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An Experimental Verification of the Theory of Compound Nucleus*

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The compound nucleus Zn^{64} was formed by bombarding Ni^{60} with α-particles and Cu^{63} with protons. The ratios of the cross sections $\sigma(\alpha,n):\sigma(\alpha,2n):\sigma(\alpha,pn)$ for Ni^{60} were found to agree with the ratios $\sigma(p,n):\sigma(p,2n):\sigma(p,pn)$ for Cu^{63}, giving a direct verification of the theory of compound nucleus. The observed cross sections for the (p,n), $(p,2n)$, and (p,pn) reactions on Cu^{63} and (α,n), $(\alpha,2n)$, and (α,pn) reactions on Ni^{60} have been compared with the theoretical cross sections calculated on the basis of the statistical model. The observed anomalous behavior of the (p,pn) and (α,pn) cross sections with respect to the $(p,2n)$ and $(\alpha,2n)$ cross sections respectively are discussed.

I. INTRODUCTION

THE present theories of nuclear reactions, for not too high an excitation ($<\sim$100 Mev), are based on the famous compound nucleus assumption of Bohr.[1] According to this assumption a nuclear reaction proceeds in two stages: first, the formation of a quasi-stable compound nucleus through the absorption of the incident particle by the target nucleus; second, the disintegration of the compound nucleus by the emission of either the original incident particle (scattering) or the emission of another particle or a photon. For fairly heavy nuclei ($Z>30$), the intermediate compound state has a mean life which is long compared with the time a nucleon takes to cross the nucleus ($\sim10^{-21}$ to 10^{-22} sec.). As a result of the comparatively long mean life of the compound state, the second process is independent of the first. This permits us to express the cross section of a reaction of the type $A+a\rightarrow C^*\rightarrow B+b$ in the following manner:[2]

$$\sigma(a,\,b)=\sigma_a(\epsilon)\eta_b(E), \tag{1}$$

where $\sigma_a(\epsilon)$ is the cross section for the absorption of the particle a of kinetic energy ϵ by the target nucleus A to form the compound state C^*. $\eta_b(E)$ is the probability of disintegration of C^* into the final state $B+b$. $E=\epsilon+B_a$ is the excitation energy of the compound state C^*, B_a being the binding energy of the particle a to the target nucleus A.

If the compound nucleus C^* is now formed in the same state of excitation by another process $A'+a'$, the cross section for disintegration into the same final state, $B+b$, will be given by

$$\sigma(a',\,b)=\sigma_{a'}(\epsilon')\eta_b(E),$$

where ϵ' is the kinetic energy of the incident particle a'. Because of the differences in the binding energies between the two cases, ϵ' will be different from the kinetic energy ϵ of a of the previous case. $\eta_b(E)$ will be the same in the two cases, because of the basic assumption that the mode of decay of the compound nucleus C^* is independent of the mode of its formation.

If C^* decays into a different final state, $D+d$, the corresponding cross sections will be given by $\sigma(a,\,d)=\sigma_a(\epsilon)\eta_d(E)$, $\sigma(a',\,d)=\sigma_{a'}(\epsilon')\eta_d(E)$. Hence we have

$$\sigma(a,\,b)/\sigma(a,\,d)=\eta_b(E)/\eta_d(E)=\sigma(a',\,b)/\sigma(a',\,d). \tag{2}$$

An experimental verification of the relationship (2) constitutes a direct test for the validity of Bohr's compound nucleus assumption.

