On the Photodisintegration of Beryllium and Deuterium

F. E. MYERS* AND L. C. VAN ATTA†
Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts
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High voltage x-rays have been used to redetermine the thresholds for the photodisintegration of beryllium and deuterium nuclei, giving 1.627±0.010 Mv and 2.183±0.012 Mv, respectively. The ratio of the two cross sections (σ_{Be}/σ_D) at 15 kv above the threshold voltage is approximately 10. The angular distribution of the neutrons from the photodisintegration of deuterium has been investigated, with x-rays of 2.43 Mev maximum energy, and found to be approximately isotropic. On the basis of these data, the value of the ratio of the photomagnetic to photoelectric cross section is estimated to be 6 to 1.

THE most direct method of determining the binding energy of the deuterium and beryllium nuclei is to measure the voltage threshold for the photodisintegration process. Previous measurements of these thresholds give values ranging from 2.17 to 2.25 Mv for deuterium[1] and from 1.55 to 1.63 Mv for beryllium.[2] These values have been redetermined in the present research under conditions which provide good sensitivity and give a direct measure of the threshold voltage.

The essential features of the experiment are the use of high voltage x-rays[3] to produce the disintegrations and a boron-trifluoride filled proportional counter to detect the resulting neutrons. The arrangement of the apparatus (Fig. 1) provides good sensitivity by locating the target material in the region of maximum x-ray intensity and close to the neutron counter. The obvious disadvantage is that the neutron counter is also exposed to intense radiation, and it is of some interest that a proportional counter can be operated under these conditions. The height of the pulses increases steadily and the amplitude of the background disturbance decreases as the x-ray intensity is reduced. Thus for reliable counting it is only necessary to introduce sufficient lead shielding to bring the pulses well above background for the highest x-ray intensity to be used. Since the counter sensitivity depends on the x-ray intensity, it is also necessary to calibrate the counter with a standard neutron source (Ra-Be) as a function of tube voltage and current. For the range of voltages used in this experiment the maximum change in counter sensitivity was approximately 30 percent. The background counting rate was shown to be

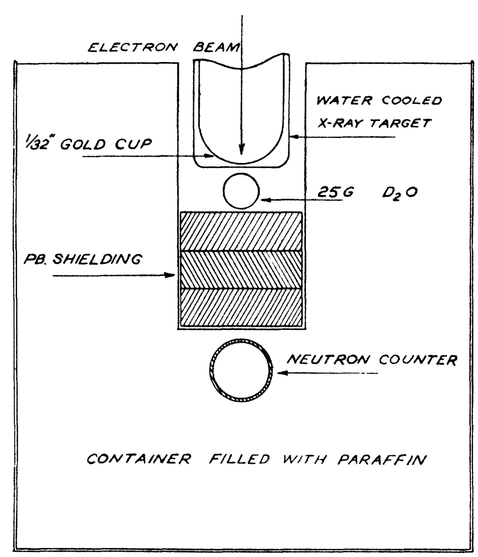

FIG. 1. Schematic diagram of the apparatus used for determining the threshold voltages. The scale of the drawing is indicated by the total thickness (3″) of the lead shielding.

* On leave of absence from New York University, and now at Frankford Arsenal, Philadelphia, Pennsylvania.
† Now with the Department of Electrical Engineering, Massachusetts Institute of Technology.
[1] J. Chadwick, N. Feather, and E. Bretscher, Proc. Roy. Soc. **A163**, 366 (1937); J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938); H. A. Bethe, Phys. Rev. **53**, 313 (1938); G. Stetter and W. Jentschke, Zeits. f. Physik **110**, 214 (1938); F. T. Rogers and M. M. Rogers, Phys. Rev. **55**, 263 (1939); K. Kimura, Kyoto Coll. Sci. Mem. **22**, 237 (1940).
[2] G. B. Collins, B. Waldman, and E. Guth, Phys. Rev. **56**, 876 (1939); M. Korsumskij, N. Nikolaevskaja, and M. Bakh, J. Exper. and Theor. Phys. U.S.S.R. **9**, 517 (1939); L. S. Skaggs, Phys. Rev. **56**, 22 (1939).
[3] Details of the x-ray source and x-ray tube have been published: L. C. Van Atta, D. L. Northrup, R. J. Van de Graaff, and C. M. Van Atta, Rev. Sci. Inst. **12**, 534 (1941).

