In Fig. 10 are shown excitation functions for reactions involving emission of an alpha particle and a neutron or a proton. The computed cross sections based on expression (3b) are consistently too large. This can be interpreted as indicating that Newton's[25] choice of values for j_Z and j_N for Ni and Cu isotopes is not consistent with his values for Zn and Ga. The agreement between experimental and computed values based on expressions (3a) and (3c) is qualitatively satisfactory. The experimental data for the alpha reactions were taken from Porile and Morrison[5] with adjusted energy scale.

In summary, it appears that there is little basis for a choice between formula (3a) and (3c) for level density. Formula (3b) is essentially of the same form as formula (3c); however, the specific recommendations of values for j_N and j_Z and the resulting values of a do not provide a qualitatively good fit for reactions involving emission of alpha particles. The incorporation of gamma de-excitation generally shifted the peak values in the excitation functions to a higher energy and the fit to experimental values could generally be improved by a proper choice of k. The fit obtained with both (3a) and (3b) suggests that the reactions of 10- to 25-MeV He^3 particles with copper targets are similar in mechanism to the reactions of 15- to 40-MeV alpha particles. Although a number of "improvements" were incorporated in the computations, the agreement of theory with experiment must be regarded as no better than qualitative. Indeed, it is doubtful that excitation function data alone can provide an adequate basis for quantitative conclusions as to reaction mechanism. The degree of fit does suggest, however, that the computations employed here are useful in predicting approximate reaction cross sections.

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(p,n) Cross Sections at 6.75 MeV*

R. M. HUMES†, G. F. DELL, JR., W. D. PLOUGHE, AND H. J. HAUSMAN
Department of Physics, The Ohio State University, Columbus, Ohio

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The (p,n) partial reaction cross sections at 6.75 MeV have been measured for the isotopes Sc^{45}, V^{51}, Mn^{55}, Cu^{63}, Cu^{65}, Ga^{69}, Ga^{71}, and Br^{79}. The results of the measurements in millibarns are 179±9, 480±31, 440±40, 239±13, 566±37, 981±98, 649±69, and 86±5, respectively. The purpose of the experiment is to provide information on reaction cross sections for comparison with optical-model computations. A preliminary comparison of the variation of the cross sections with mass number is made with the partial wave penetrabilities computed from an optical-model potential.

INTRODUCTION

THE optical model has been successfully used in fitting the general features of neutron total elastic cross sections, proton elastic cross sections, and polarizations. The parameters obtained for the potential are relatively insensitive to mass number, although there appears to be a Z dependence for proton scattering. However, there are a number of areas of disagreement between model prediction and experiment. The optical-model parameters are not unique for a given set of data, and some of the parameters may vary widely and still be consistent with a single set of data. Furthermore, the model parameters deduced from proton elastic scattering and polarization data have led to predicted reaction cross sections which are smaller than measured reaction cross sections. As an example, the comparison between experimental and calculated proton-reaction cross sections at 10 MeV as reported by Meyer and Hintz[1] shows the discrepancy to be about 100 mb for the copper and zinc isotopes.

A number of experiments have been reported in the literature[2] on studies of proton-induced reactions which can be compared with optical-model computations. These experiments have measured angular distributions of elastically scattered protons, the polarization of the scattered proton beam, and total reaction cross sections. These quantities have been studied on the isotopes of copper, Cu^{63} and Cu^{65} by a number of groups at proton energies of from 6 to 18 MeV. The data at a proton energy of 10 MeV has been analyzed by Nodvik and Saxon[3] and a set of consistent parameters published. The discrepancy between the experimental reaction cross sections and the reaction cross sections calculated from a set of optical-model parameters consistent with the elastic scattering and polarization data appears to be the most serious from the standpoint of obtaining a

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† Taken in part from a thesis submitted by R. M. Humes to the Graduate School of The Ohio State University in partial fulfillment of the requirements for the degree Master of Science.

[1] V. Meyer and N. Hintz, Phys. Rev. Letters **5**, 207 (1960).

[2] As examples: H. Taketani and W. P. Alford, Phys. Rev. **125**, 291 (1962); R. D. Albert and L. F. Hansen, *ibid.* **123**, 1749 (1961); B. W. Shore, N. S. Wall, and J. W. Irvine, Jr., *ibid.* **123**, 276 (1961); R. D. Albert, *ibid.* **115**, 925 (1959); C. A. Preskitt, Jr., and W. P. Alford, *ibid.* **115**, 389 (1959); H. A. Howe, *ibid.* **109**, 2083 (1958); N. M. Hintz, *ibid.* **106**, 1201 (1957); G. W. Greenlees, L. G. Kuo, and M. Petravic, Proc. Roy. Soc. (London) **A243**, 206 (1957); J. P. Blaser, F. Boehm, P. Marmier, and P. Scherrer, Helv. Phys. Acta **24**, 441 (1954).

