

Effect of target density uncertainties on extracted experimental cross sections for the $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$, ^{46}Sc reactions

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Abstract. The production optimization of medical radioisotopes for various applications requires careful analysis of all production parameters. The importance of such radioisotopes in nuclear medicine cannot be overemphasized. During cross section calculations, experimentalist sometimes find more than one reported literature value of a certain parameter, each leading to a different effect on the overall cross sections. In the present work, we considered the effect of slight variations of density values of titanium reported in the literature on the experimental cross sections. Several reported density values (4.50, 4.51 and 4.54 g/cm³) were found in the literature, but only the lowest and highest values (4.50 and 4.54 g/cm³) were considered in this study. The said densities were used to calculate the cross sections of $\text{Ti}(\alpha, x)^{51}\text{Cr}$, ^{46}Sc radioisotopes. The corresponding trends of the excitation functions of ^{51}Cr and ^{46}Sc were analyzed for the selected density values. The calculated cross sections from the different density values have been analyzed and compared graphically to show the level of variations, as well as comparison with theoretical TALYS code calculated cross sections. About 1 percent variation of the cross sections have been observed. Following the observed slight variation in cross sections effect of the various density values, we recommend that IAEA could update its nuclear data service database to include recommended density values for all metals using reliable sources.

1 Introduction

Production cross sections of radioisotopes are important for their applications in nuclear medicine, astrophysical studies and many other fields. From the popular cross section equation Eq. (1) [1], several parameters and quantities such as the beam intensity, atomic density, target thickness, atomic decay data, etc. are involved during calculation of the cross sections. Small variation of one quantity or parameter could lead to an effect on the overall cross sections. As an example, a slight difference in the values of decay characteristics of one radioisotope may give an obvious difference of final cross section values.

Density is one of the important parameters useful in the calculation of cross sections. However, following the availability of many works in the literature, researchers sometimes find several values of the atomic densities on same element. Each of these values when used in Eq. (1), would give a particular value of cross sections. A simple online search of density of titanium will yield several literature values such as 4.5 g/cm³ [2], 4.51 g/cm³ [3,4] and 4.54 g/cm³ [5].

The aim of the present work is to have a closer look on the effect of atomic density on the overall cross section calculations of ^{46}Sc and ^{51}Cr via $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$ and $^{nat}\text{Ti}(\alpha, x)^{46}\text{Sc}$ reactions respectively. Both ^{46}Sc and ^{51}Cr are very important radioisotopes with several applications.

Following the good decay characteristics of ^{46}Sc ($T_{1/2}$ = 83.79 d, decay modes: β^- (100%); 889 keV (I_γ = 99.98), 1120.545 keV (I_γ = 99.99)), the radioisotope has been proposed as ideal in beam monitoring, just as the popularly known ^{48}V radioisotope [6]. Similarly, the excellent decay characteristics of ^{51}Cr and its fine shape of excitation function which make it useful in monitoring irradiations under alpha beams [7]. The ^{51}Cr is also used to label red blood cells for measurements of mass or volume of blood [8,9] and in labeling platelets to determine their survival period as well as in diagnosis of gastrointestinal bleeding through sequestration studies [9].

2 Experimental

The detailed experimental procedure is available in our previous studies [1, 10]. The stacked-foils activation technique was employed for the irradiation of target while an offline HPGe γ -ray spectrometry was used to measure the emitted gamma activities from the irradiated foils. Titanium foil 10.40 μm thick (source: Goodfellow company, UK, purity: >99.6%) of isotopic natural composition (^{46}Ti : 8.25 %; ^{47}Ti : 7.44 %; ^{48}Ti : 73.72 %; ^{49}Ti : 5.41 %; ^{50}Ti : 5.18 %) [11] was used as a target material in a stack also consisting of foils of copper and holmium. A target holder in the form of Faraday-liked cup was made to hold the prepared stack for the irradiation by

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alpha beam. The irradiation was done using the AVF cyclotron of RI Beam Factory, Nishina Centre for accelerator-based science, RIKEN Institute, Japan.

The irradiated foils were transferred from the irradiation room to a hot laboratory where a gamma ray spectrometer was used for measurements of gamma activities using a high-resolution HP Ge γ -ray spectrometer. The spectrometer was coupled to a 4096 multi-channel analyser as well as some other associated electronics. Analysis of the gamma spectra was performed using a gamma program, a Maestro software (ORTEC; Ver. 7.01).

