JULY 15, 1939 PHYSICAL REVIEW VOLUME 56

Study of Uranium and Thorium Fission Produced by Fast Neutrons of Nearly Homogeneous Energy

R. LADENBURG, M. H. KANNER, H. BARSCHALL AND C. C. VAN VOORHIS
Palmer Physical Laboratory, Princeton, New Jersey

(Received May 22, 1939)

We have determined the effective cross section of the uranium and thorium fission for *d–d* neutrons of 2.4 Mev and found the values 5×10^{-25} cm^2 and 1×10^{-25} cm^2, respectively, with an uncertainty of about 25 percent. We have further shown that the ratio of the cross sections for Th and U fission is the same within 10 percent for neutrons of 2.1, 2.4, 2.9 and 3.1 Mev average energy.

THE discovery, by Hahn and Strassmann,[1] of the "fission" of uranium and thorium into nuclei of medium mass and charge under neutron bombardment has opened a new field of research. A successful interpretation of this process has been given by Meitner and Frisch[2] on the basis of Bohr's liquid-drop model, and Bohr[3] has drawn attention to the variation of the cross sections for the various transmutation processes in uranium and thorium with neutron energy. In this connection Professor Bohr raised the question of the behavior of uranium and thorium under bombardment by homogeneous neutrons of variable energy. The problem has been attacked in this laboratory using the homogeneous $d-d$ neutrons produced by the bombardment of heavy ice with deuterons from our 400-kv transformer-rectifier set.[4] It is possible to vary the energy of the neutrons between 2.1 and 3.1 Mev by varying the angle of observation with respect to the deuteron beam. The yield of the fission processes was observed by the method first used by Frisch,[5] i.e., by the observation of the high energy fragments in a parallel-plate ionization chamber connected to a linear amplifier and scale-of-eight counting unit. The ionization chambers used were lined with finely powdered U_3O_8 and ThO_2, respectively. The chambers were placed approximately 10 cm from the target, which was bombarded by 60–80μa of D_2^+ ions or by 20–30μa of D^+ ions at 370 kv. The neutron yield is about the same in either case and corresponds to 5–10 g Ra+Be. The current was measured by an integrating device operating a mechanical counter, controlled by the switch which also controls the recorder of the linear amplifier. The important datum here is the "yield," that is, the number of fissions observed per microcoulomb of bombarding deuterons. The proportionality of the neutron yield to the integrated current was established in earlier measurements.

The results of a large number of runs are contained in Table I. Column 1 gives the angle α between the deuteron beam and the direction of observation, and column 2 gives the energy and type of ion used. Column 3 gives the mean neutron energy, calculated from the conservation equations putting $Q=3.2$ Mev, and column 4 shows the energy spread. The spread given is due principally to the finite thickness of the ice target and very little to the finite solid angle subtended by the ionization chamber.[6] It may be calculated from the excitation function of the reaction, which is well known.[4] The lower limit given is that at which the number of neutrons per unit energy interval is 10 percent of that at the upper limit. We have not taken into account the presence of one-Mev neutrons reported by Bonner; due to their small relative abundance we do not think that their effect on the fission is significant, especially in view of the results at 0.5 Mev reported by Roberts, Meyer and Hafstad.[7] The last column of the table contains

---

[1] O. Hahn and F. Strassmann, Naturwiss. **27**, 11 (1939).

[2] L. Meitner and O. R. Frisch, Nature **143**, 239 (1939).

[3] N. Bohr, Phys. Rev. **55**, 418 (1939).

[4] See R. Ladenburg and Richard B. Roberts, Phys. Rev. **50**, 1190 (1936); Richard B. Roberts, Phys. Rev. **51**, 810 (1937); R. Ladenburg and M. Kanner, Phys. Rev. **52**, 911 (1937).

[5] O. R. Frisch, Nature **143**, 276 (1939).

[6] This holds for 0° and for 148°; at 90° the finite thickness of the target has relatively less and the finite solid angle has more influence upon the spread of the energy.

