Fission Cross Sections of the Uranium Isotopes, 233, 234, 236, and 238, for Fast Neutrons

R. W. LAMPHERE
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received March 7, 1956)

Fission cross sections of the uranium isotopes, 233 and 238, have been measured from 5 and 500 kev, respectively, to 3-Mev neutron energy. Results of similar measurements to 4 Mev for U^{234} and U^{236} are included.

Neutrons were produced by use of a beam of monoenergetic protons from a Van de Graaff generator impinging upon a tritium gas target, for all work except the low-energy end of the U^{233} curve, where the $Li^7(p,n)Be^7$, and $V^{51}(p,n)Cr^{51}$ reactions were employed. A U^{235} fission foil was used to measure neutron flux. Measured quantities were the ratios of the fission cross sections of other isotopes to that of U^{235}, and these ratios are believed to be accurate to about 2%. Ratios were interpreted by use of the currently-accepted curve for fission cross section of U^{235} as presented in the neutron cross section compilation BNL-325.

The U^{233} cross section decreases monotonically with increasing energy except for a small rise around 200 kev, and a broad maximum around 2.1 Mev.

The U^{238} curve shows a long tail extending down to 0.500 Mev, as contrasted with U^{236} which drops sharply near threshold. This tail shows two plateaus at 1.2 and 1.0 Mev and one perhaps at 0.65 Mev. The cross section rises to 0.59 barn at 3 Mev.

INTRODUCTION

MEASUREMENTS of the fast fission cross sections for U^{233} and U^{238} have been made previously at Los Alamos and elsewhere, and have appeared from time to time in the classified literature. However, it was felt worthwhile to make separate measurements at another laboratory.

The procedure followed quite closely in most respects that used for the U^{234} and U^{236} measurements.[1] Additional techniques applied to some of the measurements included use of an 8-foil fission chamber, and also of a spiral chamber for some of the U^{238} work, and use of the $Li^7(p,n)Be^7$ and the $V^{51}(p,n)Cr^{51}$ reactions for the lower portion of the U^{233} curve. The V neutron source was used from 4.8 kev to 152 kev, and the Li source from 148 to 542 kev. The T source was used above 317 kev. Suitable targets of these materials were bombarded with monoenergetic protons supplied by the large Oak Ridge Van de Graaff in the case of the T and Li. The small, high-current Van de Graaff was used to bombard the V.

The U^{234} and U^{236} results, previously reported,[1] are included here for completeness, and also because the accepted curve for the U^{235} cross section has been changed slightly in the meantime. Furthermore, since the U^{235} cross section up to 3 Mev has become available, it is now possible to report the ratios to U^{235}. These ratios are felt to be more accurately known than the U^{235} cross section itself, and so are given in some detail in order that, as the U^{235} cross section becomes better known, the ratios may be used directly to get the other cross sections to comparable accuracy.

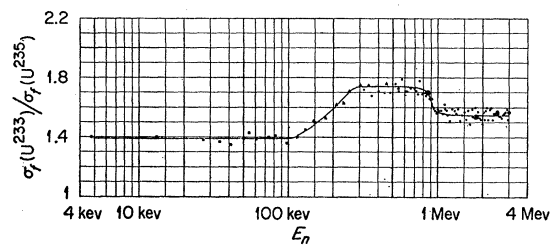

FIG. 1. The ratio of the fission cross section of U^{233} to that of U^{235} as a function of neutron energy.

[1] R. W. Lamphere and R. E. Greene, Phys. Rev. **100**, 763 (1955).

RESULTS

Figures 1–3 show the measured fission ratios as functions of neutron energy. Two circles around a point indicate that the counting statistics were ½% or better. A single circle indicates statistics of 1% or better. The standard deviations for other points exceed 1%. Table I summarizes the standard deviations and energy resolutions of points taken to establish these ratio curves. The table, in conjunction with the energy-

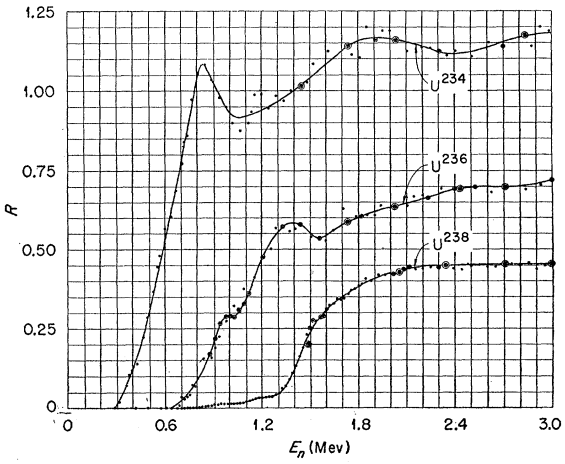

FIG. 2. The ratios, R, of the fission cross sections of the uranium isotopes 234, 236, and 238, to that of 235.

independent uncertainties estimated in a later paragraph, reflects the degree of integrity of each curve at any given energy.

