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wo years ago, the King's Centre for Visualization in Science (KCVS) at The King's University, Edmonton released a new digital interactive version of the IUPAC Periodic Table of the Elements and Isotopes with accompanying educational resources at an International Conference on Chemistry Education. It can be found at www. isotopesmatter.com. The effort was part of an IUPAC project [1]. The science behind this new table was developed by Inorganic Chemistry Division scientists working for over a decade on an earlier IUPAC project [2]. These projects were joint efforts between the IUPAC Committee on Chemistry Education (CCE) and the Inorganic Chemistry Division.

The atomic weight of an element is not a constant [3] nor is it a fundamental property of an element, but can be determined from the product of the atomic mass of each stable or long-lived radioactive isotope of an element in naturally occurring materials and the corresponding mole fraction (isotope abundance) of that isotope in the element. However, the atomic-weight value of an element is still the fundamental link between the mass and the amount of substance of a chemical element.

For any element that has two or more stable isotopes, there is the possibility that the relative amounts of the stable isotopes may not be the same in all samples of that element in naturally occurring materials. This variation of the fraction of each isotope in an element can cause a variation in the element's atomic weight. With time, improvements in instrumentation for measurement of isotopic abundances has caused this variation in atomic-weight values of some elements to have a larger span than the improved, lower uncertainty measurement in a single material. In lieu of the previously accepted value and uncertainty for an element, if an IUPAC evaluation of variability in isotopic composition has been completed, the atomic weight of the element can be listed as an interval, which includes an upper and lower bounds. The best estimate for the atomic weight is a value somewhere within these upper and lower bounds, but not the average of the upper and lower bounds [3].

For the education community and the public to understand fully (1) how atomic-weight values can be determined from the product of the isotopic abundance and atomic-mass values of the stable isotopes of an element, (2) why atomic weights are no longer considered to be constants of nature, and (3) why the atomic-weight values of some elements are listed with intervals, people will need to become more aware of the abundances and applications of isotopes.

Figure 1 displays the IUPAC Periodic Table of the Elements and Isotopes (IPTEI) that was developed to help users better understand the concept of isotopes. Currently, 253 stable isotopes and 3092 unstable isotopes have been identified for the 118 chemical elements. There are 289 isotopes that determine the standard atomic weights of the 84 elements that are assigned a standard atomic weight. Of these, 36 are radioactive isotopes that have a half-life value sufficiently long and an isotopic abundance value in naturally occurring substances that is sufficiently large that they contribute to the determination of the atomic weight of elements. The IPTEI is based on the design of the original Mendeleev Periodic Table. However, instead of a display of chemical and physical properties of each element, the IPTEI lists all stable and long-lived radioactive isotopes for each element, which contribute to the atomic weight for that element. This Periodic Table lists these isotopes and a pie chart for each element indicates the mole fraction of each isotope (the isotopic abundance in nature) in the element by the relative size of its pie slice for that element. The isotope mass number is listed around the pie chart in black for stable and in red for long-lived radioactive isotopes. Atomic-weight values and associated uncertainties are provided for 71 elements, and atomic-weight intervals are provided for 13 elements having a standard atomic weight expressed as an interval. Elements with a standard atomic weight expressed as an interval also have a conventional atomic-weight value listed for users who may need it in industry, trade, commerce, or education (e.g. for molecular-weight calculations).

An element-by-element review [4] is soon to be published and will accompany the IPTEI. Its information can also be readily accessed through the interactive digital version of the IPTEI [5]. This review includes additional information not shown on the print version of the Periodic Table itself for each element, including a chart of all known stable and radioactive isotopes of each of the 118 elements, with the radioactive isotopes listed in one of three half-life ranges. It should be noted that, on average, there are more than an order of magnitude as many radioactive isotopes (3092) as there are stable isotopes (253). To aid in the calculation of the atomic weight of each element, a table of stable and long-lived radioactive isotopes having characteristic terrestrial isotopic compositions that determine the standard atomic weight of that element

