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FISSION CROSS SECTION MEASUREMENTS

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Work done by:

Roland W. Davis
John S. Wahl

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ABSTRACT

A measurement has been made of the absolute fission cross section of U^{235} for a neutron energy of 14 Mev, with the result

$$\sigma_F(U^{235}) = 2.21 \pm 0.13 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

Measurements were made of the fission cross sections of U^{236} and of Pu^{239} relative to U^{235} for 2.5- and 14-Mev neutrons. The values obtained are:

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = 0.697 \pm 0.028 \ (2.5 \pm 0.2 \text{ Mev})$$

$$= 0.783 \pm 0.022 \ (14.1 \pm 0.3 \text{ Mev})$$

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.58 \pm 0.06 \ (2.5 \pm 0.2 \text{ Mev})$$

$$= 1.26 \pm 0.04 \ (14.1 \pm 0.3 \text{ Mev})$$

If the fission cross section of U^{235} is taken as 1.25 ± 0.06 and 2.18 ± 0.08 barns at neutron energies of 2.5 and 14 Mev respectively, one obtains

$$\sigma_F(U^{236}) = 0.87 \pm 0.06 \text{ barns } (2.5 \pm 0.2 \text{ Mev})$$

$$= 1.70 \pm 0.09 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

$$\sigma_F(Pu^{239}) = 1.98 \pm 0.13 \text{ barns } (2.5 \pm 0.2 \text{ Mev})$$

$$= 2.75 \pm 0.14 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

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1. Introduction

The present measurements of fission cross sections are a part of the continuing program of the Los Alamos Cockcroft-Walton group (P-4). Previous measurements have been made by Nyer.[1-4] The primary motivation for instituting measurements at the present time was to remeasure the fission cross section of Pu^{239} for 14-Mev neutrons, since the previous measurement had given a value which seemed anomalously low. However, in view of the higher neutron intensities presently available at the Cockcroft-Walton accelerator, the improvements in the isotopic composition of available samples of fissionable material, and better foil making techniques, it seems desirable to institute a general program of fission cross-section measurements.

2. Experimental Procedure

2.1 Apparatus

The present measurements were made in a double "back-to-back" ionization chamber similar in design to that previously employed by Nyer.[3] The chamber is shown in Fig. 1. The chamber wall was a spherical steel shell 3-1/2 in. in diameter, with a 0.035-in. wall thickness. Centered in the sphere was the high voltage electrode consisting of a 0.015-in.-thick brass disc 2-7/16 in. in diameter. On each side of the high voltage electrode was placed a circular collecting electrode of aluminum 2-1/16 in. in diameter and 0.005 in. thick. These were separated from the central electrode by 0.140 in. Foils of fissionable material were prepared on 0.002-in.-thick platinum discs 1-1/2 in. in diameter, with the active deposit covering a circle usually 1 in. in diameter. The foils were fastened to the high voltage electrode by small tabs of Scotch tape. In order to reduce the mass of material near the foils to as small an amount as possible, a hole 1-1/4 in. in diameter was cut in the center of the high voltage electrode. Thus the two foils were separated from each other by only ~0.015 in. of gas. The collector electrodes and high voltage electrode were supported inside the steel sphere by two spiders made of 0.006-in.-thick brass channel, from which they were electrically insulated by small quartz or teflon rods.

The chamber was filled with a mixture of 97 per cent Linde rare gas grade argon and 3 per cent commercial CO_2, to a pressure of 300 mm absolute for measurement of fission fragments. It has been pointed out by Nyer[3] that since fission fragments have their greatest rate of energy loss at the beginning of their range, whereas that of alpha particles is smallest initially, it is advantageous in reducing alpha-particle background to use small spacings and low pressures. This also assists in reducing background from reactions in the gas. Under the conditions of the present experiment, the energies lost in the gas by particles whose path is

- 5 -

TO PREAMPLIFIER

COLLECTOR ELECTRODES

HIGH VOLTAGE
ELECTRODE
AND FOILS

FILLING
LEAD

B

B

TO HIGH
VOLTAGE
SUPPLY

TO PREAMPLIFIER

VIEW A-A

0   1   2

SCALE, INCHES

A

A

FISSIONABLE
MATERIAL IN
THIS AREA

VIEW B-B
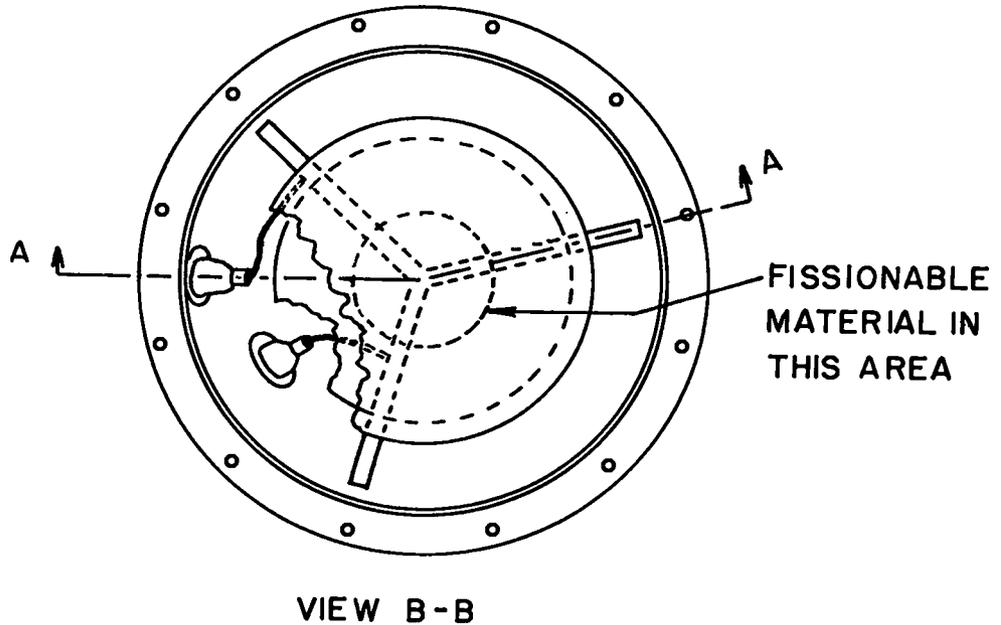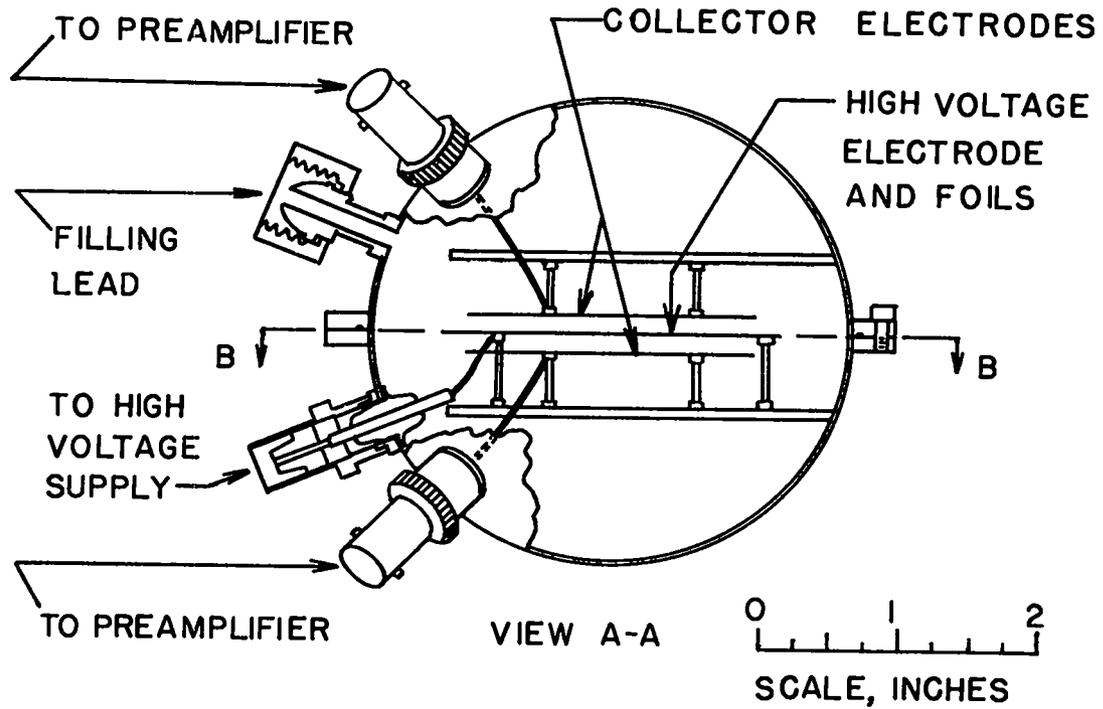
Fig. 1 Double ionization chamber.

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normal to the electrodes is 6 Mev for fission fragments, and 160 kev for 5-Mev alpha particles. A relatively small proportion of the alpha particles can lose all their energy in the chamber.