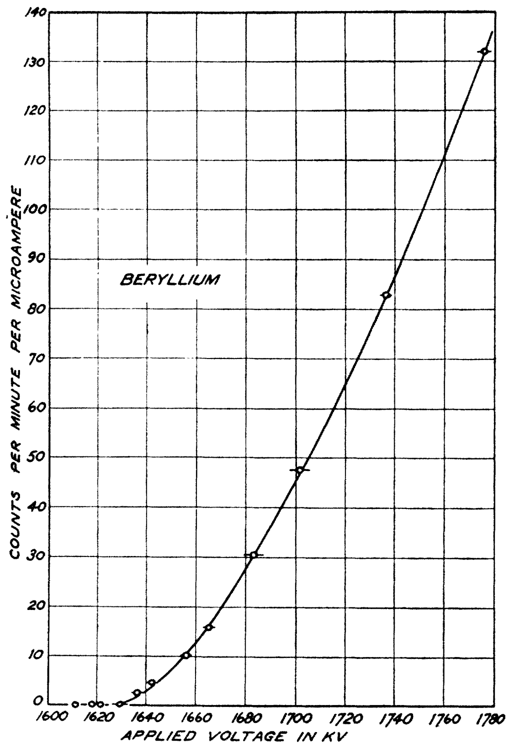

FIG. 2. Neutron counting rate *versus* tube voltage for beryllium. The length of the horizontal line through each point represents the average value of the voltage fluctuation. Corresponding vertical lines representing the expected statistical fluctuations in the counting rate have been omitted, since they would fit within the small circles representing the data points.

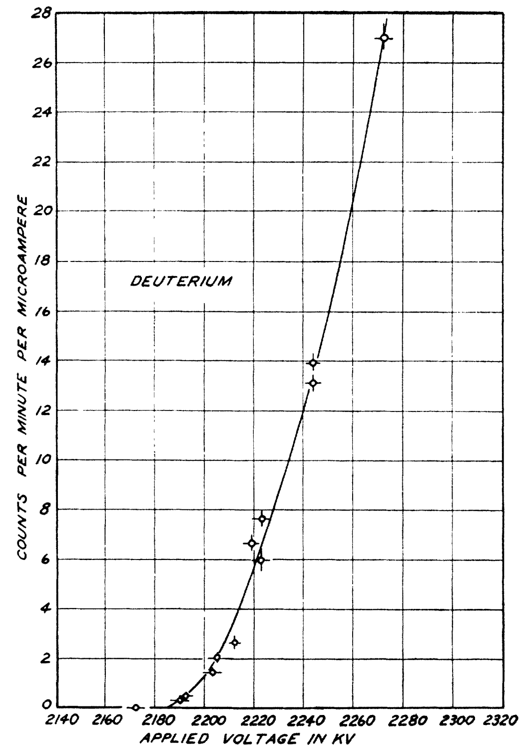

FIG. 3. Neutron counting rate *versus* applied voltage for deuterium. The horizontal and vertical lines through the data points represent, respectively, the average voltage fluctuations and the expected statistical error in the counting rate.

negligible by operating below threshold with the target material in place, and above threshold with the target material removed.

Results obtained with this apparatus are shown in Figs. 2 and 3, in which the counting rate, reduced to unit electron current and corrected for counter sensitivity, is plotted against tube voltage. If these data are plotted in double logarithmic form as shown in Figs. 4 and 5, straight lines are obtained for assumed values of threshold indistinguishably near those read from Figs. 2 and 3. Since the straightness of these lines is sensitive to the value assumed, this procedure has been used to define the threshold. The values obtained in this way are 1.627 ± 0.010 Mv for beryllium on the basis of one determination and 2.183 ± 0.012 Mv for deuterium on the basis of four determinations. The probable errors on a relative scale being independent of the voltage calibration,[4] are about one-half as large as those indicated.

For a comparison of the cross section for the two processes it is convenient to use the analytic expressions for the curves shown in Figs. 2 and 3. Over the limited range of voltage used the experimental points are reasonably well fitted by the expressions $Y_B = 0.075(V - V_B)^{1.5}$ for beryllium and $Y_D = 0.005(V - V_D)^{1.9}$ for deuterium where the voltages are expressed in kilovolts. Whereas the numerical values of the constants may be affected by the apparatus, their relative values should be significant. The larger multiplying constant and smaller exponent in the case of beryllium indicate a cross section which is larger initially but which increases more slowly than in the case of deuterium. By allowing for the

[4] It should be noted that the voltage scale has not been checked against other reactions, so it is impossible to assign precise limits to the voltage uncertainty. The figures cited are based on extensive tests on the performance of the generating voltmeter.

increase of efficiency of x-ray production with voltage,[5] and taking the relative amounts of target material into consideration (40 g Be, 25 g D_2O), it becomes possible to estimate the ratio of the two cross sections. At 15 kv above the respective thresholds, where the analytic expressions still fit the experimental points, the ratio $\sigma_B/\sigma_D \approx 10$. This agrees as closely as can be expected with the value of 13 for the ratio as found by Kimura,[1] who used 2.198-Mev γ-rays from radium for his determination.

