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).

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The Neutron Energy Spectrum from U[235] Thermal Fission*

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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).

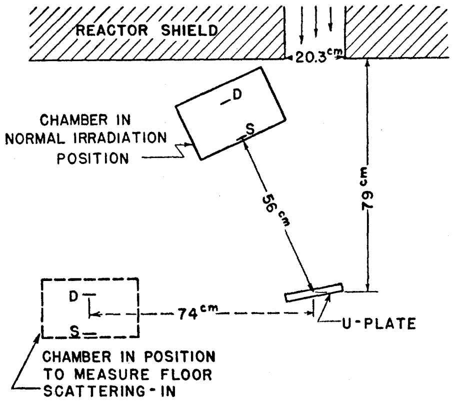

FIG. 1. Relative positions of detecting chamber, thermal neutron beam, and fast neutron source.

but these contributions to the counting rate were measured as indicated in Fig. 1, found to be less than 4 percent even after introduction of the factor 2.3 to account for the different solid angles used by the scattered neutrons for the two chamber positions, and therefore were subtracted from the observed counting rates without significantly disturbing their precision.

To avoid errors from pile power fluctuations (which seldom exceeded 5 percent) a monitoring fission counter was used in a position where its counting rate was about 50,000 per minute. This counter was turned on and off in coincidence with the Ranger counts so that accurate normalization of all Ranger counts to constant neutron source strength was possible.

For exploring different parts of the neutron spectrum, two different fast neutron sources and four different resolutions were used in six different studies, as indicated in Table I. First used as fission neutron source was a plate of natural uranium 0.5 cm thick and 15 cm in diameter; later used was a disk of pressed uranium oxide enriched in U^{235} and of similar dimensions to the first source so that it provided 8.6 times as many fast neutrons per unit of thermal neutron flux.

In the first study S was mounted on the chamber[2,3] wall, 13.0 cm from D; in the other studies it was mounted on a sliding card just in front of the first counter, and a collimator made by drilling closely spaced 0.16-cm diameter holes in a 0.3 cm thick plate was mounted between the first and second coincidence counters. For the position of S in Study No. 1 the mean energy of the protons observed is 0.95 times the energy of the neutrons producing them; for the position of S and the collimator used in the other studies this factor becomes 0.92.

TABLE I. Summary of experimental conditions. S denotes the thickness of the paraffin layer,[a] D the thickness of the effective detector, A_0 the minimum absorption path, A_m the maximum absorptive path; the last two columns give the total number of points and hours per study.

Study	Neutron source	S c.a.e.	D c.a.e.	A_0 c.a.e.	A_m c.a.e.	Points	Hours
1	natural U	4	4.16	0.92	37.28	10	13
2	natural U	1	1.03	0.35	13.41	14	19
3	natural U	4	4.16	0.35	76.57	20	17
4	natural U	16	16.0	0.35	270.5	20	14
5	enriched U	1	1.03	0.35	15.31	16	20
6	enriched U	$\frac{1}{4}$	0.36	0.35	3.06	12	13

[a] See reference 5.

TABLE II. Calculation of U^{235} fission neutron energy distribution. Given in successive columns are the mean absorptive path, A_{mean}, for the observed protons; the range resolution, δA; the energy E corresponding to A_{mean}; the observed counting rate $C(A)_{\text{mean}}$ after normalization to uniform fast neutron source strength and uniform proton source and detector thickness; the neutron-proton scattering cross section $\sigma(E)$; the slope $(dR/dE)_E$ of the proton range-energy relation; the product of $C(A)$ by $(\sigma^{-1}dR/dE)_E$ to give numbers which are proportional to the distribution-in-energy $N(E)$ of the observed protons and hence to $N(1.08E)$ for the fission neutrons; and, finally, the fractional statistical uncertainty for each value of $N(E)$.

