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Reaction Cross Section for Low-Energy Alpha Particles on ^{59}Co†

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The reaction cross sections for α particles in the energy range 12.5–18.7 MeV with ^{59}Co were determined by summing measurements of the cross sections for the (α,n) reaction and those for charged-particle emission. These results are then combined with other reported investigations to obtain the reaction cross sections for incident α-particle energies 8–25 MeV. Comparison of these results with those from an optical-model calculation gives excellent agreement.

1. INTRODUCTION

Recently, investigations have been conducted in this laboratory to examine the area of validity of the independence hypothesis.[1] In this work, the decay of the compound nucleus ^{63}Cu formed by the reactions $\alpha+{}^{59}$Co and $p+{}^{62}$Ni was studied. Complementary to this investigation, it was of interest to measure the energy dependence of the reaction cross section of α particles with ^{59}Co, since these cross sections are related to the probability of the inverse process: the reemission of an α particle from the ^{63}Cu compound nucleus. In the absence of experimental data, inverse-reaction cross sections are usually calculated from the optical model and then employed in statistical-model interpretations of compound-nucleus reactions. It was therefore of interest to see how accurately these optical-model calculations can reproduce the measured energy dependence of the reaction cross section in this particular system.

The reaction cross sections for incident α particles in the energy range 12.5–18.7 MeV were obtained through separate measurements of the cross sections for the ^{59}Co(α,n) reaction and reactions in which either a proton or an α particle is emitted. The cross section for single-neutron emission was measured down to an incident energy of 8 MeV. Included in these measurements, but not separated, are contributions (probably small) from the ^{59}Co(α,d), ^{59}Co(α,t), and ^{59}Co$(\alpha,{}^3$He$)$ reactions.

Previous measurements of this reaction system include the work of Stelson *et al.* on the (α,n) cross section from 8 to 11 MeV,[2] and Stearns on the $(\alpha,\alpha n)$, $(\alpha,\alpha 2n)$, $(\alpha,2p)$, and $(\alpha,2n)$ cross sections above 18 MeV.[3] In addition, the reaction cross section for the same system at a projectile energy of 24.7 MeV was measured by Budzanowski *et al.*[4] Where comparable, our results are in good agreement with these other measurements.

2. EXPERIMENTAL

A. General

All irradiations were performed at the Yale University Heavy Ion Accelerator. Projectiles with the appropriate energies were obtained by inserting aluminum degrading foils of known thickness into the beam path prior to a magnetic-analysis system. The incident projectile energy was verified by measuring the energy of the α particles elastically scattered from a thin Al target. The range-energy calculations of Williamson *et al.* were used to account for the small energy loss in the targets.[5] In this manner the average α-particle energy was known to 1% and the energy resolution of the beam estimated to be about 1 MeV from the target thickness.

Thin targets of natural cobalt (2.09 and 2.47 mg/cm^2) were positioned in a scattering chamber for the irradiations, while beam monitoring was performed using a magnetically protected Faraday cup connected to an Elcor Integrator.

B. Charged-Particle Emission

The cross sections for proton and α-particle emission were measured, using a movable solid-state telescope system, consisting of a thin (178-μ) silicon surface-barrier transmission detector and a thick (3-mm) lithium-drifted silicon detector. The first detector was of sufficient thickness to stop α particles of energy less than 17 MeV and protons less than 4.2 MeV. To discriminate protons from α particles, a gating pulse was generated for all particles losing less than 4.2 MeV in the first detector. This in turn triggered a multichannel analyzer that collected the sum of the signals from both detectors. Since the cross section for α emission below 5 MeV is negligible, it is reasonable to assume that the sum spectrum covering the region 2–15 MeV did not contain any contributions from α particles. The spectra of the emitted α particles, which were all stopped in the first detector, were collected separately in another

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[1] N. Dudey, M. J. Fluss, B. Foreman, L. Kowalski, and J. M. Miller, in *Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966* (Academic Press Inc., New York, 1967), Abstract No. 7.14, p. 803.

[2] P. H. Stelson and F. K. McGowan, Phys. Rev. **133**, B911 (1964).

[3] C. M. Stearns, Ph.D. thesis, Columbia University, 1962 (unpublished).

[4] A. Budzanowski, A. Dudek, K. Grotowski, J. Kuzminski, N. Niewadniczanski, A. Strzalkowski, J. Szmider, and R. Wolski, Institute of Nuclear Physics, Krakow, Poland, Report No. INP-441/PL, 1965 (unpublished).