In view of the interest in the angular distribution of neutrons from the photodisintegration of deuterium,[6] the numbers of neutrons emitted in the forward direction and at right angles to the incident x-rays were measured at a voltage near the threshold. The apparatus (Fig. 6) consisted of a small flask of D_2O, 7.5 cm from the x-ray target in the forward direction, a sheet of silver located 10 cm from the D_2O, either in the forward direction or at right angles, and a beta-ray counter and recording circuit for measuring the silver activity. For the angular comparison the x-ray tube was operated at an average of 2.43 Mv and 60 microamperes. While this gives a maximum quantum energy of 0.25 Mev above threshold, the major part of the intensity lies within 0.10 Mev of threshold. The thin walled glass flask holding the heavy water was spherical and only 0.5 cm in radius to avoid appreciable neutron scattering. The size of the silver sheet, 6.6 cm by 4.6 cm, represented a compromise between good geometry and high intensity. Again for the sake of intensity the silver was enclosed between sheets of paraffin, as shown in the figure. The G-M beta-ray counter operated a recording counting rate meter[7] which considerably simplified the labor of analyzing the results. The silver was regularly activated for 3.75 minutes, and then as quickly as possible, it was rolled into a cylinder and placed in a standard position around the G-M counter. The resultant

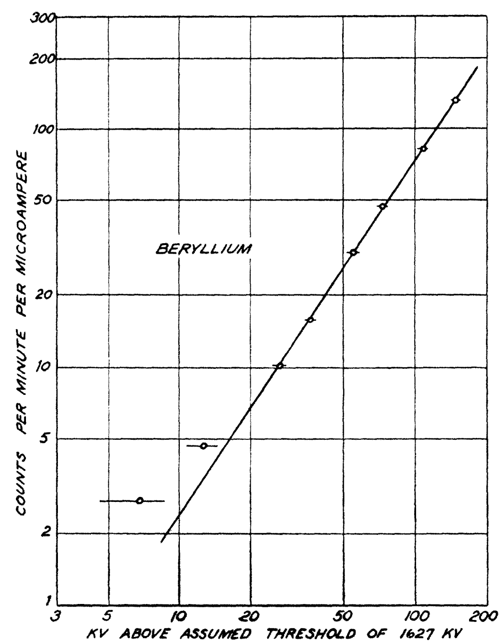

FIG. 4. Log-log plot of the neutron counting rate *versus* voltage above threshold for beryllium. Note that the apparent fluctuations at the lower voltages are exaggerated by the scale used. Due to the rapid increase in counting rate with voltage, the first points are expected to lie to the left of the curve, but the possibility that the curve undergoes a slight change in slope is not excluded.

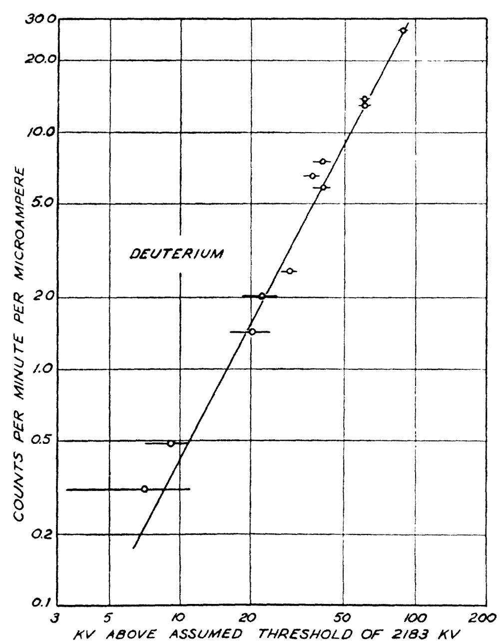

FIG. 5. Log-log plot of the neutron counting rate *versus* voltage above threshold for deuterium. Note that the average voltage fluctuation for the first point is only ± 5 kv.

