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LOS ALAMOS SCIENTIFIC LABORATORY
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UNIVERSITY OF CALIFORNIA

Report written:
July 13, 1954

LAMS-1700 This document consists of 16 pages

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AVERAGE FISSION CROSS SECTION OF U^{237} FOR INTERMEDIATE ENERGY NEUTRONS

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A measurement of the average fission cross section of U^{237} for neutrons of intermediate energies was made by members of Group P-2. The experimental arrangement is given in Fig. 1, and Figs. 2, 3, and 4 show the details of the fission chamber. The chamber had on one side a foil of Np^{237}, and on the other side a foil made from uranium which had been separated from the debris of one of the 1954 series of Pacific shots. The ratio of the counting rates of the two sides of the chamber was observed as a function of the time. Since U^{237} was the only isotope present having a short half-life, a time-variation of the ratio could be related to the U^{237} cross section. The neutron spectrum was investigated by replacing the U^{237} foil with foils of U^{238}, U^{236}, and U^{235}, and measuring the ratio of fission counting rates of these isotopes to that of Np^{237}.

Background was found to be negligible: no counts were observed when the voltage was removed from the center electrode with the reactor on, and none were seen with the voltage on and the reactor off. In order to avoid drift, the electronic circuits were operated from voltage regulated supplies, and were kept in constant temperature cabinets. The circuits were tested, and discriminator biases set by means of a pulser, before each set of 6 half-hour runs. The chamber was neither moved nor refilled during the U^{237} measurements. Bias curves for each side of the chamber were taken before each set of runs, and no changes were

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observed throughout the experiment. To investigate possible drift of the apparatus, the counting rates of the two sides of the chamber were separately compared to the pile monitor, a fission counter imbedded in the top of the bismuth wall which separates the North Thermal Column from the reactor core. Within the accuracy of the monitor, the Np^{237} counting rate remained constant, while that of the U^{237} decreased with time.

Masses of the standard foils were estimated by alpha counting and pulse height analysis. These measurements were made by Groups CMR-4 and J-11. The U^{235} content of each foil was measured by Group J-11 using thermal fission counting techniques.

A mass spectrographic analysis of the material from which the U^{237} foil was prepared was made at Argonne National Laboratory (Report ANL-WMM-1217). The results of this analysis are given below.

U^{235}:	0.61 ± 0.01 % by weight
U^{236}:	0.38 ± 0.01
U^{237}:	1.07 ± 0.02
U^{238}:	97.93 ± 0.02

The U^{237} content is that which existed at shot time. The U^{235} content as determined from thermal fission measurements was used to convert the percent abundances to absolute values. The composition of the foil at the time counting was started (T_o) was found to be:

U^{235}:	3.92×10^{14} atoms
U^{236}:	2.43×10^{14}
U^{237}:	4.95×10^{14}
U^{238}:	$621. \times 10^{14}$

Radiochemical analysis of the foil material is being carried out by members of Group J-11. Preliminary results indicate a value for the U^{237} content of the foil which is 20% lower than that given above. Although the mass spectrographic determination was used in this report, the final results are subject to correction when the radiochemical measurements have been completed.

The Np^{237} foil used as a comparison contained 588×10^{14} atoms of Np^{237}.

The measured ratios of fission counting rate were extrapolated to zero bias. The magnitude of this correction, which arose from differences in slope of the bias curves for the various foils, was in no case more than 2%. The ratios of average cross sections obtained from measurements with the standard foils were found to be:

$$\frac{\bar{\sigma}_{28}}{\bar{\sigma}_{37}} = 0.091\,, \quad \frac{\bar{\sigma}_{25}}{\bar{\sigma}_{37}} = 8.8\,, \quad \frac{\bar{\sigma}_{26}}{\bar{\sigma}_{37}} = 0.27$$

The ratio of the fission counting rate of the U^{237} foil to that of the Np^{237} foil is given by the expression:

$$R = \frac{N_{25}\,\bar{\sigma}_{25} + N_{26}\,\bar{\sigma}_{26} + N_{28}\,\bar{\sigma}_{28} + N_{37}\,\bar{\sigma}_{37} + N_{27}\,\bar{\sigma}_{27}\,e^{-\lambda t} + N_{27}\,\bar{\sigma}_{37}(1-e^{-\lambda t})}{N^{*}_{37}\;\bar{\sigma}_{37}}$$

where N_i = atoms of isotope "i" in the U^{237} foil at $t = 0$.

N^{*}_{37} = atoms of Np^{237} in the comparison foil.

$\bar{\sigma}_i$ = average cross section of isotope "i".

λ = decay constant of U^{237} = 0.1027 day^{-1}.