[5] C. F. Williamson, J. Bouzot, and J. Picard, Commissariat a l'Energie Atomique, France, Report No. CEA-R 3042, 1966 (unpublished).

analyzer, which was gated by anticoincidence events. Included in these measurements are the small contributions from deuterons and tritons (in the proton spectra) and ^{3}He (in the α spectra). A schematic representation of the associated electronic system is shown in Fig. 1.

Energy calibration was achieved using the prominent α emissions of the Th*C* chain and those of ^{241}Am. The solid angle of the ΔE-E telescope was determined to ±1% with an ^{241}Am source of known α intensity. The reported absolute cross sections for charged-particle emission are valid to within an over-all experimental error of ±15%. The known differential cross section and angular distribution of the ground-state proton transition from the reaction $^{12}C(\alpha,p)^{15}N$ at 18.3 MeV was measured to check the experimental efficiency, and reasonable agreement was obtained with results reported previously.[6]

Typical spectra of the emitted α particles and protons observed at 135° (lab) for an incident beam energy of 15.7 MeV are shown in Fig. 2.

C. Neutron Emission

The cross section for single-neutron emission was obtained from the yield of the reaction product ^{62}Cu. Irradiations of a target foil for 2–5 min were performed in the scattering chamber with the α-particle energy again monitored via the elastic scattering peak. The beam intensities, monitored with the Faraday cup every 15 sec, were usually quite uniform in time.

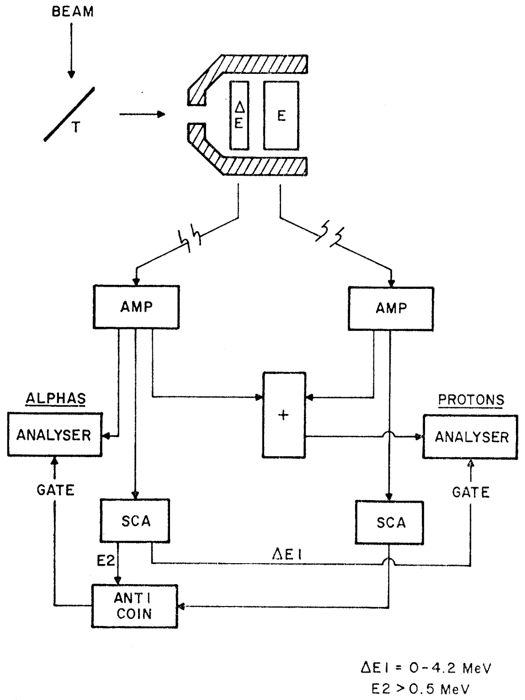

Fig. 1. Schematic representation of the associated electronics used for detecting charged particles. This block diagram does not include all of the necessary electronics and is merely illustrative of the principle used to discriminate α's from protons.

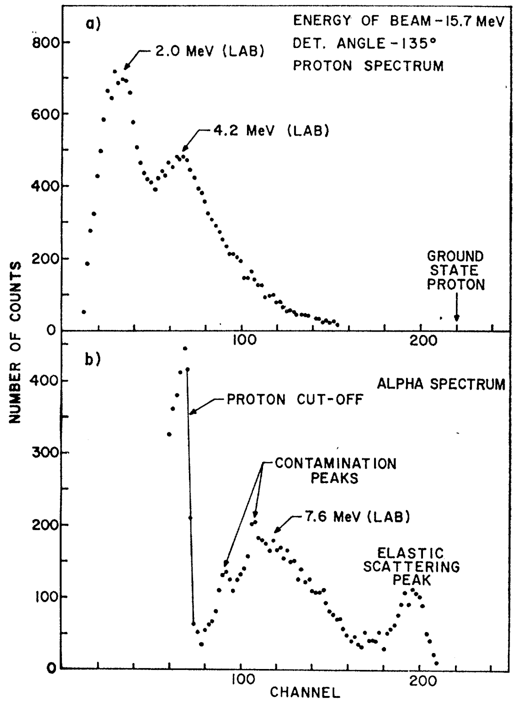

Fig. 2. (a) Typical energy spectra of protons emitted at 135° (lab) for an incident α energy of 15.7 MeV. The secondary peak in the continuum (2.0 MeV) is explained in the text. (b) Typical energy spectra of α's emitted at 135° (lab) for an incident α energy of 15.7 MeV. The contamination peaks arise from the presence of carbon and oxygen on the target.

The induced positron activity from the residual product ^{62}Cu ($T_{1/2}=9.6$ min) was measured by recording the coincidence counts of the resulting annihilation γ rays. The target was sandwiched between two pieces of copper foil of sufficient thickness to stop the emitted positrons, with the subsequent annihilation γ rays detected in two coaxial 7.6×7.6-cm NaI scintillation counters placed on opposite sides of the sandwich. The absolute efficiency of this detector system was determined to ±5% by using a calibrated ^{22}Na source of positrons.