[7] Roberts, Meyer and Hafstad, Phys. Rev. **55**, 416 (1939).

the ratio of thorium to uranium fission yields, together with their probable errors. These values show that the yield ratio is constant to within 10 percent in the energy region investigated. The value at 2.1 Mev is slightly higher than the others, but the precision of the measurements is not sufficient to make this very significant.

TABLE I. *Data on fission by neutrons of varying energy.*

α		AVERAGE NEUTRON ENERGY	SPREAD OF THE ENERGY	YIELD Th/U
148°	Molecules of 370 kv	2.11 Mev	2.06–2.18 Mev	0.392 ± 0.012
90°	Molecules of 370 kv	2.44 Mev	2.33–2.55 Mev	0.352 ± 0.013
0°	Molecules of 370 kv	2.90 Mev	2.75–2.98 Mev	0.365 ± 0.010
0°	Atoms of 350 kv	3.12 Mev	2.85–3.24 Mev	0.370 ± 0.015

It is possible also to determine roughly from these measurements the variation of the individual Th and U cross sections with neutron energy. However, the angular distribution of the $d-d$ neutrons is known only approximately,[8] and therefore we can say only that the cross sections for fission of U and Th do not change by more than 30 percent in the energy range investigated. This result seems surprising at first sight in view of the fact that at 0.5 Mev the fission of U is very small and that of Th is not even measurable,[7] and that according to new experiments[9] both cross sections increase rapidly above 0.5 Mev. However, according to a paper of Bohr and Wheeler to appear in the near future, these facts can be understood in terms of the competition in the compound nucleus between the fission process and the process of neutron escape. In the energy region with which we are concerned, the fission cross section will in fact be determined by the ratio of the probabilities for fission and for neutron escape; and whereas the first of these increases more rapidly at lower energies than those with which we deal in this paper, it seems reasonable that the two probabilities will rise at comparable rates at higher energies.

It should be noted that the Th to U yield ratio given in column 5 of Table I does not represent the true cross section ratio, since there is a large uncertainty in the amounts of Th and U effective in the chamber. This is due to the way the powders were fastened to the chamber walls, and also to ignorance of the range-energy relation for the fragments in ThO_2 and in U_3O_8. The true values of the cross sections can be obtained only by the use of ionization chambers coated with known amounts of Th and U, arranged in layers thin compared with the range of the fragments (2–3 cm in air). This condition was met, and the true cross sections determined by sputtering a layer of approximately 0.2 mg/cm^2 of U or Th on a thin platinum plate in an atmosphere of argon,[10] and using this plate as one of the electrodes in the parallel plate ionization chamber. The amount of material present in the case of U was determined both by careful weighing of the Pt before and after sputtering, and by counting the U alpha-particles. The Th could be determined only by weighing, and not by counting the Th alpha-particles, due to uncertainty in the retention of thorium emanation and its decay products in the thorium layer.

This ionization chamber was bombarded by the 2.4-Mev neutrons emitted from the heavy ice target at 90° to the beam of deuteron molecules accelerated by 356 kv. The absolute number of these neutrons per microcoulomb of deuterons is known from our former calibration.[4] Its value is 2.34×10^5 neutrons per microcoulomb of deuteron atoms of 100 kv and therefore $N = 2 \times 2.34 \cdot 10^5 \times 3.36 = 1.58 \cdot 10^6$ neutrons per microcoulomb of deuteron molecules at 356 kv; 3.36 is the increase of the yield from 100 to 178 kv according to our excitation function. At a distance $d = 9.4$ cm from the target we obtained $n = 4.04 \cdot 10^{-3}$ fission per microcoulomb for 2.36 mg U and $n = 1.95 \cdot 10^{-3}$ fission per microcoulomb for 5.5 mg Th. If a is the number of atoms of U or Th on the bombarded plate, the effective cross section for the fission process is

$$\sigma = n 4 \pi d^2 / a N.$$

In this way we find for uranium $\sigma = 5 \times 10^{-25}$ cm^2 and for thorium $\sigma = 1 \times 10^{-25}$ cm^2, with an uncertainty of about 25 percent which is mainly due to the uncertainty in the absolute number of

---

[8] A. E. Kempton, B. C. Browne and R. Maasdorp, Proc. Roy. Soc. **A157**, 394 (1936).

