

Research Article

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Determination of the energy transitions and half-lives of Rubidium nuclei

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Abstract: The photonuclear reactions, first extensively studied in the 1970's and performed using the gamma rays obtained via bremsstrahlung, are a standard nuclear physics experiment. In this study, a non-enriched Rubidium sample was irradiated with photons produced by a clinical linear electron accelerator (cLINACs) with energies up to 18 MeV with the aim of activating it through photonuclear reactions. The activated sample was measured with a high purity germanium detector (HPGe) with the aim of measuring the transition energies and half-lives. The spectroscopic analysis performed on the obtained data yielded high quality results for the transition energies with precision matching or surpassing the literature data. For the half-lives the results were consistent with the literature, most notably the half-life of ^{84m}Rb decay was determined as 20.28(2) m. The results for both energies and half-lives further show that the clinical linear accelerators can be successfully used as an efficient tool in experimental nuclear research endeavors.

Keywords: Rubidium; photonuclear reaction; half-life; energy transitions.

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1 Introduction

The photon-induced nuclear reactions, which are commonly referred to as photonuclear reactions [1], have great significance in the field of nuclear physics [2–5]. Among other aspects, understanding the photonuclear reactions has an implication for the general performance of the reactors and their accurate understanding is an important part of any reactor core simulation. Additionally, understanding the photonuclear reactions is essential in nuclear astrophysics where the process of nucleosynthesis relies heavily on the interaction between photons and nuclei. Consequently, the knowledge of photonuclear reactions influences our understanding on the observed abundances of elements [6]. Hence, many photonuclear reaction experiments are motivated by needs of nuclear astrophysics [7–13].

Historically, the first photonuclear experiments were performed on deuterium in 1934 by Chadwick and Goldhaber [14] using 2.62 MeV gamma-rays of ^{208}Tl [15]. Presently, the photo-nuclear reactions are performed using dedicated superconducting linacs at several facilities around the world, most notably at S-DALINAC at TU Darmstadt [16, 17] and ELBE in Forschungszentrum Dresden in Rossendorf [18]. As a more recent development, a new innovative approach to these issues has been achieved through the use of non-superconducting clinical linear accelerators (cLINACs). The idea was initially proposed by Mohr et al. [19] and further developed by Boztosun et al. [6].

As a way of gaining knowledge on binding energies, identification of nuclear levels and nuclear deformations, the photonuclear data is important for the application in radiation protection, dosimetry, calculation of the absorbed dose, designing radiation shielding and activation analysis [1, 14, 20–22]. In addition, photonuclear reactions

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can be used as a tool for other fields of research and application outside of nuclear physics. Some of these fields are archaeological and forensic science, material analysis, medical science, environmental science, geological science, meteoroid analysis, etc. Specific examples of these applications can be seen in food analysis [23], chlorine and halogen analysis [24], international safeguards and security [25], characterization of geological, biological and environmental materials.

First photonuclear experiments in Turkey were performed on Zn element at Akdeniz University a few years ago and then described in detail in Ref. [6] and Ref. [26]. Also, the feasibility of utilizing a cLINAC was demonstrated by accurately determining the transition energies as well as the half-life values of Zn isotopes. Since then several more experiments on photonuclear reaction were performed at Akdeniz University on; platinum isotopes [15], Nb isotopes [27], Ga isotopes [1], Pr isotopes [28], Er isotopes [29] as well as several other studies have not been published yet. This manuscript is a part of the ongoing focus of researchers at Akdeniz University and their collaborators to explore the activation of nuclei via photonuclear reaction and to study the subsequent decay and its properties. Here we focus on the study of transition energy and the half-lives of ^{84}Rb and ^{86}Rb isotopes obtained from ^{85}Rb and ^{87}Rb target nuclei and compare our results to the literature data.

The paper is organized as follows; in Section 2 we explain the experiment, linac and the detectors; the results of the experiments are given in Section 3. Finally, summary and conclusions of our results are presented in Section 4.

