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Investigation of alpha particle induced reactions on natural silver in the 40–50 MeV energy range

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ABSTRACT

Natural silver targets have been irradiated by using a 50 MeV alpha-particle beam in order to measure the activation cross sections of radioisotopes in the 40–50 MeV energy range. Among the radio-products there are medically important isotopes such as ^{110m}In and ^{111}In. For optimizing the production of these radioisotopes and regarding their purity and specific activity the cross section data for every produced radioisotope are important. New data are measured in this energy range and the results of some previous measurements have been confirmed. Physical yield curves have been calculated by using the new cross section data completed with the results from the literature.

1. Introduction

As silver is a basic material for producing radioisotopes for medical and for industrial applications it is of fundamental importance to know the corresponding nuclear data of the produced radioisotopes (cross section and yield) with reasonable accuracy. Among the produced radioisotopes e.g. ^{111}In plays an important role in nuclear medicine as diagnostic isotope [1], but its relatively long half-life allows also industrial and research applications [2]. ^{109}Cd is an interesting radioisotope from the point of view of medical applications as a parent of ^{109m}Ag [3–5]. Nuclear data for alpha particle induced reactions on silver have already been measured by several authors [6–12]. In this work in the frame of a higher energy alpha experiment series by using stacked foil technique we covered the energy range 40–50 MeV using high purity silver foils as targets in order to complement the failing data in this energy range and resolve the contradictions between the existing data.

2. Experimental

The irradiations have been performed on a dedicated beam line of the K70-MeV AVF cyclotron of the RIKEN RI Beam Factory by using an E_α = 50.73 ± 0.3 MeV beam. The exact beam energy was determined by using the time of flight (TOF) setup [13]. The well-established stacked foil technique was used for assessing the excitation function of the different nuclear reactions. A combined stack was constructed, it contained foils for two experiments, i.e. Ag + α and Ni + α cross section measurements. In this work we discuss only the results on silver. The used target foils were high purity (at least 99.99%) Goodfellow © foils with the following thicknesses: Ag: 30 and 8.25 μm. The actual thickness of the foils, which was in general different from the nominal one, was determined by weighting the whole metal sheet purchased, and measuring the exact lateral size, from which an average thickness was determined, assuming that the whole sheet was homogeneous and had even thickness all over the sheet. The ^{nat}Ti(α,x)^{51}Cr reaction on titanium foils (Ti: 10.9 μm) was used as a monitor reaction to check and correct the beam intensity and energy degradation through the whole stack. The foils are ordered in groups in such a way that we could compensate or avoid the activity loss or excess activity because of recoil effect of the radioisotope in question. Only those foils were involved in the final evaluation, where the recoil from the particular target foil was compensated by the recoil from the preceding foil (same material), or it was measured together with the following foil (different material) if the preceding foil was not the same material. The Ag foils were arranged in one block, i.e. one after each other, because for silver we were interested in the high energy part. (50–40 MeV range). The first 10 foils of the stack were silver. The first Ag foil was thick (30 μm), because in this case the recoil was proportionally small, all the others were thinner

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(8.25 μm). In the case of the thin Ag foils the recoil effect was compensated, because foil from the same material, Ag was before each target foil. The irradiation lasted for one hour at 200 nA beam current. After a short cooling time the stack was disassembled into single foils or pairs of foils and the gamma-ray measurements begun. A HPGe semiconductor detector based spectrometer was used for the gamma-ray measurements. Three series of measurements have been performed on silver targets with different cooling times from 20 h to 10 days. The spectra were evaluated later by using the automatic software [14] and in special cases (overlapping multiple and/or weak peaks) manual evaluation by using a home-developed evaluation software [15] was also performed. The activity of the Ti monitor foils, which were also inserted into the stack in pairs, in order to compensate the recoil effect of the lower energy foil of the pair, were also measured later in order to fit the beam energy and intensity. The whole excitation function of the $^{nat}Ti(\alpha, x)^{51}Cr$ monitor reaction was re-measured and the results were compared with the recommended values of the IAEA monitor reaction database [16]. The final beam energy and intensity were adjusted according to the best fit with the recommended values [17]. Based on these results the initial parameters for all calculations were set. The used nuclear data are listed in Table 1 for all measured radioisotopes.

