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THE FISSION NEUTRON SPECTRUM OF PLUTONIUM

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ABSTRACT

The fission neutron spectrum of plutonium, ${}_{94}Pu^{239}$, as produced by thermal neutrons, has been measured from about 0.4 to 7 Mev. The measurement was made by exposing nuclear emulsion plates to the neutrons arising from a plutonium sample bombarded by thermal neutrons from the Los Alamos "water boiler". The neutron energies were deduced by measuring the lengths of proton recoils produced in the nuclear emulsion; only proton recoils making a small angle with the incoming neutron direction were selected for measurement. Good geometry was emphasized in the experiment, and effort was directed toward eliminating factors that might modify neutron energies, such as nearby scattering objects, collimating devices, etc. The results show a spectral curve with a maximum between 0.7 and 0.8 Mev and having an approximately exponential decrease after 2 Mev. A comparison with Watt's empirically deduced relation for the thermal-induced fission neutron spectrum of ${}_{92}U^{235}$ shows that the present results are in agreement within statistical error with this relation in the most reliable energy region of the present measurement, i.e., from 0.5 to about 5 Mev.

THE FISSION NEUTRON SPECTRUM OF PLUTONIUM

INTRODUCTION

The motive for making this measurement of the fission neutron spectrum of plutonium stemmed from measurements of neutron spectra by nuclear emulsions inside the Los Alamos fast reactor. These measurements emphasized a need for knowing the unmodified or pure fission spectrum of plutonium in order that the degraded reactor spectrum could be compared with the original emitted neutron energies. A previous measurement[1] on the fission spectrum of plutonium by nuclear emulsion and cloud-chamber methods yielded a curve having a maximum between one and 2 Mev. Another measurement[2] of the plutonium spectrum carried out by ionization-chamber techniques indicated a maximum around one Mev or less.

The present measurement was planned in order to clarify the discrepancies in the previous measurements. Also, it was realized that better data could be obtained with present nuclear emulsions than with the older halftone plates used by Richards. The measurements were carried out with the original purpose in mind, i.e., to try to establish accuracy around the maximum of the curve so that a comparison could be made between the pure fission and reactor spectra in the neighborhood of this region and down to as low an energy as the film technique would permit. Therefore, only enough proton-recoil tracks were measured to obtain the necessary accuracy in the lower-energy region of the spectrum.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement used in this measurement is illustrated in Fig. 1. The plutonium sample consisted of a disk, 0.5" in diameter and 0.125" thick.[3] The fission was produced by bombarding the plutonium with thermal neutrons from the "water boiler". The thermal column of the boiler was arranged for a maximum flux of thermal neutrons by removing the central graphite stringer as far as the cadmium curtain. Since the 4.25"-square thermal beam produced in this manner was too large for the small sample, a boron collimator having a 2.25" diameter hole was inserted to reduce the width of the beam.

The plutonium sample was removed 30" from the wall of the thermal column and was about 32" above floor level. Also, all other large scattering objects in the room were at least twice the above distances from the plutonium. All possible precautions were taken to prevent modification of the neutron spectrum from the plutonium before it reached the nuclear emulsions.

The nuclear emulsion plates were orientated with their emulsion planes parallel to radii from the plutonium sample. A number of plates were used at various distances from the plutonium in order to select the furthest plate (for better resolution) having a reasonable track density. All the plates were placed inside a 1/32"-thick cadmium cylindrical shield so as to minimize the $N^{14}(n,p)C^{14}$ reaction in the plates caused by thermal neutrons in the room. The placing of the plates outside the geometrical beam path defined by the thermal-column aperture assured a minimum of background neutrons from the water boiler reaction sphere and also a minimum of gamma-ray fogging.

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[1] H. T. Richards, LA-556 (1946) and LA-84 (1944).

[2] H. Staub and D. B. Nicodemus, apparently unpublished; see LA-84 (1944).

[3] It is recognized that a better sample geometry would have been a thin strip of plutonium, but this was difficult to fabricate and the above sample was already available.

[redacted]

The plutonium sample was given a 34-hour irradiation with the water boiler running at a power of 5.5 kw.

A background experiment was performed by substituting a 10-gram piece of bismuth of approximately the same dimensions as the plutonium sample and repeating the identical experimental procedure described for the plutonium. Since bismuth has roughly the same scattering properties as plutonium for neutron energies greater than 0.1 Mev, such an experiment would show if any neutrons from the water boiler were scattered into the plates. Also, if neutrons having energies above the cadmium resonance existed around the room, the background plates would record the $N^{14}(n,p)C^{14}$ reaction in the emulsions as well as proton-recoil tracks from background neutrons having energies greater than 0.3 Mev.

The original experimental details are recorded in Notebook No. 2939.

ANALYSIS OF NUCLEAR PLATES

Both Ilford and Eastman plates were employed in the experiment. The Ilford plates were type C2, 100 microns thick,[4] batch No. Z2283; the Eastman plates were type NTA, 75 microns thick,[4] batch No. 391,987. The nuclear emulsions were processed according to the following recipe, with all solutions at 68°F:

1. Soak in water for 20 minutes;
2. Develop in D-19 (1:4 dilution) for 25 minutes; agitate;
3. Fix in acid hypo for about two hours; agitate;
4. Wash about two hours and dry.

The plates were analyzed on Leitz microscopes using a 90x oil-immersion objective and either 8x or 10x compensating eyepieces. One eyepiece contained a suitable micrometer scale and the other a 20° angle having a bisecting line. Acceptable tracks were defined as those that were contained within a rectangular pyramid having a half-angle of 10° about the forward direction in the developed emulsion. The experimental criteria for the track angular limits of ± 10° in the plane of the emulsion was set by the 20° angle contained in one of the eyepieces. The criteria for the azimuthal or dip angular limits of ± 10° was determined by means of the depth of focus of the microscope. Since the depth of focus was about one micron for the above microscopes, this meant that at least 6 microns of the track should be in clear focus for the azimuthal angle to be within ± 10°. Since the proton-recoil track may suffer a scattering in the emulsion and change the horizontal or azimuthal angle, it is important that these angular criteria be applied to the beginning of the track whenever possible. However, in borderline cases at angles near 10°, it was sometimes necessary to use a long length of track in order to determine the dip angle accurately. The problem of estimating azimuthal angles $\leq 10°$ for tracks shorter than 6 microns (~0.5 Mev) is a subject in itself. This problem and other subjects associated with the use of nuclear emulsions at neutron energies less than 0.5 Mev are discussed in another report.[5] In the present experiment, tracks shorter than about 3 microns were not measured.

All tracks satisfying the above angular criteria were measured, except those lying within 5 microns from the top and bottom surfaces of the emulsion. This volume of emulsion was ignored so as to decrease the correction factor for tracks

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[4] It would have been desirable to use a thicker emulsion in order to reduce the correction factor required for tracks leaving the emulsion surfaces.

[5] N. Nereson and F. Reines, LADC-748 (1950).