2 Experimental details

To be successful the photonuclear reactions necessitate a sufficiently energetic and luminous photon source to be able to activate the target nuclei well. In the experiment presented here we used, a cLINAC linac, SLI-25 manufactured by Philips Medical Systems (currently a part of Elekta TM Synergy TM) [30]. The experiment was performed in two parts. The first was the irradiation, which activated the sample, and the second was the residual activity measurement. The SLI-25 cLINAC was able to provide photon beams in the energy range from 4 MeV to 25 MeV. For this experiment 18 MeV end-point energy photon beam was used. The SLI-25 beam exit was shown in Figure 1. As can be seen in the figure, 0.3 mm thick Tungsten foil, was used to convert the electrons to photons. Subsequently, the photon beam was shaped and collimated such that a

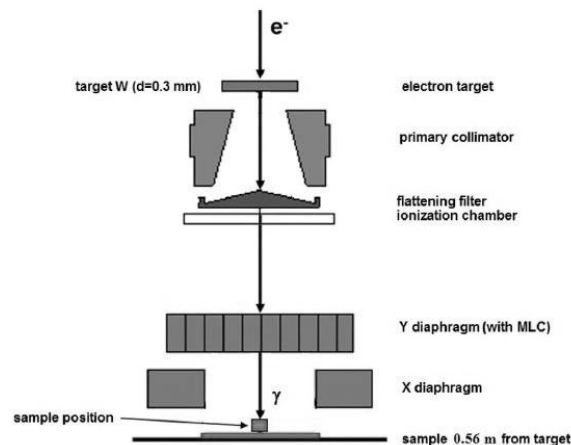


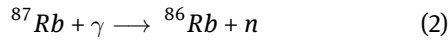
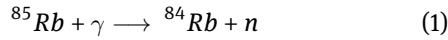
Figure 1: Schematic view of the cLINAC setup

40x40 cm² spatially flat and uniform field of photons is created at 100 cm. This is the simplest configuration of the cLINAC head components such that they do not interfere with the sample irradiation. Typically the multi-leaf collimator (MLC) is used to create a field matching the shape and size of the tumor being irradiated. Since this was not necessary for our experiment the MLC was simply left at its maximum opening, which gave the above mentioned 40x40 cm² field at 100 cm. The sample that was irradiated was placed at a 56 cm distance from the Tungsten foil.

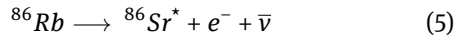
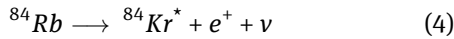
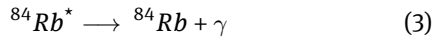
The target was Rubidium, which had two stable isotopes (^{85}Rb and ^{87}Rb), whose natural abundance and separation energies can be found in Ref. [31]. In this study, the used sample was dust weighing about 10 g placed in a small isinglass case. The irradiation time was about 60 min ensuring good activation of the sample.

After irradiation, the sample was placed into the high-purity germanium HPGe detector (p-type, coaxial, electrically cooled) used for the measurement. The detector was placed into a 100 mm thick lead shield. To protect the detector from X-rays arising in lead, the inner surface of the shield was covered by a 2 mm thick copper foil. The bias supply, an amplifier, an ADC (analog-to-digital converter) and a computer were parts of the detector system. The relative efficiency of the detector was 40% and its energy resolution was 768 eV FWHM at 122 keV (^{57}Co) and 1.85 keV at 1332 keV (^{60}Co) [32]. The sample was placed in front of the detector about 10 min after the irradiation and the counting of γ -ray lasted for three days. Throughout the counting, spectra were automatically recorded at regular time periods. Initially, those time intervals were short, designed to pursue the short-lived isotopes, while the later ones were longer in order to focus on longer-lived isotopes.

