Then from the experimental upper limit and the calculated lower limit, one has

$$(1.3\pm0.7)\times10^{-5}>\lambda_+/\lambda_->(2.21\pm0.16)\times10^{-5}M_+^2/M_-^2, \quad (6)$$

and

$$M_+^2/M_-^2<0.59\pm0.28. \quad (7)$$

On the basis of the shell model the β^+ and β^- transitions can be represented, respectively, by $(d_{3/2})^p\rightarrow(f_{7/2})^n$ and $(f_{7/2})^n\rightarrow(d_{3/2})^p$.[8] It is expected therefore that $M_+^2\cong M_-^2$.

The upper limit obtained for M_+^2/M_-^2 is not surprising, however. As an indication of values to be expected, Feenberg[9] has pointed out that the squares of the matrix elements for unique first forbidden transitions spread over a range of 10 according to the empirical evidence. For example, in $_{33}As_{41}^{74}$, $(f_1t)_+/(f_1t)_-=0.63$,[10] $[f_1=(1/20)(W_0^2-1)f]$; and in $_{53}I^{126}$, $(f_1t)_+/(f_1t)_-=0.12$.[11]

We would like to thank Professor F. Rasetti for many helpful discussions.

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Reactions of Alpha Particles with Germanium-70 and Zinc-70*

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The reactions $Ge^{70}(\alpha,2n)Se^{72}$, $Ge^{70}(\alpha,pn)As^{72}$, $Zn^{70}(\alpha,pn)Ga^{72}$, and $Zn^{70}(\alpha,2p)Zn^{72}$ were studied with alpha particles of 20–40 Mev, and their excitation functions were measured. The results are compared with evaporation calculations based on the assumption of compound-nucleus formation.

INTRODUCTION

THE mechanisms of nuclear reactions at moderate energies, 20 to 40 Mev, have long been the subject of discussion and much contradictory evidence has been presented.[1] In particular, the fact that (α,pn) and (p,pn) cross sections are often larger than the cross sections of competing $(\alpha,2n)$ and $(p,2n)$ reactions has, on the one hand, been cited[2] as supporting evidence for a direct-interaction mechanism, and has, on the other hand, been interpreted[3–6] in terms of level density effects in the framework of compound-nucleus theory.

It seemed of interest to investigate comparable α-induced reactions with two isobaric target nuclei, and to see whether the measured cross sections and their energy dependence could be accounted for by the statistical theory. The target nuclei chosen were Zn^{70} and Ge^{70} and the reactions studied were $Zn^{70}(\alpha,2p)Zn^{72}$, $Zn^{70}(\alpha,pn)Ga^{72}$, $Ge^{70}(\alpha,pn)As^{72}$, and $Ge^{70}(\alpha,2n)Se^{72}$. Figure 1 shows in detail the evaporation paths which can lead to these products under the assumption of a compound-nucleus mechanism.

EXPERIMENTAL

Targets.—Natural germanium was used for the study of $Ge^{70}(\alpha,2n)Se^{72}$ and $Ge^{70}(\alpha,pn)As^{72}$ reactions. The targets were prepared by evaporation of metallic germanium in a high vacuum onto 0.001-inch gold foils to thicknesses of 0.151 ± 0.002 and 0.85 ± 0.04 mg/cm^2. The reactions $Zn^{70}(\alpha,pn)Ga^{72}$ and $Zn^{70}(\alpha,2p)Zn^{72}$ were studied with targets of enriched zinc-70 (48 and 59 atom-percent Zn^{70}) electroplated on 0.001-inch gold foils to thicknesses in the range of 0.20 to 0.85 mg/cm^2.

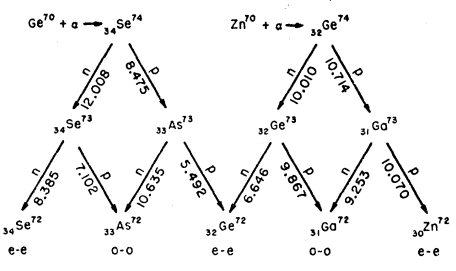

FIG. 1. Evaporation paths leading from the compound nuclei Se^{74} and Ge^{74} to the product nuclei of $A=72$. The neutron and proton separation energies[13,14] (in Mev) are shown. The even-even (*e-e*) and odd-odd (*o-o*) character of the product nuclei is indicated.

