Measurement of ^{107}Ag(α,γ)^{111}In Cross Sections

Coral M. Baglin, Eric B. Norman[#], Ruth-Mary Larimer[*], Gregory A. Rech

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

Abstract. Cross sections have been measured for the ^{107}Ag(α,γ)^{111}In reaction at several α-particle energies between 7.8 MeV and 11.9 MeV. This reaction is of interest because it can provide a check on calculations of low-energy (α,γ) cross sections required for stellar nucleosynthesis predictions. Stacks of natural Ag foils of 1 μm thickness and 99.97% purity were bombarded with ^{4}He^{+} beams. Following irradiation, the yields of the 171-keV and 245-keV photons produced in the 2.805 day electron-capture decay of the ^{111}In product nucleus were measured off-line. The Ag foils were interleaved with 99.6% purity, 6 μm thick natural Ti foils so that known cross sections for the ^{48}Ti(α,n) reaction could be used to check the accuracy of the beam current integration. For any given beam energy, beam energy degradation in the foils resulted in lower effective bombarding energies for successive foils in the stack, enabling measurements to be made for several energies per irradiation. The measured cross sections are compared with published statistical-model calculations.

INTRODUCTION

Surprisingly few measurements of (α,γ) cross sections exist at energies near the Gamow window for p process nuclei. A measurement several years ago by Somorjai *et al.* [1] of ^{144}Sm(α,γ) cross sections yielded values which were almost an order of magnitude lower than expected from statistical model predictions on which stellar nucleosynthesis calculations rely heavily. More recently, measurements of ^{96}Ru(α,γ) cross sections [3] gave values roughly half those expected from statistical model calculations performed using the recent NON-SMOKER code [2]. Hopefully, measurements of (α,γ) cross sections for additional nuclides in this mass region may establish trends and indicate whether refinements of the theoretical treatment of the α channel in the NON-SMOKER calculations are called for.

EXPERIMENTAL DETAILS

Beam

100 nA to 1 μA beams of ^{4}He^{+} ions from the Lawrence Berkeley National Laboratory's 88" cyclotron were used to bombard stacks of Ag and Ti foils. Each stack of foils was mounted on a water-cooled, electrically-insulated Cu Faraday cup with magnetic electron suppression just upstream of the targets. Irradiation times ranged from 1 hour to 4 hours and charge integrations varied from 600 μC to 6600 μC. The extracted beam energies used were 8.5 MeV, 8.63 MeV, 9.0 MeV, 11.05 MeV and 12.0 MeV. However, after energy degradation in the foils, the energies at the center of the Ag foils ranged from 7.8 MeV to 11.9 MeV and those at the center of the Ti foils ranged from 6.6 MeV to 11.16 MeV.

[#] Present Address: Lawrence Livermore National Laboratory
[*] Deceased

Targets

The Ag foils, obtained from Goodfellow Cambridge Limited, were 99.9% pure natural Ag self-supporting foils and were 1 μm (1.05 mg/cm^2) thick. Based on energy-loss calculations performed using the program TRIM [4], the $^4He^+$ ions are expected to lose 214 keV to 277 keV in these targets at the energies used. The natural Ti foils were supplied by Alfa Aesar (Johnson Matthey); they were of 99.6% purity and 6 μm (2.71 mg/cm^2) thick. The expected energy loss traversing the target varied from 825 keV to 1122 keV. The manufacturers' stated foil thicknesses were checked for four Ag foils and six Ti foils by measuring the energy loss experienced by 5.5178 MeV α-particles from a ^{241}Am source when traversing each foil. The energy loss combined with dE/dx calculated by TRIM [4] indicated foil thicknesses that deviated from the nominal foil thickness by at most 2% for all but one Ag foil for which the deviation was 10%.

Detectors

Three different Ge detectors were used to record γ-ray spectra out of beam. Two were 100 cm^3 n-type HPGe detectors with different thickness Be windows and almost identical efficiencies above ~120 keV. The third, situated in a low-background environment, was a 300 cm^3 p-type detector with Mg end cap. All γ-ray spectra were measured with the irradiated foil adjacent to the detector end cap (i.e., using ~0 cm source-to-detector distance).

