Fission Cross Section of U^{235} for Fast Neutrons*

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An absolute measurement of the fission cross section of U^{235} for 1.27-Mev neutrons has been made. The neutron flux was measured with a recoil-proton proportional counter using a thin solid radiator of hydrogenous material. In addition, relative cross sections have been measured between 0.403 and 1.620 Mev. These relative measurements also utilized a recoil-proton flux monitor. The cross section has a constant value of 1.27 ± 0.044 barns in the neutron-energy interval between 1.0 and 1.5 Mev.

I. INTRODUCTION

THE absolute fission cross section of U^{235} for fast neutrons is of particular interest since it has been used extensively as a standard in the determination of the cross sections of other fissionable materials. This cross section has been measured by many investigators.[1–7] In the present paper a measurement is described which is similar to and patterned after that used by Hall, Koontz, and Rossi[1] at Los Alamos in 1944 and described by Rossi and Staub.[2]

In this experiment the ratio of the fission cross section to the hydrogen scattering cross section was measured directly at several energies. A thin U^{235} fission foil and a thin solid hydrogenous radiator were mounted back to back and placed in a counter with which the fissions and recoil protons could be recorded simultaneously. The absolute fission cross sections were then calculated from the known hydrogen cross sections.

The energy dependence of the cross section of U^{235} was determined at 14 points between 0.403 and 1.620 Mev. The difference in procedure between the relative and absolute measurements consisted only in use of different foils of fissionable and hydrogenous materials. In order to make an absolute measurement, it is necessary to determine the total number of fissions occurring in a foil. This requires that the foil be thin compared to the range of fission fragments. With such a foil and the available neutron fluxes, fissions were obtained at a rate of about one thousand per hour. This absolute measurement was made at one energy; then a thick foil of uranium was used to obtain the relative cross section at other energies. Since counting rates of recoil protons were high, thin foils of hydrogenous materials could be used. Because the recoil-proton range varied with energy for the neutron energies used, it was necessary to use many different thicknesses of proton radiators.

The neutron source consisted of monoenergetic neutrons which were produced in a tritium gas target by protons from the 2.5-Mev electrostatic accelerator. The energy spread of neutrons was approximately ±35 kev for neutrons of 1.27 Mev.

II. EXPERIMENTAL

A. Counters

The fission ionization chamber and the recoil-proton proportional counter were enclosed in the same envelope (see Fig. 1). This double counter was surrounded with cadmium to reduce the background in the fission chamber coming from low-energy room-scattered neutrons. The fissionable material and a thin layer of hydrogenous material were deposited on thin platinum foils which were placed back to back and comprised part of a grounded electrode common to the two counters. One advantage of this system was that both materials were deposited as uniform layers of the same diameter and were separated from each other by only a few thousandths of a centimeter. The neutron-flux measurement by the recoil-proton detector was thus made at the same time and essentially in the same place as the counting of the fissions. Therefore, knowledge of the exact distance of the detectors from the neutron source and small angular misalignments were unimportant; to some extent also effects of perturbations of the neutron flux by the counter itself tended to cancel out.

The fission counter was essentially a parallel-plate ionization chamber (actually the electrodes were sections of cylinders). The platinum foil with the U^{235} deposited upon it was bent around the cylinder of the proportional counter so that the two foils were back to back and the deposits were centered upon each other.

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[1] P. G. Koontz (private communication).

[2] B. Rossi and H. H. Staub, *Ionization Chambers and Counters, Experimental Techniques* (McGraw-Hill Book Company, Inc., New York, 1949), pp. 165–171.

[3] A. O. Hanson and D. L. Benedict, April, 1943 (unpublished).

[4] R. F. Taschek and C. M. Turner, Los Alamos Scientific Laboratory Report MDDC-737, November 1945 (unpublished).

[5] L. W. Seagondollar, Los Alamos Scientific Laboratory Report LA-562, May 1946 (unpublished).

[6] Szteinsznaider, Naggiar, and Netter, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 245, paper P/355.

[7] Work of W. D. Allen, reported by P. Egelstaff, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 291.

The detector of recoil protons consisted of a proportional counter 5 cm in diameter and with a counting length of 6 cm, the length being fixed by use of field tubes as described by Cockroft and Curran.[8] This counter was lined with a thin platinum cylinder which could be removed and carefully cleaned to minimize contamination by hydrogenous materials. The counters were operated at a pressure of argon-carbon dioxide which assured that all protons of interest were stopped in the gas.