For all measurements with fast neutrons the chamber was covered with a cadmium shell 0.015 in. thick.

Pulses from electrons reaching the collector electrodes were amplified by Los Alamos Model 101 preamplifiers and amplifiers. Delay line clipping was employed to give roughly rectangular pulses usually 2 μsec long. The amplified pulses were counted by Model 750 scalers and in most cases simultaneous pulse-height distributions were measured with 10- and 18-channel pulse-height analyzers of Johnstone's design.[5] In a few measurements with Pu^{239}, where the alpha-particle background was troublesome, Model 503 amplifiers and preamplifiers with 0.2-μsec delay-line clippers were employed. These amplifiers were generally unsatisfactory and it was finally found possible to make good measurements with a 101 amplifier using a single section of a 19-section 4-μsec delay-line clipper, which gave reasonably rectangular pulses about 0.8 μsec long.

Under these conditions voltage saturation of both fission fragment and alpha-particle pulses was obtained with about 200 volts on the high voltage electrode. The cross-section measurements were made at 500 volts.

The pulse-height distributions from fission fragments are calculated to be of the form

$$N(E)dE = kE^{-2}dE \quad (E > E_o)$$

$$= O \quad (E < E_o)$$

where E_o is the minimum pulse height, due to a fragment whose path is normal to the foil. Experimental distributions are approximately of this form with some smearing due to background, foil thickness, and amplifier noise at the low energy cutoff.

2.2 Neutron Sources

The neutron source used for measurements at 2.5 and 14.1 Mev was the 250-kv Cockcroft-Walton accelerator of Group P-4. Neutrons were produced by $D(d,n)He^3$ and $T(d,n)\alpha$ reactions when 250-kev monatomic deuterium ions impinged on a zirconium target in which deuterium or tritium had been occluded. Neutron intensities were monitored by counting either the alpha particles from the T + d reaction or, in the case of the D(d, n) reaction, the protons from the concomitant reaction, D(d,p)T, in a known geometry. All measurements were made with the center of the foil on a line passing through the target and at 90 deg to the incident deuterons,

the plane of the foil being normal to this line. Under these conditions the energies of the primary neutrons are about 14.1 ± 0.3 Mev and 2.5 ± 0.2 Mev for the T + d and D + d reactions, respectively. The indicated energy spreads are the maximum values during the course of the measurements, and are due primarily to the finite solid angle subtended by the foils.

Some measurements were also carried out with thermal neutrons. These were performed by placing the chamber and a Po-α-Be neutron source in a graphite pile which was roughly in the form of a cube 5 ft on each edge. The distance between the chamber and the source varied between 12 and 41 in. in various measurements. Comparisons of two U^{235} foils, or the determination of U^{235} in a foil having no other thermal-fissioning nuclide, are insensitive to the precise shape of the neutron spectrum. However, a comparison of U^{235} and Pu^{239} foils showed that the neutron flux was not strictly thermal even at the largest source-to-chamber distance. The interpretation of these results is not quite unambiguous, as will be seen later.

2.3 Alpha-particle Measurements

Robert Penneman, Larned Asprey and Melvin Bowman of DP Site (LASL) have been of great help in making measurements of alpha-particle disintegration rates.

In addition, the author set up a low-geometry scintillation counter for the measurement of total disintegration rates. The apparatus is shown in Fig. 2.

It has been shown that alpha particles back-scattered from the backing material of a foil are nearly all emitted at angles greater than about 65 deg to the normal.[6] Thus in a low-geometry measurement one should not see any of these back-scattered alpha particles. Small angle scattering from the walls of the apparatus may cause some alpha particles which would otherwise not be counted to enter the defining aperture and be counted. This was investigated experimentally by taking counts with and without the antiscattering baffles, and the effect was found to be negligible. The calculated geometry includes the effect of finite size of the foil, which is assumed to be uniform. A non-uniform foil would thus not be correctly assayed; however, since the whole correction for foil size is only 0.5 per cent, the unknown correction for non-uniformity cannot exceed this value.

Two alpha-particle pulse-height distributions obtained from Pu^{239} foils placed in the counter of Fig. 2 are shown in Fig. 3. It will be seen that an appreciable number of counts, about 3 and 0.8 per cent in the examples shown, are below the main peak. Since the alpha particles counted are emitted essentially normal to the foil, it seems that these low-energy particles originate from deep in the foil and have actually lost considerable energy before reaching the scintillation crystal. It is believed that a measurement of the ratio of pulses at low energy to

ACTIVE AREA
OF FOIL I"

ANTISCATTERING
BAFFLES

DEFINING APERTURE
$\frac{3}{8}$" DIAMETER

PUMPING
LEAD

STILBENE CRYSTAL
I" DIAMETER x
$\frac{7}{32}$" THICK

PHOTOMULTIPLIER
TUBE
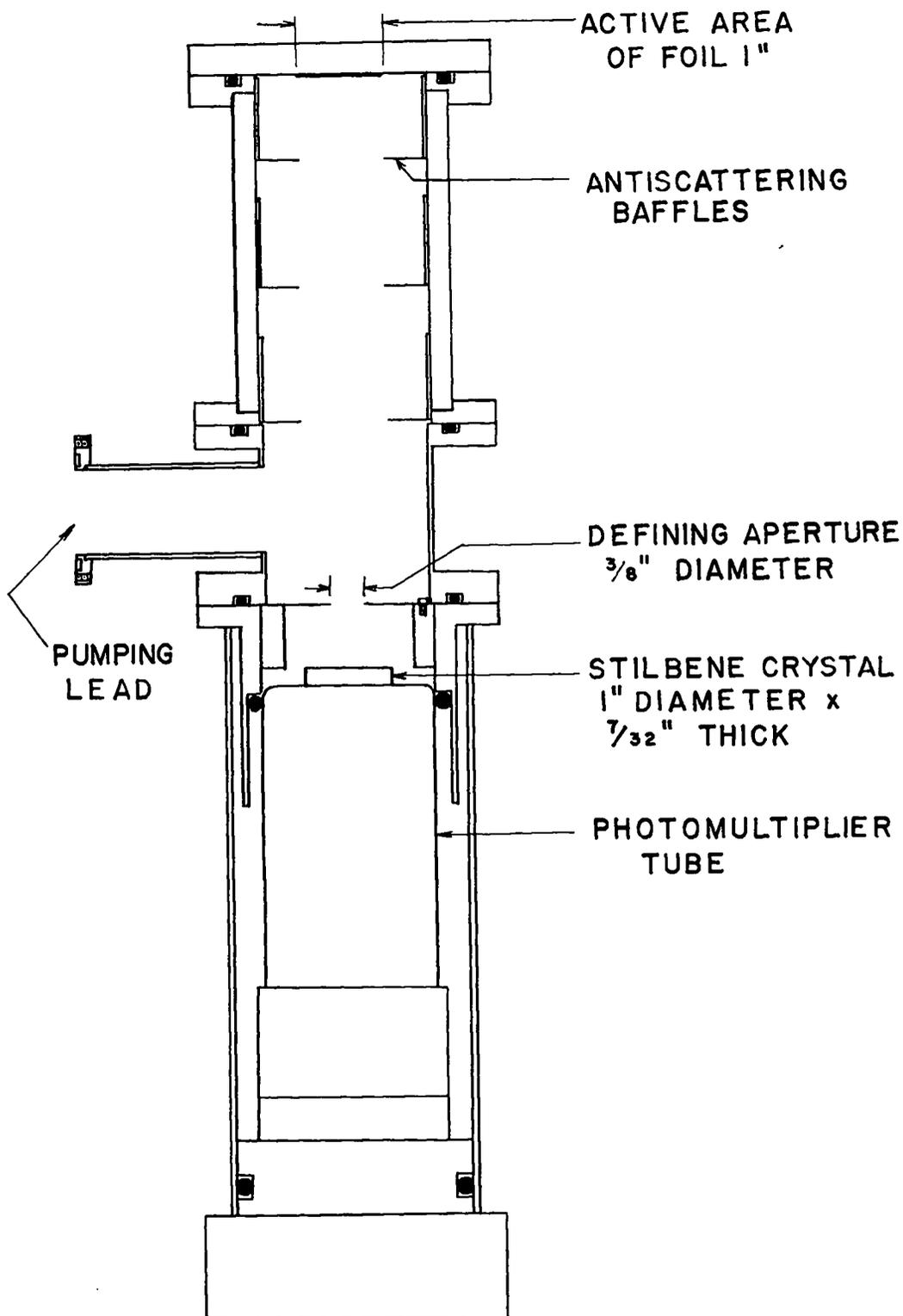
Fig. 2 Low-geometry alpha-particle counter.
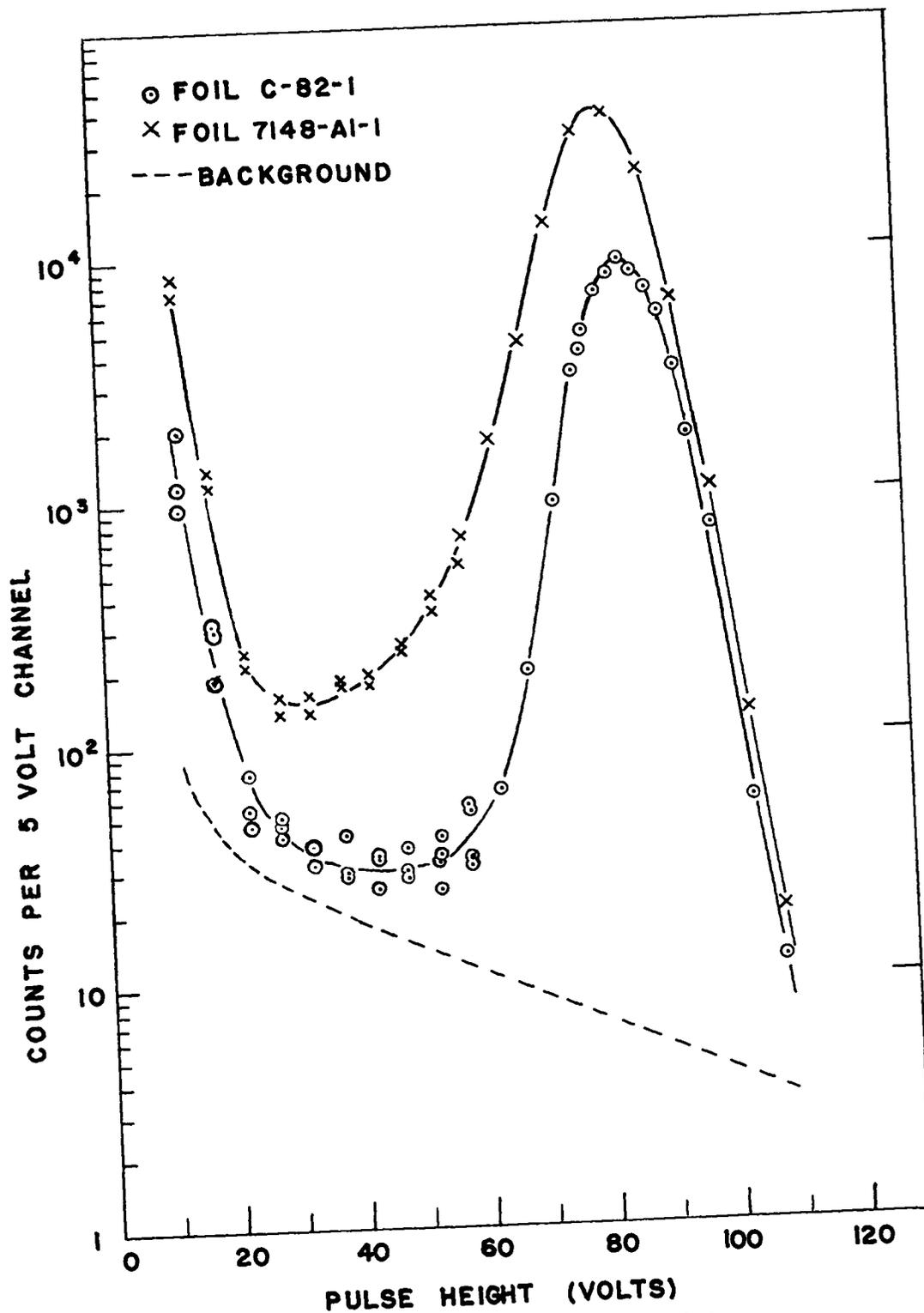
Fig. 3 Alpha-particle pulse-height distributions.

