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# Neutron-Induced Fission Cross Sections of $U^{234}$ and $U^{236}$

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The fission cross sections of the uranium isotopes, 234 and 236, have been measured from their thresholds to 4.0-Mev neutron energy by use of neutrons from the $T(p,n)He^3$ reaction. Neutron energy spread varied from 60 to 100 kev for most points.

$U^{234}$ has a threshold at about 300 kev, rises to 1.24 barns at 850 kev, dips to 1.08 barns at 1.06 Mev, rises to 1.47 barns at 1.9 Mev, dips to 1.40 barns at 2.4 Mev, and then rises to 1.55 barns at 4.0 Mev. Variations in between these points appear smooth with the energy spread present in the neutron beam.

Similarly, $U^{236}$ has a threshold at about 670 kev, rises to 0.36 barn at 970 kev and remains nearly constant to 1.04 Mev when it again rises, reaching 0.75 barn at 1.4 Mev, falling to 0.66 barn at 1.56 Mev, rising to 0.89 barn at 2.5 Mev, falling to 0.87 barn at 2.7 Mev, and then rising to 0.99 barn at 4.0 Mev.

The thresholds referred to are the energies at which the cross sections are only about 1% of their values on the relatively flat portion of the curve between 2 and 3 Mev.

Results are believed to be accurate to 6.0%.

## INTRODUCTION

THE $U^{234}$ cross section has been measured earlier at this laboratory,[1] but with foils having a large uncertainty in the amount of uranium deposited. Through the efforts of one of us foils were prepared which had an estimated error of less then 1% in the amount of deposited uranium. Foils were plated with the isotopes 234, 236, and also 235 which was used as the flux monitor. Although $U^{236}$ had been measured previously at Los Alamos and at this laboratory it was felt advisable to run over it again since there was some question of foil accuracy in the earlier work.

The fission cross section of $U^{234}$, or $U^{236}$, was compared to that of $U^{235}$ by mounting two foils back-to-back in the double ionization chamber shown in Fig. 2, and placing the chamber in a beam of neutrons of known energy. The ratio of cross sections obtained from the raw data is subjected to various corrections to be described, and then multiplied by the $U^{235}$ cross section to yield the fission cross section of the isotopes, 234 and 236, as plotted in Fig. 1.

A correction was determined for the effect of neutrons scattered from the fission chamber material. This amounted to 0.6% for $U^{234}$ and 1.9% for $U^{236}$. Accordingly all measured values were increased by these amounts. The $U^{236}$ results are in good agreement with the latest Los Alamos work.[2] The $U^{234}$ results show that the cross section reported in reference 1 should be increased by 16%.

Other fast neutron fission cross sections which have been published in the unclassified literature include $Np^{237}$,[3] $Th^{232}$,[4] and natural uranium.[4]

## RESULTS

Figure 1 shows the fission cross sections of $U^{234}$ and $U^{236}$, and Tables I and II list the points upon which the curves are based. The number of counts varies widely from point to point. The statistics listed apply to the count ratio of unknown to monitor foil, and so reflect the statistical counting accuracy of the cross section. Background was zero in all cases. Those points on the curve which have very good statistics are circled. The way in which the neutron energy spread varied

[1] R. W. Lamphere, Phys. Rev. **91**, 655 (1953).

[2] R. L. Henkel (private communication).

[3] E. D. Klema. Phys. Rev. **72**, 88 (1947).

[4] *Neutron Cross Sections*. U. S. Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1952).