The incident beam intensity on our stack was calculated using gamma activities from a Ti foil placed at the front position of the irradiated stack, making the foil to receive a 50 MeV alpha beam delivered by the cyclotron. The beam intensity of the alpha beam was determined using the IAEA recommended $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$ monitor reaction ($\sigma = 26.4$ mb at $E_\alpha = 50$ MeV) [12]. The calculated intensity of the alpha beam was considered constant throughout the stack and was thus used for the calculation of cross-sections of each stacked foil. The alpha beam energy on each foil in the stack was calculated using a computer software, SRIM-2003 [13].

The cross-sections, $\sigma(E)$, of the studied radioisotopes were extracted from experimental data using the activation formula used in our previous studies [14-18] by taking into account some target parameters such as thickness and density, as well as the parameters of the incident bombarding particles. The calculations of the cross sections were done twice using two literature titanium density sources: 1) 4.50 g/cm³. 2) 4.54 g/cm³.

$$\sigma(E_i) = \frac{C(E_i)\lambda}{\varepsilon_\gamma I_\gamma t_h \rho \varphi (1 - e^{-\lambda t_{irr}})(e^{-\lambda t_{cool}})(1 - e^{-\lambda t_{mea}})}, \quad (1)$$

In which $C(E_i)$ stands for the net counts of the nuclide under the photo-peak area at the j -th sample, λ represents the decay constant ($\lambda = [\ln 2]/T_{1/2}$) of the radioisotope,

ε_γ is for efficiency of detection, t_h is the thickness (cm) of the irradiated foil while ρ is the atomic density of the target (8.49×10^{22} atoms/cm³). Similarly, φ is the intensity of the alpha beam (5.45×10^{11} particle/s), while t_{irr} , t_{cool} and t_{mea} respectively are for irradiation, cooling and measurement time.

The decay data of the ^{46}Sc and ^{51}Cr were adopted from the ENSDF library [19,20] and retrieved from the interface of Live Chart of nuclides [21]. The Q-values presented in Table 2 were calculated based on the AME mass evaluation [22] and were extracted via the Q-tool system [23].

3 Results and Discussion

The measured production cross-sections of ^{46}Sc and ^{51}Cr radioisotopes using two different literature density values are tabulated in Tables 2 and 3 respectively. The excitation functions are shown in Figs. 1 and 2 together with the evaluated data from the TENDL-2014 library [24].

The ^{46}Sc was identified and analysed through the gamma activities of its intense and interference free gamma line, $E_\gamma = 889.277$ keV ($I_\gamma = 99.9840\%$). The ^{46}gSc decays to stable ^{46}Ti via β^- decay (100%). The cross-section of this radioisotope is cumulative, as it has two states (^{46}gSc and ^{46}mSc). The isomeric state (^{46}mSc) has very short half-life ($T_{1/2} = 18.75$ s), and could not be measured in the present experimental conditions, eventually decayed within 5 mins of EOB (end of bombardment) to ^{46}gSc ($T_{1/2} = 83.79$ d) via IT (100 %) process. In Table 2, the measured cross-sections for ^{46}Sc for the two used densities have been presented, whereas Fig. 1 compares the measured excitation functions with the theoretical calculation from the Talys nuclear reaction code via the TENDL-2014 library. The extracted data of TENDL-2014 indicate lower values relative to the present measurement.

TABLE 1: Decay data of the radioisotopes adopted in this study as evaluated decay data in the ENSDF library [19, 20] extracted from the interface of Live Chart of nuclides [21] while Q-values [22] were extracted from Qtool system [23].

Nuclide	Half-life	Gamma-ray energy, E_γ (keV)	Branching ratio, I_γ (%)	Contributing reactions
^{46}gSc	83.79 d	889.28	99.98	$^{47}\text{Ti}(\alpha, p\alpha)^{46}\text{Sc}$
		1120.55	99.99	$^{48}\text{Ti}(\alpha, d\alpha)^{46}\text{Sc}$
				$^{49}\text{Ti}(\alpha, n\alpha)^{46}\text{Sc}$
				$^{50}\text{Ti}(\alpha, d\alpha 2n)^{46}\text{Sc}$
^{51}Cr	27.7025 d	320.0824	9.910	$^{47}\text{Ti}(\alpha, \gamma)^{51}\text{Cr}$
				$^{48}\text{Ti}(\alpha, n)^{51}\text{Cr}$
				$^{49}\text{Ti}(\alpha, 2n)^{51}\text{Cr}$
				$^{50}\text{Ti}(\alpha, 3n)^{51}\text{Cr}$
				EC and β^+ (100%) decay of ^{51}Mn

Table 2. Measured cross-sections for $^{nat}\text{Ti}(\alpha,x)^{46}\text{Sc}$ nuclear processes.

