Excitation Functions for the $(\alpha,\alpha n)$ and $(\alpha,2pn)$ Reactions on Ce^{142}†

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Cross sections have been measured radiochemically for the reactions $Ce^{142}(\alpha,\alpha n)Ce^{141}$ and $Ce^{142}(\alpha,2pn)Ce^{143}$ in the helium-ion energy range 16.8–40.1 Mev. The cross section for the $(\alpha,\alpha n)$ reaction begins to rise sharply at about 25 Mev and reaches a value of 69±5 mb at 40.1 Mev. The cross section for the $(\alpha,2pn)$ reaction begins to rise at about 32 Mev and reaches a value of 2.5±0.4 mb at 40.1 Mev. An upper limit of ~0.1 mb for the cross section for the reaction $Ce^{142}(\alpha,\alpha p)La^{141}$ in the energy range covered by this study has also been obtained. The results for the $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ reactions are discussed in terms of these possible mechanisms: compound nucleus formation and decay, knock-on, and direct inelastic scattering followed by neutron evaporation. The results seem to be most consistent with the last mechanism. The existence of a measurable cross section for the $(\alpha,2pn)$ reaction in this energy region suggests that the reaction proceeds mainly by He^3 emission, probably by a stripping mechanism. The data reported are consistent with the hypothesis that in this energy range at most one particle is emitted as a result of direct interaction.

INTRODUCTION

FAIRLY large cross sections for the $(\alpha,\alpha n)$ reaction have been observed in the heavy element region at bombarding energies below 50 Mev.[1–3] Of the possible mechanisms for this reaction, the following seem to be the most likely: (1) compound nucleus formation and decay, (2) a "knock-on" process in which the incident helium ion strikes a neutron and both collision partners escape from the nucleus, or (3) direct inelastic scattering of the incident helium ion followed by evaporation of a neutron from the resulting excited residual nucleus. Some evidence regarding the mechanism can be obtained by comparison of the values of the $(\alpha,\alpha n)$ cross section with the predictions of the compound nucleus theory and with the values of the $(\alpha,\alpha p)$ cross sections. The distinction between mechanisms (2) and (3) can be made on the following basis: a knock-on process like (2) would be expected to result in the emission of a proton almost as often as a neutron because of the high energy of the emitted particles, whereas the excited residual nucleus resulting after helium-ion scattering in process (3) would not be expected to evaporate protons as readily as neutrons because of the high Coulomb barriers occurring in the heavy-element region. Thus, for case (2), the $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ cross sections should be about the same size, whereas for case (3), the $(\alpha,\alpha n)$ cross section should be much larger than the $(\alpha,\alpha p)$ cross section.

This work was undertaken to determine the mechanism of the $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ reactions by measurement of the excitation function for the $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ reactions on Ce^{142} at incident helium-ion energies up to 40 Mev. The excitation function for the $(\alpha,2pn)$ reaction was also measured and the mechanism of that reaction is discussed.

EXPERIMENTAL PROCEDURES

Targets of enriched (90.08%) Ce^{142} were prepared by painting onto 0.001-in. aluminum foil, using a modification of a technique developed by Dodson *et al.*[4] These targets were bombarded in the external beam of the Brookhaven 60-in. cyclotron at helium-ion energies up to 40 Mev, using a foil-wheel and Faraday cup assembly previously described.[5] The energy of the helium ions striking the target was adjusted by means of interposed aluminum degrading foils. The range-energy data of Bichsel[6] were used to calculate the final energy. The irradiated targets were dissolved in concentrated hydrochloric acid with a few drops of 30% hydrogen peroxide to ensure that the cerium was present in the (III) state, lanthanum carrier was added, and the rare-earth hydroxides were precipitated with 6*M* sodium hydroxide. The precipitate was dissolved in 8*M* nitric acid with a few drops of 30% hydrogen peroxide. The cerium was then oxidized to Ce(IV) by the addition of solid ammonium peroxydisulfate with a little silver nitrate as catalyst. The Ce(IV) was extracted into a solution of 30% tributyl phosphate (TBP) and 70% carbon tetrachloride. This step was performed five times with fresh portions of the organic phase. The cerium was then back-extracted into 1*M* hydrochloric acid by reduction with sodium bisulfite. Cerous oxalate was then precipitated and mounted on filter paper for counting.