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plutonium foil, not shown on Fig. 3, a value of 7 per cent was obtained for this ratio.

2.4 Foils

The foils used in the measurements are individually discussed below:

2.4.1 U^{235} Foil No. RM-BF-401

This foil was prepared by painting. It was used by Nyer in the measurements of $\sigma_F(U^{235})/\sigma_F(U^{238})$ for 14-Mev neutrons.[3] The weight of the active material was 1.286 ± 0.005 mg as U_3O_8. The isotopic analysis of the U^{235} used for this foil as given by Group CMR-4 is U^{234}, 0.55 per cent; U^{235}, 95.7 per cent; U^{238}, 3.75 per cent. The alpha-particle rate as determined in a 2π counter was 47,144 counts/min. If 52 per cent geometry is assumed for this measurement (to take account of back-scattering) one obtains 1511 d/sec, in reasonable agreement with the 1450-d/sec rate computed from the weight and isotopic composition of the foil.

2.4.2 Diven's 365-μgm U^{235} Foil

Ben Diven kindly lent the author one of his U^{235} foils. This foil is one of a set of four used by Diven in a comparison of the U^{235} fission cross section with the (n,p) cross section in the range 0.4 to 1.6 Mev neutron energy.[7] The foils were electroplated by Buddy Warren of Group J-11 from their 99.85 per cent U^{235}. It is not known what the other constituents are; however, the following Oak Ridge analysis[8] of a batch of 99.85 per cent U^{235} may be useful as a guide: U^{234}, 0.01 per cent; U^{235}, 99.85 per cent; U^{236}, 0.07 per cent; U^{238}, 0.07 per cent. The weight of each foil was determined by Buddy Warren in two ways, and Diven made comparisons between the foils by alpha-particle and fission counting. The foils were also compared by Diven with four painted foils prepared by John Povelites. All these comparisons indicated an over-all consistency of better than 1 per cent.

The weight of this foil was 364.63 μgm from measurements during the electroplating and 363.82 μgm from a fission comparison with a standard U^{235} foil.

The specific alpha activity of this foil is 160 d/sec/mg, as determined from Diven's alpha-particle count and Warren's weight determination. The measurement was made in a 2π chamber and it is assumed that the effective geometry is 52 per cent. The specific alpha activity computed from the assumed isotopic analysis given above is 103 d/sec/mg. The difference between the measured and computed specific activities is most likely due to the uncertainty in the isotopic analysis of the 99.85 per cent U^{235}. For example, an increase in the U^{234} abundance from 0.01 to ~0.035 per cent would remove the discrepancy.

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2.4.3 U^{235} Foil No. RM-401-38

This foil was painted by John Povelites. The weight of active material is 1097 μgm as U_3O_8, stated by Povelites to be 95.7 per cent U^{235}. If one assumes that the other constituents are 0.6 per cent U^{234} and 3.7 per cent U^{238}, the calculated alpha-particle activity of 1340 d/sec is in agreement with the value 1326 d/sec observed in a 2π chamber (geometry assumed to be 52 per cent).

2.4.4 U^{236} Foils No. 5894-3 and 5894-4

These foils were painted by John Povelites from material stated by him to be 95.3 per cent U^{236}. No other information on the isotopic composition is available, so use has been made of an Oak Ridge analysis[8] of a batch of 95.3 per cent U^{236} to obtain the following weights:

	Oak Ridge Analysis, % by weight	Weight for Foil 5894-3, μgm	Weight for Foil 5894-4, μgm
U^{234}	0.15	1.4	1.5
U^{235}	4.18	39.4	42.5
U^{236}	95.31	897.4	970.1
U^{238}	0.36	3.4	3.7

The weights listed for the two foils are, based on their measured weights as U_3O_8, 1112 and 1202 μgm respectively. A comparison of foils 5894-4 and RM-401-38 was made in the graphite pile to determine the U^{235} content in the U^{236} foil. The value obtained was 43 μgm $\pm$ 3 per cent, in good agreement with the weight given in the table.

2.4.5 Pu^{239} Foil No. 7148-A1-1

This foil was used by Nyer in his measurement of $\sigma_F(Pu^{239})/\sigma_F(U^{238})$ for 14-Mev neutrons.[3] The weight of the foil was 1.137 mg as PuO_2. The isotopic analysis is 99.03 per cent Pu^{239}, 0.97 per cent Pu^{240}. (The value 98.03 per cent for Pu^{239} given on p. 14 of LAMS-938 is a misprint.) Hence the isotope weights present on the foil are calculated to be Pu^{239}, 993 μgm; Pu^{240}, 10 μgm.

This foil was reweighed by John Povelites in October 1952, and was found to be 70 μgm lighter than it had been originally. A measurement of the total alpha-particle disintegration rate, made by Larned Asprey, gave 1.07 x 10^8 d/min. Another measurement made by the author with the low-geometry scintillation counter gave 1.04 x 10^8 d/min. The mean disintegration rate, combined with the isotopic composition given above, leads to the following weights: Pu^{239}, 735 μgm, Pu^{240}, 7.3 μgm.

It is not known whether the 70-μgm weight loss was of backing material or of PuO_2. Even assuming the latter, it appears that the foil contains ~200 μgm of inert matter.