Energy (MeV)	Cross-sections (mb)		Cross section difference (mb)	Difference (%)
	$\rho = 4.54 \text{ g/cm}^3$	$\rho = 4.50 \text{ g/cm}^3$		
50.2	76.089	76.765	0.676	0.881
47.4	69.731	70.351	0.620	0.881
42.9	42.423	42.800	0.377	0.881
38.1	16.332	16.477	0.145	0.881
32.8	4.429	4.468	0.039	0.881
26.8	2.103	2.121	0.019	0.881

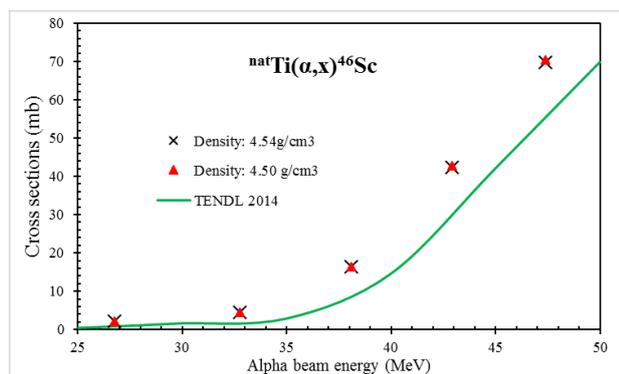


Fig. 1. Excitation function for $^{nat}\text{Ti}(\alpha,x)^{46}\text{Sc}$ reaction

The extracted cross sections for ^{51}Cr ($T_{1/2} = 27.7025 \text{ d}$) were shown in Table 3 using the two density values indicated in the table. The ^{51}Cr decays through EC (100%) decay to ^{51}V . Measurement of this radioisotope was performed via its relatively intense gamma line, $E_\gamma = 320.0824 \text{ keV}$ ($I_\gamma = 9.910\%$). The excitation functions of the ^{51}Cr for the two considered densities are shown in Fig 2 together with extracted TENDL-2014. The TENDL-2014 underestimates the measured cross-sections as presented in Fig. 2.

Table 3. Measured cross-sections for $^{nat}\text{Ti}(\alpha,x)^{51}\text{Cr}$ nuclear processes.

Energy (MeV)	Cross-sections (mb)		Cross section difference (mb)	Difference (%)
	$\rho = 4.54 \text{ g/cm}^3$	$\rho = 4.50 \text{ g/cm}^3$		
50.2	26.137	26.369	0.232	0.881
47.4	34.339	34.644	0.305	0.881
42.9	35.844	36.163	0.319	0.881
38.1	46.428	46.840	0.413	0.881
32.8	61.753	62.302	0.549	0.881
26.8	72.849	73.497	0.648	0.881
19.7	209.406	211.267	1.861	0.881
10.4	412.603	416.270	3.668	0.881

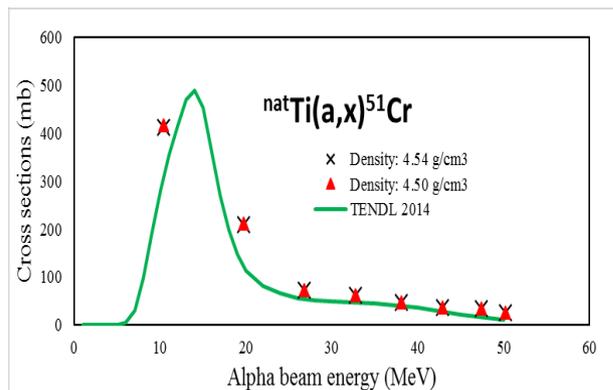


Fig. 2. Excitation function of $^{nat}\text{Ti}(\alpha,x)^{51}\text{Cr}$ reaction

4 Conclusion

The experimental cross-sections of ^{46}Sc and ^{51}Cr radioisotopes have been obtained from experimental data assuming two different density values (4.50 and 4.54 g/cm^3). The calculations indicate a slight variation of the overall cross sections relative to the slight density differences. An average of one (1) percent variation was observed in both production cross section. The variation could be much higher in other metals where the reported density literature data is much wider than in titanium.

As a very active monitoring body, the IAEA is recommended to update their database with density values of all metals using the most reliable literature sources. This will help to minimize the slight variations observed by different researchers based on density difference and in turn will lead to better optimization.

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