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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 $(\alpha,n)$, $(\alpha,2n)$, and $(\alpha,pn)$ 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 $(\alpha,pn)$ 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 ($\sim 10^{-21}$ 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]

$$\sigma(a, b)=\sigma_a(\epsilon)\eta_b(E), \quad (1)$$

where $\sigma_a(\epsilon)$ is the cross section for the absorption of the particle $a$ of kinetic energy $\epsilon$ 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 $\epsilon'$ is the kinetic energy of the incident particle $a'$. Because of the differences in the binding energies between the two cases, $\epsilon'$ will be different from the kinetic energy $\epsilon$ 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

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

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.

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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).

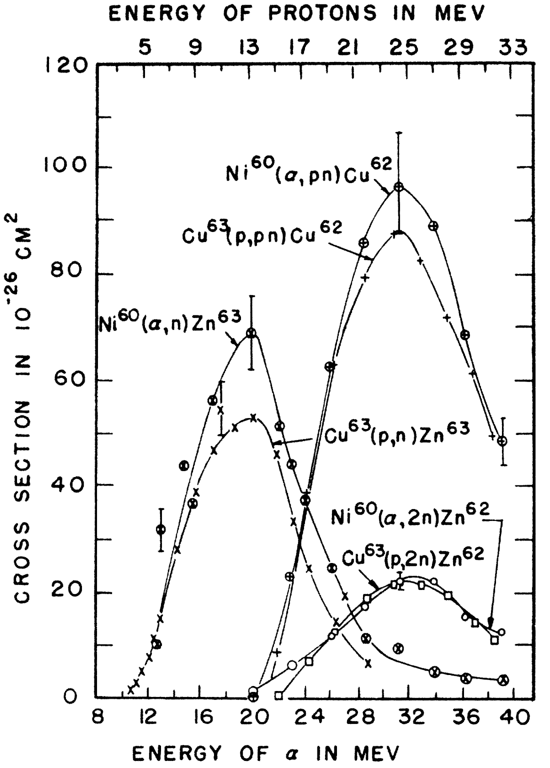

FIG. 1. Experimental cross sections for $(p,n)$, $(p,2n)$, $(p,pn)$ reactions on $Cu^{63}$ and for $(\alpha,n)$, $(\alpha,2n)$, $(\alpha,pn)$ reactions on $Ni^{60}$ plotted against $\epsilon_p$ and $\epsilon_\alpha$ respectively. The scale of $\epsilon_p$ has been shifted by 7 Mev with respect to the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

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.

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 $\alpha$-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 $(\alpha,n)$, $(\alpha,2n)$, $(\alpha,pn)$ 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 $\alpha$-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 $\epsilon_p$ of the proton required to produce a given excitation $E$ of the compound nucleus $Zn^{64}$ will be different from the kinetic energy $\epsilon_\alpha$ of the $\alpha$-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

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[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 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 $(\alpha,p)$ 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.

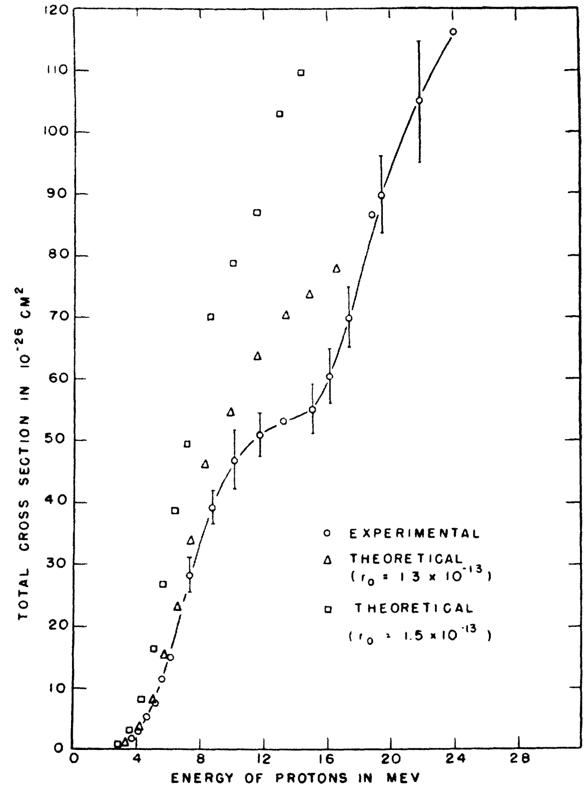

FIG. 2. Total cross section which is the sum of $(p,n)$, $(p,2n)$ and $(p,pn)$ cross sections on $Cu^{63}$ as determined experimentally is compared with theoretical $\sigma_p$ which is the cross section for the absorption of a proton by $Cu^{63}$ nucleus.

