PHYSICAL REVIEW VOLUME 87, NUMBER 6 SEPTEMBER 15, 1952

A Study of the Spectrum of the Neutrons of Low Energy from the Fission of U^{235}†

T. W. BONNER,* R. A. FERRELL,‡ AND M. C. RINEHART
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received April 14, 1952)

A cloud chamber has been used to determine, in the energy range 0.05 to 0.7 Mev, the distribution of prompt neutrons produced by the fissions of U^{235} in a thermal neutron beam. The ratio of proton recoils in the energy range 0.05 to 0.6 Mev to the recoils in the energy range 0.6 Mev to infinity was also determined. The data fit a distribution function $N(E)=\sinh(2E)^{\frac{1}{2}}e^{-E}$.

THE neutron spectra of the fission of U^{235} and Pu^{239} have been extensively studied by various techniques.[1–6] The photographic plate technique and the ionization chamber method were the first to be widely used to study the spectra. Both of these methods have limitations with regard to minimum energy of neutrons which may be detected.

In 1945, Richards[6] carried out experiments from which he hoped to obtain information on the neutrons below 1.5 Mev. He used a cloud chamber filled with hydrogen gas and alcohol vapor, and obtained data down to 250 kev. These rather preliminary experiments were interrupted by the end of the war. However, his data indicated a very strange neutron distribution—very few neutrons at 250 kev, in fact only about $\frac{1}{10}$ as many as at 1 Mev. This result is quite contrary to an evaporation model[4,7,8] where at very low energies the number of neutrons should increase as $E^{\frac{1}{2}}$.

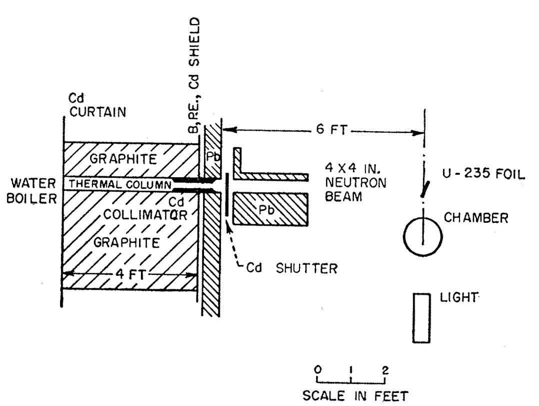

FIG. 1. The relative position of the beam of thermal neutrons, the Cd shutter, the U^{235} foil and the cloud chamber are shown in this diagram.

In view of these puzzling results, it was considered desirable to look at the energy distribution of neutrons from about 50 kev to 600 kev, using cloud-chamber techniques. In order to get longer proton tracks for a given energy in the cloud chamber, hydrogen gas was used at a pressure of $\frac{1}{3}$ of an atmosphere; and water vapor was used in place of alcohol, reducing the stopping power of the vapor by a factor of about three. With this mixture, a stopping power of 0.10 was obtained and a recoil proton with an energy of 50 kev has a track length of 7 mm. Under the experimental conditions, tracks of this length were believed to be the shortest tracks that could be reliably measured, both with regard to length and direction, although shorter tracks were easily observable on the photographs.

The experimental set-up is shown in Figs. 1 and 2. The source of neutrons was the thermal column of the Water Boiler. The neutrons were collimated by cadmium so that a beam of thermal neutrons with a 4-in. by 4-in. cross section was obtained at the front of the thermal column. Since the neutrons had a cadmium ratio of 400 under the conditions of the experiment, there were only 0.25 percent with energies over a few volts. This beam of thermal neutrons had a flux of 5×10^5 neutrons per cm² per sec at a distance of 6 ft from the face of the pile, where the U^{235} foil was placed. The foil was 3 cm by 10 cm by 0.010 inches thick, making the source strength of fission neutrons approximately equal to $5\times10^5\times30\times2.5=3.7\times10^7$ neutrons per sec. The cloud chamber was placed well outside the beam of neutrons, at a distance of 35 cm from the U^{235} sample. The cloud chamber, about 12 in. in diameter and about 9 in. deep, was especially designed to

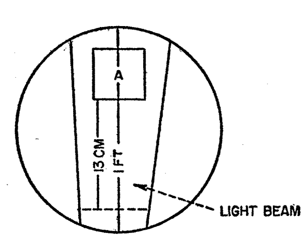

FIG. 2. Enlarged top view of the cloud chamber showing the region A where the recoils must originate in order to be counted.

