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A NUCLEAR PLATE CAMERA FOR FAST NEUTRON SPECTROSCOPY AT THE BULK SHIELDING FACILITY

J. L. Meem
E. B. Johnson

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A NUCLEAR PLATE CAMERA FOR FAST NEUTRON SPECTROSCOPY AT THE BULK SHIELDING FACILITY

J. L. Meem
E. B. Johnson

Introduction

An intensive program of instrument development is underway at the Bulk Shielding Facility(1) for the purpose of realizing instruments which will measure the effect of shielding materials on the neutron and gamma ray spectra from a reactor. The development of a proton recoil counter to be used as a Fast Neutron Spectrometer is nearing completion. Preliminary reports on this instrument are available(2,3), and a rough check on the U^{235} fission spectrum has been made(4).

The principle of operation of this instrument is to have fast neutrons strike an hydrogenous radiator, ejecting recoil protons which are detected by a counter. Since photographic emulsions are also sensitive to such recoil protons, it was decided to build a nuclear plate camera to be used as a fast neutron spectrometer in the same way as the proton recoil counter. A camera which is much more complicated but which incorporates the same principles of operation has been constructed at Los Alamos(5). The main advantage of nuclear plates is that all of the fundamental constants are available for calculating the fast neutron spectrum, once the length of the proton tracks in the emulsion has been measured. No calibration of a nuclear plate camera is necessary. The chief disadvantage (and a serious one for shielding work) is the length of time required for microscopic examination of the plates. At this facility it is planned to use the nuclear plate camera only as a means of checking and calibrating the proton recoil counter. All shielding data will then be taken with the latter instrument.

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(1) Breazeale, W. M., "The New Bulk Shielding Facility at ORNL", ORNL-991, May 8, 1951.
(2) Gossick, B. R. and Henry, K. M., "Neutron Energy Spectrometer", ORNL-711, June 12, 1950.
(3) Muckenthaler, F. J. and Henry, K. M., "Neutron Energy Spectrometer", SERM-91, January 24, 1951.
(4) Muckenthaler, F. J. and Henry, K. M., "Neutron Energy Spectrometer", C.F.#51-7-25, July 16, 1951.
(5) Allred, Rosen, Tallmadge, and Williams, "Nuclear Multiple Plate Camera", Review of Scientific Instruments 22, 191 (1951).

This report describes the nuclear plate camera and the results of a rough check on the U^{235} fission spectrum which established the feasibility of the method.

Apparatus

Figure 1 is a sketch of the camera giving the pertinent dimensions. The neutrons enter through a collimator and strike an hydrogenous radiator, ejecting recoil protons. A nuclear plate is placed so as to intercept protons which are ejected at an angle of 10° to the incident neutron beam. A proton produces a track in the nuclear plate, the track length being proportional to the energy of the proton. Knowing the energy of the proton, the energy of the neutron which struck it can be calculated.

For determining background, a second plate is placed on the opposite side of the camera and a platinum absorber placed so as to intercept the recoil protons from the radiator. Hence the only tracks observed in this plate are produced by background events. Both the background and the data plate are exposed at the same time.

In general, the collimator is an aluminum tube of one inch inside diameter and two feet long. When the entire assembly is placed under water, there is essentially a hole of these dimensions in the water for collimating the neutrons from the source. For weak sources, an alternate collimator is provided which is conical in shape as shown in Figure 1. This collimator is also two feet in length but is 2-3/4 in. inside diameter toward the source and one inch inside diameter next to the radiator. With this collimator, a larger area of the source is subtended and a larger radiator could be used. The actual collimation of the neutrons is not as good, of course, as with the one inch diameter tube.

Inside the camera toward the source is a 3-3/4 in. platinum liner with a one centimeter diameter hole over the radiator. This hole in the platinum defines the diameter of the radiator. When using the conical collimator, a platinum liner with a two centimeter diameter hole is used.

