# Heavy Particle Stripping*

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(Received May 11, 1955)

THE characteristic forward component in the angular distribution of the products of $(d,p)$ and $(d,n)$ reactions has been interpreted as a stripping process.[1] In fact, the angular distributions are directly related to the orbital angular momentum of the captured particle and the effective radius of capture. Recently refined calculations[2] have included the interaction of the outgoing particle and the residual nucleus as well as Coulomb corrections. The experimental data indicate agreement at angles in the forward quadrant with the theoretical predictions of the shell model. Experiments in the range of 1-Mev bombarding energy show angular distributions which also suggest that stripping may be an important process.[3]

It is proposed that stripping can also occur from nuclei other than the deuteron. For example, stripping of a neutron or proton from the target nucleus should exhibit a higher intensity in the backward quadrant, where, of course, the precise form of the angular distribution will depend on the orbital angular momentum with which the incident particle captures the stripped target nucleus. To illustrate this process, two possibilities are chosen: The $Be^9(\alpha,n)C^{12}$ and $B^{11}(d,n)C^{12}$ reactions. The calculation of the angular distribution for the heavy particle stripping has been performed using the Born approximation in a way analogous to the deuteron stripping formalism given in Bhatia *et al.*[1] In both reactions it is assumed that the heavy particle is composed of a core with a neutron in a $p$ state. The wave function for this neutron is computed by considering that the neutron is in a square well. The potential of the well is adjusted to give the proper binding energy of the neutron. Table I lists the parameters used in the following calculations.

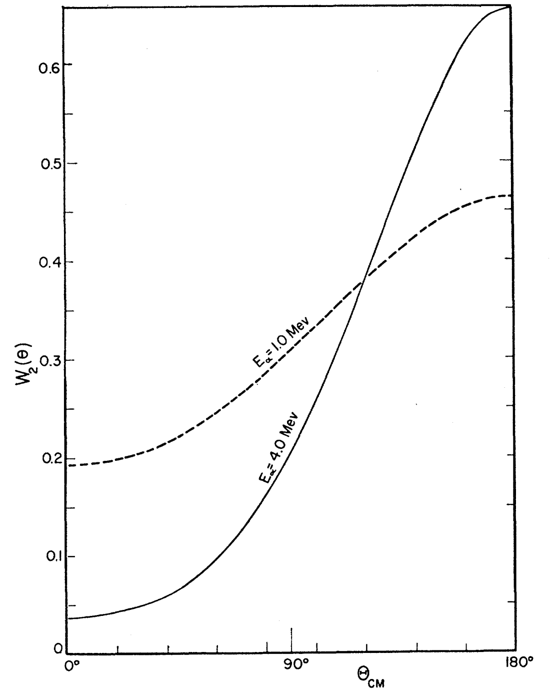

FIG. 1. The computed angular distribution of the neutrons from the reaction $Be^9(\alpha,n)C^{12}$ illustrates the process of heavy particle stripping. Distributions are shown for alpha bombarding energies of 1 Mev and 4 Mev. The radius of interaction used is $3.0\times(10)^{-13}$ cm.

TABLE I. List of parameters. Subscript 2 refers to heavy particle stripping.

| | $r_0$ $10^{-13}$ cm | $V_0$ (Mev) | $l$ | $R_1$ $10^{-13}$ cm | $l'$ | $R_2$ $10^{-13}$ cm |
|---|---|---|---|---|---|---|
| $Be^9(\alpha,n)C^{12}$ | 2.42 | 38.5 | $X$ | $X$ | 0 | 3.0 |
| $B^{11}(d,n)C^{12}$ | 3.40 | 33.2 | 1 | 4.5 | 0 | 4.5 |

The angular distribution is proportional to the product of two expressions: the first term is the internal motion factor

$$G_2^2(K_2)=\left|2(3\pi)^{\frac{1}{2}}\int_0^\infty r^2\psi(r)j_1(K_2r)dr\right|^2;$$

where $\psi(r)$ is the internal wave function of the neutron in the heavy nucleus, and $j_1(K_2r)$ arises from the combination of the exponential terms in the matrix element. The second term is the neutron centrifugal barrier term

$$j_{l'}^2(k_2R_2),$$

where $j_{l'}$ is the spherical Bessel function of order $l'$.

In the general problem of heavy particle stripping where the bombarding particle is labeled $X$ (being an $\alpha$ particle, deuteron, or proton, etc.), the angular distribution of the stripped neutrons can be written

$$W_2(\Theta)=\text{const}\times G_2^2(K_2)j_{l'}^2(k_2R_2),$$

where $M_i$= the mass of the target nucleus, $M_f$= the mass of the residual nucleus, $M_n$= the neutron mass, $k_n$= the wave number of the neutron, $k_i$= the wave number of the target nucleus, $\Theta$= the center-of-mass angle between the beam and $k_n$, $r_0$= the radius of the square well of depth $V_0$, $l'$= capture angular momentum for heavy particle stripping, $R_2$= radius of interaction for heavy particle stripping, and

$$K_2=\left\{k_n^2+\left(\frac{M_n}{M_i}\right)^2k_i^2-2\frac{M_n}{M_i}k_nk_i\cos(\pi-\Theta)\right\}^{\frac{1}{2}},$$

$$k_2=\left\{k_i^2+\left(\frac{M_i-M_n-M_f}{M_f}\right)^2k_n^2\right.$$

$$\left.+2\left(\frac{M_i-M_n-M_f}{M_f}\right)k_nk_i\cos(\pi-\Theta)\right\}^{\frac{1}{2}}.$$

When the incident particle is a deuteron, the deuteron stripping and heavy particle stripping can compete. In these cases the angular distribution can be written

$$W(\Theta)=A_1G_1^2(K_1)j_l^2(k_1R_1)+A_2G_2^2(K_2)j_{l'}^2(k_2R_2),$$

where

$$K_1=\{k_n^2+\tfrac{1}{4}k_i^2-k_ik_n\cos\Theta\}^{\frac{1}{2}},$$

$$k_1=\left\{k_i^2+\left(\frac{M_i}{M_f}\right)^2k_n^2-2k_ik_n\left(\frac{M_i}{M_f}\right)\cos\Theta\right\}^{\frac{1}{2}},$$

$l$ = capture angular momentum for deuteron stripping, and $R_1$ = the radius of interaction for deuteron stripping.

