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NEUTRON ENERGY DISTRIBUTION OF WATER BOILER FAST NEUTRON BEAM FROM 0.5 TO 6 MEV

By
Norris Nereson
Julia Carlson
Jewell Erickson

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Los Alamos Scientific Laboratory
Los Alamos, New Mexico

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Work Done By:

Julia Carlson
Jewell Erickson
Norris Nereson

Report Written By:

Norris Nereson

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Los Alamos Scientific Laboratory
Los Alamos, New Mexico

ABSTRACT

This report concerns itself with the neutron energy distribution of the east port of the water boiler with a U^{235} source inserted. The work was done with nuclear plates and provides reliable data in the energy region from 0.5 to 6 Mev. The report is essentially a supplement to LA-718 which deals with the identical neutron spectrum in the energy region from 3.3 to 17 Mev. In addition to extending the knowledge of the neutron spectrum of the water boiler fast beam, the experiment also gives information on the influence of a collimating tube on a neutron spectrum.

NEUTRON ENERGY DISTRIBUTION OF WATER BOILER
FAST NEUTRON BEAM FROM 0.5 TO 6 MEV

INTRODUCTION

The work presented in this report represents preliminary work done in the nuclear plate laboratory on the measurement of neutron spectra by nuclear emulsion technique. The technique which was first checked and which was employed in the present work was that of measuring proton recoils in the emulsion about a small angle of the incoming neutron direction.

The energy spectrum of the fast neutron beam emerging from the "glory hole" (east port) of the water boiler with the U^{235} disk source inserted had previously been measured by Watt[1] for the energy range 3.3 to 17 Mev using counter techniques. The above neutron spectrum was selected for nuclear plate measurement primarily in order to compare nuclear plate results with counter methods. It was also desired to check the results of two different microscopists on the same spectrum measurement.

This report has not been written primarily to present this preliminary nuclear plate check work, but rather to show the extension of the glory hole neutron spectrum below 3.3 Mev. It is of interest to note the energy at which this spectrum ceases to conform to a pure U^{235} fission spectrum and to observe what shape it does assume at

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

energies below 3.3 Mev. The experiment also provides information on the absolute number of neutrons present in the glory hole spectrum.

Certain modifications have been made in the water boiler between the time of the above experiments (Oct. 1948) and that of the present writing. However, these changes should not greatly affect the particular results presented in this report; furthermore, the information obtained is still valuable for comparison with results from the present water boiler geometry.

EXPERIMENTAL

A. Proton Recoil Plate Detectors

The experimental arrangement is shown in Fig. 1. Eastman type NTA and Ilford C2 plates having 100 micron thick emulsions were placed across the exit of the east port with the U^{235} disk source[2] inserted and given a suitable exposure to the fast neutron beam. The plates were wrapped with one mil thick aluminum foil and their emulsion surfaces were orientated parallel to the direction of the neutron beam. The plates were supported by two thin metal supports which were placed well outside of the neutron beam. The following processing procedure for 100 micron thick emulsions yielded clear, readable plates. All solutions are at 68° F.

1. Soak in water for 20 minutes.
2. Develop in D-19 (diluted 1:3) for 25 minutes. Agitate.
3. Fix in acid hypo (diluted 1:1) for about 2 hours. Agitate.
4. Wash in running water for 2 hours and dry.

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[2] An assembly of 31 disks of ${}_{92}U^{235}$ 0.010 inch thick equally spaced along an 18 inch Al tube: the total U^{235} mass was 54.1 grams.

The above exposures were made during September and October of 1948; the original experimental details are recorded in LA notebook #2178.

The technique of analyzing neutron spectra by measuring proton recoils in nuclear emulsion about a small angle of the forward neutron direction has been discussed more completely in previous reports[3,4]. Therefore, this report will mention only briefly the procedures and calculations involved in the analysis of the plates; for more details, the reader will be referred back to the earlier reports.

The proton recoil method of analyzing neutron spectra is convenient since $E_p = E_n \cos^2 \theta$ where E_p and E_n are the energy of the proton recoil and incident neutron respectively and θ is the angle between the neutron and proton directions. Thus, if θ is made small, $E_p \cong E_n$, or more accurately, E_p is only a few percent less than E_n. Therefore, only a small correction on E_p is required to determine the neutron energy E_n if the recoils are measured about a small angle to the incident neutron direction. In order for this technique to be practical, the condition that the neutron mean free path in the nuclear emulsion be large compared to the dimensions of the emulsion volume must also be satisfied[4].

The present plates were analyzed by measuring proton recoils in the processed emulsion which made less than a 10° angle with the beam or forward neutron direction. Practically, this means that from any point in the processed emulsion all acceptable proton recoils lay

[3] N. Nereson, LA-1078 (1950).
[4] N. Nereson and F. Reines, LADC-748 (1950).

within a rectangular pyramid having half-angles of 10° in the horizontal and vertical planes. Since the above angular criteria was applied to the processed emulsion and since the emulsion thickness shrinks by about a factor 2.5 upon processing, acceptable proton recoils from any point in the unprocessed emulsion lay within a rectangular pyramid of half-angle 10° in the horizontal plane and half-angle 25° in the vertical or azimuthal plane. The exposures were such that approximately 5 forward proton recoil tracks were contained in the entire emulsion thickness within the above angular limits for each microscope field (see Table I). From experience gained since this time, the above track density is considered too high by about a factor of two for most accurate analysis of short tracks.

The energy resolution resulting from the above angular criteria is 11% around 0.5 Mev and 6% at 2 Mev[4]. Energy resolution is here defined as the energy half-width of the proton recoil distribution obtained from neutrons of energy E_n divided by E_n. The above energy resolution is amply sufficient for the spectral curve obtained in this experiment.