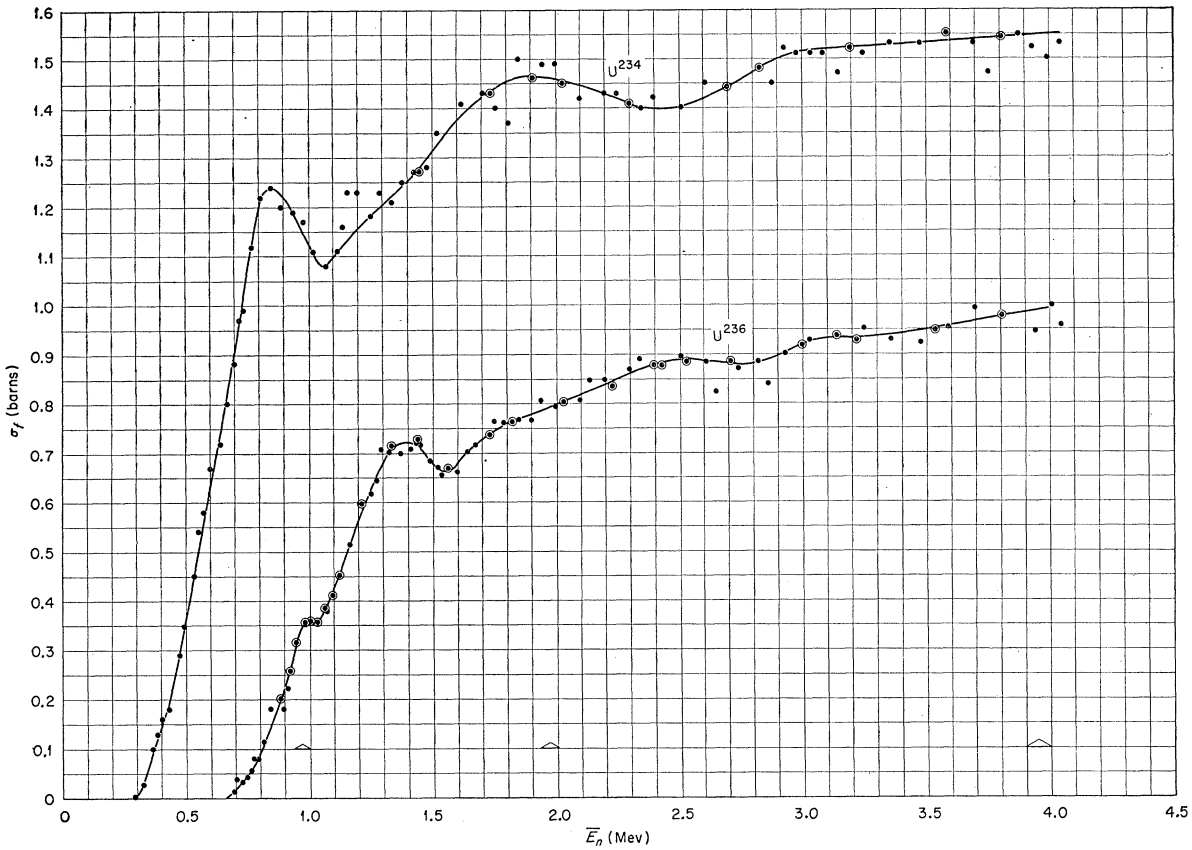


FIG. 1. Fission cross sections of the uranium isotope, 234 and 236, as a function of neutron energy.

with energy is shown by the little triangles below the curves, although in the region of the first irregularity in the $U^{236}$ cross section, resolution was improved somewhat by thinning the gas target. This irregularity was first observed by Henkel *et al.*[2] at Los Alamos. Our findings in this region are in excellent agreement with theirs.

The curves show the cross sections intersecting the zero axis, which of course is not strictly true. The fission reaction, being exothermic, does not show a true threshold, and what one considers as the threshold will depend on the application. For example, these isotopes can still be used as good reliable threshold detectors since the cross sections change so rapidly with energy.

The reason for the dips in the curves is not known. Possibly it is due to resonance effects in certain fission modes with neutron energy. Analysis of fission products obtained with neutrons of energy corresponding to a minimum in cross section, compared to a similar analysis for neutrons corresponding to some other part, say a maximum, of the curve might yield pertinent information on this point.

## PROCEDURE

The main features of the procedure were the same as in reference 1. Some changes and additions were made to improve accuracy, and these will be described.

As before, the thick foil technique was used; the thick foils contained 4.0 milligrams of uranium plated over a one inch diameter circle. These were placed back to back in the double fission chamber shown in Fig. 2, one foil containing $U^{235}$ and the other either $U^{234}$ or $U^{236}$. The Oak Ridge 5-Mev Van de Graaff was used, together with a tritium gas target, to produce the neutrons. The fission chamber was placed in front of the gas cell at 0° relative to the proton beam so that the foils subtended a 15° half-angle as seen from the cell. The chamber was surrounded with a 0.020-inch thick cadmium shield.

The thin foils used for reference contained only 0.200 milligram of uranium. This reduced self-absorption of fission fragments to a very low value so that differences in self-absorption between the $U^{235}$ foils and the $U^{234}$ or $U^{236}$ foils could be neglected. Self-absorption could only be serious if plating was very nonuniform. To check this point several of the thin foils were divided into 4 approximately equal concentric areas by using masks, and the alpha activity from each area measured. The activity per unit area for the thin foils was found to be constant to within 25% in all cases. Examination under a microscope showed the surfaces of the foils to be coated all over, with very little clustering. The backing material was in all cases 0.002-in. thick nickel shim

TABLE I. Points taken to determine curve of $\sigma_f(U^{234})$ *versus neutron energy.*