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This may be written

$$R = A + Be^{-\lambda t}$$

where

$$A = \frac{N_{25}}{N^*_{37}} \cdot \frac{\bar{\sigma}_{25}}{\bar{\sigma}_{37}} + \frac{N_{26}}{N^*_{37}} \cdot \frac{\bar{\sigma}_{26}}{\bar{\sigma}_{37}} + \frac{N_{28}}{N^*_{37}} \cdot \frac{\bar{\sigma}_{28}}{\bar{\sigma}_{37}} + \frac{N_{27} + N_{37}}{N^*_{37}}$$

$$B = \frac{N_{27}}{N^*_{37}} \left[\frac{\bar{\sigma}_{27}}{\bar{\sigma}_{37}} \quad -1 \right]$$

The experimental data are shown in Fig. 5. The solid curve was obtained by fitting a curve of the form $R = A + Be^{-\lambda t}$ to the experimental points by the method of least squares. The constant λ was chosen to correspond to a half life of 6.75 days for U^{237}. The values of the constants, when corrected to zero bias, together with the standard deviations obtained from the dispersion of the experimental points, are:

$$A = 0.1626 \pm 0.0001 \qquad B = 0.0084 \pm 0.0001$$

From B we obtain $\dfrac{\bar{\sigma}_{27}}{\bar{\sigma}_{37}} = 2.00$

To interpret these results, it is necessary to construct a neutron spectrum which, when combined with the known fission cross sections of U^{235}, U^{236}, U^{238}, and Np^{237}, will yield the experimental values of the ratios of average cross sections.

The low-energy end of the spectrum is determined by the B^{10} absorber which surrounded the chamber. Boron enriched to 82% B^{10} has a thermal cross section of 3270 barns. The cross section obeys a 1/v law up to approximately 10 kev, and then is constant. If the attenuation of the boron absorber is arbitrarily set equal to 1 at 10 kev, then the attenuation remains 1 at higher energies, and is equal to $1.31\, e^{-27.2/\sqrt{E}}$ for $E < 10$ kev.

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At energies below the lower limits of the fission spectrum and of inelastic scattering, the neutrons should follow the 1/E distribution characteristic of slowing down in a moderator. We therefore assume that, for energies below 100 kev, the neutron spectrum follows a 1/E law as modified by the boron attenuation.

Measurements of the spectrum above 1 mev by J. E. Evans (Report LA-1395) indicate a distribution resembling a fission spectrum above 1.5 mev connected to a function which increases rapidly as one goes to lower energies.

The above forms of the two ends of the spectrum were used as starting point of a trial and error construction of a spectrum which would give the measured values of the average cross sections. Values of the fission cross sections used in this process were taken from Reports LA-1495, BNL 170 and BNL 170B.

The average value $\bar{\sigma}$ of a cross section $\sigma(E)$ over a flux distribution $\phi(E)$ is given by

$$\bar{\sigma} = \int \phi(E) \ \sigma(E) \ dE / \int \phi(E) \ dE$$

This is the same as

$$\bar{\sigma} = \int E \ \phi(E) \ \sigma(E) \ \frac{dE}{E} / \int E \ \phi(E) \ \frac{dE}{E}$$

if we let $\Psi(E) = E \ \phi(E)$ and $dE/E = C \ d(\log_{10}E)$, then

$$\bar{\sigma} = \int \Psi(E) \ \sigma(E) \ d(\log_{10}E) / \int \Psi(E) \ d(\log_{10}E)$$

This expression may be approximated by

$$\bar{\sigma} = \sum_i \Psi(E_i) \ \sigma(E_i) \ \Delta(\log_{10}E) / \sum_i \Psi(E_i) \ \Delta(\log_{10}E)$$

A range of 10 ev to 10 mev was chosen for E ($\log_{10}E$ = 1.0 to 7.0). A uniform interval of 0.1 was taken for $\Delta\log_{10}E$. Table

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1 gives the values of E, σ_{25}, σ_{26}, σ_{37}, σ_{28} together with the assumed values of Ψ which gave the final fit. Figure 6 shows Ψ as a function of $\log_{10}E$. It is to be noted that the neutron flux between any two energies is proportional to the area under the curve between these energies. The ratios of average cross sections as computed from the proposed spectrum, and as measured experimentally, are given below:

Ratio	Calculated	Experimental
$\bar{\sigma}_{25}/\bar{\sigma}_{37}$	8.83	8.8
$\bar{\sigma}_{26}/\bar{\sigma}_{37}$	0.269	0.27
$\bar{\sigma}_{28}/\bar{\sigma}_{37}$	0.0921	0.091

The calculated average cross sections for the proposed spectrum are

U^{235}	2.88 barns
U^{236}	0.088
U^{238}	0.030
Np^{237}	0.326

The above value of the Np^{237} cross section together with the measured value of $\bar{\sigma}_{27}/\bar{\sigma}_{37}$ result in a value of 0.65 barn for the fission cross section of U^{237} averaged over the spectrum of Fig. 6.