Analysis of the plates was carried out on Bausch and Lomb or Leitz microscopes using 10x or 12x compensating eyepieces and 90x or 95x oil immersion objectives. One of the eyepieces contained a 20° angle with bisecting line and the other eyepiece contained a suitable scale for measuring the length of the proton recoil tracks. The 20° angle with center line was used to judge whether or not tracks were within the limiting horizontal angle of 10°. The depth of focus of the microscope ($\sim$ 1 micron) was used to ascertain if tracks were within the maximum vertical or azimuthal angle of 10°. Thus, a 0.5 Mev proton recoil track whose length is 5.5 microns must have its track extremities within a 1 micron depth to be within the 10° azimuthal angle. The depth of focus sets a practical limit on the reliability of determining the number of <u>short tracks</u> ($<$ 0.5 Mev) within the above angular criteria. This problem is discussed more fully in another report[4], but it may be stated here that research and experience have shown that trustworthy results can easily be obtained down to an energy of 0.6 Mev.

The track data on the plate was taken along the axis of the neutron beam direction. Usually, the data was accumulated by examining consecutive fields along a particular swath; using this method, every acceptable track located in the swath would be measured. In order to minimize the number of tracks leaving the emulsion surfaces, a thickness of 5 microns was skipped from the top and bottom surfaces of the emulsion thickness, i.e., tracks originating within the above volumes were ignored. Nevertheless, a correction for tracks leaving the emulsion surfaces is still required and a curve of this correction factor versus energy is shown in Appendix I.

The neutron spectrum was determined from a total of about 2800 measured proton recoil tracks. The tracks were measured by Jewell Erickson on Eastman NTA plates numbered 33B and 31H and by Julia Carlson on Ilford C2 plate numbered I34B. The above data is recorded in LA notebooks #2347, 1897, and 2572. A summary of useful information concerning the analysis of the above plates is given in Table I.

B. Fission Threshold Detectors

Fission threshold detectors were also used to roughly determine the low energy end of the fast neutron beam from the water boiler. Compounds containing accurately known quantities of the fissionable elements $_{92}U^{235}$ ("25"), $_{93}Np^{237}$ ("37"), and $_{92}U^{238}$ ("28") were coated on nickel foils; these foils were placed against Eastman NTC plates and exposed to the fast neutron beam. The $_{92}U^{235}$ foil was half covered with cadmium metal in order to obtain a cadmium ratio for the neutrons. The original experiment is recorded in LA notebook #2178 and a summary of the data is given on page 57 of this notebook.

RESULTS

A. Proton Recoil Plates

A comparison of the two sets of data taken from the proton recoil plates by two microscopists working independently is tabulated in Table II and graphed in Fig. 2. This data is plotted against proton recoil energy, E_p. The data or number of tracks has been only corrected for the neutron-proton scattering cross section (σ_p). Considering statistical errors, the two sets of data are in agreement at energies above 0.6 Mev. For some unexplained reason, the points at 0.5 Mev show a large disagreement outside statistical error limits; the point from the I34B data seems unusually high and the point from plates 31H and

33B looks much too low. If the above discrepancy in number of tracks is taken into account, the total number of tracks measured in each of the two sets of data is approximately the same.

Judging from work performed on the reliability of nuclear emulsions at low energies[4] and the agreement of the present two sets of data, one would conclude that the data in Fig. 2 is trustworthy at all energy points above 0.6 Mev. The data probably can be used down to 0.5 Mev although the large variation in the two sets of data at this point makes the 0.5 Mev point rather uncertain. The work on short tracks[4] has shown that the 0.35 Mev point is always too low and cannot be used without a correction factor. This correction factor amounts to increasing the data at the 0.35 Mev point by about 70%; however, it seems inadvisable to use this correction factor on the present data since at this time the technique was not sufficiently well developed.

The total combined data of this experiment are also tabulated in Table II and are plotted as circles in Fig. 3. The relative neutron flux is proportional to the number of proton recoil tracks after being corrected for σ_p and for tracks leaving the emulsion surfaces. The correction factor for tracks leaving the emulsion surfaces is shown in Appendix I. The values for σ_p are taken from the theoretical curve of Bohm and Richman[5]; this curve fits the experimental data well in the energy range covered in this experiment. In Fig. 3, note that the

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

abscissa is in terms of neutron energy, E_n, instead of proton recoil energy, E_p. Converting from E_p to E_n requires about a 5% increase in the value of E_p; this derivation is worked out in LADC-748[4].

It is possible to compute the absolute neutron flux from the proton recoil plate results. Let

$N_n(E)$ = the neutron flux from the water boiler east port in units of neutrons per 0.1 Mev per cm^2 per KW-sec.
$n_p(E)$ = the resulting proton recoils per 0.1 Mev per cm^3 per KW-sec. within the angular criteria used in examining the nuclear plates.
σ_p = the neutron-proton collision cross section at energy E.
n_H = the number of protons per cm^3 of nuclear emulsion.
G = a geometry factor which expresses the fraction of the total proton recoils which enter the angular limits used in the analysis of the plates.

Then,

$$n_p(E) = G\, N_n(E)\, \sigma_p\, n_H.$$

Previous work[4] has shown that G = 0.1. Ilford Ltd. provides the information that for Ilford emulsion, $n_H = 0.034 \times 10^{24}$ for unprocessed dry nuclear emulsion. If the present data is examined for the energy interval from 1.4 to 1.5 Mev, one finds that there are 75 proton recoils per 0.1 Mev per 720 KW-sec. of exposure per $5.37 \times 10^{-5} \times 2.4$[6] $= 1.3 \times 10^{-4}$ cm^3 of unprocessed nuclear emulsion. The latter figures reduce to $n_p(E) = 800$ proton recoils per 0.1 Mev per KW-sec. of exposure per cm^3 of unprocessed emulsion for the 1.4 to 1.5 Mev interval. Since $\sigma_p = 3.5 \times 10^{-24}$ for the 1.4 to 1.5 Mev interval,

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6 Since the thicknesses of the unprocessed NTA and C2 emulsions were 80 and 90 microns respectively, the shrinkage factor is closer to 2.4 than 2.5.