2.4.6 Pu^{239} Foils No. C-82-1 and C-82-2

These foils were electroplated by John Povelites from Clinton plutonium furnished by R. D. Baker of Group CMR-8. The yield in the electroplating process was low, so the remaining material was evaporated on foil C-82-2. The isotopic composition of Clinton plutonium was furnished by John Hand of Group W-1 as 99.78 ± 0.01 per cent Pu^{239}; 0.221 ± 0.009 per cent Pu^{240}. No information is available on the 241 or 242 concentrations, but these should be negligible. Measurements of the alpha-particle activities of the two foils were made by Melvin Bowman of Group CMR-3. Another set of measurements was made by the author using the scintillation counter previously described. Foil C-82-2 was counted with a higher geometry than that shown in Fig. 3. The geometry correction for finite size of this foil was 4 per cent and thus foil non-uniformity introduces a considerable uncertainty. The various measurements are summarized below.

	Foil C-82-1, μgm	Foil C-82-2, μgm
Povelites' balance weight as PuO_2 (reduced to weight of Pu)	160.5	822.8
Bowman's alpha-activity measurement	159.7, Pu^{239} 0.4, Pu^{240}	673.0, Pu^{239} 1.5, Pu^{240}
Author's alpha-activity measurement	159.3, Pu^{239} 0.4, Pu^{240}	700.0, Pu^{239} 1.5, Pu^{240}

The weights used in the cross-section computation were 160 μgm for foil C-82-1 and 680 μgm for foil C-82-2.

3. Absolute Measurement of the Fission Cross Section of U^{235} for 14-Mev Neutrons

For this measurement two U^{235} foils were placed in the chamber, foil RM-401-38 facing into the chamber which will be designated by A, and Diven's foil facing the chamber designated by B. The experimental arrangement is shown in Fig. 4. Measurements were made with source-to-foil distances of about 7, 14, and 20 cm. In order to reduce the uncertainty in the position of the neutron source, measurements were made in two directions from the source.

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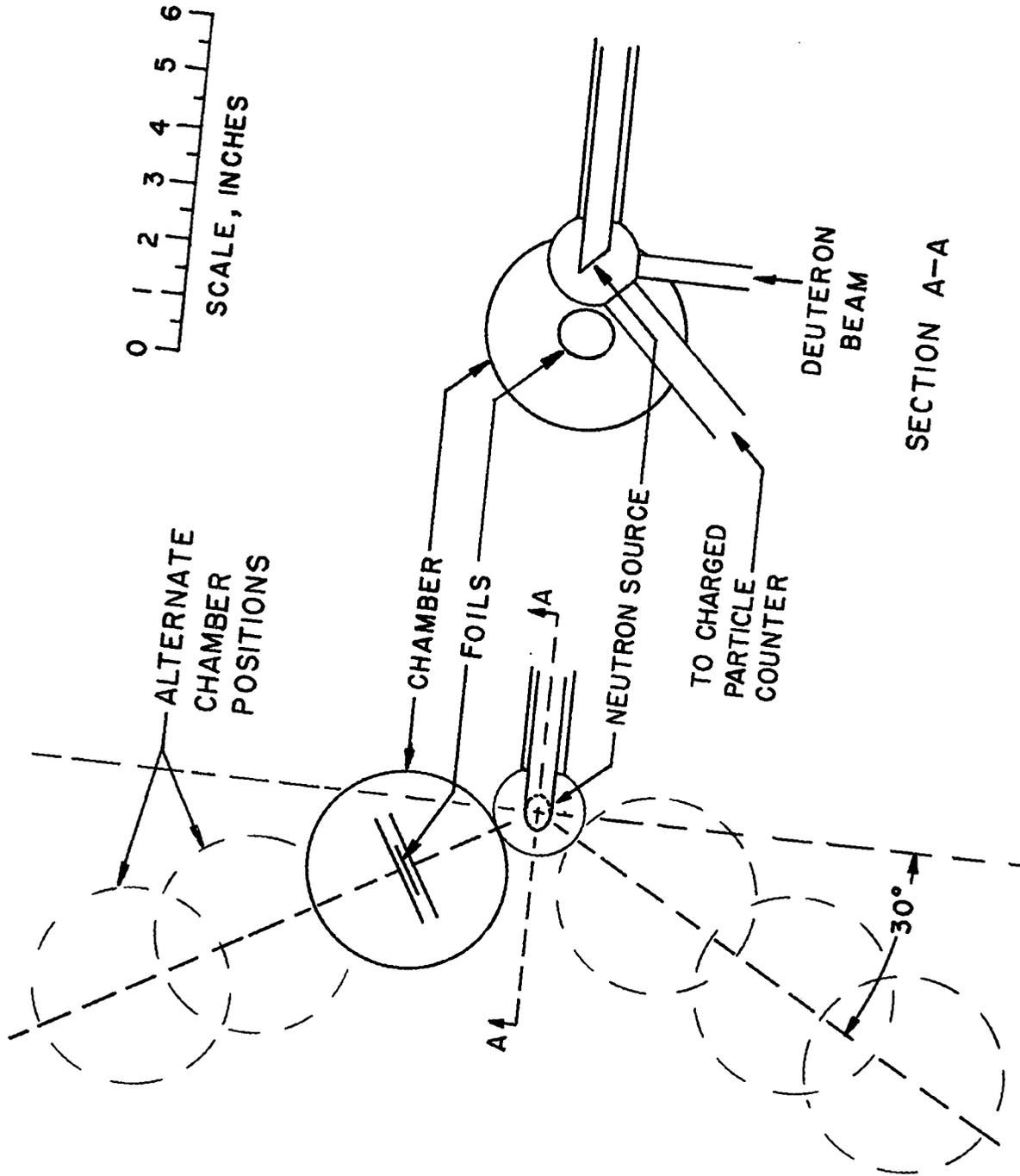
Fig. 4 Experimental arrangement for U^{235} measurements.

The two directions could not be taken 180 deg apart since then part of the foils would have been shadowed by the target backing. Six measurements were made with foil RM-401-38 nearest the neutron source, and six more with Diven's foil nearest to the source.

The pulse-height distributions obtained are shown in Fig. 5. The scaler biases were set at values corresponding to the bottom of the valley which separates fission counts from the alpha-particle and gas-reaction background. The data obtained are given in Table I.

TABLE I

$$\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 14.1 \pm 0.3 \text{ MEV}$$

Counter Position	Distance, cm	Fission Counts A	B	Counts per 10^{10} neutrons/cm^2 through foil A	B
AN*	6.43**	46314	18774	48239	19862
AN	14.78	18137	7458	49059	20310
AN	20.18	29594	12449	49688	21011
BN	20.80	28404	11994	50949	21410
BN	13.45	23272	9672	50405	20787
BN	6.45	46667	19490	48886	20103
AS	6.43	46818	18834	48804	19941
AS	12.83	25582	10588	49396	20607
AS	19.93	30263	12711	49555	20916
BS	21.30	26924	11507	50676	21557
BS	14.40	19356	8208	50236	21160
BS	8.55	26285	10880	48631	19894

*Measurement with A nearest the source, and chamber on north side of target.

**Distance for the nearest foil. The distance for the other foil is 0.5 mm greater.

N_A = 2.332 x 10^{18} atoms of U^{235} on foil A.

N_B = 0.9340 x 10^{18} atoms of U^{235} on foil B.