The peak in the neutron spectrum between 100 kev and 1 mev may be due to the presence of the bismuth between the chamber and the reactor core (see Fig. 1). As an auxiliary experiment, neutron spectra were measured with the chamber partly retracted, and with varying amounts of graphite between the chamber and the bismuth. It was found that the peak at $\sim$ 300 kev decreased with respect to the 1/E portion of the spectrum as the thickness of the graphite was increased.

It is difficult to state precise limits on the accuracy of the results of this experiment, since several of the sources of uncertainty can be estimated only subjectively. If the J-11 value for the mass of the foil is used, the U^{237} cross section is increased by 10%. We feel that, apart from the uncertainty in the mass of the foil, the average cross section of U^{237} has been determined to $\pm$ 10%. The proposed neutron spectrum may be divided into four regions by the threshholds of Np^{237}, U^{236}, and U^{238}, and it is believed that the relative flux in each region is known to $\pm$10%. The uncertainty associated with individual points on the flux distribution is considerably greater.

[redacted]

						0.00
1.5	3.16×10^1	29				0.01
1.6	3.98	46				0.01
1.7	5.01	57				0.01
1.8	6.31	36				0.02
1.9	7.94	27				0.03
2.0	1.0×10^2	25				0.04
2.1	1.26	24				0.05
2.2	1.59	22				0.06
2.3	2.00	20				0.07
2.4	2.51	18				0.09
2.5	3.16	16				0.10
2.6	3.98	14.3				0.13
2.7	5.01	12.5				0.14
2.8	6.31	11.4				0.16
2.9	7.94	9.9				0.18
3.0	1.00×10^3	8.8				0.19
3.1	1.26	7.9				0.21
3.2	1.59	7.1				0.22
3.3	2.00	6.4				0.24
3.4	2.51	5.9				0.25
3.5	3.16	5.4				0.27
3.6	3.98	5.0				0.28
3.7	5.01	4.6				0.29
3.8	6.31	4.3				0.30
3.9	7.94	3.8				0.31
4.0	1.00×10^4	3.76				0.31
4.1	1.26	3.53				0.31
4.2	1.59	3.30				0.31
4.3	2.00	3.10				0.31
4.4	2.51	2.88				0.31
4.5	3.16	2.70				0.31
4.6	3.98	2.55				0.31
4.7	5.01	2.40				0.31
4.8	6.31	2.25				0.31
4.9	7.94	2.11				0.31
5.0	1.00×10^5	2.00				0.63
5.1	1.26	1.87				0.85
5.2	1.59	1.75				1.06
5.3	2.00	1.63				1.22
5.4	2.51	1.52				1.28
5.5	3.16	1.43				1.29
5.6	3.98	1.34	0.01			1.28
5.7	5.01	1.24	0.40			1.22
5.8	6.31	1.17	0.76	0.01		1.06
5.9	7.94	1.15	1.12	0.09		0.85
6.0	1.00×10^6	1.24	1.29	0.34		0.63
6.1	1.26	1.25	1.39	0.66	0.02	0.36
6.2	1.59	1.25	1.46	0.63	0.40	0.24
6.3	2.00	1.26	1.49	0.77	0.53	0.18
6.4	2.51	1.27	1.51	0.82	0.54	0.13
6.5	5.16	1.27	1.53	0.83	0.54	0.09
6.6	3.98	1.28	1.54	0.93	0.54	0.06
6.7	5.01	1.24	1.52	0.86	0.55	0.03
6.8	6.31	1.43	1.95	1.34	1.13	0.01
6.9	7.94	2.07	2.43	1.63	1.13	0.00
7.0	1.00×10^7	2.12	2.50	[illegible]	[illegible]	