$N_n(E) = 6.7 \times 10^4$ neutrons per cm^2 per KW-sec. from 1.4 to 1.5 Mev. The flux at any other energy can be obtained by noting that on the spectral curve in Fig. 3 the data points show a relative value of 22 for the 1.4 to 1.5 Mev interval. Therefore, to convert these relative values on the spectral curve into neutron flux having the units of the previous equation, the relative values must be multiplied by a

$$\text{conversion factor} = \frac{6.7 \times 10^4}{22} = 3 \times 10^3.$$

A calculation of this conversion factor for a couple of other energy values yielded approximately the same result as above.

The following errors may be present in the above calculation. The geometry factor, G, can be calculated accurately but the personal element entering into the selection of tracks within the specified angular criteria results in an error in the knowledge of this factor. This error is estimated to be around 15% at 0.5 Mev, 10% at 0.8 Mev and 6% at energies above 1 Mev. The processed emulsion thicknesses can be measured to within 2 microns or a percentage accuracy of 5% and the shrinkage factor is known to an accuracy of about 5%. Therefore, the unprocessed emulsion volume analyzed is accurate to approximately 7%. Considering all of the above errors and the statistical error in $n_p(E)$, the value of $N_n(E)$ could be in error by as much as 15%.

Watt's data in the 3.3 to 7 Mev range on the energy distribution of the neutrons from the glory hole with the U^{235} disk source are plotted as squares in Fig. 3. Since Watt's data are given in units of neutrons per Mev per KW-sec., it is necessary to divide his data by the cross sectional area of the east port (5.08 cm^2) and by a factor 10 to make his units agree with those of the right hand scale of Fig. 3. Although most of Watt's points lie slightly below the present data, the agreement of the two sets of data below 6 Mev on the absolute number of neutrons is satisfactory (within 15%) if the calculation error in $N_n(E)$ mentioned above is taken into account. It is encouraging that the nuclear plate and counter technique show essentially the same results both on the shape of the energy distribution and on the absolute number of neutrons.

The empirical relation which Watt deduced for the neutron spectrum resulting from thermal fission of U^{235} is shown as a dashed curve in Fig. 3. This empirical curve combines his own data as well as several other sources of data on the fission neutron energies from U^{235}. The dashed curve was normalized to the present data at 2.5 Mev. The present data agree well with this curve in the region from 1.2 to 6 Mev. Above 5 or 6 Mev it is possible for the present data to be error on account of the few tracks measured at these energies. The statistical error indicates the error due to the small number of tracks measured but there are also other sources of error. First, these few tracks make it more possible for any background tracks to influence the results; secondly, since the correction factor for tracks leaving the emulsion surfaces rises steeply at high energies, the results will be quite sensitive to any inaccuracy in the calculation[7] of this factor.

[7] For example, using an inaccurate value for the thickness of the emulsion.

From the present experiment, one concludes that the east port with the U^{235} disk source inserted provides a U^{235} fission spectrum at energies above 1.2 Mev. However, at energies below 1.2 Mev there is a rather abrupt departure from the fission spectrum curve. Evidently this deviation from the fission spectrum is due to the scattering of neutrons by the U^{235} source from the water boiler reaction sphere into the glory hole. The scattering cross section of U^{235} has increased values at energies below 1-2 Mev as compared to higher energies. Also, the steel section of the collimating hole subtends a solid angle which includes part of the reaction sphere. This makes it possible for neutrons degraded in energy by the water of the reaction sphere to enter the glory hole (through a small thickness of carbon) without a scattering process; since about 80% of the fission spectrum neutrons are below 3 Mev, one would expect that most of these degraded neutrons would be below about 1.5 Mev. Finally, another small contribution to the low energy region of the spectral curve in Fig. 3 may be from inelastic scattering of high energy neutrons by the collimator walls.

As has been mentioned previously, the present data can be reliably used at energy points above 0.6 Mev. The point at 0.5 Mev is probably all right but very likely has more uncertainty associated with it than the statistical error indicates. An extension of the present data from the last reliable point at 0.7 Mev has been made in Fig. 3 using some preliminary cloud chamber data on the water boiler fast neutron beam taken by J. Evans[8]. The two sets of data were matched or

[8] J. Evans, LA Notebook #2490 (1949).

normalized by determining the number of tracks above 0.7 Mev in each set of data. The cloud chamber data are reliable down to about 0.1 Mev.

The proton recoil plate results on neutron flux can be compared with the results obtained from the fission foil threshold detectors (see section B in Results section). One way to make this comparison is to calculate the integral.

$$\int(\text{neutron flux}) \times (\text{fission cross section})\, dE = \int N_n(E)\, \sigma_f(E)\, dE$$

over the fast beam spectrum using the fission cross section for each of the threshold detectors. This integral gives the number of fissions per atom of metal per KW-sec. which should be produced if the fissionable element were placed in the fast neutron beam. Since U^{238} has a fission threshold of about 1.1 Mev, the nuclear plate data covers the energy interval required for evaluation of this integral. For Np^{237}, which has a fission threshold of about 0.4 Mev, it is necessary to use part of the cloud chamber extension to complete the above calculation. In the case of U^{235}, the integral can only accurately be calculated down to 0.1 Mev since the cloud chamber data ends at this energy; however, this calculation can be extended close to 0 Mev by a sensible extrapolation of the cloud chamber data. There is also a slight contribution to all of the above three integrals for energies above the nuclear plate data, i.e., approximately 6 Mev. This contribution was estimated to be about 5% of the value of the integral up to 6 Mev. This estimate may be too high for the U^{235} integral since the low energy values used in this calculation considerably increase the area under the spectral curve.

