Fission Neutron Spectrum of U^{235}

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A high pressure ionization chamber has been used to measure the energy distribution of proton recoils from the neutrons which are emitted during the thermal neutron fission of U^{235}. The energy spectrum of the fission neutrons is obtained by applying suitable wall corrections and by using 2.5-Mev $d-d$ neutrons for an energy calibration. Measurements were made in the range from 1 to 4 Mev, and within the experimental errors, the resulting fission spectrum follows Watt's [B. E. Watt, Phys. Rev. **87**, 1037 (1952)] semi-empirical relation, $N(E)=e^{-E}\sinh\sqrt{(2E)}$.

I. INTRODUCTION

THE energy spectrum of neutrons arising from the fission of U^{235} induced by thermal neutrons was investigated by Bloch and Staub[1] in 1943 at Stanford University. The slow neutrons used to induce fission in 2.93 kg of normal uranium were produced by first modulating a cyclotron beam of 2.6-Mev deuterons and then admitting the $Be-d$ neutrons into a large, graphite lined box in which the slow neutrons had a lifetime of about 2 milliseconds. Approximately centered in the box were the uranium sample and a high pressure ionization chamber filled with a mixture of hydrogen and argon. The ion pulses from the chamber were fed through an amplifier which was modulated so as to register counts only after the burst of fast cyclotron neutrons had decayed. These measurements extended over a range of neutron energies from 0.7 to 3.3 Mev, and showed a maximum in the fission spectrum at 0.8 Mev and a half maximum value at about 2 Mev. It was found, however, that these results were affected by some inelastic scattering in the rather heavy iron walls of the ionization chamber and possibly in the walls of the box. In addition, the accuracy of the measurements was greatly limited by the low intensity of primary slow neutrons that resulted from the modulation scheme needed to eliminate the background of fast neutrons. The present measurements (carried on during the early part of 1944) were undertaken as an attempt to obtain a more accurate fission spectrum. The results, although not in strong disagreement with the Stanford measurements, did indeed show a larger abundance of higher energy neutrons. Since the results of the present measurements have not previously been available in a complete form, they are reported here and compared briefly with subsequent data.

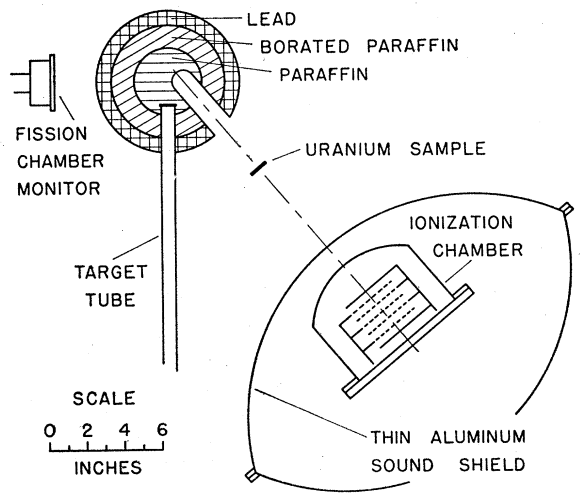

FIG. 1. Experimental arrangement. The target of the Van de Graaff accelerator is surrounded by a spherical paraffin moderator and lead shield. Thermal neutrons to irradiate the uranium sample originate from a $1\frac{1}{4}$-in. diameter howitzer in the moderator.

II. APPARATUS AND EXPERIMENTAL ARRANGEMENT

Three sets of measurements were made using different amounts of fissionable material and also slightly different experimental arrangements. They will be referred to as runs A, B, and C, respectively.

Run A: using 2.93 kg normal uranium.
Run B: using 243 g normal uranium.
Run C: using 2 g of material enriched in U^{235}.

In all three runs, the thermal neutrons to induce fission were obtained by moderating neutrons from the $Li(p, n)$ reaction produced in a Van de Graaff generator. The accelerating voltage was chosen so that the energies of the neutrons from the reaction would not exceed a few hundred kilovolts. The lithium target in each run was surrounded by a suitable paraffin moderator and lead shield, chosen so as to provide both an adequate flux of thermal neutrons and a low background of fast neutrons and gamma-rays. A typical arrangement is shown in Fig. 1, which is the geometry used during run C. The neutron beam was monitored both by a fission chamber placed near the target assembly and by means of a current integrator for the accelerated beam. The uranium sample was placed approximately midway between the target and the chamber, the distances being chosen to insure a reasonable collimation of the fission neutrons which entered the chamber directly, without allowing too large a possibility of other fission neutrons

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[1] F. Bloch and H. Staub, Los Alamos Declassified Report No. 934, 1943 (unpublished).

being inelastically scattered in the moderator and subsequently being detected. Perfect collimation of the fission neutrons was assumed in the calculation of the wall effects.