A_{mean} c.a.e.	δA c.a.e.	E Mev	$C(A)$ counts/min	$\sigma(E)$ barns	$(dR/dE)_E$ c.a.e./Mev	$KN(E)$ (Mev)$^{-1}$	$\Delta N/N$
0.65	0.30	0.400	20.3	7.20	2.01	5.7	0.04
0.92	0.30	0.525	17.6	6.16	2.30	6.6	0.06
1.18	0.30	0.635	16.3	5.65	2.53	7.3	0.05
1.45	0.30	0.725	10.3	5.32	2.81	5.4	0.07
1.59	0.30	0.790	11.6	5.11	3.00	6.8	0.07
1.86	0.30	0.865	10.7	4.91	3.19	7.0	0.07
2.12	0.30	0.945	8.2	4.67	3.32	5.8	0.10
2.29	1.02	1.000	8.4	4.59	3.40	6.2	0.02
2.39	0.30	1.030	8.1	4.47	3.45	6.3	0.10
2.65	0.30	1.095	7.2	4.30	3.71	6.2	0.11
2.92	0.30	1.160	5.1	4.15	4.01	4.9	0.15
3.10	0.30	1.215	6.8	4.07	4.14	6.9	0.12
3.35	1.02	1.26	5.7	4.00	4.2	6.0	0.02
4.33	1.02	1.49	4.4	3.6	4.6	5.6	0.02
5.40	1.02	1.70	3.7	3.4	5.2	5.7	0.03
6.39	1.02	1.88	3.11	3.20	5.7	5.53	0.02
7.33	1.02	2.04	2.34	3.05	6.0	4.61	0.03
8.30	1.02	2.20	1.87	2.92	6.3	4.03	0.03
8.3	4.1	2.20	1.87	2.92	6.3	4.03	0.02
9.38	1.02	2.36	1.66	2.81	6.9	4.07	0.03
10.30	1.02	2.50	1.24	2.71	7.1	3.24	0.04
11.40	1.02	2.64	1.13	2.62	7.3	3.15	0.04
12.34	1.02	2.77	0.83	2.53	7.5	2.46	0.06
12.5	4.1	2.80	0.94	2.51	7.6	2.85	0.03
16.7	4.1	3.32	0.56	2.26	9.0	2.23	0.05
20.8	4.1	3.76	0.35	2.09	9.8	1.52	0.08
24.6	4.1	4.15	0.23	1.95	10.2	1.20	0.12
28.7	4.1	4.55	0.14	1.83	10.9	0.83	0.13
32.4	16.0	4.87	0.134	1.75	11.8	0.90	0.07
32.6	4.1	4.91	0.14	1.74	11.8	0.94	0.19
36.7	4.1	5.23	0.09	1.65	12.2	0.74	0.30
41.1	4.1	5.57	0.07	1.57	13.1	0.58	0.25
44.2	4.1	5.80	0.10	1.53	13.3	0.86	0.27
46.4	16.0	5.98	0.069	1.49	13.6	0.63	0.10
48.4	4.1	6.11	0.05	1.47	13.8	0.47	0.3
48.4	16.0	6.11	0.022	1.47	13.8	0.21	0.15
52.5	4.1	6.43	0.03	1.41	14.4	0.31	0.7
52.7	16.0	6.44	0.016	1.41	14.4	0.16	0.21

In each of these studies neutron counts were taken for every total absorptive value between A_0 and A_m which (approximately) satisfied the relation $A=A_0+nS$, where n is an integer. Optimum coverage of the distribution-in-range of the recoil protons is then obtained, for with S equal to D, the response function is a triangle stretching from $A-S$ to $A+S$, with its maximum at A.

Background counts were taken by sliding the card bearing the paraffin layer out of sight of the counters

