Absolute Fission Cross Section of U^{235} for 2200-m/sec Neutrons

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A measurement of the fission cross section of U^{235} is described. Neutrons of 2200-m/sec velocity were selected with the A.W.R.E. Fast Neutron Chopper. Fission neutrons from a thick sample of U^{235} were detected in capsules of liquid scintillator employing pulse-shape discrimination of fast neutrons from gamma rays. The neutron flux was measured by stopping the beam in a thick sample of B^{10} and detecting the 478-keV gamma rays in a pair of sodium iodide crystals. The efficiency of the sodium iodide crystals for detecting gamma rays was established by observing coincidences between gamma-ray pulses from the detector and from disintegrations in a thin sample of B^{10} contained within an ionization chamber. The efficiency of the liquid scintillators was determined in a similar manner using a thin foil of U^{235}. A large correcting factor was discovered originating from the anisotropy introduced into the angular distribution of detected neutrons by the absorption of fission fragments in the ionization-chamber foil. The method yields an absolute value for the fission cross section, independent of any reference cross sections. A value of $\sigma_F=572\pm6$ b was obtained.

1. INTRODUCTION

One of the problems in obtaining accurate measurements of fission cross sections is that of normalizing relative fission-cross-section curves to an absolute cross-section scale. The value of the U^{235} fission cross section at a neutron velocity of 2200 m/sec provides a convenient standard.

Despite numerous attempts to measure this cross section the discrepancies among recent measurements are still large.[1–7] A critical survey of the available data was made by Sjostrand and Story.[8]

All the usual difficulties in fission-cross-section measurements were elegantly avoided in the experiment performed at the Argonne National Laboratory.[4] This experiment used a fissile foil, thicker than usually employed and therefore easier to assay; it made use of fission-neutron detection and thereby eliminated the need to measure the efficiency of a fission chamber accurately; it used a neutron chopper for energy selection and employed a new method of absolute flux determination which gave a flux value independent of any reference cross section. The result of this experiment was surprisingly high, 4% greater than the world average value and prompted a remeasurement of the fission cross section at A.W.R.E. Aldermaston, using the fast chopper and employing a method which retains the essential features of the Argonne experiment.

2. EXPERIMENTAL METHOD

The essential feature of the experiment is to measure the fission rate in a thick foil of U^{235} by using fission-neutron detection. This offers advantages from the sample point of view. As it is simply a metal foil, the U^{235} content can be determined by direct weighing. The neutron flux is measured by stopping the beam in a thick sample of B^{10} and detecting the 478-keV gamma rays in a pair of sodium iodide crystals.

Fission neutrons are detected by a bank of six small capsules of liquid scintillator, employing pulse-shape discrimination of fast neutrons from gamma rays which serves the twofold purpose of reducing gamma-ray background and eliminating detection of capture events in the uranium foil. The technique of discrimination employed is that of operating the photomultiplier tubes under conditions with space-charge saturation in their last stages.

Figure 1 is a simplified diagram of the experiment. First, the neutron beam from the chopper passes into a fission chamber containing a thin U^{235} foil of thickness 0.1 or 0.5 mg/cm^2 on one electrode. The thick uranium foil, approximately 130 mg/cm^2, is mounted on the back of this electrode. Then surrounding the counter is the bank of six liquid cells.

To determine the efficiency of the neutron counters for detecting fissions, coincidences are recorded between the chamber and the counters. The timing gate shown eliminates any pulses from the chamber during the time the chopper is open and selects just the thermal-neutron spectrum for the efficiency measurement.

A very similar procedure is used for measuring the neutron flux. Almost all those neutrons transmitted by the uranium are stopped in a B^{10} foil of thickness 85 mg/cm^2. The boron disintegrations are counted by detecting the 478-keV gamma rays from the $B^{10}(n,\alpha)Li^7$ reaction in a pair of sodium iodide crystals. A single-

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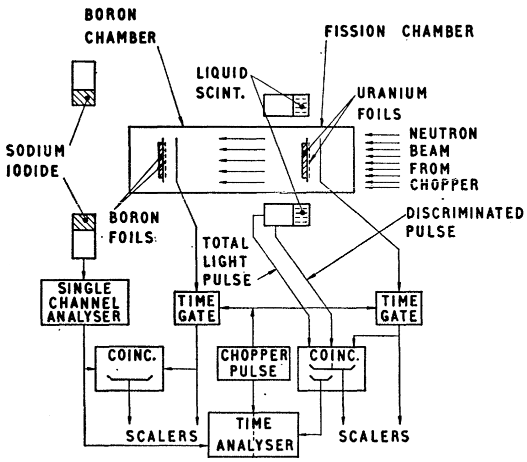

FIG. 1. Simplified diagram of U^{235} thermal-fission cross-section measurement.

channel pulse-height analyzer is set to accept the 478-keV gamma rays only, and the efficiency is measured in a manner similar to that of the neutron counter by recording coincidences between the sodium iodide crystals and pulses from a thin B^{10} foil in the ionization chamber.

If backgrounds are neglected then the efficiency of the liquid scintillators for detecting fissions (E_f) and the efficiency of the sodium iodide counters for detecting gamma rays (E_γ) are given by

$$E_f=(C_f-R_f)/F \quad \text{and} \quad E_\gamma=(C_\gamma-R_\gamma)/B\,,$$

where C_f and C_γ are the coincidence rates between the liquid scintillators and fission chamber and between the sodium iodide crystals and boron chamber, respectively; R_f and R_γ are the random coincidence rates; F and B are the fission and boron chamber rates. The 2200-m/sec disintegration rates in the thick uranium sample foil (N_f) and the thick boron foil (N_n) are given by

$$N_f=T_f/E_f \quad \text{and} \quad N_n=T_\gamma/E_\gamma\,,$$

where T_f and T_γ are the 2200-m/sec counting rates in the liquid scintillators and sodium iodide crystals, respectively. Also, N_n is related to N_0 (the 2200-m/sec neutron rate incident on the sample) by

$$N_n=N_0\times T\,,$$

where $T=e^{-\sigma_T N_a}$ and T is the transmission of the sample; σ_T is the 2200-m/sec total cross section of U^{235}; N_a is the number of atoms/cm² in the sample of U^{235}. As the fission rate is given by

$$N_f=N_0(\sigma_F/\sigma_T)(1-T)\,,$$

where σ_F is the 2200-m/sec fission cross section of U^{235}, we have

$$\sigma_F=(N_f/N_n)\times\sigma_T\times T/(1-T)\,.$$

In this expression for the cross section, σ_T appears, but it is combined with T as $(\sigma_T T)/(1-T)$ which reduces to

$$N_a^{-1}(1+N_a\sigma_T/2!+N_a^2\sigma_T^2/3!+\cdots)^{-1}.$$

Thus, for small N_a, the cross section σ_F is independent of σ_T. Actually for the foil thickness in use, $N_a\sigma_T$ is approximately 0.22, so that if σ_T were uncertain by 1% it would only affect the value of σ_F by 0.1% and in fact σ_T has been measured to 0.3% by Safford, Havens, and Rustad,[9] to 0.7% by Block, Slaughter, and Harvey,[10] and to 0.3% by Saplakoglu.[11]

During the course of the experiment, an error was detected in the measurement of the efficiency of the fast neutron counters for detecting fissions. This was caused by those fission events in the thin U^{235} foil which were not recorded in the fission chamber. Fission neutron emission is not isotropic with respect to fragment direction and the lost fissions are predominantly those with fragments travelling in the plane of the foil. Since the neutron counters do not subtend a 4π solid angle, the measured efficiency becomes a function of counter position. This effect is discussed in detail in Sec. 4.

