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Study of half life measurement and Gamma-Transitions for ^{44}Sc using Photo-Nuclear Reaction

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Abstract

An experiment based on photonuclear reaction was performed to measure half-life and study the gamma-transitions for scandium nucleus with bremsstrahlung photons of 18 MeV end point energy, generated by a clinical linear accelerator. These photons were used to irradiate scandium sample. The HPGe detector calibration for before and after counting was carried using standard point sources and a volume source. For analysis of results and spectrum gf3 and ROOT package was used. As a result of this experiment ^{45}Sc(γ,n)^{44}Sc gamma-ray energies, associated errors and half-life value of ^{44}Sc from ground state were calculated and found in agreement with the published literature values.

Keywords: Photon Activation, High Purity Germanium (HPGe) Detector, Half-life measurement, Clinical Linear Accelerator (cLINAC), γ-transitions.

1. INTRODUCTION

The understanding of nuclear structure and determination of elemental concentration in a particular sample of interest plays vital role in the field of experimental nuclear physics. Without getting specific knowledge about important phenomenona, processes and transitions in this specific area we are unable to understand complete structural picture of a nuclei [1]. In this context various activation processes like charged particle activation (CPA), neutron activation etc have been employed, but one advantageous approach for such investigation is photon activation [1-6]. Present work is based on photon activation process. In this method an interaction between a photon and a nucleus takes place. Employing a linear accelerator (LINAC) with the induction of bremsstrahlung photons this reaction can be generated. Role of clinical linear accelerator in such experiments is induction of photons. For detail study about nuclear structure this approach is playing important and significant role providing determination of gamma transitions in elements of interest [7-9].

Using medical linear accelerator Zinc isotopes (employing photo-activation approach) were studied for the first in Turkey. Reports in recent past reveals that clinical linear accelerator (cLINACs) can be used for photon generation to activate radioactivity artificially in nuclear experiments [10]. Photons used for radioactivity activation were obtained by bombarding tantalum or tungsten bremsstrahlung converter with electrons.

Present investigation focuses about half-life measurement and gamma-ray energy transition for Scandium (44Sc). This isotope has significance importance due to its positron emitting properties and positron emission tomography (PET) imaging for medical applications mostly for cancer patient's treatment. This element is playing vital role in the field of nuclear medicine as well [11]. That's why it is important to pay attention for investigation for this interesting isotope. Further in this work we demonstrate on the practical application of clinical linear accelerator (cLINACs) other than in medical field and compared our measured results with previous literature as well as NuDat database [12].

Our article is organized as follows. Introduction has been presented in first section. Materials and method part will be discussed in section 2. Results will be analyzed in section 3, following results section in last part conclusive remarks will be mentioned

2. EXPERIMENT

Using photonuclear approach as clear from name a photon source needs to activate or excite target element. In this work clinical linear accelerator SLI-25 made by Philips Medical Systems has been used in present experiment as a photon source to irradiate sample. It currently part of Elekta TM Synergy.

Irradiation of target sample was performed using the cLINACs as discussed before. It can also be considered as origin of photons [13]. Photons are generated by the electron gun using energy of 50 keV. Acceleration is the next step after injection into linac's copper cavity. The acceleration is done by radio-frequency wave with 3 GHz, S-band. Copper cavity in SLI-25 was design for traveling of wave. Power supply is provided by magnetron with nominal power of 2.5 MW at 4 MeV (low energy) and 5MW at 25 MeV (high energy).

For experiment, the sample target was placed 58 cm far from target high-Z element (in present case tungsten). This tungsten works as an electron converter. Generated bremsstrahlung photons were collimated and flattened with the help of some filters, yielding a uniform focused beam of photons without position dependence. Whole scheme has been displayed in the Fig. 1. All cLINACs follow a standard feature of collimation and focusing. Target sample was irradiated for the period of 35 minutes.