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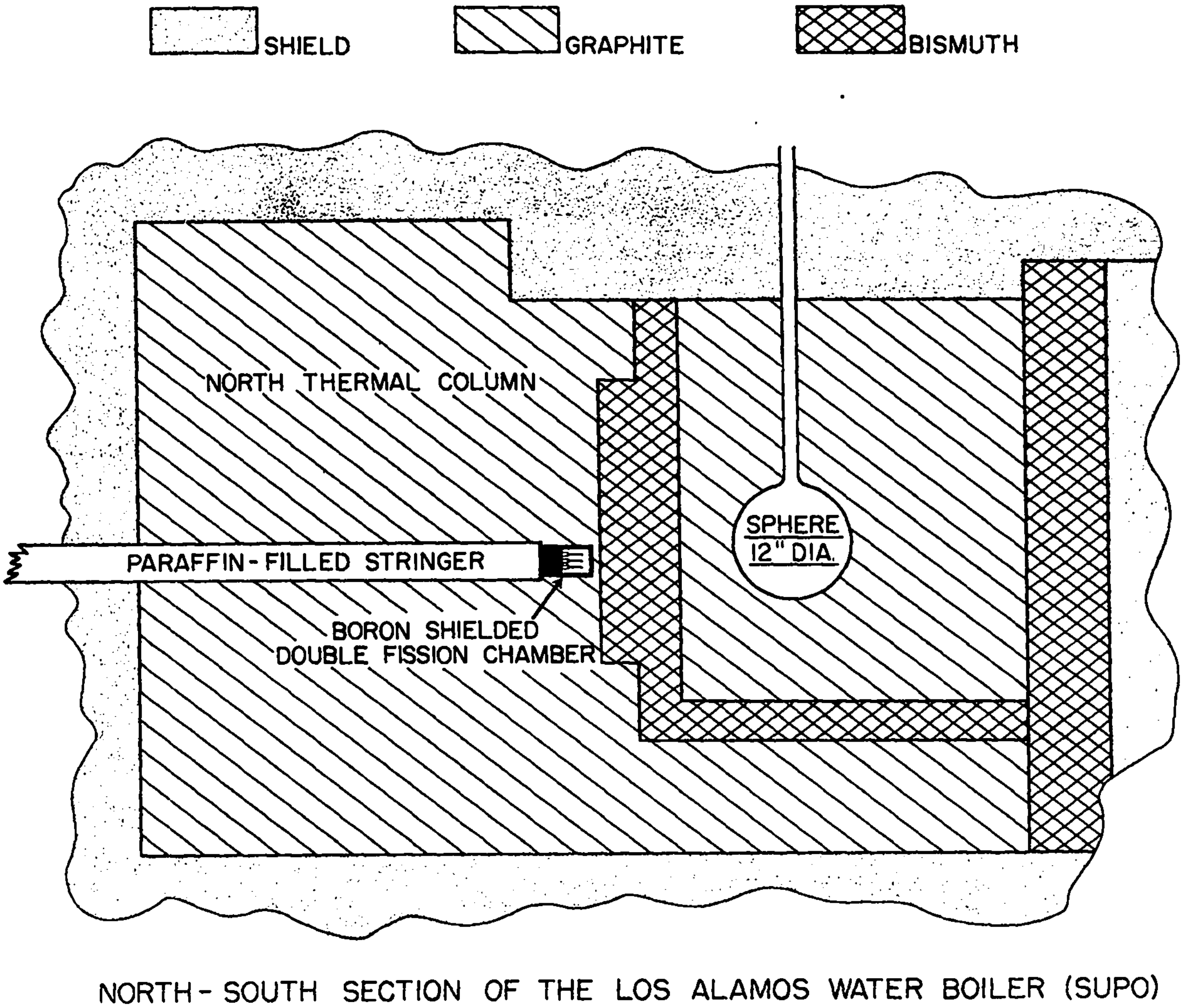

Figure 1. A schematic view of the Los Alamos Water Boiler showing the location of the fission chamber in the reactor.

