as a source of radioactive isotope(s)

^{120}Te is used for the production of $^{120\text{g}}$I, where "g" indicates ground state, *via* the ^{120}Te (p, n) $^{120\text{g}}$I reaction, which is used as a **positron emission tomography** (**PET**) and beta-emitting isotope [383, 384]. $^{120\text{g}}$I has a **half-life** of 1.36 h. ^{122}Te is used in the production of the **radioisotope** ^{122}I (with a half-life of 3.6 min) *via* the reaction ^{122}Te (p, n) ^{122}I, which is used in gamma imaging [385]. ^{123}Te is used for the production of radioactive ^{123}I (with a half-life of 13.2 h) *via* the ^{123}Te (p, n) ^{123}I reaction, which is used in thyroid imaging [386] and for *in vivo* medical studies using **single-photon emission computed tomography** (SPECT) [386]. ^{124}Te is used for the production of both ^{123}I and the PET isotope ^{124}I *via* the ^{124}Te (p, 2n) ^{123}I and ^{124}Te (p, n) ^{124}I reactions, respectively [386–389]. The half-life of ^{124}I is 100 h.

4.53 Iodine



Stable isotope	Relative atomic mass	Mole fraction
^{127}I	126.904 47	1



4.53.1 Iodine isotopes in forensic science and anthropology

^{131}I (with a **half-life** of about 8 days) and ^{129}I are both **fission** products; ^{129}I is a long-lived fission product with a half-life of 1.7×10^7 years that can be helpful in the detection of the movement of radiation after a radioactive event, such as occurred at the Japanese reactors at Fukushima. In nuclear reactors and weapons tests, uranium and plutonium undergo fission processes in which one of the fission products is the long-lived **isotope** ^{129}I. This isotope has been used as a groundwater **tracer** to determine evidence of nuclear fission, and it can also be tracked in rainwater as evidence of a fission event in the air (weapons explosion; Fig. 4.53.1) [390–392].

4.53.2 Iodine isotopes in geochronology

Natural **cosmogenic** ^{129}I enters groundwater and other terrestrial environments from the atmosphere and then decays to ^{129}Xe. The **isotope-amount ratio** $n(^{129}\mathrm{I})/n(^{127}\mathrm{I})$ can be used as a clock to estimate time since cosmogenic ^{129}I entered the system. The amount of product ^{129}Xe in such cases is too small to measure; however, excess quantities of ^{129}Xe can be found in **meteorites** and other very old samples that contained extinct **primordial** ^{129}I. Younger water bodies also can be differentiated from older water bodies by determining the amount of **anthropogenic** ^{129}I released since the 1960s from sources such as nuclear bomb tests [393, 394].

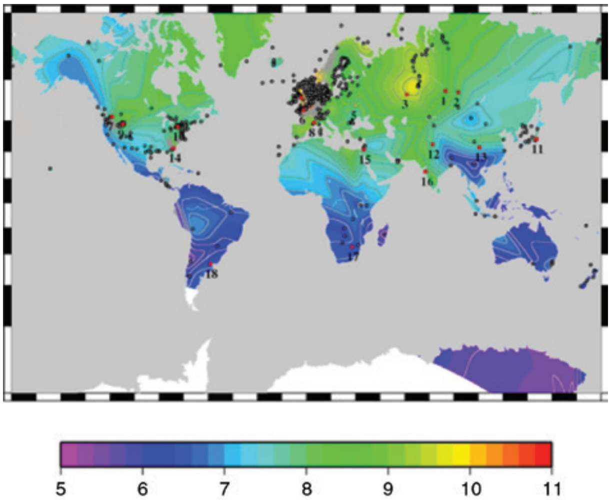
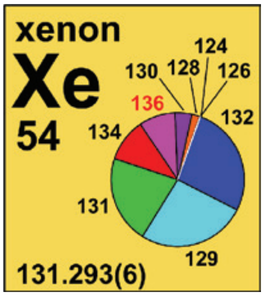


Fig. 4.53.1: Global distribution of ^{129}I in water samples before the Fukushima disaster in Japan. Scale spans 1×10^5 atoms ^{129}I/L to 1×10^{11} atoms ^{129}I/L on a logarithmic ($\lg_{10}$) scale. (Image Source: Snyder, G., A. Aldahan, and G. Possnert, 2010) [392].

4.53.3 Iodine isotopes in medicine

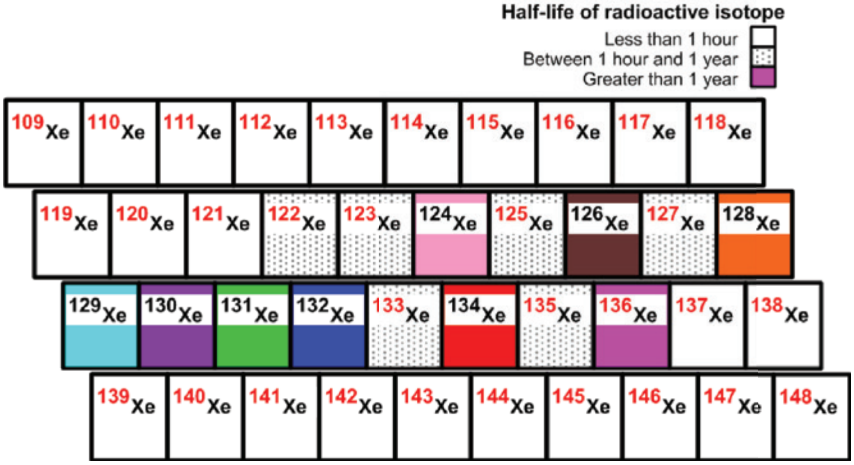
^{125}I, which has a half-life of about 59 days, is used encapsulated in **radiotherapy** to target and treat sites of cancerous tumors [395]. ^{120g}I (with a half-life of 1.36 h), where the “g” indicates ground state, and ^{124}I (with a half-life of 100 h) are **radioactive isotopes** that emit **positrons** and they are used in quantitative, diagnostic imaging of the body using **positron emission tomography** (**PET**) [383–385, 387–389]. ^{123}I and ^{131}I (with half-lives of 0.55 day and 8 days, respectively) are used with **single-photon emission computed spectroscopy** (SPECT) for basic three-dimensional imaging [386, 395]. Radioactive iodine isotopes are produced from radioactive tellurium isotope (see Section 4.52.3).

4.54 Xenon



Stable isotope	Relative atomic mass	Mole fraction
^{124}Xe	123.905 89	0.000 95
^{126}Xe	125.904 30	0.000 89
^{128}Xe	127.903 531	0.019 10
^{129}Xe	128.904 780 86	0.264 01
^{130}Xe	129.903 50935	0.040 71
^{131}Xe	130.905 08414	0.212 32
^{132}Xe	131.904 155 09	0.269 09
^{134}Xe	133.905 393 03	0.104 36
^{136}Xe†	135.907 214 48	0.088 57

† **Radioactive isotope** having a relatively long **half-life** (2.3×10^{21} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.54.1 Xenon isotopes in forensic science and anthropology

Radiogenic xenon **isotopes** are produced by nuclear reactions in atomic bombs and nuclear reactors. For example, ^{131}Xe, ^{133}Xe, and ^{135}Xe are some of the **fission** products of ^{235}U and ^{239}Pu, and finding these isotopes would be evidence of a nuclear bomb reaction. Measurements of xenon isotopes (*e.g.* in the atmosphere or the subsurface) have been used to identify contamination from these sources, for example, to detect faults in nuclear reactors or to monitor compliance with nuclear test bans (Fig. 4.54.1) [396].

4.54.2 Xenon isotopes in geochronology

The **stable isotopes** of xenon hold many clues about the formation of the **elements**, solar-system history, and Earth processes [29, 101]. For example, ^{129}Xe has been used as a detector of “extinct” **radionuclides.** Some ^{129}Xe is radiogenic as a result of being produced by the **radioactive decay** of ^{129}I (**half-life** of 1.7×10^{7} years). Because the half-life of ^{129}I is much smaller than the age of the Earth, **primordial** ^{129}I (*i.e.* that which was present at the beginning of Earth’s history) is essentially gone after it decayed to ^{129}Xe over geologic

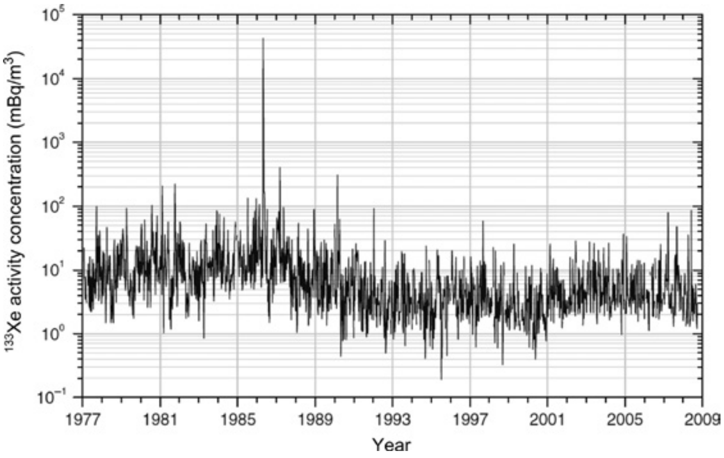


Fig. 4.54.1: The mean weekly ^{133}Xe time series in ground-level air at Freiburg, Germany, between 1977 and 2009. The record indicates persistent low levels of **anthropogenic** ^{133}Xe that are generally attributable to normal acceptable releases from nuclear power plants with variability related in part to multiple sources and changing wind patterns. A major spike occurred in 1986 during the Chernobyl reactor accident in the Ukraine region of the former USSR. The **half-life** of ^{133}Xe (5.2 days) is sufficiently long for it to escape from its source and be distributed in air near the source, but sufficiently short that long-term background levels are very low. Records such as this also can be used to detect undocumented nuclear explosions. (Modified from [396]).

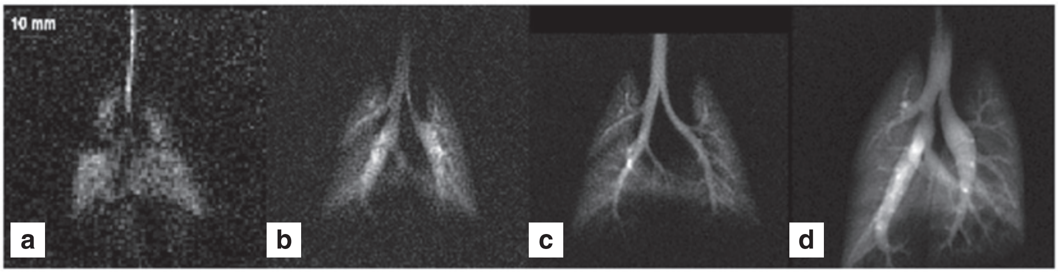


Fig. 4.54.2: Xenon ventilation imaging has progressed greatly since first being used in 1998. One of the first ^{129}Xe images (a) has been progressively improved by polarization, gas delivery technology, and magnetic resonance (MR) acquisition strategies (b–d). (Image Source: Driehuys and Hedlund, 2007, © Sage Publications) [398]).

time. This means that radiogenic ^{129}Xe could be a marker of the former existence of the "extinct" isotope ^{129}I. Because primordial ^{129}I was produced largely in **supernovae**, detection of radiogenic ^{129}Xe in **meteorites** and terrestrial samples also implies that the time elapsed between ^{129}I **supernova nucleosynthesis** and planetary condensation was short compared to the subsequent history of the Solar System. The many isotopes and reaction mechanisms of xenon have contributed numerous insights into Earth processes through the study of "xenology" (xenon isotopic variations used as geodynamic **tracers** to study the dynamics of the Earth) [397].

4.54.3 Xenon isotopes in medicine

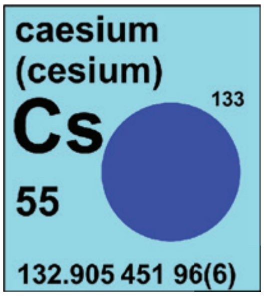
Xenon isotopes are used in numerous ways to investigate the movement of inhaled gases in lungs and other parts of the body. If **radioactive isotopes** of xenon [^{127}Xe (with a half-life of 0.1 year), ^{133}Xe, and hyperpolarized (having non-equilibrium alignment of nuclear spins, suitable for magnetic resonance) ^{129}Xe] are inhaled, they can be tracked throughout the body by externally monitoring their **decay products** using magnetic resonance microscopy [high resolution **magnetic resonance imaging** (MRI) at microscopic (nanometer) levels]

(Fig. 4.54.2). This imaging technique is used to assess how well oxygen is taken up and transported by the blood [398].

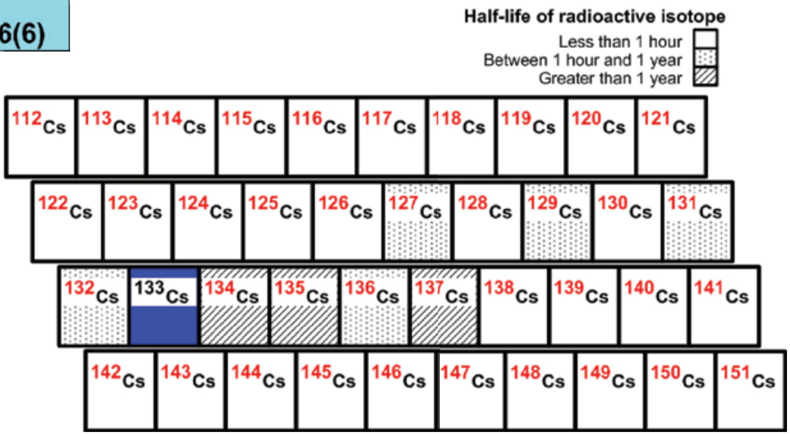
4.54.4 Xenon isotopes used as a source of radioactive isotope(s)

^{124}Xe is used in the production of **radioisotopes** ^{123}I and ^{125}I (with half-lives of 0.55 day and 59 days, respectively) *via* the reactions ^{124}Xe (n, n p) ^{123}I and ^{124}Xe (n, γ) ^{125}I, respectively, which are used in diagnostic procedures and cancer treatment, respectively [398].

4.55 Caesium (cesium)



Stable isotope	Relative atomic mass	Mole fraction
^{133}Cs	132.905 451 96	1



4.55.1 Caesium isotopes in biology

^{137}Cs (with a **half-life** of 30 years) can be used as a **tracer** in fungal mycelia (an extensive matrix of underground hyphae (stems of growth from a fungus)) to monitor the immobilization of this radioactive caesium **isotope**. After the nuclear reactor accident at Chernobyl, large quantities of ^{137}Cs were released as **fission** products into the environment. Areas with large fungal populations and fungal mycelia seemed to immobilize the ^{137}Cs isotope, which limited the spread of the **radioactive isotope** [399, 400].

4.55.2 Caesium isotopes in Earth/planetary science

River floodplains are an important site for storing suspended sediments and contaminants transferred from upstream catchments. ^{137}Cs measurements of floodplain sediments provide a technique for estimating overbank sediment deposition, and it can provide information on spatial patterns of sediment deposition (Fig. 4.55.1) [401–403].

4.55.3 Caesium isotopes in geochronology

Nuclear fission of ^{235}U (or other **fissionable** materials) yields ^{137}Cs as a product. Although ^{137}Cs is not naturally present in the environment, it can be collected from nuclear reactor processing and then used as an environmental tracer. ^{137}Cs adheres tightly to porous sediments and will follow the movement of the sediment. By exposing sediments to ^{137}Cs and allowing this combination to move dynamically, **gamma ray** spectrometry can then be used to measure the **activity** of ^{137}Cs and monitor the movement of the radioactive sediments [404–406].

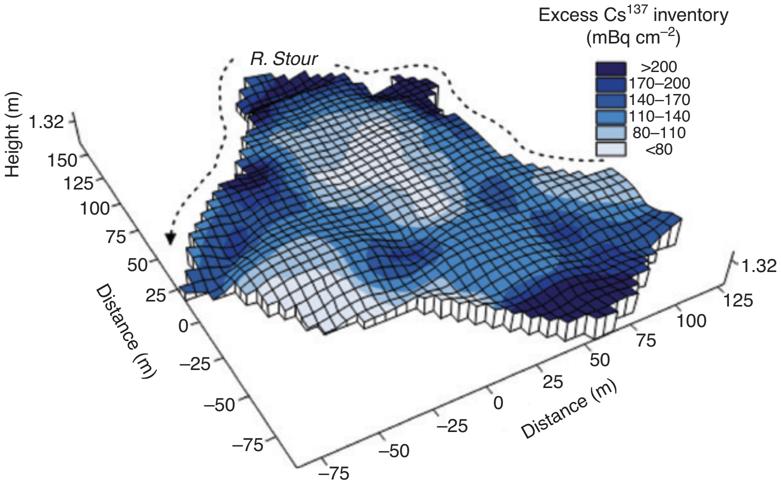


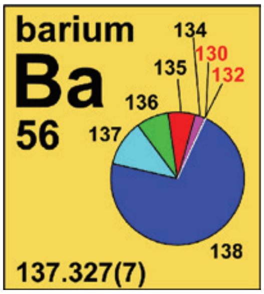
Fig. 4.55.1: Topography and excess ^{137}Cs inventory as a function of surface sediment size, less than 63 μm (modified from Walling and He [403]).

^{137}Cs dating of sediments not older than 60 years is useful in natural and artificial lakes and other environments because of its widespread production and release during atmospheric nuclear weapons testing, which began in the late 1940s, plus subsequent releases, such as during the accident at the Chernobyl nuclear reactor in April 1986. The ^{137}Cs concentration profile in a sediment core can be matched with the historical record of ^{137}Cs release to determine the approximate age profile of the sediment [406, 407].

4.55.4 Caesium isotopes in industry

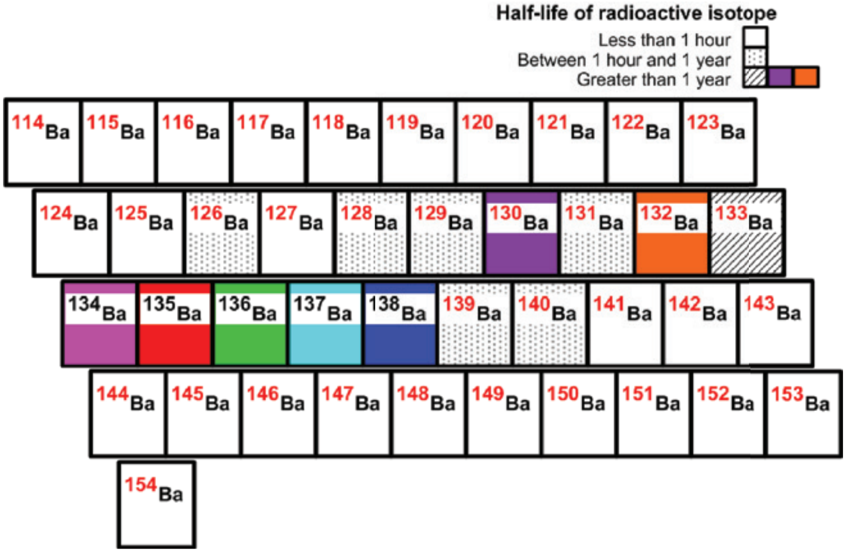
High-energy gamma rays from ^{137}Cs serve as food irradiation devices to remove bacteria and other harmful microorganisms (living single celled organisms such as virus, algae and fungus) from food. Although ^{137}Cs is not used commercially for large-scale food irradiation, it has been proposed that it can be used this way. Gamma rays from the radioactive ^{137}Cs destroy the **DNA** of organisms to enable foods to last longer (*i.e.* irradiation of fruits and vegetables stops the ripening process) and be contamination free [408, 409].

4.56 Barium



Stable isotope	Relative atomic mass	Mole fraction
^{130}Ba†	129.906 32	0.0011
^{132}Ba†	131.905 061	0.0010
^{134}Ba	133.904 508	0.0242
^{135}Ba	134.905 689	0.0659
^{136}Ba	135.904 576	0.0785
^{137}Ba	136.905 827	0.1123
^{138}Ba	137.905 247	0.7170

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. Half-lives of ^{130}Ba and ^{132}Ba are 2.2 × 10^{21} years and 1.3 × 10^{21} years, respectively.



4.56.1 Barium isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of barium possess slightly different physical and chemical properties, they can be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. von Allmen *et al.* [410] observed barium **isotopic fractionation** in the global barium cycle (Fig. 4.56.1).

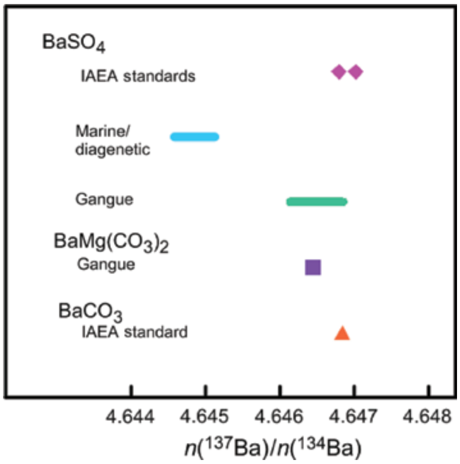
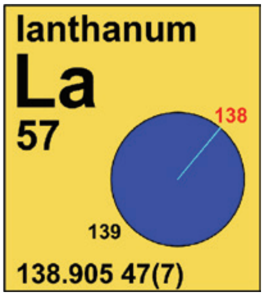


Fig. 4.56.1: Variation in **isotope-amount ratio** $n(^{137}\text{Ba})/n(^{130}\text{Ba})$ of selected barium-bearing substances (modified from [410]), assuming a measured isotope-amount ratio $n(^{137}\text{Ba})/n(^{134}\text{Ba})$ of 4.6470 for mean terrestrial barium [414].

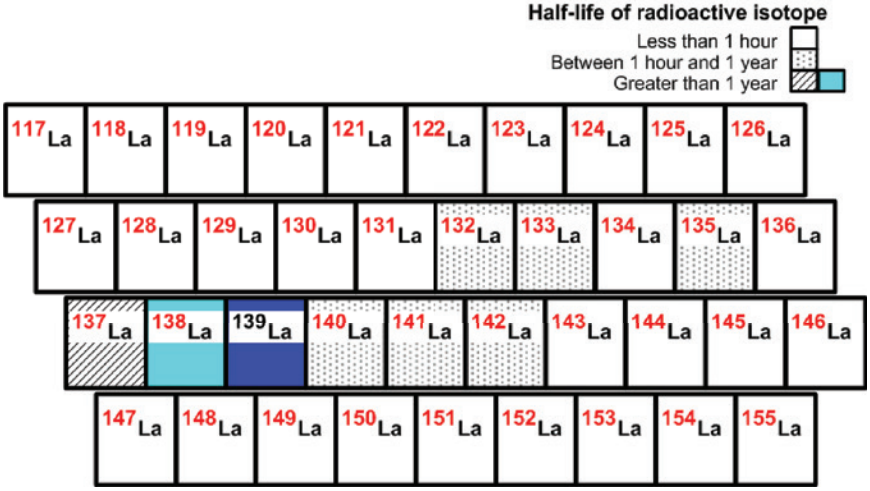
High-precision barium **isotope** measurements reveal differences of up to 25 parts per million in the **isotope-amount ratio** $n(^{137}\text{Ba})/n(^{136}\text{Ba})$ and 60 parts per million in the $n(^{138}\text{Ba})/n(^{136}\text{Ba})$ ratio between **chondrites** and the Earth. These differences probably arose from incomplete mixing of **nucleosynthetic** material in the **solar nebula**. Barium isotopes may be the **decay products** of now-extinct ^{135}Cs (with a **half-life** of about 1.6×10^6 years), which is thought to be a nucleosynthetic component. **Chondritic meteorites** have a slight excess of **supernova**-derived material as compared to Earth, demonstrating that the solar nebula was not perfectly homogenized upon formation (Fig. 4.56.1) [411–413].

4.57 Lanthanum



Stable isotope	Relative atomic mass	Mole fraction
^{138}La†	137.907 12	0.000 8881
^{139}La	138.906 36	0.999 1119

† **Radioactive isotope** having a relatively long **half-life** (1.06×10^{11} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.57.1 Lanthanum isotopes in Earth/planetary science

Studies have shown that ^{138}La (with a **half-life** of 1.06×10^{11} years) can be used along with ^{138}Ce and ^{136}Ce to measure time elapsed from a **supernova** explosion producing large numbers of **neutrinos** [415].

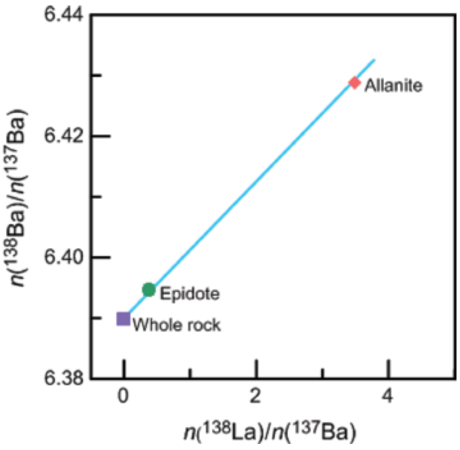


Fig. 4.57.1: Cross plot of the **isotope-amount ratio** $n(^{138}\text{Ba})/n(^{137}\text{Ba})$ and the **amount ratio** $n(^{138}\text{La})/n(^{137}\text{Ba})$ in rocks and minerals from Amîtsoq, West Greenland, which yield an age of 2.408×10^9 years [417].

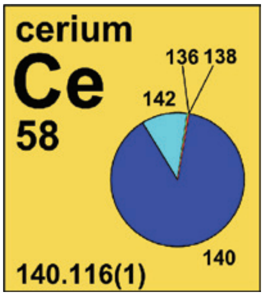
4.57.2 Lanthanum isotopes in geochronology

^{138}La decays to ^{138}Ce and ^{138}Ba, respectively, by **beta decay** with a **half-life** of 1.06×10^{11} years and by **electron** capture with a half-life of 1.56×10^{11} years. The **isotope-amount ratio** $n(^{138}\text{Ce})/n(^{142}\text{Ce})$ has been used for dating rocks on long time scales (billions of years) and as a chemical **tracer** in geochemistry [416]. The increase in **radiogenic** ^{138}Ba in rocks enriched in rare earth **elements**, such as allanite, enables one to determine the age of such rocks (Fig. 4.57.1) [417].

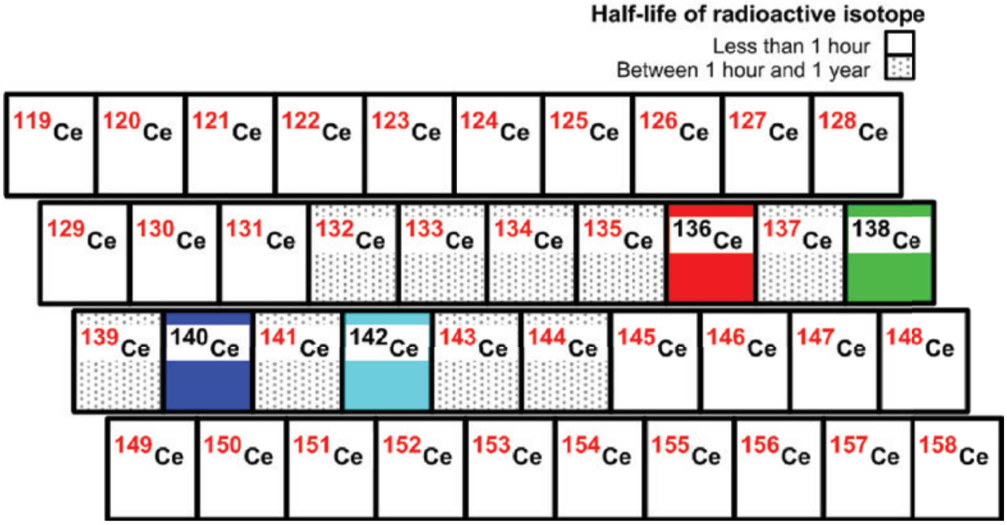
4.57.3 Lanthanum isotopes used as a source of radioactive isotope(s)

^{139}La is used for the production of the medical **radioisotope** ^{139}Ce *via* the ^{139}La (p, n) ^{139}Ce reaction [418].

4.58 Cerium



Stable isotope	Relative atomic mass	Mole fraction
^{136}Ce	135.907 129	0.001 86
^{138}Ce	137.905 99	0.002 51
^{140}Ce	139.905 45	0.884 49
^{142}Ce	141.909 25	0.111 14



4.58.1 Cerium isotopes in Earth/planetary science

When combined, ^{138}La–^{138}Ce and ^{147}Sm–^{143}Nd are two decay systems that are useful for studying processes affecting the light-rare-earth **elements** (lanthanum, cerium, praseodymium, neodymium, and samarium) and the **igneous** evolution of the Moon and Earth because different igneous materials have different cerium **isotopic compositions** (Fig. 4.58.1) and can be used in mass balance investigations [419, 420].

4.58.2 Cerium isotopes in geochronology

^{138}Ce is a **radiogenic isotope** produced by decay of ^{138}La, with a **half-life** of 1.06×10^{11} years, one of the longest clocks in **geochronology**. Thus, the **isotope-amount ratio** $n(^{138}\text{Ce})/n(^{142}\text{Ce})$ can be used for dating rocks on long time scales (billions of years) and can also be used as a chemical **tracer** in geochemical studies.

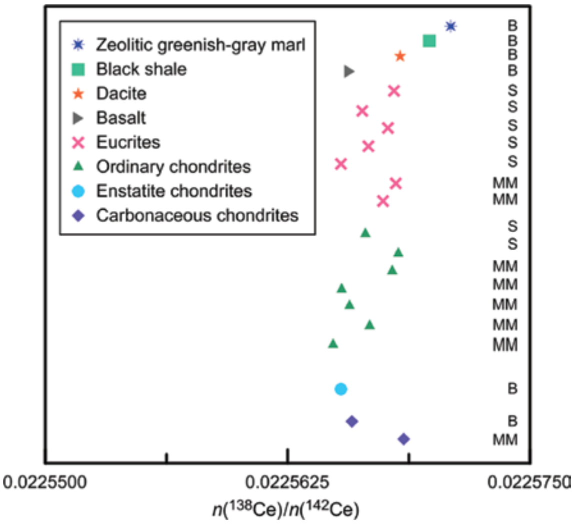
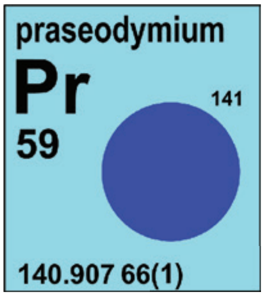


Fig. 4.58.1: Cerium **isotope-amount ratios** of selected terrestrial and extraterrestrial materials (modified from [421]). Data Sources: B, [421]; MM, [422]; S, [423].

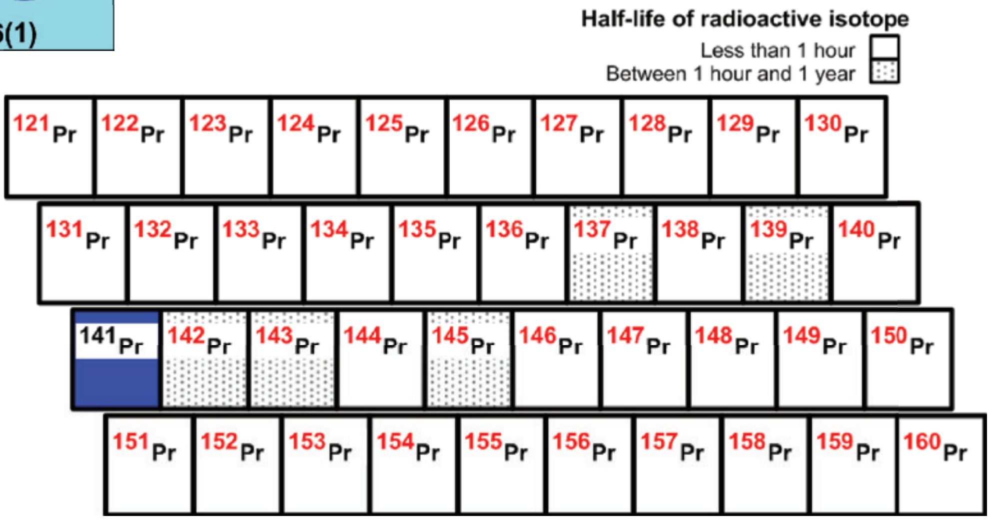
4.58.3 Cerium isotopes in medicine

^{144}Ce (with a half-life of 0.78 year) has been used for **brachytherapy** applications in cells and vessels of the body. The half-life and specific **activity** of ^{144}Ce give it a potential advantage over the commonly used **isotope** ^{192}Ir of higher dose rate at shorter distances and lower irradiation of organs outside the tumor [424]. ^{144}Ce enables the treatment of larger arteries as compared with ^{32}P, another isotope commonly used for this style of **radiotherapy**.

4.59 Praseodymium



Stable isotope	Relative atomic mass	Mole fraction
^{141}Pr	140.907 66	1



4.59.1 Praseodymium isotopes in medicine

Because of its relatively short **half-life** (19.12 h) and decay primarily by **beta decay** (96.3 percent beta decay and 3.7 percent **alpha decay**), ^{142}Pr has been proposed for two main innovative applications in medicine, namely in microsphere **brachytherapy** and in eye plaque brachytherapy [425]. ^{142}Pr is advantageous because penetration of the beta fraction of the radiation is limited to a few millimeters in tissue, therefore limiting

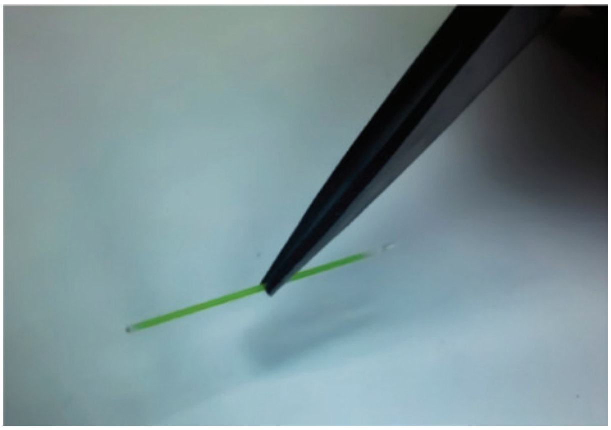
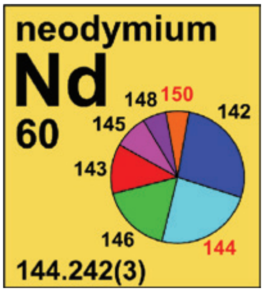


Fig. 4.59.1: Glass microcapillary for use in **brachytherapy** investigations [425], composed of a mixture of silica, aluminium, oxygen, and praseodymium-141 and praseodymium-142. The glass was irradiated in a nuclear reactor to produce radioactive ^{142}Pr from stable ^{141}Pr. Image kindly provided by Dr. Clara Ferreira (University of Oklahoma, Oklahoma City, Oklahoma, USA).

the dose of radiation to the treated site. ^{142}Pr may be produced either by fast **neutron** activation or **thermal neutron** activation of stable ^{141}Pr.

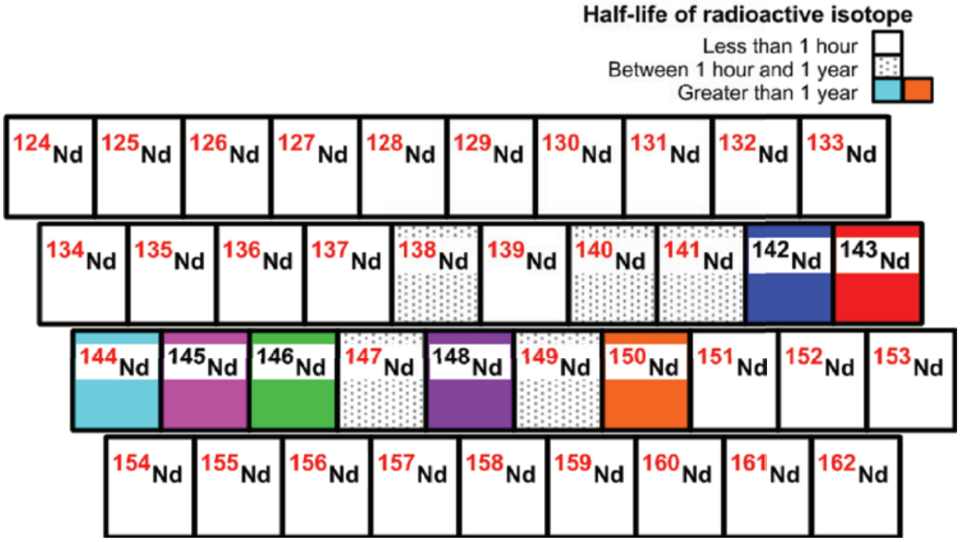
Research in metal-bearing **radiopharmaceuticals** is being conducted to determine the most efficient way to produce and process radioactive metals for ***in vivo*** tracing. This research has led to the development of a potential **radionuclide** generator that administers radioactive metal complexes to be observed during **positron emission tomography** (**PET**) imaging. A $n(^{140}\mathrm{Nd})/n(^{140}\mathrm{Pr})$ amount-ratio radionuclide generator has been designed to administer ^{140}Pr complexes, such as ^{140}Pr-**DTPA**, to be used as a **tracer** during a PET scan [426]. The half-life of ^{140}Pr is 3.4 min. The $n(^{140}\mathrm{Nd})/n(^{140}\mathrm{Pr})$ ratio radionuclide generators can also be used for administering ^{140}Pr-phosphonate complexes to identify the development of skeletal **metastases**. Once the skeletal metastases are found, ^{153}Sm-**EDTMP** can be administered as a radiotherapeutic agent to treat bone cancer (Fig. 4.59.1) [426]. The half-life of ^{153}Sm is 1.9 days.