The uncertainties of the single cross section values were estimated by calculating square root of the sum in quadrature of all single contributions [18]: beam current (5%), target thicknesses (3%), detector efficiency (5%), nuclear data (3%), peak area and counting statistics (1–20%), the overall uncertainty in the results (cross sections) was 7–20%.

3. Theoretical model calculations

We wanted to test the prediction capability of the theoretical nuclear reaction model codes. Calculations for the measured cross sections were made by using the modified TALYS 1.8 code [21] presented in the TENDL-2017 on-line library [22]. Production cross sections with the latest version of the EMPIRE code [23], (EMPIRE 3.2 (Malta) [24]), which contained the latest reference input parameters library RIPL-3 [25], were also given for comparison. The code run with the default input parameters by considering all possible reactions involved, including emission of complex particles above the reaction thresholds at the given bombarding energies.

4. Results and discussion

The experimental cross sections deduced for the $^{nat}Ti(\alpha,x)^{51}Cr$ monitor reaction were compared with the recommended cross section from the IAEA monitor reaction database [16]. After very small adjustment of the beam intensity and using the actual foil thicknesses, an excellent agreement was found between the recommended and the measured data (Fig. 1).

From Fig. 1 it is seen that the first monitor foil in the stack is placed behind the last silver target foil. Since we have a good agreement among the measured and the recommended values for the monitor reaction in the low energy segment of the stack, the energy degradation calculation within the high energy segment of the stack, the silver foils of the stack, was correct. The new results for all measured radioisotopes

Table 1
Nuclear data for the radioisotopes produced [19,20].

Isotope spin level energy (keV)	Half-life	Decay mode	E_γ (keV)	I_γ (%)	Contributing reactions	Q-value (MeV)
^{111g}In $9/2^+$	2.8047 d	ε: 100%	171.28 245.35	90.7 94.7	$^{109}Ag(\alpha,2n)$	−14.05
^{110g}In 7^+	4.9 h	ε: 100%	657.75 884.68 937.48	98 93 68.4	$^{107}Ag(\alpha,n)$ $^{109}Ag(\alpha,3n)$	−7.58 −24.04
^{110m}In 2^+62.084	69.1 min	ε: 100% β^+: 61.3%	657.75	97.74	$^{107}Ag(\alpha,n)$ $^{109}Ag(\alpha,3n)$	−7.58 −24.04
^{109g}In $9/2^+$	4.159 h	ε: 100% β^+: 4.64%	203.3	74.2	$^{107}Ag(\alpha,2n)$ $^{109}Ag(\alpha,4n)$	−15.63 −32.09
^{108g}In 7^+	58 min	ε: 100% β^+: 24.8%	632.9 875.4	100 100	$^{107}Ag(\alpha,3n)$ $^{109}Ag(\alpha,5n)$	−26.75 −44.09
^{111g}Ag ½$^-$	7.45 d	β^-: 100%	245.4	1.24	$^{109}Ag(\alpha,2p)$	−12.66
^{110m}Ag 6^+ 117.595	249.76 d	IT: 1.33%β^-: 100.4%	657.76 763.94 884.68 937.49	95.61 22.6 75 35	$^{109}Ag(\alpha,2pn)$	−21.49
^{106m}Ag 6^+ 89.667	8.28 d	ε: 100%	450.98 717.34 1045.83 1527.65	28.2 28.9 29.6 16.3	$^{107}Ag(\alpha,2p3n)$ $^{109}Ag(\alpha,2p5n)$	−37.83 −54.29
^{105g}Ag $1/2^-$	41.29 d	ε: 100%	280.44 344.52 443.37	30.2 41.4 10.5	$^{107}Ag(\alpha,2p4n)$ $^{109}Ag(\alpha,2p6n)$	−45.77 −62.23
^{109}Cd $5/2^+$	461.9 d	ε: 100%	88.03	3.64	$^{107}Ag(\alpha,2p5n)$ $^{109}Ag(\alpha,2p7n)$	−55.80 −72.26

Increase the Q-values if compound particles are emitted by: np-d, +2.2 MeV; 2np-t, +8.48 MeV; n2p-^{3}He, +7.72 MeV; 2n2p-α, +28.30 MeV.
Decrease Q-values for isomeric states with level energy of the isomer.
Abundances: ^{107}Ag (51.83%), ^{109}Ag (48.17%).