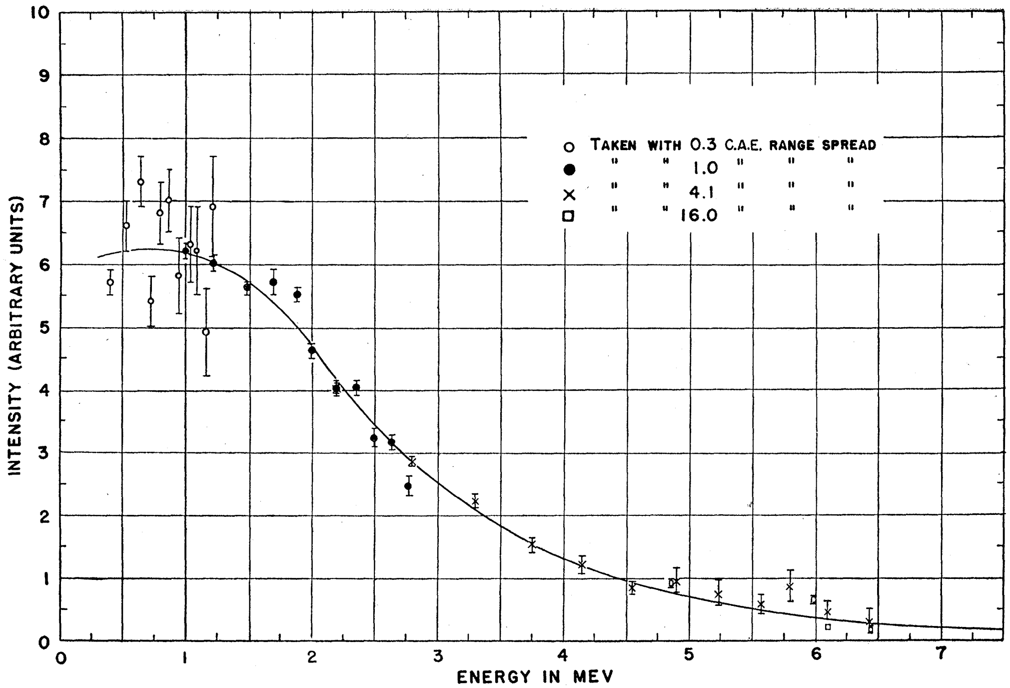

FIG. 2. The collected observations on the U^{235} fission neutron energy spectrum, for four different range resolutions of the instrument.

and dropping a 140 c.a.e.[5] aluminum absorber in front of the first counter, to match the thickness of the aluminum plate bearing the paraffin layer. The background counts averaged about 10 percent of the total counting rates.

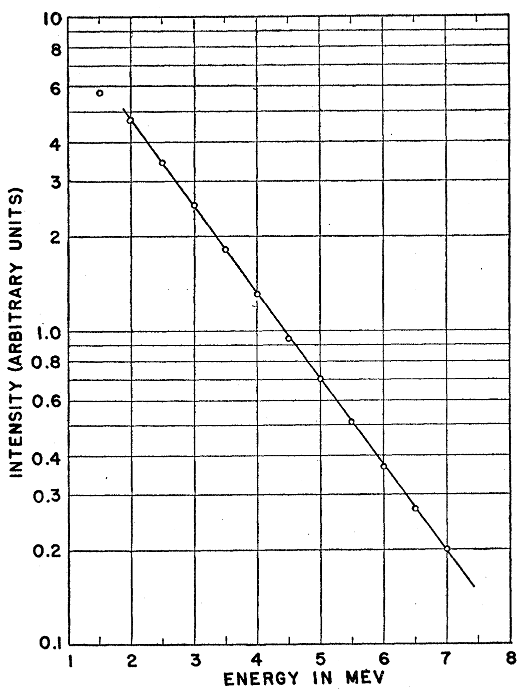

FIG. 3. The mean course of the spectrum of Fig. 2 is seen to follow closely an exponential drop between 2 Mev and 7 Mev.

After this small background correction was made, the data from these different studies were then normalized[2,4] to a common source strength and to a common S and D thickness, the natural uranium plate being chosen as the standard source, with 1 c.a.e. being chosen as the standard thickness. Division by the neutron-proton scattering cross section and multiplication by the slope of the range energy relation, dR/dE, then gives numbers, $KN(E)$, proportional to the distribution-in-energy, as listed in Table II and plotted in Fig. 2, along with their statistical uncertainties. No correction is here made for the fact mentioned above that the energy of the observed protons is 0.92 times the mean energy of the neutrons producing them. In reading this plot one should recall that the Ranger response function goes to zero at ordinates approximate to those of the two adjacent points of the same species. The solid line to indicate the mean course of the spectrum has been drawn in accord with the statistical weight of the plotted points. When this line is transformed to a logarithmic plot, as in Fig. 3, we note that from 2 Mev to 7 Mev the course of the spectrum is well described by the exponential function, $\exp(-E/1.55)$, where E is given in Mev.

The data taken were not sufficient to determine the shape of the spectrum above 7 Mev. Above 16 Mev the neutron intensity was so low as to be unobservable with the present arrangement.