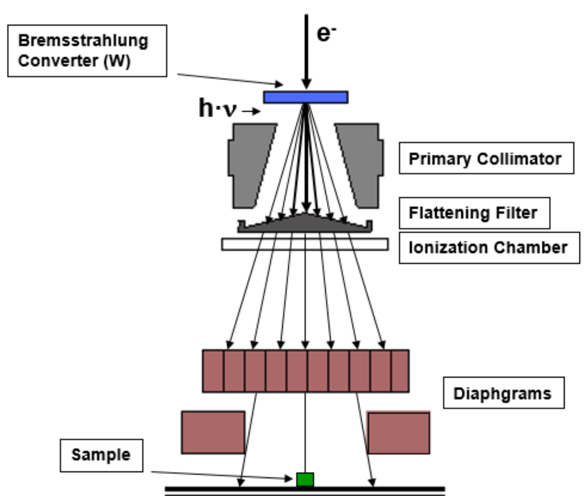

Figure 1. Schematic view of the c-LINAC setup

After irradiation the sample was measure with a high purity Germanium detector (HPGe). It is a p-type, coaxial, electrically cooled HPGe detector. This detector is covered by a 10 cm thick lead layer with inner surface shielded by 0.2 cm copper foil for reduction of Pb X-rays. The HPGe detector used in present study has 40% relative efficiency and resolution of 768 Ev FWHM at 122 keV and 1.85 keV FWHM at 1332 keV (Maestro 2012). Energy calibration was made with the help of standard point sources containing following isotopes ^{22}Na, ^{54}Mn, ^{57}Co, ^{60}Co, ^{109}Cd, ^{133}Ba and ^{137}Cs; provided by Çekmece Nuclear Research and Training Centre (IAEA 136443-2). A soil sample in addition with these point sources (supplied by Turkish Atomic Energy Authority (TAEK) containing the naturally radioactive isotopes ^{40}K, ^{226}Ra and ^{232}Th) was also utilized for calibration. During spectrum analysis only strong photo-peaks of gamma-ray energies were analysed. The HPGe was attached to a standard Nuclear Instrumentation Modules (NIM) equipment, containing analogue to digital converter, ORTEC pre-amplifier, spectroscopy amplifier, bias supply and a computer respectively. Data acquisition was carried out using MAESTRO32 software (MAESTRO, 2012). At uniform interval of time the same spectra were recorded automatically. Initially time intervals were short ~ 3s and ~ 12s, designed to follow the short lived isotopes, and while the later ones became longer when focusing on longer lived isotopes. After the gamma-ray computation for the sample was finished, spectrum for natural background was recorded. Data evaluation procedure and experimental approach performed in present study was similar to that described in [14].

Figure 2. HPGe detector setup at NUBA used in present work

3. RESULTS AND DISCUSSION

In this work we concentrated on measuring half-life and gamma ray energy transitions for ^{44}Sc nucleus, produced by bremsstrahlung photons of end-point energy of 18 MeV, measured with the help of HPGe detector. For data analysis we choose as best option to combine two different programs. First was use of standard gf3 RadWare code written by David Radford [15] of the physic division at Oak Ridge National Laboratory, Second was ROOT [16], which was a package having extensive library structure, developed by CERN. These programs were employed to check gamma ray energy peak value for ^{44}Sc and its half-lives during its decay activity. The functions we used for fitting procedure has been shown in Fig.3 on the strongest peak 1157 keV. And the corresponding gamma spectrum for ^{44}Sc has been shown in Fig.4.