4.60 Neodymium



Stable isotope	Relative atomic mass	Mole fraction
^{142}Nd	141.907 729	0.271 53
^{143}Nd	142.909 820	0.121 73
^{144}Nd†	143.910 093	0.237 98
^{145}Nd	144.912 579	0.082 93
^{146}Nd	145.913 123	0.171 89
^{148}Nd	147.916 90	0.057 56
^{150}Nd†	149.920 902	0.056 38

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic abundance** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. The half-lives of ^{144}Nd and ^{150}Nd are 2.1 × 10^{15} years and 1.3 × 10^{20} years, respectively.



4.60.1 Neodymium isotopes in geochronology

^{143}Nd is a **radiogenic isotope** produced by decay of ^{147}Sm, with a **half-life** of 1.06×10^{11} years. Thus, the **isotope-amount ratio** $n(^{143}\mathrm{Nd})/n(^{144}\mathrm{Nd})$ can be used for dating rocks on long time scales and as a chemical **tracer** in geochemistry (Fig. 4.60.1) [427, 428]. The very small accumulation of ^{142}Nd in billion-year-old metamorphosed rocks from Greenland [from the relatively short-lived (about 68×10^{6} years) **alpha decay** of ^{146}Sm] provided evidence that the crust of the Earth formed before the young planet was more than 100×10^{6} years old. This is because only a short amount of time could have elapse to incorporate the ^{146}Sm **parent radionuclide** into the ancient Greenland minerals before it decayed [429, 430].

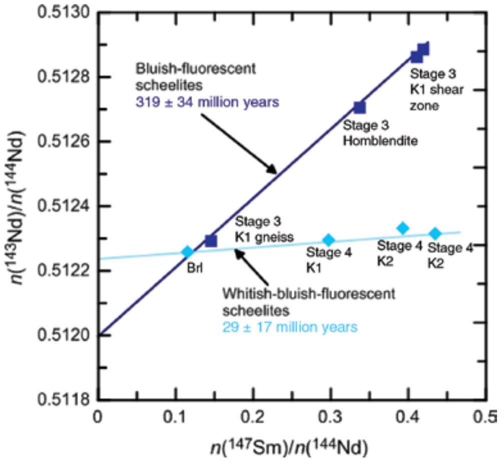
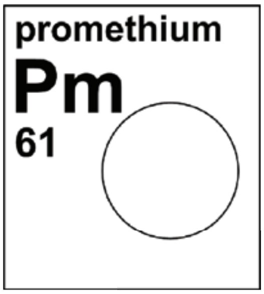


Fig. 4.60.1: Cross plot of $n(^{143}\text{Nd})/n(^{144}\text{Nd})$ **isotope-amount ratio** and $n(^{147}\text{Sm})/n(^{144}\text{Nd})$ **amount ratio** for two periods of scheelite (calcium tungstate; ore of tungsten) mineralization (metamorphism) (modified from [428]). ^{143}Nd is produced by decay of ^{147}Sm. Rock containing higher amounts of ^{147}Sm at time of mineralization will over time produce higher amounts of ^{143}Nd (*e.g.* sample stage 3 K1 shear zone and sample stage 4 K2). Alternatively, rocks containing lower amounts of ^{147}Sm at time of mineralization will over time produce lower amounts of ^{143}Nd (*e.g.* sample stage 3 K1 gneiss and sample Brl). Samples from an older mineralization event will have proportionally more ^{143}Nd because of the longer accumulation time for ^{143}Nd; thus, the line through the bluish-fluorescent scheelites with an age of $(319 \pm 34) \times 10^6$ a has a substantially higher slope than the line through the whitish-bluish-fluorescent scheelites with an age of $(29 \pm 17) \times 10^6$ a. These lines from which age of mineralization (crystallization) can be determined are called **isochrons**.

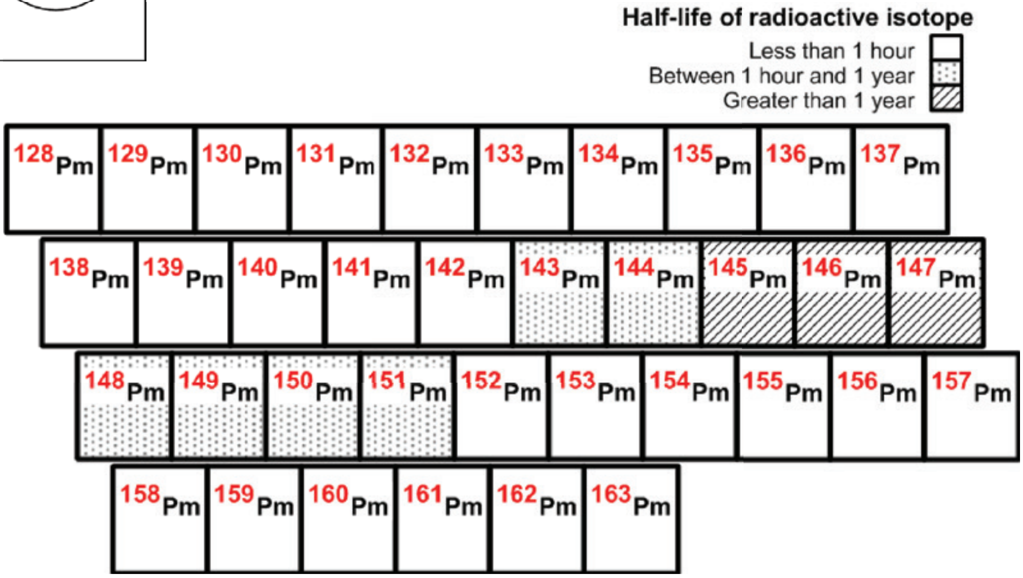
4.60.2 Neodymium isotopes used as a source of radioactive isotope(s)

^{146}Nd has been used in the production of ^{147}Pm (with a half-life of 2.6 years), *via* the reaction $^{146}\text{Nd}\ (\text{n}, \gamma)\ ^{147}\text{Nd}$, which is followed by a subsequent electron decay reaction, $^{147}\text{Nd} \rightarrow {}^{147}\text{Pm} + \beta^-$ reaction. ^{147}Pm is a radioactive power-generation source [431].

4.61 Promethium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.61.1 Promethium isotopes in industry

The beta-particle-emitting **isotope** ^{147}Pm (with a **half-life** of 2.68 years) is used in the nuclear fuel industry to measure the thickness of the inner surface layer of graphite in the cladding tube where the nuclear fuel rod is placed in a nuclear fuel reactor (Fig. 4.61.1). The graphite serves as a protective layer against mechanical contact between the nuclear fuel rod and the Zircaloy cladding (fuel-rod holding tube) and as a diffusion barrier against **fission** products. By placing a layer of ^{147}Pm along the inner surface of the cladding before the graphite, the long half-life of ^{147}Pm and constant beta-particle emission provide a reliable and simple technique to measure the thickness of the graphite along the inner surface of the tube (called the beta-ray backscatter technique) [432–434].

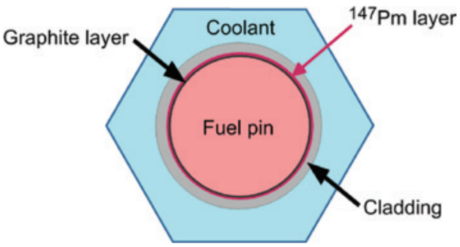
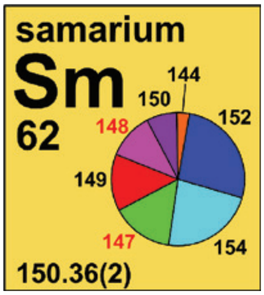


Fig. 4.61.1: The beta-ray backscatter technique requires a layer of ^{147}Pm between the cladding and the graphite layer to measure the thickness of the graphite along the inner surface of the cladding tube. (Modified from [308]).

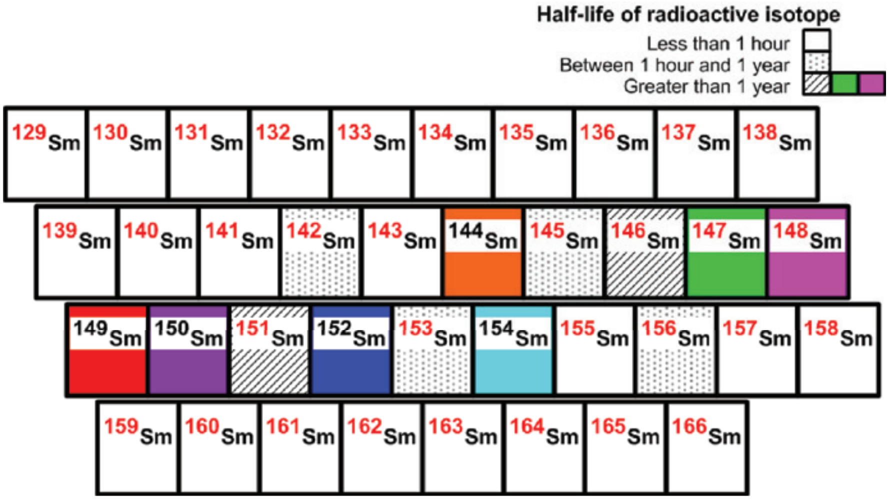
The **beta decay** property of ^{147}Pm makes this **radioisotope** an ideal candidate for **nuclear batteries** (beta **voltaics**). Long-lived power supplies for remote and sometimes hostile environmental conditions are needed for space and sea missions, and nuclear batteries can uniquely serve this role. A **nuclear battery** using beta voltaics can have an energy density (quantity of energy per unit mass) near a thousand watt-h per kilogram with 21 percent efficiency, which is much greater than the best chemical batteries [435].

4.62 Samarium



Stable isotope	Relative atomic mass	Mole fraction
^{144}Sm	143.912 01	0.0308
^{147}Sm†	146.914 904	0.1500
^{148}Sm†	147.914 829	0.1125
^{149}Sm	148.917 191	0.1382
^{150}Sm	149.917 282	0.0737
^{152}Sm	151.919 739	0.2674
^{154}Sm	153.922 22	0.2274

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. The half-lives of ^{147}Sm and ^{148}Sm are 1.06 × 10^{11} years and 7 × 10^{15} years, respectively.



4.62.1 Samarium isotopes in Earth/planetary science

One possible origin for the Moon is from debris ejected by an indirect giant impact of Earth by an astronomical body the size of Mars when the Earth was forming [436]. The kinetic energy liberated is thought to have melted a large part of the Moon forming a lunar magma ocean. Samarium **isotope** measurement results [437], along with measurements of isotopes of hafnium, tungsten, and neodymium[438], suggest that lunar magma formed about 70 × 10^6 years after the Solar System formed and had crystallized by about 215 × 10^6 years after formation. ^{147}Sm (with a **half-life** of 1.06 × 10^{11} years) is used to study the formation of potassium, rare earth **elements**, and phosphorus-rich rocks [439].

4.62.2 Samarium isotopes in geochronology

^{147}Sm is used for determining formation ages of **igneous** and metamorphic rocks *via* analysis of the minerals which compose them, such as those shown in Fig. 4.62.1 [440–442].

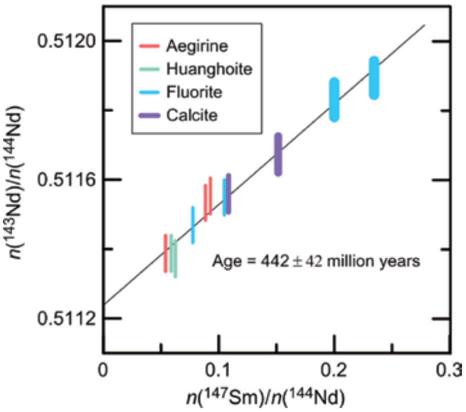


Fig. 4.62.1: Cross plot of $n(^{143}Nd)/n(^{144}Nd)$ **isotope-amount ratio** and $n(^{147}Sm)/n(^{144}Nd)$ **amount ratio** of carbonate and fluorocarbonates at the Bayan Obo rare-earth-element-niobium-iron deposit in Inner Mongolia, China (modified from [442]). ^{143}Nd is produced by decay of ^{147}Sm. Rock containing higher amounts of ^{147}Sm at time of mineralization will over time produce higher amounts of ^{143}Nd (*e.g.* fluorite samples). Alternatively, rocks containing lower amounts of ^{147}Sm at time of mineralization will over time produce lower amounts of ^{143}Nd (*e.g.* huanghoite samples). Samples from an older mineralization event will have proportionally more ^{143}Nd because of the longer accumulation time for ^{143}Nd; thus, the slope of the line through the samples above correlates to the time since mineralization (formation), and such a line is called an **isochron**.

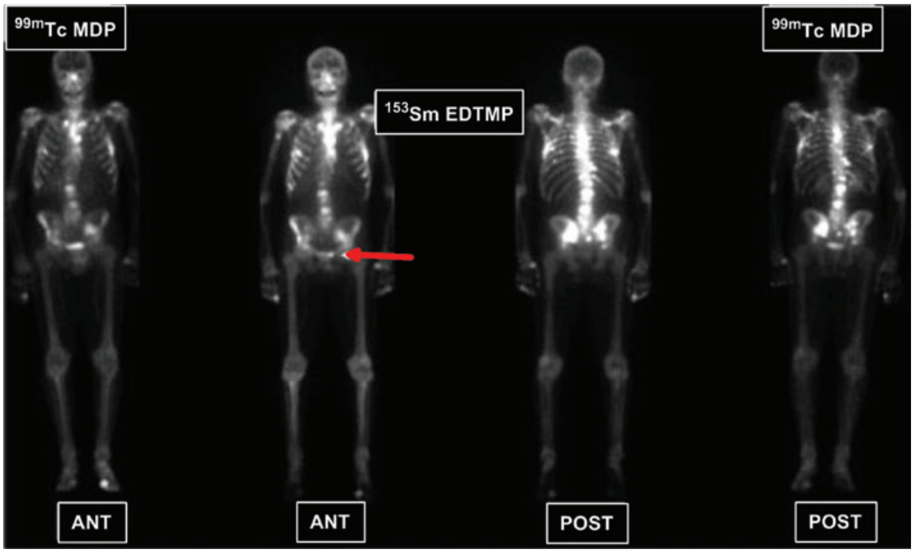


Fig. 4.62.2: Targeting of bone **metastases** with ^{153}Sm-**EDTMP** in a prostate cancer patient. ANT indicates the anterior view of the patient; POST indicates the posterior view of the patient; arrow represents uptake in the pubic bone of the patient. (Image Source: Pandit-Taskar, Batraki, and Divgi, 2004) [445].

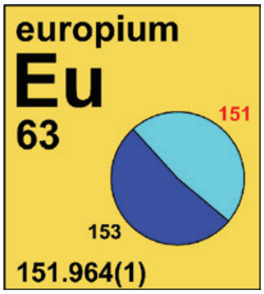
4.62.3 Samarium isotopes in medicine

The **radioisotope** ^{153}Sm (with a **half-life** of 1.9 days) is used in medicine to treat the severe pain associated with cancer that has spread to bones (Fig. 4.62.2) [443–445].

4.62.4 Samarium isotopes used as a source of radioactive isotope(s)

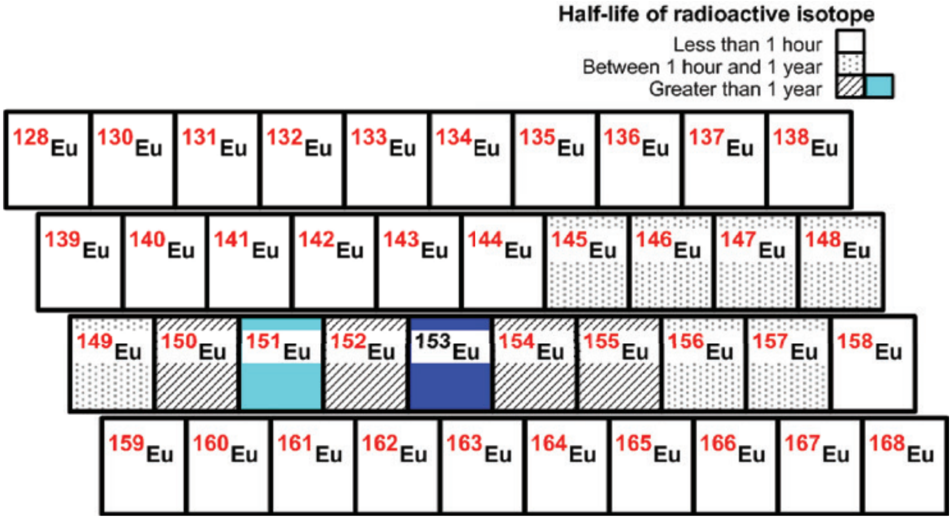
^{147}Sm bombarded with ^{40}Ca produces the radioisotope ^{182}Pb [446].

4.63 Europium



Stable isotope	Relative atomic mass	Mole fraction
^{151}Eu†	150.919 857	0.4781
^{153}Eu	152.921 237	0.5219

† **Radioactive isotope** having a relatively long **half-life** (5×10^{18} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.63.1 Europium isotopes in geochronology

For more than 40 years, weapons-grade plutonium was manufactured by the Krasnoyarsk Mining and Chemical Combine in the now closed town of Krasnoyarsk Krai, Russia, using single-pass uranium-graphite

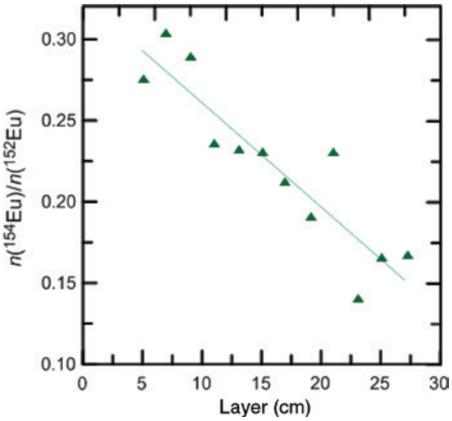


Fig. 4.63.1: Variation in the **isotope-amount ratio** $n(^{154}\text{Eu})/n(^{152}\text{Eu})$ along the vertical profile of floodland sediments at the tail end of Atamanovskii Island, Russia (modified from [447]).

Fig. 4.63.2: ^{152}Eu is used as a reference source for calibrating gamma-ray spectrometer systems like the one pictured here. (Photo Source: Snyder and Duval, 2003. U.S. Geological Survey Open-File Report 03-029) [450].

production reactors [447]. Water from the Yenisei River was used for heat removal from the reactor core. Radioactively contaminated water was discharged into the Yenisei River and was a primary source of contamination of bottom sediments and floodland for hundreds of kilometers down gradient from the Krasnoyarsk Mining and Chemical Combine. In 2002, radioactive contamination of the bottom sediments and floodlands was composed primarily of ^{137}Cs, ^{152}Eu, ^{154}Eu, and ^{60}Co [447]. The decrease in the **isotope-amount ratio** $n(^{154}\mathrm{Eu})/n(^{152}\mathrm{Eu})$ down the depth profiles (Fig. 4.63.1) enables one to determine the age of bottom sediments and floodlands of the Yenisei River and calculate their average formation rates [447].

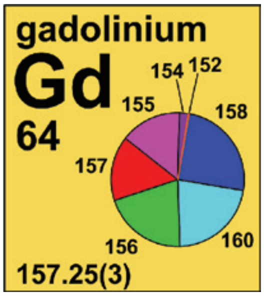
4.63.2 Europium isotopes in industry

Europium **isotopes** have been used in nuclear-control applications because they are good **neutron** absorbers [448]. ^{152}Eu (with a **half-life** of 13.5 years), which is produced by ^{151}Eu *via* the neutron capture reaction ^{151}Eu (n, γ) ^{152}Eu, and ^{154}Eu (with a half-life of 8.59 years) are used as reference sources for calibration in **gamma ray** spectroscopy (Fig. 4.63.2) [449].

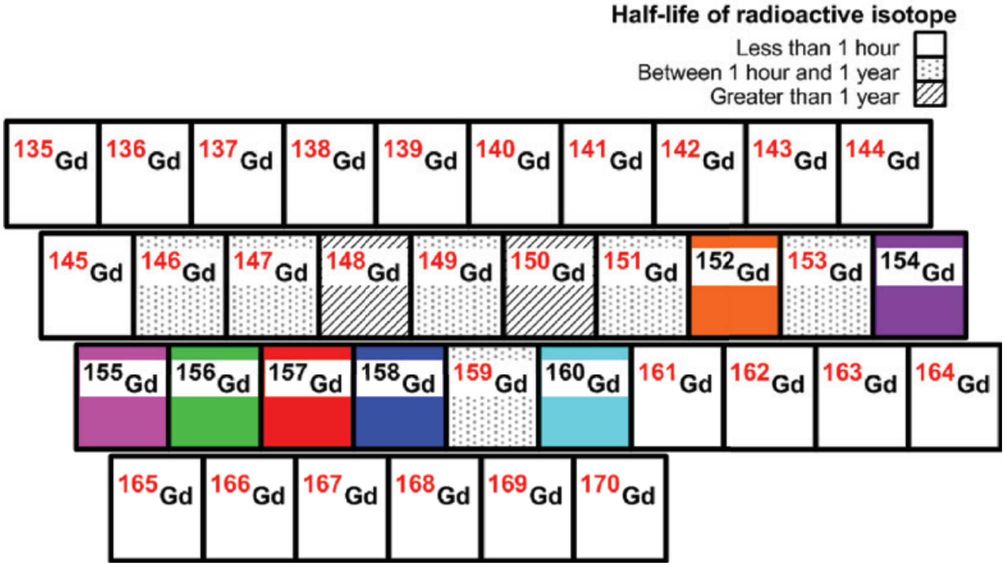
4.63.3 Europium isotopes used as a source of radioactive isotope(s)

Reactions on ^{153}Eu can produce the therapeutic **radionuclide** ^{153}Sm (with a half-life of about 1.9 days) *via* fast neutron irradiation ^{153}Eu (n, p) ^{153}Sm [451].

4.64 Gadolinium



Stable isotope	Relative atomic mass	Mole fraction
^{152}Gd	151.919 799	0.0020
^{154}Gd	153.920 873	0.0218
^{155}Gd	154.922 630	0.1480
^{156}Gd	155.922 131	0.2047
^{157}Gd	156.923 968	0.1565
^{158}Gd	157.924 112	0.2484
^{160}Gd	159.927 062	0.2186



4.64.1 Gadolinium isotopes in Earth/planetary science

The lunar surface is continuously exposed to cosmic radiation, and the interaction between planetary material and **cosmic rays** produces secondary **neutrons**. The neutron flux can be investigated using the large neutron capture cross sections of ^{149}Sm, ^{155}Gd, and ^{157}Gd. For example, ^{157}Gd will absorb neutrons and be converted to ^{158}Gd. On a cross plot of $n(^{158}\text{Gd})/n(^{160}\text{Gd})$ **isotope-amount ratio** and $n(^{157}\text{Gd})/n(^{160}\text{Gd})$ isotope-amount ratio (Fig. 4.64.1), values will move from the lower right corner to the upper left corner of the cross plot with increasing time or increasing flux.

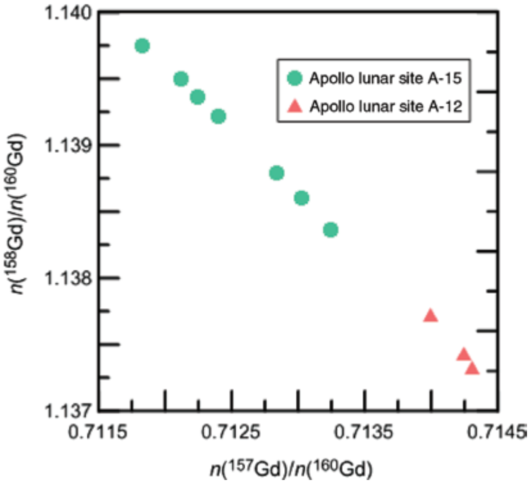


Fig. 4.64.1: Cross plot of $n(^{158}\text{Gd})/n(^{160}\text{Gd})$ and $n(^{157}\text{Gd})/n(^{160}\text{Gd})$ **isotope-amount ratios** of samples from Apollo lunar sites A-12 and A-15 (modified from [452]).

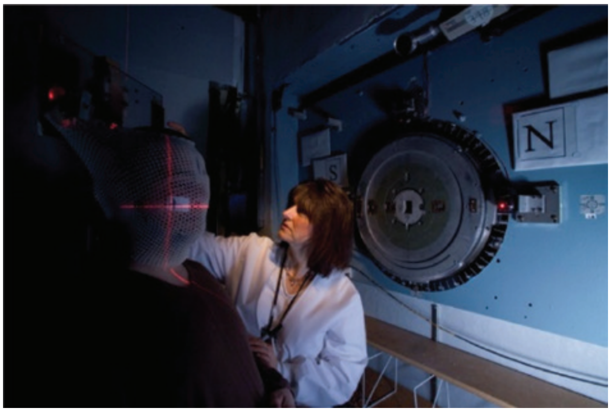
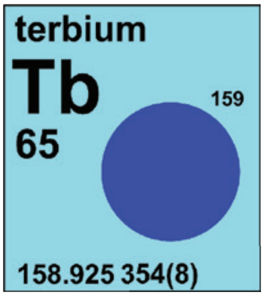


Fig. 4.64.2: Patient undergoing **neutron** therapy. The red lasers cross to target the patient's tumor. A beam of neutrons is fired at the target to stop the growth and eradicate the tumor. (Photo Source: Reidar Hahn, Fermilab Visual Media Services Photo Database, Fermi National Accelerator Laboratory) [457].

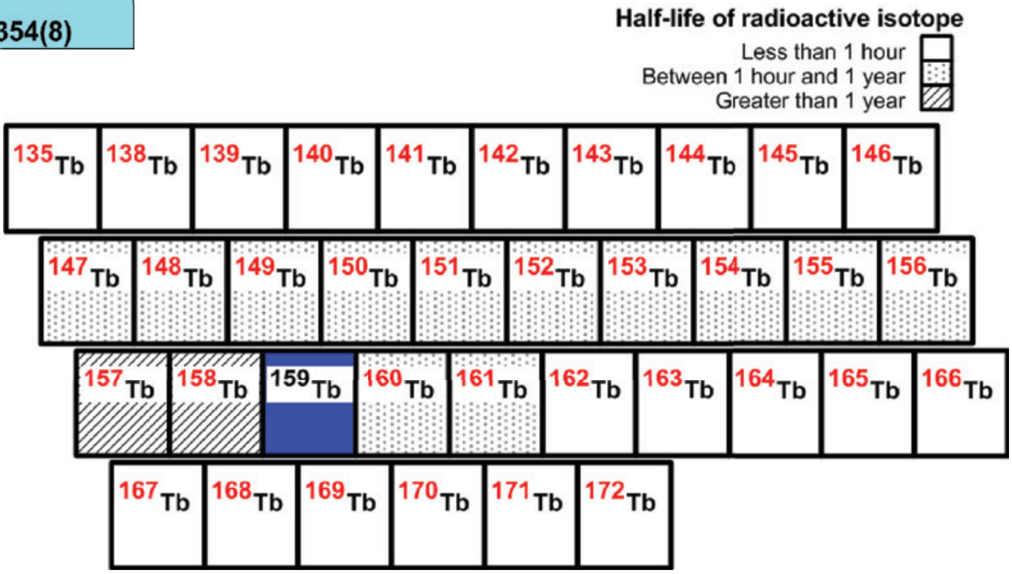
4.64.2 Gadolinium isotopes in medicine

The addition of ^{157}Gd to Neutron Capture Therapy (NCT) has been shown to be more effective at targeting tumors than the previous method of using only ^{10}B for the treatment (Fig. 4.64.2) [453]. ^{153}Gd (with a **half-life** of 0.66 years) is used in the production of **photon** line sources (an optical source that emits one or more spectrally narrow lines as opposed to a continuous spectrum) to manufacture ^{153}Gd line sources [454]. ^{153}Gd is also used as a photon source of the dual-photon absorptiometry (DPA) technique that is used to measure bone mineral content (BMC). Studies for this technique have been conducted in horses and humans [455, 456].

4.65 Terbium



Stable isotope	Relative atomic mass	Mole fraction
^{159}Tb	158.925 354	1



4.65.1 Terbium isotopes in medicine

^{149}Tb (with a **half-life** of 4.1 h) is being used in targeted **radiotherapy** using **alpha particles** for labeling **radioimmunoconjugates** in cancer treatments [458, 459]. ^{161}Tb (with a half-life of 6.9 days) attached to a bioconjugate (two **covalently** linked molecules, one or more of which is a biomolecule), is being used in

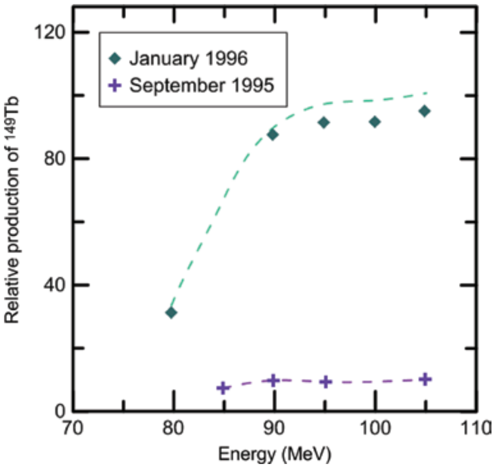
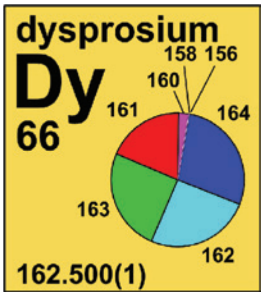


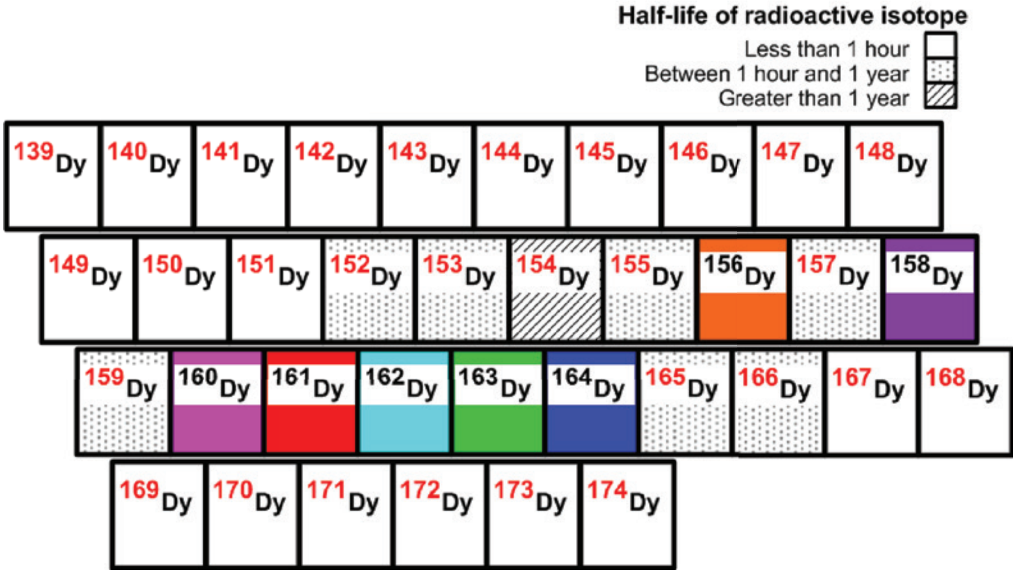
Fig. 4.65.1: ^{149}Tb is produced from the reaction ^{142}Nd(^{12}C,5n)^{149}Dy, which is followed by a subsequent **positron** decay reaction $^{149}\mathrm{Dy} \rightarrow {}^{149}\mathrm{Tb} + \beta^{+}$. A ten-fold increase in production is achieved by optimal beam geometry (modified from [461]).

cancer therapy as a targeted radiation treatment of cancer cells [459, 460]. ^{161}Tb is being used for imaging as it allows for on-line monitoring of its distribution using **gamma cameras** [460]. ^{149}Tb is produced by the reaction ^{142}Nd(^{12}C,5n)^{149}Dy, which is followed by a subsequent **positron** decay reaction $^{149}\text{Dy} \rightarrow {}^{149}\text{Tb} + \beta^+$. It can also be produced by the reaction ^{141}Pr(^{12}C,4n)^{149}Tb; beam geometry is important for satisfactory yield of ^{149}Tb (Fig. 4.65.1) [461].

4.66 Dysprosium



Stable isotope	Relative atomic mass	Mole fraction
^{156}Dy	155.924 284	0.000 56
^{158}Dy	157.924 41	0.000 95
^{160}Dy	159.925 203	0.023 29
^{161}Dy	160.926 939	0.188 89
^{162}Dy	161.926 804	0.254 75
^{163}Dy	162.928 737	0.248 96
^{164}Dy	163.929 181	0.282 60



4.66.1 Dysprosium isotopes in industry

The **isotopes** of dysprosium are highly magnetic and have been the subject of physics research involving interactions of isotopes and the structure of lattice supersolids (spatially ordered material with superfluid properties, *i.e.* zero viscosity). The Magneto-Optical Trapping (MOT) chamber is used for slowing atoms (isotopes) to study the physics of neutral atoms by using a laser light to cool atoms ("Doppler cooling") and magnetic quadrupole fields to slow and "trap" the neutral atoms (Fig. 4.66.1) [462, 463].

^{164}Dy has a large **neutron absorption cross section**, so dysprosium is used for **control rods** [464]. ^{161}Dy has been a key isotope for studying the Mössbauer Effect, which is the resonance and absorption of **gamma ray** emissions on nearby atoms in a solid state [465].

4.66.2 Dysprosium isotopes in medicine

^{165}Dy (with a **half-life** of 140 min) is commonly used in arthritis therapy (**radiosynovectomy**). Rheumatic inflammation of the membranes of joints is often treated by the injection of ^{165}Dy-ferric oxide directly into the joint space of the knee. Leakage from the joint has been shown to be minimal [467].

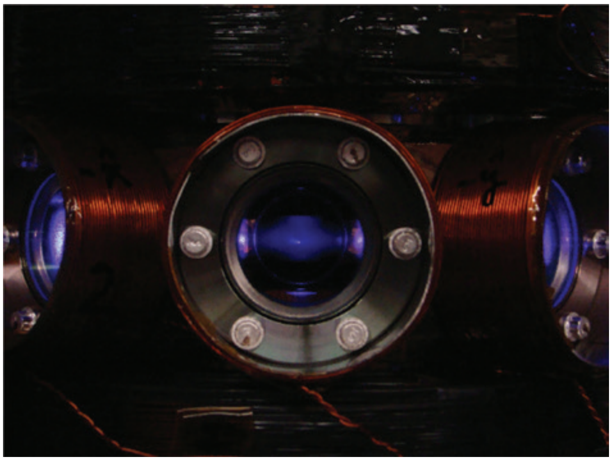
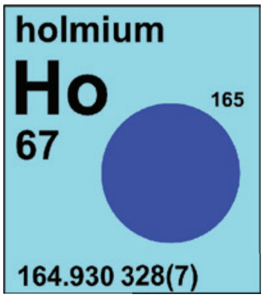


Fig. 4.66.1: Magneto-Optical Trapping (MOT) of **isotopes** of dysprosium. (Used with permission from: Prof. Benjamin Lev, Stanford University) [466].

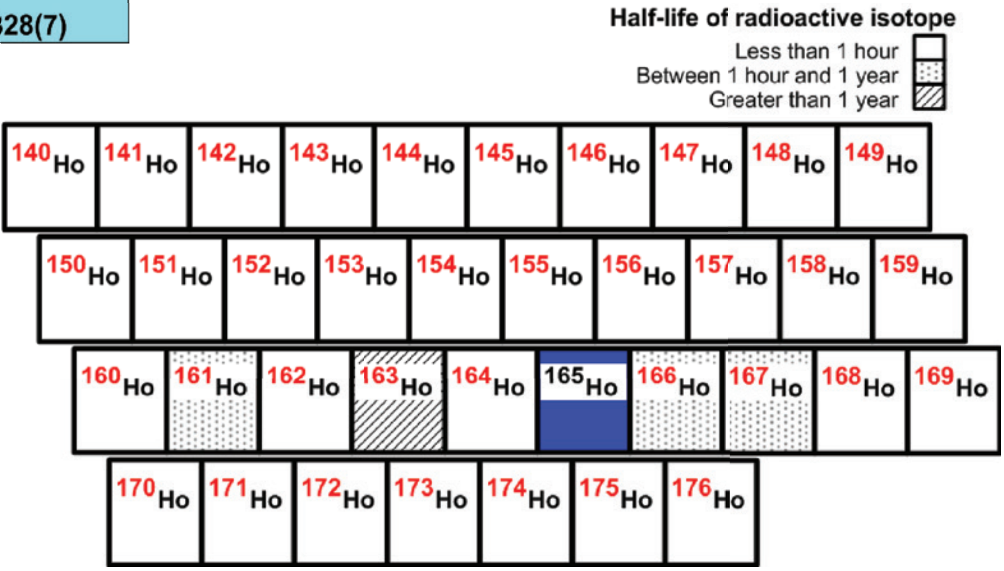
4.66.3 Dysprosium isotopes used as a source of radioactive isotope(s)

^{164}Dy is used to produce ^{166}Dy (with a half-life of 3.4 days) *via* double neutron capture [468–470]. ^{166}Dy, which decays to ^{166}Ho, is used in cancer and arthritis therapy [468, 471].

