Alpha-Gamma Reaction*

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The cross section of the reaction $Ni^{58}(\alpha,\gamma)Zn^{62}$ was measured as a function of the incident alpha-particle energy from ~10 to 17 Mev. The cross section at 17 Mev is about 0.4 mb and decreases gradually with decreasing energy. The experimental curve is compared with calculations assuming the formation of the compound nucleus. Two different gamma-ray width formulas are used; one is Weisskopf's single-particle formula for electric dipole radiation and the other is obtained from the known gamma-ray width derived from photonuclear absorption cross sections. The former has about the right order of magnitude at the middle of the range investigated but behaves quite differently from the experimental curve. The latter shows fairly good agreement with the experiment, indicating the existence of the giant resonance. A calculation is also made for the reaction $Ni^{60}(p,\gamma)Cu^{61}$ cross section and the results fit quite well again with the experimental cross section reported by B. L. Cohen *et al.*, indicating the possibility of explaining the reaction cross section without the assumption of the "capture of the proton from the orbit." In both cases, the calculated values are too low at the high-energy side. This may be explained by some failure of the assumptions in the calculations.

INTRODUCTION

PHOTONUCLEAR reactions have revealed many interesting characteristics, especially since extensive studies were started after the development of high-energy electron accelerators. One of the useful methods to investigate the phenomena of the photonuclear reactions is, however, the study of the inverse reactions. Especially, this method may be helpful to determine the occurrence of the "direct emission"[1,2] in photonuclear reactions or "the capture of the incident particle from the orbit"[3] in the case of the inverse reactions The conclusion of most of the experiments is that the photonuclear reaction goes mainly through compound states of the nucleus,[4,5] but there are always some indications of direct processes in the photonuclear reaction[6,7] and it has been reported that the assumption of "capture of the protons from the orbit"[3,8] is necessary for explaining the (p,γ) reaction cross sections.

In this connection, an investigation of the (α,γ) reactions is interesting since the reduced charge of an alpha particle in the vicinity of a nucleus is zero or very small compared to that of a proton $(\sim e/2)$ or a neutron $(\sim -e/2)$. Therefore the capture of the alpha particles from the orbit is very unlikely. So, the cross section of the (α,γ) reaction should give the gamma-ray width of the highly excited compound nucleus.

Also, the comparison of the (p,γ) and the (α,γ) cross sections should answer the question of whether the capture of protons from the orbit occurs to a significant extent or not.

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EXPERIMENTAL PROCEDURE AND RESULTS

The reaction $Ni^{58}(\alpha,\gamma)Zn^{62}$ was chosen for the first investigation. Zn^{62} has a convenient half-life of 9.33 hr, with a 10-min daughter which emits high-energy positrons. Zn^{63}, which emits high-energy positrons with a half-life of 38.3-min, is produced simultaneously by the (α,n) reaction on Ni^{60} and provides a convenient calibration. Since the excitation curve for the reaction $Ni^{60}(\alpha,n)Zn^{63}$ is known, the comparison of the two activities will be sufficient to determine the (α,γ) cross section.

A stack of 0.001-inch foils of natural nickel was bombarded with the external beam of the Purdue cyclotron. The alpha-particle energy was reduced to 17 Mev by an absorber since the reaction $Ni^{60}(\alpha,2n)Zn^{62}$ has a threshold of 17.8 Mev. The first four foils were dissolved in small amounts of HCl with the help of positive potentials on them. Cu, Zn, and Ga carriers were added. In order to remove Ga activities, especially the 9.4-hr Ga^{66}, which might be produced from a possible Cu contamination of the target, an ether extraction of Ga from 6*N* HCl was performed twice. After removing Cu by two sulfide precipitations the Ni was removed as the hydroxide from a strongly basic solution. $Zn(OH)_2$ was finally precipitated by making the solution nearly neutral. Since only the ratios of the two Zn activities were to be measured, the chemical yields were not determined.

The four samples were covered with thin Scotch tape after drying and counted for about three days with four Geiger counters. The first part of one of the decay curves is shown in Fig. 1. The activity clearly consists of two components. After correcting for small differences in the beta counting efficiencies for the two components, for the beam intensity changes during the bombardment, and for the isotopic abundances, the cross section for the (α,γ) reaction was calculated from Ghoshal's (α,n) cross sections.[9] The results are given in Fig. 2 (curve *a*). Compared with other reactions, the excitation

[9] S. N. Ghoshal, Phys. Rev. 80, 939 (1950).