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 for the calibration source. A linear polynomial fit function has been used for before and after calibrations. The error propagation from calibration were obtained using following relation:

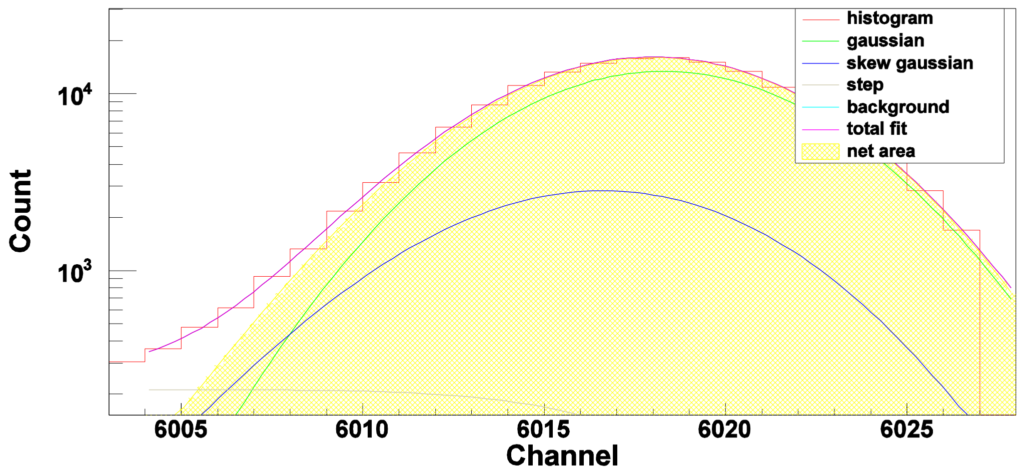

Figure 3. The functions used for fitting procedure during the analysis

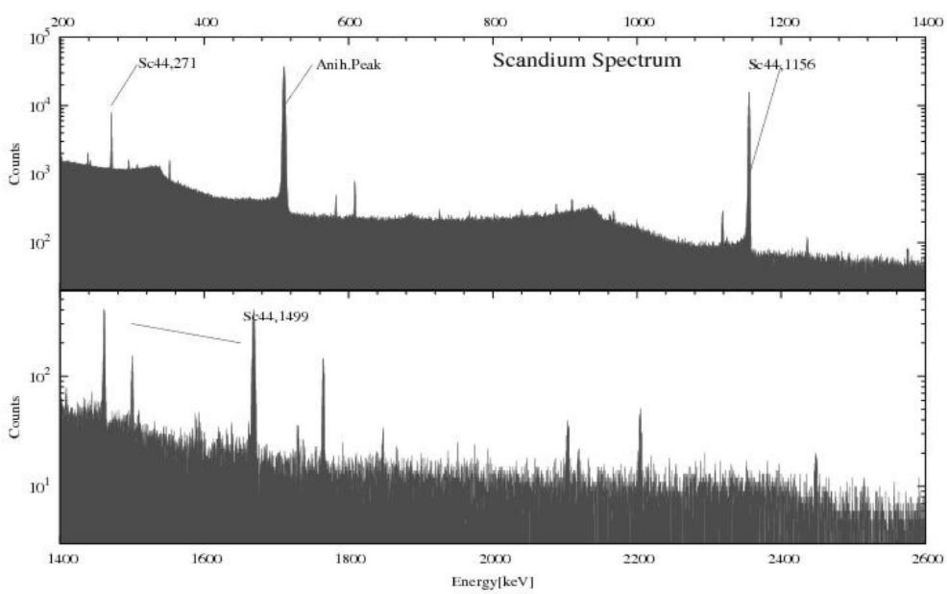

Figure 4. ^{44}Sc spectrum without any subtraction for Scandium sample which was irradiated for 3 days counting. Labelled peaks were based on energy calibration.

$$\sigma_E^2 = \sum_i^n \left(\frac{\partial E}{\partial ci}\right)^2 \sigma_{ci}^2 + 2\sum_i^n \sum_{j>i}^n Cor_{ij}\sigma_i\sigma_j \left(\frac{\partial E}{\partial ci}\right)\left(\frac{\partial E}{\partial cj}\right) + \left(\frac{\partial E}{\partial ch}\right)^2 \sigma_{ch}^2 \quad (1)$$