The data for the U^{233} and U^{238} ratios were taken in several different runs, separated by intervals of a month or more. This required setting up the experimental apparatus anew for each run. Agreement between data from each run, between data using the various neutron counters to be described (in the case of U^{238}), and between data obtained by use of the three different neutron sources (in the case of U^{233}), was satisfactory.

A small error in neutron energy can cause a large error in the neutron cross section over the steeply-rising portion of the U^{238} curve. During one run in particular, difficulty was encountered with air leaking into the

TABLE I. Summary of points taken to establish the fission ratios.

Isotope	Energy range Mev	Neutron source	Number of points	Average counting statistics %	Average resolution kev
U^{233}	0.004–0.152	V	14	2.25	5.7
	0.148–0.542	Li	9	0.90	18
	0.319–3.00	T	73	1.41	61
U^{234}	0.290–0.500	T	8	5.95	67
	0.500–3.00	T	50	1.07	69
	3.00 –4.00	T	12	0.76	99
U^{236}	0.688–0.850	T	9	6.42	61
	0.850–3.00	T	50	0.88	67
	3.00 –4.00	T	11	0.72	99
U^{238}	0.420–0.800	T	12	17.5	39
	0.800–1.30	T	25	3.44	57
	1.30 –1.499	T	10	1.27	63
	1.50 –3.00	T	43	0.66	62

tritium gas cell. Since at the same time one also had a small and variable rate of loss of tritium gas out of the cell through the 0.05-mil nickel entrance foil, it was not possible to tell from the cell pressure how much was tritium and how much was air. As air has roughly 5 times the stopping power of tritium for the incident protons, the effect of a 30% admixture of air into the 3 cm long gas cell with $\frac{1}{2}$ atmosphere total pressure would result in a decrease of 25 kev in average neutron energy at $1\frac{1}{2}$ Mev, and also of course in a greater energy spread. For example, this would account completely for the discrepancy between the curve and the point (0.34% statistics) at 1.49 Mev, and consequently this point, although shown, was not considered in drawing the curve. This uncertainty in energy was much smaller for most points, about ±10 kev, and in view of the very tight schedule of other work for the Van de Graaff, it was decided not to repeat this part of the work.

The fission cross section of U^{235}, as given in BNL-325,[2] is plotted in Fig. 4. The portion of the curve between

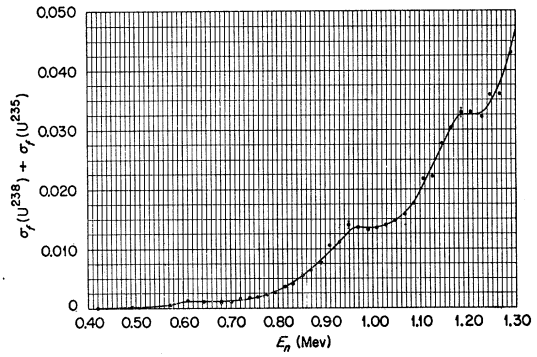

FIG. 3. The low-energy portion of the U^{238} curve from Fig. 2, drawn to an expanded scale in order to show the "plateaus."

0.4 and 1.6 Mev is based largely on the work of Diven.[3] Using this and the above ratios, the fission cross sections for the other uranium isotopes have been calculated, and are shown in Figs. 4, 5, and 6. Table II serves as an aid to closer reading of the curves. Previous work to 3-Mev neutron energy has been summarized in BNL-325. Table III shows the extent of agreement between the work described herein and the results given in BNL-325.

The minimum about 200 kev in U^{233} might be due to a peak existing in U^{235}, since the U^{235} cross section is not well established below about 400 kev. The broad rise around 2.1 Mev coincides exactly with that for U^{235}, as can be seen from the fact that the ratio curve is perfectly flat throughout this energy region.

The low-energy tail on the U^{238} cross section is shown in Fig. 6. The plateaus about 1.2 and 1.0 Mev are well established, and have been noted by others.[2] The plateau at 0.65 Mev is not definitely established because of the poor counting statistics prevailing in this region.