The efficiency calibrations of the detectors were achieved using radioactive sources. Of the sources available, only ^{54}Mn, ^{57}Co, ^{60}Co and ^{137}Cs sources were weak enough to be used at 0 cm. To obtain an additional calibration point (at 320 keV), the efficiency curve at 15.2 cm source to detector distance was determined using ^{152}Eu and ^{133}Ba multi-line sources and the resulting efficiency curve was used to calibrate the ^{51}Cr activity from one of the irradiated Ti foils which was measured at both 0 cm and 15.2 cm. Fig. 1 shows the resulting efficiency curves.

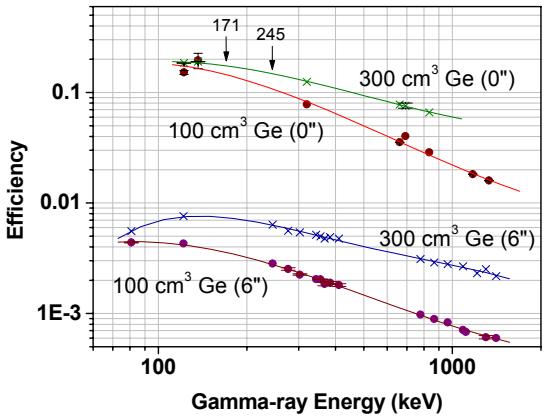

Figure 1. Efficiency curves determined for 300 cm^3 and 100 cm^3 Ge detectors at source to detector distances of ~0 and 15.2 cm (6").

Competing Reactions

At the energies investigated, several other reaction channels are open, but these lead either to stable product nuclides or to ones with relatively short half-lives. None interfered with observation of the 320-keV line resulting from ^{48}Ti(α,n) or the 171-keV and 245-keV lines from ^{107}Ag(α,γ). However, measurements of spectra from the Ti foils needed to be delayed until the 42.3 m activity resulting from the ^{46}Ti(α,n)^{49}Cr reaction had died away.

RESULTS

The number of residual nucleus atoms present at the end of the target irradiation N_{EOB} was deduced from the observed spectral line peak area C accumulated between times t_1 and t_2 after the end of the irradiation using the relation:

$$N_{EOB} = C / \varepsilon (e^{-\lambda t_1} - e^{-\lambda t_2}) I_\gamma \quad (1)$$

where ε is the detector efficiency, λ is the decay constant, and Iγ is the absolute photon intensity of the observed transition for the decay in question. The cross section was then calculated from the known numbers of beam particles and target atoms and N_{EOB} (after correction for decay during the irradiation).

^{48}Ti(α,n)

Cross sections were extracted for the ^{48}Ti(α,n)^{51}Cr reaction using the 320-keV, I_γ=9.92(5)% transition in ^{51}V following ^{51}Cr ε decay (27.7025 d). The results are displayed in Fig. 2. Except for the highest energy datum, they are in excellent agreement with the NON-SMOKER statistical-model calculation [2] averaged over the 800-1200 keV target thickness. The thin-target data from the work of Morton *et al.* [5] (not shown) also are in excellent agreement with the NON-SMOKER calculation. The present data lend support for the validity of the experimental technique used here.

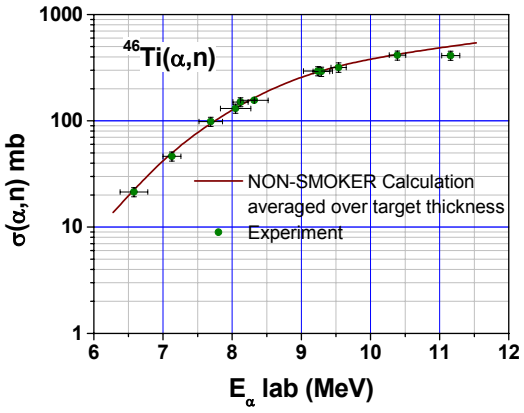

Figure 2. ^{48}Ti(α,n) cross section data measured in the present experiment compared with the NON-SMOKER calculation [2] averaged over target thickness.

^{107}Ag(α,γ)

A γ-ray spectrum in the energy region of interest resulting from E_α=11.7 MeV bombardment of a natural Ag foil is shown in Fig. 3. The 171-keV (I_γ=90.65% (25)) and 245-keV (I_γ=94.09% (18)) transitions in ^{111}Cd following ε decay (2.805 d) of ^{111}In are clearly seen. Both were used to deduce cross sections. The strong transitions at lower energy are x radiations from Pb (fluorescence), In and Cd. Since the count rate was low, spectra were accumulated for as many as 27 hours.