II. EXPERIMENTAL METHOD

In the present experiment the compound nucleus Zn^{64} was formed by alpha-bombardment of Ni^{60} and proton bombardment of Cu^{63}. The following reactions were studied:

$$\left.\begin{matrix} Ni^{60}(\alpha,n) \\ Cu^{63}(p,n) \end{matrix}\right\} Zn^{63};\quad \left.\begin{matrix} Ni^{60}(\alpha,2n) \\ Cu^{63}(p,2n) \end{matrix}\right\} Zn^{62};\quad \left.\begin{matrix} Ni^{60}(\alpha,pn) \\ Cu^{63}(p,pn) \end{matrix}\right\} Cu^{62}.$$

The excitation curves were determined by the usual stacked foil method. The alpha excitation curves were obtained by the same procedure as was followed by Kelly and Segrè,[3] using the 40 Mev alpha-beam from the 60-inch cyclotron. The proton excitation curves were determined by using the 32-Mev proton beam from the Berkeley linear accelerator. The method used in this case was essentially the same as in the determination of the alpha excitation curves, differing only in slight details.

In the case of the nickel experiment, thin foils of enriched Ni^{60} were prepared by electroplating the nickel on to copper; the copper was then dissolved by $AgNO_3$ solution. The abundance of Ni^{60} in the enriched sample was more than 85 percent. Since the exact value of this abundance was not known, this value was used in deriving the cross sections. No activity ascribable to other nickel isotopes outside of Ni^{60} was observed. Ni^{61} would produce the isotopes studied, but only at higher excitation energies. In view of its low abundance, its effect in the present experiment will be small, and therefore has been neglected.

Prepation of the Nickel sample

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[1] N. Bohr, Nature **137**, 344 (1936).
[2] Lecture Series in Nuclear Physics, U. S. Government Printing Office (MDDC-1175), (1947).
[3] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).

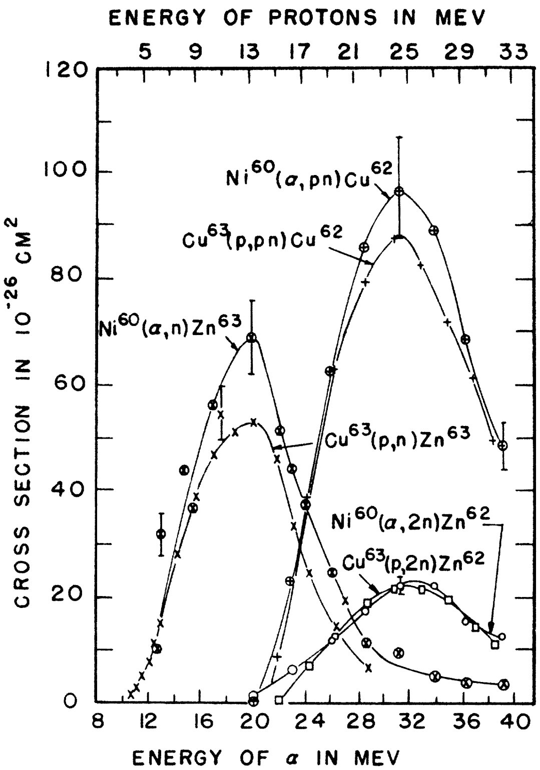

FIG. 1. Experimental cross sections for (p,n), $(p,2n)$, (p,pn) reactions on Cu^{63} and for (α,n), $(\alpha,2n)$, (α,pn) reactions on Ni^{60} plotted against ϵ_p and ϵ_α respectively. The scale of ϵ_p has been shifted by 7 Mev with respect to the scale of ϵ_α.

In the case of the $Cu+H^1$ experiment, ordinary copper, consisting of Cu^{63} (69.1 percent) and Cu^{65} (30.9 percent) was used. Cu^{65} produces the 250-day Zn^{65} and the 12.8 hr. Cu^{64} activities by proton bombardment. The activity due to the former is negligible. The Cu^{64} activity, however, interferes with the measurement of the 9.5-hr. activity of Zn^{62}. This difficulty was eliminated in the present experiment by the use of a 300 mg/cm^2 aluminum absorber in front of the counter. The radiations from Cu^{64} were stopped completely by this absorber; but the radiations from the isotopes studied were only reduced by factors of 2 or 3.

Where is Zn-62 coming from in the picture ?