| $E_n$(Mev) | $\sigma_f$(barns) | % statistics | $E_n$(Mev) | $\sigma_f$(barns) | % statistics |
|---|---|---|---|---|---|
| 0.29 | 0.003 | 50.0 | 1.71 | 1.43 | 2.8 |
| 0.32 | 0.025 | 25.0 | 1.74 | 1.43 | 0.3 |
| 0.36 | 0.098 | 12.0 | | | |
| 0.38 | 0.14 | 6.2 | 1.76 | 1.40 | 2.7 |
| 0.40 | 0.16 | 13.5 | 1.81 | 1.37 | 2.8 |
| | | | 1.85 | 1.50 | 2.8 |
| 0.43 | 0.18 | 10.0 | 1.91 | 1.46 | 0.8 |
| 0.47 | 0.29 | 3.6 | 1.95 | 1.49 | 2.7 |
| 0.49 | 0.35 | 4.5 | | | |
| 0.53 | 0.45 | 3.7 | 2.00 | 1.49 | 2.7 |
| 0.55 | 0.54 | 3.2 | 2.03 | 1.45 | 0.3 |
| | | | 2.10 | 1.42 | 2.8 |
| 0.57 | 0.58 | 3.4 | 2.20 | 1.43 | 2.7 |
| 0.60 | 0.67 | 3.3 | 2.25 | 1.43 | 2.8 |
| 0.64 | 0.72 | 1.8 | | | |
| 0.67 | 0.80 | 3.0 | 2.30 | 1.41 | 0.8 |
| 0.70 | 0.88 | 3.0 | 2.35 | 1.40 | 2.7 |
| | | | 2.40 | 1.42 | 2.8 |
| 0.72 | 0.97 | 2.6 | 2.51 | 1.40 | 2.1 |
| 0.74 | 0.99 | 2.9 | 2.61 | 1.45 | 2.7 |
| 0.77 | 1.12 | 2.8 | | | |
| 0.81 | 1.22 | 1.7 | 2.70 | 1.44 | 0.7 |
| 0.85 | 1.24 | 1.6 | 2.83 | 1.48 | 0.3 |
| | | | 2.88 | 1.45 | 2.7 |
| 0.89 | 1.20 | 1.9 | 2.93 | 1.52 | 2.1 |
| 0.94 | 1.19 | 2.8 | 2.98 | 1.51 | 2.7 |
| 0.98 | 1.17 | 2.2 | | | |
| 1.02 | 1.11 | 2.7 | 3.04 | 1.51 | 2.1 |
| 1.07 | 1.08 | 2.1 | 3.09 | 1.51 | 2.7 |
| | | | 3.15 | 1.47 | 2.1 |
| 1.12 | 1.11 | 2.1 | 3.20 | 1.52 | 0.2 |
| 1.14 | 1.16 | 2.8 | 3.25 | 1.51 | 2.0 |
| 1.16 | 1.23 | 2.1 | | | |
| 1.20 | 1.23 | 2.8 | 3.36 | 1.53 | 2.7 |
| 1.25 | 1.18 | 2.2 | 3.48 | 1.53 | 2.7 |
| | | | 3.59 | 1.55 | 0.8 |
| 1.29 | 1.23 | 2.8 | 3.70 | 1.53 | 2.7 |
| 1.34 | 1.21 | 2.2 | 3.76 | 1.47 | 2.5 |
| 1.38 | 1.25 | 2.8 | | | |
| 1.43 | 1.27 | 2.1 | 3.81 | 1.54 | 0.3 |
| 1.45 | 1.27 | 0.3 | 3.88 | 1.55 | 2.7 |
| | | | 3.94 | 1.52 | 2.1 |
| 1.48 | 1.28 | 2.8 | 4.00 | 1.50 | 2.8 |
| 1.52 | 1.35 | 2.0 | 4.05 | 1.53 | 2.8 |
| 1.62 | 1.41 | 2.6 | | | |

stock from the same roll. The same plating setup was used throughout, although different cells were used for the various isotopes to avoid cross-contamination.

Six foils of thin $U^{235}$, and ten each of $U^{234}$ and $U^{236}$ were prepared. The thermal column of the Oak Ridge graphite reactor was used to compare the fissionability of foils within each group. Since in each case they were made from the same source material, these results should give a constant figure for the fission rate per milligram for the same neutron flux. To obviate the need for flux measurements the comparisons were done as follows:

One of the thin foils, say number 1, was placed in the comparison chamber shown in Fig. 2, facing towards the front of the chamber. Another foil, say number 2, was then inserted facing towards the rear. The chamber was then put into the thermal flux and a fixed number of counts taken on the front foil. The number 2 foil was then replaced with number three and the same number of counts taken on the front foil, and so on for each of the thin foils. In this way the fissionability of all except number 1 could be compared directly without the need for making any flux measurements or corrections for absorption of the thermal neutrons by the foil backing.

The floor of the thermal column is the bottom of a tank of water about 5 feet square. The flux is fairly constant at around $7\times10^7$ neutrons/cm$^2$ sec over a square foot at the center but falls off rapidly outside of this area. To find out whether nonuniformities in flux could affect the comparisons, data was taken with the counter face down in the center of the floor of the tank, and also at 4 positions spaced around a 16-in. diameter circle surrounding the center point. At these points the rate of change of flux with radius was quite large, but no effect was apparent in the foil comparisons. Since counting was very fast, very good statistics were taken, about 0.2% being average for the standard deviation of any given ratio.