3. EXPERIMENTAL APPARATUS

Arrangement

The A.W.R.E. fast neutron chopper has been described previously.[12] The rotor in use has two sets of seven parallel slits 0.06 in. wide and 2 in. high and when rotated at 625 rpm permits thermal neutrons to pass through. Two cylindrical water tanks and one wooden collimator were introduced along the flight tube to reduce the large fast neutron background penetrating the chopper rotor, see Fig. 2. These collimators were lined with cadmium and the ends covered with boral to remove slow neutrons that would otherwise be scattered by the collimators and to reduce the probability of moderated fast neutrons arriving at the detector from the collimators.

The final collimation of the thermal-neutron beam used a sheet of boral with a 1.5 in. square aperture. The collimation system was not sufficient to remove all the time-dependent background and a small background still remained.

Ionization Chambers

The two ionization chambers, one a fission chamber and the other a boron ionization chamber were both similar in construction and were contained within the same counter assembly. Thin aluminum windows (0.003 in.) were fitted where the beam entered and left the

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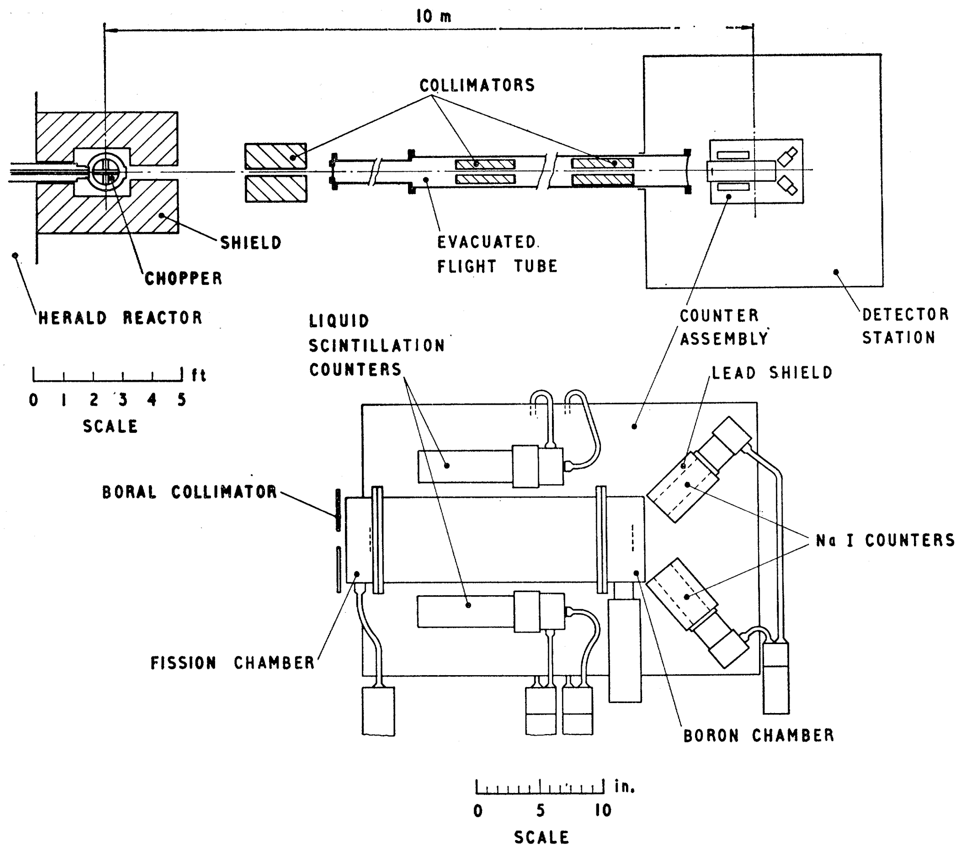

FIG. 2. Arrangement of the apparatus.

chamber system. Both were simple parallel-plate chambers filled at atmospheric pressure with a continuous flow of an argon-CO_2 (5%) gas mixture and were operated under electron-collection conditions.

The boron chamber was designed with the head amplifier (preamplifier) coupled directly to the chamber to reduce to a minimum the extra capacity that would be introduced by a connecting cable.

Figure 3 shows pulse-height distributions from both chambers. These curves were taken using a 0.5 mg/cm^2 U^{235} foil in the fission chamber and approximately 45 μg/cm^2 in the boron chamber. At a later stage in the experiment two other U^{235} foils were used, 0.1 and 0.14 mg/cm^2. The pulse-height distributions for these foils are shown in Figs. 4(a) and 4(c). The shapes of the distributions were influenced by the geometry of the chamber since the anode plate was closer to the source than the range of the most energetic fission fragments, 1.3-cm separation compared to a fragment range of the order of 2.2 cm. Subsequently two further pulse-height distributions were measured with the anode plate replaced by a ring giving the distributions of Figs. 4(b) and 4(d). Although the foil of Fig. 4(d) is nominally thicker than that of 4(b) the pulse distribution indicates that there is less absorption of energy in the foil, presumably because this foil had an evaporated and more uniform deposit of U^{235}.

The efficiencies of the chambers with the operating biases in use were greater than 90% for the fission chamber (0.5 mg/cm^2 foil), about 98% for the 0.1 mg/cm^2 U^{235} foil and approximately 95% for the boron chamber.

Sodium Iodide Counters

The 478-keV gamma rays from the B^{10} disintegrations in the thick boron foil were detected with two sodium iodide crystals, one on each side of the chamber. The use of a balanced system, such as this, minimizes errors due to foil nonuniformities. Both crystals, $1\frac{3}{4}$ in. diam and 2 in. long were surrounded with a cylindrical lead shield 0.6 in. thick. Pulses from both photomultipliers were fed into a transistor emitter follower circuit built directly into the potential divider resistor chain supplying the dynode voltages.

A pulse-height distribution for the combined set of pulses is shown in Fig. 3(c), which also shows the range of pulse heights selected for measurement with a single-channel pulse-height analyzer.