The hump at 2.1 Mev in the U^{235} curve is slight. Possibly it would be found to be nonexistent if sufficient data were accumulated from 1 to 3 Mev. However, if it is real, then the existence of maxima at precisely the same energy in U^{233} and U^{235} is remarkable. The ratio of the fission cross section of U^{238} to that of U^{235} is characterized by a slow steady rise between 2 and 3 Mev. The maximum in the U^{235} curve causes the merest suggestion of a maximum to appear in the U^{238} cross

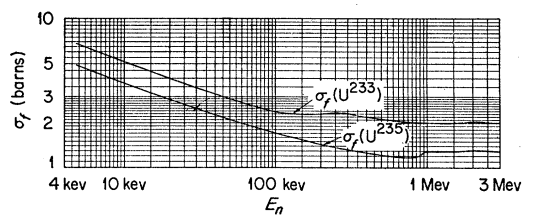

FIG. 4. The fission cross sections of U^{233} and U^{235} *versus* neutron energy. The curve for U^{235} has been taken from reference 2. That for U^{233} has been derived from the ratio curve in Fig. 1, and this curve for U^{235}.

[2] D. J. Hughes and J. A. Harvey, Neutron Cross Sections, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).

[3] Benjamin C. Diven, Los Alamos Scientific Laboratory Report LA-1336, February 3, 1953 (unpublished).

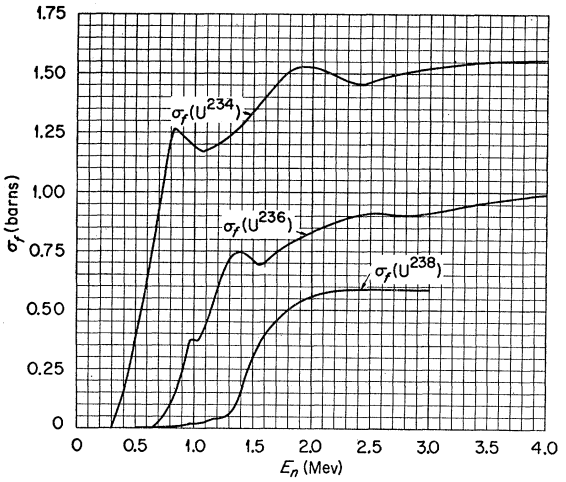

FIG. 5. The fission cross sections of the uranium isotopes 234, 236, and 238, as derived from Fig. 2 and the U^{235} curve in Fig. 4.

section when the ratio curve is interpreted by use of the U^{235} cross section.

PROCEDURE

Following reference 1, foils were prepared which contained about 4.0 mg of natural uranium plated over a circle of one-inch diameter on nickel backing 0.002 inch thick. These were carefully compared to very thin foils containing only 0.200 mg on a circle of one-inch diameter, to find an equivalent weight, W', which is always less than 4 mg by an amount proportional to the counting loss due to self-absorption and to bias setting. Similar foils were made from U^{233} and from U^{235}. In fact, the U^{235} foils were the same ones described in reference 1, and in addition, 3 more of the 4 mg foils were made and calibrated for use in the 8-foil chamber. All foils were prepared by R. E. Greene. The heavy foils of U^{233} or of natural uranium were placed back to back with foils of U^{235} in the fission comparison chambers. In each case, six of the thin foils served to determine the equivalent weights of the 4 mg foils. The use of natural uranium for the U^{238} determinations is to be preferred over pure U^{238} as its use facilitates neutron weighing and alpha activity comparisons, while the correction for U^{235} content is small and can be made to good accuracy. It is not so good, however, for measurements down on the low-energy tail since counts from the U^{235} are then comparable to counts from U^{238} fissions and so impair the statistical accuracy. Therefore, this portion of the curve was investigated both with the 8-foil chamber, shown in Fig. 7, and also with a spiral counter of conventional design.[4]

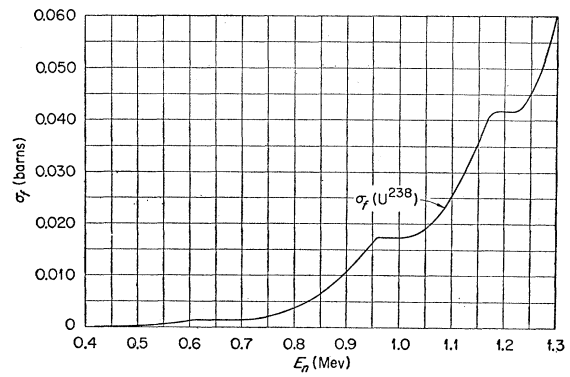

FIG. 6. The low-energy portion of the U^{238} curve from Fig. 5, drawn to an expanded scale to show the "plateaus" in the cross section.

