The Relation between Stripping and Compound Nucleus Formation in Deuteron Reactions

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An estimate is made of the relative probability for stripping and compound nucleus formation in the Mg^{26} (d,p) Mg^{27} reaction, by comparing the yields of final nuclei formed as a result of d,p and d,α processes on Mg^{26}, and by n,p and n,α processes on Al^{27}.
We find that the ratio of the stripping cross section to the cross section for compound nucleus formation varies with deuteron energy and reaches a maximum value of 8-9 for deuteron energy 1-2 mev.

IT is well known that when deuterons interact with nuclei transformations of the type (d,p) and (d,n) can proceed in two ways: via the stripping reaction, in which only one of the nucleons which constitute the deuteron is absorbed by the nucleus, while the other goes on; or in the usual way in which the deuteron as a whole is absorbed by the nucleus and a compound nucleus is formed which upon decaying can emit one of the nucleons. The reaction products—final nucleus and emergent nucleon—can be the same for both mechanisms. Until now it has been possible to make only rough quantitative estimates of the relative probabilities of the two possible mechanisms from studies of the angular distributions of nucleons emitted in deuteron reactions. However this method cannot give sufficiently reliable results, since the angular distributions of nucleons produced as a result of stripping and compound nucleus breakup are known only approximately at present.

We have applied a different method in order to give a more precise quantitative estimate of the relative probability of the two mechanisms. Two reactions were selected (one with deuterons, the other with some other particles, for example neutrons) in which the same compound nucleus is formed. We shall denote by A_1 and A_2 the target nuclei which are subjected to bombardment, by C^* the excited compound nucleus, and by B_1 and B_2 the nuclei formed as a result of emission from the compound nucleus of a proton and an α-particle, respectively. We can then describe the processes considered in the following schematic form:

$$A_1 + D^2 \rightarrow C^* \begin{matrix} \nearrow B_1 + p \\ \searrow B_2 + \alpha \end{matrix},$$

$$A_2 + n \rightarrow C^* \begin{matrix} \nearrow B_1 + p \\ \searrow B_2 + \alpha \end{matrix}$$

If only one mechanism were possible for these reactions, via the formation of a compound nucleus, and if the energies of the deuterons and neutrons were chosen so that the excitation energy of the compound nucleus were the same in both cases, then for both reactions the ratio of the number of nuclei of type B_1 to the number of type B_2 would always have to be the same, since the mechanism of breakup of the compound nucleus does not depend on how it was formed. However, in the first reaction the process leading to emergence of a proton, (d,p), can proceed in two ways. Therefore in this case the number of final nuclei B_1 should be greater, and be proportional to the sum of the cross sections for stripping, compound nucleus formation, and a term F due to the interference between the two processes. Thus the number of final nuclei B_1 in the first process will be proportional to

$$\sigma(d,\ p) = \sigma(d,\ p)_{\text{st.}} + \sigma(d,\ p)_{\text{c.n.}} + F.$$

In all the other cases the number of final nuclei should be proportional to the cross sections for the corresponding processes which proceed via the formation of the compound nucleus.

We selected reactions which led to radioactive nuclei B_1 and B_2 with decay periods suitable for measurement. From the decay curves of the activities we determined the ratio of the numbers of radioactive nuclei B_1 and B_2 produced in the targets as a result of irradiation with deuterons and neutrons. We shall denote by N_1 the experimentally measured ratio of the number of final nuclei B_1 formed as a result of the (d,p) reaction to the number of nuclei of type B_2 formed as a result of (d,α) reaction, and by N_2 the ratio of the number of B_1 nuclei produced by (n,p) reaction to the number of B_2 nuclei produced by (n,α) reaction. Then we have:

$$\frac{\sigma(d, p)}{\sigma(d, \alpha)} = \frac{\sigma(d, p)_{c.n.} + \sigma(d, p)_{st.} + F}{\sigma(d, \alpha)} = N_1,$$

$$\frac{\sigma(n, p)}{\sigma(n, \alpha)} = N_2.$$

Since the mode of breakup of the compound nucleus is independent of how it was formed, we must have