4.67 Holmium



Stable isotope	Relative atomic mass	Mole fraction
^{165}Ho	164.930 328	1



4.67.1 Holmium isotopes in medicine

Radiosynovectomy with ^{166}Ho-**radiopharmaceutical** agents can be used for treatment of arthritis. The **half-life** of ^{166}Ho is 1.1 days. ^{166}Ho ferric hydroxide macroaggregate ([^{166}Ho] FHMA) radiosynovectomy is being used because FHMA minimizes extra-articular (outside a joint) leakage of the **radioisotope** [472, 473]. ^{166}Ho

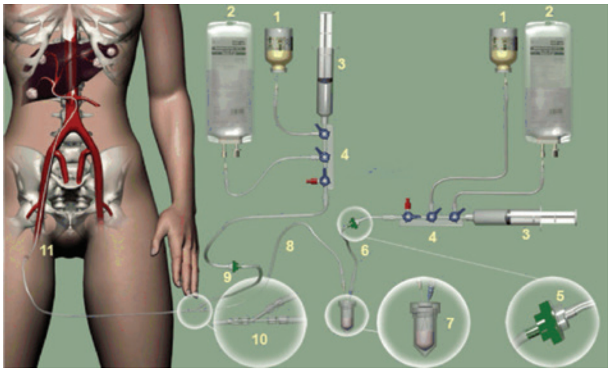


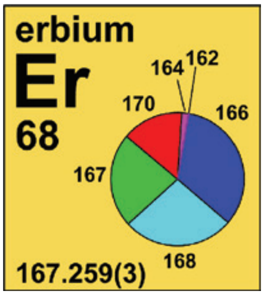
Fig. 4.67.1: Schematic overview of the administration system for ^{166}Ho-RE (radioembolization) (reprinted with permission. Copyright © 2010 Smits *et al.*; BioMed Central Ltd.) [475]. The administration system consists of the following components: iodine contrast agent (Visipaque®, GE Healthcare) (1), saline solution (2), 20-ml syringe (Luer-Lock) (3), three-stopcock manifold (4), one-way valve (5), inlet line (6), administration vial containing the ^{166}Ho-poly(L-lactic acid) microspheres (7), outlet line (8), flushing line (9), Y-connector (10) and catheter (11).

has been used for **radioimmunotherapy** (RIT) with labeled antibodies [474]. The ^{166}Ho-chitosan complex (a linear polysaccharide, which is a long-chain molecule like cellulose that is used by the body for energy storage) is being used for hepatic (liver) cancer therapy [475]. ^{166}Ho-labeled radiopharmaceuticals have been used for alleviating pain from bone **metastases** [443, 473, 476].

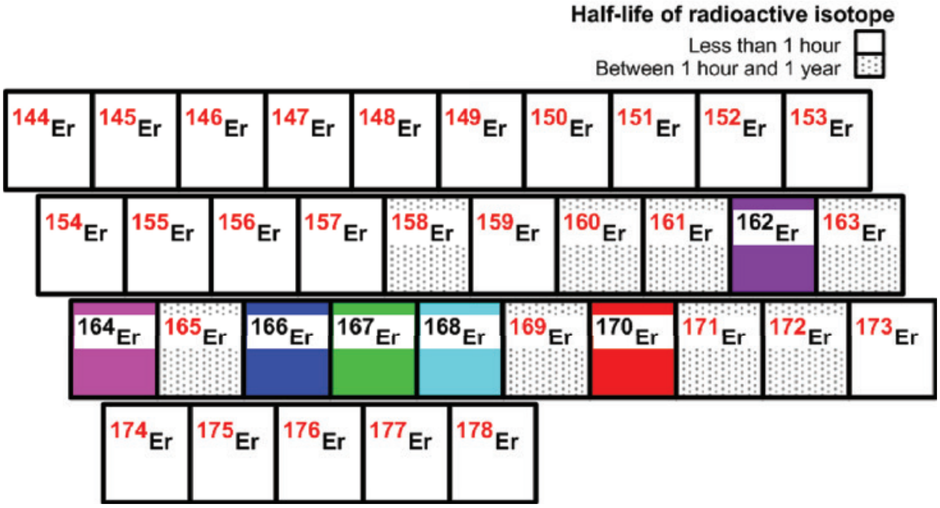
^{166}Ho microspheres have been used for intra-arterial radioembolization (treatment where radioactive particles are delivered to a tumor through the bloodstream) of liver metastases (Fig. 4.67.1) [475]. ^{166}Ho is paramagnetic and emits both beta and **gamma radiation**, which makes it ideal for radioembolization. These properties also enable the distribution of ^{166}Ho microspheres to be visualized with **magnetic resonance imaging** and **single-photon emission computed tomography** (SPECT) [475].

The ^{166}Ho-Patch is a specially designed radioactive skin patch that is used for external radiation of superficial skin cancers and Bowen's disease in areas that are sensitive and difficult to treat by methods that are more destructive and have poor cosmetic results (*i.e.* areas of the face) [477, 478].

4.68 Erbium



Stable isotope	Relative atomic mass	Mole fraction
^{162}Er	161.928 787	0.001 39
^{164}Er	163.929 207	0.016 01
^{166}Er	165.930 299	0.335 03
^{167}Er	166.932 054	0.228 69
^{168}Er	167.932 376	0.269 78
^{170}Er	169.935 48	0.149 10



4.68.1 Erbium isotopes in biology

Radiolabeled ^{171}Er (with a **half-life** of 7.5 h) tablets have been used to study bowel movements of individuals using external **scintigraphy**. Such tablets have an enteric coating and contain small amounts of stable erbium oxide (^{170}Er) initially. The tablets are then irradiated at a low **neutron** flux to produce radioactively labeled ^{171}Er tablets, *via* the ^{170}Er (n, γ) ^{171}Er reaction. This method is a noninvasive approach for determining gastric emptying rates and visualizing segments of the digestive system in an individual [479, 480].

4.68.2 Erbium isotopes in medicine

^{169}Er (with a half-life of 9.4 days) is used in **radiosynovectomy**, which is a regularly practiced **radiotherapy**, on rheumatoid arthritis patients whose condition is resistant to standard methods of treatment (Fig. 4.68.1). Rheumatoid arthritis is a chronic, inflammatory, autoimmune disease of the joint capsule (synovial sac), which is lined with a thin membrane called the synovium, of an individual's moveable joints (synovial joints). In radiosynovectomy, the **radiopharmaceutical** called ^{169}Er- citrate colloid, which contains

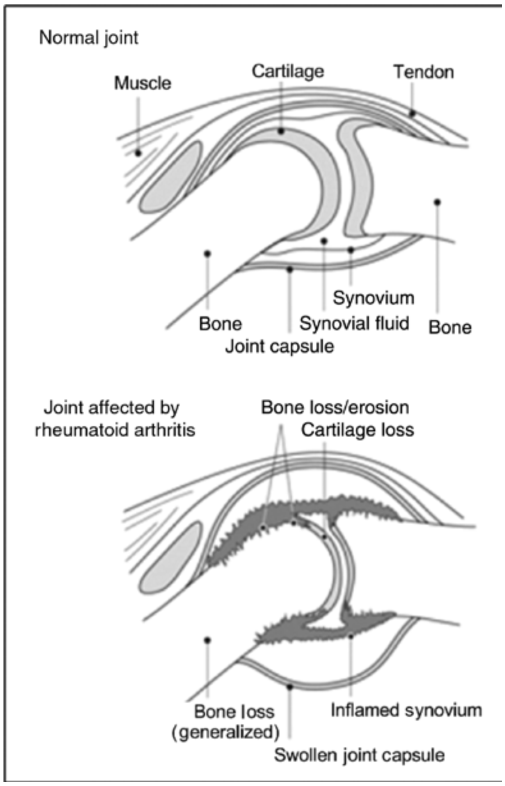
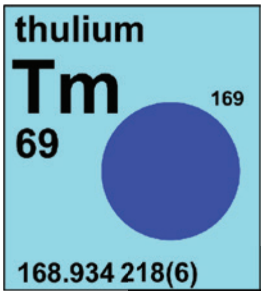


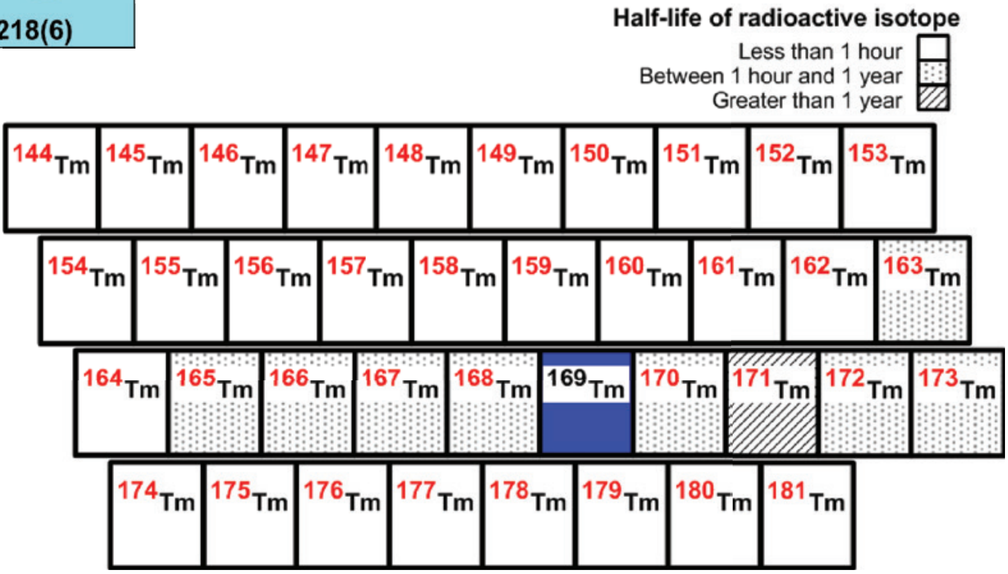
Fig. 4.68.1: Normal joint (top) vs. joint affected by rheumatoid arthritis (bottom) (modified from [485]).

colloidal particles that are labeled with β-emitting ^{169}Er, is directly injected into the synovial cavity (the cavity between the bones in a moveable joint inside of the synovium) of the affected joint. These radioactive-colloid particles are then phagocytized (engulfed) by macrophage-like synoviocytes as well as other phagocytizing inflammatory cells in the patient's synovium. Necrosis (tissue death) and the inhabitation of cell proliferation (increase in number of cells) result from the radiation of the synovium and therefore, temporarily halts synovitis (which is the condition of when the synovium thickens with inflammation) and improves synovial joint function [481–484].

4.69 Thulium



Stable isotope	Relative atomic mass	Mole fraction
^{169}Tm	168.934 218	1



4.69.1 Thulium isotopes in industry

^{170}Tm (with a **half-life** of about 130 days) is used in the **petrochemical** industry for industrial **radiography** to test welds in pipes and tanks [486].

4.69.2 Thulium isotopes in medicine

^{167}Tm (with a half-life of 9.2 days) is useful for tumor and bone studies [487]. Stable ^{169}Tm can be bombarded in a nuclear reactor to create ^{170}Tm, *via* the ^{169}Tm (n, γ) ^{170}Tm reaction, which emits **X-rays** and has been used in portable X-ray equipment as a radiation source [488]. ^{170}Tm has been used in high-dose-rate (HDR) **brachytherapy** [489] and for use in **radiosynovectomy** of medium sized joints (Fig. 4.69.1) [490].

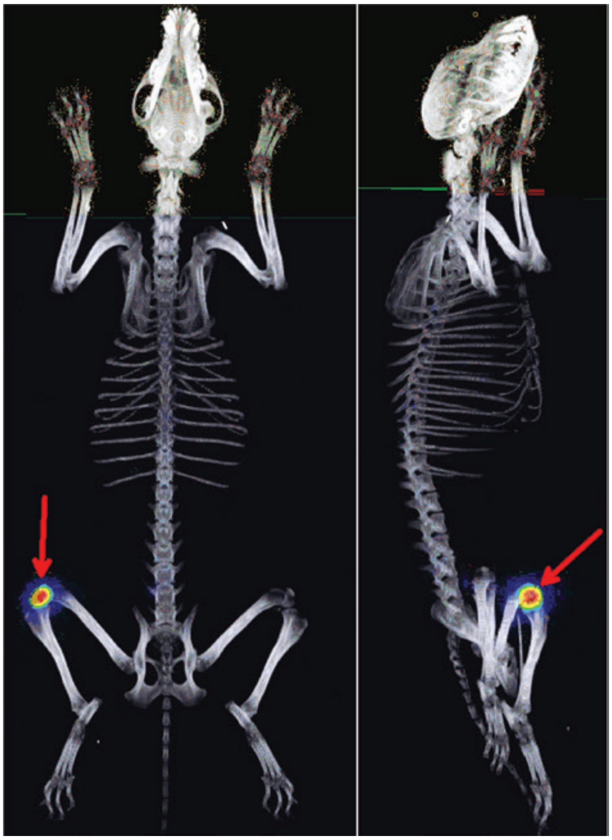
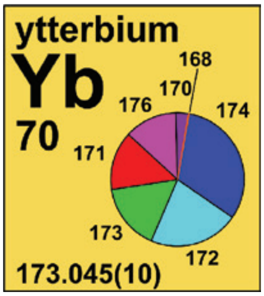
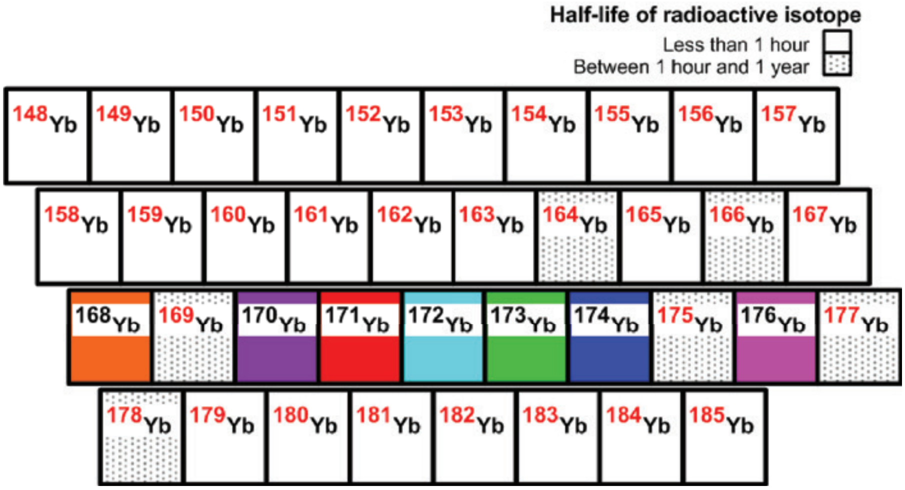


Fig. 4.69.1: Wholebody **single-photon emission computed spectroscopy** (colored layer in image) and CT scan of Beagle dog recorded after 4 h of administration of ^{170}Tm-labeled microparticles [490]. Radioactive-colloid accumulation is displayed in the right knee joint. The Beagle did not suffer any health impairment. Image kindly provided by Dr. Andras Polyak (Dept. of Nuclear Medicine, Hannover Medical School, Germany).

4.70 Ytterbium



Stable isotope	Relative atomic mass	Mole fraction
^{168}Yb	167.933 889	0.001 26
^{170}Yb	169.934 767 25	0.030 23
^{171}Yb	170.936 331 52	0.142 16
^{172}Yb	171.936 386 66	0.217 54
^{173}Yb	172.938 216 22	0.160 98
^{174}Yb	173.938 867 55	0.318 96
^{176}Yb	175.942 5747	0.128 87



4.70.1 Ytterbium isotopes in industry

^{169}Yb (with a **half-life** of 32 days) emits **gamma rays** and can be used to create a radiographic image of an object without the use of electricity. A capsule containing ^{169}Yb is placed on one side of the object being

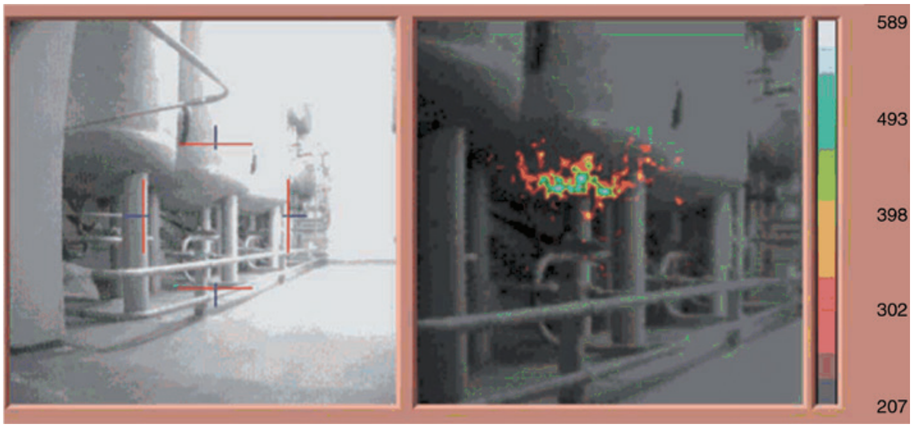


Fig. 4.70.1: **Gamma cameras** are typically used to identify radioactive holdup (material that does not come out of a process as product or waste). The picture to the left is of a tank and the picture to the right shows the radioactivity in the tank. (Photo Source: International Atomic Energy Agency, 2008) [493].

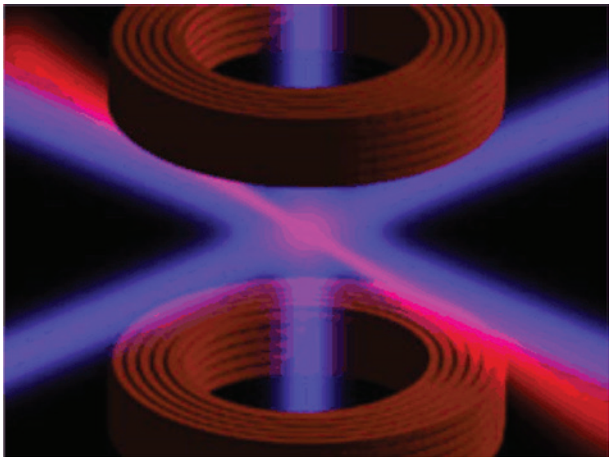


Fig. 4.70.2: The insides of the National Institute of Standards and Technology's (NIST) optical atomic clock. The red rings are magnetic coils and the red laser beam is an optical lattice. The intersecting violet lasers cool the ytterbium atoms. (Image Source: National Institute of Standards and Technology, 2006) [497].

screened and photographic film is placed on the other. The result will indicate flaws in metal casting or welded joints [491, 492]. **Gamma cameras** use ^{169}Yb as a radiation source (Fig. 4.70.1). Gamma cameras are used to locate sealed radioactive sources and hot spots in historical waste. Images of the gamma ray intensity are made and then the 2-D distribution is superimposed on a picture or video image [493, 494].

^{171}Yb has been used for making an atomic clock by making use of a ytterbium optical lattice (formed by the interference of counter-propagating laser beams) (Fig. 4.70.2) [495–497].

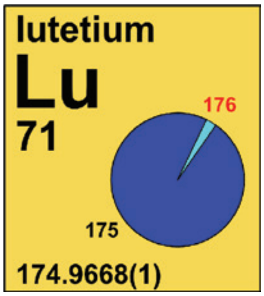
4.70.2 Ytterbium isotopes in medicine

In the treatment of prostate cancer with **brachytherapy** seed implants, ^{169}Yb has been suggested as an alternative to using ^{125}I and ^{103}Pd [498, 499].

4.70.3 Ytterbium isotopes used as a source of radioactive isotope(s)

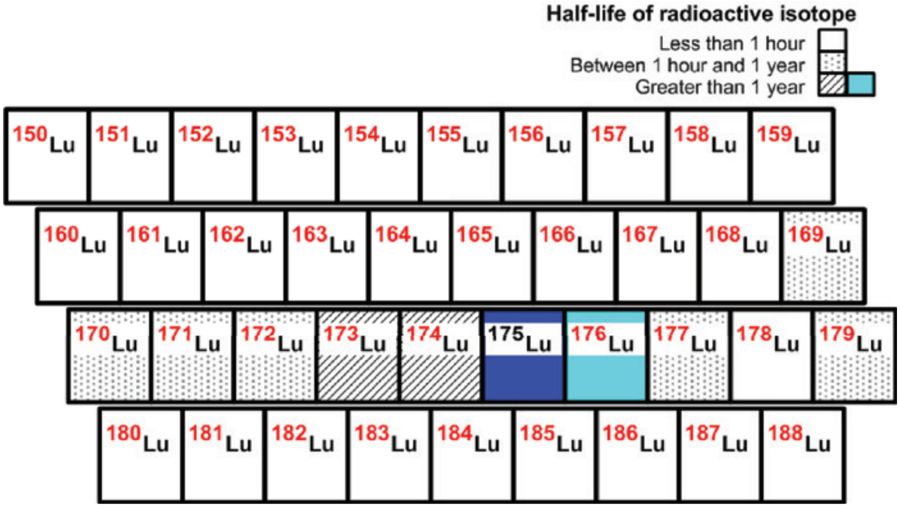
The **radioisotope** ^{169}Yb is manufactured using ^{168}Yb *via* the reaction ^{168}Yb (n, γ) ^{169}Yb.

4.71 Lutetium



Stable isotope	Relative atomic mass	Mole fraction
^{175}Lu	174.940 777	0.974 01
^{176}Lu†	175.942 692	0.025 99

† **Radioactive isotope** having a relatively long **half-life** (3.73 × 10^{10} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.71.1 Lutetium isotopes in biology

^{176}Lu (with a **half-life** of 3.73×10^{10} years) is used in labeling experiments to quantify absolute protein abundance (absolute quantities of proteins in a cell) and examine the extent of synthesis of proteins under specific biological conditions [500]. ^{175}Lu has been used as a yield **tracer** in **inductively coupled plasma mass spectrometry** (ICP-MS) determination of plutonium in urine [500].

4.71.2 Lutetium isotopes in medicine

^{177}Lu (with a half-life of 160 h) has potential for use as an **isotope** for **radioimmunotherapy** for the treatment of small, soft tumors and for imaging purposes (Fig. 4.71.1) [501].

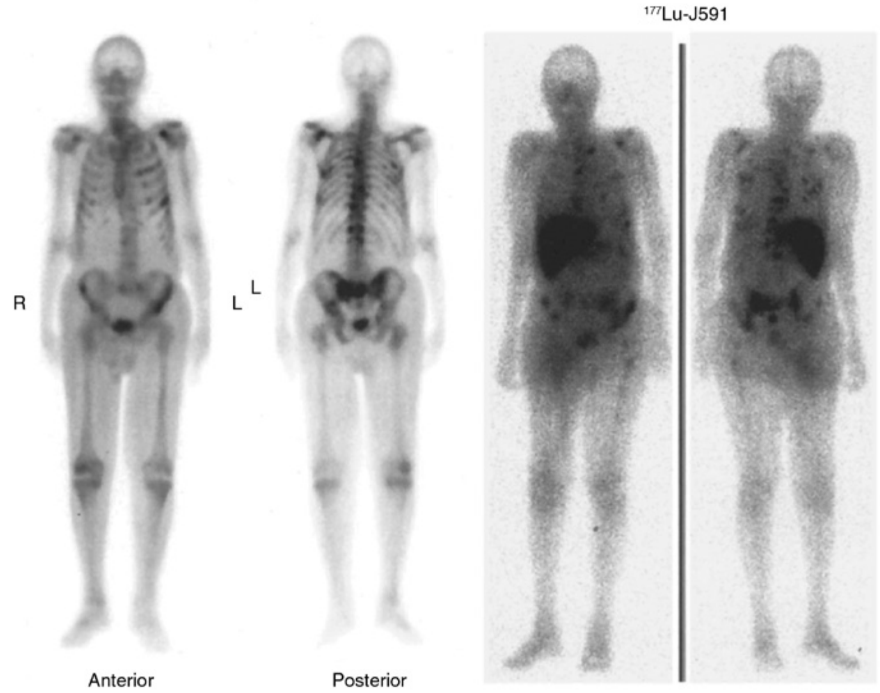
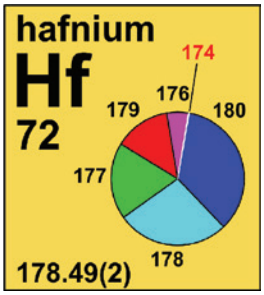


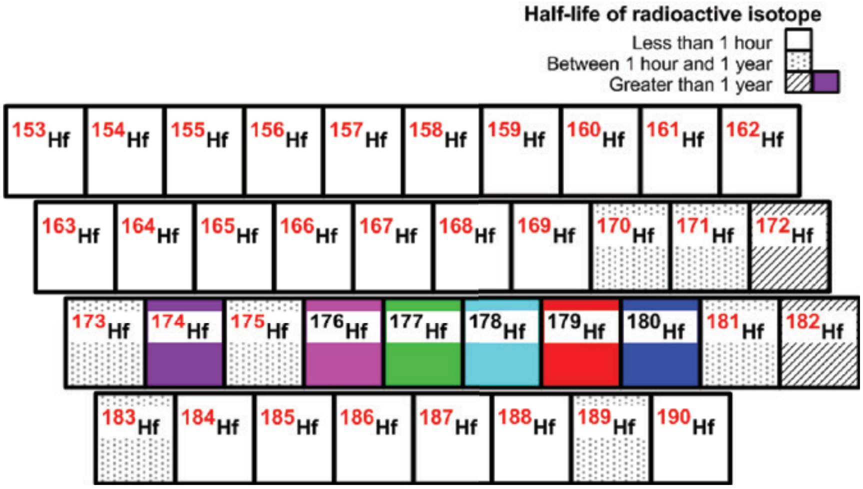
Fig. 4.71.1: Bone scan (on left) and ^{177}Lu scan (on right) done 10 days apart on a patient with prostate cancer (PC), which metastasized to his bones, and who is being treated with the experimental drug ^{177}lutetium-labeled J591 (^{177}Lu-J591). The primary areas of uptake of this drug in the body are in PC **metastases**, which appear as small dark spots in both sets of scans, and in the liver (the large dark spot in the ^{177}Lu scans). The location and number of metastases is clearer in the ^{177}Lu scan than in the bone scan. (Image Source: Bander, Milowsky, Nanus, Kostakoglu, Vallabhajosula and Goldsmith, 2005, © American Society of Clinical Oncology. All rights reserved.) [501].

4.72 Hafnium



Stable isotope	Relative atomic mass	Mole fraction
^{174}Hf†	173.940 05	0.0016
^{176}Hf	175.941 41	0.0526
^{177}Hf	176.943 230	0.1860
^{178}Hf	177.943 709	0.2728
^{179}Hf	178.945 826	0.1362
^{180}Hf	179.946 560	0.3508

† **Radioactive isotope** having a relatively long **half-life** (2.0×10^{15} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.72.1 Hafnium isotopes in geochronology

Some ^{176}Hf is **radiogenic** as a result of it being formed as a product of **beta decay** of radioactive ^{176}Lu (**half-life** of 3.73×10^{10} years) [301]. Thus, relations between the **isotope-amount ratios** $n(^{176}\text{Hf})/n(^{177}\text{Hf})$ and $n(^{176}\text{Hf})/n(^{176}\text{Lu})$ have been used to determine the ages of minerals and rocks. Because of the long half-life of ^{176}Lu, these ratios have been used in **geochronology** studies that document some of the oldest rocks in the Solar System and on Earth (Fig. 4.72.1).

Hafnium **isotopic compositions** of terrestrial materials evolved differently depending on the relative rates of ^{176}Hf production. Geologists can use calculated lutetium-hafnium ages and the initial isotope-amount ratio $n(^{176}\text{Hf})/n(^{177}\text{Hf})$ along with other isotopic data from the oldest rocks in the Earth to infer that the Earth's crust differentiated within the first few hundred million years after condensation of the oldest solid matter in the Solar System [502].

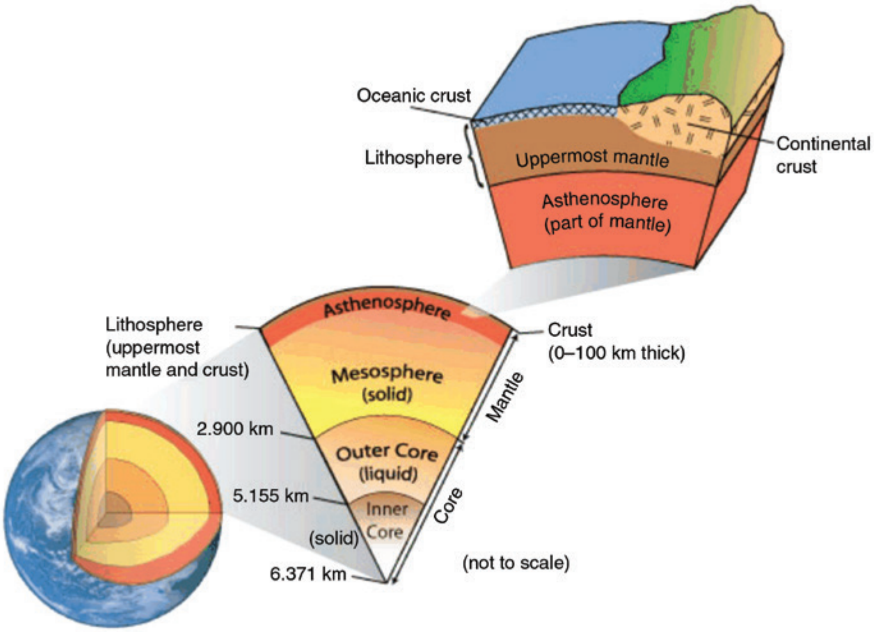
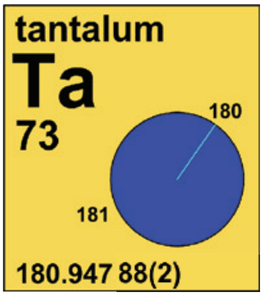


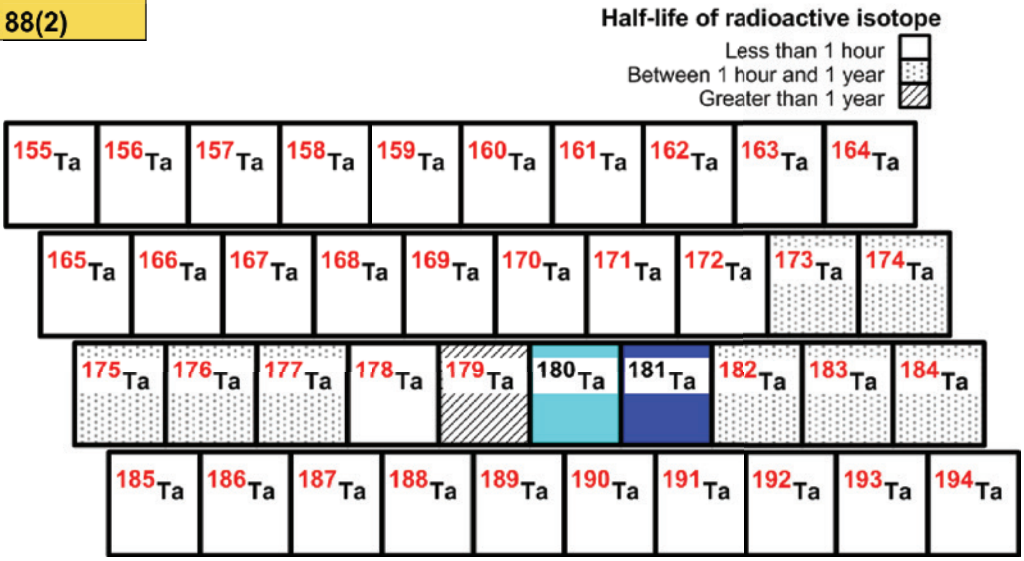
Fig. 4.72.1: Separation of the Earth into layers (crust, mantle, inner core, and outer core) was largely caused by gravitational differentiation (separating different constituents at temperature where materials are liquid or plastic, owing to differences in density) early in Earth's history. (Image Source: University of Wisconsin-Madison Space Science and Engineering Center) [505].

Radioactive ^{182}Hf decays to ^{182}W with a half-life of 8.9×10^6 years, which is much less than the age of **meteorites** and the Earth. Therefore, measurements of the amounts of hafnium and tungsten **isotopes** in meteorites and terrestrial samples reveal the earlier presence of ^{182}Hf. As a result, this provides information about chemical differentiation and evolution of the early Solar System [503, 504].

4.73 Tantalum



Stable isotope	Relative atomic mass	Mole fraction
^{180}Ta	179.947 47	0.000 1201
^{181}Ta	180.947 999	0.999 8799



4.73.1 Tantalum isotopes in medicine

^{178} Ta (with a **half-life** of 9.3 min) is used in medical studies, such as **first-pass radionuclide angiography** of mice, to better understand cardiovascular disease. Radionuclide angiography uses a pinhole lens fitted

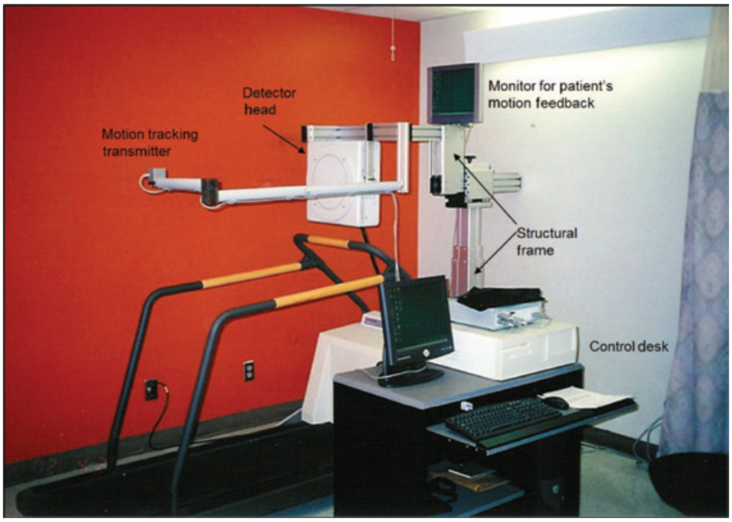


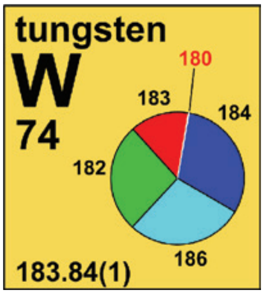
Fig. 4.73.1: Multiwire **gamma camera** containing a ^{178}Ta generator. [Photographer: Ami Iskandrian, M.D. University of Alabama at Birmingham (used with permission)] [511].

to a high-speed multiwire proportional camera and a $n(^{178}\mathrm{W})/n(^{178}\mathrm{Ta})$ amount-ratio generator for minimally invasive quantification of murine ventricular (heart) functions (Fig. 4.73.1) [506, 507]. The multiwire **gamma camera** has a ^{178}Ta generator incorporated in its housing, and it provides portable and laboratory ventricular function assessments for cardiovascular patients [507, 508]. **Intravenous** injections of ^{178}Ta are used in **gated equilibrium blood pool imaging** [509]. ^{183}Ta (with a half-life of 5.1 days) has potential for use in **radionuclide** pharmaceuticals and as a **tracer** for toxicity studies of ecosystems [510].

4.73.2 Tantalum isotopes used as a source of radioactive isotope(s)

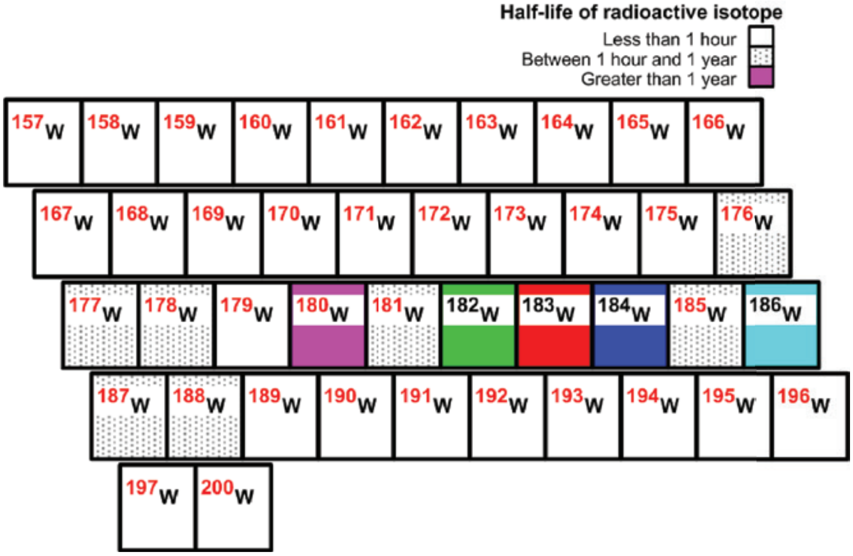
^{181}Ta is used to produce ^{178}W, which decays to ^{178}Ta *via* the reaction ^{181}Ta (p, 4 n) ^{178}W, which is followed by a subsequent **electron** capture decay reaction of ^{178}W to finally yield ^{178}Ta. ^{178}Ta is important for medical studies as noted in Section 4.73.1.

4.74 Tungsten



Stable isotope	Relative atomic mass	Mole fraction
^{180}W†	179.946 713	0.0012
^{182}W	181.948 206	0.2650
^{183}W	182.950 225	0.1431
^{184}W	183.950 933	0.3064
^{186}W	185.954 365	0.2843

† **Radioactive isotope** having a relatively long **half-life** (1.5×10^{18} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.74.1 Tungsten isotopes in Earth/planetary science

^{182}W is the stable product of the decay of ^{182}Hf, which has a **half-life** of 8.9×10^6 years. Although ^{182}Hf was present at the dawn of the Solar System, this **isotope** has long since decayed. During the formation of the planets, including Earth, the **elements** hafnium and tungsten were partitioned into silicate minerals (rock forming minerals with silicon-oxygen bonds that constitute more than 90 percent of the Earth's crust) and metal phases, respectively. The measurement of excessive amounts of ^{182}W, arising from the decay of ^{182}Hf that accumulated in silicate minerals, has been used to estimate the time that elapsed between the formation of the Solar System and accretion of the planets (Fig. 4.74.1) [512, 513].