A. Use of Spiral Counter

The spiral counter contained 117 mg of pure U^{238} (except for 6.1 parts per million of U^{235}). It was mounted at 10° to the beam axis and at a distance so that it subtended a half-angle of 5.7° about the 10° line. A long counter of conventional design was placed at 10°

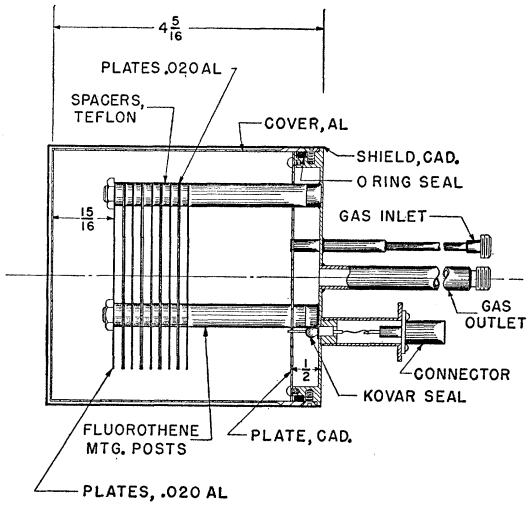

FIG. 7. The 8-foil fission comparison chamber used in many of the U^{238} measurements. Dimensions are given in inches.

on the opposite side of the beam axis and at a distance such that it subtended a like half-angle as seen from the tritium gas cell from whence the neutrons originated. A normalization point was taken to 0.84% statistics at a neutron energy of 2.03 Mev, and the U^{238} cross section taken to be 0.561 barn from the work done with the other two counters. The long-counter response was assumed to be independent of neutron energy between 2.03 Mev and 420 kev, and was used as a flux monitor. Thus for any energy in this region, the ratio of spiral to long counter counts served to determine the U^{238} cross section by simply dividing this ratio by the ratio at the normalization point and then multiplying by 0.561 barn.

Since a spiral counter has no observable plateau, it is important to monitor the gain of the amplifier in the counting channel very carefully. A check for gain

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

changes was made by returning to the normalization point after all data had been taken. Six hours were required for all the data, and the spiral counter counts at the normalization point for a fixed long counter count were 113.9 and 111.3 scales of 64 at start and finish, respectively. The average of these figures was used in the calculations. The discriminator setting which would just eliminate noise (no counts in a 5-minute interval) was found, and all data taken with a setting 1.5 times this. Occasional checks for noise were made during the course of the work but none was observed.

B. 8-Foil Counter

By use of the 8-foil fission comparison chamber shown in Fig. 7, the counting rate was increased by a factor of about 2.6 over that obtainable with a similar 2-foil chamber which is described in reference 1. It was mounted in the neutron beam so that the first pair of foils subtended a half-angle of 15° as seen from the target. The foils were mounted in pairs, always with a natural uranium one back to back with one of U^{235}. All 8 foils used in this counter had previously been tested to find the radial distribution of uranium on them. This was done by successively masking concentric areas with thin Al foil and alpha counting the unmasked portion. The specific activities from four approximately equal concentric areas were measured for each of the 8 foils. A variation of plus or minus 10% was found in some cases. In placing them in the chamber they were matched so that, as far as possible, foils with closely similar distributions were placed back to back. This cut down the error which can arise when one compares foils with different radial deposition densities in the neutron beam from a Van de Graaff. This error arises from the fact that the neutron intensity falls off with angle measured from the 0° (beam) axis.[5] The correction for this effect was calculated to be −0.1% at 2.5 Mev. For the 2-foil chamber, foils were picked which had essentially the same radial distributions so that the correction was negligible.

The ratios of the W's for the four pairs of foils used in this chamber differed slightly. It was necessary, therefore, to calculate the ratios of the neutron fluxes at the four positions in the chamber in order to determine a properly weighted over-all figure for the mass ratio of the natural uranium to the U^{235}. This calculation involves simple integrations to get $\langle r^{-2}\rangle_{Av}$ for each position, since the neutron source is a line rather than a point. Since these calculations are simple they will not be discussed in detail. As the front pair of foils subtends a half-angle of 15°, it is clear that the average angle for all foils will be less, and it turns out to be 12.9°, properly weighted for flux density and W' variations over the four positions.

Because of the relatively fast count rate obtainable with this chamber, points were taken very close together over the entire curve. The inelastic scattering correction turned out to be greater than for the 2-foil chamber, and is discussed in the Appendix.

[5] Willard, Blair, and Kington, Phys. Rev. **90**, 865 (1953).

TABLE II. Fission cross section ratios to U^{235}; and fission cross section in barns at several energies, for the uranium isotopes 233, 234, 236, and 238.