$$\sigma(d, p)_{c.n.} / \sigma(d, \alpha) = \sigma(n, p) / \sigma(n, \alpha).$$

From these relations we find that

$$\frac{\sigma(d, p)_{st.} + F}{\sigma(d, p)_{c.n.}} = \frac{N_1 - N_2}{N_2}.$$

As already mentioned, this relation is valid if the compound nuclei formed as a result of capture of deuterons and neutrons have the same energy of excitation. However even if this condition is fulfilled we might anticipate some difference because of the fact that even if we have a sharply defined excitation energy, the states of the compound nucleus may be different if there are several wide overlapping levels in this region of excitation energy. In this case errors can arise only if the compound nucleus in different excited states has different probabilities for decay into the various channels and if the probabilities of formation of these states by deuterons and neutrons are not the same. In our experiments the energies of the particles producing the reactions were not strictly monochromatic, which should reduce such errors through an averaging over a series of levels. No resonance phenomena were observed, so that we can assume that errors associated with them were insignificant.

We chose the following two reactions:

$$Mg^{26} + D^2 \nearrow Mg^{27} + p \quad \searrow Na^{24} + \alpha, \qquad Al^{27} + n \nearrow Mg^{27} + p \quad \searrow Na^{24} + \alpha.$$

These transformations lead to Mg^{27} with a half-life of 9.4 min and β-ray endpoints of 0.79 mev (20%) and 1.77 mev (80%), and to Na^{24} with a half-life of 15 hr with the end point of the β-spectrum at 1.39 mev. The radioactive products of other reactions and of reactions with other magnesium isotopes (the experiments were done with the normal mixture of Mg isotopes), have lifetimes very different from those used by us and did not disturb the measurements. In order to obtain the same excitation of the compound nucleus Al^{28} in these reactions, we had to use a neutron energy about 6 mev greater than the energy of the deuterons. The ratios of the numbers of radioactive nuclei produced by (d,p) and (d,α) processes on magnesium for different deuteron energies were found from curves of the decay of activity induced in the various layers of thin magnesium foils placed in the deuteron beam from the cyclotron. The activities were measured with a standard thin-walled Geiger-Muller counter and a scale-of-64 counting circuit. The ratios of activities as a function of deuteron energy E_d are shown as curve a in Fig. 1.

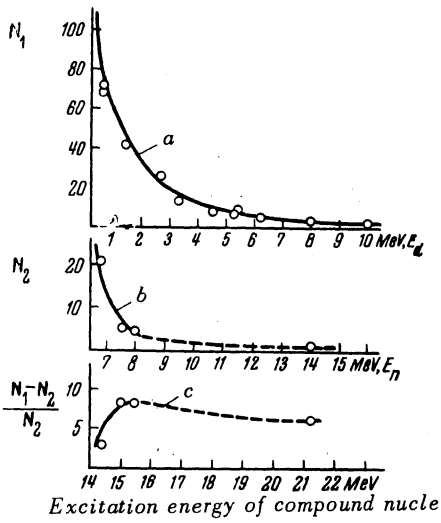

FIG. 1. a– ratio of d,p to d,α cross section; b– ratio of n,p to n,α cross section; c– ratio of stripping cross section to cross section for reaction going via compound nucleus formation.

The D–D reaction was used to obtain monochromatic beams of neutrons. The deuteron target was a layer of zirconium subjected to long irradiation with low energy deuterons (0.8 mev). The length of the preliminary deuteron irradiation of the foil was chosen to assure deposition of 1 C of deuteron ions per cm^2 of irradiated surface of the foil. According to published work,[1] under these conditions the neutron yield from the foil reaches saturation. It is well known that zirconium can adsorb hydrogen in relatively large quantities, so we may expect that all the D atoms impinging on the zirconium will be concentrated close to the surface in a layer of thickness no greater than a few microns. If we now irradiate the foil with faster deuterons, we may expect to obtain quite uniform energy neutrons. To test the degree of homogeneity of the neutrons thus obtained, experiments were

carried out to determine their energy spectrum by measuring ranges of proton recoils in thick-layered emulsions. To do this, the plate was placed in a special holder below the zirconium target inside the cyclotron chamber.