[redacted]

leaving the emulsion surfaces. The above procedure was strictly followed for Ilford plate I44$_2$ whose average developed thickness was 38 microns; however, for Eastman plates 44$_1$ and 44$_2$, whose average developed thickness was 21 microns, tracks were also accepted in the above 5-micron thicknesses if the acceptable tracks pointed into the emulsion volume and not out of the emulsion volume. The latter procedure aided in further decreasing the correction factor and in obtaining more tracks per field from the thin Eastman emulsions. The tracks leaving the emulsion surfaces were not measured, but their number was recorded. Figure 5 in Appendix I shows the correction factor, as a function of energy, to be applied for tracks going out of the emulsion surfaces.

The plates were scanned by taking successive swaths in the long direction of the plate. Consecutive fields were analyzed for each particular swath, and about 0.2 mm was skipped between adjacent swaths. The area of analysis on the plates was restricted to an area about 0.5" wide by 2" long starting 0.25" from the end of the plate closest to the plutonium. Within the above area, the maximum angle that a neutron from the plutonium sample could make with the center line of the plate (or forward direction) was 4° for plates 44$_1$ and 2.5° for plates 44$_2$ and I44$_2$.[6] The average angle of the incoming neutron with respect to the center line of the plate is less than one-half the above maximum values. The energy resolution set by the above angles is well within that set by the ± 10° horizontal and ± 25° azimuthal angular limits in the undeveloped emulsion.[7]

The total of about 5500 proton-recoil tracks about the forward direction in plates 44$_1$, 44$_2$, and I44$_2$ were measured by microscopists Julia Carlson and Shirley Suttman. The data is recorded in Notebooks Nos. 2572, 2670, 2674, and 2085; a summary of the data is presented in Notebook No. 2674 on pages 95 to 98.

The background plates were analyzed in the same manner as the 44$_1$ and 44$_2$ data plates. The only difference consisted in using a 50-micron emulsion thickness instead of a 75-micron thickness. To compensate for the smaller volume, only 2 microns was skipped from the top and bottom surfaces of the emulsion. This procedure, of course, increased the probability of tracks leaving the emulsion surfaces.

RESULTS

The data obtained from the nuclear plates in this experiment have been grouped into four sets of data. Table I gives various information concerning these data sets, such as number of tracks, number of fields, emulsion thickness, etc. The table also gives the result of the background run, i.e., with the bismuth substituted for the plutonium sample. The 49BkgE$_2$ plate represents the background for the position of the 44$_2$ plates, while the 49BkgE$_1$ plate represents the background for the position of the 44$_1$ plates.

It was thought that the background might be high in the 0.5- to 0.7-Mev region due to the 0.62-Mev proton from the thermal-neutron reaction with the nitrogen in the plates, but this is observed not to be the case. Instead, the background tracks are distributed quite uniformly over the region from 0.3 to 2.5 Mev; if there is any maximum at all, it appears to be in the 2.0- to 2.4-Mev region. Background tracks greater than about 2.5 Mev have a fair chance of leaving the thin emulsion volume so that not many tracks greater than this energy appear in the analysis. It is not clear why such a large discrepancy in the number of tracks leaving the emulsion surfaces

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[6] The 44$_3$ plates were not analyzed because there were very few tracks per field.

[7] The difference in thickness between a processed and unprocessed C2 or NTA emulsion is usually around a factor of 2.5.

TABLE I. NUCLEAR PLATE STATISTICS

Summary of Data and Background Plate Analysis

Plate Function	Plate Number	Micro-scopist	Total Microscope Fields Analyzed	Field Area in Square Microns	Developed Emulsion in Microns	Effective Emulsion Thickness Analyzed	Total Tracks	Tracks Leaving Emulsion Surfaces	Tracks per Field per 10 Microns of Thickness Analyzed
Data	I44$_2$	S. S.	6,112	9,161	38	28	965	59	0.056
Data	44$_2$	J. C.	26,015	8,490	20	15	1663	82	0.043
Data	44$_1$	J. C.	3,714	8,490	22	17	1506	90	0.24
Data	44$_1$	S. S.	5,785	9,161	21	16	1510	65	0.16
Background	49BkgE$_2$	J. C.	7,640	8,490	14	12	36	25	0.004
Background	49BkgE$_1$	J. C.	2,560	8,490	14	12	36	9	0.012

Background Plate Data

Energy Interval	No. of Tracks for Plate 49BkgE$_2$	No. of Tracks for Plate 49BkgE$_1$	Energy Interval	No. of Tracks for Plate 49BkgE$_2$	No. of Tracks for Plate 49BkgE$_1$
0.3 - 0.5	3	3	2.5 - 2.7	0	0
0.5 - 0.7	1	0	2.7 - 2.9	0	0
0.7 - 0.9	0	1	2.9 - 3.1	0	0
0.9 - 1.1	1	1	3.1 - 3.3	0	0
1.1 - 1.3	0	3	3.3 - 3.5	0	0
1.3 - 1.5	2	1	3.5 - 3.7	1	0
1.5 - 1.7	0	0	3.7 - 3.9	0	0
1.7 - 1.9	0	2	3.9 - 4.1	0	0
1.9 - 2.1	1	8	4.1 - 4.3	0	1
2.1 - 2.3	1	7	Tracks out of Emulsion	25	9
2.3 - 2.5	1	0			

[redacted]

exists between the two background plates. It would appear as though these background tracks come from the water boiler, since the absolute track background is higher on the plate that was closer to the thermal-neutron beam. The closer plate may have touched the edge of the beam defined by the 4.25" graphite collimator. The 18" boron collimator should have eliminated this latter effect for thermal neutrons, but some fast neutrons may have leaked through the boron collimator. Expressed in terms of tracks per field for a given emulsion thickness analyzed, the background tracks average about 8% of the data plate tracks for the 44_2 plates and about 6% of the data plate tracks for the 44_1 plates. This was considered a negligible background effect, and the data plates were not corrected for any background tracks.

A comparison of the several sets of data taken is shown in Fig. 2. The data were originally tabulated in 0.1-Mev intervals, but in this presentation these intervals have been summed into larger groups in order to improve the statistical accuracy of each point and to present a clearer comparison. The agreement is quite good except around the maximum of the curve; here, the Data I points are lower than the rest of the data, and one of the points from Data II is considerably higher than the other data. Data I is the least trustworthy of these four sets, since it was taken by one of the microscopists who was just learning the technique; it probably reflects the usual initial difficulty, or the error of overlooking the shorter tracks. However, since Data I represents only 1/6 of the total data, its effect on the combined data is quite small. These data have not been corrected for tracks leaving the emulsion surfaces. The data have only been corrected for the variation of the n-p scattering cross section with energy. A curve of this cross section is given in Appendix II.

The 44_2 plates were analyzed first, since slightly better energy resolution was possible from these plates. However, when the background runs indicated a smaller background percentage on the 44_1 plates, an approximately equal amount of data was taken from the 44_1 plates. Actually, no significant difference between the data from the 44_1 and 44_2 plates can be observed in the results shown in Fig. 2.