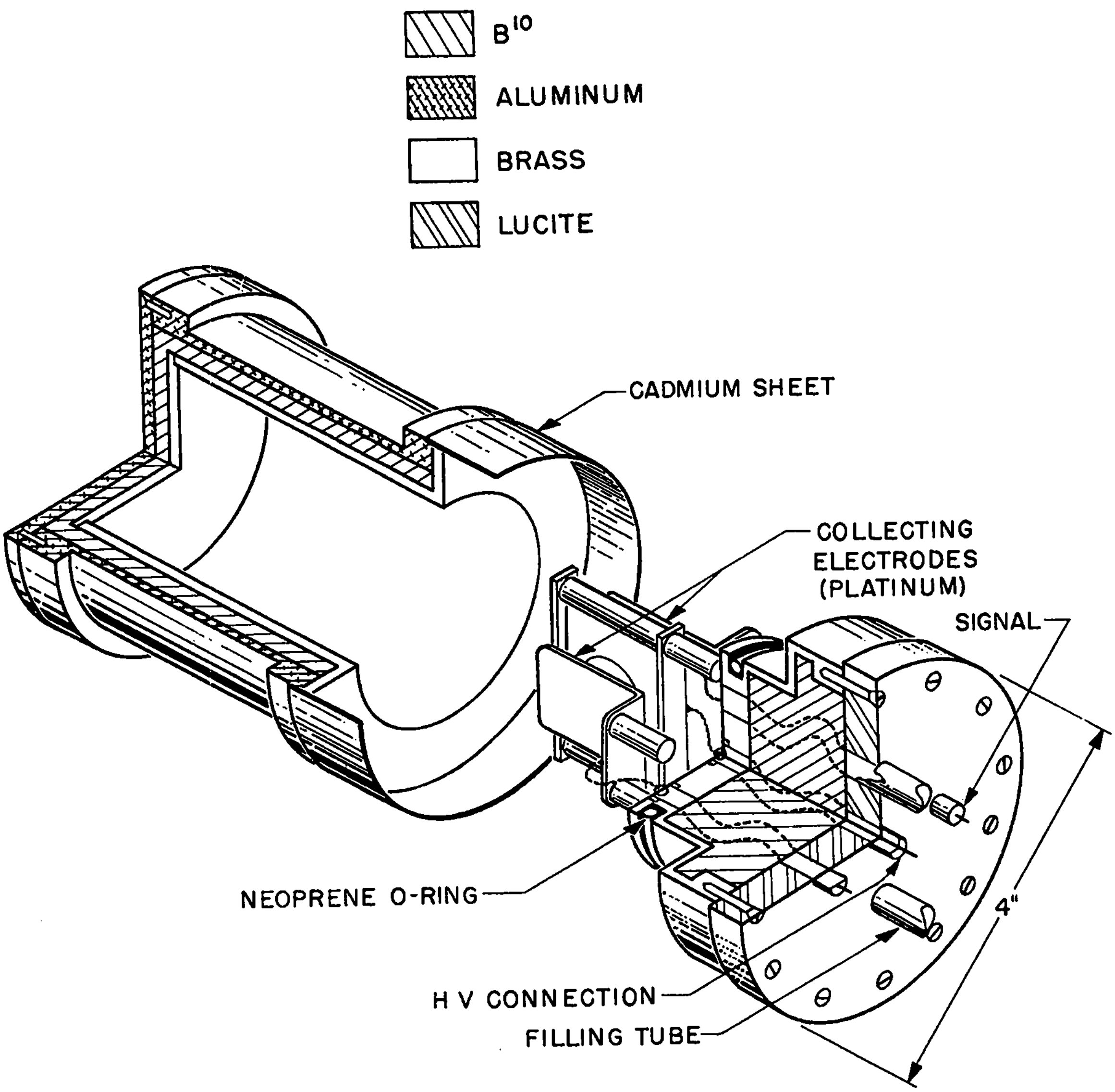

Figure 2. The boron shielded double fission chamber. The center high-voltage electrode carries a foil on each side. The two outer plates serve as collecting electrodes.

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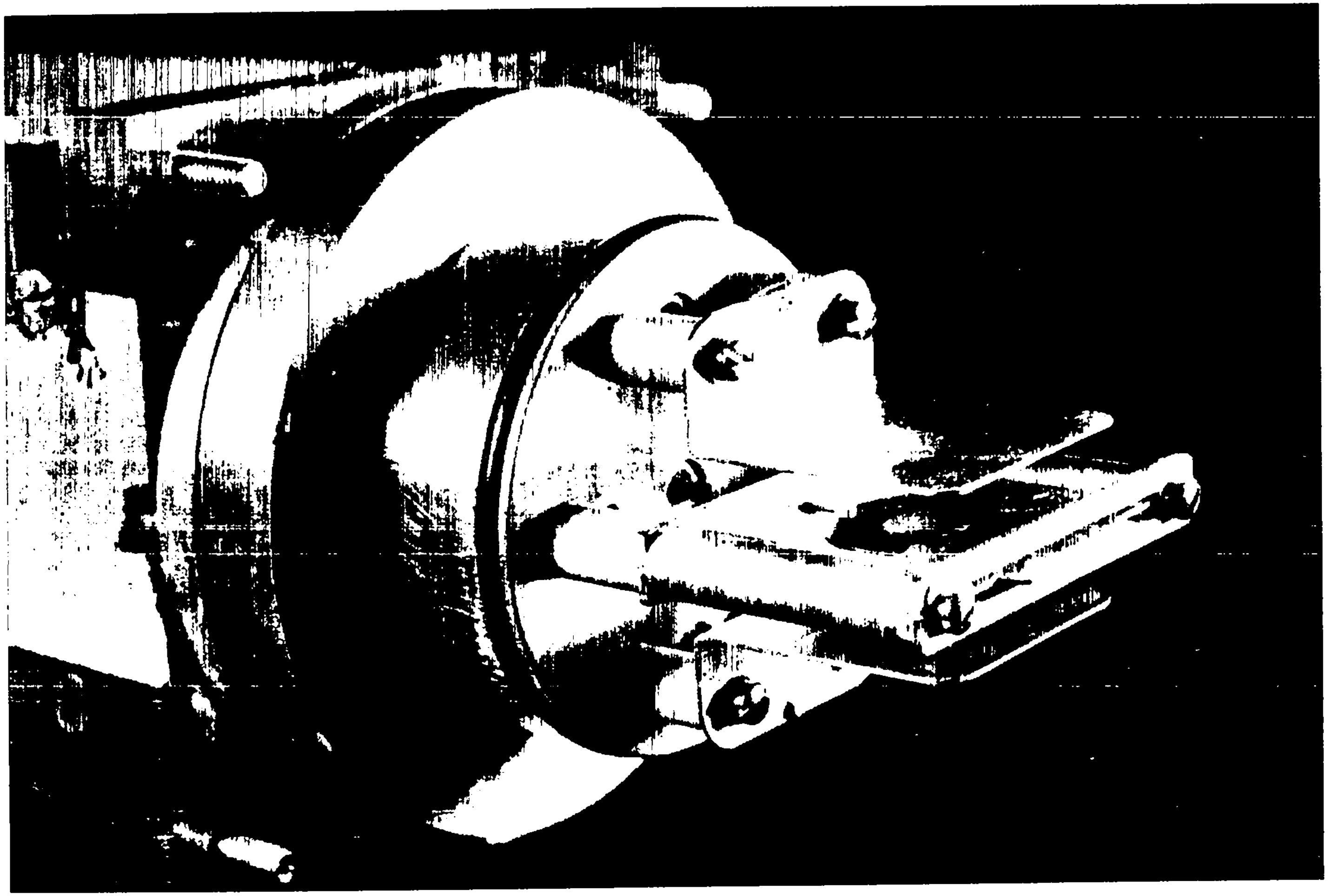