The following results were obtained by numerical integration of the integrals. The fast fission cross sections were obtained from LA-994[9].

$$\int_{\sim 1.1\ \text{Mev}}^{\infty} N_n(E)\,\sigma_{f(28)}dE = \left[6 + (5\%)6\right] \times 10^{-19} = 6.3 \times 10^{-19} \text{ fissions per atom of } U^{238} \text{ per KW-sec.}$$

$$\int_{\sim 0.4\ \text{Mev}}^{\infty} N_n(E)\,\sigma_{f(37)}dE = \left[2.8 + (5\%)2.8\right] \times 10^{-18} = 2.95 \times 10^{-18} \text{ fissions per atom of } Np^{237} \text{ per KW-sec.}$$

$$\int_{0}^{\infty} N_n(E)\,\sigma_{f(25)}dE = \left[4.3 + (5\%)4.3\right] \times 10^{-18} = 4.5 \times 10^{-18} \text{ fissions per atom of } U^{235} \text{ per KW-sec.}$$

The error associated with the above calculations is estimated to be about 10%. The U^{235} integral was extended down to 0 Mev (actually down to about 0.3 volt, the Cd cutoff) by extrapolating the cloud chamber data from 0.1 to 0 Mev. The extrapolation was such that it merely extended the previous data without slope change, i.e., the relative spectral value for the entire 0 to 0.1 Mev interval was taken as 46. The contribution to the U^{235} integral from the 0 to 0.1 Mev interval was about 13%.

B. <u>Fission Foils</u>

The results on the fission foils exposed to the fast neutron beam are tabulated in Table III. Two sets of results from two different exposures are shown. The agreement between the two sets of data is fairly satisfactory except for the results from the U^{235} foil without cadmium. In exposure number 1, the U^{235} disk source was about one foot

[9] W. Nyer, LA-994 (1949).

closer to the fission foils than in exposure number 2 and this may have affected the number of thermal neutrons. The averages of the two exposure groups were taken as the final results in this experiment. The U^{235} foil (no Cd) results were not averaged since this data is not actually needed in this experiment.

A comparison between the values obtained from integration of the fast beam spectrum and the fission foil values is shown below.

Fissionable element	Fissions/atom of metal/KW-sec. derived from fission foils	$\int N_n(E)\,\sigma_f\,dE$
U^{238}	$6.6 \pm 0.2 \times 10^{-19}$	$6.3 \pm 0.6 \times 10^{-19}$
Np^{237}	$3.1 \pm 0.1 \times 10^{-18}$	$2.95 \pm 0.3 \times 10^{-18}$
U^{235} (With Cd)	$4.9 \pm 0.2 \times 10^{-18}$	$4.5 \pm 0.4 \times 10^{-18}$

The agreement is well within the error attached to the two sets of results. The error on the fission foil results is only the statistical error while the error on the integrated results involves both an estimated calculation and statistical error. The fission foil results are about 5% higher in the case of U^{238} and Np^{237} while for U^{235} the fission foil result is about 10% higher. The fact that all of the fission foil results are higher could be due to some systematic error in one of the two sets of results such as a wrong value for the exposure quantity, inaccurate conversion factor, etc.

Although the U^{235} results are within the quoted errors as they stand, it is interesting to see how the integrated value can be brought closer in agreement with the fission foil result. First, this can be accomplished by raising the entire cloud chamber extension (i.e., the region from 0 to 0.6 Mev) by about 15% and using the same extrapolation as described above. A second method is to retain the spectral curve in Fig. 3 and to modify the above extrapolation. For example, close agreement can be obtained by using an unchanged slope extrapolation from 0.1 Mev to about 100 volts and then by using a 1/E neutron distribution from 100 to 0.3 volts.

Appendix I

This appendix gives the correction factor to be applied to the proton recoil track data for tracks leaving the emulsion surfaces. The numerical values used in this calculation for the processed emulsion were effective thickness analyzed = 26 microns and total emulsion thickness = 36 microns, i.e., tracks originating in a 5 micron emulsion thickness at the surface and bottom of the emulsion were ignored. A shrinkage factor of 2.5 was used for converting to the original unprocessed emulsion. Except for numerical values, this calculation is identical to that described in Appendix I, case II, in LA-1078. The reader is referred to this report for details of the calculation.

Correction factors from the present calculation are listed in Table II and a graph of correction factor versus proton recoil energy is shown in Fig. 4.

Nuclear Plate Type	Microscopist	Plate Number in LA Notebooks	Average Thickness of Processed Emulsion	Effective Emulsion Thickness Analyzed	Average Exposure	Microscope Field Area	Number of Fields Analyzed	Proton Recoil Tracks Measured	Proton Recoil Tracks Leaving Emulsion Surfaces	Processed Emulsion Volume Analyzed
Eastman NTA 100 microns thick	J.E.	31H	33 microns	23 microns	22 KW-min.	5200 sq. microns	80	645	5	0.96×10^{-5} cm^3
Eastman NTA 100 microns thick	J.E.	33B	33 microns	23 microns	10 KW-min.	5000 sq. microns	110	592	2	1.26×10^{-5} cm^3
Eastman NTA 100 microns thick	J.E.	31H and 33B	33 microns	23 microns	15 KW-min.			1237	7	2.22×10^{-5} cm^3
Ilford C2 100 microns thick	J.C.	I34B	38 microns	28 microns	10 KW-min.	3000 sq. microns	375	1580	39	3.15×10^{-5} cm^3
Eastman NTA and Ilford C2	J.E. and J.C.	31H, 33B and I34B	36 microns	26 microns	12 KW-min.			2817	46	5.37×10^{-5} cm^3

Table I. Information on Proton Recoil Nuclear Plates Analyzed in Present Experiment.