While the 18 MeV photons are sufficient to create several isotopes neighboring the ^{85}Rb and ^{87}Rb , in our analysis we observed a lesser subset due to the practical considerations of cross section and detector sensitivity. The reactions, which produced the observable isotopes for their half-lives and energy transitions study, were:



As a result of these reactions the decay of the following products was observed:



The detector spectrum was calibrated using a set of point sources and one volume source, which were provided by the Çekmece Nuclear Research and Training Center (IAEA 1364-43-2) and the Turkish Atomic Energy Authority (TAEK), respectively. The point sources contained ^{133}Ba , ^{60}Co , ^{22}Na , ^{54}Mn , ^{109}Cd , ^{57}Co , ^{137}Cs and ^{133}Ba isotopes and volume source contained different natural radioactive isotopes (^{40}K , ^{226}Ra and ^{232}Th) with known activities. The sources were counted twice, at the beginning of the experiment and at the end of the experiment. This additional experimental step was performed to ascertain and control any systematic errors which may arise due to temperature, humidity, power supply inconsistency or any other source which might cause the electronics to create a channel shifts. By averaging over the centroid positions of the calibration sources we included systematic errors into the energy calibration and subsequently into the transition energy values. The averaging is taking into consideration the stability of the electronics and accounts for any possible channel shift into our quoted uncertainty values. In addition, a background count was also carried out to ensure that there were no overlaps between the sample and the background peaks.

The MAESTRO software provided by the detector manufacturer ORTEC was used for data acquisition. Peak analysis was performed with RadWare software [33], while the remaining fitting procedures, like calibrations, were performed in ROOT [34]. For the energy calibration a choice was made for a cubic fit since it gave the lowest χ^2/ndf . The fit obtained, via ROOT, is shown in Figure 2. After the calibration has been determined all sample peak positions

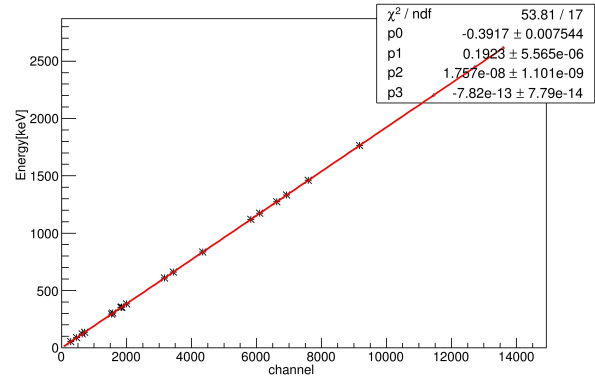


Figure 2: Energy calibration graph

were identified with the aid of the RadWare software. The values obtained for the peak positions were combined with the calibration fit obtained in ROOT to determine the energies. At the end of the data analysis procedure, the peaks were assigned to isotopes based on their energy with the aid of the literature. The results obtained and the comparison to the literature data are shown in Table 1, 2 and 3. We also note that the experimental technique and the data evaluation method of this study are identical to those reported in the earlier publications. More details can be found in Ref. [6].

3 Results

Six different transitions coming from two decays of ^{84}Rb and one transition from the decay of ^{86}Rb have been observed. Tables 1, 2 and 3 are showing the obtained values compared to the literature values. As a standard practice, we have labeled the gamma-ray observed with the parent nuclei in the beta-decay even though the observed photons come from the transition in the daughter nuclei. The association can be clearly observed from the Eq. 4 and Eq. 5. The obvious exception is the isomeric transition of ^{84m}Rb , which is just a gamma-decay and the photon association fits the elements as well. For the ^{84m}Rb decay, as shown in Table 1, the agreement with the literature is excellent, with the small difference for the 463.6 keV state. However, in all of these cases, the results we have obtained are of superior quality to the literature values. This is quite understandable for older references [35, 36] but for the most recent measurement [37] the reason of such a strong improvement in precision is likely partly due to the authors who merely state that the uncertainties for all energies below 1500 keV are ≤ 0.1 keV and do not reporting their

