Thresholds for Slow Neutron Induced Reactions

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THIS note discusses the possibility of determining the threshold energy of a particular mode of disintegration of a compound nucleus that can be formed from a stable nucleus by slow neutron capture. If ordinary slow neutron capture, characterized by the $1/v$ law, can produce the reaction, it is reasonable to believe that the energy of the newly formed compound nucleus is greater than that required for the mode of disintegration in question. Then if it were possible to introduce the neutron with a variable and measurable amount of negative kinetic energy, one could find the smallest excitation energy of the compound nucleus that would produce that disintegration. This can be accomplished by bombarding the original nucleus with deuterons, and selecting those reactions in which the outgoing proton carries off more energy than the incident deuteron minus the binding energy of the deuteron.

The selection of individual (d, p) processes of this type requires that coincidences be measured between one or more of the products of the nuclear reaction and outgoing protons of particular energies. An interesting case in which this could perhaps most readily be accomplished is the fission of one of the slow neutron fissionable heavy nuclei. The problem of detecting coincidences between fission fragments and protons in the presence of a strong deuteron beam, and at the same time measuring the proton energy, would present some experimental difficulties but does not seem to be insoluble.

The observations of Gant,[1] and of Jacobsen and Lassen,[2] on deuteron induced fissions in uranium and thorium, show a threshold at about 8 Mev. Since the normal isotopic mixture of uranium was used, any effect due to U^{235} of the type described above might well have escaped observation. It would be necessary to perform the coincidence experiment with enriched U^{235} or some other slow neutron fissionable isotope, and to use deuterons of energy not much above 8 Mev in order that the background due to fission following capture of the whole deuteron be minimized.

The reaction envisaged here would be expected to go according to the Oppenheimer-Phillips process. Volkoff's[3] expression for the energy transfer has been multiplied by the neutron sticking probability, which is assumed to be proportional to Bethe's[4] expression for the level density, to yield approximate energy distributions for the outgoing protons. These are shown in Fig. 1, for bombarding deuteron energies of 4, 6, and 8 Mev. Each curve is arbitrarily normalized to unit maximum; the total yields from all (d, p) processes are estimated from the transmutation function[3] to be in the ratio 1:1000:15,000 for the three bombarding energies. The curves of Fig. 1 must not of course be taken literally in the regions of relatively large proton energies, for then the large spacing of the levels of the compound nucleus will give the protons a group structure.

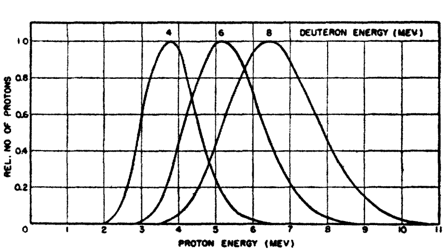

FIG. 1. Approximate energy distribution for outgoing protons.

The threshold energy for fission of the compound nucleus, such as U^{236}, is probably of the order of the photo-fission thresholds measured for U and Th by Haxby, Shoupp, Stephens, and Wells[5] and by Koch[6]; these are somewhat greater than 5 Mev. Thus one would expect fissions to occur for proton energies that are less than the incident deuteron energy by more than 1 Mev, if one assumes that the binding energy of a neutron in the compound nucleus is about 6 Mev. Thus if fission competes favorably with other modes of disintegration of the compound nucleus when it is energetically possible, Fig. 1 indicates that a substantial fraction of the outgoing protons will be accompanied by fissions, and that the threshold will appear near the maximum of the proton distribution.

[1] D. H. T. Gant, Nature **144**, 707 (1939).
[2] J. C. Jacobsen and N. O. Lassen, Phys. Rev. **58**, 867 (1940).
[3] G. M. Volkoff, Phys. Rev. **57**, 866 (1940).
[4] H. A. Bethe, Rev. Mod. Phys. **9**, 89 (1937).
[5] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **58**, 92 (1940).
[6] H. W. Koch, University of Illinois Thesis (1944).

A New Method for Displacing the Electron Beam in a Synchrotron*

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A REQUIREMENT has been placed on the design of the 300-Mev synchrotron at M.I.T. that the electron beam strike the target during an interval of approximately one microsecond followed by a reduction of the beam to a minimal background level. The importance of this requirement stems from two important uses of the machine: (1) the identification of mesons through their characteristic half-life of two microseconds; and (2) the use of time-of-flight velocity analysis of mesons.

A method has been developed which makes it possible not only to displace the synchrotron orbit rapidly so as to strike an internal target, but also to force the beam out of the magnet always at the same point. The method consists of increasing the magnetic field on one half of the orbit and decreasing the field on the other half a corresponding amount. The two coils, whether in series or parallel, have zero coupling with the main magnet excitation coil. Two practical advantages acrue to this method of ejection: (1) the coils need not go into the gap; and (2) the total inductance (including mutual) is very low. This last point makes it possible to force the beam entirely past the target in times of the order of two microseconds. The computed values for the 300-Mev M.I.T. machine are: ejection capacitor 2.7μf; capacitor voltage 12,000 v; time for total γ-ray pulse 2μ sec.; and peak current in the ejection coil 1400 amp.