The combined results from Data I, II, III, and IV is tabulated in Table II, and graphed in Fig. 3 where the relative number of neutrons per 0.1 Mev energy interval, n(E), is plotted against neutron energy, E_n. The four sets of data were first individually corrected at 0.1-Mev intervals for long tracks leaving the emulsion and then added together. In Fig. 3, the combined data have been averaged over appropriate larger-energy intervals, depending upon the energy resolution demanded by the curve. Since neutron energy instead of proton-recoil energy is plotted in Fig. 3, it was necessary to increase the proton-recoil energy by 5% to yield the average neutron energy.[8] Another small correction arises from the fact that σ_p had been taken at energy E_p in Fig. 2 instead of at E_n which is required for Fig. 3; however, this correction amounts to only a few percent. Therefore, the ordinate figures represent the corrected total number of proton recoils per 0.1 Mev divided by σ_p at the given neutron energy.

The present results for the fission neutron spectrum of ${}_{94}Pu^{239}$ induced by thermal neutrons have been compared with the same phenomena for ${}_{92}U^{235}$. An empirical expression worked out by Watt[9] appears to fit the U spectrum over a wide energy range; this relation was normalized to the present results at 2 Mev and is drawn as a dashed curve in Fig. 3. The present Pu spectrum results are in agreement, within statistical error, with the U spectrum curve in the energy region from 0.5 to 4.5 Mev. Beyond 4.5 Mev, the Pu data lie above the U curve. It is unwise

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[8] This energy-correction calculation is worked out in LADC-748 (1950).

[9] B. Watt, LA-718 (1948).

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TABLE II. NUCLEAR PLATE DATA USED IN FIG. 3

Corrected Data

E_p (Mev)	E_n (Mev)	Plates 44_1 and 44_2 C.P.R.T./σ_p*	Plate I44_2 C.P.R.T./σ_p	All Plates n(E) C.P.R.T./σ_p
0.35	0.37	29.2×10^{24}	7.9×10^{24}	37.1×10^{24}
0.45	0.47	32.1	3.6	35.7
0.55	0.575	56.0	9.2	65.2
0.70	0.735	63.5	8.9	72.4
0.90	0.945	52.5	8.7	61.2
1.15	1.21	49.5	8.6	58.1
1.45	1.52	47.6	9.9	57.5
1.75	1.84	41.0	8.3	49.3
2.05	2.15	40.0	8.7	48.7
2.35	2.46	30.5	8.2	38.7
2.75	2.88	23.0	4.9	27.9
3.25	3.41	17.5	4.3	21.8
3.75	3.94	13.1	4.0	17.1
4.25	4.46	9.4	2.6	12.0
4.75	4.99	9.2	2.3	11.5
5.25	5.51	6.8	1.6	8.4
5.75	6.04	3.8	1.5	5.3
6.25	6.56	6.3	0.8	7.1
6.75	7.08	2.0	1.0	3.0
7.30	7.65	1.5	1.0	2.5

Uncorrected Data

Proton-Recoil Energy Interval (Mev)	Plates 44_1 and 44_2 P.R.T. **	Plate I44_2 P.R.T.	Proton-Recoil Energy Interval (Mev)	Plates 44_1 and 44_2 P.R.T. **	Plate I44_2 P.R.T.
0.2 - 0.3	21	12	2.5 - 3.0	245	55
0.3 - 0.4	130	60	3.0 - 3.5	151	41
0.4 - 0.5	193	24	3.5 - 4.0	90	32
0.5 - 0.6	325	54	4.0 - 4.5	50	17
0.6 - 0.8	656	92	4.5 - 5.0	38	13
0.8 - 1.0	471	78	5.0 - 5.5	22	7
1.0 - 1.3	590	102	5.5 - 6.0	9	5
1.3 - 1.6	499	103	6.0 - 6.5	12	2
1.6 - 1.9	373	77	6.5 - 7.0	3	1
1.9 - 2.2	335	73	7.0 - 7.6	2	3
2.2 - 2.5	226	62			

*C.P.R.T./σ_p means (proton-recoil tracks per 0.1-Mev corrected for tracks leaving emulsion surfaces) / (σ_p taken at energy E_n).

**P.R.T. means number of measured proton-recoil tracks in energy interval specified in first column.

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[redacted]

to state that this a real discrepancy, since the present experiment was not especially designed or intended for accuracy at high energies. First, the data in the higher energies is based upon few tracks but the statistical error shows this fact. Secondly, large correction factors are necessary at high energies due to the high probability that these long tracks will leave the emulsion surfaces. It is possible to make an error of about 10% in the correction factor, since it depends upon the emulsion thickness and shrinkage factor which are each known to an accuracy of about 7%. Thirdly, background tracks may be a larger percentage of the data tracks at high energies than at low energies, since very few high-energy data tracks are actually measured.

On a semi-log plot, the Pu spectrum data beyond 2 Mev shows an approximately straight-line relationship. Using the most reliable data between 2 and 4.5 Mev, one finds that for the present Pu spectrum n(E) decreases by a factor of 10 every 4.2 ± 0.2 Mev. Watt's curve diminishes n(E) by a factor of 10 every 3.7 or 3.8 Mev over this same region. Considering the statistical errors in the two spectral curves, the two slopes are just barely in agreement. It is possible that this discrepancy might be due to the different experimental arrangement used in the two experiments, i.e., the collimated-source arrangement for the U spectrum as compared with the open-source arrangement for the Pu spectrum. However, the data are not accurate enough to decide the above matter.

The point at 0.4 Mev should be fairly reliable, since its value has been corrected for the inefficiency of the nuclear emulsion to record low-energy neutrons.[5] However, since the point does represent the lowest-energy value that can possibly be used in the film data, perhaps not too much reliability should be placed on its correctness.

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APPENDIX I

Correction Factor for Tracks Leaving the Emulsion Surfaces

Case I

This case is worked out for correction of the data taken from Eastman plates 44_1 and 44_2. These plates were analyzed by measuring all forward proton recoils within the specified angular limits in a central thickness T of the emulsion (see Fig. 4a). In addition, forward proton recoils were measured in the small thickness t on either edge if the acceptable tracks were parallel to the emulsion surface or pointed toward the emulsion interior.

The assumption was made that the proton-recoil tracks were uniformly distributed within the angular limits about the forward direction. This assumption is good enough for this calculation, since one makes only about a 2% error in the correction if the average angle of the proton-recoil is 10°.