Three thicknesses of radiator are provided. These are 0.7229, 5.35, and 12.95 milligrams per square centimeter. The radiators are made of polyethelene, which has the same composition as paraffin, $(CH_2)_n$.

Figure 2 is a photograph of the disassembled instrument, and Figure 3 shows the assembled camera with the conical collimator. In this experiment, Ilford nuclear plates with 50 micron thick type C-2 emulsion were used because the range-energy relations for this emulsion are well known. All handling of the undeveloped plates was done in total darkness.

When the plates had been loaded in the camera, the camera was evacuated to approximately 3 mm. of mercury absolute, pumped at this pressure for about 10 minutes, then sealed. The pressure generally rose to about 6 mm. mercury absolute within a short time. At pressures less than this, the emulsion would have been dehydrated excessively.

After exposure, the plates were processed by the following method, with all solutions at 18°C.

I. 20 minutes in dilute (2:1) D-19 developer with agitation
II. Wash
III. 10 minutes in 2% acetic acid with agitation
IV. Wash
V. 60 minutes in fixer with some agitation
VI. Wash in running water overnight

The plates were read with a Leitz Ortholux binocular microscope using Periplanatic 12X eyepieces and an apocromatic 90X oil immersion objective. One of the eyepieces was equipped with a disc on which a square lattice five squares on a side had been ruled. Inscribed in this lattice was a 20° angle having a bisecting line. Calibration of this disc against a stage micrometer made it possible to record the track lengths in terms of scale divisions of the eyepiece disc.

Because of the exposure geometry, the scanning of the plates was relatively simple. As can be seen from Figure 1, a proton ejected from the radiator proceeds into the undeveloped emulsion of the nuclear plate at an angle of 10° (on the average) to the surface of the emulsion. Upon development these emulsions shrink to about one half thickness. Accordingly an observed track should appear to proceed at an angle of 5° to the surface in the developed emulsion. Acceptable tracks were defined as those originating in the upper surface of the emulsion and contained within a rectangular pyramid having a half-angle of 10° about the forward direction in the undeveloped emulsion. A track having its origin elsewhere in the emulsion could not have been caused by a proton from the radiator. However, since it is possible that high energy protons will not ionize silver atoms right at the upper surface of the emulsion, long tracks which apparently had their origin within 4 microns of the upper surface were accepted. In no case did a track on these plates appear to leave the bottom of the emulsion. In the plane of the emulsion, the angular limits of ± 10° were set by the bisected 20° angle on the eyepiece disc. In practice, the azimuthal or dip angle limit of 5° into the <u>developed</u> emulsion was determined by means of the depth of focus of the microscope. Since the depth of focus for this microscope was approximately one micron, a track acceptable with respect to dip angle had to be in focus for at least 11 microns of its length. Because high energy protons are often scattered as they travel through the emulsion, it is

quite likely that these criteria of angular limits will be satisfied only at the origin of the track. In the case of tracks shorter than 11 microns, the azimuthal or dip angle was not estimated. Because of the correction in proton energy due to the radiator, this included only that group of tracks of average energy about 1.5 Mev. In this experiment, tracks shorter than about 5 microns were not measured. To avoid duplication, the plates were scanned in a series of traverses one field of view wide (approximately 75 microns) and 5 centimeters long at intervals of 0.2 millimeters. All traverses were made near the center and well away from the ends of the plates. Consecutive fields of view were read in each traverse. The same total area was scanned on both the data and background plates.

Procedure

As has been stated, when taking data on shielding materials, it is expected that the one inch collimating tube will be used. However, for the experiment described herein, the conical collimator was used because of the weakness of the source. The experiment was carried out in the water tank above the thermal column on top of the X-10 pile. Approximately 100 grams of U^{235} divided into nine slugs were placed in the center of the thermal column as a neutron source. The large end of the collimator was placed against these slugs with the whole assembly under water. The time of exposure was 88 hours. The radiator used in this experiment was 5.35 milligrams per square centimeter thick and 2.5 centimeters in diameter. The data plate was number 51 and is referred to as such hereafter. The microscopic data are on file in data book number A-96 at the Bulk Shielding Facility.