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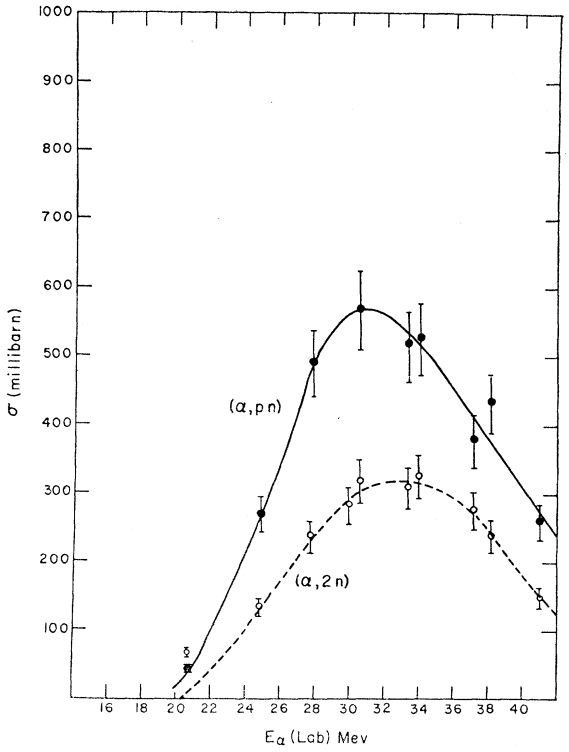

FIG. 2. Measured cross sections for the $Ge^{70}(\alpha,2n)$ and $Ge^{70}(\alpha,pn)$ reactions.

The thicknesses of the deposited elements on the target foils were determined both by weighing and by direct chemical analysis.

Bombardments.—Stacks of target foils were bombarded in the deflected He^{++} beam of the Brookhaven 60-in. cyclotron. In the bombardments the target layers faced the incoming beam, thereby avoiding the loss of recoiling products from the target foil. With this arrangement, the recoils are captured in the gold backing of the target foil. The exposed target area was of the order of 0.3 cm^2. The energy of the 41.6±0.5 Mev alpha particles was degraded with aluminum foils of measured thicknesses.[7] The beam was monitored by means of a Faraday cup. The beam intensities used for the bombardments were of the order of 1–3 microamperes. Irradiation times were in the range of 1 to 5 hours.

A detailed description of the target assembly used as well as an analysis of the performance of the Faraday cup, used in this experiment, have been published elsewhere.[8]

Chemistry.—The products of the reactions were chemically separated by conventional radiochemical procedures.[9]

Targets were dissolved in HCl containing minimum HNO_3. Selenium and arsenic were separated from the germanium-gold solution by distillation of their bromides. Selenium was reduced to the metallic form, arsenic was precipitated as the As_2S_3. Gallium was extracted with isopropyl ether after removal of gold from the HCl solution, and then precipitated as the 8-hydroxy quinoline derivative. Zinc-72 production was determined through its daughter Ga^{72} which was extracted and processed the same way as the Ga fraction some 48 hours after the purification of the zinc fraction. All final samples were precipitated on fixed-diameter filter paper disks and mounted on aluminum plates. Chemical yields were determined by addition of known amounts of carriers during dissolution of the targets, and by a subsequent quantitative instrumental chemical analysis of the measured samples.

Measurements.—The measurements of the sample activities were performed at calibrated geometries with a 3×3 inch NaI(Tl) crystal connected to a 100-channel pulse-height analyzer. In the determination of the individual reaction products advantage was taken of their characteristic gamma spectra and decay half-lives.

26-hour arsenic-72 was determined by the photopeak of its 0.835-Mev gamma ray whose abundance is 76.6%.[10]