The ionization chamber used in these measurements was the same one used at Stanford.[1] A complete description of this chamber is also given by Rossi and Staub.[2] Since lower gas pressures were used here than in the earlier Stanford measurements, it was possible to use a thinner $\frac{1}{8}$-in. steel chamber housing. Although the steel back plate of the chamber was $\frac{7}{16}$ in. in thickness, estimates of the inelastic scattering in the chamber walls indicated that its effect on the spectrum was small compared to the random statistical errors in the measurements. The chamber was filled with a mixture of purified hydrogen and argon to a total absolute pressure of 220 lb/in.^{2} giving a stopping power of 5.68. The gas mixture also contained a trace of oxygen, because it was essential that the ions be collected without gas multiplication which might otherwise occur near the wire grids of the chamber electrodes. The chamber was operated at 8700 volts. The ion pulses were fed through a single 1603 tube preamplifier into a linear amplifier whose time constants were a few milliseconds. Appreciable microphonics resulted from the use of these relatively long time constants needed for ion collection. The microphonics, which were induced largely in the woven grid structure of the collecting electrodes, were greatly reduced in the present measurements by the construction of a sound shield consisting of a thin-walled evacuated metal shell. The chamber and preamplifier were suspended by rubber within the sound shield, and the entire arrangement likewise suspended by suitably loaded springs. In spite of the sound shield, the noise level in the vicinity of the electrostatic generator, together with the radiation background, prohibited the measurements to extend below 1 Mev.

During run A, the energy distribution of the proton recoils was measured by feeding the amplified pulses into an electronic differential pulse-height analyzer, similar to the one used in the Stanford measurements.[1] Photographic recording[3] of the pulses was used for runs B and C. Repeated background measurements were taken during all runs with the uranium sample removed. Linearity and reproducibility of the amplifying and recording system were checked during each run by means of artificial pulses fed directly to the collecting system of the chamber. An energy calibration of the recorded pulse heights was obtained between runs by separate measurements with 2.5-Mev $d-d$ neutrons. In addition, the $d-d$ measurements provided a check on the accuracy of the entire experimental method and the wall effect calculations. A typical recoil pulse-height distribution and calculated neutron spectrum from such a calibration run is given by Rossi and Staub.[2]

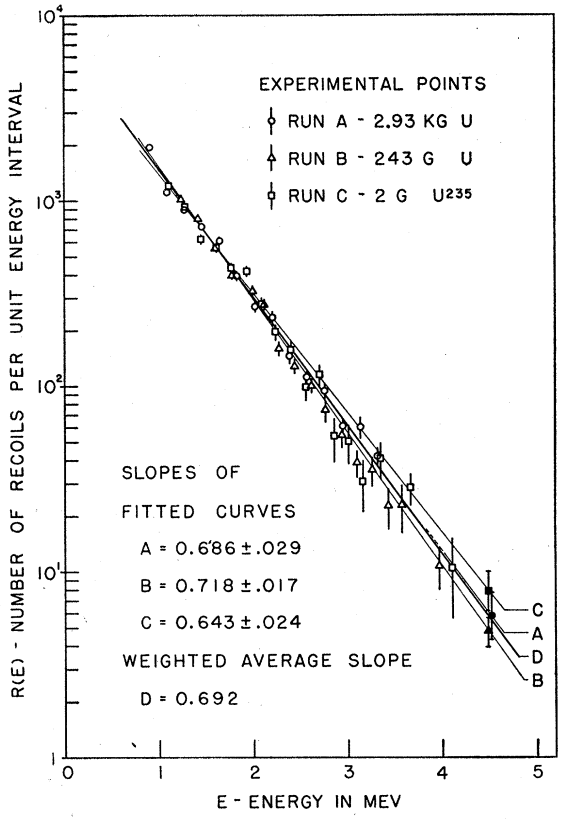

FIG. 2. Measured energy distribution of proton recoils. The data are corrected for background and interval width. The solid points at 4.5 Mev are calculated points.

III. MEASUREMENTS AND RESULTS

The semilogarithmic plot in Fig. 2 shows the number of proton recoil pulses per unit energy interval as a function of the pulse height in Mev. The three sets of data plotted for the runs A, B, and C have been arbitrarily normalized at 1.6 Mev. No pronounced departure from linearity is indicated by the data, and therefore since the assumption of a simple exponential recoil distribution greatly simplifies the calculations of the wall effects, a straight line fit has been made for each of the three sets of data by the method of least squares. Although a linear fit could be made in each case with reasonably good accuracy, there is admittedly no theoretical justification for this simplifying procedure. The calculated magnitudes of the slopes of the three fitted curves together with their standard probable errors are:

$$\text{Slope } A = 0.686 \pm 0.029,$$
$$\text{Slope } B = 0.718 \pm 0.017,$$
$$\text{Slope } C = 0.643 \pm 0.024.$$

The overlapping of these values is shown in Fig. 2 by the calculated points and their errors at 4.5 Mev.

[2] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), National Nuclear Energy Series, Div. V, Vol. 2, Sec. 7.11.

[3] The authors are indebted to N. Nereson for the use of his photographic recording apparatus.