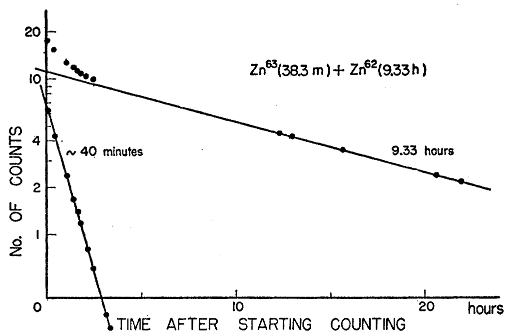

FIG. 1. One of the decay curves of zinc separated from nickel target.

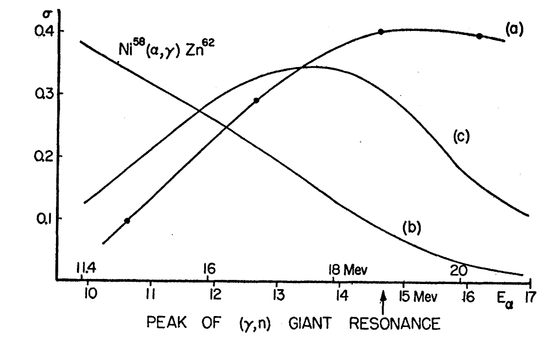

FIG. 2. Cross section of the reaction $Ni^{58}(\alpha,\gamma)Zn^{62}$ as a function of energy in millibarn. *a*, Experimental; *b*, calculated by using Eq. (5); *c*, calculated by using Eq. (6).

curve is quite flat in the energy region covered and the cross section is of the order of one thousandth of the (α,n) cross section.

CALCULATIONS OF THE CROSS SECTIONS

The experimental cross sections are to be compared with calculations made under the assumption of compound nucleus formation. The cross sections are given by[10]

$$\sigma(\alpha,\gamma)=\sigma_c(\alpha)F_\gamma'/\sum_i F_i, \quad \sum_i F_i \approx F_n+F_p, \tag{1}$$

where $\sigma_c(\alpha)$ is the capture cross section for the alpha particle. For this, the values listed in reference 10 with $r_0=1.5\times10^{-13}$ cm was used. F_p, F_n, and F_γ' are functions proportional to the neutron, proton, and the radiation width of the compound nucleus. F_γ' should correspond, however, not to the total radiation width but to that part of the radiation width which corresponds to the emission of gamma rays without subsequent particle emission.

The functions F_n and F_p have the following forms:

$$F_n(E_e)=\frac{2\pi MR^2}{\hbar^2}\int_0^{E_e-E_{bn}} E_n\omega(E)dE, \quad (E_n=E_e-E_{bn}-E); \tag{2}$$

$$F_p(E_e)=\frac{2\pi MR^2}{\hbar^2}\int_0^{E_e-E_{bp}} S(E_p)E_p\omega(E)dE, \quad (E_p=E_e-E_{bp}-E). \tag{3}$$

Here M is the nucleon mass, R is the nuclear radius (r_0 taken to be 1.5×10^{-13} cm), $S(E_p)$ is the barrier penetration probability for the protons, and $\omega(E)$ is the level density of the residual nucleus. E_e is the excitation energy of the compound nucleus, E_{bn} and E_{bp} are the binding energy of neutron and proton in the compound nucleus, respectively.

For evaluating these formulas, a method similar to that empolyed for the calculation of the proton and neutron yield ratio from self-conjugate nuclei was used.[11]

In the present calculation the assumption of identical level densities for the residual nuclei, especially when the assumption is extended to the calculation of F_γ', is not strict and there is no *a priori* reason to assume so. However, when the level density formula is written as

$$\omega(E)=Ce^{aE}, \tag{4}$$

as in the case of reference 11, there is no reason to suspect that a is violently different from one nucleus to the other over a small range of mass numbers, and also the proton spectra from (p,p') on Cu and Ni measured by Gugelot[12] show very similar behavior. So we might assume that the same and constant a value can be used for all the pertinent nuclei in the region under consideration. The values of C for the (α,p), (α,n), and (α,γ) products were taken to be 2:2:1 in the ratios according to the original treatment of the statistical theory by Weisskopf and Ewing.[13] The value of $1/a$, or the temperature of the compound nucleus, was taken to be 1 Mev according to the recent measurement by Bleuler[14] in this laboratory of the proton energy spectra from the (α,p) reaction on Cu. This value differs somewhat from the (p,p') data by Gugelot which give about 1.5-Mev if the value is taken from rather safe parts of the data, namely, proton spectra in the backward direction with the excitation energy of the residual nucleus less than 10 Mev but higher than 3 Mev. However, it is considered to be more reasonable to use the data from the (α,p) reaction, so the temperature 1 Mev was used for the calculation. The penetration probability for the protons were taken to be $(1-kB/E_p)$ with $k=0.65$, which was obtained in a similar way to that in reference 11.