The small amount of the ^{62}Cu recoiling out of the target was caught in thin aluminum catcher foils. These catcher foils were assayed in a similar fashion after appropriate corrections were made for any induced positron activities in the aluminum foils themselves.

At bombarding energies where the yields of other positron-emitting reaction products such as ^{61}Cu were not negligible, the sample was counted for longer periods of time, and the appropriate corrections made. The reported absolute cross sections for neutron emission are valid to within an over-all experimental error of ±15%.

In order to check the entire experimental system, the cross section for producing ^{68}Ga via the reaction

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[6] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1301 (1960).

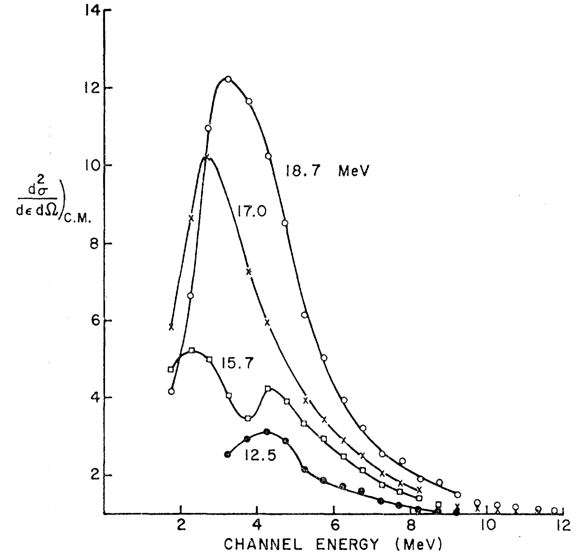

FIG. 3. The differential cross section (c.m.) for proton emission at various bombarding energies observed at 135° (lab). These spectra include contributions from the (α,p), (α,np), and (α,pp) reactions. The low-energy peak, observed for an incident projectile energy of 15.7 MeV, is illustrative of these competing processes (see text).

^{65}Cu$(\alpha,n)^{68}$Ga was measured; the value obtained of 763±80 mb at an incident projectile energy of 18.6 MeV is in satisfactory agreement with previously reported values of 700 [7] and 840 mb.[8]

3. RESULTS

A modified version of the computer program NEWDAC written by Ball[9] was used to transform the observed data for α and proton emission into the c.m. coordinate system. The use of one-particle-out kinematics at the higher bombarding energies when more than one particle may be emitted introduced a small error into this transformation procedure. The differential cross sections in the c.m. system for proton emission at various bombarding energies observed at 135° (lab) are displayed in Fig. 3. The low-energy peak in the proton spectrum for 15.7 MeV signifies the increasing contributions of processes other than single-particle emission, with increasing excitation energies in the compound nucleus.[10] However, from considerations of the energetics of the reaction it is likely that these protons originate only from the (α,np) reaction and were included in the determination of the cross section for proton emission.

The total cross section was obtained by integrating the differential cross sections $d^2\sigma/d\Omega d\epsilon$, observed at 90°, 135°, and 150° (lab), by assuming symmetry around $\frac{1}{2}\pi$. At an incident energy of 15.7 MeV, the full angular distribution from 45° to 150° for both α and proton emission was obtained and was indeed found to be symmetric around $\frac{1}{2}\pi$.

The results of this experiment are listed in Table I and displayed in Fig. 4, along with some of the results of previous investigations on this and associated reactions for α-particle energies up to 25 MeV.

4. DISCUSSION

A. Estimation of Reaction Cross Sections

The sums of the partial cross sections presented in Fig. 4 and Table I provide an estimate of the excitation function for the reaction cross section between α particles and ^{59}Co, which is represented by the solid circles in Fig. 4. For incident energies between 12.5 and 18.7 MeV, the sum includes the present measurements of cross sections for the emission of neutrons and charged particles. The cross section for neutron emission is taken to be that for the ^{59}Co$(\alpha,n)^{62}$Cu reaction, since it was found, in agreement with earlier results,[3] that the cross section for the $(\alpha,2n)$ reaction is negligible over this energy region. Below 12.5 MeV, the reaction cross section is nearly completely that for neutron emission,