B. Foils

The U^{235} foils consisted of 200 to 500 μg of U^{235} coated onto a 2.6-cm-diameter circle on a 0.013-cm-thick disk of platinum. In order to obtain an accurate measure of the amount of U^{235} on the fission foil, a set of intercomparisons of several foils was made. Weights were determined by both quantitative electroplating and by actual weighing before and after deposition, care being taken in the latter case to convert the uranium completely to U_3O_8 by heat treatment in air to insure a known composition. Alpha counting was used as a secondary method for intercomparison of the foils. They were also compared to "standard" foils of other experimenters in this laboratory by counting in double fission counters in the same neutron flux.

The proton radiators consisted of thin films (65 to 650 μg total weight) of glycerol tristearate deposited in a 2.6-cm-diameter circle on a platinum disk. The glycerol tristearate was deposited by evaporation in a vacuum, the amount deposited being determined by weighing the platinum foils before and after deposition of the glycerol tristearate. Radiators of various thicknesses were used to check the consistency of weighing as well as the thickness corrections. Two samples of glycerol tristearate, evaporated by the same method as for radiator preparation, were analyzed for hydrogen content and found to be within a few tenths of a percent of the theoretical composition.

C. Absolute Counting

After amplification, pulses from the fission counter went into a discriminator and scaler. In order to determine the optimum bias setting for the discriminator, the pulse-height distribution produced by fission fragments was observed with an 18-channel pulse-height analyzer.[9] About two percent of the fissions in the thin foils were not detected because of the thickness of the foils. Some fission fragments were totally absorbed and some were reduced in energy sufficiently to produce pulses below the bias setting. The correction for the loss of fission counts could have been made according to the methods of Rossi and Staub[2] if the deposits had been perfectly uniform and flat. However, a study of the distribution in pulse height of the low-pulse-height

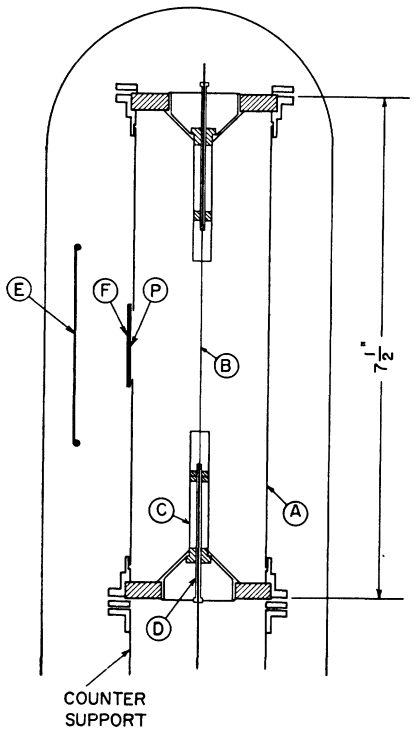

FIG. 1. Double counter including proportional counter for detection of recoil protons and ionization chamber for detection of fissions: *A*, grounded outer cylinder of proportional counter; *B*, wire at positive high voltage, *C*, "field tubes" held at an appropriate intermediate potential to maintain uniform gas multiplication along the wire in the counter region and to shield the wire from ionization produced in the gas in the region outside the counting region; *D*, "guard ring" held at same potential as the wire but insulated from it; *P*, proton radiator of glycerol tristearate coated on a metal foil and placed over the opening in counter wall, *E*, collecting electrode of the ionization chamber. The foil of fissionable material *F* is placed back to back with the proton radiator, the cylinder of the proportional counter serving as the negative electrode of the ionization chamber.

"tail" of the fission-pulse spectrum showed that there were more small pulses than could be accounted for by energy loss in a uniform, flat layer of uranium. This effect was apparently due in part to roughness of the platinum surface. The correction of less than 2% was obtained by extrapolation of the fission-pulse-height spectrum to zero pulse height and then application of an absorption correction based upon uranium thickness.

After amplification, pulses from the proton counter were analyzed by a multichannel pulse-height analyzer. Only part of the spectrum of pulse heights produced by the protons could be measured. From this part of the spectrum, the total number of neutron-proton scatterings was determined. The low-energy part of the spectrum was obscured by pulses due to recoiling carbon atoms from the radiator and by pulses due to x and γ radiation. Since the pulse height produced by a recoil proton depends on the proton energy and hence the scattering angle of the neutron, the pulse-height spectrum is determined by the angular distribution of n,p scattering. For low-energy neutrons the ideal result

[8] A. L. Cockroft and S. C. Curran, Rev. Sci. Instr. **22**, 37 (1951).
[9] C. W. Johnstone, Nucleonics **11**, 36 (1953).

