Fission Cross Section of Uranium-234

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The neutron-induced fission cross section of U^{234} has been measured from threshold to 4-Mev neutron energy, using the $T(p,n)$ reaction with a tritium gas target, and the Oak Ridge 5-Mev Van de Graaff. The curve rises from threshold at 350 kev to 1.3 barns at 4 Mev. There is a minimum at 1.08 Mev and another at 2.30 Mev. These dips are about 13 percent and 7 percent, respectively, of the cross section at these points. Statistics in these regions are sufficient to establish the fact that the minima are real to a probability of 10^9 relative to a "best fit" curve with no extrema.

RESULTS AND PROCEDURE

THIS paper reports on work done in May, 1952. The results are shown in Fig. 1. Most of the points were taken to 3 percent statistics or better, and the *shape* of the curve is believed to be good to at least 3 percent. However, the ordinate scale factor is in doubt to about 14 percent; this representing the uncertainty in the quantity of uranium deposited on the foils. The curve lies about 8 percent below that obtained by the Los Alamos group from threshold to 1.5 Mev.[1]

Fast fission cross sections of Pa^{231},[1] and Np^{237},[2] show no minima, but that for Th^{232} has a well-defined minimum on the initial rising part of the curve at 1.8 Mev.[1] These observations do not seem to fit in with what one would expect from a purely statistical model. Possibly they are due to shell structure within the nucleus.

A monokinetic neutron beam incident on foils placed back to back in a double ionization chamber served to induce fissions in two foils, one of U^{234} and the other of U^{235}. The ratio of fission pulses together with the known cross section of U^{235} served to establish the cross section of U^{234}. Figure 2 shows the comparison-type fission chamber. The center plate was held at -300 volts with respect to ground by means of a "Minimax" battery. The two foils were mounted back to back on this electrode. The two end plates collected electrons resulting from the fission fragments, and the pulses produced were fed into separate preamplifiers, with gains of about 140. Each preamplifier used a triode-connected 6AK5 input tube, a clipping circuit with an *RC* constant of 0.38 microsecond after the third stage, and a cathode-follower output that fed positive pulses over a 40-foot doubly-shielded cable to an A-1 amplifier containing a pulse-height discriminator circuit.[3] Over-all gain was about 30 200. All stages were gain stabilized by feedback. With this arrangement, correction for background, and counts from pileup of α pulses in the U^{234} were below 0.01 percent. A switch was provided for inserting a calibrated pulse generator in place of the "Minimax," so that the gains of the two identical channels could be monitored during an experiment.

A mixture of 97 percent argon plus 3 percent carbon dioxide at a pressure of two atmospheres absolute was supplied from a tank of this mixture. No purification was used, but a flow of 0.1 cubic foot per hour was maintained. The chamber was surrounded by a $\frac{1}{32}$-inch thick shield of cadmium to absorb slow neutrons that might otherwise be scattered back into it.

The foils subtended a half-angle of 15° as seen from the tritium target. Figure 3 shows the spread in energy of the neutrons striking the foils *versus* their average energy. The spread is due almost entirely to: (1) target thickness, (2) variation of neutrons energy with angle, (3) proton straggling in the entrance foil. Points were taken at 50-kev intervals.

To promote economical use of the Van de Graaff, a method using relatively thick foils was employed, whereby the fission counting rate was increased about 3.3 times; this reduced by that factor the amount of generator time required. All foils consisted of uranium plated over a one-inch circle on 2-mil thick platinum backing. Two foils were plated for each isotope; one thin foil containing about one milligram of uranium, and one thick foil containing about 4 milligrams. The quantity on the thin foil should be known as accurately as possible, but this is not necessary for the thick one. It is necessary to plate the thick and thin foils for a given isotope from the same batch of source material to

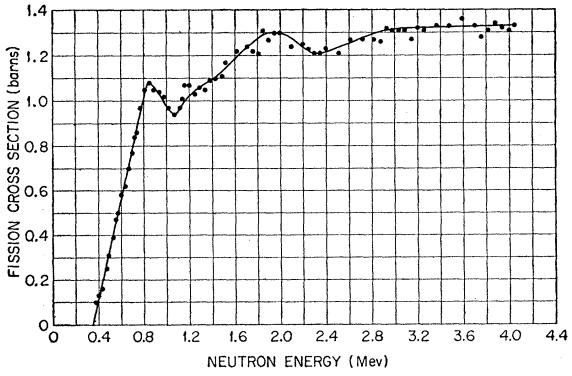

FIG. 1. Neutron-induced fission cross section of U^{234}.