4.74.2 Tungsten isotopes used as a source of radioactive isotope(s)

Tungsten-rhenium generators use ^{188}W, which is produced from ^{186}W, *via* the following double **neutron** capture reaction ^{186}W (n, γ) ^{187}W (n, γ) ^{188}W.

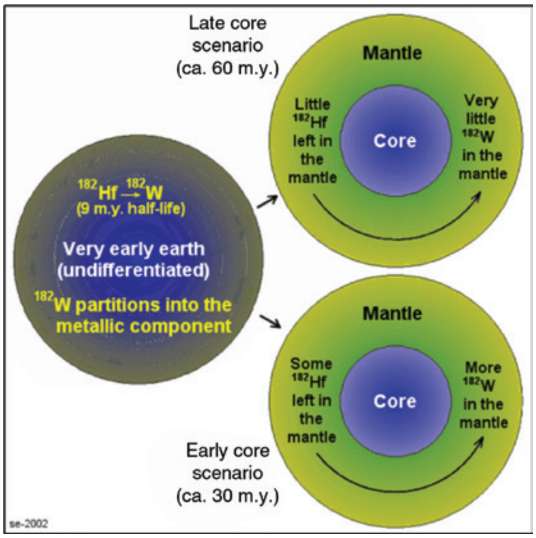
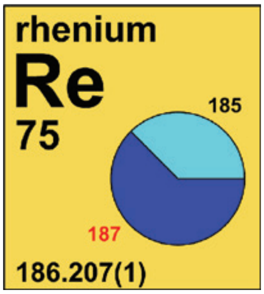


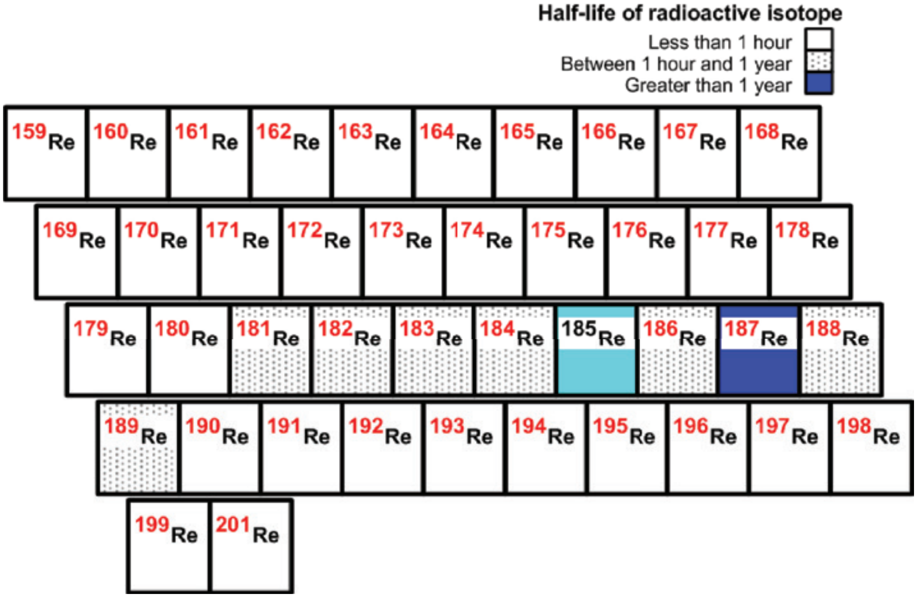
Fig. 4.74.1: Core formation scenarios. ^{182}Hf is produced during the end stages of a **supernova** explosion and decays to ^{182}W. The Early Core Scenario shows that when a core forms relatively early after a supernova explosion, a small amount of ^{182}Hf will be present in the mantle that will produce a significant amount of ^{182}W. The Late Core Scenario shows that ^{182}Hf was produced and decays to ^{182}W prior to the formation of the metallic core. Once the metallic core begins to form, it will attract tungsten because it is strongly attracted to metals. Almost all of the ^{182}W is partitioned into the metallic core and only a small amount will be left in the mantle. (Diagram Source: Steven Earle, Vancouver Island University) [514].

4.75 Rhenium



Stable isotope	Relative atomic mass	Mole fraction
^{185}Re	184.952 958	0.3740
^{187}Re†	186.955 752	0.6260

† **Radioactive isotope** having a relatively long **half-life** (4.16×10^{10} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.75.1 Rhenium isotopes in geochronology

The rhenium-osmium dating method is of special interest for the dating of rhenium-bearing ores, gold deposits, copper-nickel deposits, and **meteorites**. This method is based on the **beta-decay** of ^{187}Re (having a **half-life** of 41.6×10^9 years) to ^{187}Os, an example of which appears in Fig. 4.75.1 [515].

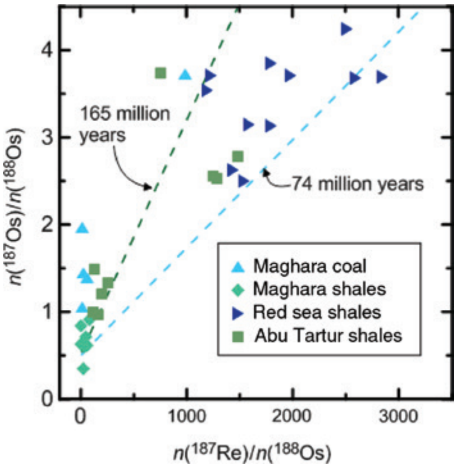
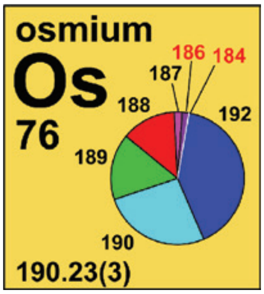


Fig. 4.75.1: Cross plot of $n(^{187}Os)/n(^{188}Os)$ **isotope-amount ratio** and $n(^{187}Re)/n(^{188}Os)$ **amount ratio** of marine and non-marine organic-rich sediments and coals from Egypt (modified from [515]). The Maghara area (about 200 km east of Cairo) has middle-Jurassic coal beds (about 165×10^6 years old, identified by the green dotted line). The age of marine black shales in the Red Sea area was previously estimated as 74×10^6 years old, identified by the blue dotted line. ^{187}Os is produced by decay of ^{187}Re. Samples from an older formation will have proportionally more ^{187}Os because of the longer accumulation time for ^{187}Os; thus, the slope of the line for the Maghara coals (turquoise triangles), having an age of 165×10^6 years, is substantially higher than the slope of the Red Sea specimens. Note the analytical challenges in obtaining isotope-amount values that plot near the 165- and 74-million-year **isochrons**. Many of the values plot between the isochrons.

4.75.2 Rhenium isotopes in medicine

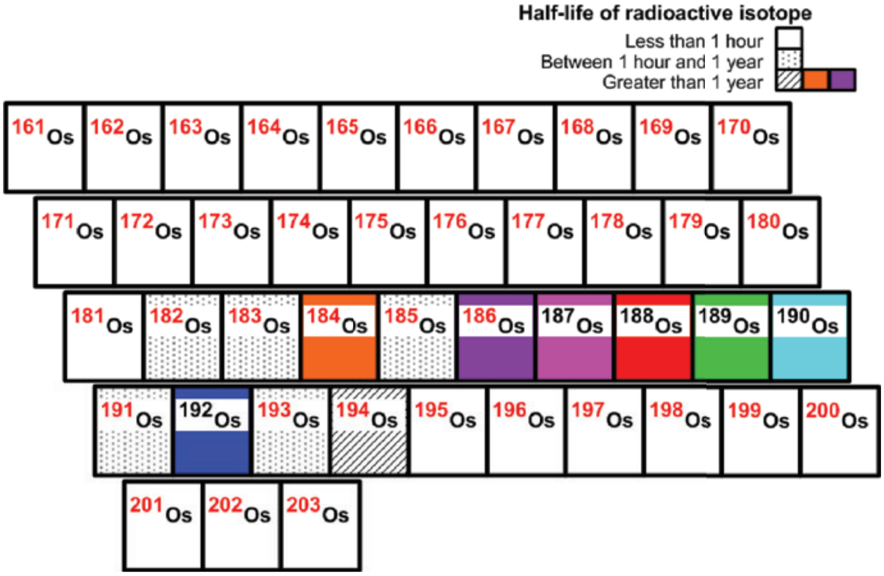
^{186}Re (with a half-life of 89 h) is a beta-emitting **radioisotope** that is used for cancer treatment, in particular for pain relief in bone cancer and in rheumatoid arthritis (see **radiosynovectomy**). It is produced from the **stable isotope** ^{185}Re *via* the ^{185}Re (n, γ) ^{186}Re reaction [188]. ^{186}Re is also used for **radiolabeling** of cancer therapeutic agents [188]. ^{188}Re (with a half-life of 17 h) is used to irradiate coronary arteries with beta particles during insertion of an angioplasty balloon (a tiny balloon that is inserted into an artery and inflated to flatten plaque build-up and improve blood flow) and in **palliative** therapy, particularly for bone **metastases**. The beta irradiation can decrease scar tissue formation after the overstretching of arteries by angioplasty.

4.76 Osmium



Stable isotope	Relative atomic mass	Mole fraction
^{184}Os†	183.952 493	0.0002
^{186}Os†	185.953 838	0.0159
^{187}Os	186.955 750	0.0196
^{188}Os	187.955 837	0.1324
^{189}Os	188.958 146	0.1615
^{190}Os	189.958 446	0.2626
^{192}Os	191.961 48	0.4078

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. The half-lives of ^{184}Os and ^{186}Os are 1.1 × 10^{13} years and 2 × 10^{15} years, respectively.



4.76.1 Osmium isotopes in Earth/planetary science

The **isotope-amount ratio** $n(^{187}\text{Os})/n(^{186}\text{Os})$ in rocks can be transferred to fluids, such as magmas, groundwaters, rivers, and oceans. Variations in the inherited $n(^{187}\text{Os})/n(^{186}\text{Os})$ ratios can provide a useful **tracer** for fluid sources and migration paths, including different layers of the Earth [301, 504, 516, 517]. **Meteorites** and meteorite dust impacting the Earth have different osmium **isotopic compositions** than terrestrial rocks and sediments. As a result, $n(^{187}\text{Os})/n(^{186}\text{Os})$-ratio studies provide evidence of continuing extraterrestrial additions to the Earth over geologic time, as well as providing a method for prospecting in the sedimentary record for large meteorite impact events that may have affected life on Earth [518].

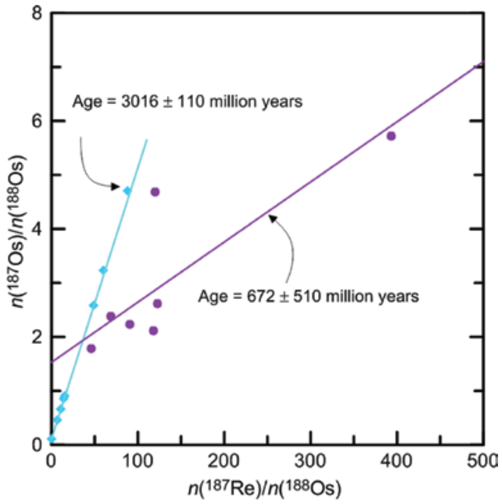


Fig. 4.76.1: Cross plot of $n(^{187}Os)/n(^{188}Os)$ **isotope-amount ratio** and $n(^{187}Re)/n(^{188}Os)$ **amount ratio** of gold and pyrite from South Africa's Witwatersrand Supergoup gold deposits (modified from [519]). The turquoise diamonds are gold-bearing samples from Vaal Reef, and they form an **isochron** with an age of about 3.0×10^9 years. The purple filled circles are euhedral pyrites (crystals having a flat surface and sharp angles) from the Venterdorp Contact Reef, and they have a much younger age of $(672 \pm 510) \times 10^6$ a.

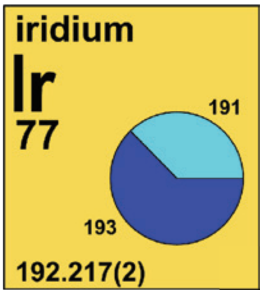
4.76.2 Osmium isotopes in geochronology

Some ^{187}Os is **radiogenic** as a result of being formed by the **beta decay** of radioactive ^{187}Re, which has a **half-life** of 4.16×10^{10} years. Variations in the isotope-amount ratio $n(^{187}Os)/n(^{186}Os)$ and **amount ratio** $n(^{187}Re)/n(^{186}Os)$ are used for **geochronology**; for example, variations in these ratios have been used to determine the ages of the Earth, Moon, and meteorites [301]. Kirk *et al.* [519] measured rhenium-osmium **isotopic abundances** in gold and pyrites from conglomerates of the Central Rand Group of South Africa (Fig. 4.76.1), which have produced over 48 000 metric tons of gold and have accounted for 40 percent of the world's total historic production [520]. The gold and rounded pyrites from the conglomerates yield an age of ~3.0×10^9 years. Kirk *et al.* find that this age is much older than that of the conglomerate, and they conclude that the gold is detrital (material wearing away by weathering or erosion) and was not deposited by later hydrothermal fluids.

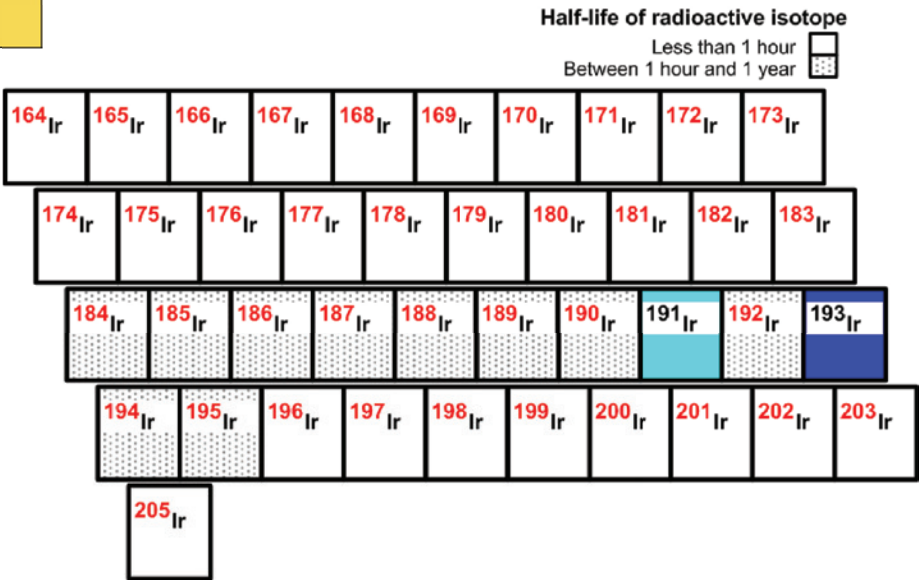
4.76.3 Osmium isotopes used as a source of radioactive isotope(s)

^{192}Os can be used for the production of the medical **radioisotope** ^{195m}Pt *via* the ^{192}Os (α, n) ^{195m}Pt reaction.

4.77 Iridium



Stable isotope	Relative atomic mass	Mole fraction
^{191}Ir	190.960 592	0.373
^{193}Ir	192.962 924	0.627



4.77.1 Iridium isotopes in industry

Metallic ^{192}Ir (with a **half-life** of 74 days) is used as a radiation source in **gamma cameras** for non-destructive testing of products for manufacturing flaws, such as aircraft parts, boilers, and pipeline welds (Fig. 4.77.1) [274].

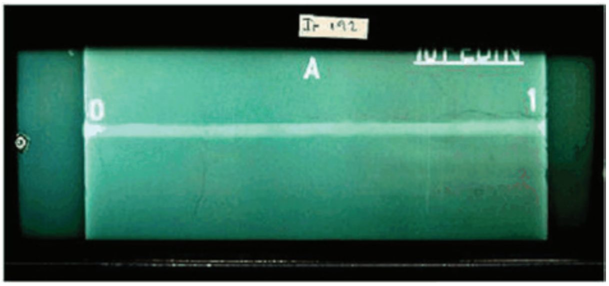


Fig. 4.77.1: This is a radiograph of a weld using ^{192}Ir as the source of radiation. The **gamma rays** given off by the **isotope** enable imperfections in the weld to be seen on the radiograph. (Photo Source: Hayward and Currie, 2006) [274].

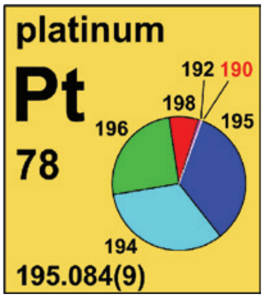
4.77.2 Iridium isotopes in medicine

Metallic ^{192}Ir is used in **brachytherapy** [188, 521–523]. ^{191m}Ir (with a half-life of 5 s) is used for blood flow imaging (angiography), especially in pediatric populations [524, 525]. The m in the superscript ^{191m}Ir indicates a **metastable state** of the isotope.

4.77.3 Iridium isotopes used as a source of radioactive isotope(s)

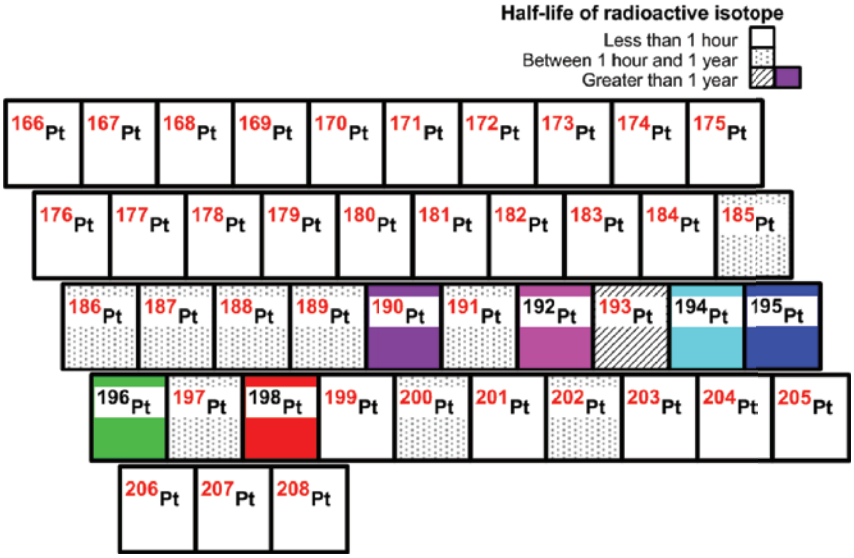
Iridium consists of two **stable isotopes** (^{191}Ir and ^{193}Ir) from which the **radioactive isotopes** ^{192}Ir and ^{195m}Pt (with a half-life of 4 days) can be produced. Both are used in **nuclear medicine**. The m in the superscript ^{195m}Pt indicates a metastable state of the isotope.

4.78 Platinum



Stable isotope	Relative atomic mass	Mole fraction
^{190}Pt†	189.959 950	0.000 12
^{192}Pt	191.961 04	0.007 82
^{194}Pt	193.962 684	0.328 64
^{195}Pt	194.964 794	0.337 75
^{196}Pt	195.964 955	0.252 11
^{198}Pt	197.967 90	0.073 56

† **Radioactive isotope** having a relatively long **half-life** (4.9 × 10^{11} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.78.1 Platinum isotopes in Earth/planetary science

Astrophysicists have confirmed an anomaly in the **isotopic composition** of platinum in the chemically peculiar HgMn star χ Lupi, where the platinum isotopic composition was shown to be a mixture of ^{196}Pt and ^{198}Pt (Fig. 4.78.1) [526].

4.78.2 Platinum isotopes in geochronology

The decay of ^{190}Pt (with a **half-life** of 4.9 × 10^{11} years) to ^{186}Os over time has been used for dating rocks and iron **meteorites** [527].

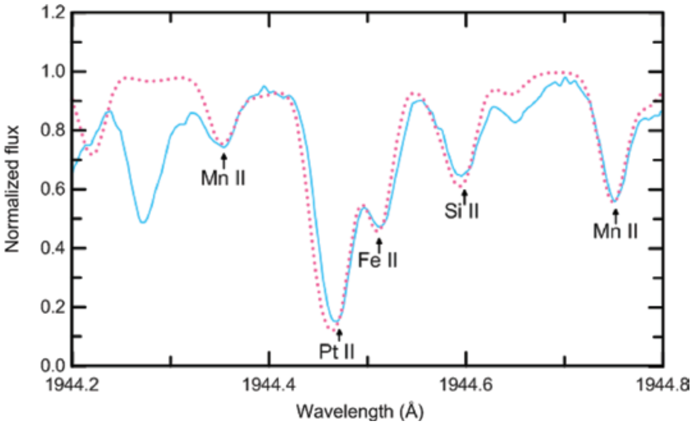
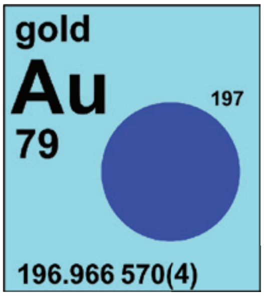


Fig. 4.78.1: Observed spectra of the chemically peculiar HgMn star χ Lupi (solid blue line) compared to a synthetic spectra calculated with a mixture of 70 percent ^{196}Pt and 30 percent ^{198}Pt (dotted pink line) (modified after [526]).

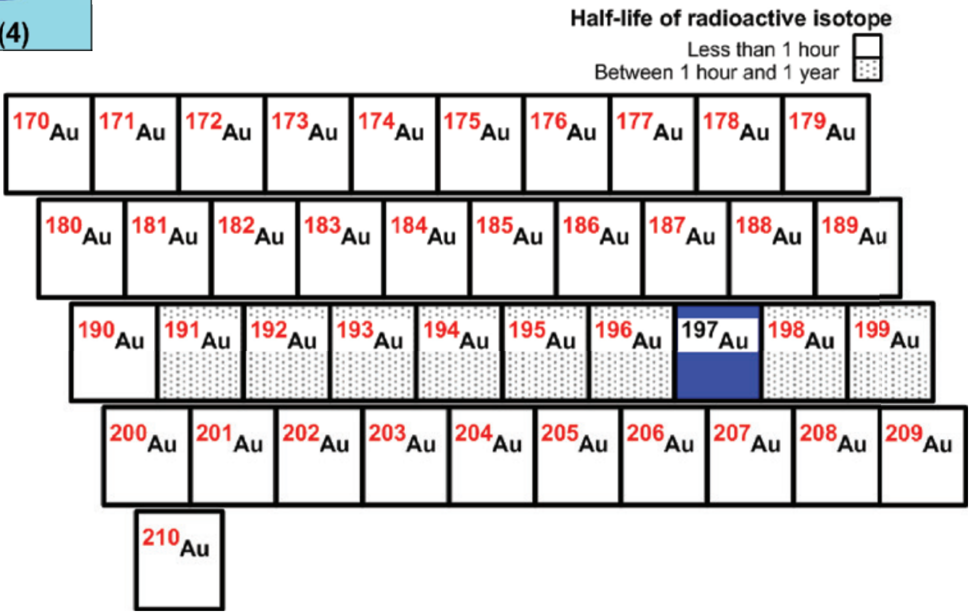
4.78.3 Platinum isotopes in medicine

$^{195\text{m}}$Pt (with a half-life of 4 days) is used for **pharmacokinetic** studies of platinum-based anti-tumor agents in cancer diagnosis and cancer therapy [188]. The m in the superscript of $^{195\text{m}}$Pt indicates a **metastable state** of the **isotope**. $^{195\text{m}}$Pt can be produced from the **stable isotopes** ^{192}Os or ^{195}Pt *via* the ^{192}Os (α, n) $^{195\text{m}}$Pt reaction and the ^{195}Pt (n, n′) $^{195\text{m}}$Pt reaction, respectively.

4.79 Gold



Stable isotope	Relative atomic mass	Mole fraction
^{197}Au	196.966 570	1



4.79.1 Gold isotopes in biology

^{195}Au (with a **half-life** of about 0.51 year) has been used to study particle movement within the lungs of rats [528]. ^{198}Au (with a half-life of 2.7 days) was used in a study to model gold cycling in plants. This study demonstrated that gold particles are retained by humates (organic constituents of soil), which contain fulvic acid, humic acid, ulmic acid, and lignin and would therefore be likely to accumulate in mull humus or forest litter [529].

4.79.2 Gold isotopes in medicine

^{198}Au has several medical uses. It has been used as both a diagnostic tool and a treatment option for cancer [530, 531].

- As a diagnostic tool, colloidal ^{198}Au is injected into the affected organ. Normal cells will take up the gold colloid, but tumor cells will not. Therefore, an abscess will show up as a "cold area" on a scan [531].
- As a treatment option, gold is intended to provide localized irradiation and can be implanted or injected into the affected area. When implanted, the gold "seed" offers an advantage over other materials in that it can be left in place due to its short half-life (2.7 days). As a colloidal injection, ^{198}Au has been found to produce improvement from a wide variety of cancers [530]. Figure 4.79.1a and 4.79.1b, respectively, show squamous cell carcinoma (cancer) on the lower left eyelid of a cat and the eyelid 6 weeks after implantation of ^{198}Au seeds [532].

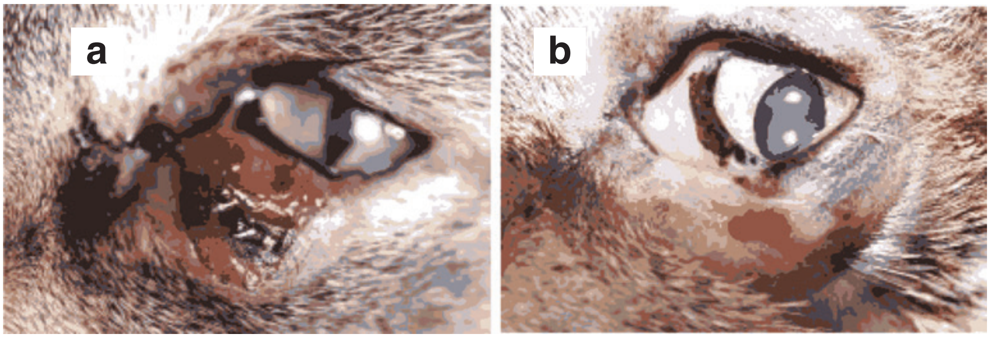
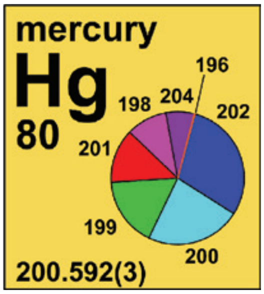


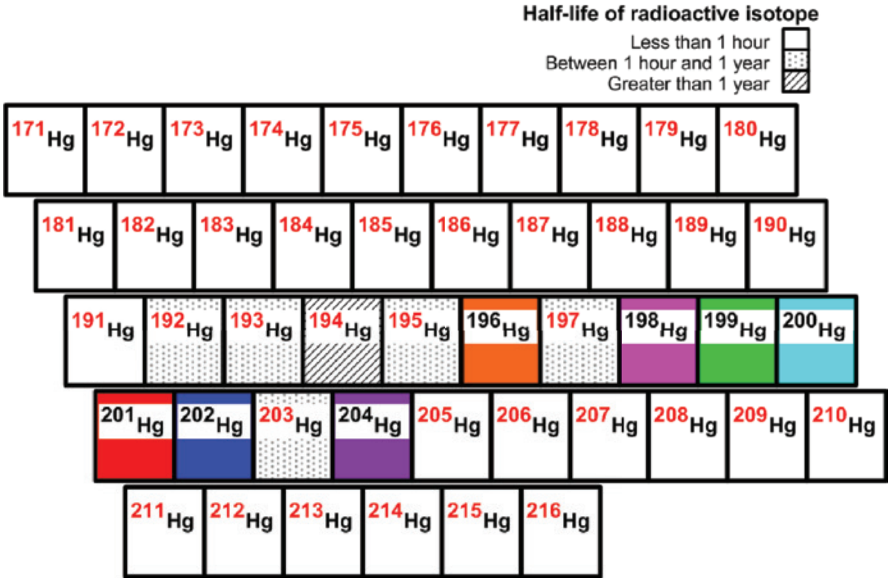
Fig. 4.79.1: (a) Squamous cell carcinoma on the lower left eyelid of a cat [532]; (b) the lower left eyelid 6 weeks after implantation of ^{198}Au seeds (Reprinted with permission. Copyright 2001 Hardman and Stanley, 2001, Australian Veterinary Journal, Wiley) [532].

Recent studies have shown the effectiveness of ^{198}Au nanoparticles and nanodevices in reducing tumor size in mice while minimizing radiation spread to other areas [530, 533, 534]. ^{198}Au has been studied and successfully used as an anti-inflammatory (a substance or treatment that reduces the body tissues response to harmful stimuli, such as swelling) for improving arthritic conditions [535, 536].

4.80 Mercury



Stable isotope	Relative atomic mass	Mole fraction
^{196}Hg	195.965 83	0.0015
^{198}Hg	197.966 769	0.1004
^{199}Hg	198.968 281	0.1694
^{200}Hg	199.968 327	0.2314
^{201}Hg	200.970 303	0.1317
^{202}Hg	201.970 644	0.2974
^{204}Hg	203.973 494	0.0682



4.80.1 Mercury isotopes in Earth/planetary science

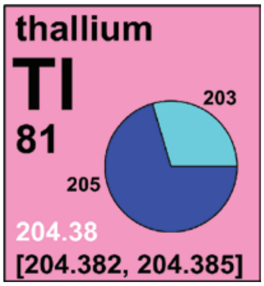
^{198}Hg, ^{200}Hg, and ^{202}Hg are **stable isotopes** of mercury that can be used to study environmental sources and environmental sinks of this **element** in aquatic and terrestrial ecosystems. For example, in an ecosystem, different stable isotopes of mercury can be added to an upland region for run-off evaluation, to a lake for direct deposition analysis, and to a wetland region for outflow contribution analysis (Fig. 4.80.1). As a result, it is possible to determine the entry points of mercury into an ecosystem and determine how the inputs of mercury affect the accumulation of this element in local fish populations. An international consortium of scientists is conducting an experiment called METAALICUS (Mercury Experiment To Assess Atmospheric Loading In Canada and the U.S.). This experiment includes determination of whether mercury contamination in fish is old or new mercury. **Tracer** studies were performed in northwestern Ontario at the Experimental Lakes Area of the Department of Fisheries and Oceans Canada [537].

Fig. 4.80.1: ^{202}Hg was added to small watersheds to study the fate of mercury from atmospheric deposition in pristine (in its original condition) lakes as part of the METAALICUS study. (Photo Source: Toxic Substances Hydrology Program, U.S. Geological Survey) [537].

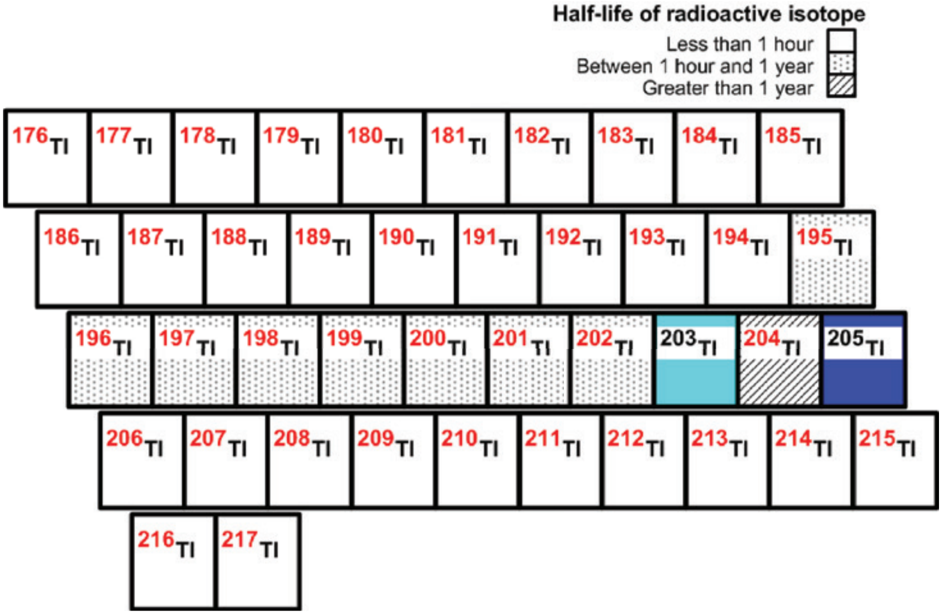
4.80.2 Mercury isotopes used as a source of radioactive isotope(s)

^{202}Hg is used to produce radioactive ^{203}Hg (with a **half-life** of 46.6 days) *via* the ^{202}Hg (n, γ) ^{203}Hg reaction, which is used in **gamma radiation** calibration and medical tests.

4.81 Thallium



Stable isotope	Relative atomic mass	Mole fraction
^{203}Tl	202.972 344	[0.2944, 0.2959]
^{205}Tl	204.974 427	[0.7041, 0.7056]



4.81.1 Thallium isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of thallium possess slightly different physical and chemical properties, they commonly will be fractionated during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are substantial variations in the isotopic abundances of thallium in natural terrestrial materials (Fig. 4.81.1). These variations are useful in investigating the origin of substances and studying environmental, hydrological, and geological processes [538]. The **isotope-amount ratio** $n(^{205}\mathrm{Tl})/n(^{203}\mathrm{Tl})$ has been used to study how trace metals are transported and distributed in hydrothermal fluids [538]. The $n(^{205}\mathrm{Tl})/n(^{203}\mathrm{Tl})$ ratio has also been used to study the cycling, distribution, and behavior of thallium in the marine environment [538].

4.81.2 Thallium isotopes in medicine

^{201}Tl **scintigraphy** is used to detect coronary artery disease [539]. Imaging of ^{201}Tl (with a **half-life** of 3 days), can be used for exercise **perfusion tests** of the myocardium (muscular tissue of the heart), which determine damage to the heart caused by a heart attack or by heart disease (Fig. 4.81.2) [539].

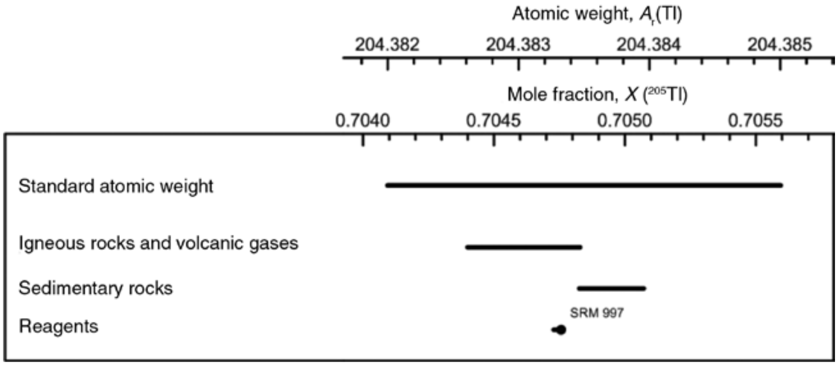


Fig. 4.81.1: Variation in **atomic weight** with **isotopic composition** of selected thallium-bearing materials (modified from [13, 17]).

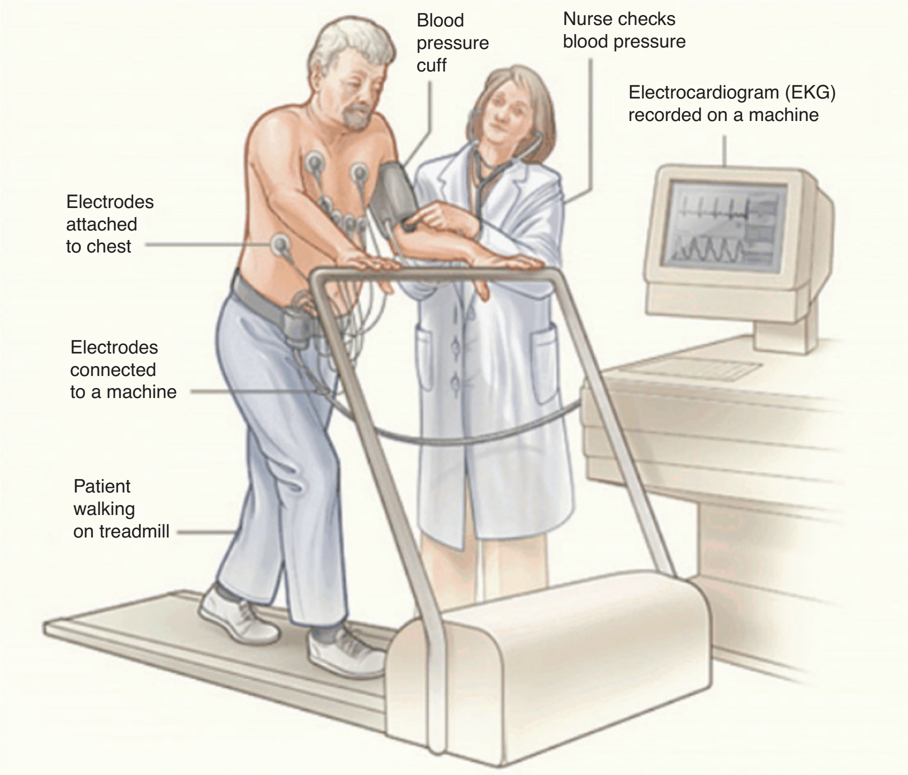
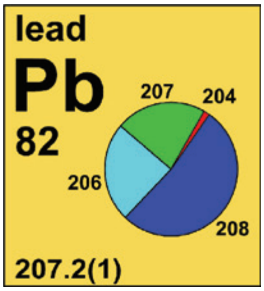


Fig. 4.81.2: During exercise myocardium **perfusion tests**, a patient will exercise on a treadmill until they have reached their maximal exercise point (determined by heart rate and age). Once they reach their maximal exercise point, a **radionuclide** (usually of thallium or technetium) is injected into the **intravenous** line in their arm, and the patient continues to exercise for a few more minutes. Once the radionuclide reaches the heart, the patient lies flat on a table and a **gamma camera** takes pictures of the heart for about 30 min. The areas of decreased blood flow or damaged tissue will be illuminated by the radionuclide. (Image source: National Heart Lung and Blood Institute, Diseases and Conditions Index, National Institutes of Health) [540].