The efficiency of the detection system for detection of 478-keV gamma rays from the B^{10} foil, including geometrical factors was about 0.5%.

Fast Neutron Counters

Fissions in the thick U^{235} foil were identified by counting fission neutrons. Liquid scintillator offered

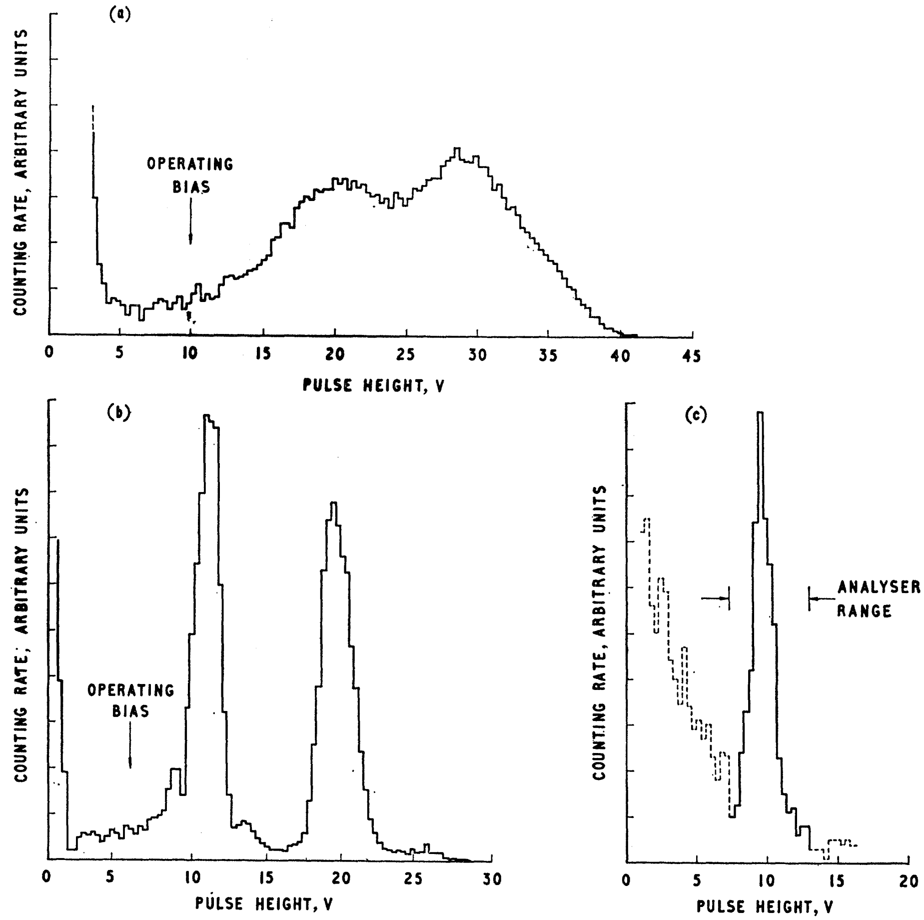

FIG. 3. Pulse-height distributions: (a) fission chamber, 0.5 mg/cm² U^{235} foil; (b) boron ionization chamber; (c) sodium iodide crystals.

the best choice of fast neutron detector as a large volume is necessary to achieve a reasonable efficiency. It was decided to use pulse-shape discrimination to distinguish fast neutrons from gamma rays, that is to say to distinguish proton recoil pulses from electron pulses. Difficulties were encountered initially in achieving good discrimination when using large cells of liquid scintillator in conjunction with 5 in. photomultiplier tubes and so an array of small cells of liquid was constructed. Each cell, 2 in. in diameter and 3 in. long, was filled with a commercially manufactured liquid scintillator NE213 and mounted on a 2-in. E.M.I. photomultiplier tube (6097B).

Various techniques of pulse-shape discrimination were investigated, and it was found that the method originated by Owen[13] gave the best degree of discrimination. With the liquid scintillator, discrimination could be observed at pulse heights corresponding to proton recoil energies of about 500 keV.

The technique employs a photomultiplier tube operating under conditions with space-charge saturation between the last dynode and the anode. A modification of the original Owen circuit described by Batchelor *et al.*[14] was employed to remove high-energy gamma-ray pulses by a timing technique. A set of characteristics is shown in Fig. 5. The total efficiency of the system for detecting fissions in the U^{235} foil, including geometrical factors was about 0.5%.

Electronics

The method of measuring random coincidences is illustrated in Fig. 6 and the full block diagram is given in Fig. 7.

The three coincidence units perform the following functions. In unit A coincidences between channels 1 and 2 are used for the efficiency calibration of the sodium iodide crystal while channel 3, taking delayed pulses into coincidence with 1 and 2 determines the random rate for this circuit. Channels 1 and 2 of unit B, in coincidence, form part of the pulse-shape discriminator and identify neutrons, then the output of this coincidence circuit is put into coincidence with channel 3 to determine the efficiency of the neutron counter. Finally the triple coincidence output of B is put into coincidence with the delayed fission chamber pulses through channels 2 and 3 of C to determine the random coincidence rate for the coincidence unit B.

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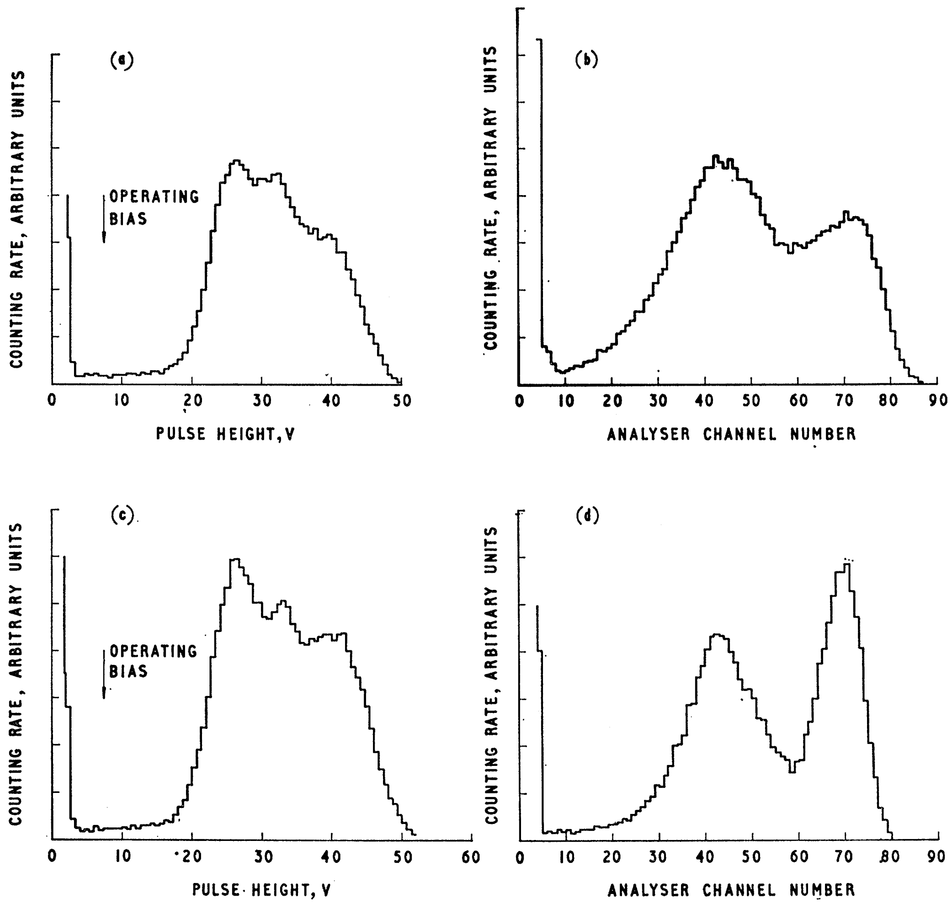