[9] Private communication from the Department of Terrestrial Magnetism, Carnegie Institution of Washington.

[10] As cathodes in the sputtering process we used pure uranium and thorium rods kindly furnished by Drs. Rentschler and Marden of the Westinghouse Company. Other uranium samples used we owe to Dr. H. B. Wahlin of the University of Wisconsin.

neutrons and to some extent to the question of whether part of the uranium and thorium metal was oxidized, so that the number of metal atoms present may be somewhat less than that calculated from the weight. By surrounding the ionization chamber with a shield of Cd $\frac{1}{2}$ mm thick, we made sure that no slow neutrons (below a few volts energy) were present. The cross section for thermal neutrons of the fission process in U has been determined in the Pupin Laboratory of Columbia to be between 2.5 and 3×10^{-24} cm^2, whereas the average cross section for the complicated spectrum of fast neutrons from a Rn-Be source was found to be about 1×10^{-25} cm^2.[11]

It is a pleasure to thank Professor Niels Bohr for his stimulating and continued interest. We wish also to thank Mr. W. Hane for valuable help in these experiments. The high voltage apparatus we owe to a grant from the Rockefeller Foundation.

---

[11] H. L. Anderson, E. T. Booth, J. R. Dunning, E. Fermi, G. N. Glasoe and F. G. Slack, Phys. Rev. **55**, 512 (1939); E. T. Booth, J. R. Dunning and F. G. Slack, Washington meeting Bulletin 1939, paper 68.

JULY 15, 1939 PHYSICAL REVIEW VOLUME 56

The Effect of Pressure on the Positive Point-to-Plane Discharge in N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, A, He, and H_2

H. C. Pollock and F. S. Cooper
Research Laboratory, General Electric Company, Schenectady, New York

(Received May 8, 1939)

The voltages at which corona first appears in a 3-mm point-to-plane gap and the breakdown voltage of the gap have been determined with N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, A, He, and H_2, and certain mixtures of these gases. This has been done with both positive and negative point polarity and over a pressure range of about 30 atmospheres. The types of corona which were observed are discussed and in particular the marked dependence of the positive point breakdown voltage on pressure in those gases which form negative ions.

Introduction

The familiar increase in sparking potential of a gap with gas pressure does not continue indefinitely with every gas for all gap geometries. Investigations of the sparking potential *vs.* pressure characteristics of air in positive point-to-plane gaps have shown that distinct maxima in the curves exist near the pressure of 10 atmospheres. The maxima first become noticeable with gap widths above one mm and are more prominent as gap widths are increased. Goldman and Wul,[1] who have recently studied this effect in nitrogen with constant potential, alternating voltage and impulse voltages applied to the point, show that at high pressures a discharge often requires a much lower voltage to propagate itself across a gap of several centimeters width than it requires at slightly lower pressures. As considerable corona precedes sparking below this transition pressure, Goldman and Wul suggest that the shape of the sparking curve for a given gap depends largely on field distortion due to space charge around the point. We are reporting in this paper a similar study of N_2, O_2, CO_2, SF_6, CCl_2F_2, A, He, H_2, and of certain mixtures of these gases. We have also observed with an oscillograph the general character of any corona preceding breakdown. The types of corona which we discuss are very similar to those which Loeb,[2] Kip,[3] and Trichel[4] have studied in air at atmospheric pressure.

Apparatus

The chamber in which the electrodes were placed (shown in Fig. 1) consisted of a glass tube

---

[1] I. Goldman and B. Wul, Tech. Phys. U. S. S. R. **1**, 497 (1935); **3**, 16 (1936). I. Goldman, Tech. Phys. U. S. S. R. **5**, 355 (1938).

[2] L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939).

[3] A. F. Kip, Phys. Rev. **54**, 139 (1938); **55**, 549 (1939).

[4] G. W. Trichel, Phys. Rev. **54**, 1078 (1938); **55**, 382 (1939).