The foils were also alpha counted and a specific

TABLE II. Points taken to determine curve of $\sigma_f(U^{236})$ *versus neutron energy.*

| $E_n$(Mev) | $\sigma_f$(barns) | % statistics |
|---|---|---|
| 0.69 | 0.014 | 29.0 |
| 0.70 | 0.038 | 10.3 |
| 0.72 | 0.034 | 21.0 |
| 0.74 | 0 044 | 18.0 |
| 0.76 | 0.056 | 13.8 |
| 0.77 | 0.081 | 4.2 |
| 0.79 | 0.080 | 13.4 |
| 0.81 | 0.115 | 4.7 |
| 0.84 | 0.182 | 5.7 |
| 0.88 | 0.203 | 1.0 |
| 0.89 | 0.182 | 4.0 |
| 0.91 | 0.224 | 5.6 |
| 0.92 | 0.259 | 1.1 |
| 0.94 | 0.316 | 0.9 |
| 0.98 | 0.358 | 0.9 |
| 1.00 | 0.361 | 0.9 |
| 1.03 | 0.358 | 1.0 |
| 1.06 | 0.387 | 1.0 |
| 1.07 | 0.380 | 3.4 |
| 1.09 | 0.413 | 1.0 |
| 1.12 | 0.452 | 0.9 |
| 1.16 | 0.516 | 2.2 |
| 1.21 | 0.598 | 0.9 |
| 1.25 | 0.618 | 2.9 |
| 1.27 | 0.645 | 2.9 |
| 1.29 | 0.710 | 2.9 |
| 1.32 | 0.701 | 2.8 |
| 1.33 | 0.717 | 0.7 |
| 1.34 | 0.718 | 2.8 |
| 1.37 | 0.700 | 2.9 |
| 1.41 | 0.710 | 2.9 |
| 1.43 | 0.723 | 2.8 |
| 1.44 | 0.728 | 0.7 |
| 1.45 | 0.719 | 2.8 |
| 1.49 | 0.684 | 2.2 |
| 1.52 | 0.671 | 2.8 |
| 1.54 | 0.656 | 3.0 |
| 1.56 | 0.670 | 0.6 |
| 1.60 | 0.662 | 2.9 |
| 1.64 | 0.702 | 1.8 |
| 1.67 | 0.717 | 2.7 |
| 1.73 | 0.737 | 0.35 |
| 1.75 | 0.766 | 1.9 |
| 1.79 | 0.763 | 2.2 |
| 1.82 | 0.763 | 0.9 |
| 1.85 | 0.766 | 2.0 |
| 1.90 | 0.768 | 2.6 |
| 1.94 | 0.807 | 2.8 |
| 2.00 | 0.794 | 1.8 |
| 2.03 | 0.803 | 0.35 |
| 2.10 | 0.807 | 2.5 |
| 2.14 | 0.847 | 2.7 |
| 2.20 | 0.849 | 2.5 |
| 2.23 | 0.835 | 0.9 |
| 2.30 | 0.871 | 1.7 |
| 2.34 | 0.891 | 2.7 |
| 2.40 | 0.879 | 0.8 |
| 2.43 | 0.876 | 0.35 |
| 2.51 | 0.895 | 1.4 |
| 2.53 | 0.884 | 0.7 |
| 2.61 | 0.885 | 1.5 |
| 2.65 | 0.823 | 1.9 |
| 2.71 | 0.886 | 0.34 |
| 2.74 | 0.872 | 2.7 |
| 2.82 | 0.885 | 1.8 |
| 2.86 | 0.840 | 2.7 |
| 2.93 | 0.900 | 1 2 |
| 3.00 | 0.918 | 0.7 |
| 3.03 | 0.928 | 2.5 |
| 3.14 | 0.937 | 1.0 |
| 3.22 | 0.926 | 0 31 |
| 3.25 | 0.951 | 2 3 |
| 3.36 | 0.928 | 1.9 |
| 3.48 | 0.922 | 2.5 |
| 3.54 | 0.947 | 1.0 |
| 3.59 | 0.951 | 1.8 |
| 3.70 | 0.991 | 2.2 |
| 3.81 | 0.976 | 0.35 |
| 3.94 | 0.944 | 2.5 |
| 4.01 | 0.996 | 1.1 |
| 4.05 | 0.957 | 5.0 |

activity obtained on the basis of the weights gotten from the quantitative plating procedure. The results from the alpha and neutron comparisons were used to estimate a probable error in the actual mass of the material on the thin foils. The thick foils were then neutron weighed in the thermal column, using the same thin foil in the front compartment as before for each isotope, and an equivalent weight, $W'$, determined from the thick foil counts compared to the average of all the other thin foils under the same conditions. Thus the use of many thin foils serves not only to estimate our probable foil error, but also to reduce it by the square root of the number of thin foils. This is not a check against any systematic error which might be present in the foil preparation, but since this is a comparison experiment such an error would have to differ between the $U^{235}$ and the $U^{234}$ or $U^{236}$ foils in order to cause errors in the cross sections.

