Measurement of cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction from 5.9 to 8.7 MeV

M. S. Basunia,[1] E. B. Norman,[1,*] H. A. Shugart,[2] A. R. Smith,[1] M. J. Dolinski,[2] and B. J. Quiter[3]
[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[2]*Department of Physics, UC Berkeley, Berkeley, California 94720*
[3]*Department of Nuclear Engineering, UC Berkeley, Berkeley, California 94720*
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We have measured cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction in the 5.9- to 8.7-MeV energy range using an activation technique. Natural Cu foils were bombarded with α beams from the 88″ Cyclotron at Lawrence Berkeley National Laboratory (LBNL). Activated foils were counted using a γ-spectrometry system at LBNL's Low Background Facility. The ^{63}Cu(α, γ)^{67}Ga cross sections were determined and compared with the latest NON-SMOKER theoretical values. Experimental cross sections were found to be in agreement with theoretical values.

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I. INTRODUCTION

Cross-section measurements for charged-particle capture reactions on nuclei heavier than iron are important for nucleosynthesis studies [1] and for testing statistical model predictions. The inner zones of supernovae, where temperatures exceed 10^9 K, are places where proton and α-particle reactions on medium to heavy nuclei may be important in determining the mix of elements and isotopes that emerge from such stellar explosions. In a series of measurements of thick-target yield for proton-capture and α-induced reactions, Roughton *et al.* reported a few proton-capture reactions on elements heavier than iron [2,3]. Within the past few years, some proton-capture cross sections in the $A = 90$–100 mass region [4–6] and α capture on ^{144}Sm, ^{70}Ge, ^{96}Ru, and ^{112}Sn isotopes [7–10] have been reported. Experimental α-capture cross sections on ^{96}Ru and ^{144}Sm were about 2.5 and 5–7 times lower, respectively, than the reported theoretical values. For the two data points available from a study of the ^{112}Sn(α, γ)^{116}Te reaction [10], the agreement between the theoretical S factor and the experimentally deduced value is good at the higher energy but poor at the lower energy. An earlier measurement of α capture on ^{40}Ca also found cross sections to be about 3–5 times lower than the theoretical predictions [11]. However, the experimental S-factor values for the ^{70}Ge(α, γ)^{74}Se reaction were in agreement with statistical model calculations [8]. Thus it is important to investigate α-capture cross sections for different mass regions to test the theoretical models. Rapp *et al.* [9] suggested additional α-induced cross-section measurements be performed over a wider mass range for understanding and improving the situation. Demetriou *et al.* pointed out that theoretical estimates of the α-particle capture rates within the statistical model of Hauser-Feshbach remain highly uncertain due to the poor knowledge of the α-nucleus optical model potential at low energies and proposed improved global α-optical model potentials for low energies [12].

Here we report the measured cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction in the 5.9- to 8.7-MeV energy range using an activation technique. Experimental procedures and comparison of the measured data with the latest theoretical values are presented and discussed.

II. MEASUREMENTS

A. Target preparation and irradiation

Natural Cu foils of thickness ~1 mg/cm^2 used in this experiment were purchased from ACF-Metals, Tucson, Arizona, USA. The foils were floated on water from glass slides and mounted on circular aluminum holders. Three stacks of targets, each having four ^{nat}Cu and one ^{nat}Ti foil of thickness 2.7 mg/cm^2, were prepared. The target stacks were mounted on a thick water-cooled copper block that also served as a beam stop. Two stacks were irradiated, each for an hour, with α beams of energies 8.8 and 7.9 MeV from the 88″ Cyclotron at Lawrence Berkeley National Laboratory (LBNL). The beam current was 1 μA. The third stack was irradiated for 6 h with 7.0-MeV beam energy and 0.1-μA current. The uncertainty in the beam energy was about 1%. The incident α-beam energy on the successive foils was calculated based on the energy loss through Cu foils using dE/dx values estimated using the TRIM (the transport of ions in matter) code [13]. On average, the loss per Cu foil was about 300 keV. The beam current was integrated using a Brookhaven Instruments Corporation Integrator.