Correction factors for:	Foil A	Foil B
Foil thickness	K_A = 1.015	K_B = 1.004
Scattered neutrons	C_A = 1.002	C_B = 1.002
Source-to-foil distance (mean correction)	Z_A = 1.021	Z_B = 1.021
Corrected $\sigma_F(U^{235})$	2.181 ± 0.004 barns (standard deviation derived from number of counts)	2.242 ± 0.007 barns (standard deviation derived from number of counts)
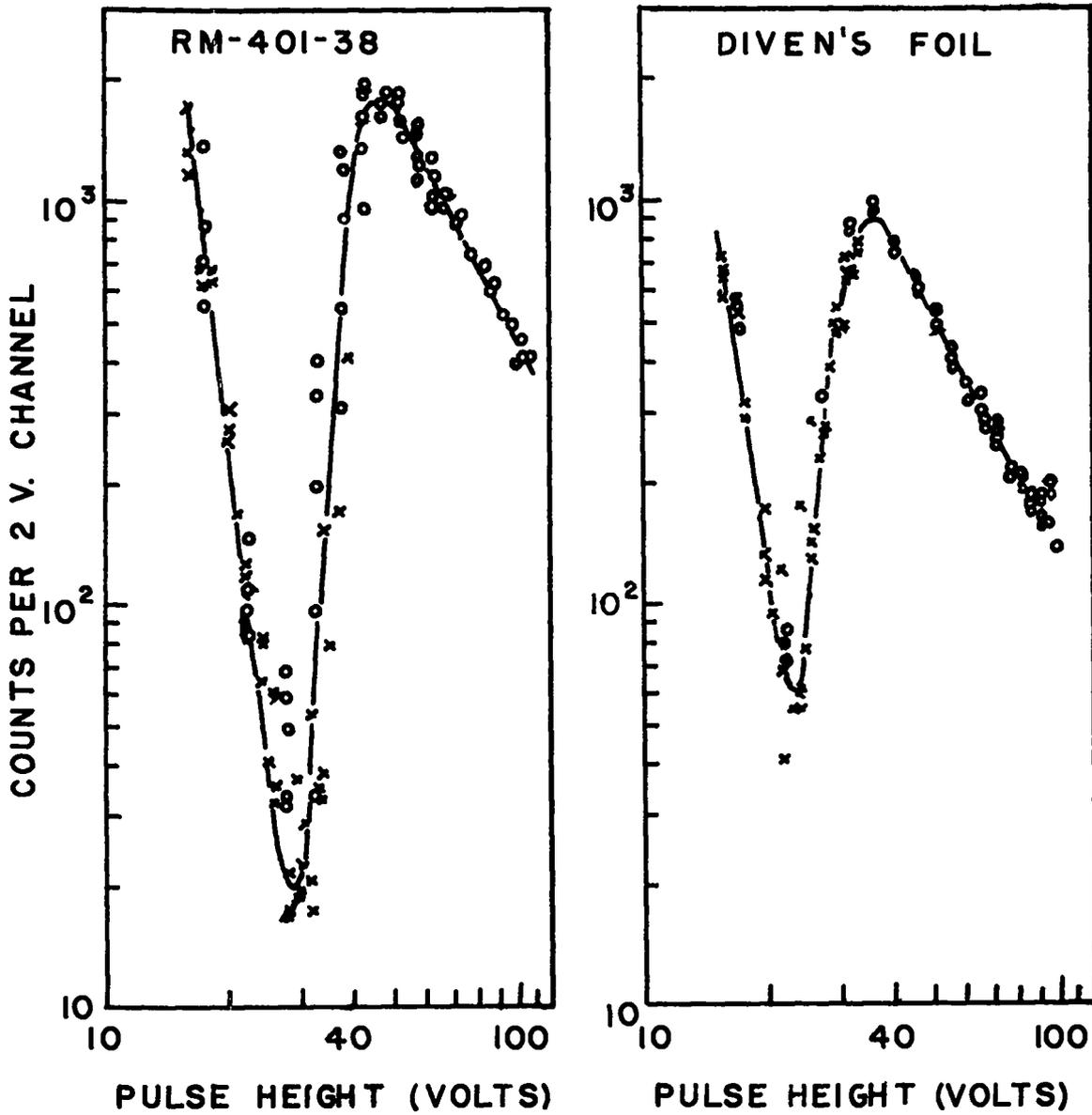
Fig. 5 U^{235} pulse-height distributions in fission chamber.

Several corrections have been applied to the data in Table I in order to obtain final cross-section values.

1. A correction for fission fragments lost in the foils. This amounts to 1.5 per cent for foil A and 0.35 per cent for foil B, if it is assumed that the foils are uniform. The assumption of uniformity cannot be justified, but is the best that can be made without a detailed knowledge of the microscopic foil structure. The correction factors used are designated by K in the table.

2. A correction for fission due to low-energy neutrons. The effect has been measured by John Seagrave of Group P-4, using spiral U^{235} and U^{238} chambers, with and without a 0.015-in.-thick cadmium cover. The only background of any consequence is that due to epicadmium neutrons. The relative contribution increases as r^2 and is 2.2 per cent at 20 cm. Appropriate correction has been made at each distance.

3. A correction for "inelastic" neutrons scattered into the foil by the chamber and by other nearby materials. The scattered neutrons are mostly in the energy range below 4 Mev.[9] Here the fission cross section of U^{235} is nearly independent of energy and a correction can be calculated which is essentially independent of the shape of the spectrum of scattered neutrons. The correction is 0.2 per cent, and is designated by C in Table I.

4. A systematic error in the measurement of the distance between the neutron source and the foils due to a shift of the beam spot away from the center of the target sphere. Since measurements were made in two directions from the neutron source, it was possible to check the centering of the beam spot in one direction. However, de-centering in a line at right angles to this could introduce an error. The existence of this effect is deduced from the variation of apparent cross section with distance between the neutron source and the chamber. A least-squares calculation was made to obtain the correction, the mean value of which is designated by Z in Table I.

When these corrections are applied to the data, one obtains cross-section values as follows:

$$\sigma_F(U^{235}) = 2.18 \pm 0.004 \text{ barns for foil A}$$

$$= 2.24 \pm 0.007 \text{ barns for foil B}$$

The errors given are the statistical standard deviations. The difference between the values obtained from the two foils must be attributed to an error in the weight of one or both foils.

The value of the fission cross section of U^{235} for 14-Mev neutrons is taken as 2.21 ± 0.13 barns, which is the mean of the values obtained for the two foils.

The error in this value is made up of the following contributions:

(a) 2 per cent uncertainty in foil weight;

(b) 2 per cent uncertainty in r⁻ where r = distance between source and foil;

(c) 5 per cent uncertainty in neutron flux at the foil [in addition to the flux uncertainty due to (b) above] . ·

These values are largely arbitrary. The over-all uncertainty is thus ±6 per cent.

The value 2.21 ± 0.13 barns is in agreement with a previous determination by Nyer.[3] His measurement of 2.16 ± 0.09 barns was based on an absolute measurement of the cross section of U^{238} and a measurement of $\sigma_F(U^{235})/\sigma_F(U^{238})$. The best value, obtained by averaging the present value with that of Nyer, is 2.18 ± 0.08 barns.

4. $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for 14-Mev Neutrons

In these measurements three different Pu^{239} foils and two U^{235} foils were used. The best results are obtained from a comparison of Pu^{239} foil C-82-1 and U^{235} foil RM-401-38, and these will be considered first.

For Pu^{239} foil C-82-1, good agreement was obtained between the measured weight and the weight obtained from two independent alpha-particle counts. The quality of this foil was also good, as indicated by the scintillation-counter pulse-height analysis which gave 0.8 per cent low-energy alpha particles. U^{235} foil RM-401-38 was one of the two used in the absolute measurement given above. On the basis of the agreement between results obtained from it and from Diven's foil, it is believed that the weight of this foil is known to 2 per cent.

Two sets of measurements were made with these foils. The results are given in Table II. An equal number of measurements were made with each foil nearest the source. All were made at the closest distance between source and foils which could be used, namely 6.5 cm. Figure 6 shows a typical pulse-height distribution obtained.

The correction factors for foil thickness are based on the assumption of uniform foil thickness. The correction for low-energy neutrons includes the effect (∼ 0.2 per cent) for inelastically scattered neutrons, and a correction of 0.3 per cent for the effect of epicadmium neutrons. It will be recalled that the latter was measured with a U^{235} spiral chamber, and presumably is not correct for Pu^{239}, which has a large resonance near 1 ev. However, since the correction is small, the uncertainty is not believed to be important in determining the over-all error. The final result is

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.26 \pm 0.04$$

where the quoted error is due primarily to the assumed ±2 per cent uncertainty in the weight of each foil.

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TABLE II

$$\sigma_F(Pu^{239})/\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 14.1 \pm 0.3 \text{ MEV}$$

A, foil C-82-1

B, foil RM-401-38

First Run

Chamber Position	Distance, cm	A Counts	B Counts	A/B
A nearest source	6.5	20245	92086	0.2198
		20228	92167	0.2195
		20141	92502	0.2177
B nearest source	6.5	20064	90760	0.2211
		20694	94187	0.2197
		20444	92882	0.2201

Mean A/B = 0.2196 ± 0.0007
(statistical standard deviation)

$$N_A = 0.402 \times 10^{18} \text{ atoms of } Pu^{239}$$

$$N_B = 2.332 \times 10^{18} \text{ atoms of } U^{235}$$

Correction factors for:	Foil A	Foil B
Foil thickness	$K_A = 1.008$	$K_B = 1.015$
Low energy neutrons	$C_A = 0.995$	$C_B = 0.999$

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = \frac{A}{B}\frac{N_B}{N_A}\frac{K_A}{K_B}\frac{C_A}{C_B}$$

$$= 1.260 \pm 0.004 \text{ (statistical standard deviation)}$$

Second Run

Chamber Position	Distance, cm	A Counts	B Counts	A/B
B nearest source	6.5	20596	94630	0.2176
		25266	116,748	0.2164
A nearest source	6.5	21236	95642	0.2220
		25694	116,780	0.2200

Mean A/B = 0.2190 ± 0.0009
(statistical standard deviation)

Correction factors same as above.