	Ratios to U^{235}				Fission cross section in barns				
E (Mev)	U^{233}	U^{234}	U^{236}	U^{238}	U^{235}	U^{233}	U^{234}	U^{236}	U^{238}
0.0048	1.39	0.000	0.000	0.000	4.90	6.81	0.000	0.000	0.000
0.010	1.39	0.000	0.000	0.000	3.70	5.14	0.000	0.000	0.000
0.100	1.39	0.000	0.000	0.000	1.71	2.37	0.000	0.000	0.000
0.500	1.74	0.300	<0.005	0.0003	1.22	2.12	0.38	<0.006	0.0003
1.000	1.57	0.931	0.291	0.0136	1.28	1.99	1.19	0.372	0.0174
1.500	1.55	1.042	0.550	0.235	1.28	1.99	1.34	0.707	0.302
2.000	1.55	1.165	0.633	0.426	1.31	2.03	1.53	0.831	0.558
2.500	1.55	1.125	0.698	0.452	1.30	2.02	1.46	0.910	0.587
3.000	1.55	1.185	0.714	0.457	1.28	1.99	1.52	0.912	0.586
4.000	...	...	...	...	...	...	1.56	0.990	...

C. Measurements on Uranium-233 Using Neutrons from the $V^{51}(p,n)Cr^{51}$ Reaction

The 2-foil counter was used in all work on the U^{233} ratio. Since this ratio varies only slightly with neutron energy, inelastically scattered neutrons will have a negligible effect on the results. The thick U^{233} foil was so alpha-active that a short clipping time of 0.38 microsecond was used in the preamplifier, and a somewhat higher bias setting was employed in the amplifier. It was still possible to operate the counter on a plateau, but alpha pileup would introduce an occasional background count. This was less than 0.1% of the count rate from fissions, and was easy to evaluate, so the small correction was made for each point. The constancy of the fission ratio to that of U^{235} means also that room-scattered neutrons may be neglected. The work using the T and Li sources followed in all respects the procedure described in reference 1.

The work using V neutrons required some special considerations due to the low yield of neutrons from this reaction. One compensating advantage is that the mass of the V nucleus is so large that energy spread with angle is small for the emitted neutrons, so that one can set the counter as close as possible to the V target. Therefore a cover $\frac{3}{8}$ inch shorter than the one used in reference 1 was made, and most of the data were taken with this. Now, however, it is necessary to measure more accurately the distance between V target and U foils, as the $1/r^2$ correction for foil separation becomes appreciable, amounting to as much as 1.8% for some of the data. U foil separation was estimated to be 0.005 inch, but to reduce errors from an inaccurate

TABLE III. A comparison at selected energies of the fission cross sections in barns for uranium 233, 234, 236, and 238 with those given in the Brookhaven compilation, BNL-325.

	From BNL-325				From this work			
E(Mev)	U^{233}	U^{234}	U^{236}	U^{238}	U^{233}	U^{234}	U^{236}	U^{238}
0.029	2.91	0.000	0.000	0.000	3.48	0.000	0.000	0.000
0.150	2.36	0.000	0.000	0.000	2.28	0.000	0.000	0.000
0.500	2.06	0.415	0.000	0.000	2.12	0.38	<0.006	0.0003
1.000	1.95	1.20	0.35	0.0145	1.99	1.19	0.372	0.0174
2.000	1.87	1.56	0.80	0.528	2.03	1.53	0.831	0.558
3.000	1.85	1.53	0.86	0.545	1.99	1.52	0.912	0.586

estimate of this, about half the data were taken with foils reversed in order. Agreement between data taken with foils in "normal" and "reversed" order was excellent when this $1/r^2$ correction, and the usual beam momentum correction (which varied from 0.07% to 0.39% in the 5 to 150 kev range) were applied.

It was necessary to make accurate evaluations of the background for each run. This originated from *d-d* neutrons due to traces of deuterium in the ion source, and coming from the vicinity of the bending magnet; and also from a few neutrons coming from work in progress on another Van de Graaff located in the same building. There was also an occasional alpha count from the U^{233}. Four different runs were made to get the 4.8- to 152-kev data, using the V source. These runs were separated by intervals of a month or more. For each run, background conditions were found to be different due to such things as the amount of deuterium left in the ion source and vacuum piping from previous experiments, distance from bending magnet to fission chamber and the amount of shielding between them, and to some extent to work in progress on the other Van de Graaff. The background was evaluated for each run by operating about 10% of the time just below the $V(p,n)$ threshold at intervals spaced throughout the run, and also by recording counts during those times when the machine was off entirely. Background was then split into two parts; one time-dependent only, and the other dependent only on the number of Coulombs of beam striking the target. The running time, T, and the charge, Q, were recorded for each point taken, and a correction of the form, aT plus bQ, applied. The constants, a, and b, were different for each run, and for the two isotopes. Total correction for background varied from 10% to 0.6%, depending on energy and on conditions during the particular run. The machine was by far the greatest source of background for the first run, but improvements in deuterium handling, beam focusing, and shielding, resulted in successively smaller machine background, and in the final run there was no contribution at all from the machine. Most of this improvement resulted from the design of a new lens by C. H. Johnson which allowed the entire mass-one beam, which sometimes exceeded 100 microamperes, to be brought to bear on the V target which was now located in a scattering room about 20 feet from the magnet. This was accomplished without the need of extra strong-focusing lenses. Since fairly heavy beams, of 100 microamperes or more, of protons can now be obtained some distance from the bending magnet, a more or less permanent water shield has been installed between the magnet and the scattering room. This effectively eliminates machine background.