8.4-day selenium-72 was determined through its

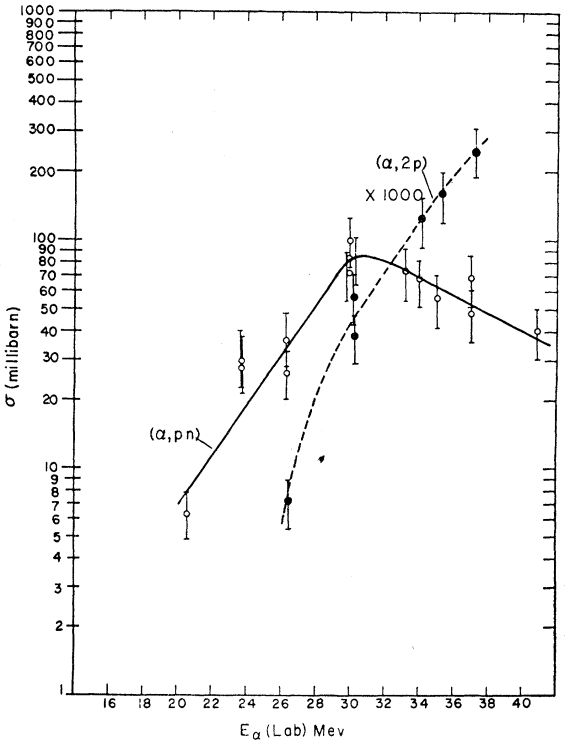

FIG. 3. Measured cross sections for the $Zn^{70}(\alpha,pn)$ and $Zn^{70}(\alpha,2p)$ reactions.

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daughter As^{72}; thus the ratio of As^{72} and Se^{72} yields is free from counting efficiency corrections.

14.3-hour gallium-72 was determined by the photopeak of its 0.84-Mev gamma ray whose abundance is 96.7%.[11]

49-hour zinc-72 was determined through its daughter, Ga^{72}; this again eliminates counting efficiency corrections in the relative yields.

The counting efficiencies of all measured gammas were the same, because they are of the same energy. The geometry, as well as the total counting efficiency were calibrated by means of the 1.28-Mev gamma ray of a calibrated standard sodium-22 source.[12]

RESULTS

The measured cross sections for the reactions studied are shown in Figs. 2 and 3. The estimated errors ($\pm 10\%$ for the $Ge^{70}+\alpha$, and $\pm 25\%$ for the $Zn^{70}+\alpha$ reactions) are shown. The uncertainty in energy is $\leqslant 0.5$ Mev at the upper end of the energy scale and increases to ~ 1 Mev at the lowest energies. The alpha-particle threshold energies for the reactions studied, as computed from mass[13] and decay energy[14] data, are: 18.8 Mev for $Ge^{70}(\alpha,2n)$, 16.0 Mev for $Ge^{70}(\alpha,pn)$, 14.5 Mev for $Zn^{70}(\alpha,pn)$, and 14.9 Mev for $Zn^{70}(\alpha,2p)$.

DISCUSSION

The shape of the $Ge^{70}(\alpha,2n)Se^{72}$, $Ge^{70}(\alpha,pn)As^{72}$, and $Zn^{70}(\alpha,pn)Ga^{72}$ excitation function curves follow the general characteristics of a compound nucleus mechanism for similar reactions in the same mass region. The $Zn^{70}(\alpha,2p)Zn^{72}$ excitation function differs in its shape from the three other curves. This is probably due to the effect of the large barrier for two proton evaporations, which results in shifting of the peak to higher energies. On the other hand, one cannot exclude the possibility of a non-compound-nucleus mechanism for this reaction.

It may be noted that $Zn^{70}(\alpha,pn)$ cross sections are substantially lower than the $Ge^{70}(\alpha,pn)$ cross sections. One can conclude that the unobserved $Ge^{70}(\alpha,2n)$ reaction must, at the peak value of the two-particle emission functions, have a cross section of the order of 10 times that of the $Ge^{70}(\alpha,pn)$ reaction. Thus the ratio of $(\alpha,pn)/(\alpha,2n)$ cross sections is greatly different on the two sides of the stability valley, a result which would not be expected if direct interaction were the predominant mechanism for the (α,pn) reactions.

An attempt was made to calculate the cross sections of the reactions according to the statistical theory.[15] The method was exactly that used by Porile[16] in his analysis of the α-particle reactions of Zn^{64}. Odd-even effects on level densities were taken into account by the formalism of a characteristic level,[17] and for the displacements δ of the characteristic levels Cameron's[18] shell and pairing energies were used. Semiquantitative agreement with the experimental data was obtained and the large difference in (α,pn) cross sections for Ge^{70} and Zn^{70} was well reproduced; but the calculated ratio of $(\alpha,pn)/(\alpha,2n)$ cross sections on Ge^{70} was too small by about a factor 2 at the peak of the excitation function. This ratio was found to be very sensitive, however, to the choice of δ values, and much better agreement with the experimental results reported here has been obtained with a different choice of pairing energies in the course of extensive evaporation calculations by Dostrovsky, Fraenkel, and Friedlander.[19] The parameter a in the level density expression $W(E)=C\exp[2(aE)^{\frac{1}{2}}]$ was varied between $A/10$ and $A/20$ and this was found not to affect the calculated cross sections substantially.

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