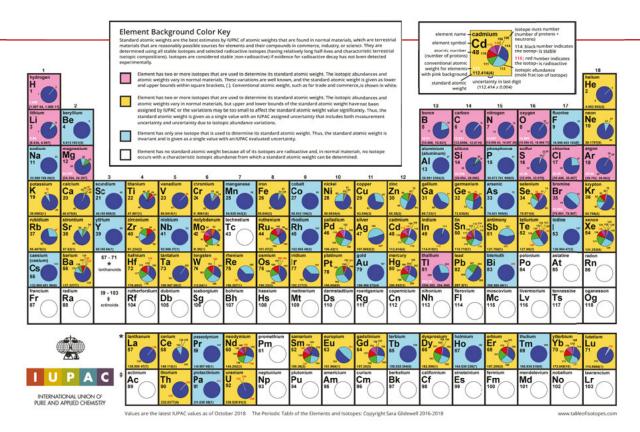


Fig. 1. IUPAC Periodic Table of the Elements and Isotopes [kindly modified by Sara Glidewell from The Periodic Table of Elements and Isotopes®, copyright by Sara Glidewell (www.tableofisotopes.com), and used with permission].

A background color scheme is associated with each element cell. A white cell indicates an element that has no stable or long-lived radioactive isotopes that contribute to a standard atomic weight. Blue is the background color of a cell for an element that has only one stable or long-lived radioactive isotope that contributes to its standard atomic weight. The standard atomic weight of elements having a blue background is given as a single value with a measurement uncertainty. 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 of an element having a yellow background is given as a single value with an uncertainty that includes both measurement uncertainty and uncertainty due to isotope-abundance variation. The variation in isotopic abundances may be too small to exceed the measurement uncertainty and affect the atomic-weight value. 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 exceeds measurement uncertainty and is well known. The standard atomic weight is given as lower and upper bounds within square brackets. Figure 2 displays an example of an element cell for each of the four background color schemes, with the element's pie chart of stable and long-lived radioactive isotopes and the mass numbers of the isotopes.

are listed in the IPTEI IUPAC report [4], along with the relative atomic mass and the mole fraction (isotopic abundance) of each of these isotopes of the element. An example of some of the additional information that does not appear on the IPTEI itself, but does appear in the IPTEI IUPAC report [4] and on the electronic IPTEI [5], is shown in Figure 3. It includes the element cell from the IPTEI, the previously described table of relevant isotopes, and a chart that contains all of the stable and radioactive isotopes of the element.

To emphasize the everyday importance of isotopes, applications of both the stable and radioactive isotopes for each element are highlighted for their practical uses in science and in everyday life in one or more of seven different categories in the

element-by-element review section of the soon to be published IPTEI IUPAC report [4]:

- for biology, there are 24 different isotopes from 18 different elements.
- for Earth and planetary science, there are 86 different isotopes from 54 different elements,
- for forensic science and anthropology, there are 27 different isotopes from 13 different elements,
- for geochronology (including isotopic dating of materials), there are 57 different isotopes from 39 different elements,
- for industry, there are 70 different isotopes from 34 different elements,
- for medicine, there are 110 different isotopes from 58 different elements,

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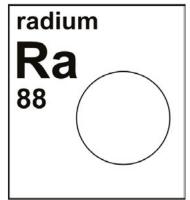
 for isotopes used to produce other radioactive isotopes, there are 58 isotopes from 35 different elements.

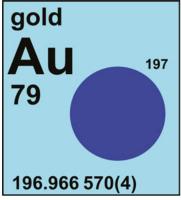
These applications provided for each element are exemplary and are not intended to encompass all isotope applications for an element. Overall, the IPTEI IUPAC report [4], also available in the electronic IPTEI [5], presents 432 applications from 96 different elements. For example, in the case of a radioactive isotope, consider that the human body contains the element potassium and one of its isotopes, potassium-40, 40 K, which is radioactive. 40 K is part of the naturally occurring isotopic composition of potassium; thus, the human body is naturally radioactive. In the case of stable isotopes, consider that the amount ratio, $n(^{13}\text{C})/n(^{12}\text{C})$, in testosterone in the human body varies from that ratio in synthetic testosterone. This fact can be used to detect performance enhancing drug use (doping) in sports.

