Deuteron Induced Fission in Uranium and Thorium

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By means of deuteron beams from the cyclotron, the variation of fission yield with deuteron energy is determined for uranium and thorium. In both cases, a rapid rise is found in the region from 8 to 9.5 Mev. For an energy of 9 Mev, the cross section in uranium is estimated to be 5×10^{-27} cm^2, and for this energy the ratio between the cross sections for uranium and thorium is found to be 0.7, supporting the theoretical expectation that we have in these fission processes to do with successive transformations.

According to theoretical considerations,[1] fission of heavy nuclei by deuteron impact cannot be expected to occur unless the deuteron has sufficient energy to penetrate the Coulomb field around the nucleus without breaking up. Thus, appreciable effects are not to be expected at energies much below ten million volts. This conclusion is confirmed by the experiments of Gant[2] who found a threshold for deuteron induced fission in uranium of about 8 Mev. Gant did not, however, attempt a quantitative determination of the cross section for the process. In view of the desirability of a closer study of the problem[3] and especially of a comparison between the effects induced by deuteron bombardment in thorium and uranium, experiments have recently been made in this Institute with the object of obtaining measurements of cross sections for fission at various deuteron energies in both elements.

These experiments were made by means of the cyclotron built in the Institute in the course of the last two years, the construction of which will be described in a forthcoming publication in the *Proceedings of the Copenhagen Academy*. After various recent improvements, the cyclotron is now able to give fairly steady deuteron beams of a few microamperes up to about ten million volts. The beam has an energy spread of about 0.5 Mev and has nearly constant intensity over this region.

In the measurements with uranium, four aluminum targets upon which had been evaporated thin layers of uranium (about 1.5 mg/cm^2) were mounted in a rotating holder provided with absorbing foils. This holder could be inserted by means of a vacuum lock into the cyclotron chamber and each target in turn exposed to the deuteron beam, the foils serving to reduce the energy of the deuterons by a known amount for each individual target. The fission products were collected on aluminum foils fastened in the holder in such a way as not to intercept the beam. During the irradiation, the holder was rotated constantly in order to insure that all targets received the same deuteron current. After an irradiation period of ten to twenty minutes, the target holder was removed from the cyclotron chamber. Measurements of the beta-ray activity of the foils with the fission products were begun after the lapse of about ten minutes and continued for some ten hours. Separate experiments made to determine the background effect due to stray neutrons in the cyclotron showed that, for energies above 8 Mev, the number of fissions so produced was negligible compared with the deuteron effect.

The variation of fission cross section in uranium with deuteron energy is shown in Fig. 1, where the open circles indicate differences between the measured yield values for energies differing from one another by an amount which is less than the energy spread of the beam. Thus, the curve through these points is an approximation to a "differential yield" curve, corresponding to the yield to be expected from an infinitely thin target bombarded by a monochromatic beam. For a determination of the absolute value of the cross section, a single point was taken with a fixed target to which the deuteron beam current was kept as constant as possible. From the

[1] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).
[2] D. H. T. Gant, Nature **144**, 707 (1939).
[3] N. Bohr, Phys. Rev. **58**, 864 (1940), preceding paper.

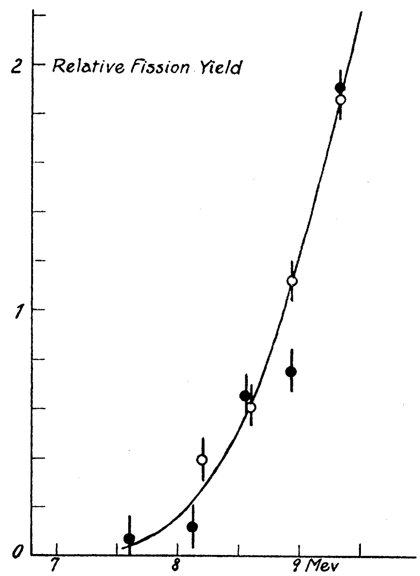

FIG. 1. Relative variation of fission yield with deuteron energy; full circles refer to uranium, open circles to thorium.

geometry of the collecting and counting arrangement, we have a means of estimating the number of fission processes occurring in the target. Assuming the average number of beta-particles given off per fission fragment during the counting period to be about three, we calculate the cross section for fission in uranium of 9-Mev deuterons to be about 5×10^{-27} cm^2. We observe from the curve that the rise with deuteron energy is very rapid in the interval investigated. Thus, the experiments indicate that the cross section will continue to increase for still higher energies, presumably reaching, for an energy somewhat above 10 Mev, a value comparable with nuclear dimensions, as is to be expected from the theory.

In order to make a comparison between the effects in thorium and those in uranium, two targets coated with thick layers of U_3O_8 and ThO_2 were mounted on the rotating holder in the vacuum chamber and bombarded alternately by a deuteron beam of 9- to 9.5-Mev energy. At this energy, it was found that the yield for thorium was 0.75 that of uranium. Because of the thickness of the layers of uranium and thorium oxide on the target, we should, in estimating the ratio of the cross section for fission in the two elements for a given deuteron energy, take into account that the stopping power in the uranium layer for the fission fragments escaping from it will be somewhat larger in proportion to the amount of heavy element present. In fact, because of the greater number of oxygen atoms in the U_3O_8 than in ThO_2, the relative stopping power for fission fragments can be expected to be about 10 percent greater in the uranium than in the thorium target. We may conclude, therefore, that the average fission cross section of thorium for 9- to 9.5-Mev deuterons is about 0.7 that of uranium. As explained in the paper by Bohr cited above,[3] this result confirms the view that, in the fission of uranium and thorium by deuterons, we have to do with successive transformations of the compound nucleus.

The fission yields at various energies for thorium were determined in the same way as those for uranium, using, however, in this case thick targets of ThO_2. The results are, in relative measure, represented by the full circles in Fig. 1. To facilitate comparison of the higher yields from the thick targets, the scale is chosen so that the values at a deuteron energy of 9.3 Mev for uranium and thorium are put equal. We see that the curve drawn fits equally well both sets of points, indicating that the cross section for uranium and thorium rises in very much the same way with deuteron energy in the two elements, as was to be expected from the theory on account of the small difference in charge number of the two elements.

In conclusion, the authors wish to thank the director of the Institute, Professor N. Bohr, who suggested the problem, for his continued interest in the work and for many valuable discussions of its theoretical implications. Our thanks are due also to Mr. Høffer Jensen for preparing the uranium targets.