The results of one such series of measurements are shown in the histogram of Fig. 2. From the histogram it is apparent that in this experiment we had an intense neutron group with an energy somewhat less than 8 mev and a quite strong continuous background in the neutron energy region below 5 mev. The energy of the fast neutron group is in good agreement with the expected value. The

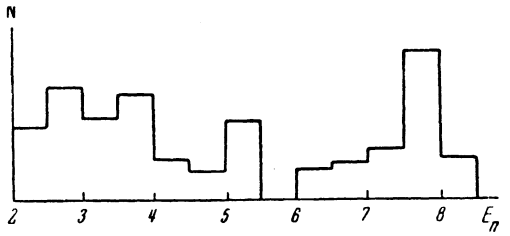

FIG. 2. Distribution in energy of number, N, of neutrons from D–D reaction on a zirconium target whose surface is saturated with deuterium.

background of slower neutrons apparently arises from the presence of deuterium all through the zirconium plate and from the zirconium itself, as well as from the beam striking parts of the cyclotron chamber and from collisions of the deuterons with gas in the chamber. The presence of quite large numbers of relatively slow neutrons should have no essential effect on the results of the experiment, since both of the reactions used by us are endothermic (for the Al^{27} (n,p) Mg^{27} reaction, $Q_0 = 1.92$ mev, while for Al^{27} (n,α) Na^{24}, $Q_0 = -3.17$ mev) and most of the slow neutron group is either below the threshold for these reactions or is in a region where the yield is small. To estimate the effect of the neutron background we carried out the following control experiment. First we measured the activity induced by the neutrons in aluminum when the zirconium target was saturated with deuterium, and then under the same conditions irradiated the aluminum target from a layer of zirconium without deuterium. It turned out that the activity of the target in the second experiment did not exceed 10% of the activity in the first experiment.

To determine the ratio N_2, we placed a piece of rolled aluminum foil below the Zr-D target and irradiated the latter in the cyclotron.

The experiments with the zirconium target were done for three deuteron energies, all below 5 mev, since at higher energies considerable numbers of neutrons appear from the reaction with zirconium. In addition we used 14 mev neutrons. Measurements of target activity were made under the same conditions as for the magnesium targets. The values obtained for the ratio N_2 as a function of neutron energy E_n are shown in Fig. 1b. The dashes show the assumed behavior of the curve in the neutron energy region where N_2 was not measured. The values of $(N_1 - N_2)/N_2$, which gives the ratio of the probabilities of the two possible mechanisms for deuteron interaction with nuclei, are given in Fig. 1c.

From the curves of Figure 1 we see that the yield of protons increases relative to the yield of α-particles as we decrease the deuteron energy, both for reactions with deuterons and with neutrons. This obviously arises from the fact that reactions yielding protons are more exothermic; in addition, for lower excitation energy of the compound nucleus, the effect of the potential barrier is greater in reactions in which α-particles are formed. The ratio $(\sigma_{st.} + F)/\sigma_{c.n.}$ is a maximum (within the range of deuteron energies for which the measurements were made) for deuteron energy 1–2 mev, and equals 8–9. We do not know the relative phase for these processes, so that we can say only that the actual value of the ratio $\sigma_{st.}/\sigma_{c.n.}$ lies within the limits 4 to 16. A decrease of $(\sigma_{st.} + F)/\sigma_{c.n.}$ when the deuteron energy is increased or decreased can arise either from a change in F or from a change in the ratio of the cross sections for the two interaction mechanisms. The sharp decrease of this quantity when we go to low deuteron energies cannot, it appears, be explained solely by changes in F, and is evidence that $\sigma_{st.}$ decreases faster than $\sigma_{c.n.}$. This is in contradiction with the ideas developed by Oppenheimer and Phillips,[2] but can be explained on the basis of stripping theory.[3] The capture by the nucleus of a neutron with large values l of angular momentum should be less probable for low deuteron energies. Therefore as the deuteron energy is lowered, only those states of the final nucleus should be formed which can occur for $l = 0$, and in many cases this may be associated with a decrease of the probability of the process.

[1] Campbell, Korsmeyer and Ralph, Phys. Rev. 94, 791 (1954).

[2] J. R. Oppenheimer and M. Phillips, Phys. Rev. 48, 500 (1935).

[3] S. T. Butler, Proc. Roy. Soc. (London) 208A, 559 (1951).

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