The probability of an acceptable proton-recoil track of length ℓ leaving the emulsion surface from a particular point in the thickness T is A_o/A_T, where A_T is the total area traced out by the end of the track within its angular limits, and A_o is the area outside the emulsion surfaces formed by the end of the track within its angular limits. Thus, in Fig. 4a, the probability that a track of length ℓ starting at point 4 in the thickness T will leave the emulsion is

$$\frac{(S_1+S_2)\,w}{(\ell 2\times 25^\circ/57.3^\circ)\,w} \;,$$

where w is the arc length traced out by the end of ℓ as it swings through a horizontal angle of 20° or 0° ± 10°. Since the width of the emulsion is extremely large compared to w, the value of w is irrelevant. The average probability, P_1, of a track of length ℓ leaving the emulsion surfaces from the thickness T is:

$$P_1 = \frac{\int_o^{T/2} A_o\,dT}{\int_o^{T/2} A_T\,dT} \;.$$

It seemed simplest to evaluate this integral graphically. This was done by summing A_o/A_T over six points in the thickness T as shown in Fig. 4a. The calculations were simplified by replacing

$$A_T = 2\ell(25^\circ/57.3^\circ)\,w = 2\ell w(0.436)$$

with

$$A_T \simeq 2\ell w \sin 25^\circ = 2\ell w(0.422) \quad ;$$

also, by replacing

$$S_1 = \ell(25^\circ/57.3^\circ) - \ell \arcsin d/\ell$$

with

$$S_1 \simeq \ell \sin 25^\circ - d_1 \quad ,$$

and similarly for S_2. The approximations for A_T and A_o are both smaller than the true values; however, since they appear in ratio form, the error in P_1 is quite small (~3%). The results are tabulated in Table II.

It is also necessary to calculate the average probability, P_2, of a track of length ℓ leaving the emulsion surface from the thickness t when only acceptable tracks pointing toward the interior of the emulsion are considered. As before, for a particular

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point, this probability is A'_0/A'_T. For example, in Fig. 4a, the probability that a track of length ℓ starting at point 2 in thickness t will leave the emulsion surface is

$$S_3 w/\ell(25^\circ/57.3^\circ)\,w \quad .$$

The average probability, P_2 is

$$P_2 = \frac{\int_0^t A'_0\,dt}{\int_0^t A'_T\,dt} \quad .$$

The value of P_2 was obtained graphically by summing A'_0/A'_T over six points in the thickness t. This calculation has also been simplified by replacing

$$A'_T = \ell(25^\circ/57.3^\circ)\,w = w\ell(0.436)$$

by

$$A'_T \simeq w\ell \sin 25^\circ = w\ell(0.422)$$

and

$$A'_0 = w\left[\ell(25^\circ/57.3^\circ) - \ell \arcsin d_2/\ell\right]$$

by

$$A'_0 \simeq w\left[\ell \sin 25^\circ - d_2\right] \quad .$$

The results are shown in Table II. The values obtained from the above calculations are based upon shrinkage factor of 2.5 and values of t = 5 microns and T = 11 microns for the processed emulsion. Therefore, in the unprocessed emulsion, t = 12.5 microns and T = 27.5 microns.

Finally P_1 and P_2 must be combined to obtain the average probability, P, of an acceptable track of length ℓ leaving the emulsion surfaces from either thickness T or t. Since the probability of finding a track in a finite emulsion thickness is proportional to that thickness,

$$P = \frac{TP_1 + (2t/2)P_2}{T+t} = \frac{27.5P_1 + 12.5P_2}{40} = \frac{P_1 + 0.45P_2}{1.45}$$

The correction factor by which the proton-recoil data must be multiplied is $1/(1-P)$. A graph of the correction factor versus energy is shown in Fig. 5.

Case II

This case is worked out for the correction of the data taken from Ilford plate 144_2. In this case, only the forward proton-recoil tracks originating in the thickness T were measured. The calculation of this correction factor is identical with the procedure for calculating P_1 in Case I. The numerical values used in this calculation were a shrinkage factor of 2.5, t = 5 microns and T = 28 microns for the processed emulsion. In the unprocessed emulsion, t = 12.5 microns and T = 70 microns. A reference figure is illustrated in Fig. 4b, and the results are shown in Table III and graphed in Fig. 5.

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TABLE III.

RESULTS ON CALCULATION OF CORRECTION FACTOR FOR TRACKS LEAVING THE EMULSION SURFACES

Case I: t = 12.5 microns and T = 27.5 microns in the unprocessed emulsion.

E_p (Mev)	ℓ (Microns)	P_1	P_2	P	Correction Factor
1.65	30	0	0	0	1.00
2.00	40	0.02	0	0.01	1.01
2.30	50	0.07	0	0.05	1.05
2.60	60	0.12	0	0.08	1.09
2.90	71	0.19	0	0.13	1.15
3.13	80	0.25	0	0.17	1.20
3.35	90	0.30	0	0.21	1.27
3.56	100	0.38	0.008	0.24	1.33
4.00	120.5	0.48	0.10	0.36	1.56
4.58	150	0.58	0.27	0.48	1.92
5.47	200	0.69	0.46	0.62	2.60
6.23	250	0.75	0.56	0.69	3.22
6.94	300	0.79	0.63	0.74	3.84
7.56	350	0.82	0.69	0.78	4.55

Case II: t = 12.5 microns and T = 70 microns in the unprocessed emulsion.

E_p (Mev)	ℓ (Microns)	P	Correction Factor
1.65	30	0	1.00
2.00	40	0.01	1.01
2.30	50	0.03	1.03
2.60	60	0.05	1.05
2.90	71	0.08	1.09
3.13	80	0.11	1.12
3.35	90	0.13	1.15
3.56	100	0.16	1.19
4.00	120.5	0.21	1.27
4.58	150	0.30	1.43
5.47	200	0.45	1.82
6.23	250	0.56	2.27
6.94	300	0.64	2.78
7.56	350	0.68	3.12

[redacted]

[redacted]

APPENDIX II

N-P Scattering Cross Section

This appendix merely gives the n-p scattering cross section versus energy curve which was used in converting the data from number of proton recoils to number of neutrons. The curve is illustrated in Figs. 6a and 6b. This curve is the theoretical curve of Bohm and Richman[10] which is presented in two standard cross-section references.[11]

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[10] Bohm and Richman, Phys. Rev. 71, 567 (1947).

[11] Goldsmith, Ibser and Feld, Rev. Mod. Phys. 19, 261 (1947). The Science and Engineering of Nuclear Power, Vol. 1, C. D. Goodman, EDP (Addison Wesley Press, Cambridge 1947).