Two days were allowed for the decay of 3.8-hr La^{141},

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[1] R. Vandenbosch, T. D. Thomas, S. E. Vandenbosch, R. A. Glass, and G. T. Seaborg, Phys. Rev. **111**, 1358 (1958).
[2] B. M. Foreman, Jr., W. M. Gibson, R. A. Glass, and G. T. Seaborg, Phys. Rev. **116**, 382 (1959).
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[4] R. W. Dodson, A. C. Graves, L. Helmholz, D. L. Halford, R. M. Potter, and J. G. Povelites, *Miscellaneous Physical and Chemical Techniques of the Los Alamos Project*, edited by A. C. Graves and D. K. Roman, National Nuclear Energy Series (McGraw-Hill Book Company, Inc., New York, 1952), Vol. V-3, p. 1; J. R. Grover (private communication).
[5] J. R. Grover, B. M. Foreman, Jr., B. D. Pate, C. P. Baker, and J. Hudis, Brookhaven National Laboratory Report BNL-654 CT-211 (unpublished).
[6] H. Bichsel, Phys. Rev. **112**, 1089 (1958); H. Conzett and coworkers, University of California (unpublished).

which was not extracted by the TBP, into Ce^{141}. Then cerium carrier was added, the extraction was repeated, and a cerium oxalate source was prepared as before.

The radioactivity of the samples resulting from the above procedure was measured with end-window proportional counters, and the decay curves were followed for several months. The 145-kev gamma ray[7] from the decay of Ce^{141} was measured with a sodium-iodide scintillation spectrometer.

The $(\alpha,\alpha n)$ cross section and an upper limit to the $(\alpha,\alpha p)$ cross section were determined from the counting rate of the gamma ray, and the $(\alpha,2pn)$ cross section was determined from the beta-particle counting rate of[7] 33-hr Ce^{143} as found by resolution of the decay curve.

In one experiment, the $(\alpha,\alpha p)$ cross section was measured directly. The La^{141} product was separated from the Ce^{142} target by ion exchange and the decay of the beta activity was followed.

RESULTS

The cross sections for the reactions $Ce^{142}(\alpha,\alpha n)Ce^{141}$ and $Ce^{142}(\alpha,2pn)Ce^{143}$ are listed in Table I and plotted in Figs. 1 and 2. The limits of error were estimated to be 7% and 15%, respectively, at all energies except 39.3 Mev, where the chemical yield was more uncertain than in the other bombardments. The limits of error for the $(\alpha,2pn)$ cross section do not include an estimated uncertainty of about 20% in the counting efficiency of the proportional counter, a possible source of a systematic error in the cross sections.

The cross sections at 33.9 Mev are upper limits only, because not all the helium-ion beam current was collected during the bombardment at this energy. An estimate of the $(\alpha,2pn)$ cross section at this energy was obtained by a normalization procedure based on the smooth curve of Fig. 1 and the measured upper limit for the $(\alpha,\alpha n)$ cross section. The value thus calculated is indicated by a triangle in Fig. 2.

An upper limit to the $(\alpha,\alpha p)$ cross section of 0.1 mb was obtained at all energies. A value of 0.16 ± 0.04 mb was measured (limits of error estimated) for the cross section for this reaction at 38.0 Mev. In view of the fact that the decay curve of the lanthanum fraction from this bombardment shows large components from impurities, this is considered satisfactory agreement with the measured upper limit.

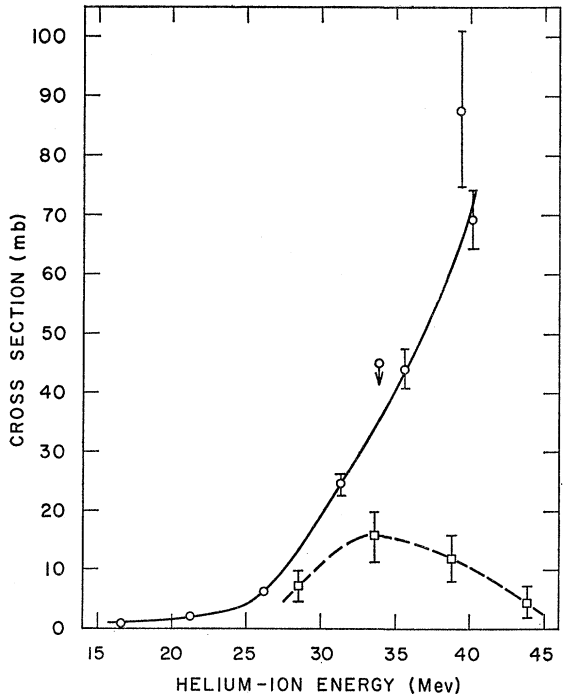

FIG. 1. Excitation function for the reaction $Ce^{142}(\alpha,\alpha n)Ce^{141}$. Circles, experimental values; squares, results of the Monte Carlo calculation.

[7] K. Way, *et al.*, Nuclear Data Sheets (National Academy of Sciences, National Research Council).