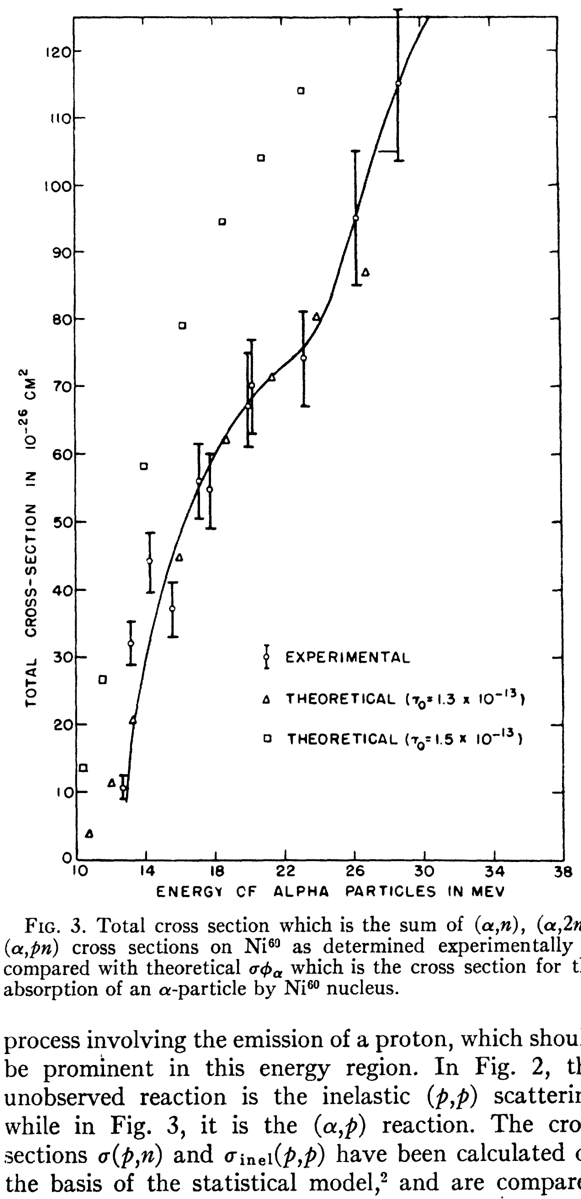

FIG. 3. Total cross section which is the sum of $(\alpha,n)$, $(\alpha,2n)$, $(\alpha,pn)$ cross sections on $Ni^{60}$ as determined experimentally is compared with theoretical $\sigma\phi_\alpha$ which is the cross section for the absorption of an $\alpha$-particle by $Ni^{60}$ nucleus.

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

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[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 $(\alpha,pn)$ 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 $\mathrm{Cu}^{63}$ and $\sigma(\alpha,pn)$ for $\mathrm{Ni}^{60}$ are each about 4 times as high as those of $\sigma(p,2n)$ for $\mathrm{Cu}^{63}$ and $\sigma(\alpha,2n)$ for $\mathrm{Ni}^{60}$. This is in agreement with a similar ratio between the cross sections of the $(\gamma,pn)$ and $(\gamma,2n)$ processes on $\mathrm{Zn}^{64}$ 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

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

$\sigma_p$ 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 $(\epsilon_p+B_p-B_{n_1}-B_b-\epsilon)$, $\epsilon$ being the energy of the first emitted neutron, $\epsilon_p$ 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

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

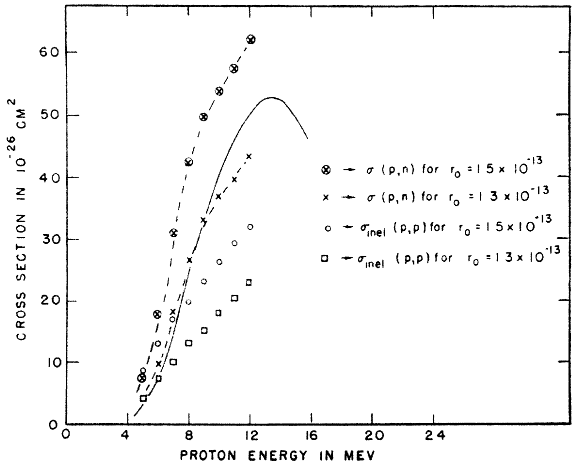

FIG. 4. Comparison of the measured $(p,n)$ cross section on $\mathrm{Cu}^{63}$ with theoretical values, calculated on the basis of statistical theory. The solid line is the experimental cross-section curve.

where $\epsilon'$ 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 $\mathrm{Cu}^{63}$. 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 ($\mathrm{Cu}^{62}$) has a level density greater than that in the second case which is an even-even nucleus ($\mathrm{Zn}^{62}$). 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.

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[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 $\mathrm{Zn}^{62}\rightarrow\mathrm{Cu}^{62}$ transformation. It may be off by as much as 1 Mev.