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.256 \pm 0.005 \text{ (statistical standard deviation)}$$
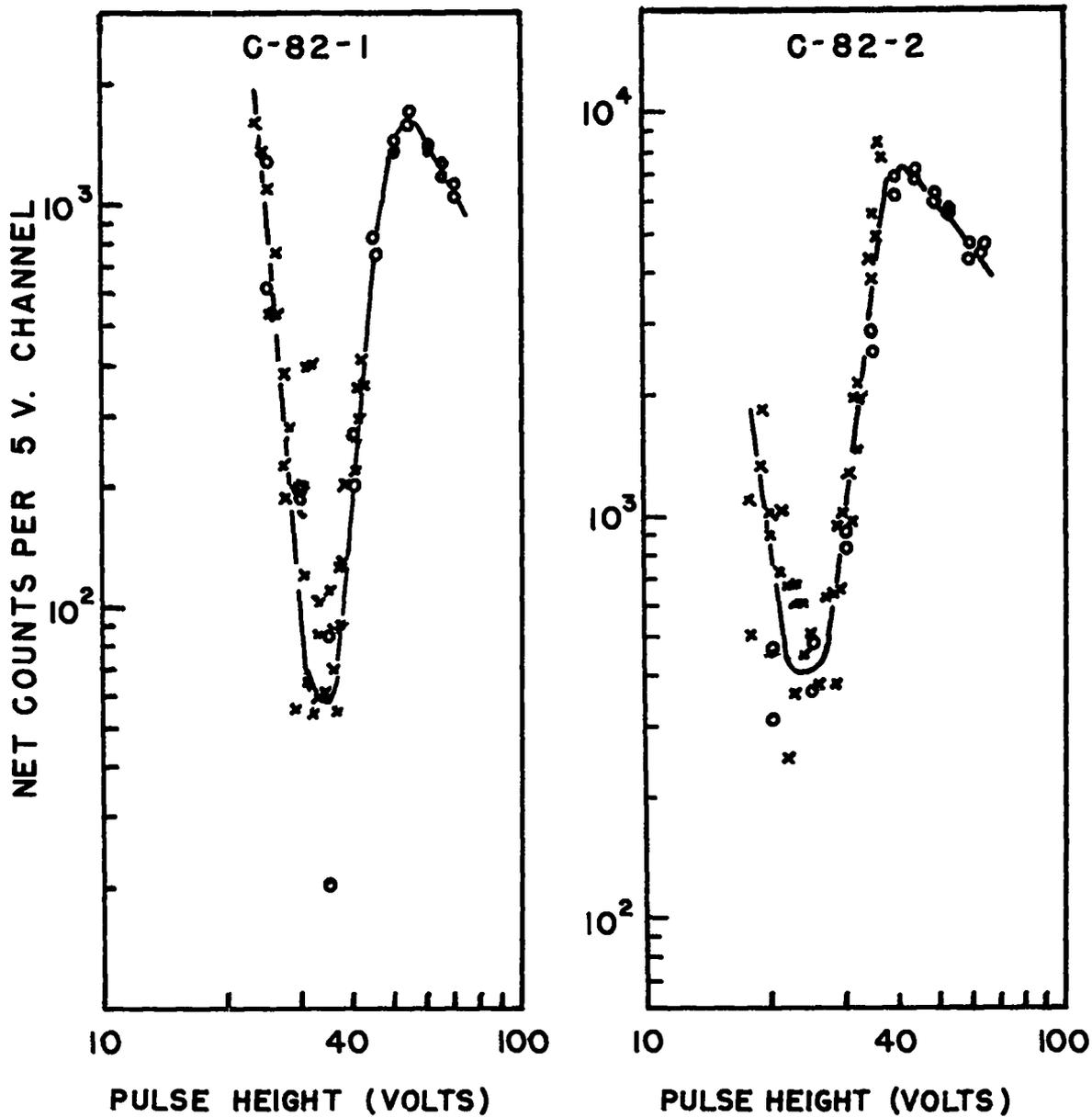
Fig. 6 Pu^{239} pulse-height distributions in fission chamber.

With the value

$$\sigma_F(U^{235}) = 2.18 \pm 0.08 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

one obtains

$$\sigma_F(Pu^{239}) = 2.75 \pm 0.14 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

This value is in considerable disagreement with the previous measurement of Nyer,[3] who obtained 1.75 ± 0.09 barns. In view of the difference in these values, it was felt desirable to obtain as much confirmation as possible for the new value. Some of the measurements are (a) $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for 2.5-Mev neutrons, for which a previous value is available. This is discussed in Sec. 5. (b) $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for thermal neutrons, discussed in Sec. 6. (c) $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for 14-Mev neutrons, but measured with different foils. This will now be considered.

Measurements were made with Pu^{239} foil C-82-2 and U^{235} foil RM-401-38. Foil C-82-2 showed a considerable discrepancy between balance weight and weight from alpha-particle counting. The latter weight determination was the one used for cross-section calculation. In addition a pulse height analysis of the alpha particles emitted normal to the foil in a low-geometry counter showed that about 7 per cent of the alpha particles had lost 25 per cent or more of their initial energy before emerging from the foil. Thus the calculated foil-thickness correction of about 1 per cent is undoubtedly much too small.

The details of the measurement were the same as used for the measurement with foil C-82-1. The results are not given in detail because of their lower accuracy.

One obtains

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.20$$

and

$$\sigma_F(Pu^{239}) = 2.62 \text{ barns}$$

when no corrections are made for foil thickness. This is already well above the old value for $\sigma_F(Pu^{239})$.

As a matter of interest it may be noted that if a 7 per cent foil thickness correction is made for the Pu^{239} foil, and the calculated 1.5 per cent correction is made for the U^{235} foil, one obtains

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.27$$

and

$$\sigma_F(Pu^{239}) = 2.77 \text{ barns}$$

in good agreement with the values obtained previously. The 7 per cent foil-thickness correction cannot, of course, be exactly justified.

A measurement was also made with Pu^{239} foil 7148-A1-1 and U^{235} foil RM-BF-401. These foils were those used by Nyer in his measurements[3] of $\sigma_F(Pu^{239})/\sigma_F(U^{238})$ and $\sigma_F(U^{235})/\sigma_F(U^{238})$. The Pu^{239} foil balance weight differed considerably from the alpha-counting weight. The latter was used in the cross-section determination.

An alpha-particle pulse-height analysis in a low-geometry chamber showed that 3 per cent of the plutonium alpha particles had lost more than 25 per cent of their energy before leaving the foil.

The results obtained are

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.21$$

and

$$\sigma_F(Pu^{239}) = 2.64 \text{ barns}$$

These do not include any corrections for foil thickness. If a 3 per cent correction for Pu^{239} foil thickness and the calculated 1.75 per cent correction for the U^{235} foil are made, one obtains

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.23$$

and

$$\sigma_F(Pu^{239}) = 2.69 \text{ barns}$$

again in good agreement with the results obtained from foil C-82-1.

It may be worth noting that the major portion of the discrepancy between Nyer's measurement and that obtained here is due to his use of the balance weight of foil 7148-A1-1, instead of the weight as obtained from the alpha-particle disintegration rate. It can be calculated that Nyer's ratio of fission counting rates for foils 7148-A1-1 and RM-BF-401 (had he measured this ratio instead of measuring each foil against a U^{238} foil) would have been 0.744, in fairly good agreement with the ratio 0.830 obtained in the present experiment.

5. $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for 2.5-Mev Neutrons

These measurements were made with Pu^{239} foil C-82-1 and U^{235} foil RM-401-38. The details are shown in Table III. No correction is made for inelastically scattered neutrons. The contribution of epicadmium neutrons is assumed to be the same for both foils.

The result is

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.58 \pm 0.06 \ (2.5 \pm 0.2 \ \text{Mev})$$

and with $\sigma_F(U^{235}) = 1.25 \pm 0.06$ barns,[10] this gives

$$\sigma_F(Pu^{239}) = 1.98 \pm 0.13 \ \text{barns} \ (2.5 \pm 0.2 \ \text{Mev})$$

The error in the ratio of cross sections is made up of an assumed 2 per cent error in the weight of each foil, together with a statistical error of 2.6 per cent.

The value for $\sigma_F(Pu^{239})$ agrees well with the value 1.94 barns given in the compilation of the AEC Neutron Cross Section Advisory Group.[11]

A comparison was also made of the thick Pu^{239} foil (No. C-82-2) with U^{235} foil RM-401-3? This gave the results

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = 1.51$$

when no correction is made for low-energy pulses lost below the bias energy, and

$$\frac{\sigma_F(Pu^{239})}{U_F(U^{235})} = 1.59$$

TABLE III

$$\sigma_F(Pu^{239})/\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 2.5 \pm 0.2 \text{ MEV}$$

A, foil C-82-1

B, foil RM-401-38

Chamber Position	Distance, cm	A Counts	B Counts	A/B
A nearest source	6.5	628	2177	0.288
		586	2225	0.263
B nearest source	6.5	598	2058	0.291
		585	2208	0.265
			Mean A/B =	0.277 ± 0.007

(statistical standard deviation)

$$N_A = 0.402 \times 10^{18} \text{ atoms of Pu}^{239}$$

$$N_B = 2.308 \times 10^{18} \text{ atoms of U}^{235}$$

Correction factors for:	Foil A	Foil B
Foil thickness	$K_A = 1.008$	$K_B = 1.015$
Low energy neutrons	$C_A = 0.9973$	$C_B = 0.9973$

$$\frac{\sigma_F(Pu^{239})}{\sigma_F(U^{235})} = \frac{A}{B} \frac{N_B}{N_A} \frac{K_A}{K_B} \frac{C_A}{C_B}$$

$$= 1.58 \pm 0.04 \text{ (statistical standard deviation)}$$

when the same corrections are made as were used for these foils at 14 Mev.