Calculations and Results

Assume a neutron of energy E_n strikes the radiator, knocking out a proton of energy E_p at an angle of 10° to the incident beam. Then

$$E_p = E_n \cos^2 \theta \qquad \text{where } \theta = 10^\circ$$

$$\text{or} \qquad E_p = 0.970\ E_n$$

Values for E_n and the corresponding values for E_p are tabulated in Table I, as are the ranges in paraffin[6] of the protons. On the average, a proton must travel through one half the thickness of the radiator or 2.68 milligrams per square centimeter before reaching the interior of the

(6) Hirschfelder and Magee, Phys. Rev. 73, 207 (1948)

camera. The residual range in paraffin and the corresponding proton energies E_p' are also given in Table I. The difference between E_p and E_p' is the possible error in energy of the proton and 2/3 of this is taken as the probable error. Also tabulated are the ranges of protons of energy E_p' in the nuclear plate emulsion.(7)

In Table II are listed the results of scanning plate 51 and the corresponding background plate. The area scanned was 0.2695 cm^2, having 537 acceptable tracks. For the same area of the background plate there were 119 tracks, leaving a net of 418 tracks. In general it is advisable to read many more tracks than this, but since the work is very time consuming and the object of this experiment was only to prove feasibility, no more time was spent on scanning this plate.

Having determined the number of tracks caused by neutrons of various energies, the number of neutrons per square centimeter per second at each energy interval which struck the radiator can now be calculated.

Let $P(E_n)$ = the number of protons ejected by neutrons of energy E_n which were observed. The plate area scanned which gave this number of tracks was 50 mm. long and 0.539 mm. wide. Referring to Figure 1, it can be seen that the path of a proton traveling from the center of the radiator to the center of the plate will subtend an angle of 10° with the direction of the incident neutron beam. Proton paths from the center of the radiator to the near and far edges of the scanned area subtend angles of $11^\circ 34'$ and $8^\circ 49'$ with the direction of the incident beam. Since the radius from the centerline of the camera to the midpoint of the surface of the plate was 3.2 cm., the area of a right cylindrical surface described by rotation of the scanned area of the plate about the camera centerline was 20.07 x 5 cm^2. The ratio of scanned area to the total area of this cylindrical surface was $\frac{0.0539}{20.07} = 2.686 \times 10^{-3}$, and the number of protons ejected from the radiator to this total area was

$$\frac{P(E_n)}{2.686 \times 10^{-3}} = 3.724 \times 10^2 \, P(E_n).$$

The fraction of the total possible scattering angles in the center of mass system lying between $8^\circ 49'$ and $11^\circ 34'$ is

$$\frac{\int_{17^\circ 37'}^{23^\circ 8'} d \cos \varphi}{\int_{0^\circ}^{180^\circ} d \cos \varphi} = 1.675 \times 10^{-2},$$

where the angle φ is taken in the center of mass system and is twice the corresponding angle in the laboratory system.

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(7) Lattes, C. M. G., Fowler, P. H., and Cuer, P., Nature 159, 301

Therefore the total number of protons of energy corresponding to E_n ejected from the radiator was

$$\frac{3.724 \times 10^2}{1.675 \times 10^{-2}} P(E_n) = 2.223 \times 10^4 P(E_n).$$

The area of the radiator was 3.14 cm^2 (r = 1 cm.) and the thickness was 5.35 mg/cm^2. Let D be the density of the radiator in $grams/cm^3$. Then the volume of the radiator in cubic centimeters was

$$\frac{3.14 \times 5.35 \times 10^{-3}}{D} = \frac{1.68 \times 10^{-2}}{D} cm^3$$