† This work done under the auspices of the AEC during the summer of 1948.
* Now at Rice Institute, Houston, Texas.
‡ Now at Princeton University, Princeton, New Jersey.
1 W. H. Zinn and L. Szilard, Phys. Rev. **56**, 619 (1939).
2 Rotblat, Pickavance, Rowlands, Hall, and Chadwick, unpublished report BR-47 (1942).
3 W. E. Bennett and H. T. Richards, unpublished report CF-325 (1943).
4 Bloch, Staub, Hammermesh, Nicodemus, and de Vault, unpublished Los Alamos Declassified Report No. 934 (1943).
5 H. T. Richards and I. H. Perlman, unpublished Los Alamos Declassified Report No. 909 (1944).
6 H. T. Richards, unpublished Los Alamos Report No. 556 (1946).
7 N. Feather, unpublished report BR-335 (1942); R. Peierls, unpublished report MS-65 (1942).
8 G. N. Plass, unpublished report CF-1261 (1944).

have as small an amount of scattering material in it as possible. To this end, the cloud chamber was placed $49\frac{1}{2}$ inches above the floor and the chamber walls were made of $\frac{3}{16}$-inch Pyrex glass. The walls and roof of the room were negligible scatterers because of their large distance from the chamber. A fast-acting, mechanical cadmium shutter was placed at the opening of the thermal column to allow synchronization of the flux of neutrons on the U^{235} sample with the expansion of the cloud chamber. Excessive general fogging of the cloud chamber was caused by the large number of hard gamma-rays coming from the cadmium plates of the shutter. A thick collimator of lead was effective in reducing the intensity of gamma-radiation in the chamber to a level sufficiently low that it did not cause troublesome fogging in the cloud chamber. A somewhat better method of eliminating gamma-radiation would be to use a shutter made of enriched boron of mass 10, which gives off fewer gamma-rays than cadmium. Even more important, these gamma-rays only have a quantum energy of 479 kev and can easily be absorbed by a small amount of lead. A shutter of this type was not used because of the prohibitive fabrication time.

TABLE I. The data on the energy distribution of the recoil-protons and the neutrons.

Energy interval in kev	Track length in cm	No. of tracks	σ in barns	Track-length correction	Relative No. (N) of neutrons per 100-kev interval
50–99	0.7–1.4	24	14.5	1.04	34.2±5.0
100–199	1.5–2.8	43	11.6	1.09	40.3±4.1
200–299	2.9–4.5	41	9.3	1.15	50.6±5.3
300–399	4.6–6.4	34	7.6	1.23	55.3±6.5
400–499	6.5–8.5	29	6.6	1.33	58.6±7.2
500–699	8.6–13.5	51	5.6	1.50	68.0±6.5

Under the experimental conditions outlined above, from 5 to 15 recoil protons were obtained each time the cloud-chamber expanded. As a check to make sure that fast neutrons from the pile were not causing recoil-protons in the cloud chamber, expansions of the cloud-chamber were observed without opening the cadmium shutter. Under these conditions less than 1 percent as many tracks were observed.

RESULTS

2800 pairs of stereoscopic pictures were taken with the apparatus and approximately 25,000 recoil protons were observed. In order to obtain the energy distribution of the neutrons, only recoil protons which made angles of less than 15° with the direction of the incident neutron were measured, ensuring that essentially all the energy of the neutron was transferred to the proton. In order to minimize the geometrical correction for the probability of observing tracks of different lengths, only tracks were measured which began in region A of the cloud chamber as indicated in Fig. 2. Thus tracks with lengths up to 13 cm have almost as great a probability of ending in the illuminated section of the cloud chamber as tracks of much shorter length. The tracks which were measured fell into two categories—those that ended in the gas, and those that continued into the wall of the chamber. A total of 437 tracks were measured which began in region A and made angles less than 15° with the direction of the primary neutrons. Of these tracks, 237 ended in the gas and 200 continued into the walls of the chamber.

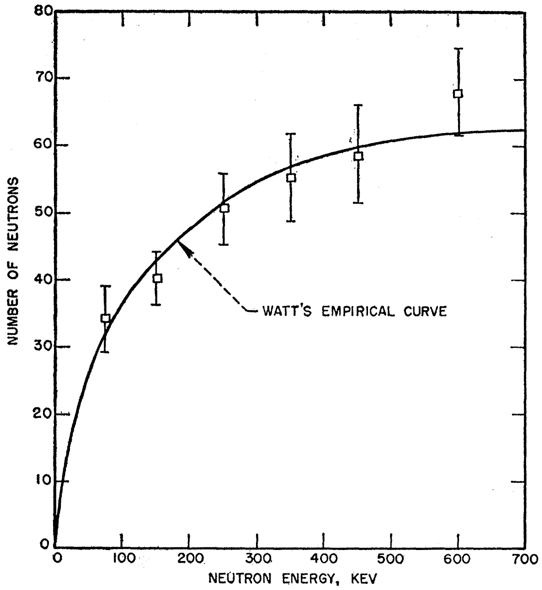

FIG. 3. The experimental distribution in energy of the neutrons compared with the empirical formula.

The data on these recoil-protons are given in Table I, in the form of the relative number of recoil-protons in a given energy interval. To convert from the number of recoil protons to the number of primary neutrons one must take into account the varying cross section for neutron-proton scattering, which is indicated by σ in Table I. As a final correction one must multiply by the geometrical correction factor for the probability of measuring tracks of different lengths. This factor varied from 1.04 for tracks with a length of 1.1 cm to 1.56 for tracks with a length 12.2 cm. The relative number of neutrons $N(E)$ with different energies is obtained from these calculations.