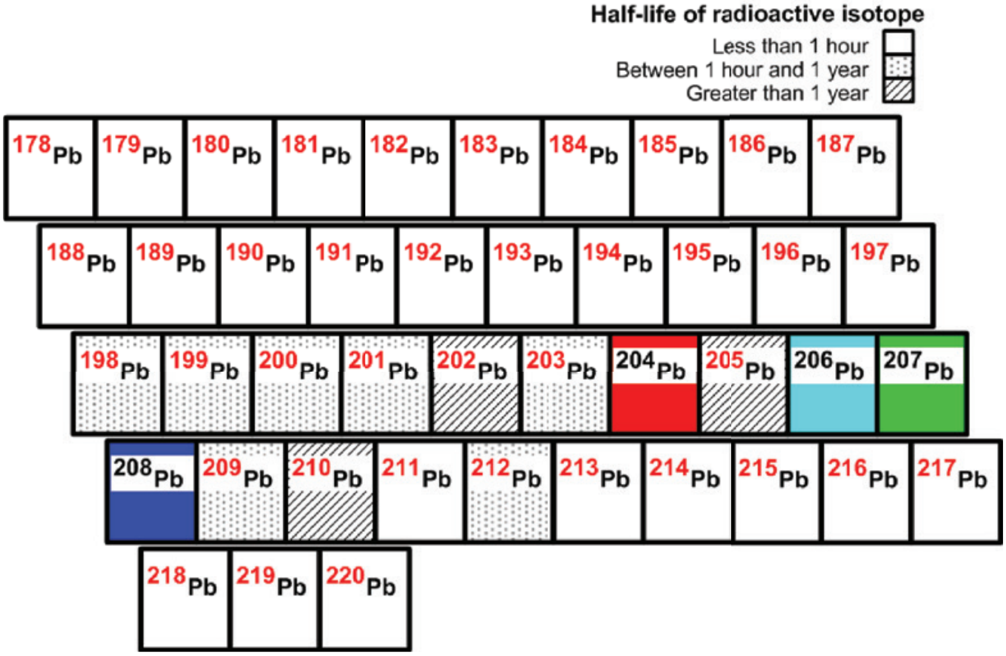
4.81.3 Thallium isotopes used as a source of radioactive isotope(s)

^{203}Tl is used in the production of ^{201}Tl *via* the ^{203}Tl (p, 3 n) ^{201}Pb reaction, which is followed by a subsequent **electron** capture decay reaction of ^{201}Pb to finally yield ^{201}Tl. ^{205}Tl is used as an alternative target in the production of ^{201}Tl.

4.82 Lead



Stable isotope	Relative atomic mass	Mole fraction
^{204}Pb	203.973 043	0.014
^{206}Pb	205.974 465	0.241
^{207}Pb	206.975 897	0.221
^{208}Pb	207.976 652	0.524



4.82.1 Lead isotopes in Earth/planetary science

The study of lead **isotopic compositions** is used to model the distribution of pollution in water and on land (Fig. 4.82.1). For example, in one study of Lake Härsvatten in Sweden, the **isotope-amount ratio** $n(^{206}\text{Pb})/n(^{207}\text{Pb})$ measured at different sediment depths in different areas throughout the lake showed patterns of accumulation of lead pollution. In some cases, these patterns could be related to sediment distribution patterns. Another study used ^{210}Pb (with a **half-life** of 22.6 years) dating methods to study the vertical accretion of sediments in canals and wetland areas in Louisiana over the last 80 to 100 years [541, 542].

Three of the **stable isotopes** of lead (^{206}Pb, ^{207}Pb, and ^{208}Pb) are produced by the **radioactive decay** of **isotopes** of uranium and thorium (^{238}U, ^{235}U, and ^{232}Th, respectively) and are largely unaffected by environmental and metallurgical processes. Therefore, by examining various isotope-amount ratios of lead isotopes, it is possible to approximate the age of a material. It is also possible to use this information to trace the origins of an object or material [543–546].

4.82.2 Lead isotopes in forensic science and anthropology

Different geographic regions may have characteristic terrestrial lead isotopic compositions because of variations in the ages and chemical composition of the rocks and minerals in the local environment. There-

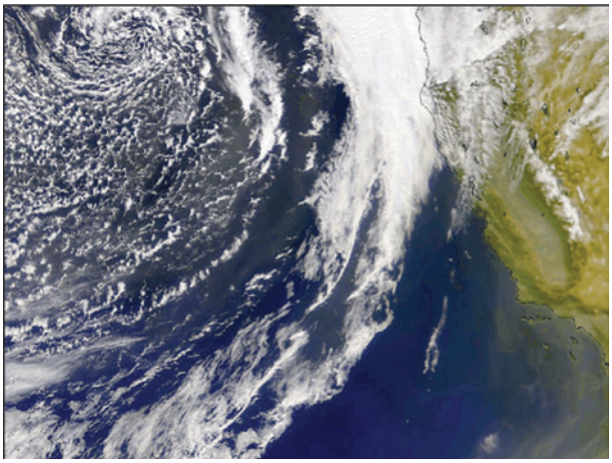


Fig. 4.82.1: Suspended atmospheric dust over California; it is likely that this dust originated in Asia based on lead-isotope studies. (Photo Source: SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE, NASA Earth Observatory, 2001) [551, 558].

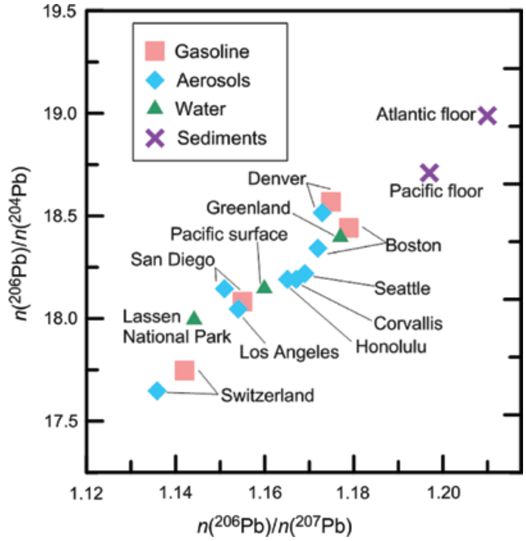


Fig. 4.82.2: Cross plot of $n(^{206}\text{Pb})/n(^{204}\text{Pb})$ and $n(^{206}\text{Pb})/n(^{207}\text{Pb})$ **isotope-amount ratios** of lead in selected materials (modified from [548]).

fore, lead produced at a particular location can have a unique lead isotopic composition and it is possible to trace the history and origins of pollutants by measuring the relative amounts of the four stable isotopes of lead (^{208}Pb, ^{207}Pb, ^{206}Pb, and ^{204}Pb) (Fig. 4.82.2) [547, 548]. Using **isotopic abundance** data, the source of this toxic metal can be identified as it moves through air and water and eventually to living systems [547, 549]. Scientists have analyzed lead in air pollution in California and found that it originated from Asia. Airborne particles from China have relatively higher amounts of ^{208}Pb, which distinguishes the lead isotopic signature between airborne particles from Asia and North America. This knowledge could have implications in understanding the mixing of particles in the atmosphere and how pollutants are transported over vast distances [547, 549–551]. Mapping the distribution of lead pollution by studying ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb also allows the identification of those human activities that contribute the highest amounts of lead to the environment [547, 549, 552].

The measurement of the isotopic composition of lead in blood can help to determine the source of this toxic **element** in the body [553]. Lead is stored in bones and teeth. If a person moves to a different geographical region, the isotopic composition of the lead in the teeth is maintained, recording their place of origin. Bone can store lead for long periods of time (about 20 years), and some skeletal lead may be older and have a different isotopic composition than other skeletal lead. These differences reflect exposure to lead of different origins. By studying the isotope-amount ratio $n(^{206}\text{Pb})/n(^{204}\text{Pb})$ and $n(^{207}\text{Pb})/n(^{206}\text{Pb})$ in bone and teeth, it is possible to determine someone's place of origin. For example, isotopes of lead were analyzed in the teeth and bones of a human mummy, known as the "Iceman", to help determine his place of origin [554, 555].

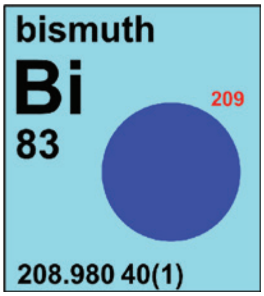
^{210}Pb is a relatively short-lived **radioactive isotope** of lead that is constantly produced by the decay of ^{222}Rn in the atmosphere. While living, humans naturally incorporate ^{210}Pb from the environment into bones and tissues. The amount of ^{210}Pb in the body reaches equilibrium such that the ^{210}Pb ingested is in equilibrium with the ^{210}Pb that decays. When a person dies, this incorporation of ^{210}Pb ceases and the relative amount of this isotope in the body decreases. Therefore, measurement of the ^{210}Pb **activity** in a corpse can help determine time of death [556, 557].

Lead isotope-amount ratios $n(^{206}\text{Pb})/n(^{204}\text{Pb})$, $n(^{207}\text{Pb})/n(^{204}\text{Pb})$, and $n(^{208}\text{Pb})/n(^{204}\text{Pb}))$ along with isotope-amount ratio of silver, $n(^{107}\text{Ag})/n(^{109}\text{Ag})$, and isotope-amount ratio of copper $n(^{65}\text{Cu})/n(^{63}\text{Cu})$ have been used to determine the origin of European coins (see Section 4.29 on copper) and to investigate the flow of goods in the world market over time [237]. Metals from Peru and Mexico and those from European mining have distinct isotopic signatures that enable the origin of the metal to be determined by examining the isotopic compositions of silver, copper, and lead in the coins. Abundant silver sources mined in Mexico and Peru in the 16th century were used to mint coins, but were not a major influence in the European coin market until the 18th century [237].

4.82.3 Lead isotopes in geochronology

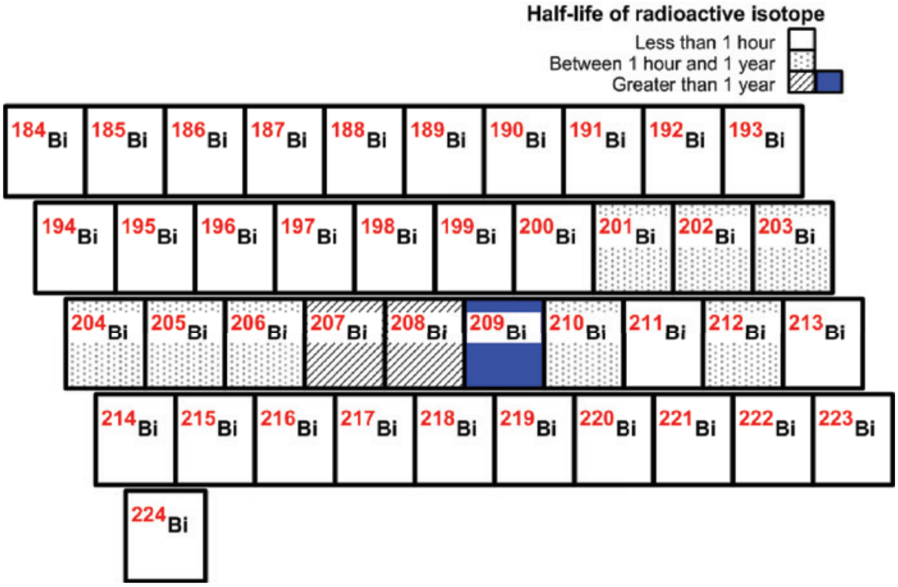
The three natural radioactive-decay chains beginning with ^{238}U, ^{235}U, and ^{232}Th each have comparable half-lives that are much longer than the radioactive isotopes that follow until the production of stable isotopes of ^{206}Pb, ^{207}Pb, and ^{208}Pb, respectively. Therefore, one can measure the relative amounts of the **radiogenic** isotopes of lead to determine the length of time that has elapsed since uranium and thorium atoms were incorporated into rocks and minerals. Typically, this method is used to date minerals that are tens of millions to billions of years old. The uranium-lead dating method was used to determine some of the first accurate ages of the Earth (about 4.55×10^9 years) [554–556].

4.83 Bismuth



Stable isotope	Relative atomic mass	Mole fraction
^{209}Bi†	208.980 40	1

† **Radioactive isotope** having a relatively long **half-life** (2.0 × 10^{19} years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.83.1 Bismuth isotopes in medicine

^{212}Bi and ^{213}Bi (with **half-lives** of 1 h and 0.76 h, respectively) are both used in medicine for **radioimmunotherapy** as bismuth-labeled **monoclonal antibodies** to treat cancer cells from melanoma (skin cancer) (Fig. 4.83.1) and ovarian cancer [559]. Figure 4.83.2 compares the biologic effect of ^{131}I and ^{213}Bi using a specific monoclonal antibody, B-B4, coupled to ^{213}Bi by a chelating agent (a substance that can form multiple bonds to a single metal ion). ^{213}Bi is a mixed alpha and beta emitter with a half-life of 0.76 h. The primary mode of decay is by beta emission to the very short-lived alpha emitter ^{213}Po. The 8.4 MeV **alpha particle** emitted by ^{213}Po has a path length of 76 μm in human tissue and is responsible for its cytotoxic effects (toxic to living cells). ^{213}Bi is produced from a series of alpha particle decays beginning with ^{225}Ac, which is a pure alpha emitter with a half-life of 10 days. A schematic of the Institute for Transuranium Elements (ITU) Standard ^{225}Ac/^{213}Bi Radionuclide Generator is shown in Fig. 4.83.3.

^{212}Bi has been used for radioimmunotherapy of leukemia and for targeting the vascular endothelial cells (thin layer of simple squamous cells that forms the interface between circulating blood or lymph and the remainder of the vessel wall) of tumors [560].

4.83.2 Bismuth isotopes used as a source of radioactive isotope(s)

^{209}Bi is bombarded with **neutrons** in a nuclear reactor to form radioactive ^{210}Bi. The ^{210}Bi (with a half-life of 5 days) decays via the reaction $^{210}\text{Bi} \rightarrow {}^{210}\text{Po} + \beta^-$. The half-life of ^{210}Po is 138 days and it is used in static eliminators in machinery [75].

Fig. 4.83.1: Melanoma (skin cancer) on a patient's foot. ^{212}Bi and ^{213}Bi are both used as bismuth-labeled **monoclonal antibodies** to treat cancer cells from melanoma. (Photo Source: Kelly Nelson, National Cancer Institute) [561].

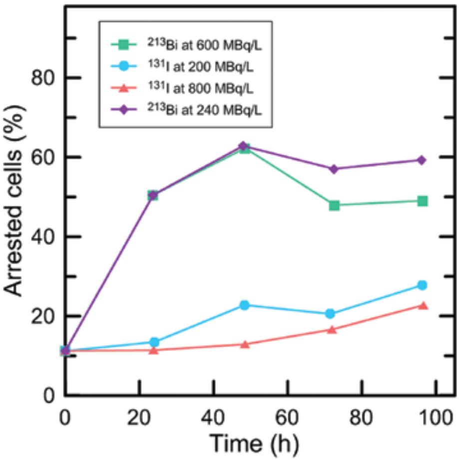


Fig. 4.83.2: Comparison of biological effectiveness of ^{213}Bi and ^{131}I when coupled to the specific **monoclonal antibody** B-B4 (modified after [562]); MBq/L, million becquerel per litre.

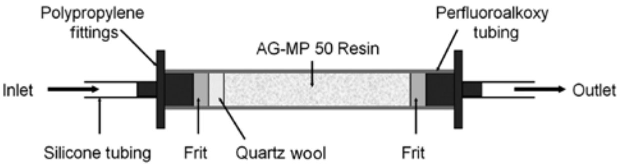
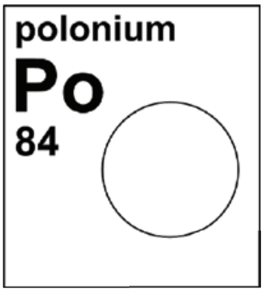
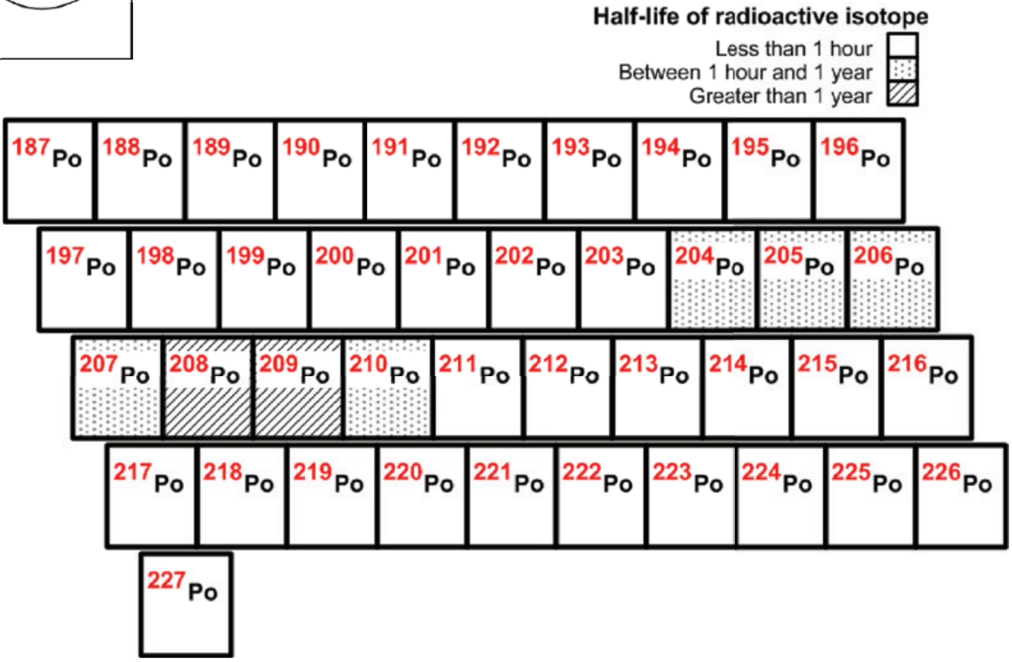


Fig. 4.83.3: Schematic of the Institute for Transuranium Elements (ITU) Standard ^{225}Ac/^{213}Bi Radionuclide Generator. Image kindly provided by Dr. Alfred Morgenstern, European Commission, Joint Research Centre – Institute for Transuranium Elements, Karlsruhe, Germany.

4.84 Polonium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



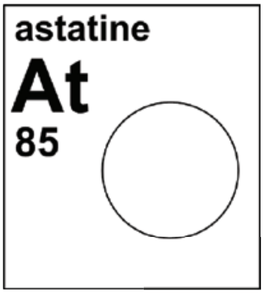
4.84.1 Polonium isotopes in industry

^{210}Po (with a **half-life** of 138 days) is used as static eliminator to remove static electricity in machinery. This is useful in machinery that produces electricity easily, for example, *via* rolling paper, manufacturing sheet

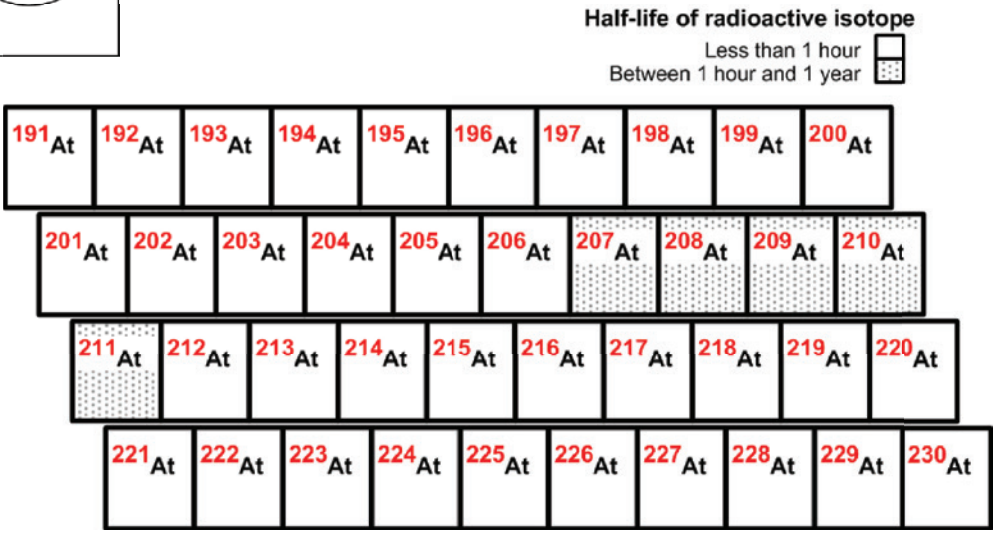
Fig. 4.84.1: Staticmaster™ Alpha **Ionizing** Brushes for cleaning optical surfaces and photographic films have a soft, non-abrasive brush and a ^{210}Po cartridge. (Photo Source: Reston Stable Isotope Laboratory of the U.S. Geological Survey) [564].

plastics, and spinning synthetic fibers, which all readily produce static [75, 563]. ^{210}Po can also make use of its static eliminating properties when used in brushes that function to clean camera lenses and photographic films (Fig. 4.84.1) [75]. ^{210}Po has been used to manufacture atomic weapons. When combined with beryllium, polonium can act as a **neutron**-producing initiator. However, because of its short half-life, ^{210}Po is no longer used in this manner [75].

4.85 Astatine



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.85.1 Astatine isotopes in medicine

^{211}At (with a **half-life** of 7.2 h) is known to accumulate in the thyroid and occasionally is the preferred treatment for **hyperthyroidism** and thyroid cancer because the particles emitted from ^{211}At provide more energy than **radiolabeled** iodine, the other treatment method (Fig. 4.85.1). However, astatine has shown a tendency to induce tumors, so its use is limited [565]. The ^{211}At-labeled di-carborane (cluster of boron, carbon, and hydrogen atoms) **ligand** known as the Venus Flytrap Cluster (VFC) has been used as a robust pharmaceutical in **radiotherapy** treatment [566].

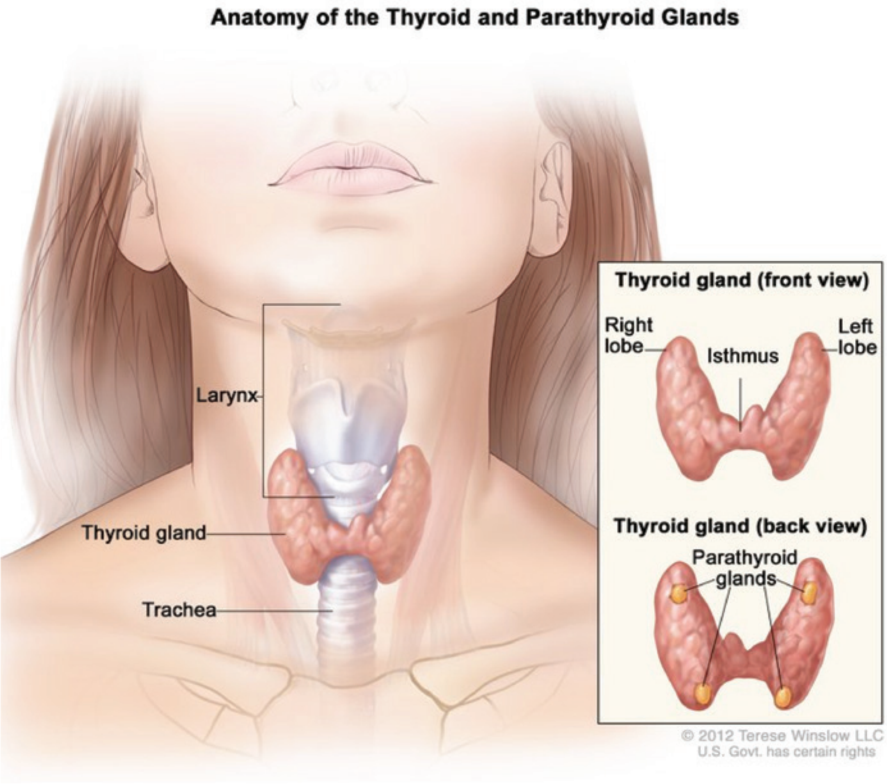
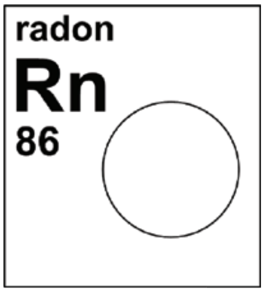
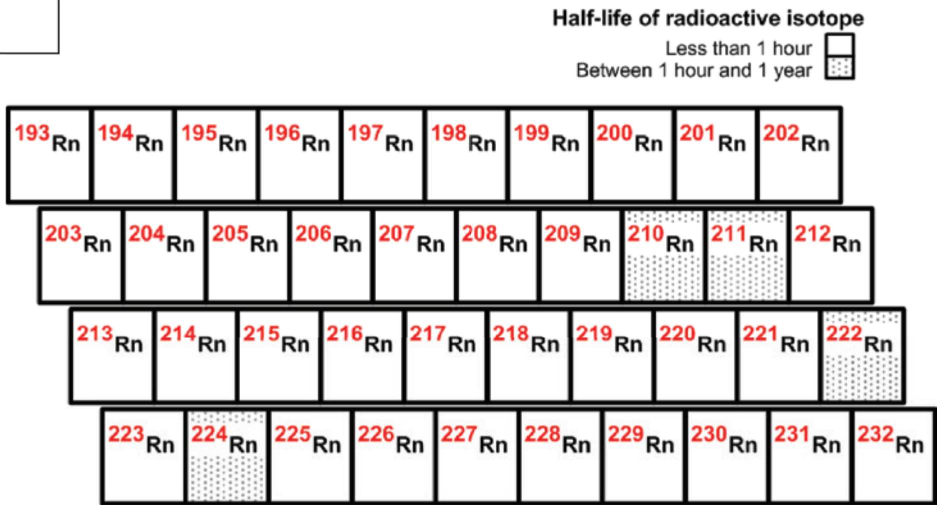


Fig. 4.85.1: ^{211}At treats **hyperthyroidism** and thyroid cancer. (Image Source: © 2012 Terese Winslow LLC, U.S. Govt. has specified rights) [567].

4.86 Radon



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.86.1 Radon isotopes in Earth/planetary science

Both ^{220}Rn and ^{222}Rn (with **half-lives** of 56 s and 3.8 days, respectively) are used to study underground environmental and atmospheric gaseous-transport processes [568–570]. The interaction of radon with streams and rivers enables it to be used as a **tracer** in groundwater studies (Fig. 4.86.1). ^{222}Rn has a short **residence time** in streams and river channels, which leads to radon loss. As a result, if an area of a stream or river has a

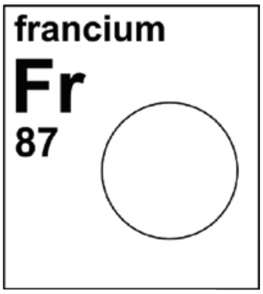
Fig. 4.86.1: Air-water equilibrator, which strips radon out of water and into the gas phase so it can be used as a groundwater **tracer**. (Photo Source: John Crusius, U.S. Geological Survey) [573].

high concentration of radon, it suggests that there are local groundwater inputs [568–570]. In a deep (100 m) contaminated aquifer at a refinery site in Mexico, where the contaminated source was too deep to be directly accessible for sampling, Schubert *et al.* [571] collected groundwater samples from a few wells available at the site. They used the partitioning of the natural tracer ^{222}Rn between uncontaminated groundwater and the NAPL (non-aqueous phase-liquid, such as oil, gasoline, and petroleum) source zone, and they were able to approximately identify the location of the NAPL source zone. As noted in Section 4.88.1, ^{222}Rn has been used to quantify submarine groundwater discharge [572].

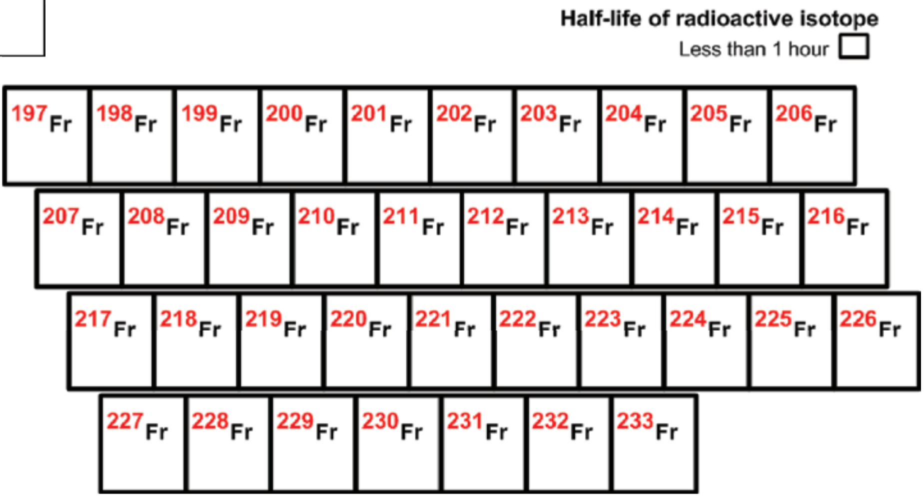
4.86.2 Radon isotopes in geochronology

^{222}Rn has been used as a tool to date groundwater in combination with other **isotopes** or elemental ratios (*i.e.* helium/radon and xenon/radon **amount ratios**) [568, 574].

4.87 Francium



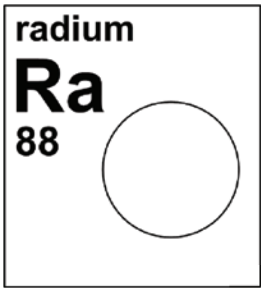
Stable isotope	Relative atomic mass	Mole fraction
(none)		



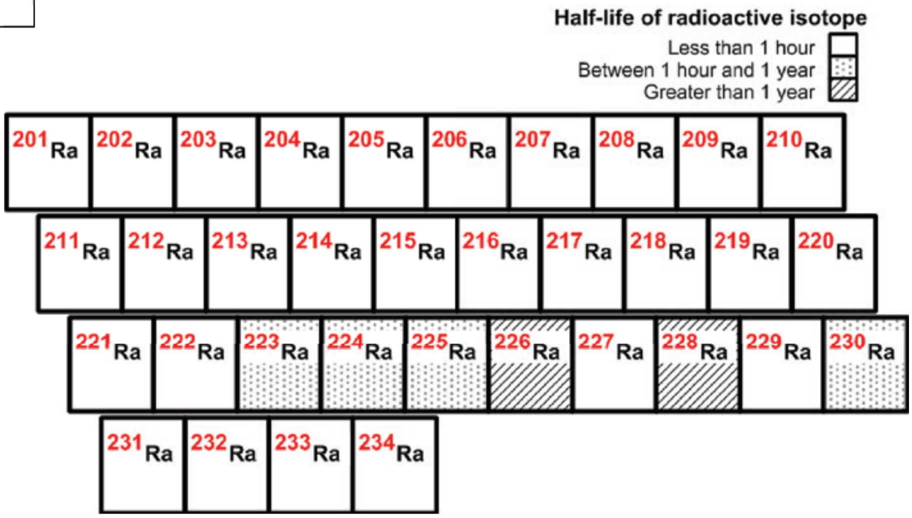
Francium was discovered in 1939 by Marguerite Perey, a physicist at the Curie Institute in Paris, France (Fig. 4.87.1). ^{223}Fr (with a **half-life** of 22 min) occurs naturally in uranium minerals as a result of actinium decay. However, it is estimated that no more than approximately 30 g of francium is present in the Earth's crust at any time. Francium can be produced artificially for research by bombarding thorium with **protons**. Francium was named in honor of Perey's home country, France [575–577]. Francium has no known isotopic applications outside of scientific research.

Fig. 4.87.1: Francium was discovered in 1939 by Marguerite Perey, a physicist at the Radium Institute in Paris, France. Photo kindly provided by Musée Curie (Coll. ACJC), Institut Curie, Centre National de la Recherche Scientifique, Paris, France.

4.88 Radium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.88.1 Radium isotopes in Earth/planetary science

The **radioactive isotopes** ^{223}Ra (with a **half-life** of 275 h), ^{224}Ra (with a half-life of 88 h), ^{226}Ra (with a half-life of 1600 years), and ^{228}Ra (with a half-life of 5.75 years) are used as **tracers** to determine water flow rates. They are ideal environmental tracers because they behave conservatively once released into a water mass (meaning only mixing and decay processes affect their distribution) [578]. The **activity** ratios $A(^{224}\text{Ra})/A(^{223}\text{Ra})$, $A(^{223}\text{Ra})/A(^{226}\text{Ra})$, $A(^{224}\text{Ra})/A(^{228}\text{Ra})$, and $A(^{228}\text{Ra})/A(^{226}\text{Ra})$ have been used in lake studies to monitor and detect water inflow and mixing, to determine sources of inflowing water, and to monitor introduced water masses as they move within a body of water (*i.e.* a lake) [578, 579]. For example, submarine groundwater discharge is an important pathway that transports dissolved substances from aquifers below a seabed to the coastal ocean. Submarine groundwater discharge can be difficult to quantify because it is both spatially and temporally variable. As a result, its relative importance in coastal ocean chemical budgets is commonly poorly known. Peterson *et al.* [572] used an hourly time series of measurements of multiple radium **isotopes** ^{223}Ra, ^{224}Ra, and ^{226}Ra to quantify submarine groundwater discharge. They also used ^{222}Rn (with a half-life of 3.8 days) measurements to independently quantify submarine groundwater discharge.

4.88.2 Radium isotopes in geochronology

^{226}Ra and ^{228}Ra can be used for dating materials up to a few thousand years in age because the half-lives of ^{226}Ra and ^{228}Ra are 1600 years and 5.75 years, respectively, even though the long-lived ^{226}Ra is found in nature as a result of its continuous production by the decay of ^{238}U. For example, long-lived ^{226}Ra has been used to date a limestone cave in central Switzerland, corals in the Indian Ocean, and Pleistocene gravel terraces [580].

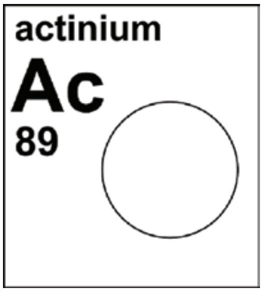
Fig. 4.88.1: **Brachytherapy** seeds shown with a penny (19-mm diameter) for scale (modified from [582]).

The activity ratio $A(^{224}\mathrm{Ra})/A(^{223}\mathrm{Ra})$ is a potential age calculator for old lake water because the low ^{223}Ra and ^{224}Ra activities in old lake water are relatively unaffected by mixing [579].

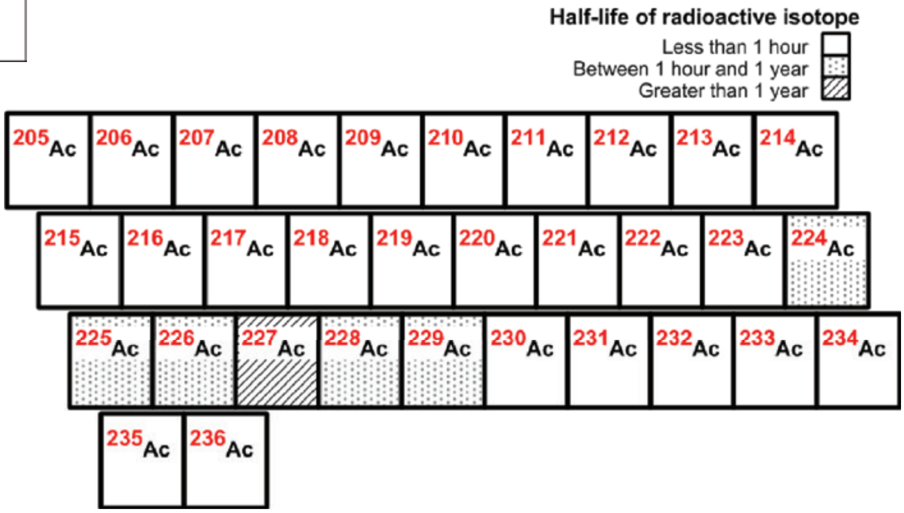
4.88.3 Radium isotopes in medicine

^{226}Ra is used in **brachytherapy** (Fig. 4.88.1), which is a method of localized treatment of various types of cancer. A sealed implant (such as a rod, seed, or needle) containing the radioactive isotope ^{226}Ra is inserted into or near a patient's tumor to apply a high dose of radiation to the tumor. The sealed implant is inserted by a physician or by an automated device (called a remote afterloader), and it is removed from the patient once the tumor is destroyed [75, 581].

4.89 Actinium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.89.1 Actinium isotopes in Earth/planetary science

^{227}Ac (with a **half-life** of 21.77 years) has been used as a **tracer** of deep-sea mixing in the oceans. By determining concentrations of ^{227}Ac in a water column, scientists can study the rates and patterns of mixing and other vertical exchange processes [583]. As a product of the ^{235}U decay chain, ^{227}Ac and other **radioisotopes** have been used to determine information about the movement of fluids in mid-oceanic ridges and basaltic melts [584, 585].

4.89.2 Actinium isotopes in medicine

^{225}Ac (with a half-life of 10 days) can be used in cancer treatments (Fig. 4.89.1). The **isotope** is attached to a chelating agent (a substance that can form multiple bonds to a single metal ion) and delivered to the problem site. The emissions of **alpha particles** from actinium and its **daughter products** cause tumor death [586]. ^{225}Ac in a series of alpha decays produces ^{213}Bi (with a half-life of 0.76 h), which is also used for **radioimmunotherapy** [587].