As a check on the possibility of loss of material from the thick foils during the course of the work they were alpha counted immediately after being plated, and once again after all experimental work had been completed with them. In each case counts were to 0.15% statistics, and no loss of material was found.

Having in this manner obtained foils of accurately known equivalent weight, $W'$, the measurements of cross sections of $U^{234}$ and $U^{236}$ proceeded much as in reference 1. Thin (0.05 or 0.10 mil) nickel foil was used to admit the protons into the tritium gas cell. Practically no straggling was observed in proton energy, so that neutron energy spread was taken as the square root of the sum of the squares of energy spread with angle (over a 15° angle) and target thickness.

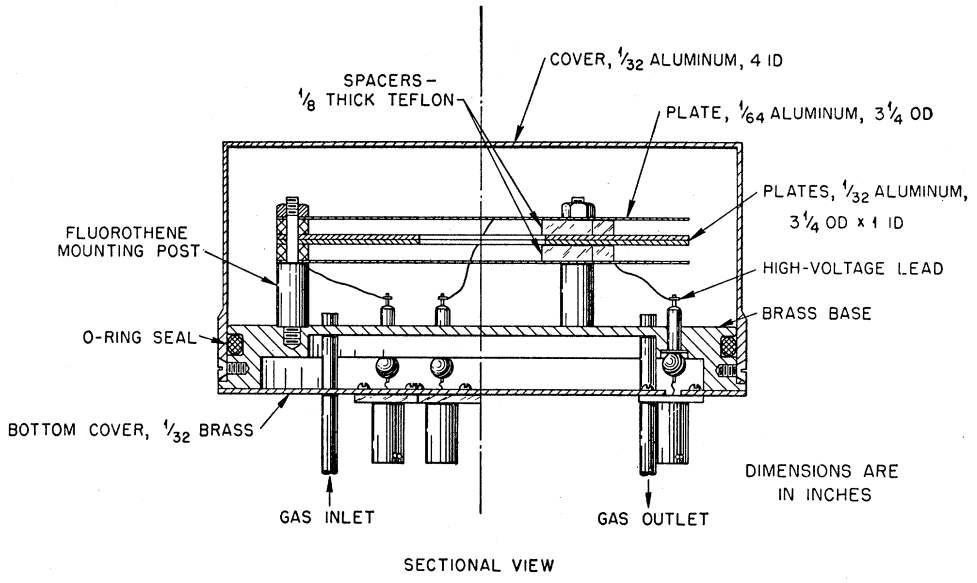


FIG. 2. Fission chamber for counting fission events from two different foils.

## PREPARATION OF URANIUM FOILS

The foils were prepared by electrodepositing uranium onto two-thousandths inch nickel shim stock using the method similar to that of Cohen and Hull.[5] Two weights of foils were prepared for each isotope, 0.200 mg and 4.00 mg deposited on an area of one inch diameter centered on a $2\frac{1}{8}$-inch disk. Quantities of urano-uranic oxide equivalent to forty milligrams of each isotope were accurately weighed in platinum dishes. The platinum dishes were placed in small covered beakers and the uranium oxide was carefully dissolved in nitric acid. The resultant uranyl nitrate solution was quantitively transferred to a fifty-ml volumetric flask and brought to volume with rinsings. From this flask of 0.8 mg uranium per ml a second flask was prepared from a volumetric aliquot to have a concentration of 0.04 mg of uranium per ml.

The four-milligram foils were prepared by pipetting three ml of solution from the parent flask and five ml of 0.4 Molar ammonium oxalate solution (electrolyte) into the plating cell. The plating cell was a short glass cylinder held firmly to the nickel foil by stout rubber bands. A soft rubber gasket between the glass cell and the foil defined the area of the deposit and made a water tight seal between the two. The foil was supported by a stainless steel base plate which held the hooks for the rubber bands. A split watch glass covered the cell. The solution was stirred by a platinum anode, rotating at 450 rpm and the nickel foil served as the cathode. The cell assembly was immersed in a water bath at 90°C during the plating operation. The current was one ampere with an initial voltage of eight volts that increased to fifteen volts as the ammonium oxalate was consumed. After twenty minutes an additional two ml aliquot of the uranium solution was transferred to the cell and, after a total deposition time of thirty minutes, a second five-ml portion of ammonium oxalate solution was added. The 0.200-milligram foils were prepared by adding five ml aliquot of the more dilute uranium solution and five ml of the electrolyte solution to the cell with no further additions of either solution to the cell. The total deposition time for both weights of foils was one hour. The completed foils were ignited for one minute at 400°C to convert the electrodeposited hydrated uranium oxide, of uncertain composition, to urano-uranic oxide.