The effect on the electrons in the beam is such that the equilibrium orbit is larger on one side of the magnet and smaller on the other side. The equilibrium orbit varies as $\Delta R/R=-\Delta B/[B(1-n)]$ where $\Delta B/B$ is the impressed fractional variation in the field at the orbit and n the usual exponent of radial dependence of the field. For $n\cong\frac{3}{4}$, the natural period of the radial oscillation is twice the period of rotation in the orbit. Thus, the forced radial oscillations in the beam are similar to those developed in a linear harmonic oscillator driven by a square wave at twice the resonant frequency. Since the build-up time of the driving force is long compared with one period, only equilibrium oscillations need be considered. The resulting radial oscillation amplitude, A, is to the first order,

$$A/R=4\Delta B/\pi nB.$$

Direct integration of the electron's equations of motion gives the same result.

Thus, if $n\cong\frac{3}{4}$, a one percent change in B produces oscillations of amplitude equal to 1.7 percent of the radius. These oscillations are 180° out of phase with the driving displacement and of the same frequency regardless of the value of n. The electrons reach maximum radius all at the same place, a fact which facilitates ejection of the entire beam.

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The Relative Probability of the (d, p) and the (d, n) Reactions in Bombarded Bismuth

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The bombardment of bismuth (209) with high energy deuterons leads to the formation of both radium E and radium F (polonium). The latter is an alpha-emitter of half-life 140 days, while radium E emits beta-radiation with a half-life of 5 days, thereby converting into radium F. By noting the building-up of the alpha-emission from the target following bombardment, it is possible to determine the total number of each of the product atoms formed. Radium E (bismuth (210)) is formed by a (d, p) reaction while the formation of radium F follows from a (d, n) process. It is thus possible to observe the relative probability for the two competing processes.

Earlier investigations[1] have been made of this effect up to about 9.5 Mev. These results indicated that in this energy range the (d, p) reaction is much more probable. The ratio of the two yields was found to change from a value greater than 10 at 7 Mev down to about 5, at 9.5 Mev. This apparent anomaly that the proton can escape more easily than a neutron from an excited nucleus was reconciled by consideration of the Oppenheimer-Phillips process, according to which the deuteron need not enter the nucleus but dissociates outside into a scattered proton and a neutron that proceeds on into the nucleus. At higher energies it would appear reasonable to expect that the OP effect should greatly diminish and the above ratio fall to a value of one or even less.

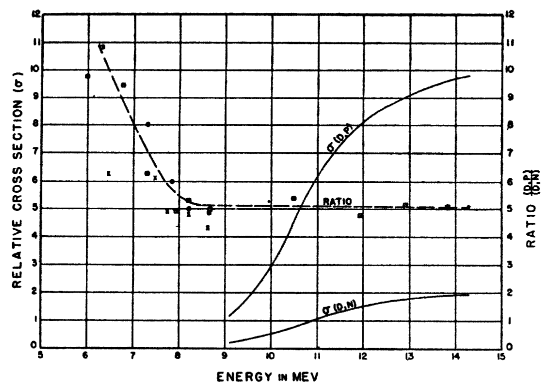

Fig. 1. Excitation curves and ratios obtained in this and other experiments.

Through the courtesy of Professor R. D. Evans and the kind assistance of Dr. Eric Clarke this phenomenon was studied up to 14.5 Mev by bombardment with the MIT cyclotron. Two types of bombardment were made. In one, a series of identical targets were exposed singly in turn to equal bombardments, each succeeding target being covered with an increasing thickness of aluminum foil so as to reduce the bombarding energy by the desired amount.

In another bombardment a stack of thin bismuth foils each of about 40 mg per cm^2 was exposed to a single bombardment. By using an alpha-counter with a thin window the growth of activity in each target was followed for many days, as in the previous investigations. From the growth curve the number of atoms of each kind produced could be readily determined. Since the exposure of each of the foils in the stack is identical it is possible to indicate an excitation curve for each process.

These excitation curves at the high energy together with the ratios obtained in this and previous experiments are shown in Fig. 1. The excitation curves seem to indicate an approach to saturation. The absolute cross sections can be determined only approximately since the effective geometry of the counter cannot be accurately determined. Within this limit the ordinate 10 may be regarded as 25×10^{-28} cm^2. The relative yields have no such uncertainty.

It is apparent that the ratio does not drop at higher energies to a value of one or less as had been expected but seems to remain within the experimental limit, at a value close to five.

Mr. R. W. Safford aided in this investigation, and the support of the Horace H. Rackham fund is gratefully acknowledged.

[1] J. M. Cork, J. Halpern, and H. Tatel, Phys. Rev. **57**, 371 (1940); D. Hurst, R. Latham, and W. Lewis, Proc. Roy. Soc. **A174**, 126 (1940); H. Tatel and J. M. Cork, in press.