The titanium foil, at the end of each stack, was used for beam current calibration using the ^{48}Ti(α,n)^{51}Cr reaction and for catching the recoil ^{67}Ga radioisotopes from the preceding copper foil to estimate the recoiled fraction.

B. Data acquisition and analysis

Following each irradiation, the copper targets were counted immediately using an HPGe detector to measure the ^{68}Ga activity, produced through the ^{65}Cu(α,n)^{68}Ga reaction. All the copper foils were later recounted for longer periods of time to measure the ^{67}Ga activity using another HPGe detector, 80% relative efficiency, at LBNL's Low Background Facility

*Present address: Lawrence Livermore National Laboratory.

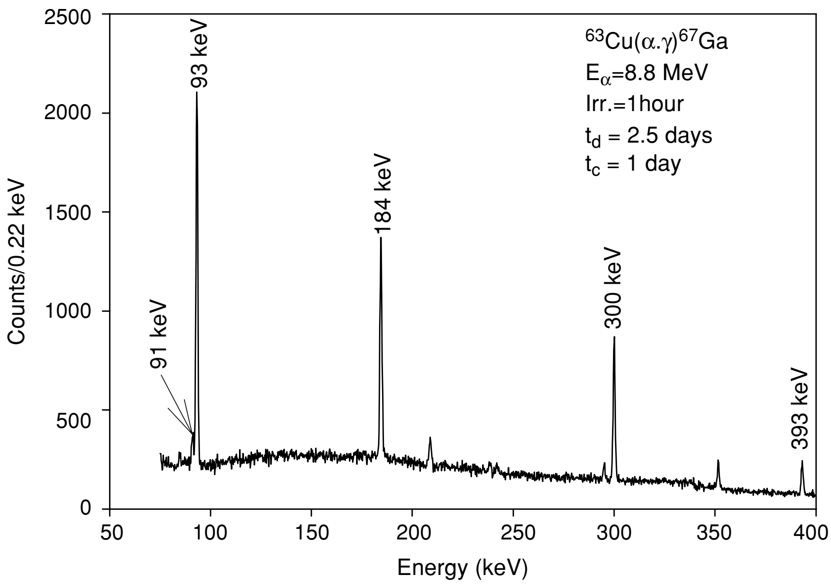

FIG. 1. A partial HPGe γ-ray spectrum of ^{67}Ga characteristic γ lines. (t_d and t_c are decay and counting times.)

(LBF). The energy resolution of the HPGe detector was 1.9 keV (FWHM) at $E_\gamma = 1332.5$ keV. γ-ray energy spectra were accumulated in 16,384 channels using an ORTEC PC-based acquisition system. A partial HPGe γ-ray spectrum collected at the LBF is shown in Fig. 1 for the characteristic γ energies of ^{67}Ga. The ^{67}Ga radioactivity in samples bombarded with the two highest beam energies was sufficiently high to count at 25 and 15 cm away from the detector end cap. However, for the lowest beam energy, samples were counted at the end cap surface of the HPGe detector. Efficiency calibration of the HPGe detectors was done using calibrated point sources of ^{22}Na, ^{54}Mn, ^{57}Co, ^{60}Co, ^{109}Cd, ^{133}Ba, and ^{137}Cs purchased from Isotope Products Laboratories. The efficiency curve for the surface counting position was generated from the peak efficiency data at 25 cm using count ratios of single γ sources at surface position and 25 cm [14]. Single γ lines at 88.0, 320.1, 661.4, and 834.8 keV from ^{109}Cd, ^{51}Cr, ^{137}Cs, and ^{54}Mn, respectively, were used. The ^{51}Cr source was available from the current experiment.