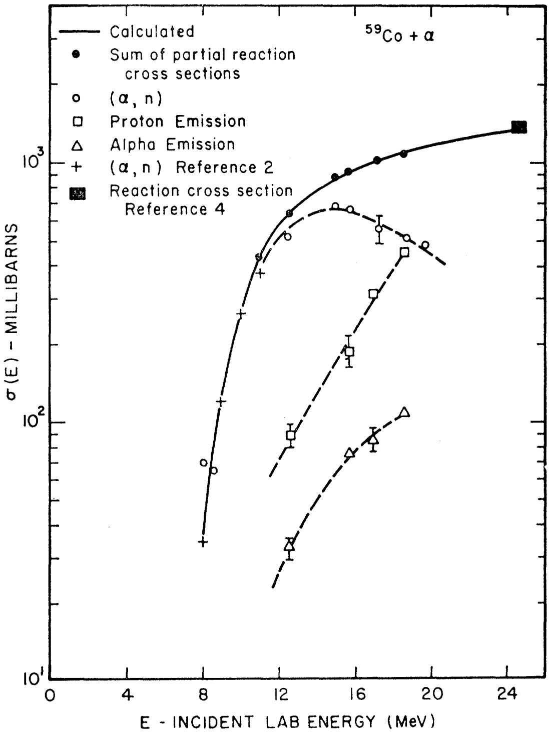

FIG. 4. The excitation function for the reaction of incident α particles in the energy range 8–18.7 MeV with a natural cobalt target. The solid line indicates the results of an optical-model calculation with the parameters given in Table II, while the experimental results are represented by the individual points. The dashed lines are merely a smooth curve drawn through the data points. The points for proton emission include any emission of d and ^{3}H, while those for α emission include ^{3}He. The point at 24.7 MeV is from Ref. 4.

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[7] E. A. Bryant, D. R. F. Cochran, and J. D. Knight, Phys. Rev. **130**, 1512 (1963).

[8] N. Porile and D. L. Morrison, Phys. Rev. **116**, 1193 (1959).

[9] J. B. Ball, Oak Ridge National Laboratory Report No. ORNL-3405, 1963 (unpublished).

[10] N. O. Lassen and A. Sidorov, Nucl. Phys. **19**, 579 (1960).

TABLE I. Experimental partial-reaction cross sections.

Incident energy (MeV)	Single-neutron emission (mb)	α emission (mb)	Proton emission (mb)
8.0	34		
8.1	70		
8.6	64		
12.5	514	32	89
15.0	676		
15.7	656	76	185
17.2	556	84	307
18.65	505	110	452
19.7	481		

but the rapidly diminishing contribution from charged-particle emission was estimated by a linear extrapolation of the data obtained above 12.5 MeV.

The point at 24.7 MeV is from Ref. 4 and includes contributions from neutron emission, measured by activation analysis, and from charged-particle emission, measured by particle detectors.

Estimates of reaction cross sections made by summing partial cross sections are susceptible to error because of the possible emission of more than one charged particle per interaction, difficulties in separating inelastically scattered from elastically scattered α particles, and possible asymmetry in the c.m. angular distributions of the emitted charged particles. Threshold and Coulomb-barrier considerations lead to the conclusion that multiple charged-particle emissions should be negligible in the energy region considered. The elastic scattering peak was always clearly evident and could be easily subtracted from the spectrum. As mentioned earlier, the angular distributions of the integrated spectra of both protons and α particles show symmetry about 90° in the interval 45°–150°.

B. Comparison with Optical Model

It was of interest to determine the accuracy with which optical-model calculations could predict the reaction cross sections over the energy range observed in this study. This is especially of interest because the cross section changes rapidly with energy in this region. To that end, optical-model calculations were carried out with the ABACUS-II program,[11] using a potential $V(r)$ of the usual form,

$$V(r)=V_c(r)+(U+iW)f(r),$$

where V_c is the Coulomb potential and the second term is the usual complex optical potential, with a radial dependence of the Saxon-Woods form

$$f(r)=\{1+\exp[(r-R)/a]\}^{-1}.$$

TABLE II. Optical-model parameters used in calculations.[a]

$U=92.5$ MeV
$W=15.0$ MeV
$a=0.52$
$R=5.976\times10^{-13}$ cm
$R_c=5.22\times10^{-13}$ cm

[a] See Ref. 4.

The optical-model parameters used were those determined by Budzanowski *et al.*[4] from the angular distribution of elastically scattered α particles for just the $(\alpha+{}^{59}\text{Co})$ system and are listed in Table II.

The results of these calculations are illustrated in Fig. 4 (solid line). The remarkable agreement shown between the experimental and calculated values over the entire energy range of interest indicate the success of the optical model with these parameters for describing this reaction system, although, as usual, the particular set given in Table II is probably not unique.

ACKNOWLEDGMENTS

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[11] E. O. Auerbach, Brookhaven National Laboratory Report No. BNL-6562, 1962 (unpublished).