Figure 2 illustrates a calculation in which both types of stripping might occur.

Figure 1 shows a calculation of heavy particle stripping for the $\mathrm{Be}^9(\alpha,n)\mathrm{C}^{12}$ reaction at 1 Mev and 4 Mev. The increase of intensity in the backward direction is evident. Figure 2 shows the results for the $\mathrm{B}^{11}(d,n)\mathrm{C}^{12}$ reaction to the ground state. The dotted curve indicates the contribution of heavy particle stripping using the parameters shown. The solid curve shows the sum of the usual deuteron stripping, plus the heavy particle stripping. The curves are drawn for a bombarding energy of 4.1 Mev, and the experimental points of Class, Price, and Risser[4] are superposed. The theoretical curves were drawn so that the heavy particle stripping is normalized at 160° where the contribution from deuteron stripping is very small, and the deuteron stripping is normalized at 20°. The fit seems fairly good, suggesting that a heavy particle stripping process may exist, in spite of the fact that the stripped neutron comes from a closed $P$ shell and is strongly bound. Calculations at an energy of 3.5 Mev and 4.7 Mev also show agreement with the experimental data.[4]

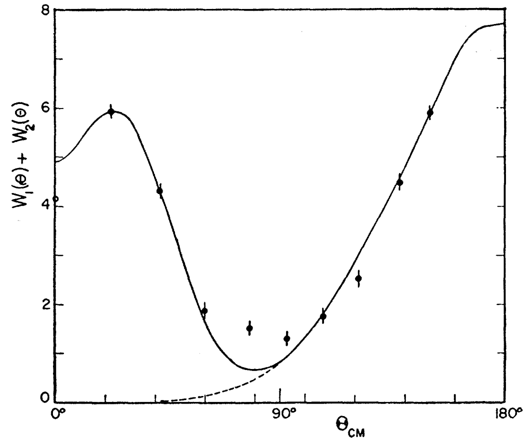

FIG. 2. The angular distribution of the neutrons from the reaction $\mathrm{B}^{11}(d,n)\mathrm{C}^{12}$ illustrates the type of reaction in which both deuteron stripping and heavy particle stripping can occur. The radius of interaction for both processes is $4.5\times(10)^{-13}$ cm. $E=4.1$ Mev. The experimental points are those of Class, Price, and Risser.

If indeed the heavy particle stripping accounts for the backward component of the angular distribution of the neutrons from the reaction $\mathrm{B}^{11}(d,n)\mathrm{C}^{12}$, the cross section for this process must be comparable with that for the deuteron stripping. An estimate of the nuclear matrix element can be obtained by using the partial width technique suggested by Bhatia.[1] This involves an estimate in this particular reaction of the sticking probability for a deuteron and the "$\mathrm{B}^{10}$ core." From the available data it appears that the cross sections for the reactions involving a deuteron and $\mathrm{B}^{10}$ are relatively high, suggesting that the heavy particle stripping in $\mathrm{B}^{11}(d,n)\mathrm{C}^{12}$ could be of the same order of magnitude as the deuteron stripping. The fact that the outgoing neutron can belong to the target nucleus has been suggested by Grant,[2] by considering the effect of exchange terms in the stripping problem. We have not considered these effects in our simple calculation.

We are indebted to Professor Calvin Class for discussing his recent results with us. We would like to thank Professor T. H. Berlin for many stimulating discussions.

* This work was supported in part by the U. S. Atomic Energy Commission.

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[2] W. Tobocman and M. Kalos, Phys. Rev. **97**, 132 (1955); I. P. Grant, Proc. Phys. Soc. (London) **67**, 981 (1954); I. P. Grant, Proc. Phys. Soc. (London) **68**, 244 (1955).

[3] Pruitt, Hanna, and Swartz, Phys. Rev. **87**, 534 (1952).

[4] Class, Price, and Risser (private communication, to be published).

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# Fast $E2$ Transition Probabilities from Coulomb Excitation*

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(Received July 15, 1955)

WE thought it worthwhile to present a summary of our results on positions and lifetimes of excited states of nuclei in the region $Z=60$ to $Z=92$ ("strong coupling region")[1] and $Z=22$ to $Z=48$ ("weak coupling region").[1] We shall confine ourselves to even-even nuclei because they lend themselves more readily to a systematic description. $E2$ Coulomb excitation allows us to observe only one excited state in all cases (the first-excited state having character $2^+$); the systematic trend in the positions of these states is well known.[2] Our studies of thin-target excitation functions using alpha particles,[3] as well as some thick-target excitation functions extending from 2.5 Mev to 7.00 Mev alpha-particle energy (a range in yields of $>10^4$), in perfect agreement with the semiclassical $E2$ theory,[4] convince us that we are able to extract meaningful reduced $E2$ transition probabilities $B(E2)$ from measurements of the total excitation cross sections. A few cases of overlap