Figure 3. A photograph of the fission chamber with the cover removed.

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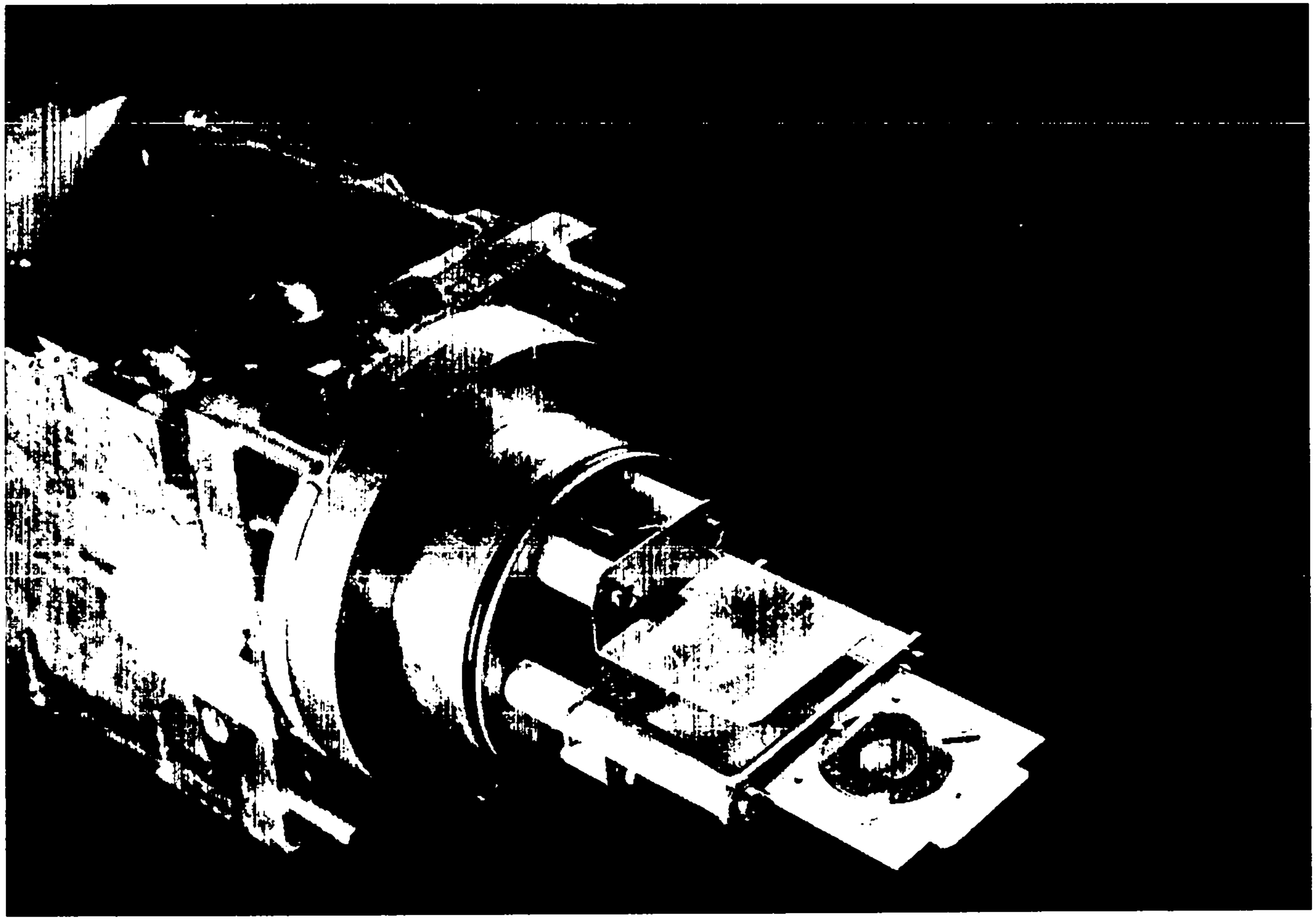