[1] *Neutron Cross Sections*, Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952).
[2] E. D. Klema, Phys. Rev. **72**, 88 (1947).
[3] W. H. Jordan and P. R. Bell, Rev. Sci. Instr. **18**, 703 (1947).

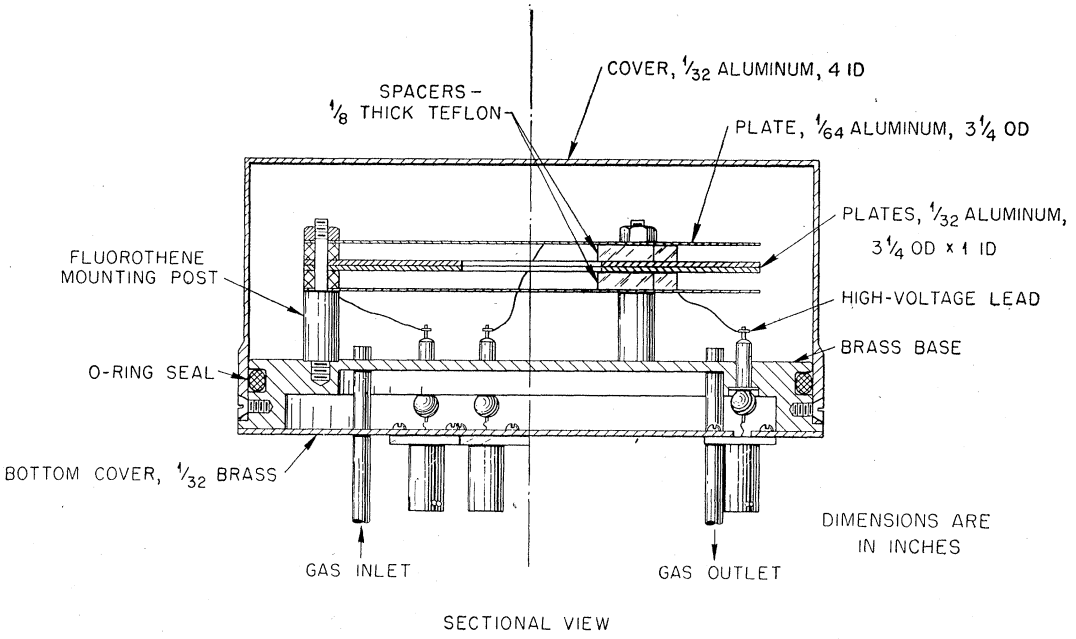

FIG. 2. Double ionization chamber used for comparing fissionability of two foils.

insure that their isotopic composition of fissionable material be precisely the same. The two foils of the *same* isotopic content, one thick and one thin, were placed in the fission chamber back to back, and exposed to neutrons from a Po–Be source for several hours. Thus the ratios of fission yields were found to 0.2 percent for the pair of U^{234} foils and for the pair of U^{235} foils. The thick ones were then used with the Van de Graaff neutrons to find the ratio of the U^{234} cross section to that of the U^{235} as a function of neutron energy.

As a check on the accuracy of the thick-foil technique, several points were taken using the two thin foils, and these points were found to lie on the curve obtained with the thick ones.