[3] J. S. Nodvik and D. S. Saxon, Phys. Rev. **117**, 1539 (1960).

TABLE I. $\sigma(p,n)$ at $E_p=6.75$ MeV.

Isotope	Cross section (mb)
Sc^{45}	179 ± 9
V^{51}	480 ±31
Mn^{55}	440 ±40
Cu^{63}	239 ±13
Cu^{65}	566 ±37
Ga^{69}	981 ±98
Ga^{71}	649 ±69
Br^{79}	85.6± 4.8

single set of parameters. The need for additional experimental reaction cross section measurements is the motivation for these experiments. These experiments are part of a number of partial reaction cross-section measurements which are being conducted at this laboratory in the mass range $27 \leq A \leq 81$.

DESCRIPTION OF EXPERIMENT

Targets were chosen for study in the mass range 45 to 81 for the following reasons. At the cyclotron bombarding energy of 6.75 MeV, excitation of the compound nucleus was sufficiently high to insure an experimental averaging over a reasonable number of compound states. The bombarding energy was sufficiently above the Coulomb barrier so that a large number of exit channels —(p,p'), (p,α), and (p,n)—were available for the reaction. It is to be noted that the level densities for the low-lying excited states of the energetically possible reaction channels are larger for targets of odd-even isotopes than for even-even target nuclei. The larger the total number of exit channels, the smaller the relative probability for the decay of the compound system through the compound-elastic channel. The compound-elastic scattering, which is indistinguishable experimentally from elastic scattering, is computed as a reaction process but is not measurable experimentally as such. Hence, reasonable comparison between experimental and computed reaction cross sections are possible only when the compound elastic contribution is small. Finally, targets were chosen such that the residual nuclei from the (p,n) partial reaction cross sections were radioactive.

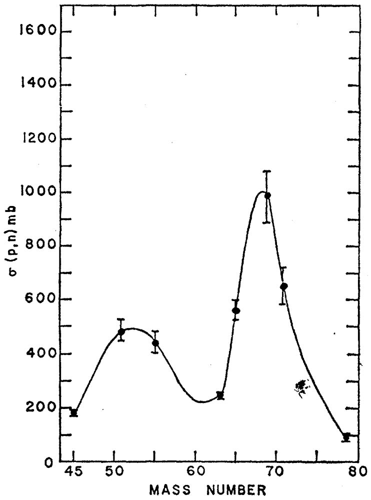

FIG. 1. (p,n) cross section as a function of mass number at an incident proton energy of 6.75 MeV. The solid curve is not a theoretical fit but serves to guide the eye through the experimental points.

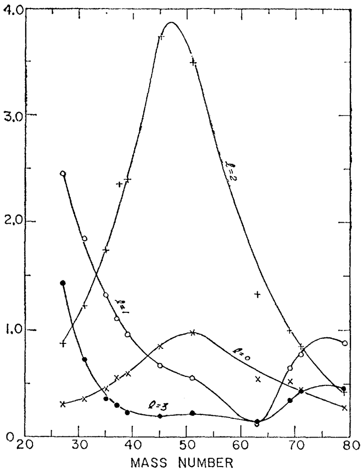

FIG. 2. A plot of the computed partial-wave penetrabilities as a function of mass number. The imaginary part of the optical potential is of a Gaussian shape peaked at the nuclear surface—the surface absorption potential.

The external cyclotron beam of 6.75-MeV protons was focused by a pair of quadrupole magnets onto targets located a distance of 15 ft from the cyclotron. An Eldorado model CI-110 current integrator was used to determine the amount of charge collected. After bombardment, the targets were placed either in a 3-in.×3-in. NaI well counter or adjacent to a thin-walled proportional counter, depending upon whether the principle decay mode was γ emission or characteristic x radiation following electron capture. The well crystal efficiency was determined over the energy spectrum of interest with a set of calibrated sources. The sources in turn were calibrated using the total efficiency computations of Miller *et al.*[4] The efficiency and effective solid angle of the proportional counter were determined for a fixed geometry by measuring the coincidences between the Cu x ray and the 1.114-MeV γ ray from the decay of a calibrated Cu^{65} source.