All γ spectra were analyzed using ORTEC Gamma Vision software. The 91- and 93-keV γ lines of ^{67}Ga slightly overlapped in the tail. The combined area of these two peaks was used together to determine the ^{63}Cu(α,γ)^{67}Ga cross section. The cross sections were deduced from the well-known activation equation:

$$A_o = n\sigma\phi(1 - e^{-\lambda t}), \tag{1}$$

where A_o = ^{67}Ga activity at the end of irradiation (disintegrations/s), n = number of ^{63}Cu nuclei (cm^{-2}), σ = cross section (cm^2), ϕ = number of incident α particles (s^{-1}), and $(1 - e^{-\lambda t})$ = growth factor for a decay constant λ and irradiation time t.

The activity A_o at the end of irradiation was deduced from the measurement using the following equation:

$$A_o = \lambda N_o = \lambda C/\{I_\gamma \varepsilon (e^{-\lambda(t_{cs}-t_{ie})} - e^{-\lambda(t_{ce}-t_{ie})})\}, \tag{2}$$

where N_o = number of ^{67}Ga nuclei at the end of irradiation; t_{cs}, t_{ce}, t_{ie} = counting start, counting end, and irradiation end times, respectively; C = net area under the peak for a counting duration $(t_{cs} - t_{ce})$, I_γ = γ-ray intensity, and ε = detector peak efficiency.

Cross sections for the ^{63}Cu(α,γ)^{67}Ga reaction were deduced using all ^{67}Ga γ rays and were found to be statistically consistent to one another. Nuclear data for the product nuclei used in this experiment are presented in Table I. Cross sections for the ^{63}Cu(α,γ)^{67}Ga reaction reported in this paper are deduced using the 184-keV γ ray. In all γ spectra, this peak had smooth tailing on both sides with statistically reasonable peak area. Absolute γ-ray intensities of ^{67}Ga are deduced in this work considering the recent ^{67}Ga decay data [16] and using relative γ-ray intensities from Ref. [17]. We used a 184-keV γ-ray intensity of $20.7 \pm 0.1\%$, about 2% lower than the value in Ref. [15]. There was an overlapping bombarding energy for the last foil of the first

TABLE I. Nuclear data of the product radioisotopes used in this experiment [15].

Nuclear reaction	Half-life	E_γ (keV) (I_γ%) uncertainty for the least significant digit(s)
^{63}Cu(α,γ)^{67}Ga	3.26 d	91.3(3.16 *9*), 93.3(39.2 *10*), 184.6(21.2 *3*), 300.2 (16.8 *22*), 393.5(4.68 *6*)
^{65}Cu(α,n)^{68}Ga	67.63 min	1077.4 (3.0 *3*)
^{48}Ti(α,n)^{51}Cr	27.7 d	320.1 (9.92 *5*)

TABLE II. Measured cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction.

Energy (lab) (MeV)	Cross section (mb)
8.65 ± 0.09	1.08 ± 0.16
8.37 ± 0.08	1.04 ± 0.16
8.08 ± 0.08	0.93 ± 0.14
7.80 ± 0.08	0.69 ± 0.10
7.54 ± 0.08	0.41 ± 0.06
7.24 ± 0.07	0.26 ± 0.04
6.99 ± 0.07	0.18 ± 0.03
6.88 ± 0.07	0.13 ± 0.02
6.56 ± 0.07	0.07 ± 0.01
6.22 ± 0.06	0.026 ± 0.004
5.88 ± 0.06	0.012 ± 0.002

stack and the first foil of the second stack. The agreement between these two cross sections for the common energy was excellent. This served as a cross-check for the two different sets of irradiation for the ^{63}Cu(α, γ)^{67}Ga reaction cross-section measurement.