[redacted]

[redacted]

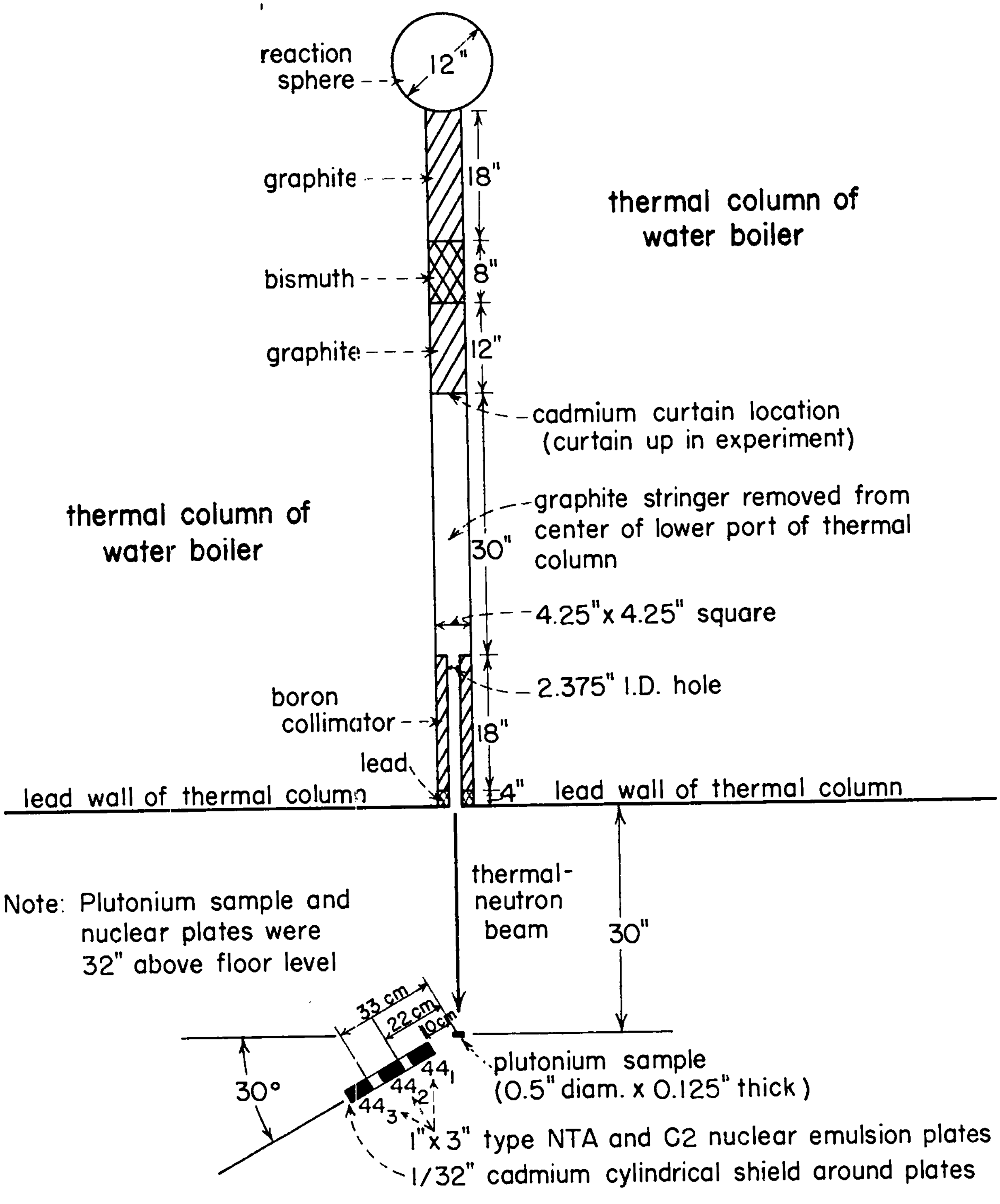

Fig. 1 Experimental arrangement

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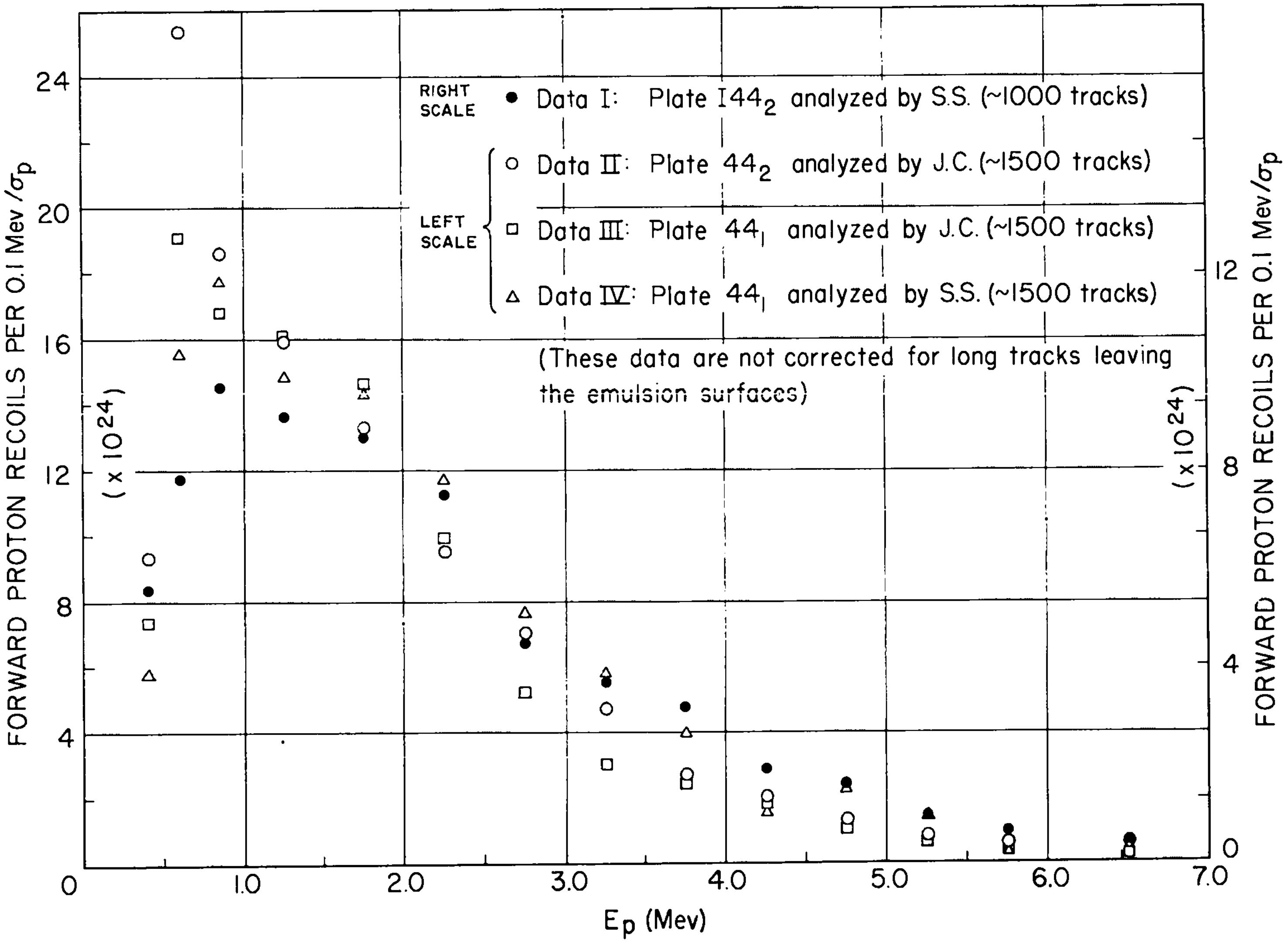