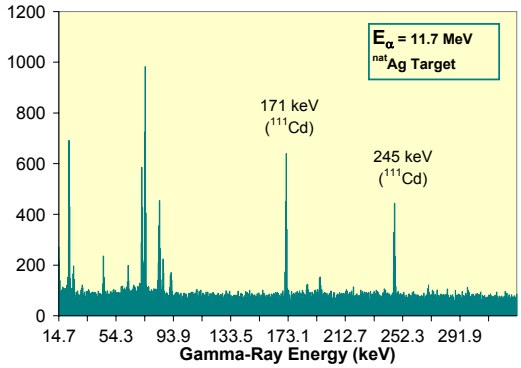

Figure 3. γ-ray spectrum in energy region of interest for E_α=11.7 MeV at center of natural Ag target; 4.9 h accumulation time.

Preliminary cross-section data are shown in Fig. 4. The uncertainties in energy arise primarily from the cyclotron beam energy (~100 keV) and from an assumed 10% uncertainty in dE/dx values used to assess the energy lost in preceding targets in the stack. For the second half of the irradiations, the Ti foils were placed last in the stack of foils to minimize the latter contribution. The indicated cross section uncertainties include ~10% uncertainty in detector efficiency, statistical uncertainties in peak area determination (2% to 38%) and estimated variation in target thickness (<5%).

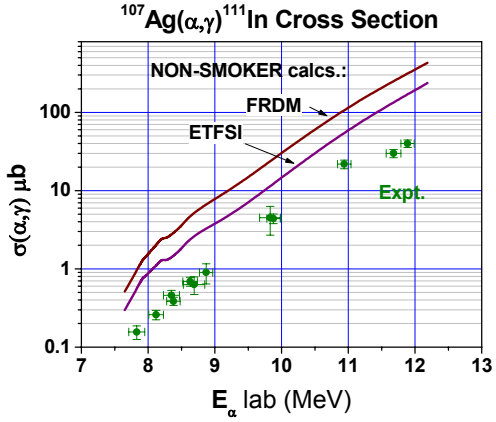

Figure 4. Preliminary cross section data for the ^{107}Ag(α,γ) reaction compared with NON-SMOKER calculations using masses and level densities from the finite-range droplet model (FRDM) and from extended Thomas-Fermi model with Strutinsky integral (ETFSI) [2].

CONCLUSIONS

While the basic energy dependence of the measured ^{107}Ag(α,γ) cross sections is consistent with the NON-SMOKER code calculations [2], their absolute values are consistently low by factors of about three to six, depending on which mass model was used in the NON-SMOKER calculation (see Fig. 4). Measured (α,γ) cross sections for both ^{144}Sm [1] and ^{96}Ru [3] have also proved to be significantly lower than the SMOKER and NON-SMOKER statistical-model code predictions, respectively, whereas those for ^{70}Ge [6] are in good agreement with statistical model calculations. As noted by Rapp *et al.*, this suggests that the theoretical treatment of the α channel in the statistical model calculations may need to be refined for the heavier nuclides.

ACKNOWLEDGMENTS

Funding for this work was provided by the US Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC03-76SF00098.

REFERENCES

1. E. Somorjai, Zs. Fülöp, Á.Z. Kiss, C. Rolfs, H.-P. Trautvetter, U. Greife, M. Junker, M. Arnould, M. Rayet, H. Oberhummer, *Nucl. Phys.* **A 621**, 293c-296c (1997).
2. T. Rauscher and F.-K. Thielemann, *Atomic Data and Nuclear Data Tables* **79**, 47-64 (2001); and URL: http://quasar.physik.unibas.ch/~Tommy/nosmo.html.
3. W. Rapp, M. Heil, D. Hentschel, F. Käppeler, and R. Reifarth, *Phys. Rev.* **C 66**, 015803-11 (2002).
4. J.F. Ziegler and J.P. Biersack, *The Stopping and Range of Ions in Solids*, New York, Pergamon Press, 1985; and URL: http://www.srim.org/.
5. A.J. Morton, S.G. Tims, A.F. Scott, V.Y. Hansper, C.I.W. Tingwell, and D.G. Sargood, *Nucl. Phys.* **A 537**, 167-182 (1992).
6. Zs. Fülöp, Á.Z. Kiss, E. Somorjai, C.E. Rolfs, H.-P. Trautvetter, T. Rauscher, H. Oberhummer, *Z. Phys.* **A 355**, 203-207 (1996).