Titanium foils were counted after about 7 days at the LBF for the ^{51}Cr and recoiled ^{67}Ga activities using the HPGe spectrometry system. This length of decay period allowed the 91.3- and 93.3-keV ^{67}Ga peaks to appear in the spectra. Recoiled ^{67}Ga activity was determined using Eqs. (1) and (2) and was found to be about 10%–14% in this experiment. Assuming a uniform ^{67}Ga recoil out of the successive foils in the stack, a correction of 12% was made for the first Cu foil ^{67}Ga activity in each stack.

Measured cross sections for the ^{48}Ti(α,n)^{51}Cr reaction were compared with the published experimental data [18] for beam current calibration. The comparison provided very reliable current integration of the Brookhaven Instruments Corporation Integrator for the 8.8- and 7.9-MeV beams. For the 7.0-MeV beam, the comparison was incomplete using the ^{48}Ti(α,n)^{51}Cr reaction, because in this case published cross sections were only partially available for the interacting α-energy range through the titanium foil. However, employing other cross-checks, such as simultaneous ^{65}Cu(α,n)^{68}Ga cross-section measurement and comparison with known experimental results, we are confident of the current integrator reading for the 7.0-MeV beam.

Considering all uncertainties of detector efficiency calibration, target foil thickness, beam current, counting statistics, decay data, and recoil fraction, we report 15% uncertainties for the measured cross sections.

III. RESULTS AND DISCUSSION

Measured cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction are presented in Table II. In Fig. 2, measured values are presented along with the latest theoretical values of the NON-SMOKER statistical model [19]. Theoretical data points were obtained using the finite range droplet model masses from Ref. [19]. These data points were not available in regular intervals in the studied energy range. However, from Fig. 2, it can be seen that the agreement between the experimental and theoretical data are reasonably good for the ^{63}Cu(α, γ)^{67}Ga reaction cross sections.

A comparison of measured ^{65}Cu(α,n)^{68}Ga cross sections in this work with those of Stelson and McGowan [20] was made. Their excellent agreement provides an indication of the experimental integrity for the reported ^{63}Cu(α, γ)^{67}Ga cross-section measurement.

Based on the present results and those from studies of the ^{70}Ge(α, γ)^{74}Se reaction [8], it appears that the theoretical calculations of (α, γ) cross sections in the mass region of $A = 60-70$ are in reasonably good agreement with the experimental data.

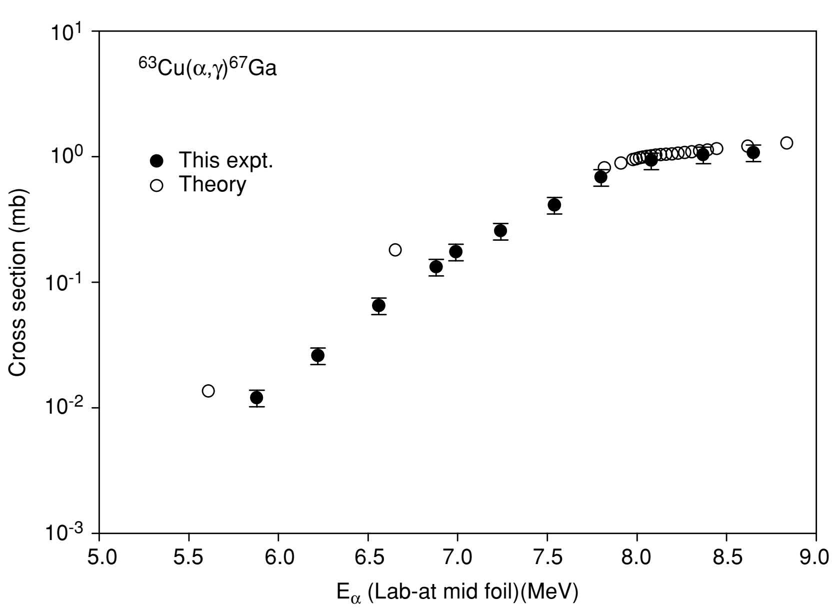

FIG. 2. Experimental and theoretical cross sections for the ^{63}Cu(α, γ)^{67}Ga reaction.

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