FIG. 4. Pulse-height distributions from fission chamber; (a) and (b), 0.1 mg/cm² U^{235} foil (painted deposit); (c) and (d), 0.14 mg/cm² U^{235} foil (evaporated deposit). Distributions for two chamber geometries are shown; (a) and (c) used a collector electrode in the form of a plate and this was the geometry in use during the experiment while in (b) and (d), measured subsequently, the plate was replaced by a ring.

The additional equipment in Fig. 7 enclosed by dashed lines permits the continuous monitoring of the background from both scintillation counters during the experiment. Pulses from the scintillators are selected by two timing gates, triggered by the chopper, which selected pulses corresponding to a region of time after the thermal neutrons have arrived at the detector. These background pulses are fed into a rate meter and chart recorder so that a continuous visible check on the background is available. Any malfunction of the counter or changes in the background level can be instantly observed on the chart records.

A 1024-channel time-of-flight analyzer was used in the experiment in a mode permitting it to function as two separate analyzers each with 512 channels.

Foil Data

A summary of the foil characteristics appears in Tables I and II. The uranium foils of type 1 in the table were metal foils, each being cleaned in acid to remove any oxide layer. These were then sealed by cold welding into an aluminum container under a helium atmosphere. The container walls were 0.01 in.

TABLE I. Foil data.

Number	Foil material	Thickness	Area	Backing	Remarks
1 (Thick foils)	U^{235}	Typical, 131 mg/cm²	2×2 in.		Collimated area 1.5×1.5 in. sealed in aluminum can
2	B^{10}	approx. 85 mg/cm²	2×2 in.	0.003 in. Al	Painted deposit
3 (Ionization chamber foils)	U^{235}	0.5 mg/cm²	2×2 in.	0.003 in. Al	Painted deposit
4	U^{235}	0.1 mg/cm²	2×2 in.	0.005 in. Pt	Painted deposit
5	U^{235}	0.14 mg/cm²	2×2 in.	0.003 in. Al	Evaporated deposit
6	B^{10}	approx. 45 μg/cm²	2×2 in.	0.003 in. Al	Evaporated deposit

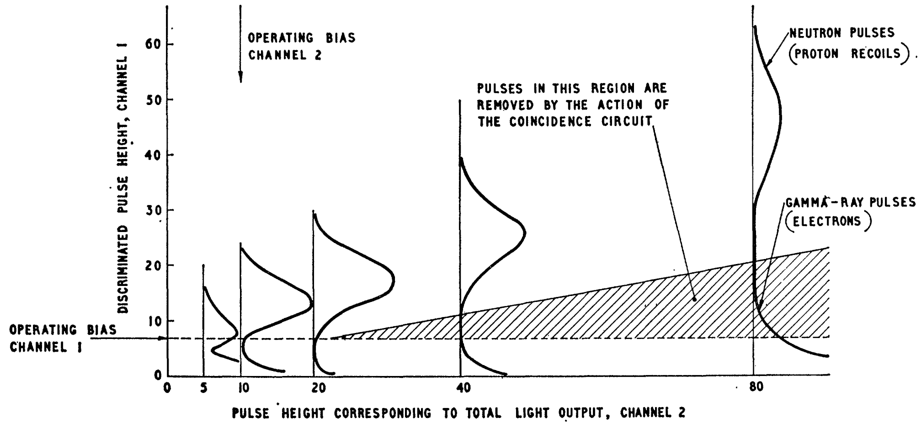

FIG. 5. Characteristics of fast-neutron counters. Individual discriminated pulse-height spectra are shown for various values of the pulse height of the corresponding nondiscriminated pulses.

thick. The average foil thickness was determined initially by weighing the accurately machined 2×2 in. sample foil and subsequently by cutting out the center 1.5×1.5 in. and weighing this portion since this was the part intercepted by the beam during the experiment. The results of the two measurements agreed to better than 1% but the second measurements are those used in the calculation of the fission cross section. The boron foil 2 was prepared as a painted deposit on a 0.003 in. thick aluminum backing, using a "binder" of Formvar. The binder used about 5 cc of a solution of 1 g to 100 cc solvent. Uranium foils 3 and 4 were prepared as a painted layer of a nitrate solution and then fired to oxide, while foil 5 and the boron foil, 6, were evaporated on to the backing.

TABLE II. Analysis of uranium and boron foils.

Foil 1, U^{235}		Foil 2, B^{10}	
Uranium-235	92.93%	B^{10}/B ratio	91.4%
Uranium-234	1.17%	Silicon	0.5%
Uranium-236	0.18%	Iron	0.01%
Uranium-238	5.72%	Magnesium	0.3%
Iron	0.028%	Carbon	1.35%
Silicon	0.015%	Hydrogen	0.55%
Carbon	0.051%	Boron	93.5%
		Oxygen	3.78%

The uniformity of the ionization chamber foils was investigated by scanning them with a neutron beam of 0.25 in. diam while the uranium sample foils were studied with a micrometer. The thickness variations were as follows:

Boron. The small variation of thickness of foil 2 is unimportant as this foil is thick enough to stop substantially all the neutron beam.

The evaporated deposit of foil 6 reduced in thickness by approximately 4% at the edges of the deposit.

Uranium. Foils of type 1 were found to have a taper in their thickness in one direction of +3% to −3% of their average thickness and random fluctuations of ±7% from point to point.

The painted deposits of foils 3 and 4 had random fluctuations up to ±7% of the average thickness while the evaporated deposit of foil 5 reduced in thickness by about 4% at the edges of the deposit.