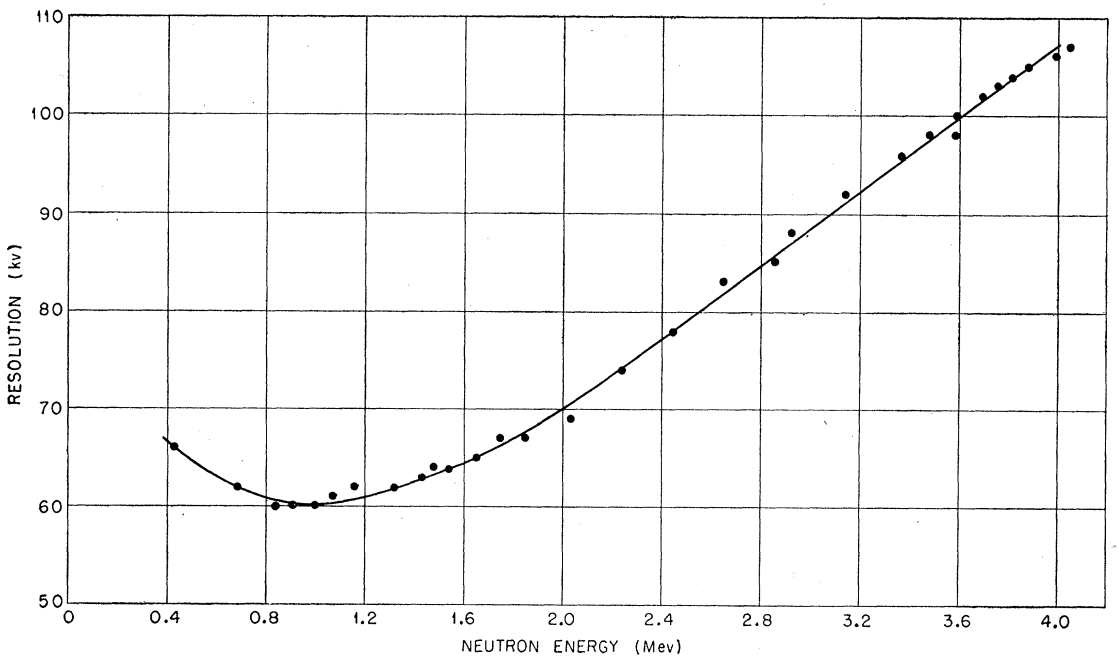

FIG. 3. Energy spread in that portion of the neutron beam incident on fissionable foils.

DISCUSSION OF ERRORS AND CORRECTIONS

A. Foils

These were prepared by the assay laboratory of the Y-12 electromagnetic separation plant, using electrodeposition and a standard assay procedure thought to be good to 0.8 percent. However, for some reaon as yet unknown, successive foils plated from the same batch of isotopic material showed disagreement between weight ratios gotten from the standard assay procedures and ratios of fission counts obtained by placing them back to back in the fission chamber and irradiating for a long time with Po—Be neutrons. This was sufficiently serious to make the ordinate scale of Fig. 1 uncertain to 14 percent but will not affect the shape of the curve.

B. Effect of Amplifier Gain Changes

Figure 4 shows the slopes of the plateaus for thick and thin foils obtained by counting fission pulses for various pulse-height discriminator settings while the foils were being irradiated by Po—Be neutrons. The plateaus for the thick foils have sufficient slope, so that some attention must be paid to the amplifiers to guard against excessive relative gain changes. The pulse generator served as a monitor, and gain changes were compensated for by adjustment of the pulse-height selectors. Relative gain changes were held to 0.2 volt on the pulse-height selector dial, and from Fig. 4 this can be shown to alter the count rate by 0.12 percent for the 4-mg foils. It was easy to hold the relative gains to this degree of precision.

C. Thick Foil Equivalent Weights

These were found to 0.2 percent in terms of the thin foil weights.

D. Scattering

It is inevitable that some neutrons will be scattered from walls and objects in the room, and some of these will find their way back into the fission chamber. The great majority of these will be degraded in energy below the threshold of U^{234} and so will produce fissions only in the U^{235}. This will result in the measured value of the U^{234} cross section being too low by a small amount. From measurements made at two different energies and two different distances between neutron source and fission foils, this correction factor was determined to be 1.01 ± 0.01. This factor has not been applied to the ordinate of Fig. 1.

