Photonuclear reactions induced by a clinical linac

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Abstract. The use of a clinical linac in photonuclear experiments is a novel concept. At Akdeniz University a program has been started focused on inducing photonuclear reactions with a Philips SLI-25 clinical linac. A bremsstrahlung photon beam produced by the linac is used to create radioactive nuclei. The decay of said nuclei is observed with a high-purity germanium detector. During the course of the experiment the spectrum of the irradiated sample is recorded. By analyzing the spectrum the energies of gamma-ray transitions in the daughter nuclei as well as the half-life of the parent nucleus are obtained. The results obtained thus far, starting with Zinc nuclei will be presented.

The study of the photon-induced nuclear reactions has been a focus of interest over the years. The motivation for studying the interaction of photons with nucleus are many, but primarily photonuclear reactions experiments are aimed at and motivated by astrophysical references to nucleosynthesis, see Ref. [1, 2, 3, 4] and references there-in. In addition applications of the photonuclear reaction in elemental analysis are many. The appeal for studying photonuclear reaction also comes from availability of a good radiation source.

Photoactivation experiments involving linear accelerators have been performed at several institutions around the world Ref. [5, 6, 7, 8, 9]. In Ref. [10] a new idea of using clinical linac for photonuclear studies was presented. Locally we have had some initial success with this idea Ref. [11] and now wish to expand on it. The aim of the present work is to further expand the concept of using clinical linacs in photonuclear studies by setting up an experiment centered around a clinical linac in order to study nuclear reactions and nuclear structure and to investigate how such setups can contribute to the expansion of the nuclear physics knowledge base. For this purpose, we have chosen to study transition energies and half-lifes of isotopes created by photonuclear reactions with Zinc.

The photonuclear reactions require a source of photons to excite the target nuclei. For us this was an clinical electron linac SLI-25 manufactured by Philips Medical Systems (currently part
of Elekta TM Synergy TM). The accelerator technical documentation can be found in Ref. [12]. Its properties compare well with dedicated linacs Ref. [10].

The cLINAC primary electron beam is generated by an electron gun with an energy of about 50 keV. The electron gun in SLI-25 is a diode design with a 400 Hz pulse repetition frequency. After injection into linac’s copper cavity, the electrons are accelerated by a radio-frequency wave with 3 GHz (2856 MHz), S-band. SLI-25 copper cavity is a traveling wave design. The power is provided by the magnetron with nominal power of 2.5 MW at 4 MeV (low energies) and 5 MW at 25 MeV (high energies).

After excitation of the copper cavity, the beam falls onto the a high-Z element target, in our case, Tungsten. The Tungsten target is 0.3 mm thick and serves as an electron stopper and a bremsstrahlung photons source. The photons are collimated and flattened with several filters, as illustrated in Fig. 1 left, resulting in a spatially uniform photon beam with no position dependance. The focusing and collimation is a standard feature of all cLINAC, as it is paramount to maintain excellent spatial dose profile control when irradiating a patient. In fact, it is common to require dose knowledge to better than 3% accuracy.

Figure 1. Left: Schematic view of the linac. Right: EGS simulation of bremsstrahlung energy distribution from an electron beam accelerated over an 18 MV potential difference impacting on thick Tungsten target in Philips SLI-25 clinical linac. The distribution is normalized per incoming particle.

In our experiment, we have collimated and flattened the beam such that it covers a 40×40 cm$^2$ area at a 100 cm distance. This is a maximum area at this distance and it was chosen primarily for ease of use. Other, smaller or irregularly-shaped openings of collimators are easily achievable.

Under all of these conditions, the question of bremsstrahlung energy distribution, which comes from the linac, becomes a quite complicated one due to presence of all the filters and collimators. A simulation of the photon energy distribution coming from the SLI-25 was performed using the BEAMnrc package. The resulting distribution is shown in Fig. 1 right. For the estimate of the flux we used the delivered dose rate 5 Gy/min Ref. [12] leading to $5 \times 10^5$/ (MeVcm$^2$ s photons at $E = 6$ MeV.