Here in Eq. (1) E is calibration polynomial, as $E = \sum_i^n c_i ch^i$, calibration parameter is shown by 'c' while fitting parameters error presented with σ_{ci}, σ_{ch} for centroid errors and Cor_{ij} for correlation matrix element. Two combinations of calibration for before and after counting performed to obtain final results are [19],

$$\sigma_E^2 = \frac{\sigma_{E_{bef}}^2 + \sigma_{E_{aft}}^2 + (E_{bef} - \bar{E})^2 + (E_{aft} - \bar{E})^2}{2} \quad (2)$$

$$\bar{E} = \frac{E_{bef} + E_{aft}}{2} \quad (3)$$

Energies for before and after calibration and associated errors are denoted by E_{bef}, E_{aft},$\sigma_{E_{bef}}$, $\sigma_{E_{aft}}$ respectively.

Table 1. Comparison of Gamma-ray energies obtained in the present measurement by average the results of before and after calibration with values found in the literature (NUDAT) [12]

Element	**E_{NU}(keV)**	**σ_{NU}**	**E (keV)**	**σ_E**
^{44}Sc	1157.02	0.015	1157.114	0.06
^{44}Sc	271.24	0.01	271.263	0.011

In Table 1 a comparison between average energy and combined variance with literature values is shown. Cited results has been taken from nuclear data sheet publications and NUDAT [12]. A comparison between present results and literature demonstrates that particular peaks in the spectrum (shown in Fig. 4) points the presence of ^{44}Sc. In this spectrum only prominent peaks for ^{44}Sc are labelled while rest are either sum, escape or background peaks. We analyse only significant peaks for ^{44}Sc spectrum especially at 1157 keV and 271 keV where results of this work are in agreement with the NUDAT error bars. Precision regarding gamma-ray energies and errors are quite satisfactory and accuracy concerning with the half-life results is in good agreement with literature value. One major cause for the differences of energy values measurements should be concern with the energy resolution of HPGe detector. The energy resolution of the HPGe detector employed in the present study is 1.85 keV at 1.33 MeV. These factors can cause unfavourable effects on the measured data of the peak of interest, and plays significant role in the ambiguity.

The principle goal for present work was to focus on the calculation of half-life, gamma-ray energies respective errors for a radio isotope which has significance application in the medical field. This information tells us about half-life of parent nucleus as decay of daughter levels are in secular equilibrium with the decay of parent nuclei.

To calculate the half-life value, we have integrated the activity with the same interval of time:

$$C(T) = \int_{T-\Delta T}^{T+\Delta T} A(t)dt = C_0 e^{-\lambda\tau}(e^{\lambda\tau} - e^{-\lambda\tau}) \quad (4)$$

Where $C_0 = A_0/\lambda$ and T is counting time. Because the ΔT and λ are constants, this function only depends on T.

Using the logarithmic form of the Eq. (4), we have obtained a linear function:

$$\ln(C(T)) = A - \lambda \quad (5)$$

After fitting procedure, we have calculated the value for measured half-life from the relation

$$T_{1/2} = \frac{ln2}{\lambda} \quad (6)$$

Present results for half-life and associated errors for ^{44}Sc in comparison with literature statistics is shown in Table 2. It can be observed results for short half-life and error are in agreement with literature values [12, 17].

Table 2. Measured half-life for this work (TW) with associated error in comparison with literature (NUDAT) [12, 17-18] half-life and error.

Decay Set	$T_{1/2}$ NU[hour]	$T_{1/2}$ NU[hour]	σ_{NU}	σ_{TW}
^{44}Sc(IT)	58.61	59.81	0.1	2.2
^{44}Sc (ε)	3.97	3.95	0.04	0.04

We fitted transitions for ^{44}Sc positron decay from the ground state and as a result obtained 3.95±0.04 hours while literature value is 3.97±0.04 hours. On the other hand, the half-life value for ^{44}Sc isomeric transition from 271 keV level is not in good agreement with the literature value. Reason for this might be due to long half-life and as a result of this, weak statistic. Because of the same reason, we could not determine properly the half-life value using 1157 keV peak for ^{44}Sc positron decay from the level 271 keV. Fig. 5 and Fig. 6 show the logarithmic decay tendency of the peaks 271 keV and 1157 keV respectively.