I guess it is getting formed in the bombardment, along with Zn-64

The activities of the various isotopes studied in the present experiment were determined on an absolute scale by means of a counter with a known geometry. This was possible because of the fact that all the activities studied consisted of relatively high energy positrons. Approximately 85 percent of the time Zn^{63} decays with the half-life of 38 min. by the emission of a positron of 2.3-Mev end point. It has two softer positrons (1.5 Mev, 7 percent; 0.5 Mev, 1 percent) and also decays by K-capture 7 percent of the time.[4] Cu^{62} decays with a half-life[5] of 10.5 min. with the emission of a positron[6] of end point 2.92-Mev. Zn^{62} decays with a half-life of 9.5 hr. into Cu^{62}, predominantly by K-capture (>90 percent). It decays by a softer positron emission (0.65 Mev) the rest of the time.[6] Assuming a very small efficiency for the detection of the x-rays following the K-capture, as compared with the positrons, the observed activity of Zn^{62} will consist primarily of the 3-Mev positrons from its daughter, Cu^{62}. Since the absorption and scattering of these positrons of high energy in a thin window counter is small and can be accounted for, it is possible to determine their absolute number by means of a counter with a known geometry. The counter used had a 2.3 mg/cm^2 mica window and was placed at a distance of 10 inches from the source, the intervening space being evacuated. Four carbon baffles with openings of increasing diameter between the source and the counter prevented scattered positrons from reaching the counter.

The excitation curves of all three isotopes studied were determined simultaneously. As mentioned previously, a 300 mg/cm^2 aluminum absorber was used to absorb the radiations from Cu^{64}. The Zn^{62} and Cu^{62} excitation curves could thus be directly compared, since they are measured through the same radiation. The Zn^{63} excitation curve was obtained on a scale relative to the other two by counting the chemically separated zinc fraction and comparing the Zn^{62} and Zn^{63} activities. The similarity of the radiations of Zn^{62} and Zn^{63} makes this comparison possible. Finally a thin Ni^{60} foil irradiated with α-particles of one specific energy was used to determine the absolute activity of Zn^{62} by the method described above. This was done several hours after the bombardment, so that only the 9.5-hr. Zn^{62} activity was present.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are shown in Fig. 1, where the observed cross sections for (α,n), $(\alpha,2n)$, (α,pn) reactions on Ni^{60} and (p,n), $(p,2n)$, (p,pn) reactions on Cu^{63} are plotted as functions of the kinetic energy of the α-particles and protons respectively. The proton energy scale has been shifted by 7 Mev with respect to the alpha-energy scale in order to bring the peaks of the proton curves into approximate correspondence with those of the alpha-curves. It is clear from this figure that the ratios $\sigma(\alpha,n):\sigma(\alpha,2n):\sigma(\alpha,pn)$ for Ni^{60} agree, within the limits of experimental errors, with the ratios $\sigma(p,n):\sigma(p,2n):\sigma(p,pn)$ for Cu^{63}. This agreement, according to relationship (2), provides a direct test for the validity of the compound nucleus assumption.

The kinetic energy ϵ_p of the proton required to produce a given excitation E of the compound nucleus Zn^{64} will be different from the kinetic energy ϵ_α of the α-particle to produce the same excitation in Zn^{64}. This difference is due to the difference in the masses of $Cu^{63}+H^1$ and $Ni^{60}+He^4$. From Fig. 1, we find that its

[4] Huber, Medicus, Preiswerk, and Steffen, Helv. Phys. Acta **20**, 495 (1947).
[5] F. A. Heyn, Physica **4**, 1224 (1937).
[6] R. Hayward, Phys. Rev. **79**, 541 (1950).

value is about 7±1 Mev. Mass-spectrographic measurements by Duckworth *et al.* give a value of 5.74±0.5 Mev for this difference.[7] The two values agree within limits of experimental errors.