Proton Energy Interval in Mev	Proton Recoil Tracks from Plates: 31H and 33B	Proton Recoil Tracks from Plates: I34B	Combined Proton Recoil Tracks from Plates 31H 33B, and I34B	σ_p in Barns	Combined Tracks/ σ_p x 10^{24}: Values for every 0.1 Mev	Combined Tracks/ σ_p x 10^{24}: Averaged Values	Energy Associated with Averaged Values of Combined Tracks/ σ_p x 10^{24}: E_p (Mev) Interval	Energy Associated with Averaged Values of Combined Tracks/ σ_p x 10^{24}: E_n (Mev) Midpoint	Correction Factor for Tracks Leaving Emulsion Surfaces	Relative Neutron Spectrum. (Correction Factor) x (Combined Tracks per 0.1 Mev / σ_p x 10^{24}
0.3 - 0.4	105	135	240	7.6	31.6	31.6	0.3 - 0.4	0.37	1.0	31.6 ± 2.0
0.4 - 0.5	83	245	328	6.6	49.7					
0.5 - 0.6	83	96	179	5.9	30.3	40.0	0.4 - 0.6	0.52	1.0	40.0 ± 1.7
0.6 - 0.7	103	142	245	5.4	45.4					
0.7 - 0.8	71	57	128	5.0	25.6	35.5	0.6 - 0.8	0.73	1.0	35.5 ± 1.8
0.8 - 0.9	83	92	175	4.6	38.0					
0.9 - 1.0	54	63	117	4.4	26.6	32.3	0.8 - 1.0	0.94	1.0	32.3 ± 1.9
1.0 - 1.1	59	58	117	4.2	27.9					
1.1 - 1.2	59	41	100	4.0	25.0					
1.2 - 1.3	40	36	76	3.85	19.7	24.2	1.0 - 1.3	1.21	1.0	24.2 ± 1.4
1.3 - 1.4	47	45	92	3.7	24.9					
1.4 - 1.5	33	42	75	3.55	21.1					
1.5 - 1.6	37	26	63	3.4	18.5	21.5	1.3 - 1.6	1.52	1.0	21.5 ± 1.4
1.6 - 1.7	20	38	58	3.3	17.6					
1.7 - 1.8	26	33	59	3.2	18.4					
1.8 - 1.9	21	28	49	3.1	15.8					
1.9 - 2.0	17	36	53	3.0	17.7	17.4	1.6 - 2.0	1.89	1.0	17.4 ± 1.2
2.0 - 2.1	25	17	42	2.9	14.5					
2.1 - 2.2	21	25	46	2.85	16.1					
2.2 - 2.3	13	18	31	2.75	11.3					
2.3 - 2.4	16	19	35	2.7	13.0					
2.4 - 2.5	18	17	35	2.63	13.3	13.7	2.0 - 2.5	2.36	1.03	14.1 ± 1.0
2.5 - 2.6	29	21	50	2.57	19.5					
2.6 - 2.7	14	11	25	2.50	10.0					
2.7 - 2.8	13	10	23	2.45	9.4					
2.8 - 2.9	3	16	19	2.4	7.9					
2.9 - 3.0	9	11	20	2.35	8.5	11.1	2.5 - 3.0	2.89	1.08	12.0 ± 1.0
3.0 - 3.1	12	6	18	2.30	7.8					
3.1 - 3.2	11	4	15	2.25	6.7					
3.2 - 3.3	5	6	11	2.20	5.0					
3.3 - 3.4	6	9	15	2.17	6.9					
3.4 - 3.5	6	10	16	2.15	7.4	6.8	3.0 - 3.5	3.41	1.14	7.7 ± 0.9
3.5 - 3.6	5	10	15	2.07	7.2					
3.6 - 3.7	3	3	9	2.04	4.4					
3.7 - 3.8	3	4	7	2.01	3.5					
3.8 - 3.9	2	5	7	1.98	3.5					

Table II. Results and Computations from Proton Recoil Nuclear Plates Exposed to Water Boiler Fast Beam (Oct. 1948).

Proton Energy Interval in Mev	Proton Recoil Tracks from Plates		Combined Proton Recoil Tracks from Plates 31H 33B, and I34B	σ_p in Barns	Combined Tracks/ σ_p x 10^{24}		Energy Associated with Averaged Values of Combined Tracks/ σ_p x 10^{24}		Correction Factor for Tracks Leaving Emulsion Surfaces	Relative Neutron Spectrum. (Correction Factor) x (Combined Tracks per 0.1 Mev $/\sigma_p$ x 10^{24}
	31H and 33B	I34B			Values for every 0.1 Mev	Averaged Values	E_p (Mev) Interval	E_n (Mev) Midpoint		
3.9 - 4.0	2	2	4	1.96	2.0	4.1	3.5 - 4.0	3.94	1.22	5.0 ± 0.8
4.0 - 4.1	0	7	7	1.92	3.6					
4.1 - 4.2	3	0	3	1.88	1.6					
4.2 - 4.3	3	2	5	1.86	2.7					
4.3 - 4.4	4	2	6	1.82	3.3					
4.4 - 4.5	5	3	8	1.77	4.5	3.1	4.0 - 4.5	4.46	1.34	4.15 ± 0.8
4.5 - 4.6	4	1	5	1.75	2.9					
4.6 - 4.7	3	2	5	1.73	2.9					
4.7 - 4.8	0	1	1	1.71	0.6					
4.8 - 4.9	0	1	1	1.69	0.6					
4.9 - 5.0	4	3	7	1.66	4.2	2.2	4.5 - 5.0	4.99	1.53	3.35 ± 0.8
5.0 - 5.1	1	2	3	1.62	1.9					
5.1 - 5.2	0	1	1	1.59	0.6					
5.2 - 5.3	2	2	4	1.56	2.6					
5.3 - 5.4	1	3	4	1.52	2.6					
5.4 - 5.5	1	0	1	1.50	0.7	1.7	5.0 - 5.5	5.51	1.76	3.0 ±. 0.8
5.5 - 5.6	1	1	2	1.47	1.4					
5.6 - 5.7	2	1	3	1.45	2.1					
5.7 - 5.8	0	0	0	1.42	0.0					
5.8 - 5.9	2	0	2	1.40	1.4					
5.9 - 6.0	0	0	0	1.38	0.0	1.0	5.5 - 6.0	6.04	2.04	2.05 ± 0.8
6.0 - 6.1	1	0	1	1.36	0.7					
6.1 - 6.2	0	0	0	1.34	0.0					
6.2 - 6.3	1	1	2	1.32	1.5					
6.3 - 6.4	0	1	1	1.30	0.8					
6.4 - 6.5	1	0	1	1.28	0.8	0.8	6.0 - 6.5	6.56	2.33	1.85 ± 0.8