Procedure

All the data required to evaluate σ_F cannot be acquired in one measurement. Additional data is needed to measure background rates which are not a constant

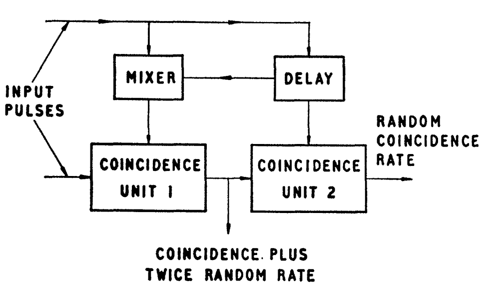

FIG. 6. Method of measuring random coincidence rates.

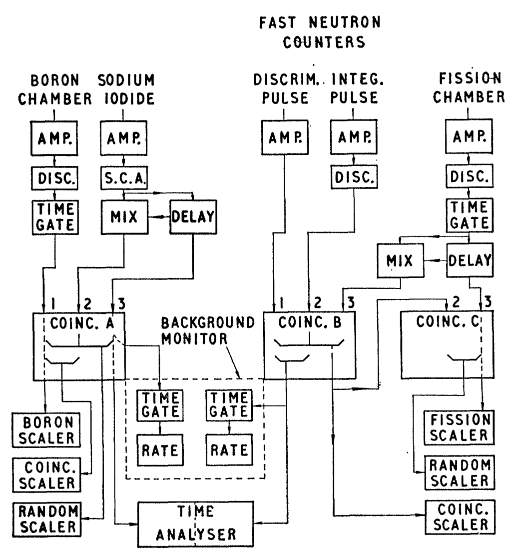

FIG. 7. Block diagram of electronics.

function of neutron flight time (time-dependent backgrounds). These fall into three categories:

(1) The fast neutrons and gamma rays penetrating the rotor can give rise to background pulses in the detector system by being scattered into it.

(2) This same background can induce disintegrations in the uranium and boron foils which occur at the same time as 0.025-eV neutrons arrive at the detector.

(3) The sodium iodide crystals can detect gamma rays from fission events in the uranium foil. The opposite effect of gamma rays from the boron foil being detected in the fast neutron counters, though possible is not expected to be important because of the gamma-ray discrimination employed in these detectors.

Measurements were made using a cadmium shutter, 0.05 in. thick which attenuated the 0.025-eV neutrons by 99.94%; this was placed in the beam close to the chopper. The insertion of the shutter removes neutrons of 0.025 eV from the beam while permitting the fast neutrons and gamma rays penetrating the rotor to pass to the detectors. The detectors then record backgrounds of types (1) and (2) but not (3).

A second way of measuring backgrounds is to remove the samples one at a time with the full beam on; in this case the detectors respond to backgrounds of types (1) and (3) but not (2).

A preliminary experiment was performed in which the cadmium shutter was inserted and the uranium foil alternated in and out of the beam. This was repeated for the boron foil. These experiments would be sensitive to backgrounds of type (2) and were found to be zero to within the experimental accuracy, that is to say they were below the level at which errors of 0.1% would be introduced into the fission cross section. With this point established the second method of background determination was used.

Three runs were made for each determination of σ_F; these are as follows:

(a) Boron and uranium foils in position.
(b) Dummy boron foil and uranium foil.
(c) Boron foil and dummy uranium foil.

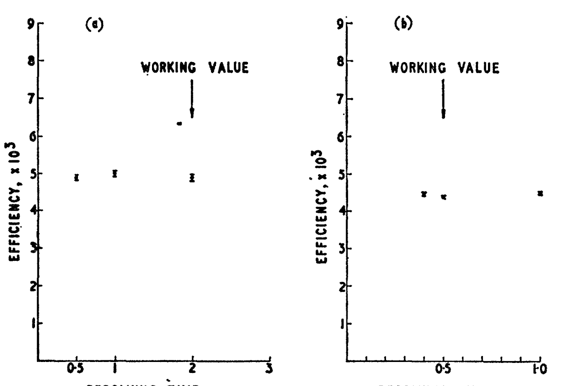

FIG. 8. Efficiency of detectors measured using various coincidence resolving times: (a) fast neutron counters; (b) sodium iodide crystals.

The dummy foils are complete foil holders but without the foil present. Run (a) gives the foil rates together with backgrounds while Runs (b) and (c) suitably normalized, measured the time-dependent backgrounds.

Six sets of data were recorded to calculate σ_F, namely those using either the 0.5, 0.1, or 0.14-mg/cm^2 U^{235} foil in the fission chamber with the fast-neutron counters set at either 45° or 90° to the beam direction.

It is evident that if any genuine coincidences were not recorded the true value of the counter efficiencies would not be measured. Hence, after adjusting all the coincidence circuit delays, both visually and by plotting delay curves, the efficiencies of the two counters were determined for three values of coincidence resolving time. These points are shown on a diagram, Fig. 8, from which it is apparent that using the values of resolving time indicated there is no measurable loss of coincidences. This experiment was repeated at intervals during the measurements.

To provide additional information on the gamma-ray discrimination properties of the fast neutron counter, a measurement was made using a gold foil (164 mg/cm^2) instead of the U^{235} foil. In this experiment the gold is expected to give 1.5 times as many capture events as occur in the U^{235} foil. No events were detected from the gold foil to within the accuracy of the measurement; that is to say, the number of events from the gold foil was not greater than 0.4% of the expected fission rate from the U^{235} foil. This experiment also serves to demonstrate that there is no appreciable detection of fast neutrons scattered from the sample, since the gold foil would scatter approximately 1.5 times as many fast neutrons as the U^{235} sample.

4. EFFICIENCY OF FAST NEUTRON DETECTORS

The first set of data was taken with all six neutron counters at an angle of approximately 45° to the direction of the neutron beam and to the plane of the fissile foils. A second set of data taken with this angle changed so that the counters were at approximately 90° to the beam direction, that is, in the plane of the foils, gave a different measured value of σ_F. The discrepancy between the two measurements is 12.7%.

This discrepancy has been attributed to the effect of those fission events in the thin foil which do not give rise to pulses that are detected in the fission chamber. As these fissions are preferentially selected in direction, being those with fragments in the plane of the foil, the anisotropy of neutron emission with respect to fragment direction results in the measured efficiency of the fission neutron detectors being different from that appropriate when all fission events are included. The measured efficiency might be expected to show a dependence on the bias used in the fission chamber.

A measurement of efficiency with bias was made with the counters in the 45° position using a single-channel pulse-height analyzer selecting pulses from the 0.5 mg/cm^2 U^{235} foil. This differential-bias curve shows a dependence of efficiency upon bias which is illustrated in Fig. 9. Making a reasonable extrapolation of the differential curve and allowing for the pulses lost below the bias level and in the foil, it would not be unreasonable to expect that the efficiency could be in error by several per cent.

Using recent data of Ramanna *et al.*[15] which gives the measured angular distribution of neutron emission with respect to fragment direction it is possible to estimate the number of lost fissions needed to account for the measured discrepancy. The loss would need to be about 8.3% of the total number of fissions. This compares with an estimated loss of 9.2%, made up of 3.2% of the fissions which never leave the foil and 6% of small pulses below the bias level in the chamber.