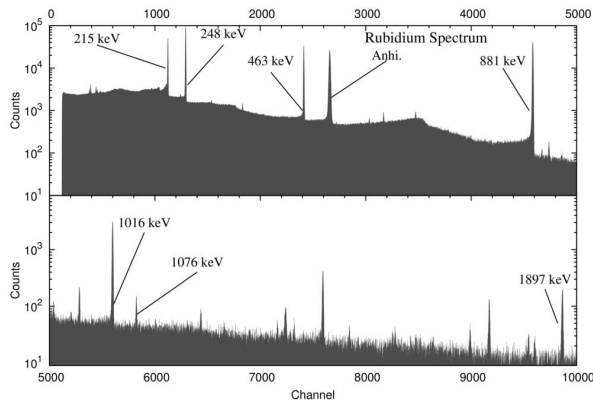


Figure 3: Gamma-ray spectrum from photonuclear reaction on rubidium target

best result. Nevertheless, we are quite satisfied to be able to report a measurement of the quality obtained.

For the beta-decay of ^{84}Rb the situation is somewhat more complex than for $^{84\text{m}}\text{Rb}$. As can be seen from Table 2 the measurement reported in the "Nuclear Data Sheets"[38] is in agreement with our measurement, but has significantly smaller uncertainties. However, it is impossible for us to comment as to why this is so, since the quoted values were obtained via private communications and have not been published. As for other, older publications shown in Table 2, our results are once again superior mostly due to improvements in detector quality.

At the end, the results obtained for the beta-decay of ^{86}Rb are shown in Table 3. As it can be seen, our result is both within the previous measurement and is far more precise than it. This is especially notable given that the result quoted in the Nuclear Data Sheets [38] is a weighted average of several measurements. This case illustrates the best the goal of our work of reducing the uncertainties in the measurement of transition energies from decay bringing them closer to the standard to which level energies have been measured in direct experiments.

Figure 3 shows the observed spectrum of the Rubidium sample. The spectrum is without any background subtraction. We have labeled the sample peaks that have been obtained, but left all the background, escape and sum peaks unlabeled. We note that, while the raw data for peak positions is in channels we have used the energy calibration to label the peaks. The detailed results for the energies are included in the tables above.

The decay curves for the stronger peaks can be used to determine the half-life of the parent, since they are in secular equilibrium. The spectra recorded needed to be divided into equal time intervals and then, for each interval, fitted

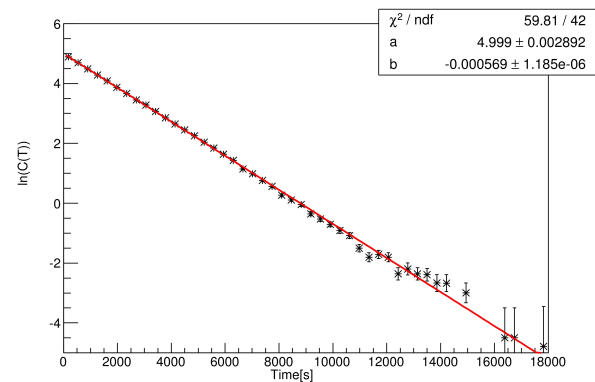


Figure 4: Fit of half-life for the $^{84\text{m}}\text{Rb}$ decay

and the value of counts determined. It is easy to show that change in the count number with time for measurement in equal time intervals:

$$C(T) = \int_{T-\Delta t}^{T+\Delta t} A(t) dt = C_0 e^{-\lambda T} \quad (6)$$

will have the same functional dependence on time as the activity ($A(t) = A_0 e^{-\lambda t}$) [1, 6, 43]. The frequency of data taking, i.e. the length of the time interval, relies on the strength of the peak. The stronger the peak the more data points can be taken and a better fit can be obtained. This is especially evident as the difference between shorter and longer half-lives were for the shorter ones having greater activity. It allows a larger number of time intervals to be used for fitting. By taking the logarithm of the obtained count values, one can convert the time dependence into a simple linear progression and thus fit it with a linear function. Through this method, in the presented work, the half-life of $^{84\text{m}}\text{Rb}$ decay, shown in Figure 4, was determined as 20.28(2) m from a weighted average, ^{84}Rb decay as 33(5) d from the 882 keV peak, and ^{86}Rb decay has been determined as 19(6) d naturally from the 1077 keV peak. We note that results for the half-life contain statistical errors only at the level of one standard deviation. The literature values of half-lives for $^{84\text{m}}\text{Rb}$, ^{84}Rb and ^{86}Rb stand at 20.26(4) m in Refs [37, 38], 32.82(7) d in Ref. [38] and 18.642(18) d in Refs [42, 44], respectively. As it is expected, the agreement for the shorter one, $^{84\text{m}}\text{Rb}$, is very good with our result having two times smaller uncertainty. At the same time, the result for the longer ones, ^{84}Rb and ^{86}Rb , is in agreement with the literature but is not as precise. This is understandable given the difference between the half-lives and the observational time. Nevertheless, we included these results for completeness sake.

Table 1: Results of energy transitions obtained from ^{84m}Rb decay and literature values (All values are in keV)

Nucleus	This Study	Ref. [35]	Ref. [36]	Refs [37, 38]
^{84m}Rb	215.610 ± 0.005	216.1 ± 0.3	216.3 ± 0.25	215.61 ± 0.10
^{84m}Rb	248.020 ± 0.005	248.24 ± 0.20	248.2 ± 0.25	248.02 ± 0.10
^{84m}Rb	463.590 ± 0.006	464.3 ± 0.4	464.5 ± 0.25	463.62 ± 0.10

Table 2: Results of energy transitions obtained from ^{84}Rb decay and literature values (All values are in keV)

Nucleus	This Study	Ref. [38]	Ref. [39]	Ref. [40]
^{84}Rb	881.591 ± 0.009	881.6041 ± 0.0016	881.46 ± 0.20	881.6 ± 0.1
^{84}Rb	1016.18 ± 0.03	1016.158 ± 0.011	1015.86 ± 0.30	1015.9 ± 0.3
^{84}Rb	1897.80 ± 0.04	1897.751 ± 0.011	1897.02 ± 0.30	1897.6 ± 0.2

Table 3: Results of energy transitions obtained from ^{86}Rb decay and literature values (All values are in keV)

Nucleus	This Study	Ref. [41]	Ref. [42]
^{86}Rb	1076.80 ± 0.01	1077.2 ± 0.5	1077.0 ± 0.4

4 Summary and conclusions

In the work presented here, we have studied the decay of nuclei produced by activating Rubidium isotopes with the aid of a clinical linac. The isotopes were produced by inducing photonuclear reactions with an 18 MeV end-point energy, bremsstrahlung beam. The activation was sufficient to observe the decays of ^{84m}Rb , ^{84}Rb and ^{86}Rb produced by neutron separation. Although the proton separation from ^{85}Rb and ^{87}Rb was likely to be occurred, no decay was observed, supposed that ^{84}Kr and ^{86}Kr were stable.

We have determined the transition energies of the several daughter nuclei in addition to the half-lives of the parent nuclei appearing in the decay. The data obtained for the transition energies show good agreement with the literature often surpassing it in terms of precision. This is not entirely surprising given that, much of the references for the transition energies are quite dated and thus this work serves to update those values to a better standard. Furthermore, in the case of ^{84}Rb we have the peculiar case of there being no publication of the transition energy data, the quoted values in Nuclear Data Sheets coming from private communications. Given that, such cases are impossible to verify or understand how they were achieved, we feel that, although out precision in that case is somewhat lesser, the transparency of publication adds merit to our results.

Besides the transition energies the data we obtained also allowed us to determine the half-lives of the parent nuclei. The results shown offer consistency with the literature data but are limited in their precision by the observational time. The only exception is the decay of ^{84m}Rb , which was in good agreement with the literature and showed half of the uncertainty seen in the literature data.

Consequently, we have obtained results that can add knowledge to the nuclear databases in regards to Rubidium. Furthermore, we have demonstrated the usefulness of cLINAC in experimental nuclear physics and overall we have once again, [1, 6, 15, 26–29] demonstrated that a clinic electron accelerator may activate nuclei well enough.

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