TABLE IV. Ratio $R=\sigma_f(U^{233})/\sigma_f(U^{235})$ using neutrons from a vanadium target. Note that with a 100-μa beam the time would be 2.78 hours per coulomb.

E kev	R	Percent statistics	δE kev	Target thickness kev	Q coul
4.8	1.402	1.7	4.0	5	5.48
13.2	1.400	2.0	6.3	8	7.52
27.0	1.375	3.2	4.4	5	7.60
34.7	1.372	2.0	2.2	5	9.79
41.0	1.354	2.2	3.1	4	3.26
50.0	1.385	2.2	2.9	4	2.70
54.6	1.430	3.3	12.2	12	1.75
60.9	1.390	2.2	3.2	6	3.57
73.8	1.400	1.9	14.5	7	3.50
82.0	1.410	2.0	3.4	4	3.74
97.5	1.361	3.0	7.6	5	2.69
115.2	1.400	3.1	7.0	5	2.91
129.1	1.451	2.3	4.4	5	2.80
152.5	1.500	2.1	4.9	4	2.98

Water cooling of the V target was necessary to dissipate the 150 watts of energy imparted to it by the beam. An atomizer was built to provide a fine sheet of spray on the target backing. This spray had to be adjusted quite carefully. Any interference with it resulted in a melted target in about 2 seconds, with disastrous effects on the vacuum in the Van de Graaff. After losing two or three targets in such a manner, a safety device was incorporated which completely eliminated such failures. This was an ion gauge mounted about two feet back along the beam pipe from the target. The ion gauge control was interlocked with the Van de Graaff belt spray supply so that a rise in pressure shut it off, promptly interrupting the beam. The targets were thin films of V evaporated on Pt or Ta disks 10 mils thick and 1.25 inches in diameter. The disk was seated on an O ring at the end of the beam tube. Inadequate cooling caused heating of this O ring which would release enough gas to shut down the machine via the interlock before even the O ring could be damaged. In fact it operated so fast that not even the sensitive trips on the vacuum gauges and pumps back at the magnet and accelerator tube had time to operate before the beam was off and the vacuum recovered.

The yield of the $V^{51}(p,n)Cr^{51}$ reaction has been measured by others,[6] and found to have many narrow resonances less than 1 kev wide spaced closely together and varying widely in height. Fourteen of these resonances, from 4.8- to 152-kev neutron energy, were picked to establish the U^{233}/U^{235} fission cross-section ratio. The V target thicknesses varied from 4 to 12 kev, most data being taken with targets 4 and 5 kev thick. For most points such targets would span more than one resonance. Average neutron energy was then determined by properly weighting the energies of the resonances spanned with their relative yields. In a few cases, the neutron energy spread was less than target thickness because of lack of levels near to the one at which the machine energy was set.

Since the $V(p,n)$ reaction has not been widely used as a source of neutrons, Table IV is included summarizing data pertinent to the points taken with this source. In this table, the results of all runs at each energy corrected for known sources of error are lumped together for brevity. Most of the data were taken with a span of 0.65 inch between V target and U foils.

[6] Gibbons, Macklin, and Schmitt, Phys. Rev. **100**, 167 (1955).

Threshold for the reaction is 1.5656±0.0015 Mev. The kinetics are defined by the relation

$$52E_n^{\frac{1}{2}}=[(1566+\delta E_p)]^{\frac{1}{2}}\cos\theta + [2601\delta E_p-(1566+\delta E_p)\sin^2\theta]^{\frac{1}{2}},$$

where E_n=neutron energy in kev, δE_p=proton energy in kev above threshold, and θ=angle of emitted neutrons with the beam axis. Table V has been computed from this relation.

ESTIMATE OF ERRORS

Sources of error have been discussed in reference 1. Table VI lists all known sources. It is, of course, possible that one or more sources of error have been overlooked. It is also possible that some systematic error exists which the experimental checks made during the course of the work (such as interchanging amplifier channels, foil positions, etc.) did not detect. Consequently a figure of 1.1% has been arbitrarily assumed for systematic errors. This is approximately equal to the root-mean-square sum of all the known sources of error.