To reduce the magnitude of the effect it is necessary to use thinner foils in the fission chamber even though it results in a very slow accumulation of data. A second experiment used a foil 0.1 mg/cm^2 thick painted on to a platinum backing.

The results of the two experiments are shown in Fig. 10. The effect of the lost fission events can be considered to be the introduction of a perturbation into the angular distribution of selected neutrons; this distribution would have been isotropic if all fission events had been included. If all the lost events had been confined in direction parallel to the plane of the foil then the perturbation would have the same angular dependence for both foils but its magnitude would be proportional to the number of lost fissions. We could then make an extrapolation to zero foil thickness, that is to say zero lost fissions, which is linear in the sense that we suppose the deviation of the measured cross section from the true value to be proportional to the number of lost fissions in each foil although this is not necessarily proportional to the foil thickness. This assumption has been made in calculating an extrapolated value. Since the lost fissions are not all parallel to the plane of the foil but are inclined at small angles to it ($<5°$), the assumption made above is not strictly true; however, it is estimated that any error in the calculation due to the angular spreads involved is not greater than 0.35%. This error has been included in the error quoted for the extrapolated value of the fission cross section.

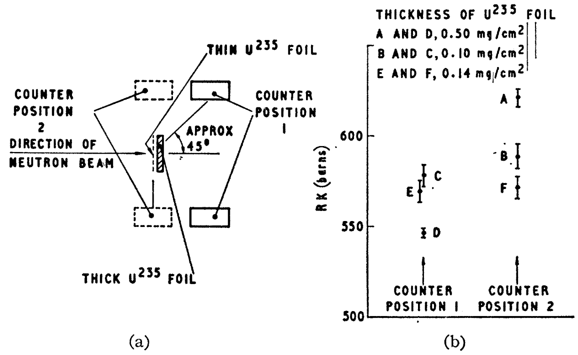

FIG. 10. Experimental arrangements: (a) positions of fast neutron counters; (b) measured values of $R\times K$ where R and K are defined in Sec. 6. (Statistical errors only are shown.)

Another experiment used a foil of 0.14 mg/cm^2 which had been evaporated onto an aluminum backing. This foil was expected to have a more uniform deposit and the pulse-height distribution of Fig. 4(d) indicates that there was less absorption of fragment energy in this foil. Also, the foil had a thin aluminum backing and hence a smaller correction for the effects of the backing. As no significant difference in the measured value of σ_F was found for the two positions of the neutron counters, a weighted average has been calculated from this data.

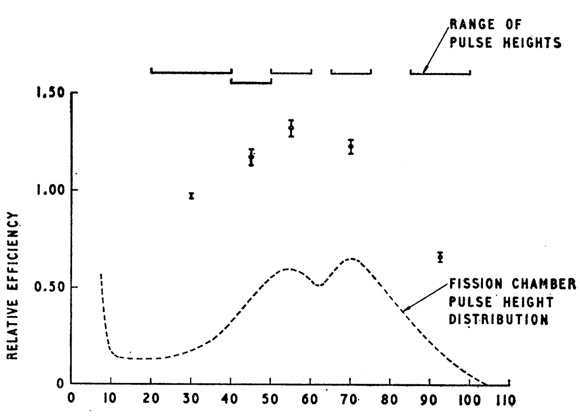

FIG. 9. Measured efficiency of fast neutron counter as a function of pulse height in the fission chamber (0.5 mg/cm^2 foil).

5. ERRORS AND CORRECTING FACTORS

Table III shows a summary of the estimated errors and correcting factors occurring in various parts of the experiment; many of these are self explanatory. Comments on some of the errors follow.

Distortion of Spectra Due to Energy Resolution

The burst shape from the chopper is almost triangular and has a width at half-height of 170 μsec under the conditions used in the experiment. This corresponds to an energy resolution of 7% at the 10 m flight station.

In the region of 2200-m/sec neutron velocity, the two timed rates from the scintillators are smooth, almost linear, functions of flight time. There would be no distortion of the shape of the two timed spectra if these were perfectly linear functions and if the chopper gave a perfectly symmetrical resolution function. Such distortions as do occur are dependent on the second differential coefficient of the spectra with respect to time. Using measured values of these coefficients in conjunction with the measured shape of the burst from

[15] R. Ramanna, R. Chaudhry, S. S. Kapoor, K. Mikke, S. R. S. Murthy, and P. N. Rama Rao, Nucl. Phys. **25**, 136 (1961).

TABLE III. Summary of errors. Terms marked with an asterisk have been included in the data analysis. Only the remaining terms are summed to evaluate the total correcting factor C.

Effect	Sign	Correction to σ_F (%)	Error in σ_F (%)
Time zero		0	0.1
Flight path length		0	0.025
Flight time accuracy		0	0.02
Resolution effects	−	0.05	<0.05
Dead time (a) Analyzer	*	0.03	≪0.03
(b) Other rates	−	0.02	0.01
Chance coincidences (a) Liquid scintillator	*	4.4	0.3
(b) Sodium iodide	*	10	0.2
Backgrounds			
(a) Constant background (i) Liquid scintillator	*	7.4	<0.1
(ii) Sodium iodide	*	5.6	<0.1
(b) Time-dependent background (i) Liquid scintillator	*	2.6	0.3
(ii) Sodium iodide	*	2.4	0.2
(c) Ionization chambers (i) Uranium		0	0
(ii) Boron	+	0.17	0.005
Efficiency of counters—effect of lost ionization chamber pulses			
(a) Uranium (E_f)		0 (See Sec. 4)	<0.35
(b) Boron (E_γ)	+	0.06	0.01
Variation of ν with fission mode—effect on E_f preferential loss of heavy fission fragments			
(a) 0.5 mg/cm² U^{235} foil	−	0.1	<0.1
(b) 0.1 mg/cm² U^{235} foil	−	0.02	<0.02
(c) 0.14 mg/cm² U^{235} foil	−	0.03	<0.03
Delayed neutrons			
0.2% correction is overcompensated	+	0.06	<0.1
Transmission effects			
(a) Sample impurities	−	0.05	0.01
(b) Error in σ_T, U^{235}		0	<0.1
(c) Error in N_a	*	0	0.1
(d) Parts of apparatus	*	0.78	<0.1
Other events in foils			
(a) Other elements		0	<0.1
(b) From U^{235}		0	<0.1
(c) From B^{10} foil		0	<0.1
(d) Thin U^{235} foil (0.5 mg/cm²)	−	0.38	0.04
(e) Thin U^{235} foil (0.1 mg/cm²)	−	0.08	0.01
(f) Thin U^{235} foil (0.14 mg/cm²)	−	0.11	0.01
Secondary fissions			
(a) From scattered thermal neutrons	−	0.4	<0.1
(b) From fission neutrons	+	0.2	<0.1
Scattering from backings into foils			
(a) U^{235}	−	0.35	<0.1
(b) B^{10}		0	<0.1
Data for 0.1 mg/cm² U^{235} foil only			
(c) Platinum backing—45°	−	1.34	0.1
—90°	−	0.69	0.1
Absorption of fast neutrons and gamma rays			
(a) U^{235}—aluminum		0	<0.3
—uranium		0	<0.1
(b) B^{10} —thin foil backing		0	<0.3
—thick foil		0	0.2
Leakage of fast neutrons through chopper (effect on E_f)		0	<0.1
New fissions from backscattered fission neutrons		0	<0.1
Beam scatter		0	<0.1
Nonuniformities of			
(a) Foils—rates		0	<0.3
—efficiencies		0	0.1
(b) Beam		0	<0.3
Geometrical effects			
(difference of thin and thick foil positions)			$<10^{-3}$