In the experiment, one Zinc sample was placed immediately outside the cLINAC head at about 56 cm source to sample distance, see Fig. 1. The sample in question was a Zinc disk weighing 5 g with 5 mm diameter and 1 mm thickness. The sample was irradiated for about 35 min. The sample was made primarily of zinc (67% by mass fraction). Since no special effort was made to isotopically enrich the target, the presence of different Zn isotopes can be considered as those of their natural abundances.
After the irradiation, the sample was transported to the Physics Department of Akdeniz University, where the high-purity Germanium detector (HPGe) detector was located. It is a p-type, coaxial, electrically cooled HPGe, placed in a well-shielded cavity. The shield is 10 cm thick lead with an inner surface covered by a 2 mm copper foil to reduce the X-rays originating in lead. The HPGe used is a gamma-ray spectrometer from AMATEK-OR TEC (GEM40P4-83) with 40% relative efficiency and 768 eV FWHM at 122 keV for $^{57}$Co and 1.85 keV FWHM at 1332 keV for $^{60}$Co Ref. [13]. The HPGe is connected to a standard NIM equipment. The sample was placed into the detector about 10 min after the irradiation and counted for three days.

Immediately before counting the sample, a set of calibration sources were counted. After the sample was counted, an equivalently long natural background spectrum was recorded. Once the background spectrum was recorded, the experiment was concluded with a second measurement of the calibration sources.

The process of photactivation applies to all the nuclei for which the bremsstrahlung radiation exceeds the reaction threshold. Given that the end-point energy of our beam was 18 MeV, it is expected that all of the stable Zn isotopes will get activated. However, our experimental setup was not designed for direct observation of the stable Zinc isotopes, so we have to rely on the radioactive decay of the created nuclei. In this respect, we list the decay reactions which we have observed in the experiment presented

$$^{63}\text{Zn} \rightarrow ^{63}\text{Cu}^* + e^+ + \nu, \quad (1)$$

$$^{65}\text{Zn} \rightarrow ^{65}\text{Cu}^* + e^+ + \nu, \quad (2)$$

$$^{69}\text{Zn}^* \rightarrow ^{69}\text{Zn} + \gamma, \quad (3)$$

$$^{67}\text{Cu} \rightarrow ^{67}\text{Zn}^* + e + \bar{\nu}. \quad (4)$$

Here too, we have yet another limitation to what we can observe. As is noticeable the beta-decay of $^{69}\text{Zn}$ is missing even though it most certainly did happen. The limitation here is the low branching ratio of the decay into the excited states of $^{69}\text{Ga}$ which goes, almost exclusively (99.998%), to the ground state.

After the data acquisition by the MAESTRO software, the peak analysis needed to be performed. However due to the limitation of the MAESTRO software, a decision was made to seek out other analysis programs. After some testing, we realized that the best option for the data analysis was to combine two different tools. One was the standard RadWare code developed for analysis of gamma-ray coincidence data, by David Radford of the Physics Division at Oak Ridge National Laboratory. The other was the ROOT, which is a package with extensive library structure, developed by CERN. The motivation for using two different programs was to strike a balance between the desired accuracy and time consumption of the data analysis.

The results obtained after analysis the sample eliminating the background peaks and performing both calibration before and after are show in Table 1 left. For calibration we used quadratic fit. And propagated the error from calibration according to:

$$\sigma^2_E = \sum_i^n \left( \frac{\partial E}{\partial \alpha_i} \right)^2 \sigma^2_{\alpha_i} + 2 \sum_i^n \sum_{j>i}^{n} \text{cov}_{ij} \left( \frac{\partial E}{\partial \alpha_i} \right) \left( \frac{\partial E}{\partial \alpha_j} \right) + \left( \frac{\partial E}{\partial \text{ch}} \right)^2 \sigma^2_{\text{ch}} \quad (5)$$

where $E = \sum_i^n a_i ch_i$ is the calibration polynomial, with $\alpha_i$ calibration parameters, $\sigma_{\alpha_i}$ are the errors of the fit parameters, $\sigma_{ch}$ is the errors of the centroid and cov$_{ij}$ is the covariance matrix.

Next we combined the two calibrations into a final result via Ref. [14]:

$$\sigma^2_E = \frac{\sigma^2_{E_{bef}} + \sigma^2_{E_{aft}} + (\bar{E}_{bef} - \bar{E})^2 + (\bar{E}_{aft} - \bar{E})^2}{2} \quad (6)$$

$$\bar{E} = \frac{\bar{E}_{bef} + \bar{E}_{aft}}{2} \quad (7)$$
where $\bar{E}_{bef}$ and $\bar{E}_{aft}$ are the energies from before and after calibration and $\sigma_{E_{bef}}$ and $\sigma_{E_{aft}}$ are the corresponding errors, respectively.