TABLE V. $V^{51}(p,n)Cr^{51}$ energetics. Cone of neutrons has just opened fully at δE_p=0.60 kev.

δE_p kev	$E_n(0°)$ kev	$E_n(0°)-E_n(20°)$ kev	$E_n(0°)-E_n(40°)$ kev
0.00	0.58	0.00	0.00
0.60	2.32	0.28	0.96
2.50	5.35	0.33	1.31
5.00	8.70	0.35	1.38
10.0	15.0	0.40	1.67
20.0	26.6	0.58	2.08
40.0	48.6	0.85	2.75
60.0	69.8	0.95	3.23
80.0	91.2	1.00	3.63
100.0	112.0	1.05	4.05
120.0	132.8	1.10	4.48
150.0	164.2	1.20	5.10

Some errors are energy-dependent, so cannot truly be represented in a table of this kind. The figures for statistical uncertainty shown in Table VI are those applying to the relatively flat portions of the ratio curves where the cross sections have attained of the order of 70% of their maximum values. For the even isotopes, fewer counts were obtained near thresholds because of the low cross sections; and for U^{233} the statistics below 150 kev were poorer than average because of the low neutron yield of the V target. Energy uncertainties need also to be considered, particularly in the rapidly changing portions of the ratio curves. On the average, these energy uncertainties are estimated to be about plus or minus 10, 2, and 1 kev, for the T, Li, and V neutron sources, respectively. Table I lists the statistical uncertainties in the ratio measurements, and the total energy spread in the neutron beam as functions of energy.

Information obtained by use of the spiral counter between 2.03 Mev and 420 kev for U^{238} is subject to the assumption of constant neutron counting efficiency over this energy range, of the long counter which was used as a flux monitor. The amount of error introduced here is not known. However, it turned out that the curve obtained with the spiral counter agreed well within statistical accuracy with that obtained with the 8-foil counter over this range. Approximately the same number of counts was taken with each type of counter.

TABLE VI. Estimate of errors, in %.

Source	U^{233}	U^{234}	U^{236}	U^{238}
W'	0.70	0.95	0.70	0.70
Statistics	0.30	0.50	0.50	0.30
Inelastic scattering	0.00	0.30	0.40	0.50
Room scattering	0.00	0.00	0.10	0.20
Foil nonuniformity	0.20	0.20	0.20	0.10
Foil separation	0.10	0.10	0.10	0.10
Beam momentum	0.10	0.10	0.10	0.10
Gain changes	0.10	0.10	0.10	0.10
Systematic	1.10	1.10	1.10	1.10
Std. dev. of ratio	1.36	1.59	1.49	1.46
$\sigma_f(U^{235})$ uncertainty	5.00	5.00	5.00	5.00
Total uncertainty	5.19	5.25	5.22	5.20

The figure of 5% for the uncertainty in the U^{235} cross section is an average for the region from 0.4 to 3.0 Mev. Below 400 kev it is greater. The cross section from 4 to 40 kev is based largely on work done at the General Electric Company, and to some extent, to work done at Brookhaven. These results have been summarized in a paper presented at the recent Geneva Conference.[7] Measurements in this region have also been made at Los Alamos.[2] The uncertainty existing in the cross section from 4 to 400 kev has been estimated to lie between 10 and 20%.*

ACKNOWLEDGMENTS

It is a special pleasure to acknowledge the help of R. E. Greene and his group for their very fine work in preparing the uranium foils. Many thanks are also due

[7] V. L. Sailor, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 199.

* *Note added in proof.*—Since this paper was written, the U^{234} fission cross section has been remeasured in much greater detail. Below 1.0 Mev the curve had been established by a relatively small number of points taken 5 years ago. It appears that an error was made in calculating the energy for these points, and is believed to have arisen from air contaminating the tritium used in the gas target. Many new measurements were made using a gas target with tritium of known purity, using a solid ZrT target, and also by use of a Li target. From this work the following comments apply to $\sigma_f(U^{234})$:

(1) A distinct tail was found extending into the low-energy region, giving σ_f=0.025 barn at 100 kev.
(2) A small "bump" was found at 320 kev where σ_f = 0.16 barn.
(3) At 400 kev the curves shown in this paper should be shifted about 50 kev to the left, and at 800 kev the shift is about 20 kev.
(4) The minimum at 1.02 Mev is a bit deeper (σ_f = 1.11 barns) than shown, and is followed by a sort of damped wave around 1.15 Mev, as suggested by the points in Fig. 2.

Curves of these cross sections plotted to much larger scale are available from the author on request.

the members of the Van de Graaff groups; J. K. Bair, H. O. Cohn, J. Judish, C. H. Johnson, J. D. Kington, P. H. Stelson, and H. B. Willard for their generous assistance in operation of the generators; and to C. R. Baldock and J. R. Sites for uranium analyses.