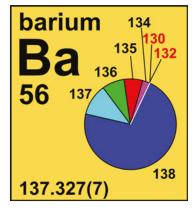
In biochemical analysis, it is easy to detect (even at low concentrations) the presence or absence of radioactive materials. Radioisotopes are used to label molecules of biological samples to determine constituents of blood, serum, urine, hormones, antigens, and many drugs. The findings from these procedures are used to diagnose diseases, such as diabetes, thyroid disorders, hypertension and reproductive problems. The tagging of cells with a therapeutic dose of radiation may lead to regression, or even cure, of some diseases.

In industry, radioisotopes are used in gamma sterilization for medical supplies and food preservation. Gamma radiography is used to scan luggage at airports. Gamma rays show flaws in metal castings or welded joints. Critical components can be inspected for internal defects without damaging the component or making it radioactive. Unlike X-ray generators, radioactive sources are small and do not require power, so they can be transported easily to remote areas where there is no power. Smoke detectors use americium-241. ²⁴¹Am, to ionize atoms of air (knock out electrons from the atom) and create a small electric current. When smoke or steam enters the ionization chamber, it disrupts the current. The detector senses the drop in current and sets off the alarm. Smoke detectors are the most abundant radioisotope-based devices used around the world.

Rapidly dividing cells are particularly sensitive to damage by radiation. Some cancerous growths can be controlled or eliminated by irradiating the area with radioactive isotopes. This is called radiotherapy. Internal radioisotope therapy is accomplished by administrating or planting a small radiation source in the target







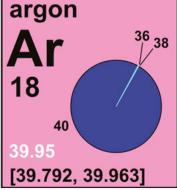


Fig. 2. Examples of the four classifications of element cells in the IPTEI. Radium, with white background, illustrates elements that have no standard atomic weight because their isotopes are all radioactive and no isotope occurs with a characteristic terrestrial isotopic abundance. The element gold, with blue background, is an example of elements having a single isotope used to determine their standard atomic weights. Barium, with yellow background, is an example of elements having two or more isotopes used to determine their standard atomic weights. Argon, with pink background, exemplifies elements having two or more isotopes that are used to determine their standard atomic weights; the isotopic abundances and atomic weights vary in normal materials, and these variations exceed measurement uncertainty, are well known, and standard atomic-weight values are given as lower and upper bounds within square brackets, []; the conventional atomic weights, such as for trade, commerce, and education are shown in white.

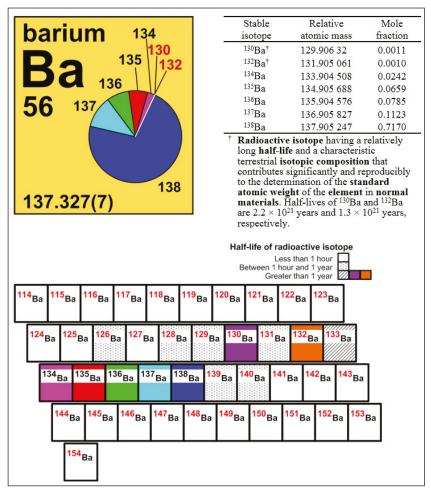


Fig. 3. Example of auxiliary information appearing in the IPTEI element-by-element review [4,5], including a table of isotopes contributing to the standard atomic weight and a chart of the stable and radioactive isotopes of the selected element (barium in this example having 41 isotopes). The background colors of stable isotopes in the chart reflect those of isotopic-abundance fraction in the pie diagram. Mass numbers of stable isotopes are shown in black and those of radioactive isotopes are displayed in red. Two isotopes (130Ba and 132Ba) have sufficiently long half-lives resulting in characteristic isotopic abundances that they are used to determine the standard atomic weight.

area. Short-range radiation therapy (called brachytherapy) is becoming the main means of treatment for cancer. Many radiation therapeutic procedures are palliative, usually to relieve pain, such as cancer-induced bone pain. These radiation procedures are preferable to traditional pain killers, such as morphine, because they improve the patient's quality of life, allowing them to be more lucid during time spent with family.