Fig. 4.89.1: The Medical Actinium for Therapeutic Treatment (MATT) is a separations process that recovers ^{225}Ac from unused nuclear fuel so the **isotope** can be used in cancer treatment and research. (Image Source: Idaho National Laboratory) [588].

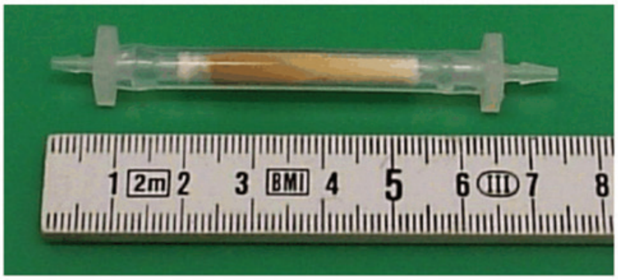
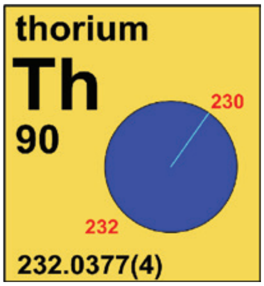


Fig. 4.89.2: Institute for Transuranium Elements (ITU) Standard ^{225}Ac/^{213}Bi Radionuclide Generator. Image kindly provided by Dr. Alfred Morgenstern, European Commission, Joint Research Centre – Institute for Transuranium Elements, Karlsruhe, Germany.

4.89.3 Actinium isotopes used as a source of radioactive isotope(s)

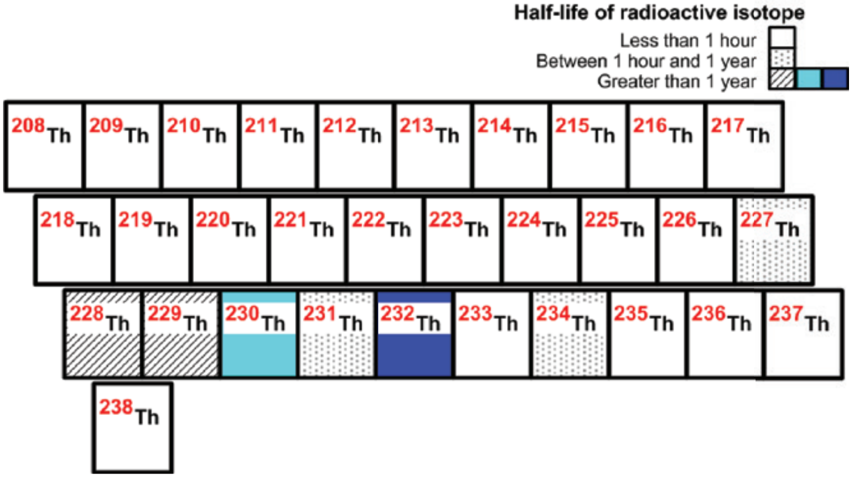
^{225}Ac, which is a pure alpha emitter, is used to produce ^{213}Bi with an ^{225}Ac/^{213}Bi radionuclide generator (Fig. 4.89.2). ^{213}Bi is a mixed alpha and beta emitter. The primary mode of decay is by beta emission to the very short-lived, alpha emitter ^{213}Po. The 8.4 MeV alpha particle emitted by ^{213}Po has a path length of 76 µm in human tissue and is responsible for its cytotoxic effects.

4.90 Thorium



Stable isotope	Relative atomic mass	Mole fraction
$^{230}Th^{\dagger}$	230.033 132	0.0002
$^{232}Th^{\dagger}$	232.038 05	0.9998

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. Half-lives of ^{230}Th and ^{232}Th are 7.56×10^4 years and 1.40×10^{10} years, respectively.



4.90.1 Thorium isotopes in Earth/planetary science

^{234}Th (with a **half-life** of 24 days) has been used as a **tracer** for estimating the flux of organic carbon in the ocean (Fig. 4.90.1) [589, 590]. ^{234}Th has been used for estimating the **residence time** of suspended particulate matter (SPM) in water columns [589].

4.90.2 Thorium isotopes in geochronology

The decay of ^{232}Th (with a half-life of 1.40×10^{10} years) to ^{208}Pb is used to date rocks based on the accumulation of the stable **daughter product** ^{208}Pb. The half-lives of the **isotopes** between the **parent radionuclide** ^{232}Th and stable endpoint ^{208}Pb all have much shorter half-lives than thorium. Therefore, the amount of ^{208}Pb that accumulates in a sample is determined primarily by the amount of ^{232}Th parent radionuclide present when the mineral was formed and the time that has elapsed since the mineral solidified [591].

Another dating method, the ^{230}Th/^{234}U method, is based on the hypothesis that the sample contains uranium, but no ^{230}Th at the time of its formation. Then, the age of the specimen is determined mainly by the amount of ^{230}Th in the specimen. Reliable ages with this method range from several thousand to approximately 350 thousand years [292].

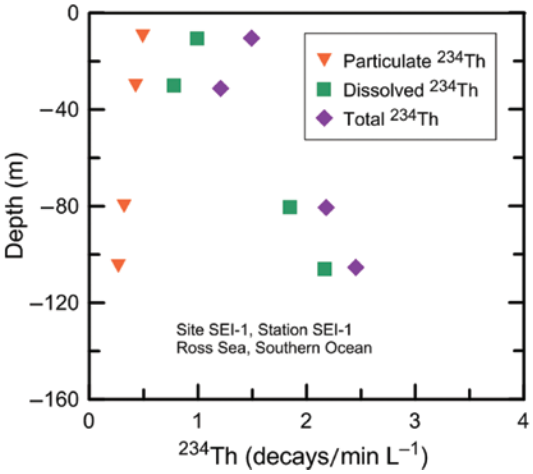
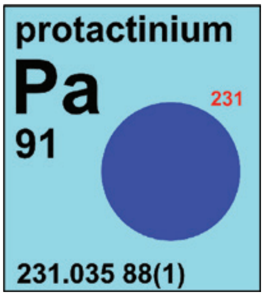


Fig. 4.90.1: Particulate, dissolved and total ^{234}Th in water column profiles in the Ross Sea, Southern Ocean (modified from [590]).

4.90.3 Thorium isotopes in industry

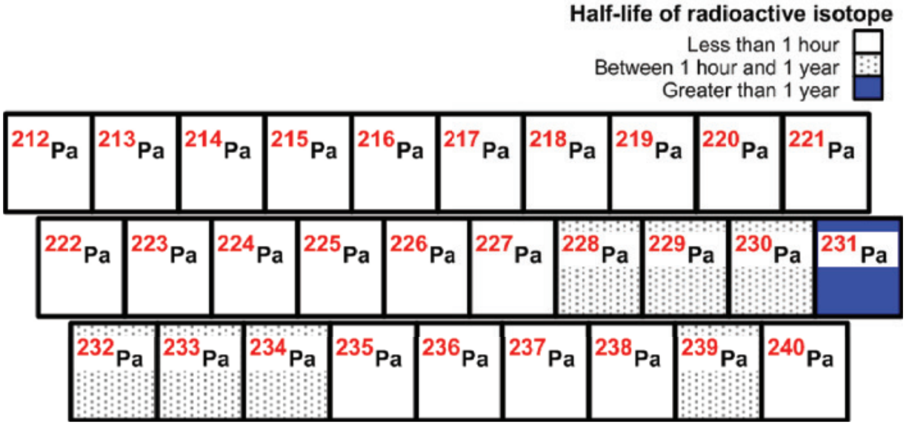
The most precise time and frequency measurements are performed with optical atomic clocks that use as a frequency standard the optical frequency generated as **electrons** change energy levels. It has been proposed that a nuclear clock, using a nuclear transition could outperform an electron transition. ^{229m}Th, with a half-life of 13.9 h, has been confirmed as a possible candidate for a nuclear clock [592]. The m in ^{229m}Th indicates a **metastable state** of the isotope. The further development of a nuclear frequency standard will require more precise determinations of the energy and half-life of the **isomer**.

4.91 Protactinium



Stable isotope	Relative atomic mass	Mole fraction
^{231}Pa†	231.035 88	1

† **Radioactive isotope** having a relatively long **half-life** (3.25 × 10^4 years) and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**.



4.91.1 Protactinium isotopes in Earth/planetary science

^{231}Pa (with a **half-life** of 3.25×10^4 years) and ^{230}Th (with a half-life of 7.56×10^4 years) are produced in seawater by **radioactive decay** of ^{235}U and ^{234}U. The **amount ratio** of radioactive production of ^{231}Pa and ^{230}Th, $n(^{231}\text{Pa})/n(^{230}\text{Th})$, is 0.093. ^{230}Th is removed from seawater in settling particulates more efficiently than ^{231}Pa, while ^{231}Pa tends to be transported farther in ocean currents. Therefore, the amount ratio $n(^{231}\text{Pa})/n(^{230}\text{Th})$ in settling particulates tends to be less than the production ratio of 0.093 unless the water mass is stationary and allows both products to settle out. Thus, sedimentary records of excess $n(^{231}\text{Pa})/n(^{230}\text{Th})$ amount ratios can provide information for changes in the relative magnitude of major ocean circulation (Fig. 4.91.1) [593, 594].

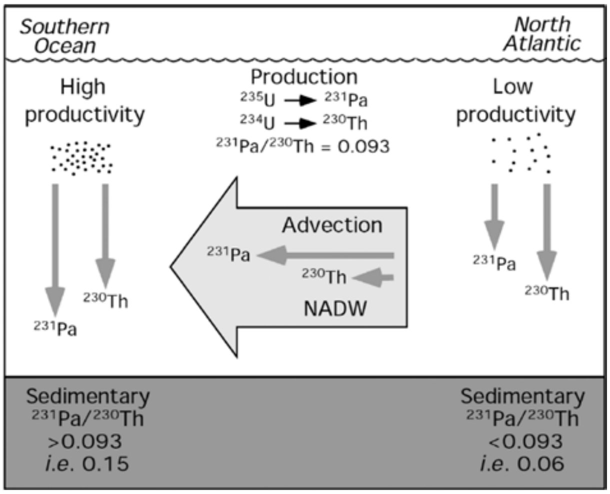
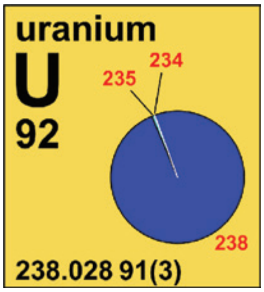


Fig. 4.91.1: Diagram of ^{231}Pa-^{230}Th fractionation (preferential separation) in the oceans. NADW is North Atlantic Deep Water. (Diagram Source: Henderson and Anderson, 2003) [595].

4.91.2 Protactinium isotopes in geochronology

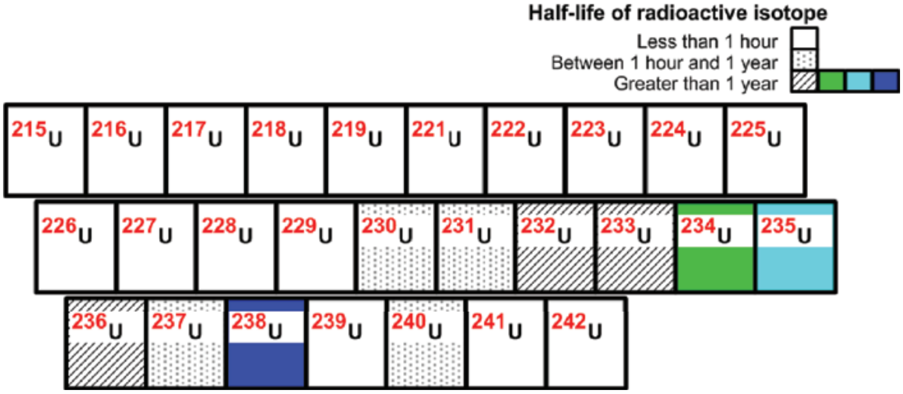
^{231}Pa is a natural **radiogenic isotope** produced by **alpha decay** of ^{235}U to ^{231}Th, followed by beta emission to form ^{231}Pa. Although its behavior in the environment as a transient member of the U-series decay chain may be complex, measurements and modeling of ^{231}Pa in relation to the **isotopes** of uranium and thorium have been used in a variety of geochronologic applications on time scales of 10^3 to 10^5 years [596, 597]. Studies include movement of water masses and particles in the oceans, rates of magma melting and movement beneath volcanoes, and ages of carbonate mineral deposits, including corals, in relation to climate change.

4.92 Uranium



Stable isotope	Relative atomic mass	Mole fraction
$^{234}\text{U}^{\dagger}$	234.040 95	0.000 054
$^{235}\text{U}^{\dagger}$	235.043 928	0.007 204
$^{238}\text{U}^{\dagger}$	238.050 79	0.992 742

† **Radioactive isotope** having a relatively long **half-life** and a characteristic terrestrial **isotopic composition** that contributes significantly and reproducibly to the determination of the **standard atomic weight** of the **element** in **normal materials**. The half-lives of ^{234}U, ^{235}U, and ^{238}U are 2.453 × 10^5 years, 7.03 × 10^8 years, and 4.47 × 10^9 years, respectively.



4.92.1 Uranium isotopes in Earth/planetary science

^{234}U (with a **half-life** of 2.432×10^5 years) is a **daughter product** of ^{238}U (with a half-life of 4.47×10^{10} years) and makes up only 0.0054 percent of the total uranium today. During the decay of the **parent radionuclide** ^{238}U nucleus (first to ^{234}Th (with a half-life of 24 days) by **alpha decay**, then to ^{234}Pa (with a half-life of 6.7 h) by beta-minus, and finally to ^{234}U by beta-minus), the energy released will damage the chemical and physical bonds holding the ^{234}U product nuclei in a mineral. As a result, ^{234}U may be leached more easily from water or rock samples than ^{238}U and the **isotope-amount ratio** $n(^{234}\text{U})/n(^{238}\text{U})$ will vary depending on the extent of water-rock interaction [598].

4.92.2 Uranium isotopes in geochronology

The three natural **radioactive decay** chains beginning with ^{238}U, ^{235}U, and ^{232}Th each have comparable half-lives that are much longer than the **radioactive isotopes** that follow until the production of **stable isotopes** of ^{206}Pb, ^{207}Pb, and ^{208}Pb, respectively. When undisturbed, the activities of daughter **isotopes** in each decay chain are equal to their parents and one can measure the accumulation of the stable isotopes of lead to date the time that has elapsed since a mineral became a closed system (a system that does not exchange matter with its surroundings). Rocks formed hundreds of millions to billions of years ago can be dated using this technique [591]. If a mineral is disturbed at some point during the decay and isotopes in the decay chain are preferentially removed from the system, the equilibria in a decay sequence will be disturbed. For example,

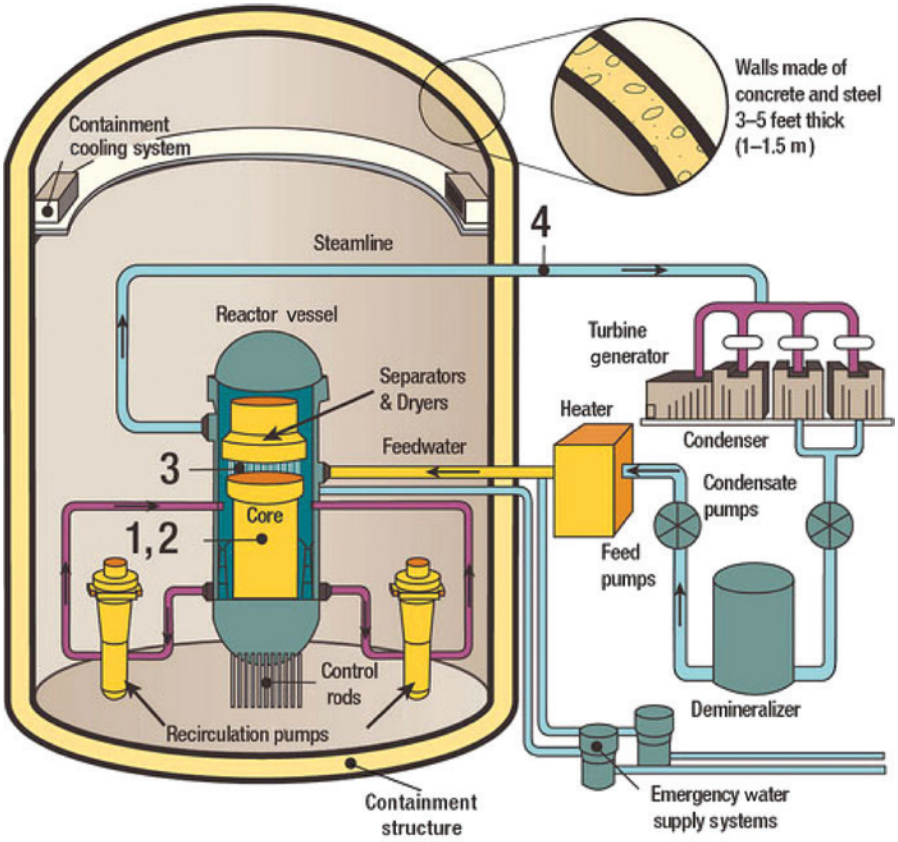


Fig. 4.92.1: Boiling water reactor fuel can be ^{235}U enriched as uranium dioxide, which would be located in the core and is identified as “Core”. (Diagram Source: U.S. Nuclear Regulatory Commission) [602].

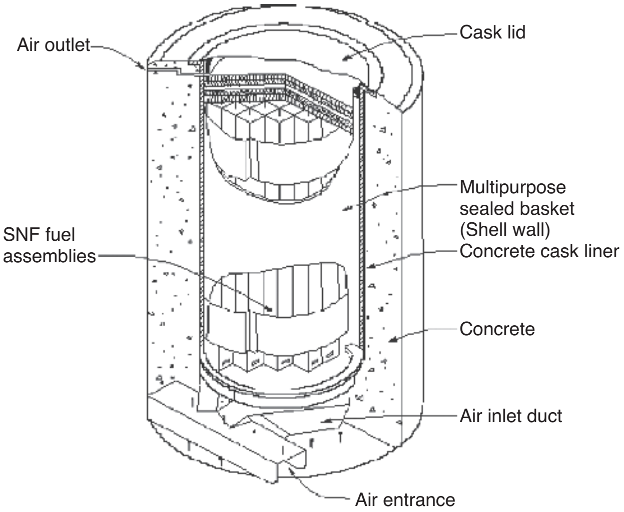


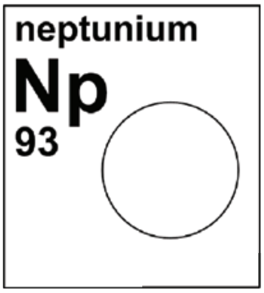
Fig. 4.92.2: DUCRETE cask diagram. DUCRETE is being proposed as a suitable material for the storage of radioactive waste. (Diagram Source: Argonne National Laboratory) [601].

one can measure the excess of ^{230}Th (with a half-life of 7.56×10^4 years) relative to the ^{234}U parent radionuclide to date carbonates (speleothems or corals) that are less than 5×10^5 years old [591].

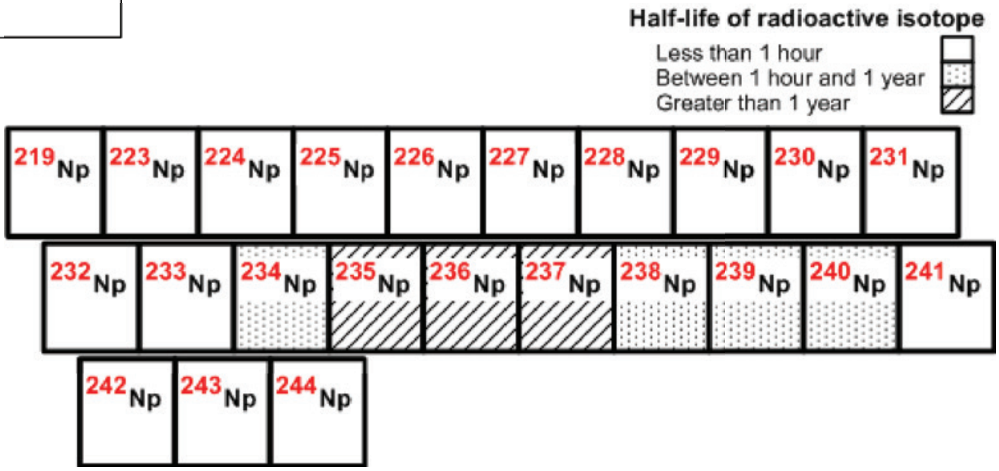
4.92.3 Uranium isotopes in industry

Nuclei of ^{235}U are split when bombarded by **thermal neutrons**. The process is known as nuclear **fission** and can release tremendous amounts of energy per uranium nucleus. The nucleus that splits will release additional **neutrons** that, if slowed down sufficiently, can cause subsequent fission events. When properly controlled, ^{235}U fission can be used to generate heat to drive steam turbines, which in turn produces electricity (Fig. 4.92.1). If the fission process is not controlled, then a rapid and explosive release of energy will occur, similar to that of nuclear weapons [599]. Uranium depleted in ^{235}U by fission in nuclear reactors (and hence greatly enriched in ^{238}U compared to “natural” uranium) is used in the manufacture of DUCRETE concrete (Fig. 4.92.2). The incorporation of the large ^{238}U nuclei makes this material an effective absorber of neutrons and **gamma rays**, and DUCRETE concrete is used to reduce fluxes of neutrons and high-energy **photons**. The **alpha particles** produced by the decay of ^{238}U are effectively absorbed by the concrete and do not pose a health risk. DUCRETE is being proposed as a suitable material for the storage of radioactive waste [600, 601].

4.93 Neptunium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



4.93.1 Neptunium isotopes in industry

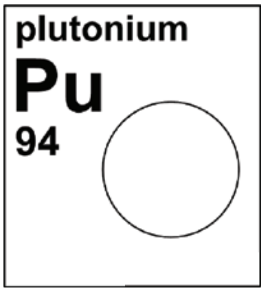
^{237}Np (with a **half-life** of 2.14 × 10^{6} years) is **fissionable**, meaning that neptunium can be bombarded with **neutrons** and, as a result, create more neutrons that are free to interact with nearby material and can be used in fast neutron reactors or in nuclear weapons (Fig. 4.93.1) [75, 603, 604]. ^{237}Np is used in neutron detection instruments [75].

Fig. 4.93.1: ^{237}Np is **fissionable** and is used in fast **neutron** reactors and in nuclear weapons. (U.S. Air Force photo by Senior Airman Alexandra Longfellow, U.S. Department of Energy) [605].

4.93.2 Neptunium isotopes used as a source of radioactive isotope(s)

^{237}Np is used in the production of ^{238}Pu (with a half-life of 87.7 years), which is an emitter of **alpha particles** used in thermoelectric generators and **radioisotope**-heater units. When ^{237}Np captures a neutron, it becomes ^{238}Np, with a half-life of 2.117 days, which decays to ^{238}Pu [75].

4.94 Plutonium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

4.94.1 Plutonium isotopes in industry

^{238}Pu (with a **half-life** of 87.7 years) is used in radiothermal generators as a heat source to produce electricity. These radiothermal generators are used to power unmanned spacecraft and interplanetary probes that venture too far from the Sun to use solar power, such as the Cassini Orbiter, the Galileo spacecraft, and the

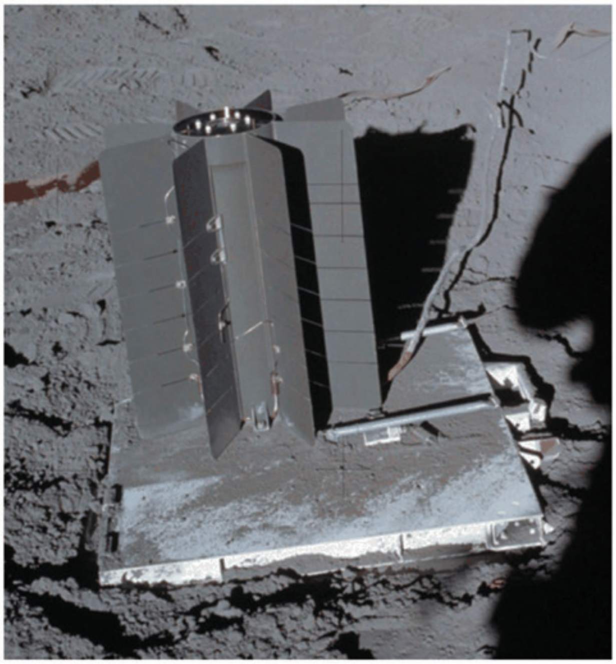


Fig. 4.94.1: ^{238}Pu is used in the SNAP-27 radiothermal generator as a heat source to produce electricity to power spacecrafts, such as for Apollo missions 12, 14, 15, 16, and 17. (Image Source: NASA) [612].

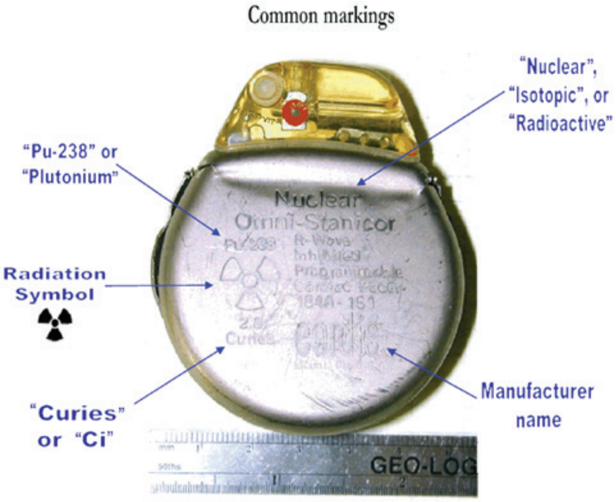
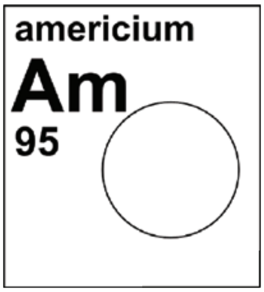


Fig. 4.94.2: ^{238}Pu is used in cardiac pacemakers, and they should be disposed of properly upon removal (modified from [613]).

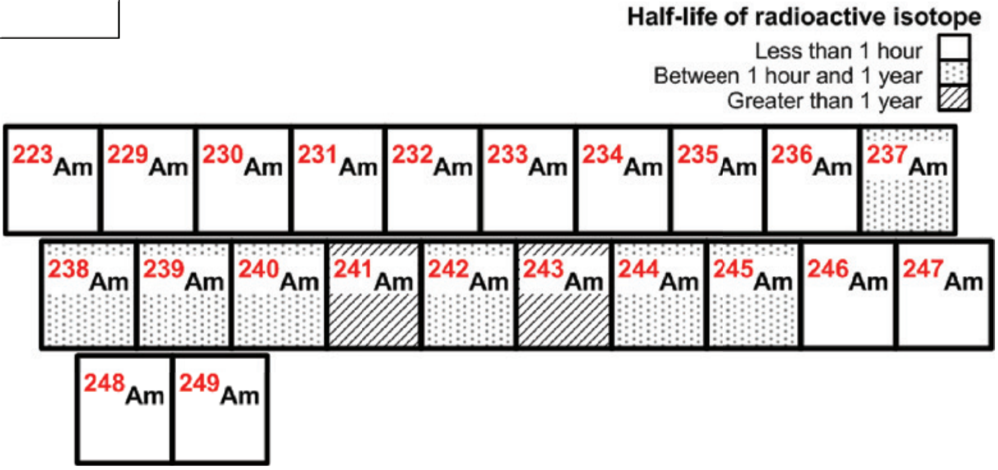
Huygens and Galileo probes [75, 606–608]. ^{238}Pu has been used in the Apollo lunar missions as part of a **nuclear battery**. The SNAP-27 (systems nuclear auxiliary power) system produced approximately 75 W of electrical power at 30 VDC per unit (Fig. 4.94.1). The energy source was a 2.5-kg rod of ^{238}Pu providing thermal power of approximately 1250 W [609]. ^{238}Pu is used in pacemakers (Fig. 4.94.2).

^{239}Pu (with a half-life of 2.41×10^4 years) is used in nuclear weapons. ^{239}Pu is easily made in nuclear reactors by bombarding ^{238}U with **neutrons** *via* the reaction ^{238}U (n, γ) ^{239}U and $^{239}\text{U} \rightarrow {}^{239}\text{Pu} + \beta^-$. The ^{239}Pu made by this reaction can itself be split by neutrons to release energy and is used for energy generation in nuclear reactors [75, 610, 611].

4.95 Americium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Americium does not occur naturally in the Earth's crust. In 1944, it was first synthesized by Glenn T. Seaborg and his team at the University of California Laboratory in Berkeley *via* multiple **neutron** capture reaction on ^{239}Pu to produce ^{241}Am : $^{239}\text{Pu}\ (\text{n}, \gamma)\ ^{240}\text{Pu}$, $^{240}\text{Pu}\ (\text{n}, \gamma)\ ^{241}\text{Pu}$, and $^{241}\text{Pu} \rightarrow {}^{241}\text{Am} + \beta^-$.

4.95.1 Americium isotopes in industry

^{241}Am (with a **half-life** of 433 days) is used in smoke detectors as an ionization source to detect smoke (Fig. 4.95.1). A small piece of ^{241}Am oxide is housed inside **ionizing** smoke detectors. The americium compound emits **alpha particles** that strike air molecules in their path, causing them to ionize. The ions carry a current from one plate in the detector to a second plate. Current flows continuously until smoke disrupts the current between the two plates. The alarm sounds when the current is disrupted by smoke [75, 614, 615].

^{241}Am is used for the control and measurement of industrial material thickness and product quality. In manufacturing, for example, a small piece of ^{241}Am is placed above a conveyer belt and a **Geiger counter** (used to count alpha particles) is placed below the conveyor belt. A specific quantity of radiation is expected to be measured by the Geiger counter. If the product being manufactured (*i.e.* glass) is thicker than expected, less radiation will be measured, and the product will be rejected [75]. The **gamma radiation** of ^{241}Am is also used in a variety of gauges. Thickness gauges, fluid-density gauges, aircraft fuel gauges, and distance-sensing devices use the density-measuring capabilities of the emitting **gamma rays** and radiation detector to function.

When ^{241}Am is mixed with beryllium (^{241}AmBe), it emits neutrons at a high rate. This high rate of neutron generation is useful in oil-well operations to monitor the rate of oil production, and it can also be used in well logging to log the porosity (fraction of void volume to total volume of a material) of the geologic units along the sides of a borehole. Gamma rays from ^{241}Am are also used as portable **X-ray** machines to determine where new wells should be drilled. When a small pellet of ^{241}Am is placed in a sealed titanium capsule, it can serve

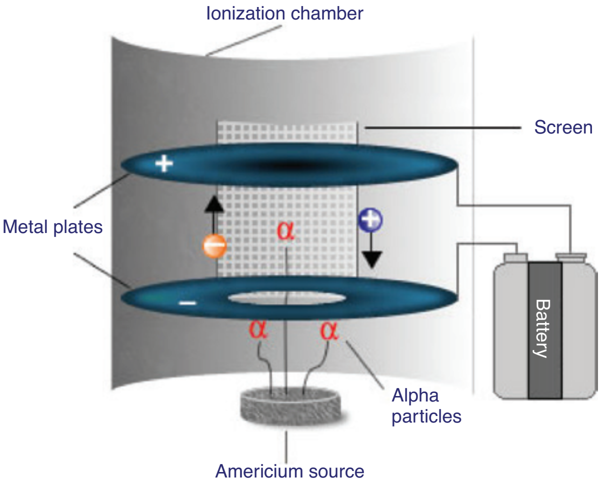


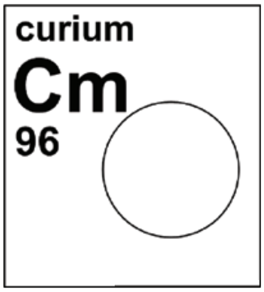
Fig. 4.95.1: In a smoke-free chamber, the ionized air molecules create a current between the two metal plates having a voltage difference. Current flows continuously until smoke disrupts the current, at which time the alarm sounds. (Diagram Source: US Environmental Protection Agency) [615].

as a portable source for gamma **radiography**, which is more penetrating than X-rays, to test various materials for defects, such as invisible cracks or faulty welds in pipelines [75, 614, 616].

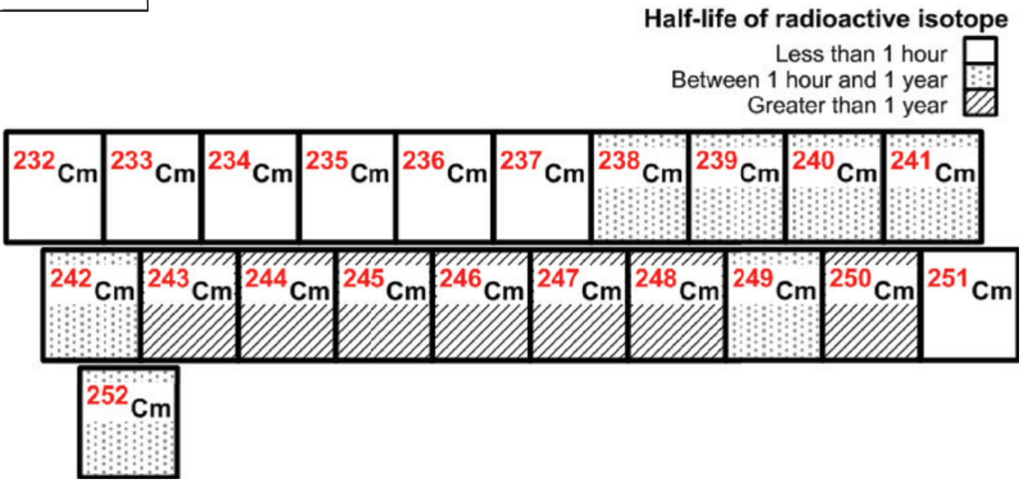
4.95.2 Americium isotopes in medicine

Gamma-ray emissions from ^{241}Am have been used as a radiation source for medical diagnostic tests. In particular, ^{241}Am has helped to provide accurate diagnoses of thyroid function, but this use of americium is now obsolete [617].

4.96 Curium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Curium does not occur naturally in the Earth's crust. It was first synthesized in 1944 by Glenn T. Seaborg and his team at the University of California in Berkeley using the reaction ^{239}Pu (^{4}He, n) ^{242}Cm. The **element** was named after Pierre and Marie Curie, who discovered radium and polonium.

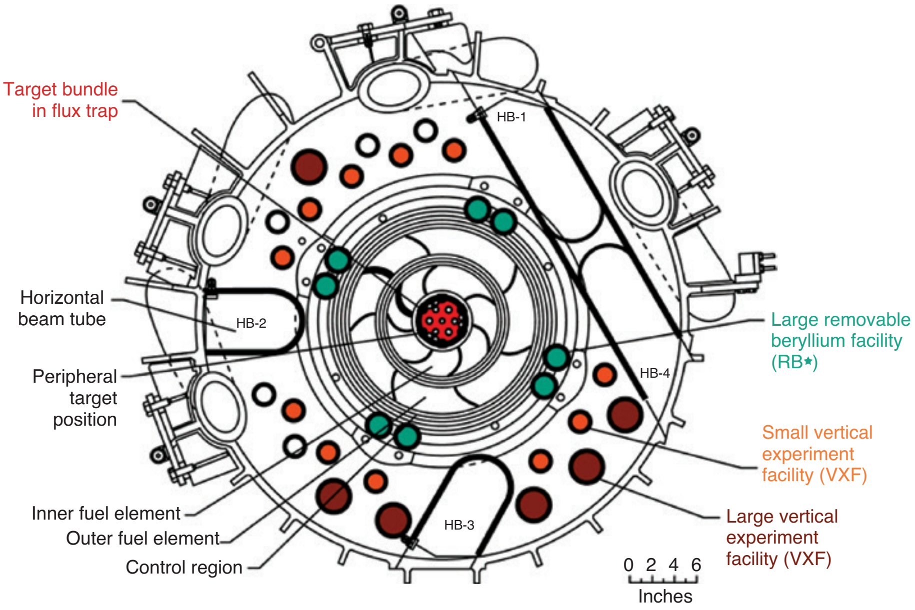
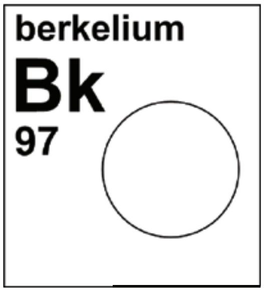


Fig. 4.96.1: Schematic drawing of the inside of a reactor core at the Oak Ridge National Laboratory's High Flux Isotope Reactor facility. ^{244}Cm is used as the target in the flux trap. (Image Source: Oak Ridge National Laboratory) [619].