Figure 4. A photograph of the fission chamber showing the method of removal of the foils.

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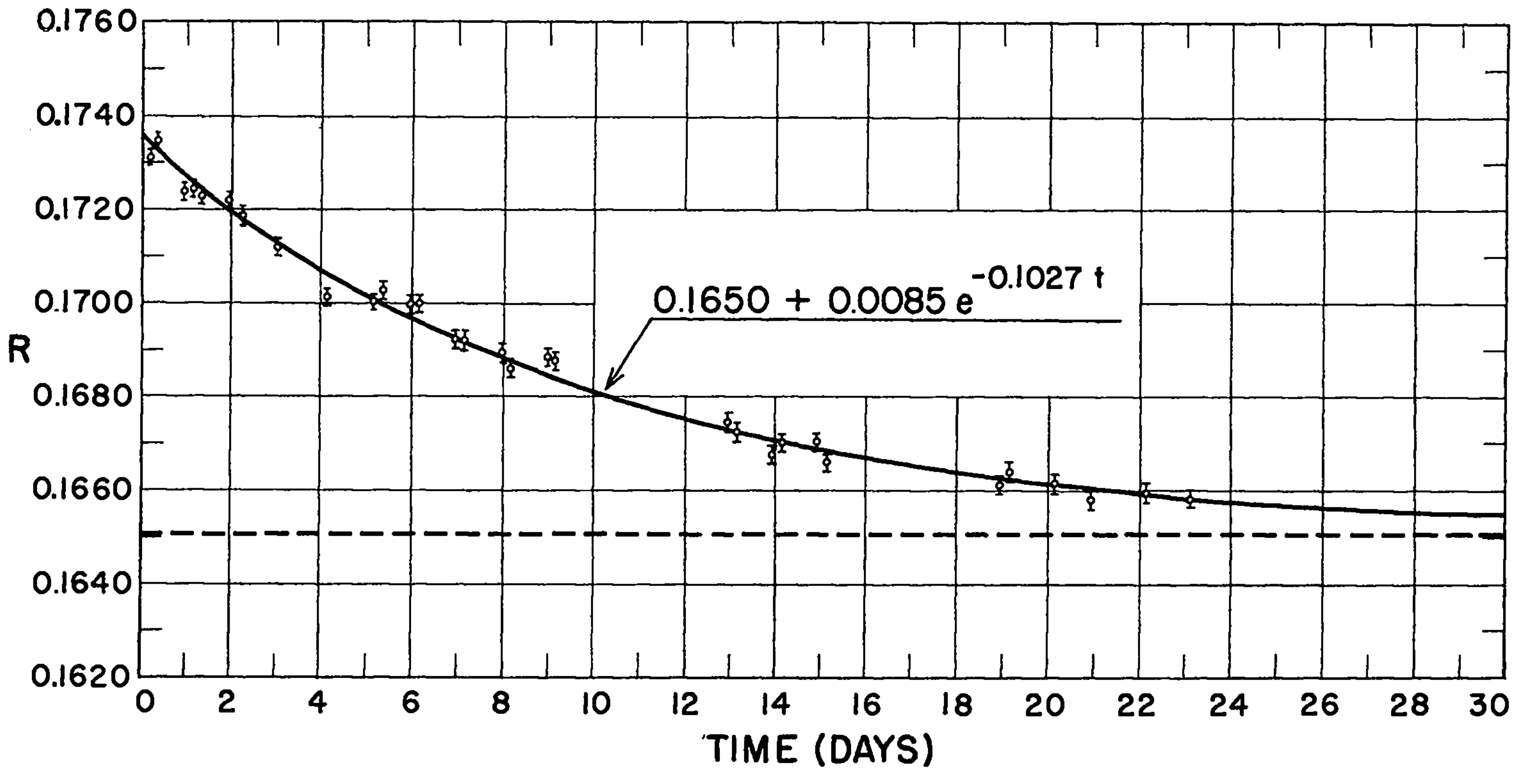

Figure 5. The ratio of the counting rate of the side of the chamber containing U^{237} to that of the side containing Np^{237}. The solid curve was obtained by fitting a function of the form $R = A + Be^{-0.1027t}$ to the experimental points by the method of least squares. A half-life of 6.75 days for U^{237} was assumed.