Since the time of exposure was 88 hours (3.168×10^5 sec.), the number of protons per cubic centimeter per second of a certain energy ejected from the radiator was

$$\frac{2.223 \times 10^4 P(E_n)}{\frac{1.68 \times 10^{-2}}{D} \times 3.168 \times 10^5} = 4.177 D P(E_n) \text{ protons}/cm^3/\text{sec.}$$

If $nv(E_n)$ is the number of fast neutrons per square centimeter per second of energy E_n striking the radiator and Σ is the macroscopic cross section, then

$$nv(E_n) \Sigma = 4.177 D P(E_n).$$

But $\Sigma = N \sigma(E_n)$ where N is the number of hydrogen atoms per cm^3 and $\Sigma(E_n)$ is the microscopic cross section.

Since the chemical formula for polyethelene is $(CH_2)_n$, there are

$$\frac{2}{14} \times 6.03 \times 10^{23} \text{ hydrogen atoms/gram}$$

and if there are D grams per cm^3, then

$$N = 0.861 \times 10^{23} \times D \text{ atoms}/cm^3.$$

$$nv(E_n) \times 0.861 \times 10^{23} \times D \times \sigma(E_n) = 4.177 D P(E_n)$$

or $$nv(E_n) = 4.851 \times 10^{-23} \frac{P(E_n)}{\sigma(E_n)}.$$

Since a constant energy interval of 0.2 Mev was used throughout, multiplying $nv(E_n)$ by 5 gives the number of fast neutrons per square centimeter per second per Mev. These are listed in Table III and plotted in Figure 4. The errors in energy result from the radiator

thickness as shown in Table I. The errors in $nv(E_n)$ per Mev are the statistical errors given in Table II.

The proton recoil counter has been used previously[4] to measure the spectrum of the same source used here. The radiator of the counter was placed only a few centimeters from the source while the radiator for the camera was two feet away. Regardless, it was expected that the shape of the spectrum should be the same in either case. The straight line in Figure 4 was drawn with the slope determined with the proton recoil counter. The agreement is excellent considering that both measurements were quite rough.

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TABLE I

Correction for 5.35 mg/cm^2 Radiator

E_n	$E_p = \cos^2 \theta \, E_n = 0.970 \, E_n$	Range in Parrafin	Range on Leaving Parrafin	E'_p Corrected for Radiator	Probable Error $2/3 \, \frac{E_p - E'_p}{E_p}$	Range in Emulsion
Mev.	Mev.	mg/cm^2	mg/cm^2	Mev.	%	Microns
1.0	0.97	1.85	---	---	---	---
1.2	1.16	2.50	---	---	---	---
1.4	1.36	3.26	0.58	0.460	± 44.1	5.2
1.6	1.55	4.07	1.39	0.815	± 31.6	10.9
1.8	1.75	4.98	2.30	1.104	± 24.6	16.5
2.0	1.94	6.00	3.32	1.375	± 19.4	22.5
2.2	2.13	7.00	4.32	1.605	± 16.4	28.4
2.4	2.33	8.20	5.52	1.860	± 13.4	35.5
2.6	2.52	9.30	6.62	2.06	± 12.2	41.8
2.8	2.72	10.65	7.97	2.30	± 10.3	49.5
3.0	2.91	12.00	9.32	2.52	± 8.93	57.5
3.2	3.10	13.41	10.73	2.73	± 7.95	65.0
3.4	3.30	14.95	12.27	2.94	± 7.27	73.0
3.6	3.49	16.55	13.87	3.16	± 6.30	82.5
3.8	3.69	18.30	15.62	3.38	± 5.60	92.0
4.0	3.88	20.00	17.32	3.58	± 5.15	101.0
4.2	4.07	21.70	19.02	3.78	± 4.75	110.0
4.4	4.27	23.50	20.82	3.98	± 4.53	120.0
4.6	4.46	25.35	22.67	4.18	± 4.18	130.5
4.8	4.66	27.50	24.82	4.41	± 3.58	141.5
5.0	4.85	29.45	26.77	4.58	± 3.71	150.5
5.2	5.04	32.00	29.32	4.83	± 2.78	163.5
5.4	5.24	34.00	31.32	4.98	± 3.31	172.5
5.6	5.43	36.30	33.62	5.20	± 2.82	184.5
5.8	5.63	38.60	35.92	5.40	± 2.72	196.0
6.0	5.82	41.00	38.32	5.62	± 2.29	209.0