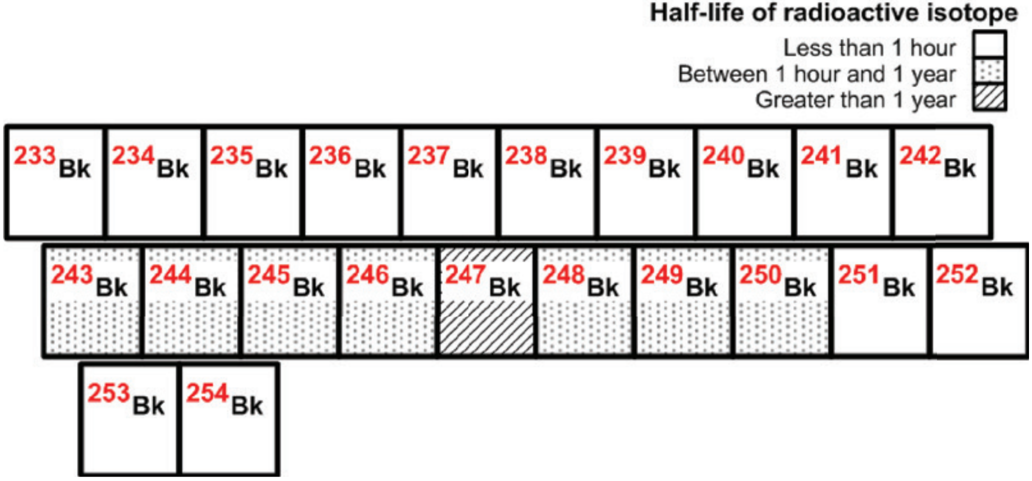
4.96.1 Curium isotopes in industry

^{244}Cm and ^{242}Cm (with **half-lives** of 18.1 years and 163 days, respectively) are strong alpha emitters (see **alpha decay**). The alpha emission from these **isotopes** creates a considerable quantity of heat that makes them useful as **alpha particle** sources, as well as heat generators in RTGs (radioisotopic thermoelectric generators) [75]. During a number of space missions based in America and Europe, ^{244}Cm was the source used for the alpha particle **X-ray** spectrometer that was on board vehicles such as the Mars Exploration Rover and the Rosetta/Philae [75, 618]. ^{244}Cm has a large **neutron** capture to neutron **fission** cross-section ratio and has been used in a nuclear reactor to produce higher mass radio-isotopes of curium (Fig. 4.96.1) [75, 618].

4.97 Berkelium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Berkelium does not occur naturally in the Earth's crust. It was first synthesized in December 1949 by Stanley G. Thompson, Glenn T. Seaborg, and Albert Ghiorso at the University of California in Berkeley using the nuclear reaction ^{241}Am (^{4}He, 2n) ^{243}Bk in the Berkeley 60-inch **cyclotron**. The **element** was named for the town in California where it was first synthesized. The first **isotope** of berkelium produced from this experiment had a **mass number** of 243 and a **half-life** of 4.5 h. ^{247}Bk has a half-life of 1.4×10^3 years, which makes it one of the least **radioactive isotopes** of berkelium. ^{249}Bk has a half-life of 320 days, which makes it possible to isolate and study on a macroscopic scale, although studies have found that the radiation given off from berkelium creates health hazards. For example, lengthy exposure to the radiation from berkelium has been shown to cause an accumulation of berkelium in the skeletal system of rats. The radiation is also unfavorable to the formation of red blood cells [620–624]. Berkelium has no known isotopic applications aside from scientific research, in which it served as a target for the production of tennessine (Fig. 4.97.1).

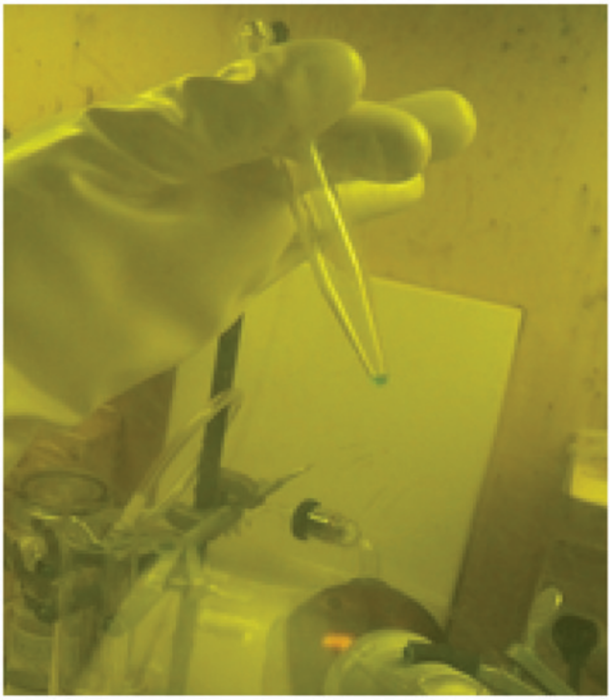
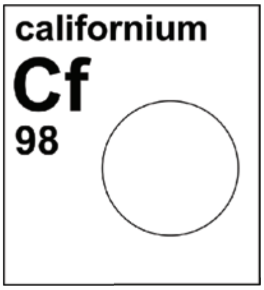
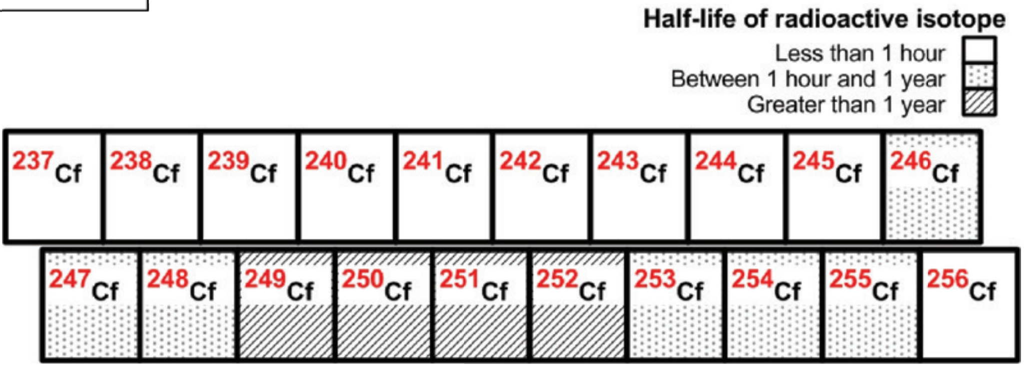


Fig. 4.97.1: The green fluid in the tip of the vial is ^{249}Bk, which was a critical **isotope** in the synthesis of tennessine (Ts). To make sure that the ^{249}Bk was in its purest form, it was synthesized in the High Flux Isotope Reactor at DOE's Oak Ridge National Laboratory and then used as the target in the Joint Institute of Nuclear Research (JINR) U-400 **cyclotron** accelerator and flooded with ^{48}Ca ions to synthesize Ts. (Photo Source: U.S. DOE Office of Science (SC), Oak Ridge National Laboratory) [620].

4.98 Californium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Californium does not occur naturally in the Earth's crust. It was first synthesized in 1950 by Glenn T. Seaborg and his team at the University of California using the reaction ^{242}Cm (^{4}He, n) ^{245}Cf. The **element** was named for the state where it was first synthesized.

4.98.1 Californium isotopes in industry

^{252}Cf is a very active source of **neutrons** (2.3×10^{6} neutrons per second per microgram) with a **half-life** of 2.65 years. The energy spectrum of the neutrons is very similar to that of a **fission** reactor and small amounts of ^{252}Cf provide an ideal portable source for low neutron flux applications [75, 625, 626]. ^{252}Cf is used for PGNAA (prompt gamma neutron activation analysis, a method for detecting many chemical elements in samples simultaneously) in the analysis of coal, cement, minerals, weapon components, and chemical munitions [627]. This method provides a quick and non-destructive elemental analysis of a sample. For example, ^{252}Cf, as the neutron source for PGNAA, is used to detect the presence of antitank mines [625].

Neutron activation analysis (NAA) uses ^{252}Cf as a portable neutron source to bombard a small sample from the area of interest with neutrons and analyze the radioactive emissions from that bombardment to help identify silver or gold ore [75]. ^{252}Cf has been used in neutron moisture gauges to locate water [628]. ^{252}Cf is used in borehole geophysical logging for subsurface PGNAA investigation of waste (Fig. 4.98.1) [629].

Formation fluid identification uses ^{252}Cf as a chemical neutron source for elastic/inelastic neutron backscattering and/or neutron activation methods in well-logging to determine water- and oil-bearing layers and other downhole properties of the well bore [629].

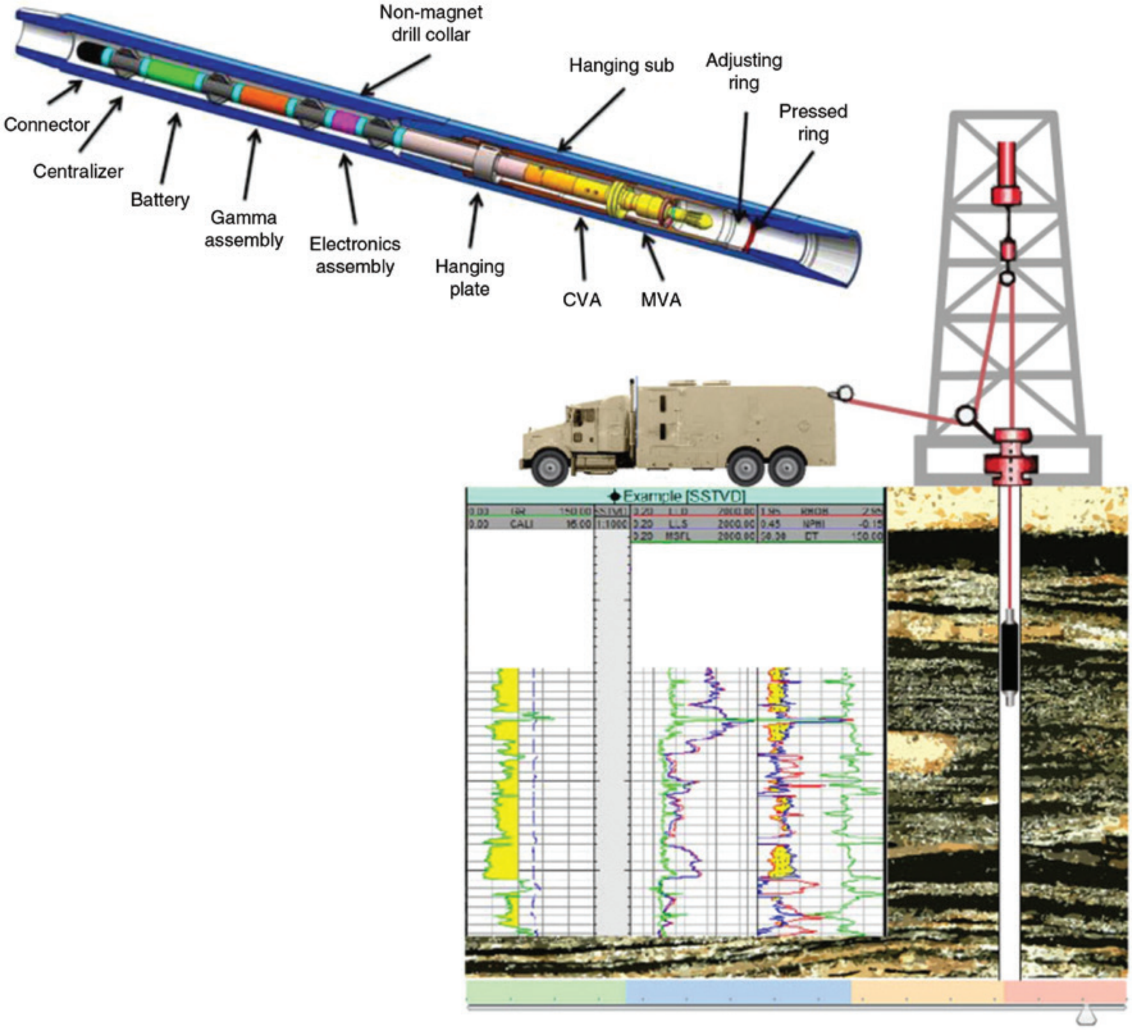
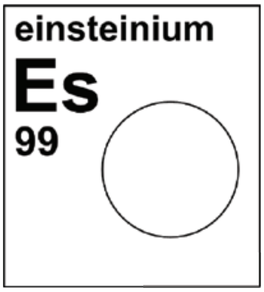


Fig. 4.98.1: Simplified diagram of a well logging operation. The geoprobe (black and silver probe in the borehole/well) contains the ^{252}Cf neutron source with supporting electronics, and it relays information about the physical properties of the surrounding rock to the control computer at the surface as the probe is lowered or raised. The example graphs next to the cross-section of the rock and borehole could indicate the presence of fluids, porosity, and/or type of rock (Photo Source: Frontier Technology Corporation).

4.98.2 Californium isotopes in medicine

^{252}Cf is sometimes used in boron neutron capture therapy (BNCT) as a source of neutrons that can be delivered close to the region of a tumor [75, 625, 626]. **Brachytherapy** can use ^{252}Cf to treat many types of cancer [75, 625, 626].

4.99 Einsteinium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Einsteinium does not occur naturally in the Earth's crust. It was first identified in December 1952 by American scientists from the Argonne National Laboratory near Chicago, Illinois, the Los Alamos National Laboratory in Los Alamos, New Mexico, and The University of California Laboratory in Berkeley, California in the debris of thermonuclear weapons. The **element** was named for Albert Einstein (Fig. 4.99.1). ^{253}Es was the first **isotope** identified; it has a **half-life** of 20.47 days. The isotope with the longest half-life is ^{252}Es, with a half-life of 472 days [630, 631].

There are no uses for isotopes of einsteinium outside of basic scientific research for the production of higher transuranic elements and studies of actinide science. Due to the radiation and heat given off by einsteinium isotopes, it is difficult to use them in experiments and studies [631].

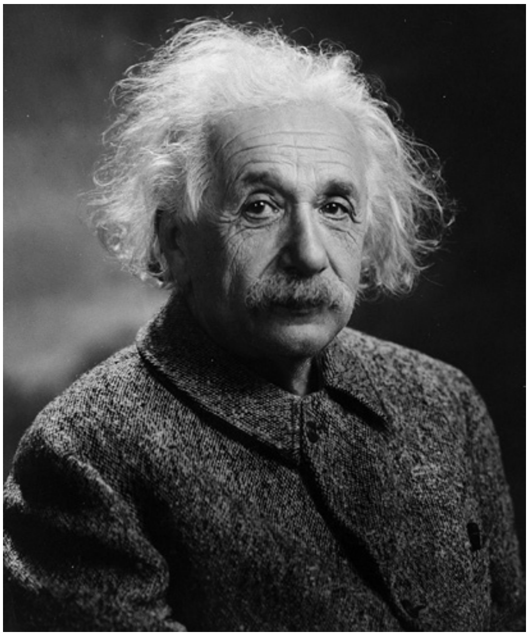
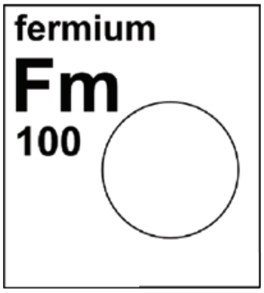
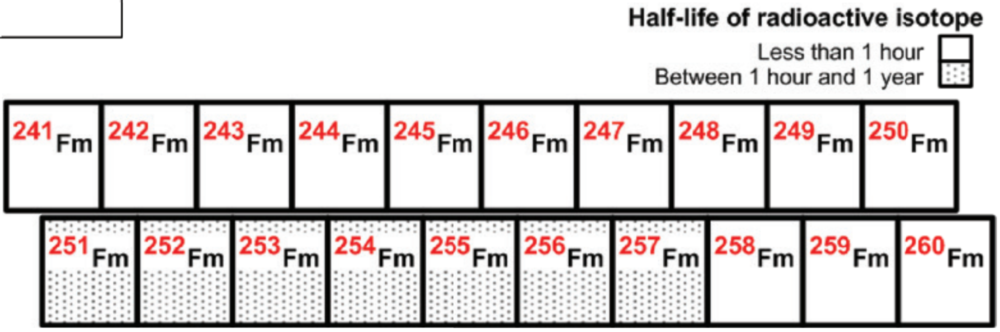


Fig. 4.99.1: Albert Einstein, from whom einsteinium derives its name. (Photo Source: © Lawrence Berkeley National Laboratory).

4.100 Fermium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

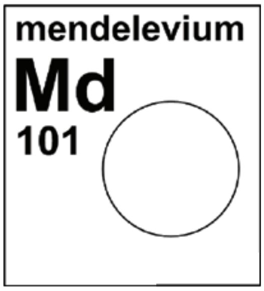


Fermium does not occur naturally in the Earth's crust. It was first identified in December 1952 by American scientists from the Argonne National Laboratory near Chicago, Illinois, the Los Alamos National Laboratory in Los Alamos, New Mexico, and The University of California Laboratory in Berkeley, California in the debris of thermonuclear weapons (Fig. 4.100.1). The **element** was named for Enrico Fermi, who built the first man-made nuclear reactor. ^{255}Fm (with a **half-life** of 20 h) was the first fermium **isotope** identified. Fermium is the heaviest element that can be formed by **neutron** bombardment of lighter elements and is thus the heaviest element that can be synthesized in macroscopic quantities [632, 633].

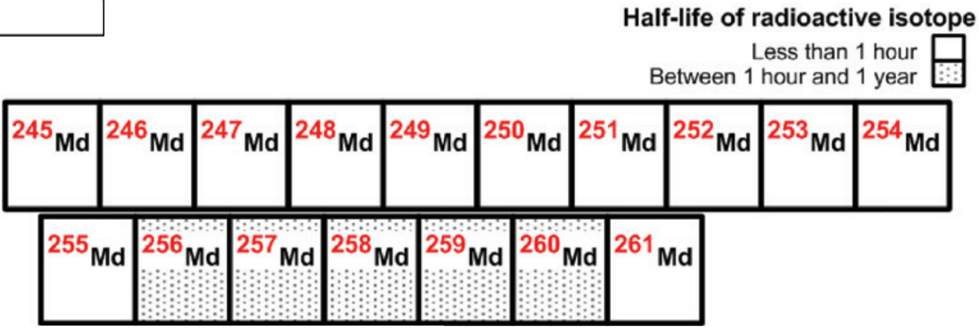
Fermium is of interest in particle physics research, but it has no commercial applications. ^{253}Fm was one of the **decay products** used to confirm synthesis of copernicium in a particle accelerator experiment [634].

Fig. 4.100.1: The first successful hydrogen bomb test (Ivy-Mike) in 1952 produced ^{255}Fm, which was the first fermium **isotope** detected [635].

4.101 Mendelevium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Mendelevium does not occur naturally in the Earth's crust. It was first synthesized in 1955 by Glenn T. Seaborg and his team at the University of California using the reactions ^{253}Es (^{4}He, n) ^{256}Md and ^{253}Es (^{4}He, 2n) ^{255}Md. Mendelevium is named for the Russian scientist, Dmitri Mendeleev (Fig. 4.101.1), who developed the Periodic Table of the chemical **elements** [636, 637]. There are no applications for **isotopes** of mendelevium aside from scientific research.

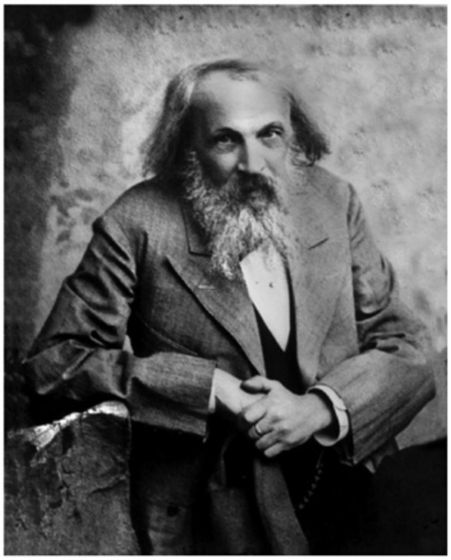
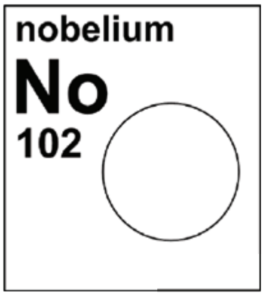


Fig. 4.101.1: Mendelevium is named after Dmitri Mendeleev to honor his contributions to the development of the periodic table of the **elements**. (Photo Source: © 2010 The Regents of the University of California, Lawrence Berkeley National Laboratory).

4.102 Nobelium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Nobelium does not occur naturally in the Earth's crust. It was first synthesized in 1966 by Russian scientists from the Joint Institute for Nuclear Research (JINR) in Dubna, Russia under Georgi Flerov. Earlier claims to have synthesized "nobelium" beginning in 1957 were shown to be erroneous. This **element** was originally named for Alfred Nobel (Fig. 4.102.1), the inventor of dynamite and founder of the Nobel prizes. The name was later retained because of its widespread use throughout the scientific literature [636, 638]. There are no uses for **isotopes** of nobelium outside of scientific research.

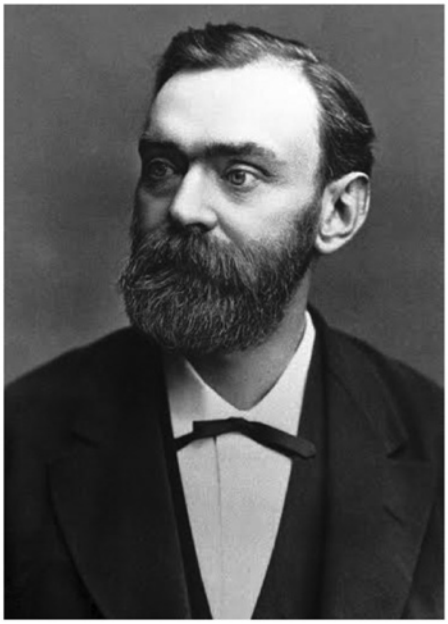
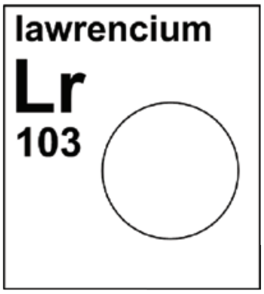


Fig. 4.102.1: Portrait of Alfred Nobel. (Image Source: Nobel Foundation) [639].

4.103 Lawrencium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Half-life of radioactive isotope
Less than 1 hour ☐
Between 1 hour and 1 year ▨

Lawrencium does not occur naturally in the Earth's crust. Credit for the first synthesis of this **element** in 1971 is given jointly to Albert Ghiorso and his team at the University of California in Berkeley and Georgi Flerov and his team at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia (Fig. 4.103.1). The element is named for Ernest O. Lawrence (Fig. 4.103.2), who developed the **cyclotron**. The chemical symbol for lawrencium was originally proposed as Lw. At the IUPAC General Assembly in 1963, lawrencium was officially accepted by IUPAC, but the symbol was changed to Lr because the Commission on Inorganic Nomenclature determined that the letter 'w' presented a problem in languages other than English [636, 640–642]. There are no known isotopic applications for lawrencium outside of scientific research.

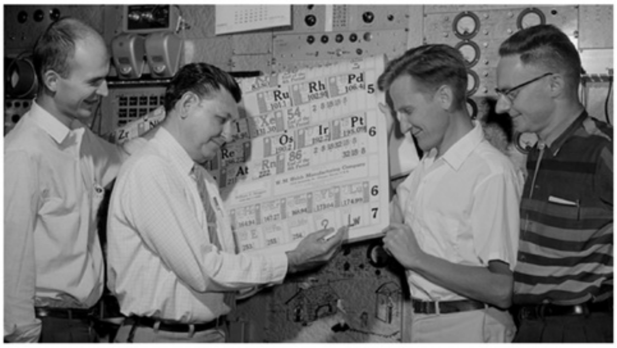
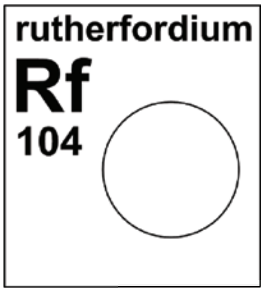


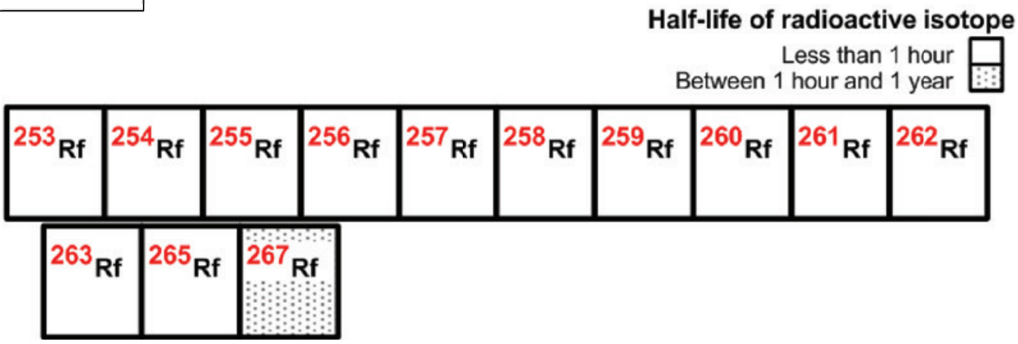
Fig. 4.103.1: The team that discovered lawrencium: Torbjorn Sikkeland, Albert Ghiorso, Almon E. 'Bud' Larsh, and Robert M. Latimer. (Photo Source: Dr. Glenn T. Seaborg, Lawrence Berkeley National Laboratory) [643].

Fig. 4.103.2: This is a photograph of Ernst O. Lawrence, who invented the **cyclotron**. **Element** 103 is named after him. (Photo Source: U.S. Department of Energy, Lawrence Berkeley National Laboratory) [644].

4.104 Rutherfordium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Rutherfordium does not occur naturally in the Earth's crust. Credit for the first synthesis of this **element** is given jointly to Albert Ghiorso and his team at the University of California in Berkeley and Georgi Flerov and his team at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. The element is named for Ernest Rutherford (Fig. 4.104.1), who won the Nobel Prize for developing the theory of radioactive transformations [645].

Rutherfordium is of interest in particle physics research, but it has no commercial applications. ^{261}Rf was one of the **decay products** used to confirm the synthesis of copernicium in a particle accelerator experiment [634].

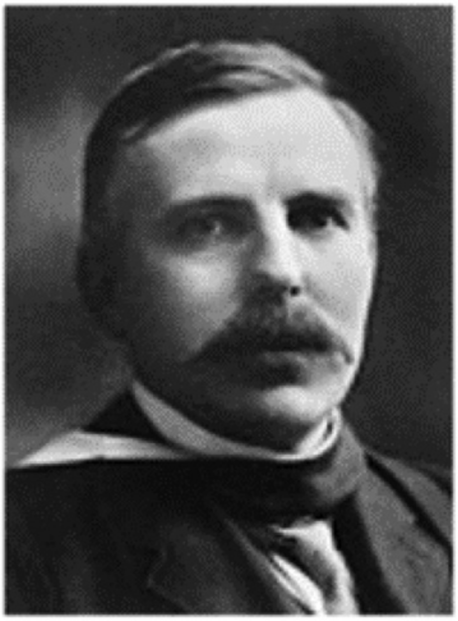
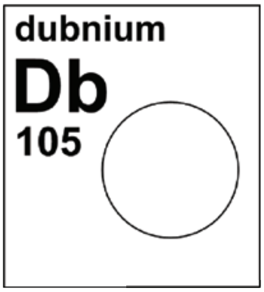
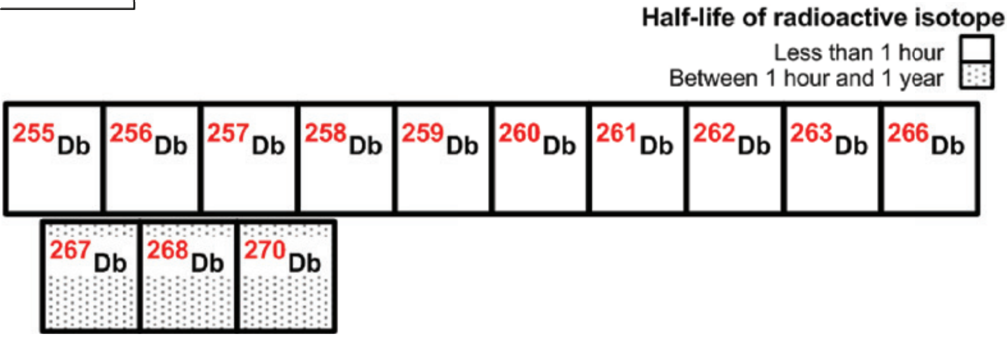


Fig. 4.104.1: **Element** 104 was named rutherfordium in honor of Ernest Rutherford. (Photo Source: Los Alamos National Laboratory) [645].

4.105 Dubnium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Dubnium does not occur naturally in the Earth's crust. Credit for the first synthesis of this **element** is given jointly to Albert Ghiorso and his team at the University of California in Berkeley and Georgi Flerov and his team at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia (Fig. 4.105.1). The element is named for the location of the Joint Institute for Nuclear Research (JINR) laboratory in Dubna, Russia [646, 647]. Dubnium has no isotopic applications outside of scientific research.

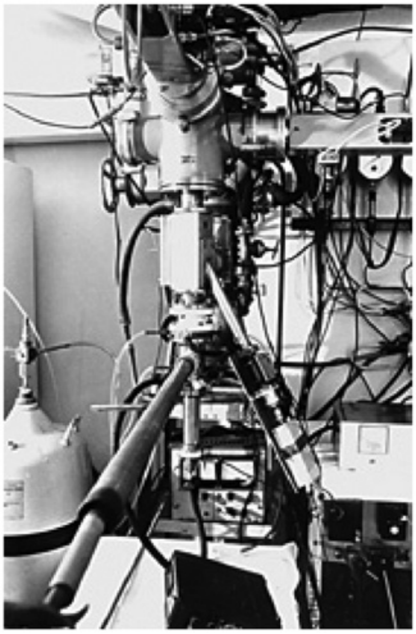


Fig. 4.105.1: Photo of the **cyclotron** U-300 used to synthesize dubnium. This is a 300-cm heavy-ion cyclotron built at the International Joint Institute for Nuclear Research (JINR) and put into operation in 1960. (Photo used with permission from Ivo J. Zvara, Joint Institute for Nuclear Research (JINR)). (Photo Source: Ivo J. Zvara, American Chemical Society, 2003) [646].

4.106 Seaborgium

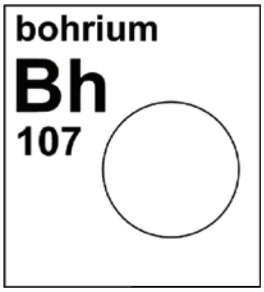
Stable isotope	Relative atomic mass	Mole fraction
(none)		

Seaborgium does not occur naturally in the Earth's crust. In 1974, seaborgium was first synthesized by Albert Ghiorso and his team at the University of California in Berkeley using the nuclear reaction ^{249}Cf (^{18}O, 4n) ^{263}Sg. The **element** is named for Glenn T. Seaborg (Fig. 4.106.1), who synthesized a number of trans-uranium elements [634, 648].

Seaborgium has no commercial applications. However, ^{265}Sg was one of the **decay products** used to confirm the synthesis of copernicium in a particle accelerator experiment.

Fig. 4.106.1: Seaborgium is named after Glenn T. Seaborg who synthesized a number of trans-uranium **elements**. (Photo Source: © Lawrence Berkeley National Laboratory).

4.107 Bohrium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Half-life of radioactive isotope

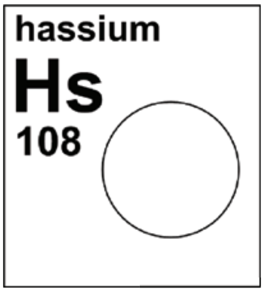
Less than 1 hour ☐

^{260}Bh	^{261}Bh	^{262}Bh	^{264}Bh	^{265}Bh	^{266}Bh	^{267}Bh	^{270}Bh	^{272}Bh	^{274}Bh

Bohrium does not occur naturally in the Earth's crust. Bohrium was first synthesized by German scientists at the GSI Center for Heavy Ion Research in Darmstadt, Germany in 1981 using the nuclear reaction ^{209}Bi (^{54}Cr, n) ^{262}Bh. The **element** is named for Niels Bohr (Fig. 4.107.1), the Nobel Prize winning physicist [649, 650]. Bohrium has no known isotopic applications aside from scientific research.

Fig. 4.107.1: Ernest Lawrence (left) and Niels Bohr (right) are pictured above. Niels Bohr's work on the structure of atoms won him the Nobel Prize in Physics in 1922. (Photo Source: © 2010 The Regents of the University of California, Lawrence Berkeley National Laboratory).

4.108 Hassium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Hassium does not occur naturally in the Earth's crust. Hassium was first synthesized by German scientists at the GSI Center for Heavy Ion Research in Darmstadt, Germany in 1984 using the nuclear reaction ^{208}Pb (^{58}Fe, n) ^{265}Hs (Fig. 4.108.1). The **element** is named for Hassia (the Latin name for the German state of Hesse), whose former capital was Darmstadt [651–653]. Hassium is used in chemical and heavy element research.

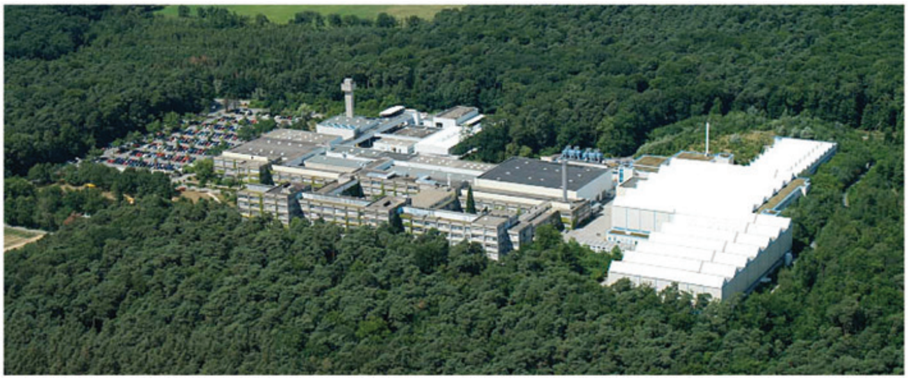
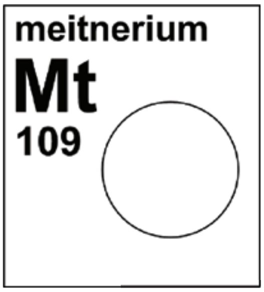


Fig. 4.108.1: GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. (Used with permission from: GSI Helmholtzzentrum für Schwerionenforschung) [654].

4.109 Meitnerium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Meitnerium does not occur naturally in the Earth’s crust. Meitnerium was first synthesized by German scientists at the GSI Center for Heavy Ion Research in Darmstadt, Germany in 1984 using the nuclear reaction ^{209}Bi (^{58}Fe, n) ^{266}MtHs. The **element** is named for the physicist, Lise Meitner (Fig. 4.109.1), who discovered the element protactinium [653, 655]. Meitnerium is used only for scientific research.

Fig. 4.109.1: Lise Meitner is the nuclear physicist, after whom meitnerium is named (used with permission of the American Institute of Physics’ Emilio Segre Visual Archives).

4.110 Darmstadtium

darmstadtium
Ds
110

Stable isotope	Relative atomic mass	Mole fraction
(none)		

Half-life of radioactive isotope

Less than 1 hour ☐

^{267}Ds	^{269}Ds	^{270}Ds	^{271}Ds	^{273}Ds	^{277}Ds	^{279}Ds	^{280}Ds	^{281}Ds	^{282}Ds

Darmstadtium does not occur naturally in the Earth's crust. Darmstadtium was first synthesized by an international team of scientists from the GSI in Darmstadt, Germany, the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, the Comenius University in Bratislava, Slovakia and the University of Jyväskylä, Finland at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt (Fig. 4.110.1), Germany in 1994 using the nuclear reaction ^{208}Pb (^{62}Ni, n) ^{269}Ds. The **element** was named darmstadtium after the place where the first synthesis was made [656–659]. Darmstadtium has no known isotopic applications aside from scientific research.

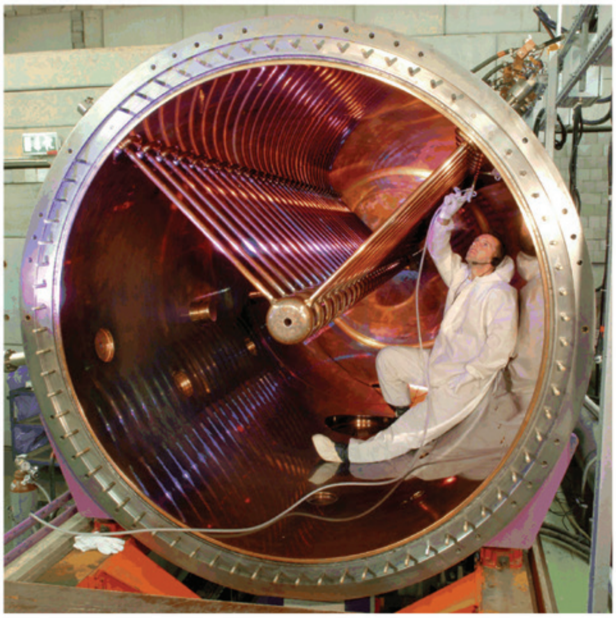
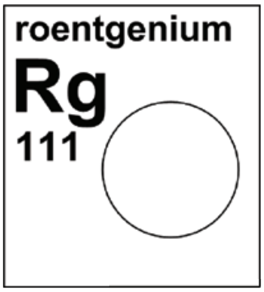


Fig. 4.110.1: View inside of the UNILAC (Universal Linear Accelerator) used to create darmstadtium at GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. (Photo Source: G. Otto, GSI Helmholtzzentrum für Schwerionenforschung GmbH) [654].