Table II. Results and Computations from Proton Recoil Nuclear Plates Exposed to Water Boiler Fast Beam (Oct. 1948).

Exposure Group Number	Fissionable Element on Foil	NTC Plate Results in Tracks/atom/KW-sec. or Fissions/atom/KW-sec.
1	25 (No Cd)	$2.0 \pm 0.1 \times 10^{-17}$
	25 (With Cd)	$4.6 \pm 0.3 \times 10^{-18}$
	37	$3.0 \pm 0.2 \times 10^{-18}$
	28	$6.4 \pm 0.2 \times 10^{-19}$
2	25 (No Cd)	$3.9 \pm 0.1 \times 10^{-17}$
	25 (With Cd)	$5.2 \pm 0.2 \times 10^{-18}$
	37	$3.2 \pm 0.2 \times 10^{-18}$
	28	$6.9 \pm 0.2 \times 10^{-19}$
Average of Groups 1 and 2	25 (No Cd)	(See Text)
	25 (With Cd)	$4.9 \pm 0.2 \times 10^{-18}$
	37	$3.1 \pm 0.1 \times 10^{-18}$
	28	$6.6 \pm 0.2 \times 10^{-19}$

Table III. Results on Fission Foils and NTC Plates Exposed to Water Boiler Fast Beam (Oct. 1948).