the chopper, corrections are necessary of approximately 0.3% for pulses from the fast neutron counter and 0.25% for pulses from the sodium iodide counter. Note, however, that these two corrections are in the same direction and only the ratio of the two counting rates is required to evaluate the fission cross section and so the error introduced even if these corrections were ignored is only of the order of 0.05%.

Dead-Time Effects

All dead-time corrections are based on measured values of the dead times present at each point of the circuits. It is convenient to divide the corrections into two parts since the largest losses are in the time-of-flight analyzer.

The effective dead time of the time analyzer is 16

μsec plus one-half of a channel width. A channel width of 32 μsec and a total counting rate of 0.6/sec result in a dead time correction of approximately 1.5%.

As the analyzer dead-time correction is the same for both the fission rate and the neutron rate and as only the ratio of these two numbers is required to calculate σ_F, there would be no error introduced in σ_F from this correction if it were not for the presence of background counts which cause a slight departure from complete cancellation leaving a residual correction of about 0.03%.

In the remaining 6 scaler rates no dead-time corrections larger than 0.5% are present and in certain cases compensatory effects occur, the combined correction applied is 0.065%.

Random Coincidences

The method used for measuring the numbers of random coincidences, indicated in Fig. 6, is an accurate method in that the random coincidences are measured simultaneously with the genuine coincidences and for the identical coincidence circuit and hence also the identical resolving time as for the genuine coincidences. The accuracy obtained is therefore limited only by the statistical errors associated with the comparatively small number of counts.

Figure 8 indicates that an accurate estimation of the number of random coincidences was being obtained, for in the points shown, the proportion of random coincidences varies by a factor of 2 or 3 from point to point.

Efficiency of Counters

It is possible for errors to be introduced through an incorrect measurement of the efficiencies of the counters either through variations of efficiency with bias in the ionization chambers or through failure to detect all genuine coincidences. Some relevant experimental data is presented in Sec. 3 where it is shown that no appreciable loss of genuine coincidences can be measured.

The effect of lost fission events in the fission chamber has been discussed in Sec. 4. By adopting the procedure described, using thinner foils (0.1 mg/cm^2), the errors resulting from an incorrect efficiency measurement are minimized and the error in σ_F is not expected to be greater than 0.35%.

Similar effects can occur in the NaI detector although these are less serious. First, the angular distribution of emitted gamma rays has been measured to be spherically symmetric with respect to the alpha-particle direction[16] so that no effects analogous to the angular dependence of E_f can occur. Second, there are four groups of particles to consider in the boron chamber, those corresponding to the Li^7 nuclei and α particles from the reaction proceeding to either the ground or first excited state of Li^7. The branching ratio for this reaction is 5.8%[17] so that only 5.8% of the events do not give a 478-keV gamma ray. The position of the bias in the boron chamber can therefore be expected to affect the measured value of E_γ if the relative proportions of selected pulses in the chamber departed from 5.8%. However, even in an extreme case with the bias set at the center of the short-range Li^7 group the efficiency could only be in error by 2.8% and in the experiment only 4.9% of the total pulses are lost, so that if all these pulses were short-range Li^7 particles only 0.32% correction would be necessary. Taking into account the shapes of the two groups of Li^7 particles reduces this correction still further and a correction of 0.06% has been applied. Note also that one measurement of σ_F in the first set of data used a bias set halfway between the two sets of groups and gave a σ_F value not significantly different from all other runs in that set.

Variation of $\bar{\nu}$

The timing gates in use selected neutrons with energies in the range 0.3 to 0.01 eV for measuring the efficiences of the counters. It is an inherent assumption in this experiment that $\bar{\nu}$, the average number of neutrons per fission, is constant over this energy range, since the fast neutron counter efficiency is directly proportional to $\bar{\nu}$.

The value of $\bar{\nu}$ varies with fission mode. As the number of lost fissions in the fission chamber depends on the range of the fission fragments in the uranium foil and as the heavy fragment of the pair has a shorter range there is a preferential loss of heavy fragments compared to light fragments. This tends to emphasize the loss of fission modes with high mass ratios for which ν is significantly different from $\bar{\nu}$. However, the magnitude of the effect is sufficiently small ($<0.1\%$) that no significant error is introduced.

Delayed Neutrons

Delayed neutrons, if later than 0.5 μsec, would not be recorded in the fission neutron counter efficiency measurement except as random coincidences which are allowed for. However, they do contribute to the measured events in the counter. Here, though, as periods are large they appear as a steady background. Although there is approximately 0.75% of the total neutron emission in the form of delayed neutrons these only add about 0.2% to the events in the thermal channel. The background correction partially compensates for this leaving a residual correction of less than 0.1%.

Events in Foils

U^{235} Foil

The capture and scattering events in elements other than U^{235} present in the uranium foil make up together

[16] B. Rose and A. R. W. Wilson, Phys. Rev. **78**, 68 (1950).

[17] G. C. Hanna, Phys. Rev. **80**, 530 (1950).

not more than 0.5% of the number of fission events. More important could be the scattering and capture by the U^{235} itself. The proportion of scattering and capture events to fission events is 1.7% and 17%, respectively. However, the gamma-ray discrimination circuits in the fast neutron counter permit only about 1 in 10^3 of the gamma-ray pulses to be recorded, thereby reducing the number of detected capture events below 0.1% of the fissions. The scattered slow neutrons could not be detected directly but only through a subsequent capture. Additional evidence that the fast neutron detector is insensitive to capture events is provided by the run using a gold foil referred to in Sec. 3.

B^{10} Foil

No component in the B^{10} foil has a cross section large enough to compete with the B^{10} and contribute even 0.1% of the events in the foil. The binding material of Formvar was used in a quantity that would be expected to produce interactions with hydrogen only to the extent of 0.015% of the number of B^{10} disintegrations.

Thin Foils

A small correction has to be applied for the additional fission events detected from the thin U^{235} foil. This is $0.38\pm0.04\%$ for the 0.5 mg/cm² foil.