If we compare these results with the literature values, it is possible to assign these peaks to specific isotopes and their transitions. In figure Fig. 2, we show the irradiated sample spectrum without any background subtractions. The assignment of peaks is evident in the figure. All the unsigned peaks are either background peaks or sum and escape peaks.

![Figure 2. Full Zn spectrum with no subtractions, for the irradiated sample after 3 days of counting. Assigned peaks based on energy calibration.](image)

The primary motivation for this study has been the study of proton rich nuclei. The case of $^{63}\text{Cu}$, as the decay product of $^{63}\text{Zn}$ a proton rich nucleus, is where we see the best results. We draw the reader’s attention to the especially good results for 1327.03 keV, 1392.55 keV, 1412.08 keV and 2026.8 keV, where our results fit almost completely within the NUDAT error bars, while having a better accuracy. In general, this range of values, between 1000 keV and 2000 keV, is where we expect that these kind of renewed studies on intermediate mass proton rich nuclei could contribute to the improvement of data on other nuclei as well. It is also our intent to continue these efforts in the future.

In addition to the transition energies, the analysis performed provided information about counts and their time evolution. This information can be used to determine the half-life of the parent nucleus as the decay of the daughter levels are in secular equilibrium with the $\beta$-decay of parent nucleus. Secular equilibrium is a very good assumption here since the half-life of the states in question is orders of magnitude smaller than the parents. The only exception is the $^{69}\text{Zn}$, which is an isomeric transition and is thus observed directly. The summary of the half-life fits for $^{63}\text{Zn}$ is given in Table 1 right.
Table 1. Left: Sample peak energies from energy calibration before and after measurement of the sample. Right: $^{63}$Cu half lives, NUDAT value 38.47 ± 0.05 min.

In addition to $^{63}$Zn, we also fitted the decay of $^{69}$Zn isomeric transition and obtained $13.76\pm0.18$ h while the literature value is $13.76\pm0.02$ h in good agreement with each other. Of the other two observed decays $^{65}$Zn and $^{67}$Cu, we were not able to fit them. The $^{65}$Zn was not fittable due to unfavorable ratio of its long half-life (244 d) and observation time (3 d). The $^{67}$Cu was not fittable due to the weakness of the signal. Like in the case of $^{63}$Cu, peaks not listed in the Table 1 right had too big errors to allow for a reasonable fit.

In the experiment presented, we have investigated the spectra and half-lifes created by photonuclear reactions on Zn isotopes. The photonuclear reactions were induced by a bremsstrahlung photon beam generated by a linac. The particularly interesting point at which we differed from previous such experiments is that this was a medical linac.

For the photonuclear reactions, we used a beam of 18 MeV end-point energy, which is well above of proton and neutron separation energies of all Zinc isotopes. However, our experiment was not designed to observe Zn levels since it was offline. Instead we observed the energy levels of the daughters of produced nuclei. These transitions, as well as the half-lifes of the parent nuclei, were our intended goal.

The experiment was separated into several parts, the crucial ones being the sample spectrum measurement, analysis and the calibrations. We have payed close attention to the calibration quality and we were confident that the end result had a good robustness and was reliable.

We have demonstrated quite confidently that the experiments such as ours can shed new light on transition energies. Indeed, we have obtained results, which are in good agreement with the literature values. But most importantly, we have obtained results better than those found in the literature in several instances. Our main contribution can be seen in the case of $^{63}$Cu, whose levels we have consistently determined to an accuracy level that is same or better than found in the literature. Thus, we believe that linac-based studies on proton rich nuclei can offer improvements of data in many intermediate mass nuclei. On the half-life side, our data is not as nearly impressive as for the transition energies. However, given the limitation of this study, it is still a nice check of consistency. Obviously, increased experience in these kind of experiments
will also contribute to improvement of results in the future.

In this paper, we have shown the results of an ongoing effort on part of the Physics Department at Akdeniz University to establish an experimental nuclear physics group. The campaign started last year with our first photonuclear reactions experiment, Ref. [11], marking a milestone in experimental nuclear physics in Turkey. Since then, as this paper illustrates, we have made significant progress in our effort to contribute to nuclear physics at large. The quality of the results shown in this paper clearly illustrates that the approach we have adopted can contribute significantly to photonuclear reaction research at large. In addition, this effort has lead to the expansion of experimental nuclear physics at Akdeniz University in terms of both experimental know-how and new possibilities of applied nuclear physics.

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