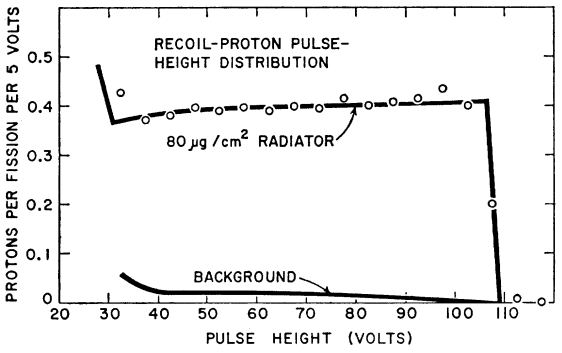

FIG. 2. Distribution of pulse heights due to recoil protons from an 80-μg/cm^2 glycerol-tristearate radiator when irradiated by 1-Mev neutrons. The detector is the proportional counter of Fig. 1. The circles are observed points with a channel width of 5 volts, background subtracted. The solid curve has the shape of the theoretical distribution of pulses from a radiator of this thickness and neutron energy spread of ± 0.030 Mev. Examination of the shape of the high-energy cutoff with narrower channels shows good agreement with the theoretical curve. The rise in the solid curve at low energies indicates pulses which might be obtained from recoiling carbon nuclei. The lower curve represents the distribution of pulses obtained from an equal irradiation of the counter with the radiator replaced by a blank platinum foil.

is a rectangular pulse-height distribution in which there are equal numbers of pulses per unit pulse-height interval up to a maximum height P_m, beyond which there are no pulses. If all pulses above a height P are detected, the fraction of all pulses detected is $(P_m-P)/P_m$. Actually, the observed distribution was distorted by neutron-energy spread and proton-energy loss in the radiator. In practice the theoretical pulse-height distribution was deduced according to the methods given in Rossi and Staub,[2] as worked out by Case,[10] taking into account the thickness of the glycerol-tristearate radiator and the neutron-energy spread. The theoretical curve was fitted to the experimental points and the total number of recoil protons computed. Figure 2 is an example of the kind of fit which was obtained.

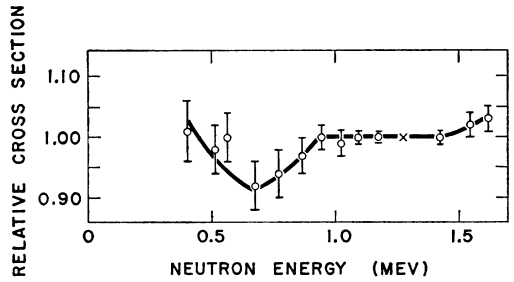

FIG. 3. Variation of the fission cross section of U^{235} with energy. The points are normalized to unity at 1.27 Mev. The errors shown are standard deviations of the ratio. If a normalizing point were taken elsewhere, the standard deviations in its vicinity would be much smaller than shown because of corrections which vary with energy.

[10] K. M. Case, Los Alamos Scientific Laboratory Report MDDC-92, February, 1945 (unpublished).

D. Corrections

Several corrections and backgrounds must be evaluated in order to determine the cross section. The effect of foil thickness and neutron-energy spread has already been mentioned. The background due to recoil protons from hydrogen contamination of the counter gas and walls was measured by inserting a blank platinum foil in place of the proton radiator and counting the remaining protons and the fissions in the usual manner in the neutron beam. Such a background is shown in Fig. 2. In the case of 1.27-Mev neutrons, each of these three backgrounds and corrections was smaller than 5%.

The effect of counter scattering was determined by surrounding the counter with additional layers of steel and cadmium and observing the change in the ratio of fission counts to recoil-proton counts. The correction which was made was about 1%.

The following smaller corrections were computed: (1) the effect of scattering in the platinum backing of the fission foils, which increased the average path length of neutrons in the radiators; (2) target scattering, which provided some neutrons of low energy at the counter; and (3) the effect of center-of-mass motion of the fission fragments on the fraction of fissions detected. The ratio of cross sections of U^{235} and hydrogen were computed from the knowledge of the amount of U^{235} on the fission foil, the amount of hydrogen in the proton radiator, the numbers of fissions and proton recoils which occurred during a run, and the numerous backgrounds and corrections.