When this measurement was made time was not available for the more extended study needed for the

[5] To avoid confusion of different length measures we introduce a special unit, the c.a.e. (centimeters of air equivalent). One c.a.e. is an absorptive unit equivalent, for range diminution of an alpha-particle or proton, to one centimeter of air at 15°C and 760 mm Hg pressure.

low and high energy ends of the spectrum. These sections have, however, been measured by other techniques by Bonner *et al.*[6] and by Watt.[7] Watt also gives[7] an empirical formula which fits satisfactorily the spectrum obtained as a composite of these three independent measurements.

In developing the instrumental techniques applied to this measurement I have been generously supported and assisted by others of the Argonne National Laboratory, as indicated in the report on the Ranger[2,3] design.

[6] Bonner, Ferrell, and Rinehart, Phys. Rev. 87, 1032 (1952).
[7] B. E. Watt, Phys. Rev. 87, 1037 (1952).

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Energy Spectrum of Neutrons from Thermal Fission of U^{235}

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A proton recoil counter has been used to determine the neutron spectrum, in the energy range 3.3–17 Mev, of a beam produced by irradiating 95 percent U^{235} (metal) in the central experimental hole of the Los Alamos Homogeneous Reactor. Most of the fissions were induced by slow neutrons. The data are combined with those obtained by D. Hill and by T. W. Bonner, R. A. Ferrell and M. C. Rinehart; the composite spectrum so obtained extends from 0.075 to 17 Mev. Fits with two general formulas are discussed.

INTRODUCTION

THE present experiment was designed specifically to obtain the high energy portion of the fission neutron spectrum, as previous investigators had measured the spectrum up to about 6 Mev.

It was known that the intensity of the very high energy neutrons would be low, so the apparatus was designed to operate stably for long periods and to have a low background count in the presence of the intense (but well collimated) beam of neutrons and gamma-rays available from a U^{235} sample placed in the central experimental hole ("glory hole") of the Los Alamos Homogeneous Reactor.[1] A more detailed report of the present experiment is available as Los Alamos Declassified Report No. 935.

APPARATUS

The neutron beam was produced by inserting samples of U^{235} (95 percent U^{235}, 5 percent U^{238}) in the "glory hole" of the water boiler, where they were exposed to a thermal neutron flux of 3×10^{11} per square centimeter per second. Two such sources were used: (1) a 28.5-g disk of U^{235} 0.168 in. thick mounted on a graphite rod, and (2) 54.1 g of U^{235} as an assembly of 31 disks 0.010 in. thick equally spaced along an 18-in. aluminum tube. Figure 1 shows the placement of the latter of these sources as well as the method of collimating the neutron beam.

It was necessary to consider the effect of neutron scattering in the walls of the collimating tube on the neutron energy spectrum of the emergent beam. A very crude calculation considering only single isotropic scattering indicated that less than one percent of this beam had been scattered in the walls. Since the most objectionable feature of such scattering is distortion of the spectrum through degradation, and since an energy loss of 3 Mev would put neutrons observed in this experiment into a group about ten times as strong as the parent group, it is believed that wall scattering is negligible in this experiment.

The distribution in energy of the fast neutrons was measured by means of the spectrometer shown in Fig. 2. Recoil protons ejected from any one of four polyethylene foils were detected by observing coincidences between counts of three proportional counters. In order to reduce the counting rates in the three counters and thereby the background produced by accidental coincidences, the counters were located outside the neutron beam as shown in Figs. 1 and 2. To increase the stability of the counter characteristics, no moving parts were placed in the counters. The distribution in energy of the neutrons was deduced from the distribution in range of the recoiling protons. Any desired combination of seven aluminum absorbers could be introduced between the polyethylene foils and the counters. An integral proton range distribution was obtained by counting all the

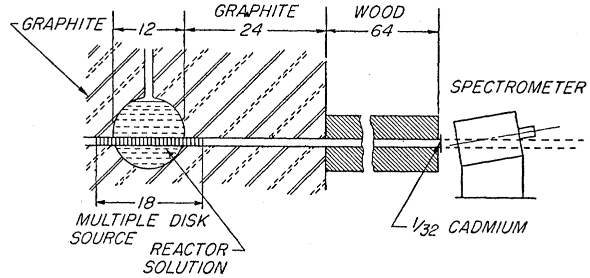

FIG. 1. Diagram of the experimental set-up to show the arrangement of materials surrounding the beam. Numbers give dimensions in inches.

[1] Rev. Sci. Instr. 22, 489 (1951).