Since the electrodeposition of the uranium onto the foil was not completely quantitative, averaging about 99.5%, the residual uranium in the deposition solution was determined by counting. The deposition solution of each foil was evaporated to dryness and the ammonium oxalate electrolyte destroyed with nitric acid. This residue was converted to the chloride with hydrochloric acid and transferred quantitatively to a silver residue counting disk, evaporated to dryness, and alpha counted. The count was divided by the specific alpha count of the isotope to determine the amount of uranium, and the foil weight was corrected by this amount.

The standard deviation of each foil computed from known sources of variances has been calculated to be approximately 0.5%. This was determined from the errors attributable to oxide impurities, oxide composition,[6] gravimetric and volumetric uncertainties, and alpha countings of the residues, as shown in Table III.

[5] B. Cohen and D. E. Hull, Report A-1235, August, 1944, Part II.

[6] F. S. Voss and R. E. Greene, (unpublished).

TABLE III. Known errors in uranium foils.

| | Percent |
|---|---|
| Uranium oxygen ratio (deviation from theoretical) | ±0.1 |
| Oxide impurities | ±0.1 |
| Gravimetric errors | ±0.3 |
| Volumetric errors | ±0.3 |
| Foil error from uncertainty of residue count | ±0.1 |
| Total error (sq. root of sum of squares) | ±0.5% Std. dev. |

## Estimate of Errors

### (1) *Fission cross section of monitor foil*

The fission cross section of $U^{235}$ used to get these results is that currently assumed to be the most accurate. The probable error is estimated to be 5%.

### (2) *Foil weights*

Equivalent weights, $W'$, of the foils are evaluated together with their probable errors in Appendix B. For the $U^{234}$ cross section the foil uncertainty will be the square root of the sum of the squares of the uncertainties in the $U^{234}$ and the $U^{235}$ foil, and similarly for the $U^{236}$ cross section.

### (3) *Statistics*

Due to the slowly varying nature of the curve and the large number of points taken, many to below 1% statistics, the over-all statistical uncertainty is estimated to be $\frac{1}{2}$%.

### (4) *Inelastic scattering*

The corrections made for this effect are felt to be good to 0.3 and 0.4% for $U^{234}$ and $U^{236}$. These are described in detail in Appendix A.

### (5) *Nonuniformity of plating*

Alpha counting studies of 4 concentric areas of equal size on the thick foils showed not over ±10% variation (instead of ±25% as was found for the thin ones) in radial distribution of uranium from foil to foil. This, together with the decrease in neutron intensity with angle[7] of the neutrons from the Van de Graaff can cause a small error, calculated to be within 0.2%. oN attempt was made to correct for this.

TABLE IV. Estimate of errors.

| Source | $U^{234}$ | $U^{236}$ |
|---|---|---|
| $W'$ | 0.95 | 0.70 |
| Statistics | 0.50 | 0.50 |
| Inel. scattering | 0.30 | 0.40 |
| Foil nonuniformity | 0.20 | 0.20 |
| Room scattering | 0.00 | 0.10 |
| Foil separation | 0.10 | 0.10 |
| Beam momentum | 0.10 | 0.10 |
| Gain changes | 0.10 | 0.10 |
| Systematic | 1.10 | 1.10 |
| Std. dev. of ratio | 1.59 | 1.49 |
| Monitor foil error | 5.00 | 5.00 |
| Total | 5.25 | 5.22 |

### (6) *Room scattering*

Many tests have been made, particularly with natural uranium *versus* $U^{235}$ to establish the size of this effect, which will be greatest for natural uranium and least for $U^{234}$. The tests consisted of taking many counts with the counter in one position, then backing it further away from the neutron source and taking many counts with all other factors the same. The average of these results was 0.3% for natural uranium, so is estimated to be 0.1 and 0.2% for $U^{234}$ and $U^{236}$. Data in Tables I and II include these corrections.

### (7) *Foil separation*

The two U foils being compared are mounted back-to-back so are separated by 0.004 in. of nickel. As the rear foil is farther from the neutron source than the first one the neutron flux density will be reduced (about 0.4% to 0.5% in all these tests). There will also be some attenuation due to the nickel, but this is very slight. The correction from these effects was taken as 0.5%. Data in Tables I and II include this correction.

### (8) *Beam momentum*

This correction is estimated to be accurate to 0.1% and is made as described in reference 1.

### (9) *Gain changes*

Relative changes in gain between the two electronics channels used to record fission counts can cause error, as described in reference 1. Experience has shown this effect to be very small, not over 0.1%.

### (10) *Systematic errors*

Allowance is made here for errors from unknown sources. It is assumed that such errors may be equal to the rms value of errors from all known sources excluding only the uncertainty existing in the monitor foil cross section.

Table IV lists these errors with the final sum, compounding the uncertainties in the usual manner. This shows that the cross-section ratios were obtained to an over-all standard error of 1.6% for $U^{234}$ and 1.5% for $U^{236}$, and that the over-all standard error for the cross section curves of the $U^{234}$ and $U^{236}$ is 5.3%.

## ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help of many other members of the laboratory. In particular we wish to thank B. Harmatz for supplying the uranium, C. R. Baldock and J. R. Sites for the mass analyses, Mrs.