If the three reactions studied were the only ones which take place when Cu^{63} is bombarded with protons then the sum of the observed cross sections should give $\sigma_p(\epsilon_p)$, the cross section for the absorption of a proton by the Cu^{63} nucleus to form Zn^{64}. The sum of the observed alpha-cross sections should similarly give $\sigma_\alpha(\epsilon_\alpha)$. The sum of the observed proton and alpha-cross sections are plotted in Figs. 2 and 3 respectively, and are compared with the theoretical values calculated by Weisskopf.[2] It is seen from Fig. 2 that the experimental curve for the total proton cross section shows a point of inflection at a proton energy of about 14 Mev. A similar inflection is shown by the total alpha-cross-section curve in Fig. 3. It is clear from the inflections in the experimental curves that some reactions have not been observed at low energies. When the cross sections for these reactions are added to the experimental curves in Figs. 2 and 3 they should give smoothly increasing curves as required by the theory. It seems reasonable to ascribe the unobserved reactions to a

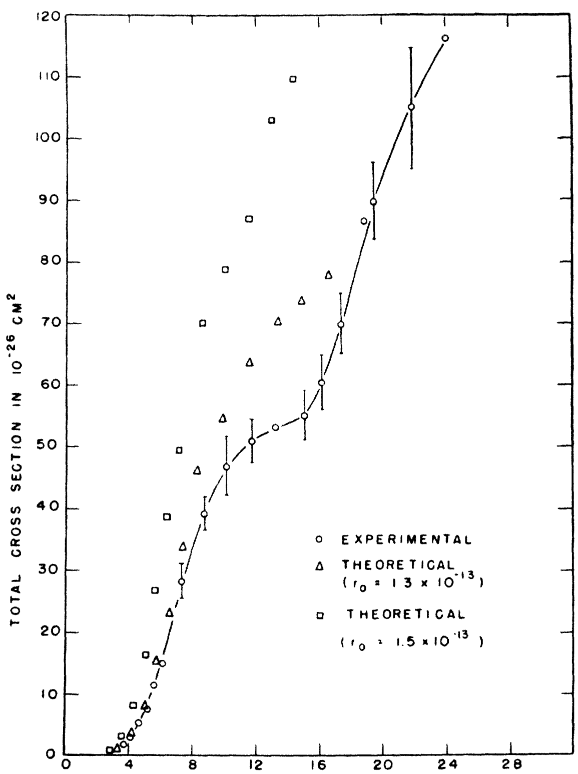

FIG. 2. Total cross section which is the sum of (p,n), $(p,2n)$ and (p,pn) cross sections on Cu^{63} as determined experimentally is compared with theoretical σ_p which is the cross section for the absorption of a proton by Cu^{63} nucleus.

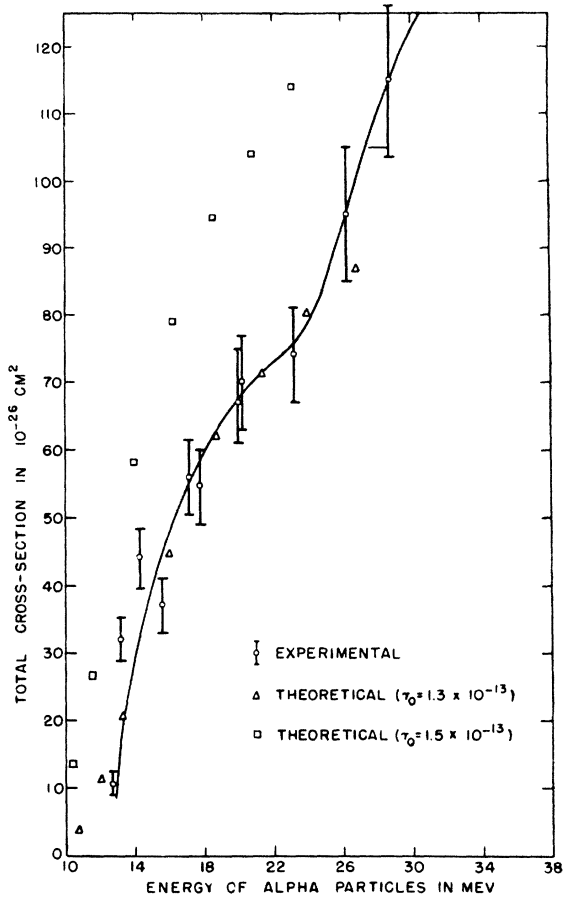

FIG. 3. Total cross section which is the sum of (α,n), $(\alpha,2n)$, (α,pn) cross sections on Ni^{60} as determined experimentally is compared with theoretical $\sigma\phi_\alpha$ which is the cross section for the absorption of an α-particle by Ni^{60} nucleus.