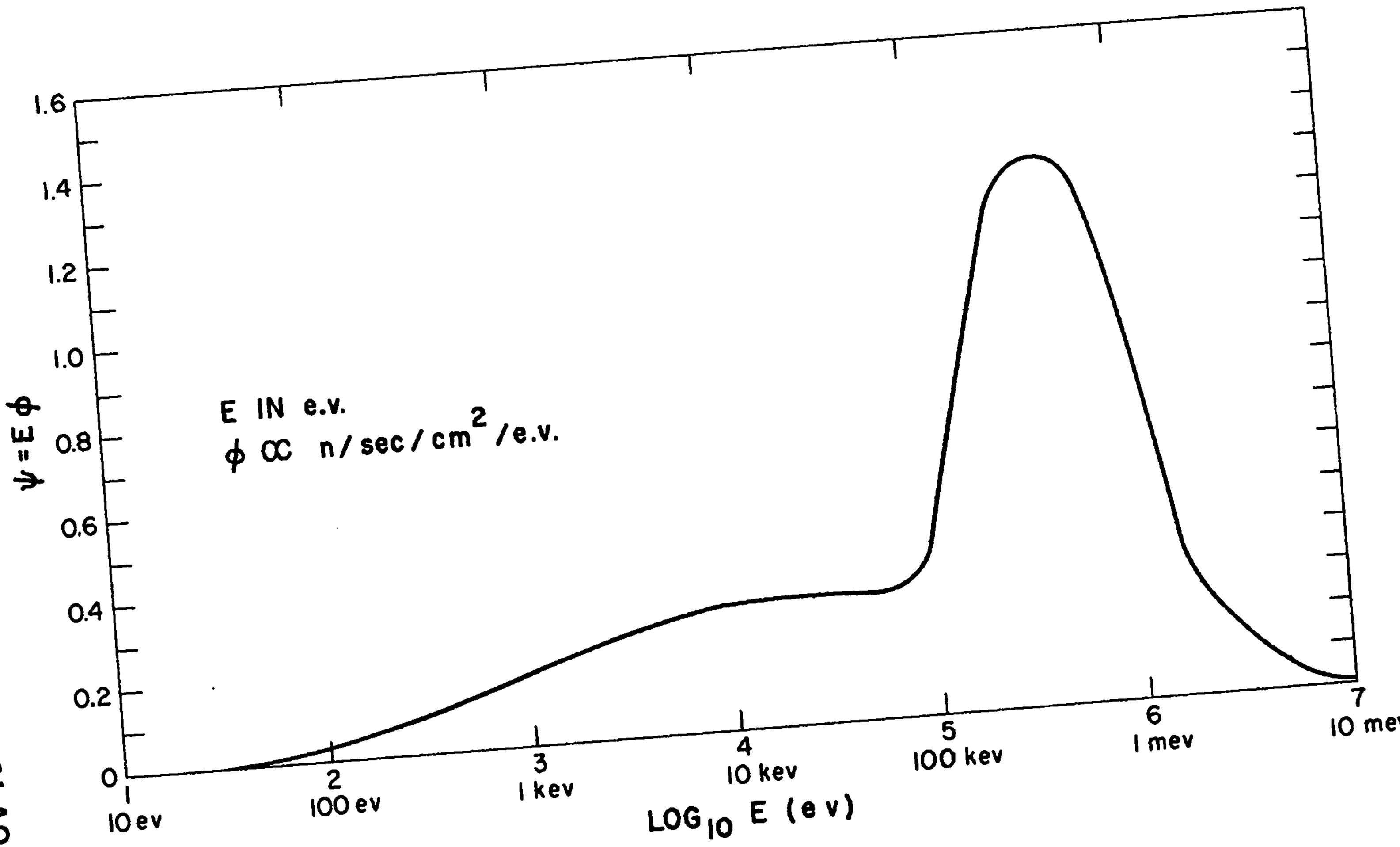

Figure 6. Proposed neutron spectrum present in the fission chamber. Total flux between any two energies is proportional to the area under the curve between these energies.

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