[7] Willard, Bair, and Kington, Phys. Rev. **90**, 865 (1953).

R. D. Ackley for carrying out the plating operations, and members of the 5-Mev Van de Graaff group, J. K. Bair, H. O. Cohn, J. D. Kington, P. H. Stelson, and H. B. Willard for operating the machine.

## APPENDIX A. COUNTER SCATTERING CORRECTION

Some of the incident neutrons will be elastically scattered by the material composing the fission comparison chamber and some will be inelastically scattered. Elastically scattered neutrons will need to suffer several collisions to be degraded much in energy so that elastic scattering is not expected to affect the counting ratio noticeably except possibly in the energy region where one of the cross sections is changing rapidly relative to the other. Preferential forward scattering will reduce the percentage of elastically scattered neutrons which enter the foils.

Inelastically scattered neutrons, however, may lose enough energy in one collision to fall below threshold for $U^{234}$ or $U^{236}$, thus causing the count rate in the $U^{235}$ to be out of proportion to that in the isotope being measured. The effect will be greater the higher the threshold, hence greater for $U^{236}$ than for $U^{234}$. A rough calculation of this effect for the case of incident neutrons of 2.8 Mev on foils of $U^{235}$ and natural uranium gave 2.9%. A later experimental evaluation of the effect under these conditions gave 2.8 plus or minus 0.3%. Since the calculations were based on simple approximations, such good agreement is fortuitous.

One estimates from geometrical considerations the flux of neutrons inelastically scattered into the uranium foils from the counter components, and then calculates how large this is in relation to the primary neutron flux incident on the foils. Next, it is necessary to make some assumption as to the energy spectrum of the inelastically scattered neutrons. Having done this, it is easy to calculate the effect of these neutrons on the measured fission ratio. This last step requires a numerical integration over the scattered neutron energy spectrum and fission cross section for each foil:

$$\text{Count rate}=N\int_0^\infty \sigma_f(E)\varphi_i(E)dE,$$

where $N$=number of uranium atoms on a foil, $\sigma_f$ =fission cross section, $\varphi_i$=inelastically scattered neutron flux density, and $E$=scattered neutron energy. Since this effect is only a small correction, a first-order calculation is sufficient.

Individual level inelastic scattering cross sections are not known in much detail, so one has to work with the total inelastic cross section for each element involved in the construction of the chamber. $\varphi_i(E)$ was obtained as follows for the three metals, Al, brass, and Cd, which accounted for most of the scattering[8]:

$$\varphi_i(E)dE=(CE)\exp[-0.5E(a/E_0)^{\frac{1}{2}}]dE.$$

[8] E. R. Graves and L. Rosen, Phys. Rev. 89, 343 (1953).

TABLE V. $\sigma_i$ for various elements.

| Element | $a$(Mev $^{-1}$) | $\sigma_i$(barns) |
|---|---|---|
| Al | 56 | 0.65 |
| Cu | 95 | 1.0 |
| Zn | 105 | 1.3 |
| Cd | 129 | 2.2 |

This gives the energy distribution of the inelastically scattered neutrons. The total number in this distribution was obtained using the values of $\sigma_i$ ($E_0$=2.8 Mev) in Table V. Brass was considered to be half copper and half zinc. These calculations say that the measured ratio of the cross sections of natural uranium to $U^{235}$ with primary neutrons of 2.8 Mev will be 3.0% too low.

If, instead of using the foregoing distribution, one assumes instead that the scattered neutrons will have a "square distribution"; constant intensity between 10 kev and 2.5 Mev and zero outside these limits, the calculations are much simpler and one obtains 2.8% instead of 3.0%, thus showing that the result is insensitive to the assumed distribution within wide limits.

Since these calculations are only approximate it was felt advisable to check them experimentally. For this purpose the chamber was fitted with 0.036-in. thick Al plates in place of the 0.016-in. ones. Then sufficient brass was added in the form of a can around the counter to simulate one which would have 2.25 times as much inelastic scattering, the proportions being such that this factor applied separately to the Al plates, the front, side, and rear of the counter, and extra brass added as required to compensate for the difference in its geometrical location from that of the counter parts.