6. $\sigma_F(Pu^{239})/\sigma_F(U^{235})$ for Thermal Neutrons

These measurements were made by placing the chamber and a Po-α-Be neutron source in a graphite pile. The foils used were Pu^{239} foil C-82-2 and U^{235} foil RM-401-38. The Pu foil is the one which had given 7 per cent low-energy alpha pulses. Because of the low counting rate it was not possible to use foil C-82-1, which was a much better foil.

Measurements were made at various distances between the neutron source and the chamber. Since U^{235} and Pu^{239} have fission cross sections which vary with energy in different ways in the thermal and electron-volt regions, the neutron spectrum with which comparisons are made is of importance. It was hoped that at sufficiently large distances a pure thermal flux could be attained. However, it appears that this is not the case for the largest distance used.

The ratios of counting rates obtained as a function of distance are shown in Fig. 7.

One can work backward from known thermal data and the measurements at 14 Mev to find what the ratio of counting rates should be for a Maxwellian neutron distribution.

$$\frac{C_{239}}{C_{235}} \text{ (14 Mev)} = \frac{N_{239}}{N_{235}} \frac{\sigma_{239}}{\sigma_{235}} \text{ (14 Mev)}$$

where C, N, and σ denote the counting rate, number of atoms on the foil, and fission cross section, respectively.

$$\frac{C_{239}}{C_{235}} \text{ (Thermal)} = \frac{N_{239}}{N_{235}} \frac{\sigma_{239}}{\sigma_{235}} \text{ (Thermal)}$$

Then,

$$\frac{C_{239}}{C_{235}} \text{ (Thermal)} = \frac{C_{239}}{C_{235}} \text{ (14 Mev)} \frac{\sigma_{239}/\sigma_{235} \quad \text{(Thermal)}}{\sigma_{239}/\sigma_{235} \quad \text{(14 Mev)}}$$

The thermal cross sections obtained from BNL-170[11] give

$$\frac{\sigma_{239}}{\sigma_{235}} \text{ (Thermal)} = 1.446 \pm 3 \text{ per cent}$$

If one takes $\sigma_{239} = 2.75$ barns at 14 Mev, one obtains the thermal counting-rate ratio
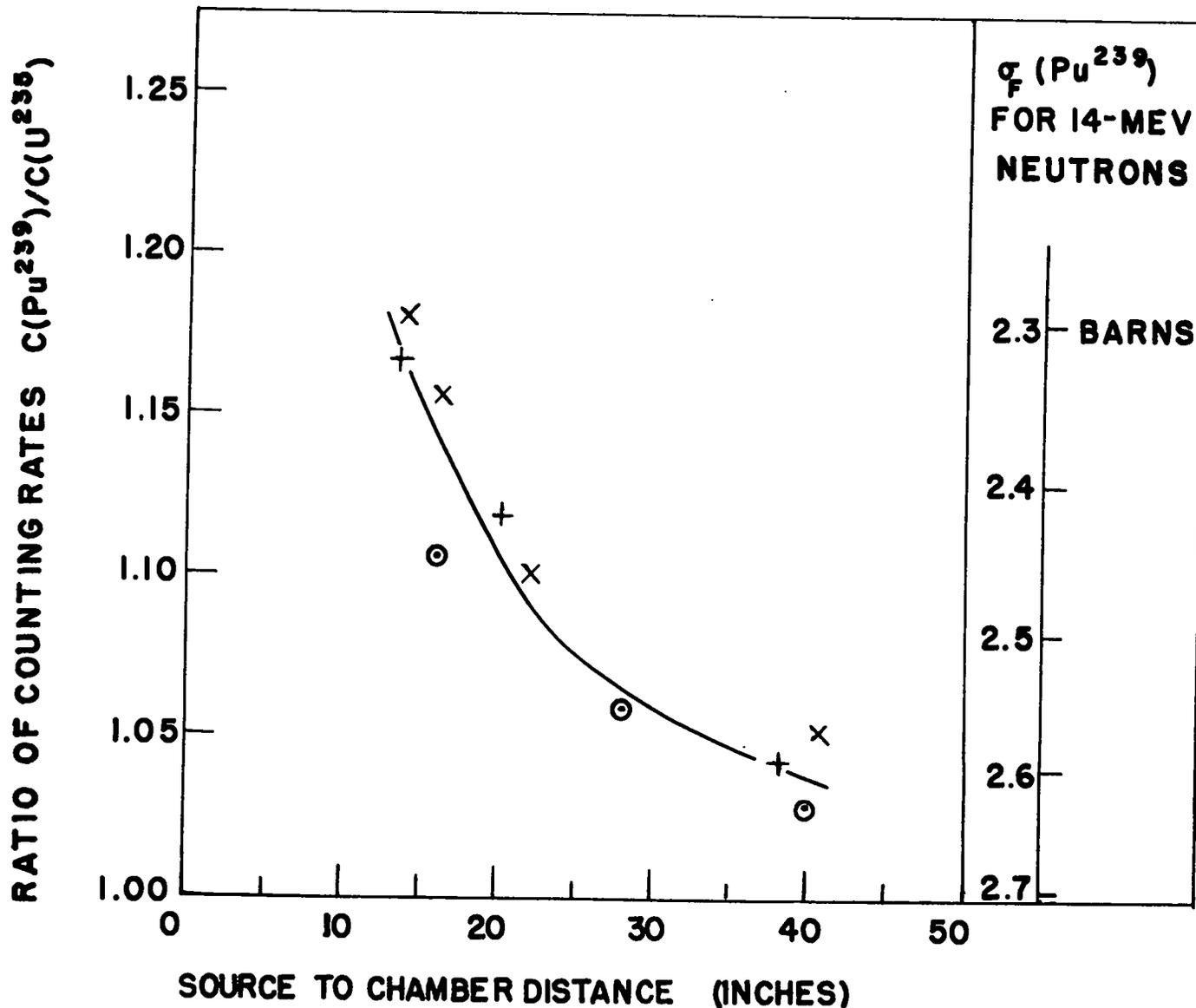
Fig. 7 Ratio of fission counts for Pu^{239} and U^{235} foils in pile as a function of source-to-chamber distance. The scale at the right gives the Pu^{239} fission cross sections for 14-Mev neutrons corresponding to various thermal counting rate ratios.
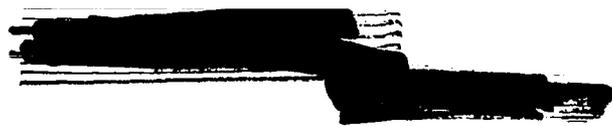
$$\frac{C_{239}}{C_{235}} \text{ (Thermal)} = 0.984$$

whereas for $\sigma_{239} = 1.75$ barns at 14 Mev, one obtains

$$\frac{C_{239}}{C_{235}} \text{ (Thermal)} = 1.544$$

This result is independent of foil-thickness corrections so long as the same foils are used for measurements at both energies. It is also independent of the weights of the foils.

It is clear that although the observed ratio of counting rates in the graphite pile does not give a very definite answer, it is much more consistent with $\sigma_F(Pu^{239}) = 2.75$ barns for 14-Mev neutrons than with the value 1.75 barns.

It appears from Fig. 7 that the ratio of counting rates is still changing at the largest distance used. Probably it would be necessary to go to distances of the order of 80 in. to get a good thermal spectrum. At this distance the counting rates would be prohibitively small. It appears that if a thermal-neutron comparison were to be repeated, it should be done at a reactor.