Fig. 2 Comparison of four sets of data from the nuclear plates

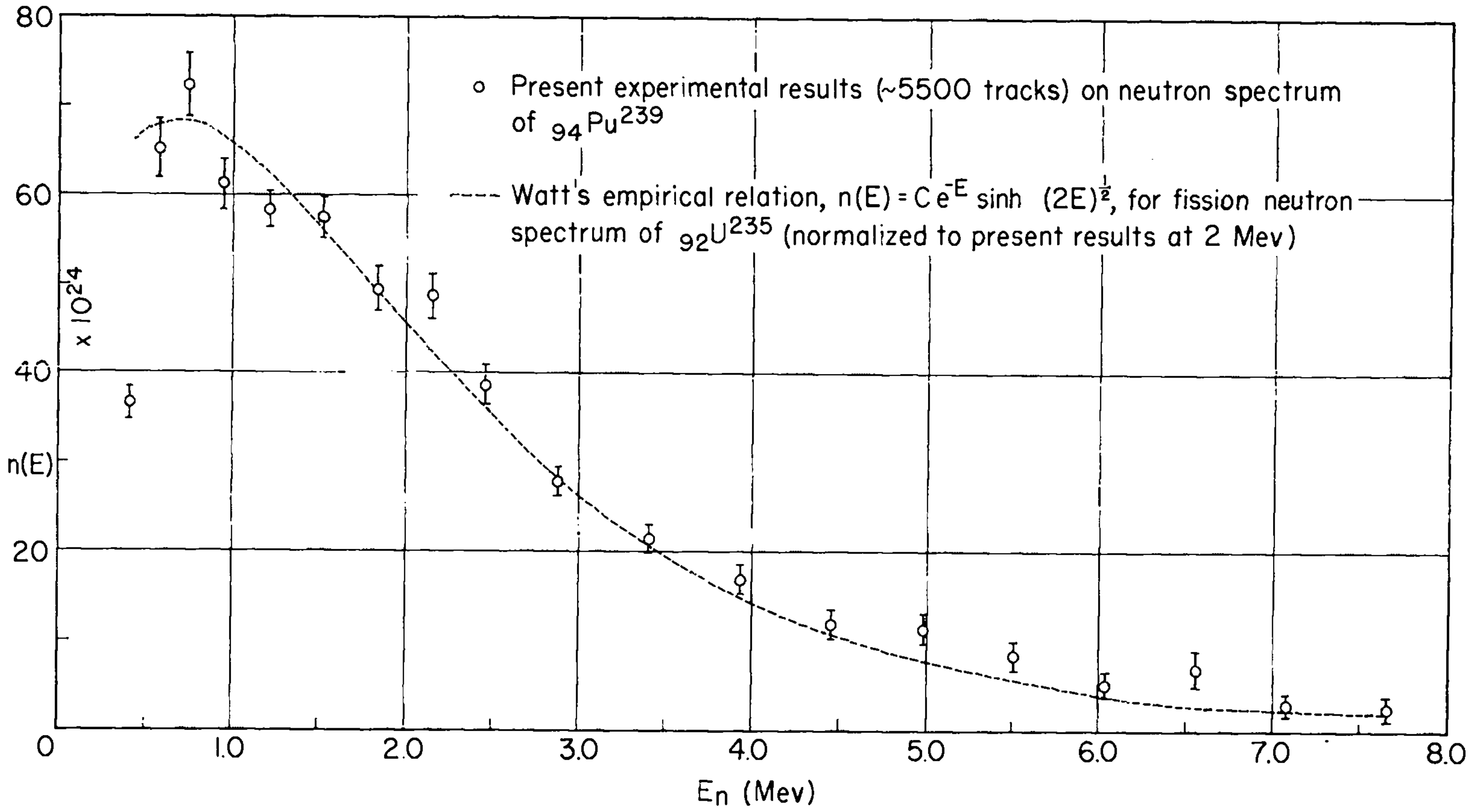

Fig. 3 Combined data on fission neutron spectrum of $_{94}Pu^{239}$ from present experiment

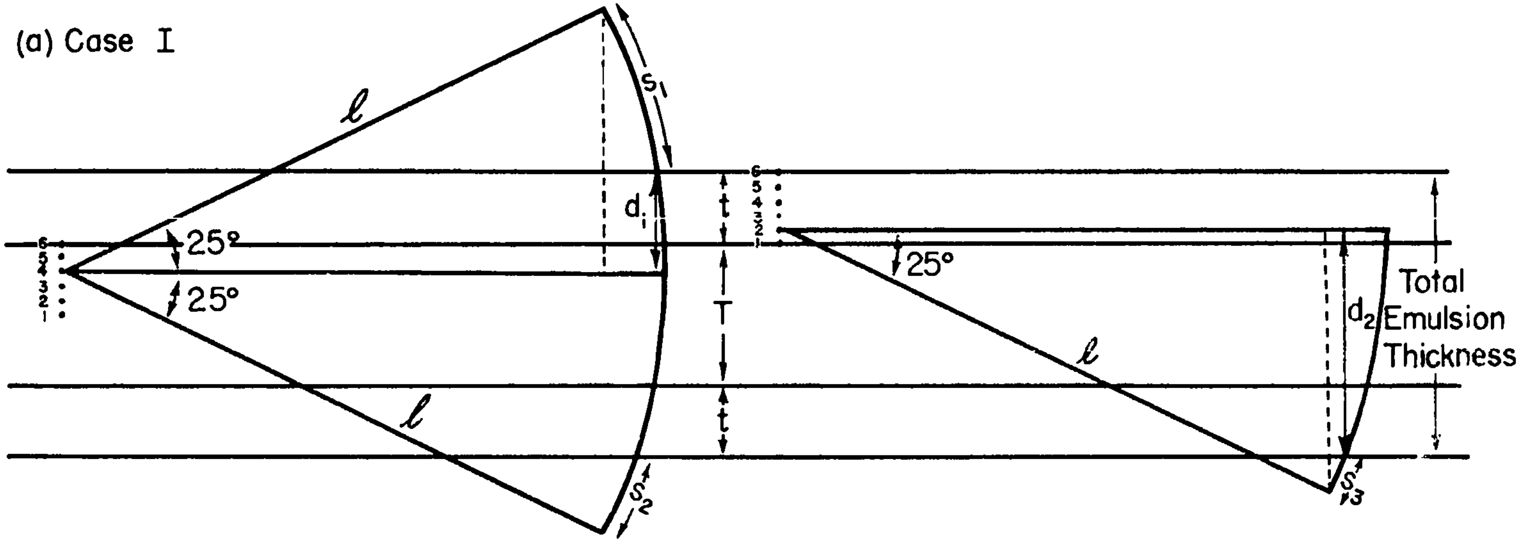

Fig. 4a Reference figures for calculating probability of tracks leaving emulsion surfaces