With this arrangement six points were taken to very good statistics with and also without the extra material, along the relatively flat portion of the curve in order to get a correction factor for the chamber at each energy. This was also done for $U^{234}$ and $U^{236}$. Within statistics these correction factors were independent of primary neutron energy. The results are shown in Table

TABLE VI. Experimental evaluation of counter scattering correction.

| | Correction factor in percent | | |
|---|---|---|---|
| $E_0$(Mev) | $U^{234}$ | $U^{236}$ | Natural |
| 1.46 | 0.53 | ... | ... |
| 1.74 | 0.47 | 3.85 | ... |
| 2.03 | −0.17 | 2.22 | ... |
| 2.05 | ... | ... | 2.56 |
| 2.34 | ... | ... | 2.64 |
| 2.43 | ... | 1.03 | ... |
| 2.71 | ... | 1.93 | 2.20 |
| 2.83 | 1.07 | ... | ... |
| 3.00 | ... | ... | 2.80 |
| 3.22 | 1.44 | 1.18 | ... |
| 3.29 | ... | ... | 3.72 |
| 3.54 | ... | ... | 2.88 |
| 3.81 | 0.39 | 0.99 | ... |
| Average | 0.62 | 1.9 | 2.8 |

TABLE VII. Isotopic composition of foils.

| | $U^{234}$ | $U^{235}$ | $U^{236}$ |
|---|---|---|---|
| $U^{234}$ | 96.16±0.02 | 0.07±0.01 | 0.03±0.01 |
| $U^{235}$ | 2.82±0.02 | 99.90±0.01 | 4.45±0.04 |
| $U^{236}$ | ... | ... | 95.15±0.05 |
| $U^{238}$ | 1.02±0.01 | 0.03±0.003 | 0.40±0.01 |

VI. All correction factors have a statistical uncertainty of 0.70%. $E_0$ is primary neutron energy. The corrections used for $U^{234}$ and $U^{236}$, respectively, were 0.62 plus or minus 0.3% and 1.9 plus or minus 0.3%. They were assumed constant and applied to all the data to get the final cross sections.

TABLE VIII. Thin foil comparisons.

| Foil | Mass | $\Delta f$ % | $\Delta\alpha$ % |
|---|---|---|---|
| 24K1 | 199.8 | monitor | +0.52 |
| 24K2 | 195.1 | −2.51 | −2.15 |
| 24K3 | 199.4 | −2.51 | −1.73 |
| 24K4 | 199.9 | 1.38 | 1.36 |
| 24K5 | 199.9 | 1.38 | 1.08 |
| 24K6 | 199.9 | 0.36 | 0.66 |
| 24K7 | 199.8 | 0.36 | 0.38 |
| 24K8 | 198.2 | −3.74 | −3.13 |
| 24K9 | 200.0 | 2.62 | 1.22 |
| 24K10 | 199.9 | 2.62 | 1.79 |
| Std. error | | 0.74 | 0.51 |
| 25K5 | 198.4 | 0.48 | 0.46 |
| 25K6 | 194.8 | 0.07 | 0.18 |
| 25K7 | 198.3 | −0.74 | −0.65 |
| 25K8 | 198.2 | −0.54 | −0.65 |
| 25K9 | 199.0 | 0.07 | 0.18 |
| 25K10 | 198.5 | 0.68 | 0.46 |
| Std. error | | 0.21 | 0.19 |
| 26K1 | 199.7 | 0.68 | 1.59 |
| 26K2 | 199.8 | −0.94 | −1.24 |
| 26K3 | 197.4 | monitor | 1.05 |
| 26K4 | 199.8 | −3.16 | −3.16 |
| 26K5 | 199.2 | −0.54 | −1.14 |
| 26K6 | 199.8 | 0.47 | 0.50 |
| 26K7 | 199.5 | 0.07 | −0.33 |
| 26K8 | 199.5 | 0.88 | 1.14 |
| 26K9 | 199.6 | 0.68 | 0.41 |
| 26K10 | 198.4 | 1.89 | 1.14 |
| Std. error | | 0.45 | 0.44 |

## 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 results are given in Table VII.

In each case the uranium underwent a chemical purification process and then was plated as previously described; all foils of a given isotope being plated from a single batch to insure the same composition for all. The fission and alpha activities were measured with the results shown in Table VIII for the thin foils. In this table the first two digits of the number indicate the principal isotopic content (24 for $U^{234}$, etc.). The mass is in micrograms as obtained by direct measurements during foil preparation. The next two columns list the deviations from the average fission and alpha activity per microgram on the basis of the masses listed in the preceding column. The standard errors listed for each group apply to the average for the whole group, as this was what was used to get the $W$'s. The deviation to be expected for a single thin foil will be greater by the square root of the number of foils involved. The standard deviation for the $U^{235}$ thin foils singly would be 0.5%. It is of interest to note that foils of $U^{233}$ and also of natural uranium were prepared in the same way, and these together with the $U^{235}$ foils showed about 0.5% average deviation, which is in good agreement with the expected spread (see paragraph on foil preparation). It is not known what caused the increased spread in the $U^{234}$ and $U^{236}$ foils.

TABLE IX. Equivalent weights of foils used to determine cross sections.

| Foil | $W'$(mg) | % Est. error |
|---|---|---|
| 24K11 | 3.405 | 0.8 |
| 25K14 | 3.571 | 0.5 |
| 26K11 | 3.583 | 0.5 |

The average of the thin foils was used in each case to determine the thick foil equivalent weights as has been described.[1] Counting statistics were 0.2% for thin foil ratios and better than 0.1% for thick foil determinations. The results are given in Table IX.