process involving the emission of a proton, which should be prominent in this energy region. In Fig. 2, the unobserved reaction is the inelastic (p,p) scattering while in Fig. 3, it is the (α,p) reaction. The cross sections $\sigma(p,n)$ and $\sigma_{\text{inel}}(p,p)$ have been calculated on the basis of the statistical model,[2] and are compared with the experimental $\sigma(p,n)$ curve for the $Cu^{63}(p,n)Zn^{63}$ process in Fig. 4. The cross sections have been calculated for two values of the nuclear radius, $r=r_0A^{\frac{1}{3}}$ cm, with $r_0=1.3\times10^{-13}$ and $r_0=1.5\times10^{-13}$ respectively. Neither of the values agree well with the experimental results, which lie in between the two.[8] This is also the case with total cross sections as seen from Figs. 2 and 3.

At higher alpha- and proton energies reactions involving the emission of two or more particles become more and more probable and processes involving one particle emission go down. This is seen in Fig. 1. One

[7] I am indebted to Dr. Duckworth for kindly communicating to me the values of the masses of Cu^{63} and Ni^{60} as measured by the Wesleyan group.

[8] It should be noted that the calculated values of $\sigma(p,n)$ are quite sensitive to the exact value of the threshold of the (p,n) process. In the present experiment this threshold could not be determined too accurately, because of the straggling effect. We used a value of 4.0 Mev for this threshold in the present calculations, which was derived from the energy release in the $Zn^{63}\rightarrow Cu^{63}$ transformation.

remarkable feature of the two particle emission processes, as seen from Fig. 1, is the large cross sections for the (p,pn) and (α,pn) reactions as compared with those for the $(p,2n)$ and $(\alpha,2n)$ processes respectively. This, at first, appears surprising, because a proton would find it difficult to come out through the Coulomb barrier. The experimental values of $\sigma(p,pn)$ for Cu^{63} and $\sigma(\alpha,pn)$ for Ni^{60} are each about 4 times as high as those of $\sigma(p,2n)$ for Cu^{63} and $\sigma(\alpha,2n)$ for Ni^{60}. This is in agreement with a similar ratio between the cross sections of the (γ,pn) and $(\gamma,2n)$ processes on Zn^{64} as observed by Strauch.[9]

The theoretical cross sections for these processes can be calculated on the basis of the statistical model.[2] In a process like (p,pn), either a neutron or a proton can be the first particle to be emitted following the formation of the compound nucleus. A second particle will follow the first particle. Let $I_n(\epsilon)d\epsilon$ denote the distribution in energy of the first emitted neutron and $I_p(\epsilon)d\epsilon$ that for the first emitted proton. Then the cross section of a process in which a neutron is emitted as the first particle after the formation of the compound nucleus and is then followed by the emission of a second particle b, will be given by

$$\sigma(p,nb)=\sigma_p\frac{\int_0^{\epsilon_p+B_p-B_{n_1}-B_b} I_n(\epsilon)\eta_b(\epsilon_p+B_b-B_{n_1}-B_b-\epsilon)d\epsilon}{\int_0^{\epsilon_p+B_p-B_{n_1}} I_n(\epsilon)d\epsilon+\int_0^{\epsilon_p} I_p(\epsilon')d\epsilon'}$$