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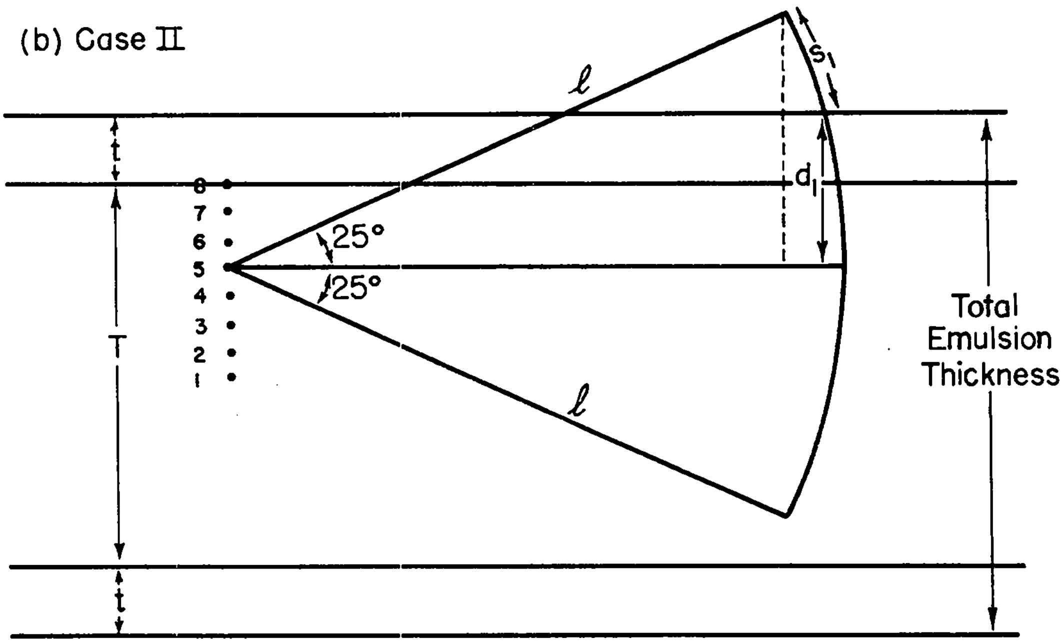

Fig. 4b Reference figures for calculating probability of tracks leaving emulsion surfaces

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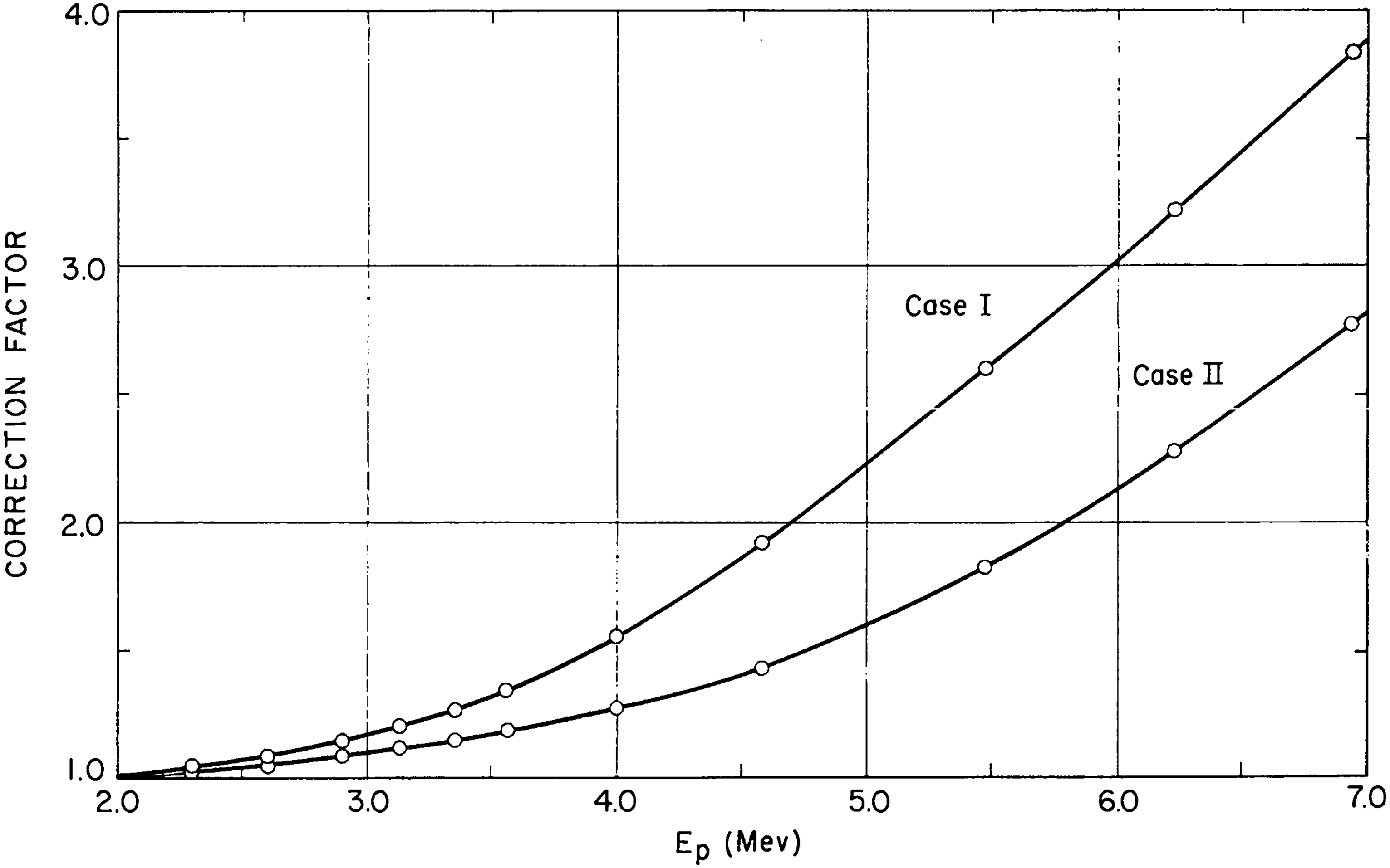

Fig. 5 Correction factor for tracks leaving emulsion surfaces versus energy (See Appendix I)

[redacted]