For calculating the F_γ', two different procedures were tried. In the first calculation, the estimate of the gamma-ray width given in reference 10, p. 649, which corresponds to an $E_\gamma{}^3$ dependence, was used. This method has been used for the analysis of (n,γ) reactions

[10] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 370.
[11] H. Morinaga, Phys. Rev. **97**, 1185 (1955).
[12] P. C. Gugelot, Phys. Rev. **93**, 437 (1954).
[13] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[14] E. Bleuler, reported in Brookhaven National Laboratory Report BNL-331(C21), p. 91.

with 10-Mev neutrons by Hayakawa and Kikuchi,[15] but in the present case F_γ' should include only that part of F_γ of the above reference, which leads to the residual activity due to only the gamma-ray emission from the compound nucleus. For the sake of simplicity, it was assumed that only the gamma rays which lead to the excited state of the residual nucleus with energies lower than its porton threshold plus 1.6 Mev were considered to be responsible for the (α,γ) reaction. For energies higher than this value, the successive proton emission was considered to become predominant. This cutoff is somewhat arbitrary but a more refined procedure does not seem warranted in view of the more serious uncertainties in the gamma-ray transition probabilities. The function F_γ' is thus given by

$$F_\gamma'=\frac{3}{4}\frac{e^2}{\hbar c}\left(\frac{R}{\hbar c}\right)^2\frac{1}{D_0}\int_0^{E^*}(E_c-E)^3\omega(E)dE. \tag{5}$$

Here D_0 is taken as 0.5-Mev and E^* is the cut-off energy mentioned above. The result is given in Fig. 2 (curve *b*). While there is some agreement between this calculation and the experiment as to the order of magnitude of the cross section, the energy dependence is wrong. The fact that the experimental cross section is smaller than the calculated one at low excitation energies is interpreted to reflect the reduction of the dipole matrix element for lower gamma-ray energies.

The second calculation was made by using the gamma-ray width obtained from the known photonuclear absorption cross section. The function is defined as[10]

$$F_\gamma'=\sum{}'k^2\sigma_c(\gamma). \tag{6}$$

Here again $\sum'$ means the summation should be made up to the cut-off energy of the residual nucleus mentioned before. k is the wave number of the gamma rays and $\sigma_c(\gamma)$ is the cross section for the capture of the gamma rays by the residual state under consideration. For changing the sum into an integral the same level density formula as used before was employed and the same cutoff as before was assumed to determine the limit of the integral. Of course, $\sigma_c(\gamma)$ should be the cross section for gamma-ray absorption by the final nucleus in its *excited state*, but there seems to be no reason to suspect that it should be very much different from that for the ground state, most certainly if the excitation is not so high. It was assumed, then, that $\sigma_c(\gamma)$ has a Gaussian shape with the location of the maximum and the half-width being the same as for the measured (γ,n) cross section for Zn^{64},[16] which should be very close to those of Zn^{62}, and the integrated total absorption cross section was taken to be equal to the dipole sum with $x=0.5$.[17]

The result is also given in Fig. 2 [curve (c)]. The agreement with the experiment appears quite satisfactory, except for the high-energy end, where the calculated values are too low.

This divergence may be due to a variety of reasons. An increase in the nuclear temperature at high excitation energies would reduce the competing particle emission and increase the (α,γ) cross section above the value calculated for a constant temperature. The energy dependence of the capture cross section for the gamma rays is not Gaussian but is flatter on the high-energy side.[18,19] This tail also may increase the alpha-gamma reaction cross section at higher energies. Finally, the basic assumption that $\sigma_c(\gamma)$ depends on the gamma-ray energy only, may break down.

Recently, the reaction $Ni^{60}(p,\gamma)Cu^{61}$ was measured up to a proton energy of 22 Mev.[8] The excitation curve was reported to be flat with a value of $\sigma(p,\gamma)\approx 10^{-27}$ cm^2. By using the same procedure as for the (α,γ) reaction, an excitation curve was calculated with a maximum cross section of about 1 mb, in good agreement with the experimental value. There seems to be no reason, then, to assume that the (p,γ) reaction does not involve the formation of the compound nucleus.

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[15] S. Hayakawa and K. Kikuchi, Progr. Theoret. Phys. (Japan) **11**, 513 (1954).

[16] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).

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[18] R. Sagane, Phys. Rev. **84**, 587 (1951).

[19] Barber, George, and Reagan, Phys. Rev. **98**, 73 (1955).