7. $\sigma_F(U^{236})/\sigma_F(U^{235})$ for 14-Mev Neutrons

In these measurements the two U^{236} foils, 5894-3 and 5894-4, were compared with U^{235} foil RM-401-38. The data are given in Table IV. Typical pulse-height distributions are shown in Fig. 8. The result is

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = 0.783 \pm 0.022$$

where the error is considered to arise from a 2 per cent uncertainty in the weight of each foil. With

$$\sigma_F(U^{235}) = 2.18 \pm 0.08 \text{ barns, one obtains}$$

$$\sigma_F(U^{236}) = 1.70 \pm 0.09 \text{ barns } (14.1 \pm 0.3 \text{ Mev})$$

This result is in agreement with Nyer's measurement,[4] which gave

$$\sigma_F(U^{236}) = 1.65 \pm 0.10 \text{ barns}$$

TABLE IV-A

$$\sigma_F(U^{236})/\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 14.1 \pm 0.3 \text{ MEV}$$

A, foil 5894-3

B, foil RM-401-38

Counter Position	Distance, cm	A Counts	B Counts	A/B
A nearest source	6.5	75422	91934	0.8204
		75942	92175	0.8239
		75018	91404	0.8207
B nearest source	6.5	75990	95205	0.7982
		75802	94714	0.8003
		75207	94248	0.7980

Mean A/B = 0.8103 ± 0.0016

(statistical standard deviation)

$$N_A = 2.424 \times 10^{18} \text{ atoms of } U^{236}$$

$$N_B = 2.332 \times 10^{18} \text{ atoms of } U^{235}$$

Correction factors for:	Foil A	Foil B
Foil thickness	$K_A = 1.016$	$K_B = 1.015$
Low energy neutrons	$C_A = 1.010$	$C_B = 0.999$

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = \frac{A}{B}\frac{N_B}{N_A}\frac{K_A}{K_B}\frac{C_A}{C_B}$$

$$= 0.7890 \pm 0.002 \text{ (statistical standard deviation)}$$
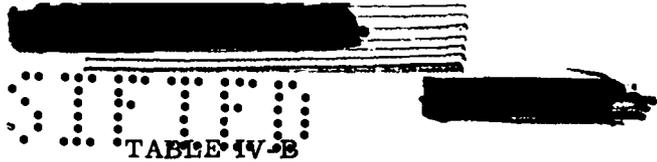
TABLE IV-B

$$\sigma_F(U^{236})/\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 14.1 \pm 0.3 \text{ MEV}$$

A, foil 5894-4

B, foil RM-401-38

Chamber Position	Distance, cm	A Counts	B Counts	A/B
A nearest source	6.5	77985	90359	0.8630
		77309	88846	0.8701
		76408	88270	0.8656
B nearest source	6.5	76694	89146	0.8603
		79557	92787	0.8574
		82754	96288	0.8594

Mean A/B = 0.8626 ± 0.0016

(statistical standard deviation)

$$N_A = 2.621 \times 10^{18} \text{ atoms of } U^{236}$$

$$N_B = 2.332 \times 10^{18} \text{ atoms of } U^{235}$$

Correction factors same as used with foil 5894-3 vs RM-401-38 at 14 Mev

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = \frac{A}{B} \frac{N_B}{N_A} \frac{K_A}{K_B} \frac{C_A}{C_B}$$

$$= 0.777 \pm 0.002 \text{ (statistical standard deviation)}$$
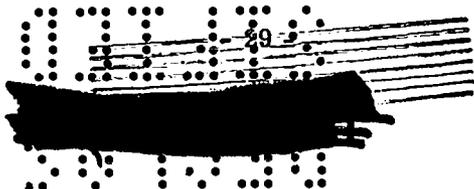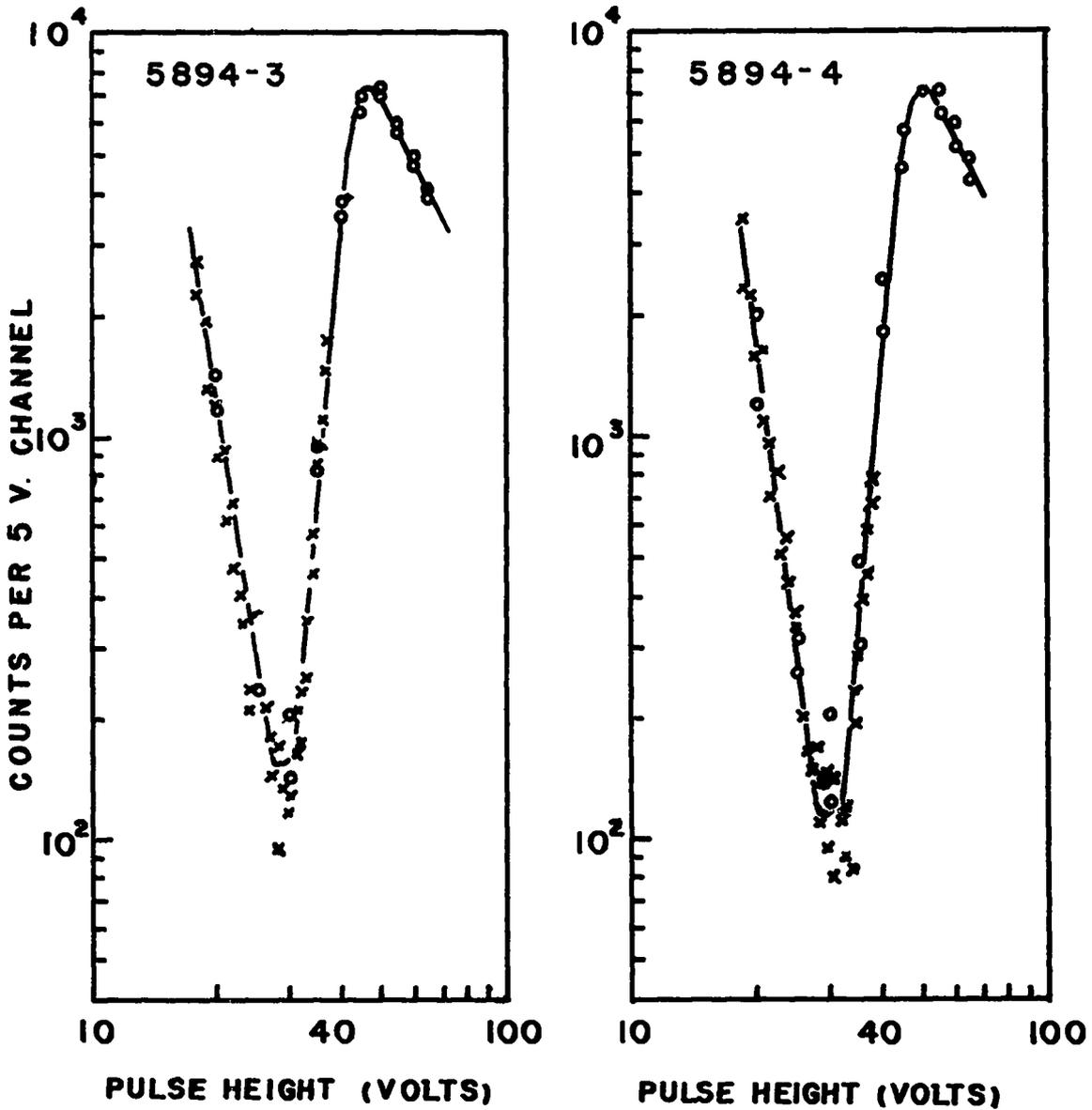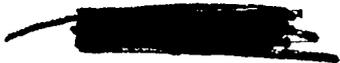
Fig. 8 U^{236} pulse-height distributions in fission chamber.
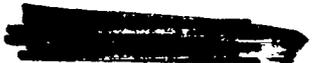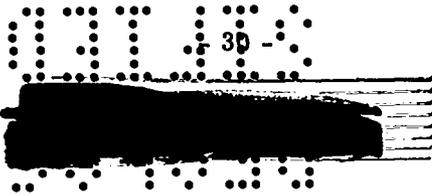
8. $\sigma_F(U^{236})/\sigma_F(U^{235})$ for 2.5-Mev Neutrons

The measurements were made with U^{236} foil 5894-3 and U^{235} foil RM-401-38. The data are given in Table V. The result is

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = 0.697 \pm 0.028$$

The quoted error arises from a 2 per cent uncertainty in the weight of each foil and a 2.4 per cent statistical error.

With

$$\sigma_F(U^{235}) = 1.25 \pm 0.06 \text{ barns}$$

one obtains

$$\sigma_F(U^{236}) = 0.87 \pm 0.06 \text{ barns } (2.5 \pm 0.2 \text{ Mev})$$

Previous measurements were made by Nyer,[4] who obtained

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = 0.40 \pm 0.04$$

and by Lamphere,[12] who obtained 0.67 for this ratio.

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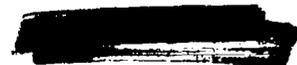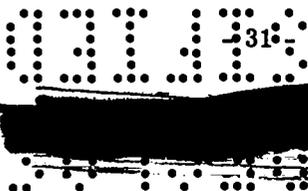
TABLE V

$$\sigma_F(U^{236})/\sigma_F(U^{235}) \text{ FOR A NEUTRON ENERGY OF } 2.5 \pm 0.2 \text{ MEV}$$

A, foil 5894-3

B, foil RM-401-38

Chamber Position	Distance, cm	A Counts	B Counts	A/B
B nearest source	6.5	1510	2004	0.753
A nearest source	6.5	1460	2046	0.714

Mean A/B = 0.734 ± 0.018

(statistical standard deviation)

N_A = 2.439 x 10^{18} atoms of U^{236}

N_B = 2.308 x 10^{18} atoms of U^{235}

Correction factors for:	Foil A	Foil B
Foil thickness	$K_A = 1.016$	$K_B = 1.015$
Low energy neutrons	$C_A = 1.000$	$C_B = 0.9973$

$$\frac{\sigma_F(U^{236})}{\sigma_F(U^{235})} = \frac{A}{B} \frac{N_B}{N_A} \frac{K_A}{K_B} \frac{C_A}{C_B}$$

$$= 0.697 \pm 0.017 \text{ (statistical standard deviation)}$$

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