III. RESULTS

The results are summarized in Table I. The values are all normalized to 1.27 barns at 1.27 Mev, the energy at which the best absolute measurements were made. The standard deviation assigned to this number is 3½%. The origins of the 3½% error are indicated in Table II. The largest single uncertainty considered is that of

TABLE I. Absolute and relative fission cross sections for U^{235}.

E_n (Mev)	σ_H (barns)	$\sigma_f(E_n)/\sigma_f(1.27\ \text{Mev})$	σ_f (barns)
1.620±0.030	3.271	1.03±0.02	1.31±0.05
1.545±0.032	3.360	1.02±0.02	1.30±0.05
1.424±0.035	3.514	1.00±0.01	1.27±0.04
1.272±0.035	3.737	1.00	1.27±0.04
1.171±0.037	3.908	1.00±0.01	1.27±0.04
1.095±0.039	4.053	1.00±0.01	1.27±0.04
1.025±0.039	4.200	0.99±0.02	1.26±0.05
0.944±0.039	4.391	1.00±0.02	1.27±0.05
0.865±0.039	4.601	0.97±0.03	1.23±0.06
0.770±0.040	4.906	0.94±0.04	1.19±0.06
0.673±0.041	5.272	0.92±0.04	1.17±0.06
0.562±0.039	5.778	1.00±0.04	1.27±0.07
0.513±0.039	6.060	0.98±0.04	1.24±0.07
0.403±0.039	6.896	1.01±0.05	1.28±0.08

TABLE II. Estimated sources of error in absolute cross section.

Effect	Size of correction %	Error %
Glycerol-tristearate weight and fitting of observed experimental recoil-proton curves	...	1.5
Glycerol-tristearate thickness correction	5	0.5
Weight of U^{235}	...	1.0
Uranium foil thickness correction	1.8	1.1
Room background of neutrons	1.3	0.2
Counter scattering	1.3	0.4
Foil scattering	0.5	0.3
Center-of-mass motion of fission fragments	0.6	0.1
Target scattering	0.2	0.1
Hydrogen contamination of counter	4.0	0.5
Hydrogen content of glycerol-tristearate	...	0.5
Extrapolation of recoil-proton pulse-height distribution	...	2.6
Root-mean-square value	...	3.5

extrapolation of the proton pulse heights to zero pulse height. The counter was tested under various conditions of gas pressure, foil thickness, and neutron energy, and excellent agreement was obtained with theoretical pulse-height distributions. Although there was no indication that there was any malfunction of the equipment, it was thought that in the assignment of errors, a generous allowance should be made for uncertainty in this extrapolation. The results are plotted in Fig. 3. These measurements are in agreement with recent measurements made at the Atomic Energy Research Establishment at Harwell, England.[7]

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Electron Scattering from Neighboring Nuclei*

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A new method of measuring small variations of the charge distributions of neighboring nuclei, such as isotopes and isotones, has been developed. The method is based on a determination of the ratio of electron scattering cross sections near the diffraction dips. Experimental results are given for the combinations Ni^{58}, Ni^{60} and Fe^{56}, Ni^{58}. Sample theoretical interpretations are presented.

I. INTRODUCTION

ELASTIC scattering of electrons from atomic nuclei, in the energy region between 100 and 200 Mev, has proved to be a sensitive method of exploring nuclear charge distributions.[1] For medium and heavy nuclei, two shape parameters can be determined accurately. These parameters characterize the radial extension and surface thickness of the charge distribution.[2] For a charge distribution which is uniform in a central region, and which drops off to zero smoothly at the edge, the following two parameters have been chosen: c, the distance from the center of the nucleus to the point at which the charge density has dropped to one half of its central value, and t, the distance in which the charge density at the edge of the nucleus drops from 90 to 10% of the central value. These parameters are only slightly dependent on the particular analytical form of the two-parameter charge distribution.[2]

An attempt has now been made to detect possible small differences in the charge distributions of neighboring nuclei, i.e., to determine small variations in the parameters c and t as the numbers of protons or neutrons in neighboring nuclei change by small amounts. This has been done by measuring ratios of cross sections. In any experiment of this kind, ratios can always be measured more accurately than individual cross sections. It is the purpose of this paper to describe the central idea of this method, some relevant calculations, and experiments showing that the method is feasible. In addition, certain conclusions may be drawn about nickel and its neighbors.

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[1] R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956). This article is a summary where references to the literature will be found.

[2] See especially Hahn, Ravenhall, and Hofstadter, Phys. Rev. **101**, 1131 (1956).