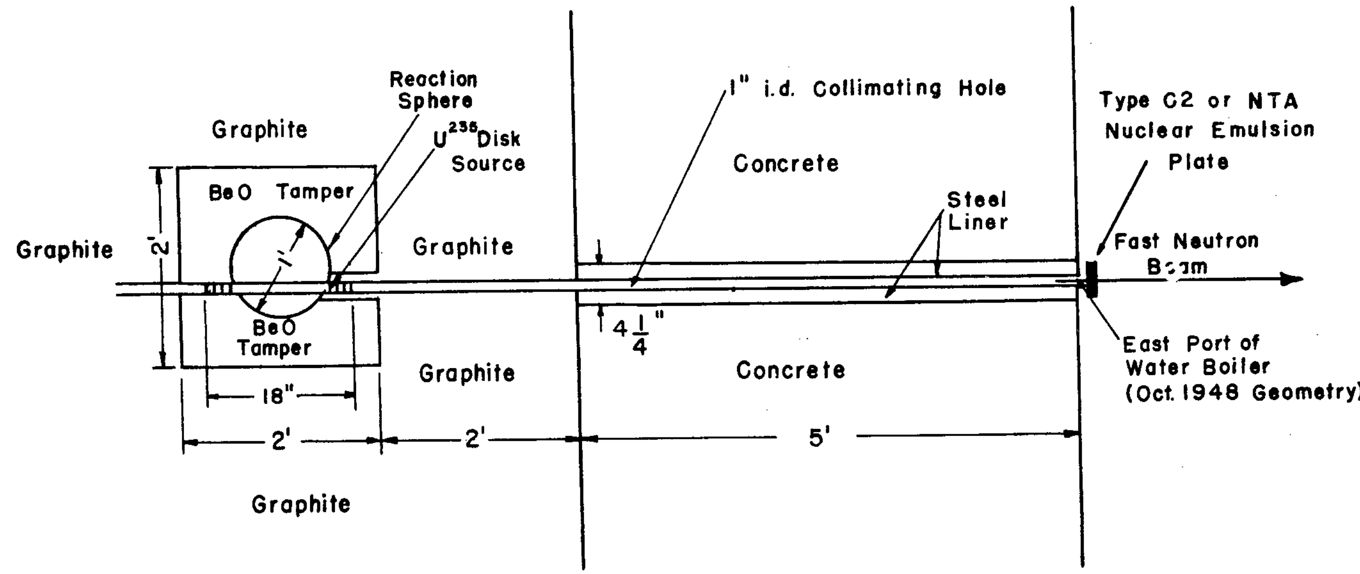

Fig. 1. Experimental Arrangement

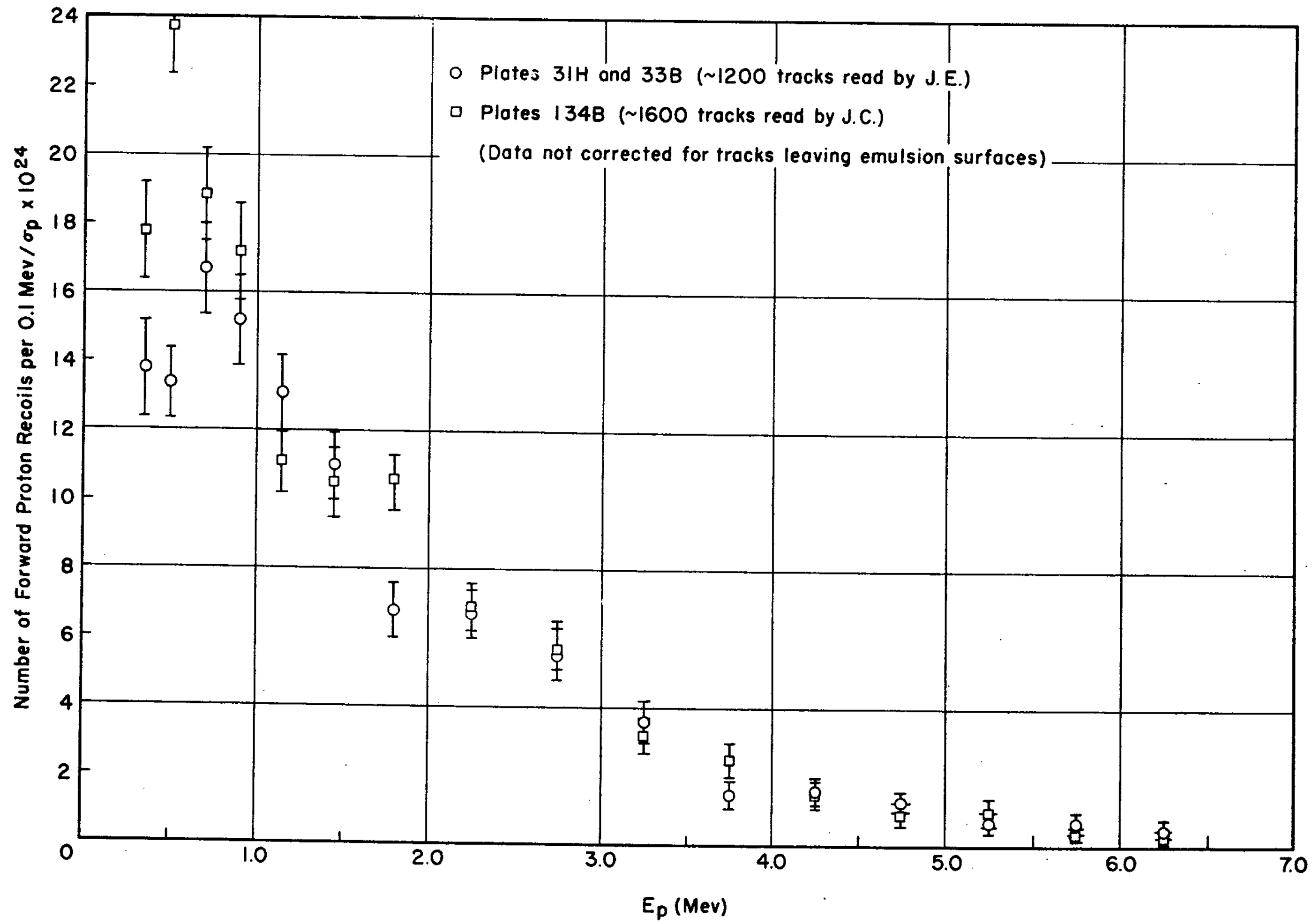

Fig. 2. Comparison of Two Sets of Data Taken in the Present Experiment.