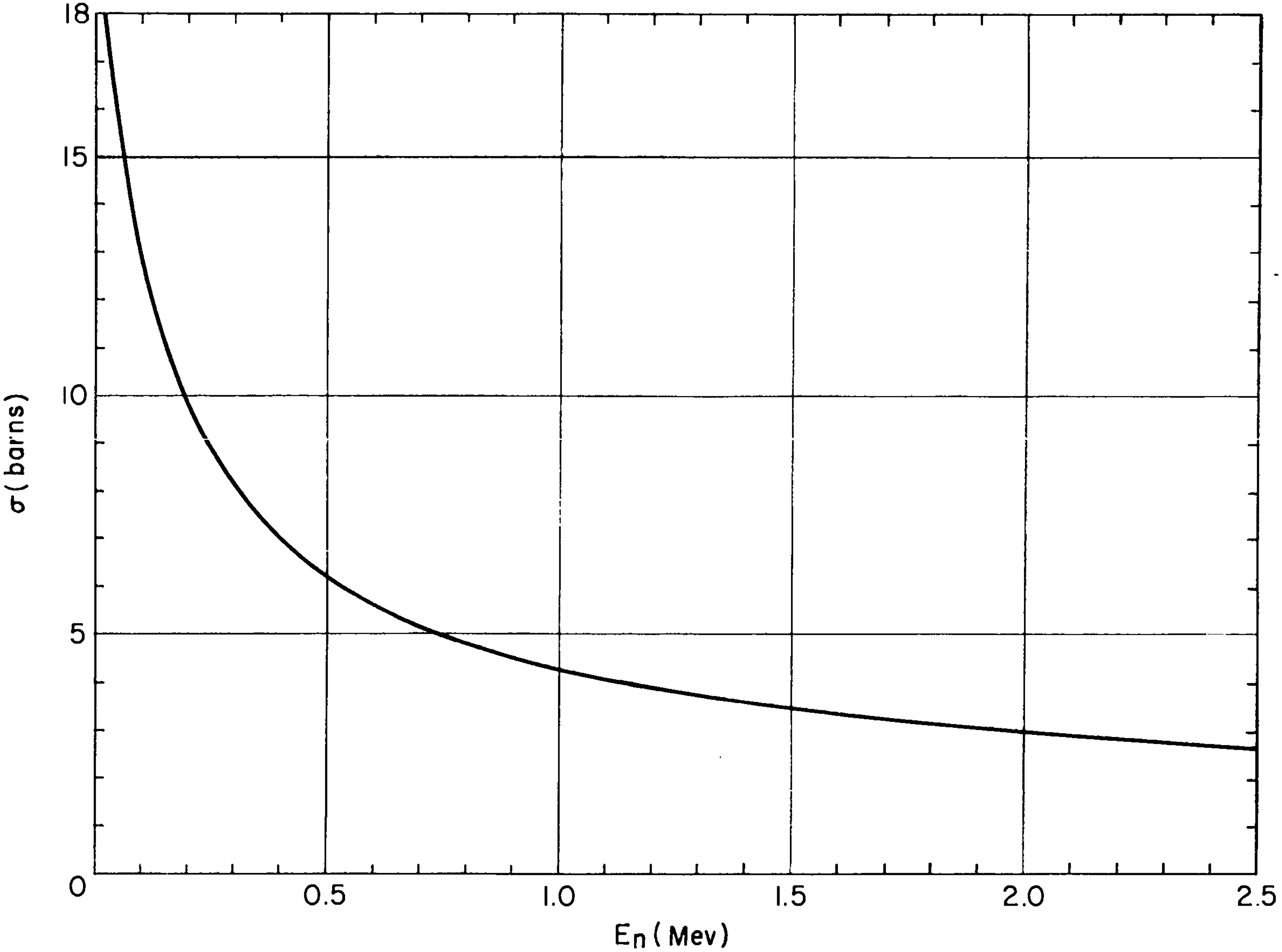

Fig 6a Neutron-proton scattering cross section versus energy

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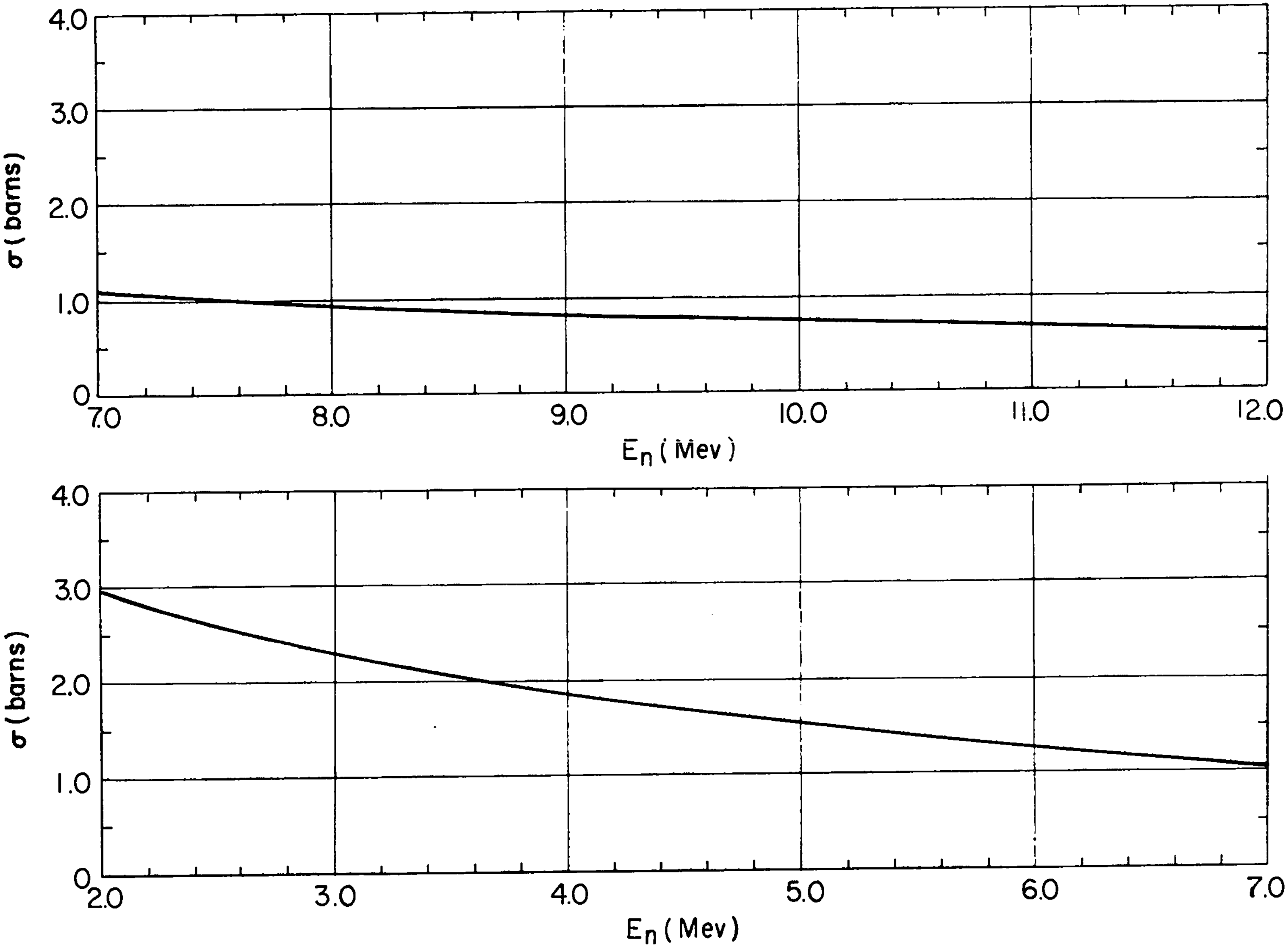

Fig. 6b Neutron-proton scattering cross section versus energy

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