σ_p represents the cross section for the formation of the compound nucleus by the absorption of the incident proton. $\eta_b(\epsilon_p+B_p-B_{n_1}-B_b-\epsilon)$ is the probability for the emission of the second particle with the maximum possible energy $(\epsilon_p+B_p-B_{n_1}-B_b-\epsilon)$, ϵ being the energy of the first emitted neutron, ϵ_p the energy of the incident proton. B_p is the binding energy of the incident proton to the compound nucleus. B_b is the binding energy of b to the residual nucleus after the first neutron is emitted. B_{n_1} is the binding energy of the first neutron to the compound nucleus. If the first particle emitted is a proton, then the cross section is

$$\sigma(p,pb)=\sigma_p\frac{\int_0^{\epsilon_p-B_b} I_p(\epsilon')\eta_b(\epsilon_p-B_b-\epsilon')d\epsilon'}{\int_0^{\epsilon_p+B_p-B_{n_1}} I_n(\epsilon)d\epsilon+\int_0^{\epsilon_p} I_p(\epsilon')d\epsilon'},$$

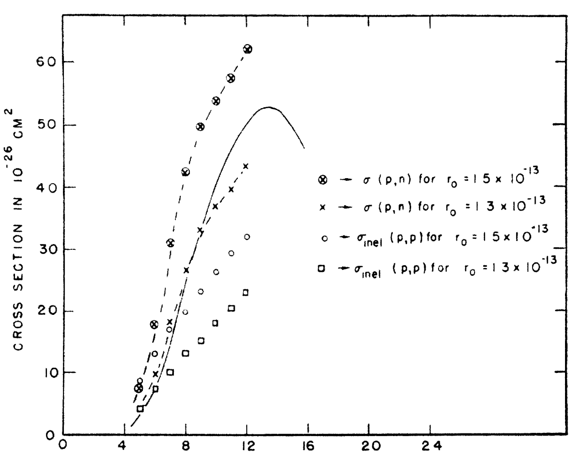

FIG. 4. Comparison of the measured (p,n) cross section on Cu^{63} with theoretical values, calculated on the basis of statistical theory. The solid line is the experimental cross-section curve.

where ϵ' is the energy of the first emitted proton. The values of the various quantities involved can be estimated.

The cross sections obtained on the basis of the above considerations show that $\sigma(p,pn)$ is of the same order of magnitude as $\sigma(p,2n)$ for Cu^{63}. Two factors favor the (p,pn) process over the $(p,2n)$ process: (a) the threshold of the former is about 3 Mev lower than the threshold of the latter;[10] (b) the residual nucleus in the first case being an odd-odd nucleus (Cu^{62}) has a level density greater than that in the second case which is an even-even nucleus (Zn^{62}). A factor of 4 between the level densities was assumed in the present calculations.[2]

In view of the very meager information available regarding the level densities of nuclei, no definite conclusion can be reached with respect to the validity of the statistical model in this part of the isotope chart. Whether or not the factor of 4 between the observed values of $\sigma(p,pn)$ and $\sigma(p,2n)$ can be explained on this basis cannot be decided at present. However, it should be noted that if a mechanism involving the emission of a deuteron is assumed in the (p,pn) process, the threshold of the process would be about 5 Mev lower than that of the $(p,2n)$ process, which would bring up the calculated values for $\sigma(p,pn)$ further.

All the above considerations also apply to the ratio between $\sigma(\alpha,pn)$ and $\sigma(\alpha,2n)$.

In conclusion, I wish to express my deep obligation to Professor Emilio Segrè for his constant encouragement and guidance during the progress of the work. Thanks are due to the crews of the 60-inch cyclotron and the Berkeley linear accelerator for their valuable cooperation in making the bombardments.

[9] K. Strauch, Phys. Rev. **79**, 241 (1950).

[10] The exact value of this difference, as in the case of the (p,n) threshold, is quite important in these calculations. The present value of 3 Mev was deduced from the energies of the radiations emitted in the $Zn^{62}\rightarrow Cu^{62}$ transformation. It may be off by as much as 1 Mev.