Radioactive products used in medicine are referred to as radiopharmaceuticals. Every organ in our body acts differently from a chemical point of view. Certain chemical elements are preferentially absorbed by specific organs, called targeting agents, such as iodine in the thyroid and glucose in the brain. Once a radioactive form of one of these substances enters the body, it is incorporated into the normal biological processes and excreted in the usual ways. Radiopharmaceuticals can be used for examining blood flow to the brain, functioning of the liver, heart or kidneys, assessing bone growth, predicting effects of surgery, and assessing changes since a treatment has begun.

In sports medicine, radiopharmaceuticals are used to diagnose stress fractures in bones, which are not generally visible in X-rays. The non-invasive nature of this technology, with its ability to reveal organ function from outside the body, makes this technique a powerful diagnostic tool.

Radioisotopes are used to estimate the age of groundwater from wells using the activity of naturally occurring radioisotopes in the water. Airborne testing of nuclear weapons during the late 1940s to the early 1960s doubled the amount of radioactive carbon-14, 14C, in the atmosphere. The increased number of 14C atoms in the environment acts as a radioactive tracer (substances containing a radioisotope and used to measure the speed of chemical processes or to track the movement of a substance through a natural system), enabling measurement of soil movement and land degradation. Levels of certain radioisotopes in environmental samples can be measured to check if nations are complying with agreements limiting the development of nuclear weaponry. Radioactive tracers

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can be used to trace small leaks in complex systems, such as power station heat exchangers. Flow rates of liquids and gases in pipelines, as well as large rivers, can be measured accurately with the assistance of radioisotopes. These are only a few of more than 400 applications of isotopes discussed in the soon to be published IPTEI IUPAC report [4] and the electronic IPTEI [5] for the education community. Hopefully, this comprehensive set of resources on isotopes will not only act as a compendium and ode to the 100 years of knowledge and discovery that have been witnessed and documented by IUPAC, but also impart a deeper and better understanding to the public about why isotopes matter.

To assist users who may not be familiar with some of the technical terms used in the applications phase of the element-by-element review, a glossary of terms is included at the end of the review to explain these terms in non-technical language.

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References

- IUPAC Project 2014-024-1-200, "Development and Global Dissemination of an IUPAC Interactive Electronic Isotopic Periodic Table and Supporting Resources for the Education Community," https://iupac.org/ project/2014-024-1-200
- 2. IUPAC Project 2007-038-3-200, "Development of an Isotopic Periodic Table for the Educational Community," https://iupac.org/project/2007-038-3-200
- T.B. Coplen, N.E. Holden, "Atomic Weights: No Longer Constants of Nature", Chemistry International 33(2), 10–15 (2011). http://dx.doi.org/10.1515/ci.2011.33.2.10
- N.E. Holden, T.B. Coplen, J.K. Böhlke, L.V. Tarbox, J. Benefield, J.R. de Laeter, P.G. Mahaffy, G. O'Connor, E. Roth, D.H. Tepper, T. Walczyk, M.E. Wieser, and S. Yoneda, "IUPAC Periodic Table of the Elements and Isotopes (IPTEI) for the Education Community (IUPAC Technical Report)", Pure Appl. Chem. 90(12), 1833-2092, 2018.
- 5. King's Centre for Visualization in Science, "Interactive Electronic IUPAC Periodic Table of the Elements and Isotopes," http://isotopesmatter.com/applets/IPTEI/IPTEI.html (accessed October 7, 2018)