[5] A. A. Petrauskas, F. E. Myers, and L. C. Van Atta, Phys. Rev. **59**, 688A (1941).

[6] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 122 (1936); J. Chadwick, N. Feather and E. Bretscher, Proc. Roy. Soc. **A163**, 366 (1937); J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938); H. Von Halban, Nature **141**, 644 (1938); B. Peters and C. Richman, Phys. Rev. **59**, 804 (1941).

[7] We are indebted to Dr. Arthur Roberts for the use of this counting rate meter.

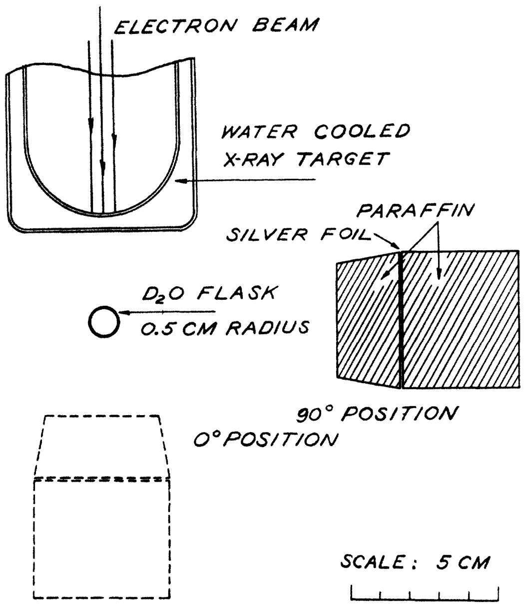

FIG. 6. Schematic diagram of the equipment used for measuring the ratio of the number of photo-neutrons ejected at 90° to that at 0° to the incident x-rays.

decay curve plotted by the recorder was of course, subject to statistical fluctuations. To minimize errors from this cause, a smooth curve fitting the data was drawn in free hand, and the counting rate was read from it 3.75 minutes after the irradiation ceased. The background of the counter was measured at frequent intervals and subtracted from the total counting rate to get the true activity of the foil. The interval of 3.75 minutes was chosen because it represents the distance between adjacent time lines on the recorder paper, and because it is long enough to prevent appreciable errors due to the time constant of the counting rate meter circuit.

Several tests were made to establish the proper functioning of the apparatus. When the x-ray tube was operated at 2.10 Mv with the D_2O in place and at 2.43 Mv with the D_2O removed, no measurable activity was observed in the silver, so that the possibility of stray neutrons from other parts of the apparatus was eliminated. When the distance between the silver and the D_2O was varied from 7 cm to 20 cm (both in the forward direction and at right angles) the activity followed the inverse square law to within expected statistical fluctuations, and indicated a constant background equal to 10 percent of the activity at the 7 cm distance.

The mean of seven measurements taken at 2.43 Mev and alternately at 0° and 90° gave 1.15 ± 0.10 as the ratio of the foil activity at 90° to that at 0° after correction for neutron background and for the slight variations in x-ray intensity caused by fluctuations in electron current and accelerating voltage. The probable error cited is twice that indicated by the internal consistency of the data. This has been arbitrarily increased to allow for the uncertainties due to geometry and neutron scattering. From these data it appears that the angular distribution of the neutrons from deuterium is approximately isotropic at voltages near threshold. This result is not necessarily in diagreement with the results of other experiments which used homogeneous radiation of much higher effective voltage.

The photo-disintegration of deuterium is usually ascribed to a "photomagnetic" and a "photoelectric" process.[8] The former is expected to predominate at voltages near threshold and to result in an isotropic neutron distribution. The latter is expected to predominate at high voltages and to result in a neutron intensity proportional to $\sin^2\theta$, where θ is measured from the forward direction of the incident quanta. A rough value for the ratio of the photomagnetic to photoelectric cross sections obtained from these data with allowance for the effect of the geometry is approximately 6. It should be emphasized that this ratio represents an average for quantum energies ranging from 0 to 0.25 Mev above threshold, with the number of quanta increasing rapidly as the threshold voltage is approached. With even less precision it is possible to estimate the order of magnitude of the total cross section: reasonable guesses as to the effective number of quanta and the sensitivity of neutron detection lead to a value of about 10^{-28} cm^2.

We are pleased to acknowledge the cooperation of the other members of the high voltage group, and in particular we wish to express our appreciation to Dr. A. A. Petrauskas who constructed the neutron counter and its associated equipment.

[8] See, e.g., first reference under 7.