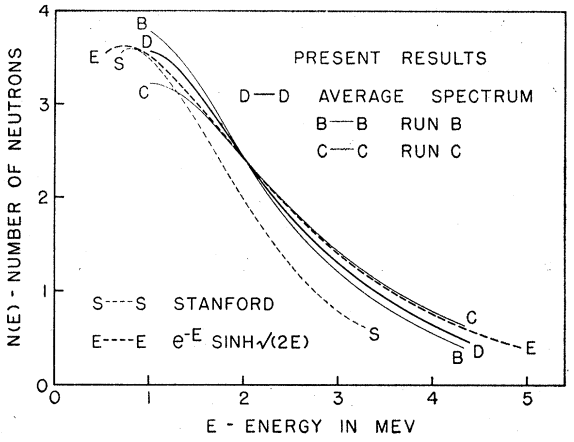

FIG. 3. Energy spectrum of U^{235} fission neutrons.

The fact that the slope for the fitted curve C is less than those of the other two runs probably has only slight significance, although it suggests the possible effect of inelastic scattering in the larger samples of normal uranium used in runs A and B. However, the Stanford measurements had shown no appreciable distortion of the $d-d$ spectrum measured with and without the 2.93-kg disk of uranium placed between the $d-d$ neutron source and the chamber.

Since the differences between the three values of the slopes given above are of the same order as their errors, and especially in view of the rather large wall effects, we have taken 0.692, the weighted average value of the three slopes, to represent our most reliable estimate of the proper recoil distribution and this is shown by curve D (Fig. 2). Furthermore, we have assumed the distributions given by curves B and C to represent the approximate limits of accuracy of the mean distribution.

The energy spectrum of the fission neutrons can readily be calculated from a given proton recoil distribution. If the wall effects are negligible, then $N(E)$ the number of neutrons per unit energy interval is given by

$$N(E)=-\frac{E}{n\cdot\sigma(E)\cdot d}\frac{dR(E)}{dE},$$

where $R(E)$ is the observed number of recoils per unit energy interval, n the number of hydrogen nuclei per cm^3, d the depth of the chamber, and $\sigma(E)$ the cross section for scattering which is assumed to be isotropic in the center-of-mass system. However, when the range of the proton recoils becomes comparable with the dimensions of the collecting volume, the neutron distribution is given by

$$N(E)=-\frac{E}{n\cdot\sigma(E)\cdot d\cdot\alpha(E)}\left[\frac{dR(E)}{dE}-f(E)\right],$$

where $\alpha(E)$ and $f(E)$ are functions which depend essentially on the geometry and the stopping power. The evaluation of these functions is discussed in detail elsewhere.[1] The calculation of the wall effects for this chamber was done at Stanford by Bloch, Hamermesh, and Weinstock. In the present measurements the chamber geometry was not altered, and thus only the appropriate corrections for the different stopping power had to be made in the analysis of the data. Values of the neutron-proton scattering cross sections used were taken from Bohm and Richman.[4]

The calculated fission spectra for each of the three recoil distributions B, C, and D are shown by the correspondingly labeled curves in Fig. 3 which give the number of fission neutrons on an arbitrary scale as a function of their energy in Mev. The three spectra are normalized at 2 Mev which is fairly close to the estimated average energy of the fission neutrons. The present measurements do not extend below 1 Mev, and hence do not quite reach the maximum in the fission spectrum at about 0.8 Mev indicated by the Stanford results which are shown by curve S (Fig. 3). The trend of the curves B, C, and D, however, suggests rather strongly the presence of a maximum in the region slightly below 1 Mev. Some additional evidence for such a maximum was obtained by the present authors from other measurements of the fission spectrum taken with a parallel-plate chamber with a thin paraffin radiator and using electron collection. These latter measurements extended between 0.5 and 1.5 Mev. Because of large wall effect corrections and rather high backgrounds in the lower energy region, no great reliability could be attributed to the results obtained below 1 Mev. The spectrum obtained showed a maximum near 1 Mev, and coincided with the present results in the region between 1 and 1.5 Mev.

Subsequent investigations[5–8] of the fission spectrum of U^{235} have shown good agreement with Watt's[5] semi-empirical relation $N(E)=e^{-E}\sinh\sqrt{(2E)}$, where E is the neutron energy in Mev. This relation is given by curve E in Fig. 3 for comparison with the present results. Curve E is likewise normalized at 2 Mev, and falls between our mean spectrum shown by curve D and that obtained from run C over the entire range of measurement from 1 to 4 Mev.

The neutron spectrum from the fission of Pu^{239} was measured at the same time as run C for U^{235} and under the same geometry. Samples of the two materials were periodically interchanged during the measurement. The slopes of the proton recoil distributions as plotted in Fig. 2 differed by only one percent, showing that the neutron spectra from the fission of the two materials were identical within the statistical accuracy of the data.

[4] D. Bohm and C. Richman, Phys. Rev. **71**, 32 (1947).
[5] B. E. Watt, Phys. Rev. **87**, 1037 (1952).
[6] N. Nereson, Phys. Rev. **85**, 600 (1952).
[7] Bonner, Ferrell, and Rinehart, Phys. Rev. **87**, 1032 (1952).
[8] D. L. Hill, Phys. Rev. **87**, 1034 (1952).