APPENDIX A. INELASTIC SCATTERING CORRECTION

The results of reference 1 were used to establish a correction for the 2-foil chamber. Since the correction is larger for U^{238} than it is for U^{234} or U^{236}, a somewhat more accurate estimate of it is attempted here. In reference 1 the correction was taken to be constant with neutron energy. For U^{238} it is clear that this effect will be considerably less down on the long tail of the curve below 1 Mev than it will be above 2 Mev. Some idea of the way this correction will vary can be gotten by considering how large it was found to be for the flat parts of the curves for U^{234}, U^{236}, and U^{238}, and by noting the shapes of the fission cross sections of these three isotopes. With these things in mind it was estimated that the inelastic scattering correction, s, varied linearly with neutron energy, from 0.6% at $E=0.80$ Mev to 2.6% at $E=1.80$ Mev, and thereafter varied more slowly, becoming 2.9% at 3.2 Mev neutron energy. The values of s are probably good to 0.4% standard error above 2 Mev and to 0.6% below. (For example, at 2.3 Mev, $s=(2.7\pm0.4)\%$.)

The scattering correction for the 8-foil counter shown in Fig. 7 was found by comparing the results of several measurements made with it to measurements made with the 2-foil counter. The correction was found to average 1.7 times as much as for the 2-foil counter, and was assumed to vary with energy in the same way as it does for the small counter. A rough calculation of the scattering correction for the large counter was made for the case of primary neutrons with 3-Mev energy. This checked very well with experiment and indicated that well over half the effect was due to the Al plates inside the counter.

APPENDIX B. FOIL COMPARISONS

The isotopic composition of the uranium used in foil preparation was determined by Dr. Baldock and Dr. Sites of this laboratory, by mass spectrographic methods. The U^{235} was 99.90% pure, hence required no correction for impurities to be applied to the experimental data. The U^{233} was $99.1\pm0.1\%$ U^{233}, $0.8\pm0.1\%$ U^{238}, and $0.2\pm0.1\%$ U^{235}. These impurities were corrected for. Impurities other than isotopic were removed by chemical methods prior to plating. The mass of uranium on each foil was determined by microchemical techniques, and the foils were then compared by alpha counting and neutron weighing as described in Appendix B of reference 1. The results are given in Table VII, and the equivalent masses, W', in Table VIII. In these tables all masses are in micrograms. The thin-foil masses are those obtained by microchemical techniques during their preparation. The next two columns list the deviations from the average fission and α activity per microgram on the basis of the masses listed. Counting statistics were 0.2% for the U^{233} foils and for the fission activity of the U^{238} foils. Statistics were 0.37% for the α activity of the U^{238} foils.

TABLE VII. Thin foil comparisons.

Foil	Mass (μg)	δf%	$\delta\alpha$%
23K1	197.8	+1.0	+1.1
23K2	197.6	0.0	+0.2
23K3	199.2	−0.2	−0.2
23K4	198.8	−0.7	−1.2
23K5	199.0	+0.3	+0.3
23K6	199.4	−0.3	0.0
Standard error		0.22	0.28
NK1	196.9	+0.8	+0.9
NK2	198.3	−0.7	−0.6
NK3	195.9	+0.2	+0.4
NK4	198.1	−0.7	−0.7
NK5	197.0	+0.1	+0.1
NK6	195.9	−0.3	−0.1
Standard error		0.22	0.23

TABLE VIII. Equivalent masses of foils used to determine cross sections.

Foil	W'(μg)
23K7	3393
NK7	3597
25K15	3602
25K14	3571
NK8	3580
NK11	3550
25K11	3554
25K13	3524
NK12	3480

The thick foils were weighed in a flux of thermal neutrons by comparing their activity with that of the thin foils. These measurements were made in the counter in which the thick foils were to be used and with the same bias and gain settings to be used later in the cross section measurements, since W' is a function of amplifier bias and gain settings. These are monitored by a pulse generator having a signal that is fed into the high-voltage plate (or plates) of the counter. Since capacities between high-voltage and collector plates will be different for different counters, the W' determined for one counter will not in general be right for a different counter unless the bias is adjusted in just such a way as to bring this about. This was done for the thick foils, NK7 and 25K14 which were used in the 2-foil chamber as well as in the 8-foil chamber. Consequently the values of W' listed in Table VIII are correct for their use in either chamber.

Over-all statistical accuracy is 0.25% for the equivalent weights. The last 8 foils in Table VIII are listed in the order in which they were placed in the 8-foil chamber, from front to back. The estimated error from all sources is 0.5% for each foil.