E. Effect of the Momentum of Incident Neutrons on Absorption Loss

The neutron beam is incident normal to the foil surface. The fission fragments will, therefore, pick up some momentum from the incident neutron that causes the fission to take place. The effect of this is to alter the amount of self-absorption, increasing the absorption loss[4] in the foil facing the neutron source, and decreasing it for the foil facing away from the source. The magnitude of this correction *for each foil* will be about 1 percent at 4 Mev, and will vary as the square root of the energy. This correction is, to first order, independent of foil thickness and of the range of the fragments in the foil. It has been applied to the data in evaluating the cross-section curve; the accuracy of the correction is at least within 10 percent, so the probable error in cross section from this source is not over 0.15 percent. An experimental verification of this factor was made by taking seven points from 2 to 3 Mev with foils "normal" and "reversed" with respect to beam direction. The mean spread in cross-section values are found to be 3.4 percent, and the calculated value is 3.5 percent for 2.5 Mev.

Since one counts all particles in a 2π solid angle, angular asymmetry in the emitted fission particles will not affect the result, providing only that symmetry exists relative to the 90° angle, in c.m. coordinates, with respect to the beam.

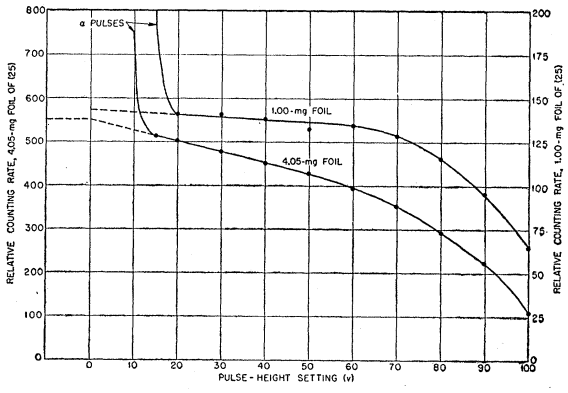

FIG. 4. Relative counting rate for U^{235} foils in fission chamber of Fig. 2 exposed to a constant intensity of thermal neutrons.

SUMMARY

The following summary of errors applied to Fig. 1:

1.	Foils	14 percent (scale factor only)
2.	Scattering	1 percent
3.	Beam momentum	0.15 percent or less
4.	Gain changes	0.12 percent
5.	Statistics	1.5 to 3 percent

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[4] E. Segrè and C. Wiegand, Phys. Rev. **70**, 808 (1946).

APPENDIX

Beam Correction

Notation

$t_1 = 0.20$ mg/cm^2 = actual thickness of the 1-mg foils,
$t_2 = 0.80$ mg/cm^2 = actual thickness of the 4-mg foils,
t' = effective thickness of foil as a result of pulse-height setting on the A-1 amplifier,
$R = 5.0$ mg/cm^2 = mean range of fission fragments in foil,
R_b = component of range imparted by beam—component normal to foil,
z = coordinate normal to foil—taken as zero at surface of foil backing and as t at surface of uranium,
W = weight of thick foil,
W' = equivalent thin-foil weight of thick foil as obtained from polonium-beryllium comparison data,
c = fissions occurring in unit thickness of foil,
N_t = total fission processes in foil,
N_{a0} = fissions not recorded owing to absorption—for case of no beam momentum,
N_{c0} = fissions that would be counted were it not for beam momentum—corrected count,
N_e = fragments extracted from foil as a result of beam momentum,
N_c = fissions actually counted,
$F = N_e/N_{c0}$ (nearly equal to N_e/N_c); then
$N_{c0} = N_c - N_e = N_c[1-(N_e/N_c)] = N_c(1-F)$.

According to Segrè,[4] the self-absorption for the thin foils should be about 2 percent and for the thick foils about 8 percent. That is, for a thin (t less than R), uniformly emitting layer, the fractional loss is $t/2R$.