4.111 Roentgenium

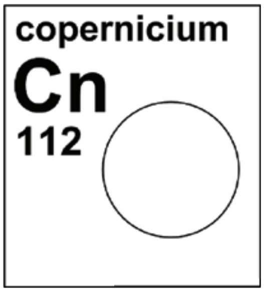


Stable isotope	Relative atomic mass	Mole fraction
(none)		

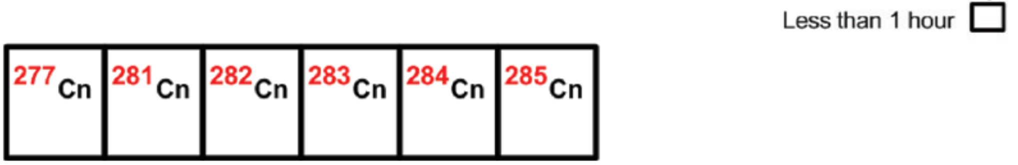
Roentgenium does not occur naturally in the Earth's crust. Roentgenium was first synthesized by an international team of scientists from the GSI in Darmstadt, Germany, the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, the Comenius University in Bratislava, Slovakia, and the University of Jyväskylä, Finland at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany in 1994, using the nuclear reaction ^{209}Bi (^{64}Ni, n) ^{272}Rg. The credit for the first synthesis was confirmed in 2003. The **element** was named after Wilhelm Conrad Roentgen (Fig. 4.111.1), who discovered **X-rays** in 1895 [660–662]. Roentgenium has no known isotopic applications aside from scientific research.

Fig. 4.111.1: Wilhelm Conrad Roentgen, discoverer of **X-rays**, after whom roentgenium was named. (Photo Source: NASA Goddard Space Flight Center).

4.112 Copernicium



Stable isotope	Relative atomic mass	Mole fraction
(none)		



Copernicium does not occur naturally in the Earth's crust. Copernicium was synthesized by scientists at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany in 1996 (Fig. 4.112.1). Sigurd Hofmann and an international team of scientists used the nuclear reaction ^{208}Pb (^{70}Zn, n) ^{277}Cn. The observed **alpha decays** led to the known nuclide, ^{269}Sg. The name, copernicium, was given to **element** 112 to honor astronomer Nicholas Copernicus, who is known for his heliocentric theory of how the planets orbit the Sun [663, 664]. Copernicium has no known isotopic applications aside from scientific research.

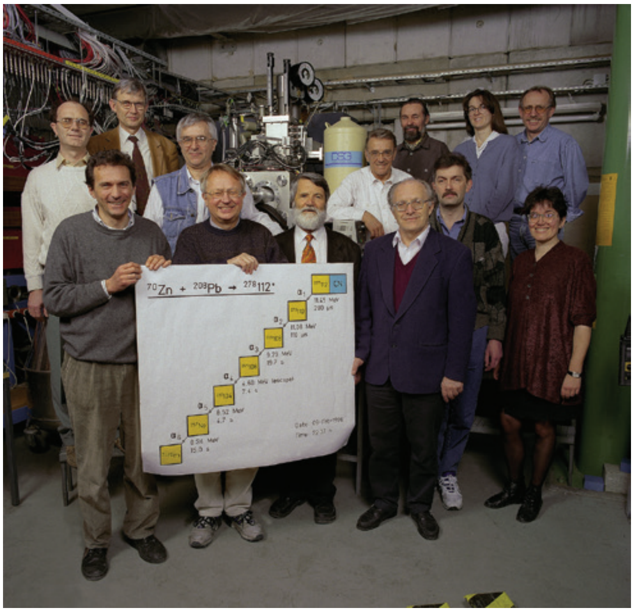


Fig. 4.112.1: The team of international scientists responsible for discovering copernicium. (Photo Source: GSI Helmholtzzentrum für Schwerionenforschung GmbH) [663].

4.113 Nihonium

Stable isotope	Relative atomic mass	Mole fraction
(none)		

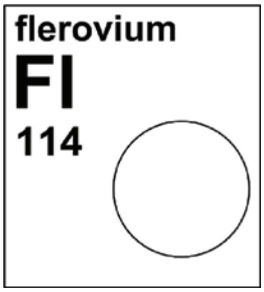
Nihonium does not occur naturally in the Earth's crust. The name nihonium and the symbol Nh are the accepted ones for **element** 113. Nihon is one of the two ways to say "Japan" in Japanese and means "the land of the Rising Sun." It is the first element to have been discovered in an Asian country [665–667].

Fig. 4.113.1: RILAC (RIKEN linear accelerator) used to synthesize nihonium (kindly provided by RIKEN).

Fig. 4.113.2: GARIS (Gas filled recoil ion separator) used to synthesize nihonium (kindly provided by RIKEN).

The synthesis of nihonium was first announced in 2004. The Joint Institute for Nuclear Research (JINR) and the Lawrence Livermore National Laboratory were able to produce two super-heavy elements by bombarding a rotating ^{243}Am disc with an ion beam of ^{48}Ca in a U-400 **cyclotron**. During the reaction, **isotopes** of moscovium, previously known as ununpentium, were synthesized and decayed in a tenth of a second to nihonium, which then decayed to roentgenium. Because the atoms of moscovium only existed for a tenth of a second, radiochemical proof was needed to support its syntheses. A Swiss scientist at the Paul Scherrer Institute (PSI) performed the radiochemical experiment by analyzing a copper plate that had been placed behind the ^{243}Am disc in the cyclotron. This copper plate collected all moscovium atoms that were synthesized and was processed through liquid chromatography techniques that yielded five times more moscovium atoms than produced by fusion alone. The direct synthesis of nihonium was announced later that year by a team of Japanese scientists from the Cyclotron Center of the RIKEN Research Institute. These scientists bombarded atoms of ^{209}Bi with a beam of ^{70}Zn in a RIKEN heavy-ion linear accelerator (RILAC), shown in Fig. 4.113.1, and gas-filled recoil ion separator (GARIS), shown in Fig. 4.113.2. Nihonium has no known isotopic applications aside from scientific research.

4.114 Flerovium



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Half-life of radioactive isotope
Less than 1 hour ☐

Flerovium does not occur naturally in the Earth's crust. Flerovium was named for the Flerov Laboratory for Nuclear Reactions of the Joint Institute for Nuclear Research (JIRN). In 1999, a collaboration of scientists from the Joint Institute for Nuclear Research in Dubna, Russia (Figs. 4.114.1 and 4.114.2) and the Lawrence Livermore Laboratory in the USA synthesized flerovium. They used nuclear reaction experiments to eventually produce ^{287}Fl by cross-bombardments of ^{48}Ca with both (even-*A*) ^{242}Pu and (odd-*A*) ^{245}Cm. The intermediate

Fig. 4.114.1: The research team at the Joint Institute for Nuclear Research (JINR) in Russia that discovered flerovium with a team from the Lawrence Livermore Laboratory in the USA. They are standing around one of the mass separators that they use to produce superheavy **elements**. (Photographer: Yuri Gripas Gamma Liaison) (Picture Source: Yuri Ts. Oganessian, Joint Institute for Nuclear Research) [668, 670].

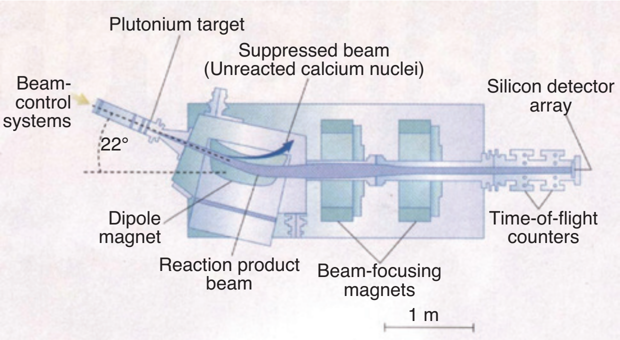


Fig. 4.114.2: Schematic diagram of one of the gas separators at the JINR in Dubna, Russia. (Photographer: Laurie Grace) (Picture Source: Yuri Ts. Oganessian, Joint Institute for Nuclear Research) [668, 671].

nuclide ^{283}Cn was observed with known decay characteristics that established the synthesis of flerovium [668, 669]. Flerovium has no known isotopic applications aside from scientific research.

4.115 Moscovium

Stable isotope	Relative atomic mass	Mole fraction
(none)		

Moscovium does not occur naturally in the Earth's crust. The name moscovium and the symbol Mc, are the accepted ones for **element** 115. The name is in recognition of the Moscow region and honors the ancient Russian land that is home to the Joint Institute for Nuclear Research (JIRN), where the discovery experiments were conducted using the Dubna gas filled recoil separator in combination with the heavy ion accelerator capabilities of the Flerov Laboratory of Nuclear Reactions.

^{48}Ca and ^{243}Am were bombarded together in a **cyclotron** during a series of experiments from 14 July to 10 August 2003 (Fig. 4.115.1). In February 2004, the results from these experiments were released in a report that stated "ununpentium" had been synthesized. This initial name means "115" in the IUPAC systematic naming scheme, which combines Latin and Greek names to produce un-un-pentium for 115. Moscovium has no known isotopic applications aside from scientific research.

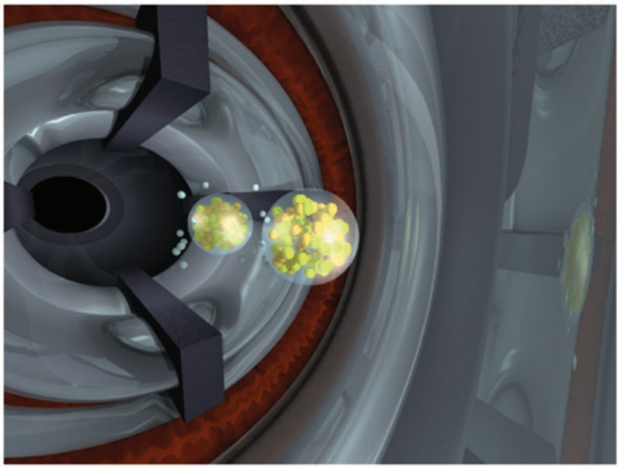
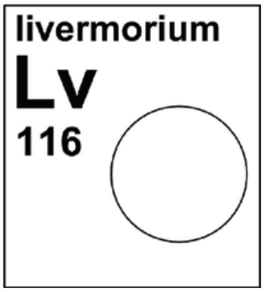


Fig. 4.115.1: Accelerated ^{48}Ca ion colliding with a ^{243}Am atom in a **cyclotron** creating moscovium and nihonium. (Diagram Source: Thomas Tegge, Lawrence Livermore National Laboratory) [672, 673].

4.116 Livermorium

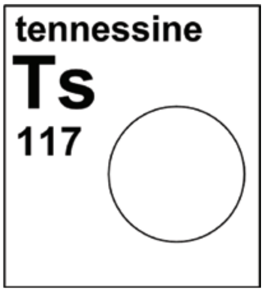


Stable isotope	Relative atomic mass	Mole fraction
(none)		

Livermorium does not occur naturally in the Earth's crust. In 2000, scientists from the Joint Institute for Nuclear Research (JINR) in Dubna, Russia (Fig. 4.116.1) worked with scientists from the Lawrence Livermore National Laboratory at the University of California and other collaborators to synthesize **element** 116. This element was first given the placeholder name ununhexium; in May of 2012 it was granted the name livermorium, with the symbol Lv. Researchers first studied livermorium as a **decay product** of oganesson and then synthesized livermorium by bombarding atoms of ^{248}Cm with ions of ^{48}Ca. The initial reaction of ^{248}Cm with ^{48}Ca produced the **isotope** ^{292}Lv. Researchers were also able to produce livermorium by bombarding ^{245}Cm with ^{48}Ca. There are four known isotopes of livermorium [669, 674]. Livermorium has no known isotopic applications aside from scientific research.

Fig. 4.116.1: Photo of the heavy ion **cyclotron** U-400 at JINR in which livermorium was synthesized. (Photo Source: Lawrence Livermore National Laboratory) [675].

4.117 Tennessine



Stable isotope	Relative atomic mass	Mole fraction
(none)		

Half-life of radioactive isotope
Less than 1 hour ☐

Tennessine does not occur naturally in the Earth's crust. The name tennessine and the symbol Ts, are the accepted ones for **element** 117. The name is in recognition of the contribution of the Tennessee region, including Oak Ridge National Laboratory (ORNL), Vanderbilt University, and the University of Tennessee at Knoxville, to super-heavy element research, including the production and chemical separation of unique actinide target materials for super-heavy element synthesis at ORNL's High Flux Isotope Reactor (HFIR) and Radiochemical Engineering Development Center (REDC) [676–679].

In 2009, two **isotopes**, ^{293}Ts and ^{294}Ts were synthesized from the bombardment of ^{48}Ca ions with ^{249}Bk nuclei (Fig. 4.117.1) in the Dubna gas filled recoil separator and the heavy ion **cyclotron** U-400. Tennessine has no known isotopic applications aside from scientific research.

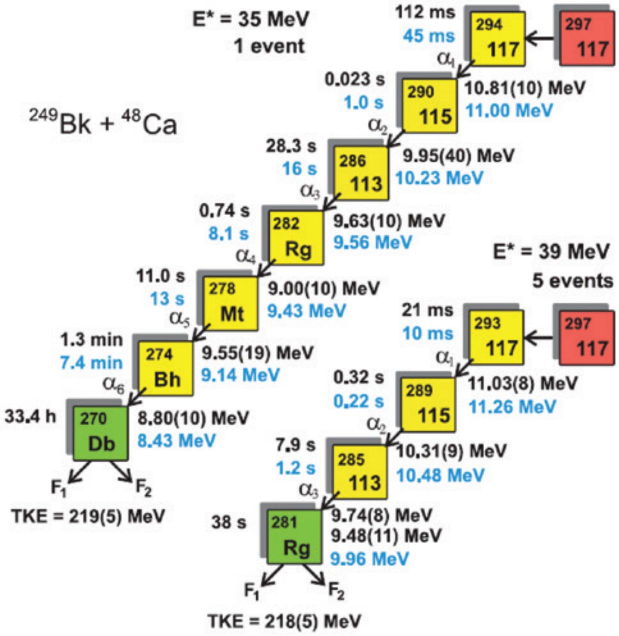


Fig. 4.117.1: Tennessine (identified as **element** 117) decay chain. Copyright ©2010 by the American Physical Society. (Reprinted with permission from Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett., v. 104, p. 142502-1 to 142502-4, 2010. DOI:10.1103/PhysRevLett.104.142502) [678].

4.118 Oganesson

Stable isotope	Relative atomic mass	Mole fraction
(none)		

Oganesson does not occur naturally in the Earth's crust. The name oganesson and symbol Og are the accepted ones for **element** 118. The name is in line with the tradition of honoring a scientist and recognizes Prof. Yuri Oganessian (Fig. 4.118.1; born 1933) for his pioneering contribution to trans-actinoid element research. His many achievements include the discovery of super-heavy elements and significant advances in the nuclear physics of super-heavy nuclei, including experimental evidence for the "island of stability."

In 2005, experiments were performed in Dubna's U-400 **cyclotron**, where ^{48}Ca bombarded a spinning target of ^{249}Cf at nearly 3×10^4 km/s to produce oganesson. With the success of creating oganesson, scientists from Livermore and Joint Institute for Nuclear Research (JINR) are starting experiments to create element 120 by bombarding a ^{244}Pu target with a beam of ^{58}Fe [680–683]. Oganesson has no known isotopic applications aside from scientific research.

Fig. 4.118.1: Prof. Yuri Oganessian after whom **element** 118 was named. (Image Source: Texas A&M University Institute for Advanced Study) [684].

5 Glossary of terms

Definitions of selected terms in this article are organized in the form of a glossary and are listed in alphabetical order. These definitions apply only to this publication. For formal definitions, the reader should consult the IUPAC Gold Book [682] and **IUPAC** recommendations.

absorption cross section – the probability of the absorption of an incident particle by a target nucleus.

accelerator mass spectrometry (AMS) – technique for measuring long-lived **radionuclides** in which ions are accelerated to extraordinarily high kinetic energies before mass analysis. The special strength of AMS among mass spectrometric methods is its power to separate a rare **isotope** from the isotope of another **element** of similar mass, *e.g.* ^{41}K from ^{41}Ca.

accrete – form a body by collecting matter, such as under the force of gravitation.

activity – the activity A of a radioactive substance B is given by $A = \lambda N_B$, where λ is the decay constant and N_B is the number of decaying entities B. The unit of A is "becquerel", symbol Bq, and $1\ \text{Bq} = 1\ \text{s}^{-1}$ (see Section 2.5, p. 20 of ref [7]).

alpha decay (α-decay) – **radioactive decay** process resulting in emission of **alpha particles**.

alpha particle – a positively charged nuclear particle identical with the nucleus of a helium atom consisting of two **protons** and two **neutrons**.

alpha particle capture – the absorption of an **alpha particle** by a target nucleus.

amount fraction (mole fraction or isotopic abundance, *x*) – the amount (symbol n) of a given **isotope** (atom) in a sample divided by the total amount of all **stable isotopes** and long-lived **radioactive isotopes** of the chemical **element** in the sample.

amount ratio – amount of a specified constituent (usually molecules, atoms, or ions) divided by the amount of another constituent in the same system.

AMS – see **accelerator mass spectrometry.**

analyte – the component of a system to be analyzed [685].

anthropogenic – resulting from human activity.

antineutrino (anti-neutrino) – see **neutrino**.

atomic number (*Z*) – The number of **protons** in the nucleus of an atom.

atomic weight (relative mean atomic mass) – the sum of the products of the relative atomic mass and the **mole fraction** of each **stable isotope** and long-lived **radioactive isotope** of that **element** in the sample. The symbol of the atomic weight of element E is A_r(E), and the symbol of the atomic weight of an atom (**isotope**) of element E having **mass number** A is $A_r(^{A}\text{E})$. Because relative atomic masses are scaled (expressed relative) to one-twelfth the mass of a carbon-12 atom, atomic weights are dimensionless.

Auger electron – an **electron** that is ejected from an atom when an inner-shell **electron** is lost and an electron with a higher energy level takes its place. The excess energy is carried off by the electron and no **photon** is emitted in the process.

Avogadro constant (N_A) – fundamental physical constant (symbols: N_A or L) representing the number of entities in one mole ($6.022\,140\,76 \times 10^{23}\ \text{mol}^{-1}$) [130], where the elementary entities may be atoms, ions, molecules, **electrons**, or other particles or specified groups of particles. The Avogadro constant is the scaling factor between the microscopic (atomic scale) and the macroscopic properties of matter.

beta decay (β-decay) – **radioactive decay** process resulting in the emission of a beta particle of either positive or negative charge (an **electron** or **positron**).

brachytherapy – the treatment of cancer, especially prostate cancer, by the insertion of radioactive implants directly into the tissue near the tumor.

chondrites (or **chondritic meteorites**) – non-metallic **meteorites** which have not undergone compositional change due to melting because they were part of primitive asteroids, and thus reflect the composition of the **solar nebula** from which our Solar System formed.

CIAAW – Commission on Isotopic Abundances and Atomic Weights (of **IUPAC**).

control rods – a rod of a **neutron**-absorbing **element** used to vary the output power of a nuclear reactor by inserting the rods into the core to absorb neutrons or withdrawing the rods from the core to allow more neutrons to interact with the fuel in the core. The results will cause fewer neutron **fissions** and decrease the power or cause more neutron fissions and increase the power, respectively.

conventional atomic-weight value – an atomic-weight value of an **element** having a **standard atomic-weight interval** that is not an interval, such as is used for trade and commerce or for education when a single representative value is needed, *e.g.* for molecular weight calculations. These values have no uncertainty values associated with them. They have been selected so that most or all atomic-weight variation in normal materials is covered in an interval of plus or minus one in the last digit [4].

cosmogenic – produced by the interaction of Earth materials (soil, rock, and atmosphere) and **meteorites** with high-energy **cosmic rays**, resulting in **protons** and **neutrons** being expelled from an atom (termed **cosmic ray spallation**).

cosmic rays – extremely high-energy radiation, mainly originating outside the Solar System, consisting of one or more charged particles, such as **protons**, **alpha particles**, and larger atomic nuclei.

covalently – sharing **electron** pairs between atoms with a stable balance of attractive and repulsive forces between atoms.

CT scan (X-ray computed tomography or X-ray CT, computerized axial tomography scan or CAT scan) – a computerized tomography (CT) scan combines a series of **X-ray** images taken from different angles and uses computer processing to create cross-sectional images, or slices, of the bones, blood vessels, and soft tissues inside your body [686].

cyclotron – an apparatus in which charged atomic and subatomic particles are accelerated by a rapidly varying (radio frequency) electric field while following an outward spiral path in a constant magnetic field.

decay product – (daughter product), any nuclide produced by a specified **radionuclide** (parent) in a decay chain.

DNA – deoxyribonucleic acid, a double stranded molecule carrying genetic instructions for reproduction of organisms.

double beta decay – a type of **radioactive decay** in which two **protons** are simultaneously transformed into two **neutrons** inside the nucleus of an atom, decreasing the **atomic number** of the atom by two.

DTPA – diethylene triamine pentaacetic acid. The U.S. Food and Drug Administration approved DTPA treatment for eliminating ingested radioactive material, such as plutonium, americium, and curium from the body.

EDTMP – ethylenediamine tetra (methylene phosphonic acid).

electron – elementary particle of matter with a negative electric charge and a rest mass of about 9.109×10^{-31} kg.

electron-capture detector (ECD) – an apparatus for detecting trace amounts of atoms and molecules (such as halogens, organometallic compounds, nitriles, or nitro compounds). The ECD uses an **electron** emitter (commonly the **radioactive isotope** ^{63}Ni) to produce a current in the detector. Any electron-absorbing compound in the carrier gas reduces the current and is thus detected.

element (**chemical element**) – a species of atoms; all atoms with the same number of **protons** in the atomic nucleus. A pure chemical substance composed of atoms with the same number of protons in the atomic nucleus [685].

excretion – the process of eliminating waste matter.

first-pass effect – a phenomenon of drug **metabolism** whereby the concentration of a drug is greatly reduced, *e.g.* by the liver, before reaching the rest of the body, substantially reducing the bioavailability of the drug.

fission – the spontaneous or particle collision-induced splitting of a heavy nucleus into a pair (or, only rarely, more) of nearly equal fission fragments (fission products), generally with some **neutrons**. Fission is accompanied by the release of a large quantity of energy.

fissionable – capable of undergoing **fission** by interaction with particles, usually **neutrons**.

G-protein coupled receptors (GPCRs) – the largest and most diverse group of membrane receptors in eukaryotes (living organisms other than bacteria and archaeabacteria). These cell surface receptors act like an inbox for messages in the form of light energy, **peptides**, lipids, sugars, and proteins. Experts estimate that between one-third and one-half of all marketed drugs act by binding to GPCRs [687].

gamma camera (scintillation camera or Anger camera) – instrument used to track the distribution in body tissue of **radioactive isotopes** (**tracers**) that emit **gamma radiation** (high energy **photons**), a technique known as **scintigraphy**.

gamma radiation – see **gamma rays**.

gamma rays (gamma radiation) – a stream of high-energy electromagnetic radiation given off by an atomic nucleus undergoing **radioactive decay**. The energies of gamma rays are higher than those of **X-rays**; thus, gamma rays have greater penetrating power.

gas chromatography (GC) – a physical method of separation of gases within a tube in which the components to be separated are distributed between two phases, one of which is stationary (stationary phase), while the other (mobile phase) is a gas (commonly helium) that moves in a definite direction.

gated equilibrium blood pool imaging – see **radionuclide angiography**.

geochronology – the science of dating and determining the time sequence of events in the history of the Earth [688].

Geiger counter – instrument for detecting and measuring **ionizing** radiation.

half-life (radioactive) – the time interval that it takes for the total number of atoms of any **radioactive isotope** to decay and leave only half the original number of atoms.

heavy water – water containing a substantial fraction (up to 100 percent) of deuterium (^{2}H) in the form of ^2H_2O or H^2HO [685].

hyperthyroidism – a condition in which too much hormone is produced in the body by the thyroid.

igneous – type of rock formed by the cooling and solidification of lava.

in vivo – in the living body (plant or animal).

inductively coupled plasma mass spectrometry (ICPMS) – a type of **mass spectrometry** in which the **analyte** is inductively heated and analyzed in a plasma created with an electromagnetic coil.

intravenous (IV) – administered into a vein.

ionizing – pertaining to the process by which an atom, molecule, or substance acquires a negative or positive charge. Commonly, one or more **electrons** are removed to give a positive charge.

IPTEI – **IUPAC** Periodic Table of the Elements and Isotopes.

IRMS – see **isotope-ratio mass spectrometry**.

isochron – a line indicating the age of formation of a suite of rock or mineral samples on a cross plot of **amount ratios** of **isotopes** of one **element** or two different elements, one of which has a **radioactive isotope** that decays to an isotope of the other element. The apparent isochron age can indicate the time since metamorphism, crystallization, shock events, differentiation of precursor melts, *etc*. For examples, see neodymium Fig. 4.60.1, samarium Fig. 4.62.1, rhenium Fig. 4.75.1, and osmium Fig. 4.76.1.

isomer – a **gamma-ray** emitting excited state of an **isotope**.

isotope – one of two or more species of atoms of a given **element** (having the same number of **protons** in the nucleus) with different atomic masses (different number of **neutrons** in the nucleus). The atom can either be a **stable isotope** or a **radioactive isotope**.

isotope ratio (*R*) – number (symbol N) of atoms of one **isotope** divided by the number of atoms of another isotope of the same **chemical element** in the same system [689].

isotope-amount ratio (*r*) – amount (symbol n) of an **isotope** divided by the amount of another isotope of the chemical **element** in the same system [689].

isotope-ratio mass spectrometry (IRMS) – the scientific field pertaining to the use of a **mass spectrometer** to measure the relative abundance of **isotopes** in a given sample, usually with an instrument having multiple ion collectors.

isotopic abundance – see **amount fraction**.

isotopic composition – term indicating that qualitative or quantitative isotopic information has been gathered [689]. Although this is not an SI quantity, this term is often followed by SI-quantity values.

isotopic dating – radiometric or radioactive dating technique that applies to all methods of age determination based on the nuclear decay of naturally occurring **radioactive isotopes** [688].

isotopic fractionation (stable-isotope fractionation) – preferential enrichment of one **isotope** of an **element** over another, owing to slight variations in their physical or chemical properties [689].

isotopic reference material – substance that is sufficiently stable and homogeneous in **isotopic composition** to serve as a measurement standard in the measurement of **isotope ratios** [690].

isotopically labeled (compound) – a mixture of an isotopically unmodified compound with one or more analogous isotopically substituted compound(s) [685].

IUPAC – International Union of Pure and Applied Chemistry.

IYC – International Year of Chemistry.

luminous – relating to light as perceived by the human eye.

ligand – the atoms or groups joined to the central atom [685].

magnetic resonance imaging (MRI) – medical imaging technique that uses strong magnetic fields to form images of the body.

malignant – pertaining to a medical condition with the tendancy to become progressively worse.

mass number (*A*) – total number of heavy particles (**protons** and **neutrons**, jointly called nucleons) in the nucleus of an atom [685].

mass spectrometer (mass spectrometry) – an instrument for separating a substance into **isotopes**, molecules, and molecular fragments according to their differing mass to charge ratios by acceleration in an electric field and dispersion into a curved trajectory by a magnetic field.

measurement uncertainty – see **uncertainty of measurement**.

metabolism – the chemical processes that occur within a living organism in order to maintain life.

metastable state – an excited state of an **isotope** with a specific **half-life** for de-excitation, usually by the emission of a **gamma ray**.

metastases – the spread of a disease-producing agency (such as cancer cells) from the initial or primary site of disease to another part of the body [691].

meteoric water – pertaining to water of recent atmospheric origin [688].

meteorite – a meteoroid that has survived atmospheric passage and fallen to the Earth's surface in one or more recoverable fragments. See also **chondrites** [688].

mole ratio (amount ratio, *r*) – amount of a specified constituent (usually molecules, atoms, or ions) divided by the amount of another constituent in the same system.

monoclonal antibodies (mAb or moAb) - identical immune cells that are all clones of a unique parent cell, in contrast to polyclonal antibodies, which are made from several different immune cells.

MRI – see **magnetic resonance imaging**.

neutrino – an elementary particle with no charge; its mass is tiny compared to other subatomic particles. An anti-matter equivalent is called an antineutrino (or anti-neutrino). Neutrinos and antineutrinos can be created in certain types of **radioactive decay**, in nuclear reactions such as those that take place in the Sun, in nuclear reactors, in **cosmic ray** interactions with atoms, and in **supernovae**.

neutron – an elementary particle with no net charge and a rest mass of about 1.675×10^{-27} kg, slightly more than that of the **proton**. All atoms contain neutrons in their nucleus except for protium (^{1}H).

NMR – Nuclear Magnetic Resonance.

normal materials – a reasonably possible source for an **element** or its compounds for commerce, industry or science; the material is not itself studied for some extraordinary anomaly and its **mole fractions** (**isotopic abundances**) have not been modified significantly in a geologically brief period include all substances, except (1) those subjected to substantial deliberate, undisclosed, or inadvertent artificial isotopic modification, (2) extraterrestrial materials, and (3) isotopically anomalous specimens, such as natural nuclear reactor products from Oklo (Gabon) or other unique occurrences [692].

nuclear battery – a device that uses **radioactive decay** to generate electricity.

nuclear medicine – the branch of medicine that deals with the use of **radiopharmaceuticals** to diagnose and treat disease.

nucleosynthesis – the production of a **chemical element** from simpler nuclei (as of hydrogen), especially in a star. See **r-process**, **s-process**, and **p-process** [693].

ocular – of or relating to the eyes or vision.

over-expressed – the excessive expression of a gene, as in making too many copies of a protein or other substance, which may play a role in cancer development.

p-process – a **nucleosynthesis** process responsible for **proton**-rich nuclei [694].

palliative – providing relief from the symptoms of an illness without treating its underlying cause.

parent radionuclide – a **radioactive isotope**, commonly in a **radionuclide** generator, that decays to produce a radioactive daughter. For example, the parent radionuclide ^{99}Mo decays to ^{99m}Tc, which is used in **radionuclide angiography.**

peptides – amides derived from two or more amino carboxylic acid molecules (these molecules may be the same or different) by the formation of a **covalent** bond from the carbonyl carbon of one to the nitrogen atom of another with formal loss of water. The term is usually applied to structures formed from α-amino acids, but it includes those derived from any amino carboxylic acid [685].

perfusion test – a test using medical imaging to observe and record the passage of fluid through the lymphatic system or blood vessels to an organ or tissue.

PET scan – see **positron emission tomography**.

petrochemical – relating to or denoting substances obtained by the processing of oil and natural gas.

pharmacokinetics – the study of the time course of drug absorption, distribution, **metabolism**, and **excretion** [695].

photon – elementary particle of electromagnetic radiation carrying energy proportional to the radiation frequency, but with zero electric charge and zero mass.

porphyrin – pigment widely distributed throughout nature consisting of four pyrroles (C_4H_4NH) joined in a ring (porphin) structure.

positron – the antimatter counterpart of the **electron**, with a mass identical to that of the electron and an equal but opposite (positive) charge.

positron emission tomography (**PET**) scan – an imaging technique that is used to observe metabolic activity within the body. The system detects pairs of **gamma rays** emitted indirectly by a **radioactive isotope** used as a **tracer**, which emits **positrons** and which is introduced into the body on a biologically-active molecule. Three-dimensional images of the concentration of the radioactive isotope within the body are then constructed by computer analysis. The imaging is often performed with an **X-ray CT scan** in the same instrument.

primordial – existing from the beginning of time.

proton – an elementary particle having a rest mass of about 1.673×10^{-27} kg, slightly less than that of a **neutron**, and a positive electric charge equal and opposite to that of the **electron**. The number of protons in the nucleus of an atom is the **atomic number**.

proxy – a measured quantity that can be used to represent the value of another quantity in a calculation.

r-process (rapid neutron capture process) – **nucleosynthesis** process that occurs when **supernovae** collapse, resulting in **neutron**-rich atomic nuclei heavier than iron.

radioactive decay – the process by which unstable (or **radioactive**) **isotopes** lose energy by emitting **alpha particles** (helium nuclei), beta particles (positive or negative **electrons**), **gamma radiation**, **neutrons**, or **protons** to reach a final stable energy state.

radioactive isotope (radioisotope) – an atom for which **radioactive decay** has been experimentally measured (also see **half-life**).

radiogenic – produced by **radioactive decay**; the resulting atom (**isotope**) may or may not be radioactive.

radiography – an imaging technique that uses electromagnetic radiation other than visible light, especially **X-rays** and **gamma rays**, to view the internal structure of non-uniform objects, such as metal parts, welded pipes, and the human body.

radioimmunotherapy (RIT) – a combination of radiation therapy and immunotherapy used to treat cancer. RIT uses engineered monoclonal antibodies **isotopically labeled** with a **radionuclide** to deliver radiation toxic to living cells to a target cell.

radioimmunoconjugate – radioactive substance that carries radiation directly to cancer cells and is made by attaching a **radioactive** molecule to an immune substance, such as a **monoclonal antibody**, that can bind to cancer cells; used to kill cancer cells without harming normal cells [696].

radioisotope – see **radioactive isotope**.

radiolabel – a mixture of an isotopically unmodified compound with one or more analogous radioactive isotopically substituted compound(s).

radionuclide – a nuclide that is radioactive [685].

radionuclide angiography (also called gated equilibrium blood pool imaging) – a test using the **radioactive isotope** ^{99m}Tc to evaluate the function of the right and left ventricles of the heart by measuring radioactivity over the anterior chest as the radioactive blood flows through the large vessels and the heart chambers.

radiopharmaceutical – **radiolabeled** compound used for diagnostic or therapeutic purposes.

radiotherapy (radiation therapy) – the treatment of disease by means of radiation from radioactive substances or **X-rays**.

radiosynovectomy – a procedure using **radioactive isotopes** therapeutically to provide relief from a condition in which the synovial membrane, which encloses each joint and secretes a lubricating fluid to enable ease of joint motions, has become inflamed and irritated.

reduction-oxidation (redox) – reduction is the gain of one or more **electrons** by an atom, and oxidation is the loss of one or more electrons by an atom.

relative atomic mass (atomic weight) – the ratio of the average mass of the atom to the unified atomic mass unit.

residence time – the average amount of time (or time duration) that a collection of particles spends in a specified system.

s-process (slow-neutron-capture-process) – a **nucleosynthesis** process that occurs at relatively low **neutron** density and intermediate temperature conditions in stars, producing **isotopes** of the **elements** heavier than iron. The s-process is important in controlling the chemical evolution of the galaxy.

scintigraphy – see **gamma camera**.

scintillation counting – measuring **ionizing** radiation using the interaction of radiation on a material and counting the resulting **photon** emissions.

semiconductors – a material or object that allows some electricity or heat to move through it and that is used for this purpose, especially in electronic devices [697].

single-photon emission computed spectroscopy (SPECT) – a **nuclear medicine** imaging technique that is able to provide true three-dimensional information using **gamma rays** from a **radiopharmaceutical**.

solar nebula – the cloud of dust and gas from which the solar system is believed to have condensed, mainly by gravitational attraction, about 4.5×10^9 years ago.

spallation – a process in which fragments of a solid (spall) are ejected from the solid due to impact or stress. In nuclear physics, spallation is the process in which a nucleus of a heavy **element** emits a large number of nucleons (**isotopes**) as a result of being hit by a high-energy particle (*e.g.* a **cosmic ray**), resulting in a substantial loss of its **atomic weight**.

stable isotope – an atom for which no **radioactive decay** has ever been experimentally measured.

standard atomic weight – an evaluated quantity assigned by the **IUPAC** Commission on Isotopic Abundances and Atomic Weights (**CIAAW**) to encompass the range of possible atomic weights of a chemical **element** that might be encountered in all samples of normal terrestrial materials. It is comprised of either an interval (currently used for 13 elements) or a value and an uncertainty (a standard atomic-weight uncertainty), which are currently used for 71 elements. A standard atomic weight is determined from an evaluation of peer-reviewed scientific publications.

standard atomic-weight interval – the upper and lower bounds determined for the **standard atomic weight** of an **element** when its isotopic and atomic weight variations in **normal material** exceed the **measurement uncertainty** of its standard atomic weight. This interval is determined by an **IUPAC** project through the evaluation of peer-reviewed scientific publications. Currently only 13 elements have been evaluated and assigned atomic-weight intervals.

standard atomic-weight uncertainty – the **standard atomic weights** of 71 **elements** (those not expressed as intervals) are reported as central values ± decisional uncertainty values. The decisional atomic-weight uncertainty is a conservative estimate of the combined effects of **measurement uncertainty** and known atomic-weight variability in naturally occurring terrestrial sources of an element. The atomic weight of any normal material containing an element should lie between the lower and upper bounds of the decisional uncertainty limits for that element with great certitude.

substrate – the surface or substance on which an organism lives.

supernova (plural supernovae) – a star that suddenly increases greatly in brightness because of a catastrophic explosion that ejects most of its mass.

tracer – a substance, which can be an **isotope**, used for tracking purposes.

thermal neutron – a neutron not bound to an atomic nucleus in thermal equilibrium with its surroundings and thus having relatively low kinetic energy.

thermoneutrality – a state of thermal balance between an organism and its environments such that bodily thermoregulatory mechanisms are inactive [698].

thermonuclear bomb – a nuclear weapon that uses the energy from a primary **fission** reaction to compress and ignite a secondary nuclear DT (deuterium-tritium; hydrogen-2, hydrogen-3) fusion reaction.

thiol – any of various compounds, having the general formula RSH, which are analogous to alcohols but in which sulfur replaces the oxygen of the hydroxyl group and which have flowery, fruity, salty, sharp, or bad smelling odors [699].

tropospheric – pertaining to the lowest layer of the atmosphere, extending to about 10 km.

uncertainty of measurement – parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurement (the quantity being measured) [685].

voltaics – of, relating to, or producing direct electric current by chemical action (as in a battery) [700].

X-rays – electromagnetic radiation with a wavelength ranging from 0.01 to 10 nanometers – shorter than those of ultraviolet rays and typically longer than those of **gamma rays**.

X-ray fluorescence (XRF) spectroscopy – the branch of science concerned with the investigation and measurement of characteristic "secondary" (or fluorescent) X-ray spectra produced when a material has been bombarded with high-energy **X-rays** or **gamma rays** – widely used for elemental analysis and chemical analysis.

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