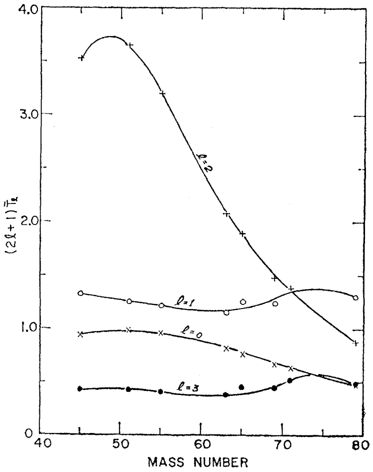

FIG. 3. A plot of the penetrabilities as a function of mass number. The imaginary part of the optical potential is of the Woods-Saxon form—the volume absorption potential.

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[4] W. F. Miller, John Reynolds, and W. J. Snow, ANL-5902 (1958).

The two dominant modes of decay for the radioactive residual nuclei studied were positron emission and electron capture. For the most complex decay three types of radiations were present: the annihilation radiation from positron decay in the target, characteristic x rays from electron capture, and γ rays resulting from decays of the excited states of daughter nuclei. For the cases wherein the decay transitions were complex, branching ratios were obtained from the National Research Council Nuclear Data Sheets.

RESULTS AND DISCUSSION

The results of the (p,n) cross-section measurements are shown in Fig. 1 and tabulated in Table I. Over the mass range investigated, the cross section has two well-defined maxima at $A=50$ and $A=74$. The cross section for the peak at $A=70$ is larger than that for $A=50$. This is attributed to the fact that although the reaction cross section will be decreasing with mass number due to the increasing Coulomb barrier, the relative strength of the (p,n) partial cross section will be larger due to the decrease in the charged-particle partial cross sections. Near the $A=70$ peak, the (p,n) cross section more nearly approaches the total reaction cross section.

Reaction cross sections for proton-induced reactions have been computed using the optical-model code of Drisko and Bassel[5] of the Oak Ridge National Laboratory. The potentials used for preliminary computations were of the form

$$V=-[V(r)+iW(r)+(\text{spin orbit})+V_c(r)],$$

where

$$V(r)=V_0\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1},$$

$$W(r)=W_0\exp\left[-\left(\frac{r-R}{b}\right)^2\right],$$

or

$$W(r)=W_0\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1},$$

$$V_c(r)=\text{the Coulomb potential},$$

and the spin-orbit interaction is:

$$(V_s+iW_s)(1/r)\left\{\frac{d}{dr}\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}\right\}(\boldsymbol{\sigma}\cdot\mathbf{l}).$$

Initial parameters for the potential, corrected for bombarding energy, were obtained from the paper by Nodvik and Saxon.[3] The parameters used are $V_0=56.8$ MeV, $W_0=6.5$ MeV, $V_s=3.5$ MeV, $W_s=1.0$ MeV, $r_0=1.26$ F, $a=0.518$ F, and $b=0.98$ F. The cross section for formation of the compound nucleus was computed and the penetrabilities T_l determined from the following

$$\sigma_c=\pi\lambdabar^2\sum_{l=0}^{l=10}(2l+1)\bar{T}_l,$$

where

$$(2l+1)\bar{T}_l=(l+1)T_l^{+}+lT_l^{-},$$
$$T_l^{\pm}=4[\operatorname{Im}(C_l^{\pm})-(\operatorname{Im}C_l^{\pm})^2-(RC_l^{\pm})^2],$$

where the C_l are the complex scattering amplitudes as determined from the optical-model computations.

A plot of the penetrabilities for surface absorption and volume absorption over the mass region $A=45$ to $A=80$ for $E_p=6.75$ MeV is shown in Figs. 2 and 3, respectively. Only the first four partial waves are shown. At approximately $A=50$, a strong resonance is observed in the $l=2$ and $l=0$ penetrabilities. A less pronounced peaking is observed in the $l=1$ and $l=3$ penetrabilities at $A=75$. It is interesting to note that the computations show the same general peaking in the penetrabilities with mass number whether one uses volume absorption or surface absorption for the imaginary part of the optical-model potential.

While there appears to be a qualitative agreement between the mass variation of the experimentally observed (p,n) cross sections and the resonant structure in the computed penetrabilities, it is possible that the relatively large (p,n) threshold in Cu^{63} accidentally emphasizes a somewhat questionable resonance interpretation. In order to make quantitative comparisons between the measured and computed cross sections, it is necessary to determine the magnitude of the competing reaction processes, (p,p'), (p,α), and (p,γ). The results of these experiments will be reported in a later paper.

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[5] R. Bassel and R. Drisko (private communication).