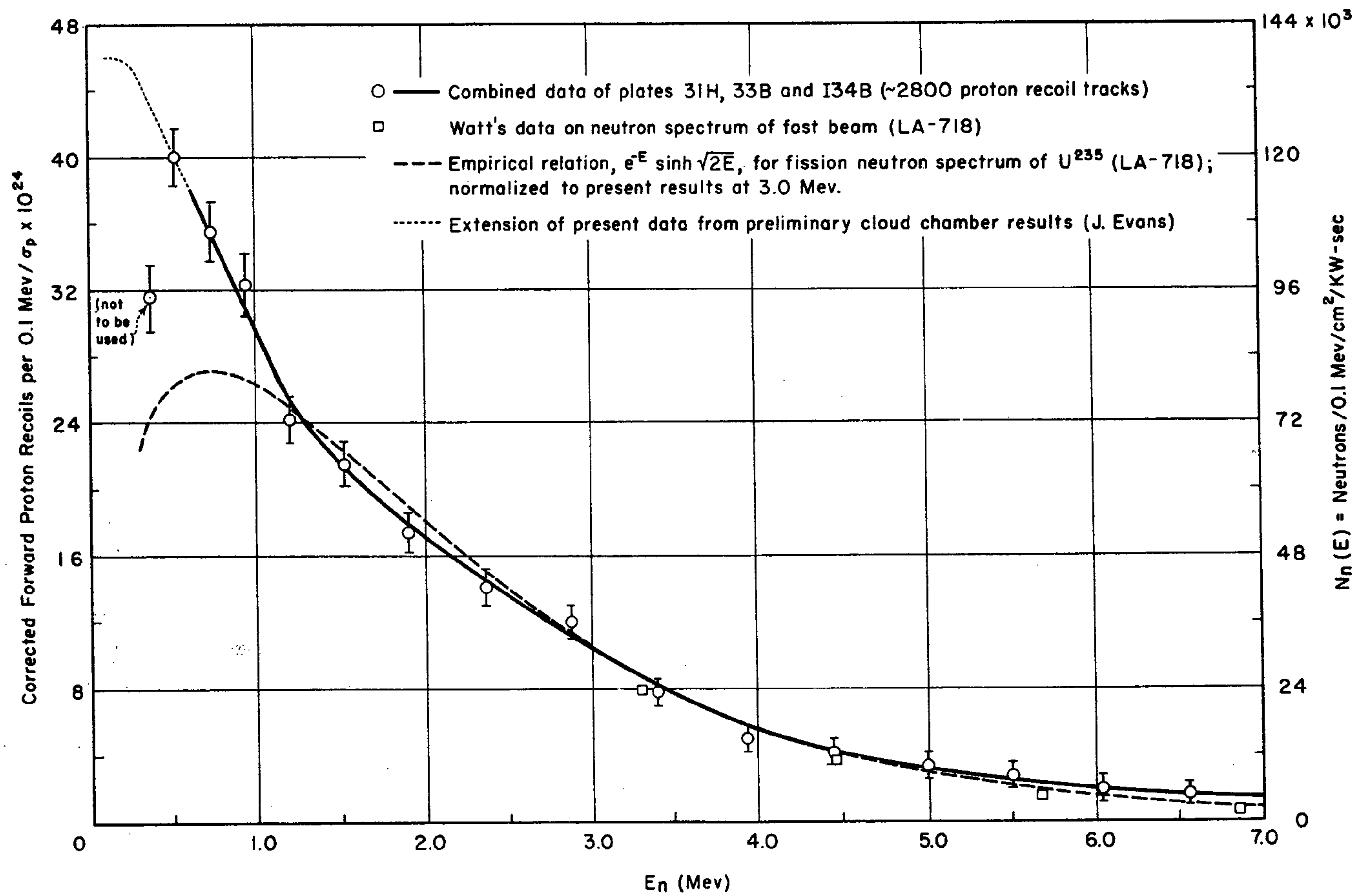

Fig. 3. Neutron Spectrum of Water Boiler Fast Neutron Beam(Oct. 1948).

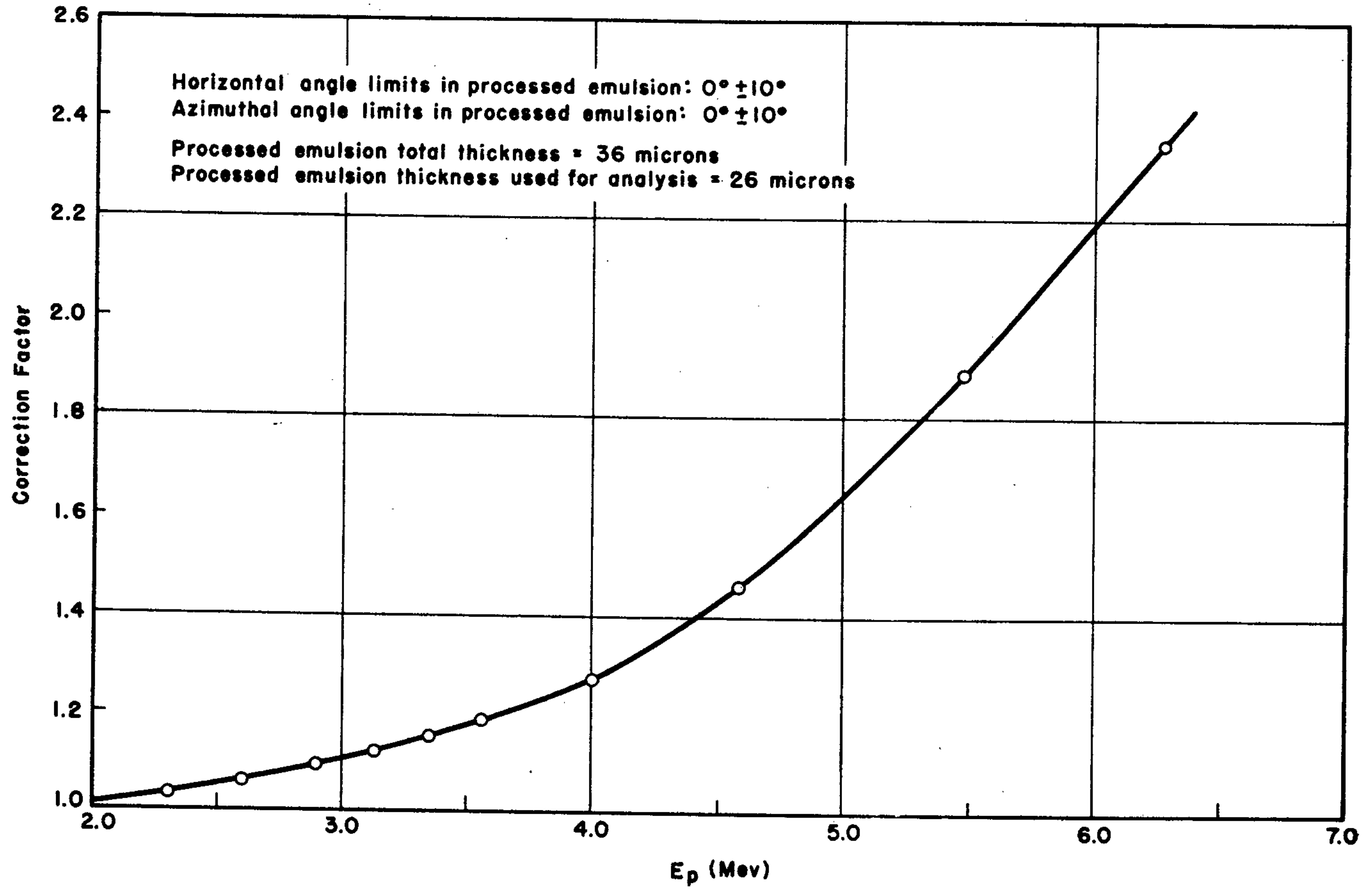

Fig. 4. Correction Factor for Tracks Leaving Emulsion Surfaces.

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