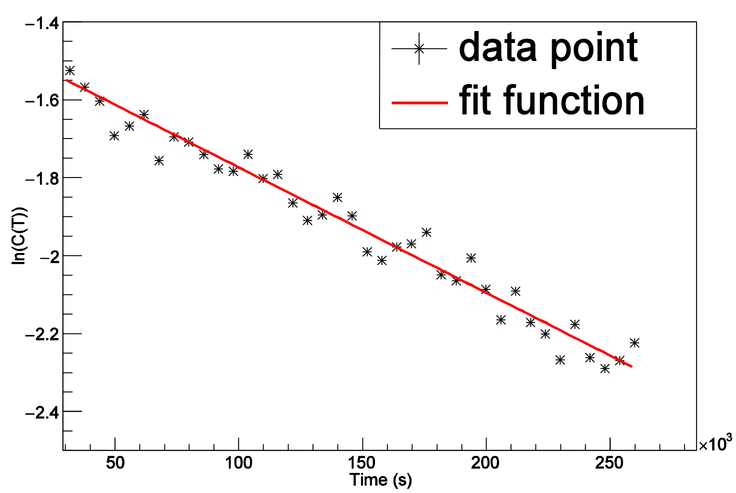

Figure 5. Logarithmic decay tendency of the peak 271 keV

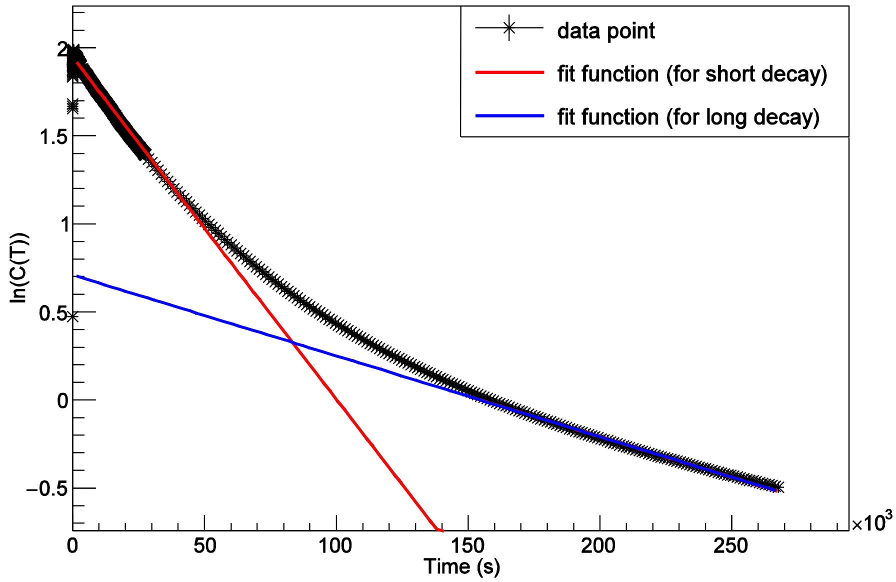

Figure 6. Logarithmic decay tendency of the peak 1157 keV

As we can see from our present results given in Table 1 and Table 2, although we have used the photon activation method, the values are satisfactory and comparable.

4. SUMMARY AND CONCLUSION

In present work we look into spectra for half-life of ^{44}Sc by photon activation approach. The photonuclear reaction were produced using a cLINACs which generate bremsstrahlung photon beam to activate the desired sample. One interesting point in present work was the employment of cLINACs for the experimental field of nuclear physics successfully. For neutron and proton separation energy of this scandium isotope we used 18 MeV as end point energy which was quite above of both these separation energies. Crucial part of the experiment was the measurement of sample spectrum, its calibrations and analysis. We calibrated these results quite deliberately and consciously so about end point results we can say confidently. Present results demonstrate acceptable and satisfactory agreement with the literature as well as measured data.

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