DISCUSSION

Since the upper limit for the $(\alpha,\alpha p)$ cross section is so much smaller than the measured $(\alpha,\alpha n)$ cross section, it appears for the reasons mentioned in the Introduction that the two reactions do not proceed by a knock-on mechanism. These reactions, therefore, probably result from inelastic scattering of the alpha particle followed by nucleon evaporation.

TABLE I. Cross sections for the reactions $Ce^{142}(\alpha,\alpha n)Ce^{141}$ and $Ce^{142}(\alpha,2pn)Ce^{143}$.

E (Mev)	σ(mb) $(\alpha,\alpha n)$	$(\alpha,2pn)$
16.6	0.81±0.06	0.088±0.013
21.2	1.65±0.12	0.11±0.02
26.1	6.4±0.4	0.096±0.014
33.1	25±2	0.15±0.02
33.9	⩽45	⩽0.62 (0.49)[a]
33.5	44±3	0.79±0.12
39.3	87±13	3.4±0.7
40.1	69±5	2.5±0.4

[a] Estimated as described in text.

To obtain further information as to the mechanism of the inelastic scattering preceding nucleon evaporation, Monte Carlo calculations were performed according to the statistical model of Dostrovsky, Fraenkel, and Friedlander[8] with the level density parameter $a=A/20$, which gives fair agreement with experimental results in a lighter mass region.[8] The pairing energies used were those given by Cameron.[9] The results of the calculation of the $(\alpha,\alpha n)$ cross section are represented by the dashed curve in Fig. 1. The error bars on the points represent statistical standard deviations. It can be seen that the calculated results disagree with the experimental data as regards both the magnitude of the cross section and

[8] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).

[9] A. G. W. Cameron, Can. J. Phys. **36**, 1040 (1958).

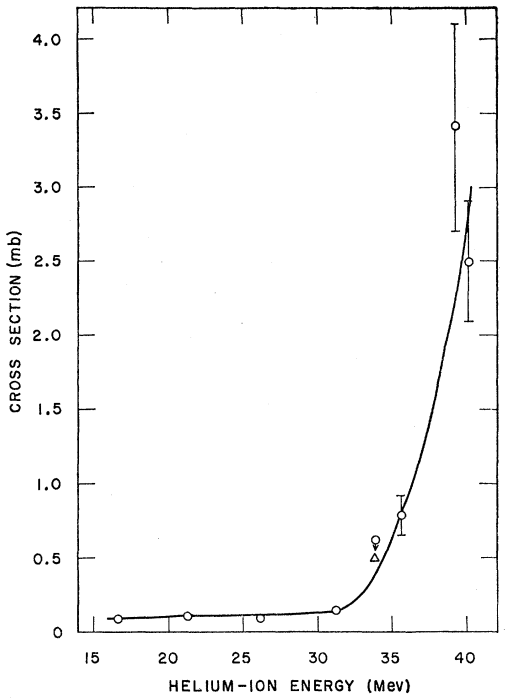

FIG. 2. Excitation function for the reaction $Ce^{142}(\alpha,2pn)Ce^{143}$. Circles, experimental values; triangle, value estimated as described in text.

its energy dependence. This disagreement indicates that either the mechanism is not one of compound nucleus formation and decay, or the calculation does not represent accurately the consequences of the compound nucleus model. In the former case, the mechanism indicated would be number (3) of the Introduction, i.e., direct inelastic scattering followed by nucleon evaporation.

The Monte Carlo calculation shows no production of the $(\alpha,2pn)$ product, Ce^{143}, by any path. The calculation also contains no case of successive emission of two charged particles. Evaporated particles generally have lower kinetic energy and thus leave the residual nucleus in a more highly excited state than do particles emitted in direct interactions. Hence, if proton emission is not probable after a proton has been evaporated from a compound nucleus (as the Monte Carlo calculations indicate), then it is surely even less probable after a proton has been emitted in a direct interaction. Hence, if the Monte Carlo calculation is valid, the observed Ce^{143} production apparently does not arise from processes in which two successive protons are emitted. This implies that both protons are emitted simultaneously, probably bound together in a He^3 particle. Evaporation of He^3 from the compound nucleus is a possibility, but no cases of He^3 evaporation were found in the Monte Carlo calculation. Because, in these calculations, 1000 events were followed for each of six excitation energies, this implies an upper limit for the (α,He^3) cross section of about 0.1% of the compound nucleus formation cross section at each energy. Although the observed $(\alpha,2pn)$ cross section is smaller than this upper limit up to a helium ion energy of about 37 Mev, it rapidly becomes larger above that energy. Therefore, the most plausible mechanism for the (α,He^3) reaction would appear to be one of direct interaction, probably stripping.

The results presented in this paper are consistent with the hypothesis previously proposed[2] that below 50 Mev no appreciable amount of direct interaction occurs in which more than one particle is emitted.

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