Secondary Fissions

Two types of secondary fissions have to be considered. Those induced by scattered thermal neutrons, resulting in approximately 0.4% additional fissions and those induced by fast neutrons from thermal fissions resulting in approximately 0.25% additional fissions.

The effects from the thin and thick foils partially compensate each other leaving a correction to be applied to the measured efficiency which is of the order of the fission multiplication in the foil, i.e., about 0.2% for the foils in use.

Absorption of Fast Neutrons and Gamma Rays

The attenuation of the fission neutrons and 478-keV gamma rays by the major parts of the apparatus, counter walls, etc. is unimportant as the radiation from the thin foils suffers identically and so the efficiency calibration automatically allows for this effect. However, the absorption in the foils themselves is relevant. Even here though the effects are partially compensated for and upper limits to the errors introduced are quoted in Table III.

Leakage through Rotor

Fast neutrons leaking through the chopper will induce fissions in the fission chamber for which $\bar{\nu}$ is not that applicable to thermal neutrons. However, a cadmium difference shows that any contribution from such neutrons to the chamber rate is no greater than 0.1%. The effect on E_f will therefore be even less.

Summary

Table III shows a summary of the errors. The total correcting factor, apart from those included in Sec.6 is:

$$
\begin{aligned}
C &= -0.75\%\pm0.78\% \text{ for } 0.5\ \text{mg/cm}^2\ U^{235} \text{ foil, counters at } 45° \text{ and } 90°,\\
&= -1.79\%\pm0.78\% \text{ for } 0.1\ \text{mg/cm}^2\ U^{235} \text{ foil, counters at } 45°,\\
&= -1.14\%\pm0.78\% \text{ for } 0.1\ \text{mg/cm}^2\ U^{235} \text{ foil, counters at } 90°,\\
&= -0.48\%\pm0.77\% \text{ for } 0.14\ \text{mg/cm}^2\ U^{235} \text{ foil, counters at } 45° \text{ and } 90°.
\end{aligned}
$$

6. RESULTS

The data derived from the time-analyzer spectra were fitted, over a range of 10 timing channels, to a suitable function using a least-squares computer program. Values of T_f and T_γ were read off from the fitted function at the channel numbers, not necessarily integral, appropriate to neutrons with a velocity of 2200 m/sec.

The primary data then yields a ratio:

$$R=[T_f\times F\times(C_\gamma-R_\gamma)]/[T_\gamma\times B\times(C_f-R_f)].$$

In the notation of Sec. 2, σ_F is calculated by multiplying by a factor K made up as follows:

$$K=T\times[\sigma_T/(1-T)]\times L\times T_P\times C,$$

where $T\times\sigma_T/(1-T)$ is computed from σ_T and N_a, using $\sigma_T=695.0\pm1.8$ b from Ref. 2; L is a channel-width correction, necessary because equal channel widths are used for recording the boron events and the fission events although the flight paths are different; T_P is the calculated transmission of parts of the apparatus in the beam and between the two foils; and C, the combined correcting factor, is the resultant of all the corrections listed in Sec. 5.

The results of several sets of measurements are summarized in Tables IV and V, the errors quoted being statistical errors. The first measurements, Table IV, were all made with a fixed counter geometry in which the liquid scintillation counters were at approximately 45° to the beam direction, and the 0.5 mg/cm² foil was in the fission chamber.

The χ^2 test for these data yields a probability of 7% of exceeding the distribution of values given above. These data serve to demonstrate the reproducibility of the results under the changes in conditions listed in Table IV but do not yield the true value of σ_F because of the effect of the variation of scintillator efficiency with angle. The data form part of the data used to

TABLE IV. Results of measurements using a fission-chamber foil of 0.5 mg/cm² and neutron counters at approximately 45° to the beam direction.

Foil thickness (mg/cm²)	Relative beam strength	Remarks	R	K	Statistical accuracy (%)	RK (barns)
133.18	1.00		0.2132	2607	1.75	555.8±9.5
133.18	1.00		0.2078	2607	1.44	541.6±7.9
133.18	1.00		0.2127	2607	1.48	554.6±8.1
133.18	1.00		0.2070	2607	1.19	539.6±6.5
133.18	1.00		0.2044	2607	2.03	532.7±11.1
133.18	1.00		0.2096	2607	1.21	546.4±6.6
133.18	1.00		0.2021	2607	1.17	527.0±6.4
133.18	0.6		0.2117	2607	1.34	551.8±7.3
135.63	0.6		0.2167	2549	1.44	552.6±7.9
135.63	1.00		0.2131	2549	1.07	543.4±5.8
135.63	1.00	Time analyzer Reversed	0.2063	2549	1.49	526.0±8.1
135.63	1.00	Wide resolving time (1 μsec) for coincidence A	0.2130	2549	1.30	543.0±7.1
135.63	1.00	High boron chamber bias	0.2141	2549	0.96	545.7±5.2
			Weighted average		0.36	543.0±2.0

TABLE V. Results of measurements using various fission-chamber foils and two different geometrical arrangements of the fast neutron counters. The first line of the table contains the weighted average of the data in Table IV, the remainder of the data was taken using a thick U^{235} foil of 135.63 mg/cm².

Thin U^{235} foil (mg/cm²)	Geometry (angle of neutron counters)	R	Statistical accruacy (%)	K	RK (barns)	Weighted average (statistical errors only) (barns)
0.5	45°		0.36			543.0±2.0
0.5	90°	0.2414	0.94	2549	615.5	619.7±4.7
0.5	90°	0.2457	1.25	2553	627.0	
0.1	45°	0.2265	2.19	2523	571.5	
0.1	45°	0.2266	2.33	2523	571.6	576.4±5.8
0.1	45°	0.2298	1.29	2523	579.6	
0.1	90°	0.2326	2.00	2542	591.5	586.6±7.0
0.1	90°	0.2296	1.51	2542	583.8	
0.14	45°	0.2220	0.98	2556	567.6	568.8±3.8
0.14	90°	0.2226	0.89	2560	569.7	

arrive at the value of σ_F. The remainder of the data appear in Table V.

From the data taken with fission chamber foil thicknesses of 0.5 and 0.1 mg/cm² an extrapolation to zero thickness has been made as described earlier and gives σ_F equal to 581.5±6.5 b.

A weighted average of the data using the 0.14 mg/cm² foil gives 568.8±3.8 b.

The error of 6.5 b on the first measurement is made up of the statistical errors, the error in Na and the extrapolation error discussed earlier while the 3.8-b error on the second measurement is due to statistics and foil. There is also a systematic error in K common to all calculated values of 0.78%. Combining the above values and including the systematic errors as well as the statistical errors, the weighted average value for σ_F becomes

$$\sigma_F = 572 \pm 6 \text{ b}.$$

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