The relative number of neutrons $N(E)$ is plotted in Fig. 3 as a function of the energy of the neutrons. The experimental curve indicates that at 100 kev there are approximately one-half as many neutrons as at 600 kev. The solid curve shown in Fig. 3 is given by the relation $N(E)=\sinh(2E)^{\frac{1}{2}}e^{-E}$, which is a semi-empirical relation obtained by Watt[9] to describe the energy distribution from 0.6 Mev to 15 Mev. This relation fits our experimental data quite well over the 75-kev to 600-kev range.

Our experimental data give more information than

[9] B. E. Watt [Phys. Rev. **87**, 1037 (1952)].

the shape of the curve from 0.05 to 0.6 Mev. Data on the relative number of recoil protons with energy greater than 0.6 Mev were also obtained, allowing a comparison of our data with any theoretical neutron distribution as regards the relative number of recoil-protons above and below 0.6 Mev. From our experimental data, we found the value of the ratio of the number of recoil protons in the range 50–600 kev to that in the range 600–∞ to be 0.54 ± 0.05, compared to a value of 0.50 from Watt's formula.[9] The calculated values were obtained by numerical integration of the curves and from the known variation of the cross section of neutron-proton scattering. This ratio fixes the scale factor used in comparing our results below 0.6 Mev with the formula. The agreement with the empirical relation is quite good, and this experiment, together with those by Watt[9] and by Hill,[10] indicates that this relation fits the entire neutron spectrum from 75 kev up to 15 Mev.

[10] D. L. Hill, Phys. Rev. 87, 1034 (1952).

PHYSICAL REVIEW VOLUME 87, NUMBER 6 SEPTEMBER 15, 1952

The Neutron Energy Spectrum from U^{235} Thermal Fission*

DAVID L. HILL†
Argonne National Laboratory, Chicago, Illinois
(Received April 14, 1952)

A Ranger measurement of the distribution-in-range of knock-on protons from thin paraffin layers indicates the distribution-in-energy from 0.4 Mev to 7 Mev of the neutrons emitted from uranium bombarded by neutrons from the thermal column of the Argonne Heavy Water Reactor. The spectrum shows a broad maximum near 0.75 Mev and follows closely an exponential drop from 2 Mev to 7 Mev with a relaxation energy of 1.55 Mev. The observed neutron intensity does not go to zero below 16 Mev.

SEVERAL observations[1] have indicated the general course above 1 Mev of the energy spectrum for neutrons released in the thermal-neutron-induced fission of U^{235}. Like most heavy particle distributions-in-energy obtained prior to 1946, however, these measurements suffer from poor statistical determination. It therefore seemed fitting, in the summer of 1946, to apply the Ranger[2,3] to the study of this problem. Approximately one week was required to obtain the data summarized in Fig. 2, based upon the range measurements of 44,000 protons ejected from paraffin layers under various conditions detailed below.

The operation of the Ranger as a neutron detector may be schematized in terms of two parallel coaxial disks, S and D, of identical diameter and thickness. The source plate, which we label S, is a layer of paraffin mounted on an aluminum plate. The effective detector, which we label D, is the interface between three coincidence counters and one anticoincidence counter. A remote control mechanism selects the range of protons stopping in D by adjusting the absorptive path between S and D. The instrument retains constant sensitivity for protons within the range of observation; for the present measurement these limiting ranges correspond to proton energies of 0.27 Mev and 17 Mev.

The Ranger was operated for the study of this energy spectrum in substantially the same manner as it was applied to the measurement[2,4] of the energy spectrum of the radium-alpha-beryllium source, CO_2 at a pressure of 40 mm Hg being used as the ionizing medium for the protons, and the test polonium alpha-source being used in the same way to insure accurate gain settings for counting the protons. The considerations there given on background, counting efficiency, energy resolution, and the expressions for the counting rates are equally applicable here when adjustment is made for the different dimensions involved.

The source of the neutrons studied was a flat circular plate of uranium metal or oxide placed in the 20-cm $\times$20-cm beam of neutrons from the thermal column of the Argonne Heavy Water Reactor. The sketch of Fig. 1 shows a top view of the irradiation arrangement. This position of equipment minimizes the number of neutrons entering the front face of the chamber after being scattered from the massive pile face. Those neutrons which pass through the chamber making an angle of more than 90° with the inner normal to the front face of the chamber can have no effect upon the counting rates. There remains a small perturbation from those neutrons scattered from the concrete floor 85 cm below the level of the thermal neutron beam and from those neutrons doubly scattered in the chamber,

* The work described in this article was done under the auspices of the Atomic Energy Project, and the information contained herein will also be included in the *National Nuclear Energy Series* (Manhattan Project Technical Section).
† Now at Vanderbilt University, Nashville, Tennessee.
[1] For citations of early work see reference 6. See also N. Nereson, Phys. Rev. 85, 600 (1952).
[2] Unpublished Atomic Energy Commission Declassified Report No. 1945-(Rev.), available from the Office of Technical Services, Department of Commerce, Washington, 25, D. C. This document gives a detailed account of the Ranger and of this measurement, as well as all other Ranger work in 1946.
[3] D. L. Hill, Rev. Sci. Instr. (to be published).
[4] D. L. Hill, Rev. Sci. Instr. (to be published).