Since fragments must have some energy after leaving the foil in order to be counted, an effective thickness t' should be used that can be obtained from the slope of the fission plateau. The effective thickness is 0.60 mg/cm^2 for the thin foil and pulse-height settings of 35 to 45 on the A-1 amplifier. Hence, for this work, the loss as a result of foil thickness for the 1-mg foils is 6 percent.

Since the foils are somewhat nonuniform and R is not the same for all fragments, experimental data were used for evaluating t' and N_{a0}/N_{c0} for thick foils:

$$t_2' = 10\frac{N_{a0}}{N_t} = 10\left(1-\frac{0.94W'}{W}\right),$$

where t_2' is for the particular pulse-height setting for which W' is evaluated. The factor 0.94 may need to be altered somewhat for pulse-height settings outside the range 35 to 45:

$$F = \frac{N_e}{N_{c0}} = \frac{N_e}{N_{a0}}\frac{N_{a0}}{N_{c0}} = \left(\frac{N_e}{N_{a0}}\right)_{\text{calc}}\left(\frac{N_{a0}/N_t}{1-N_{a0}/N_t}\right)_{\text{exp}}.$$

The last term is obtained from experimental values of W', as shown previously. The first term is calculated as follows: the number of fragments reaching the end of their range in a thickness dz will equal $czdz(1/R)$, for z less than R. Hence,

$$N_{a0} = \frac{c}{R}\int_0^t zdz = \frac{ct^2}{2R},$$

$$N_e = \frac{c}{R}\int_{t-R_b}^t zdz = \frac{cR_b}{2R}(2t-R_b);$$

therefore,

$$\frac{N_e}{N_{a0}} = \frac{R_b}{t}\left(2-\frac{R_b}{t}\right).$$

Note that the *calculated* value of N_{a0}/N_{c0} is

$$\left(\frac{N_{a0}}{N_{c0}}\right)_{\text{calc}} = \frac{t/2R}{1-t/2R} = \frac{t}{2R-t}.$$

This gives a *calculated* F of

$$F_{\text{calc}} = \frac{R_b}{t}\left(2-\frac{R_b}{t}\right)\left(\frac{t}{2R-t}\right)$$

$$= \frac{R_b}{2R-t}\left(2-\frac{R_b}{t}\right) \cong \frac{R_b}{2R} = 0.0023(E_n)^{\frac{1}{2}} \quad R \gg t \gg R_b.$$

In this work the calculated ratio of N_e/N_{a0} and the experimental ratio of N_{a0}/N_{c0} were used. Thus,

$$F = \frac{2R_b}{t'}\left(1-\frac{R_b}{2t'}\right)\left(\frac{N_{a0}}{N_{c0}}\right)_{\text{exp}}.$$

Hence,

$$R_b = R\left(\frac{E_n}{E_f}\frac{M_n}{M_f}\right)^{\frac{1}{2}} = R\left(\frac{E_n}{200}\frac{1}{235}\right)^{\frac{1}{2}}$$

$$= 0.0046R(E_n)^{\frac{1}{2}} = 0.023(E_n)^{\frac{1}{2}} \text{ mg/cm}^2,$$

where E_n is neutron beam energy in Mev. Therefore,

$$F = \frac{0.046(E_n)^{\frac{1}{2}}}{t'}\left[1-\frac{0.012(E_n)^{\frac{1}{2}}}{t'}\right]\left(\frac{N_{a0}}{N_{c0}}\right)_{\text{exp}}$$

$$= \frac{0.046(E_n)^{\frac{1}{2}}}{t'}\left[1-\frac{0.012(E_n)^{\frac{1}{2}}}{t'}\right]\left(\frac{W}{0.94W'}-1\right)$$

$$= \frac{0.046(E_n)^{\frac{1}{2}}}{10}\frac{W}{0.94W'}\left[1-\frac{0.012(E_n)^{\frac{1}{2}}}{t'}\right]$$

$$= 0.0049\frac{W}{W'}(E_n)^{\frac{1}{2}}\left[1-\frac{0.012(E_n)^{\frac{1}{2}}}{t'}\right],$$

where $t' = 10[1-(0.94W'/W)]$. Note that for thin foils, $W' = W$.