TABLE II

Net Number of Proton Tracks as a Function of Energy

Neutron Energy E_n	Foreground Tracks (F) Plate 51	Background Tracks (B) Bgrd. Plate	Net Tracks (F - B) $P(E_n)$	Statistical Error $\frac{\sqrt{F + B}}{F - B}$ %
1.5	137	47	90	15.1
1.7	104	16	88	12.4
1.9	66	12	54	16.4
2.1	44	16	28	27.7
2.3	34	3	31	19.6
2.5	31	8	23	27.2
2.7	30	3	27	21.3
2.9	23	6	17	31.7
3.1	16	1	15	27.5
3.3	13	1	12	31.2
3.5	16	2	14	30.3
3.7	4	0	4	50.0
3.9	3	2	1	224.0
4.1	5	0	5	44.8
4.3	5	1	4	61.2
4.5	2	0	2	70.5
4.7	1	1	0	--
4.9	0	0	0	--
5.1	1	0	1	100
5.3	1	0	1	100
5.5	0	0	0	--
5.7	1	0	1	100
5.9	0	0	0	--
Total	537	119	418	

TABLE III

Fast Neutron Spectrum as a Function of Energy

Neutron Energy E_n	Error in Energy	Number of Protons	Hydrogen Cross Section $\sigma(E_n)$	Neutron Flux per Mev $nv(E_n)$	Error in $nv(E_n)$
Mev	Mev	$P(E_n)$	Barns	Per Mev	Per Mev
1.5	±0.57	90	3.50	6.25×10^3	$\pm 0.94 \times 10^3$
1.7	±0.48	88	3.30	6.45×10^3	$\pm 0.80 \times 10^3$
1.9	±0.42	54	3.10	4.22×10^3	$\pm 0.69 \times 10^3$
2.1	±0.38	28	2.90	2.34×10^3	$\pm 0.65 \times 10^3$
2.3	±0.34	31	2.75	2.73×10^3	$\pm 0.54 \times 10^3$
2.5	±0.32	23	2.60	2.14×10^3	$\pm 0.58 \times 10^3$
2.7	±0.30	27	2.50	2.62×10^3	$\pm 0.56 \times 10^3$
2.9	±0.27	17	2.35	1.75×10^3	$\pm 0.55 \times 10^3$
3.1	±0.25	15	2.25	1.62×10^3	$\pm 0.45 \times 10^3$
3.3	±0.25	12	2.15	1.35×10^3	$\pm 0.42 \times 10^3$
3.5	±0.24	14	2.05	1.65×10^3	$\pm 0.50 \times 10^3$
3.7	±0.22	4	1.95	4.97×10^2	$\pm 2.48 \times 10^2$
3.9	±0.21	1	1.85	1.31×10^2	$\pm 2.93 \times 10^2$
4.1	±0.20	5	1.80	6.75×10^2	$\pm 3.02 \times 10^2$
4.3	±0.20	4	1.75	5.55×10^2	$\pm 3.40 \times 10^2$
4.5	±0.20	2	1.65	2.93×10^2	$\pm 2.06 \times 10^2$
4.7	-	0	1.60	- - -	- - -
4.9	-	0	1.50	- - -	- - -
5.1	±0.16	1	1.45	1.67×10^2	$\pm 1.67 \times 10^2$
5.3	±0.16	1	1.40	1.73×10^2	$\pm 1.73 \times 10^2$
5.5	-	0	1.35	- - -	- - -
5.7	±0.16	1	1.30	1.86×10^2	$\pm 1.86 \times 10^2$
5.9	-	0	1.25	- - -	- - -

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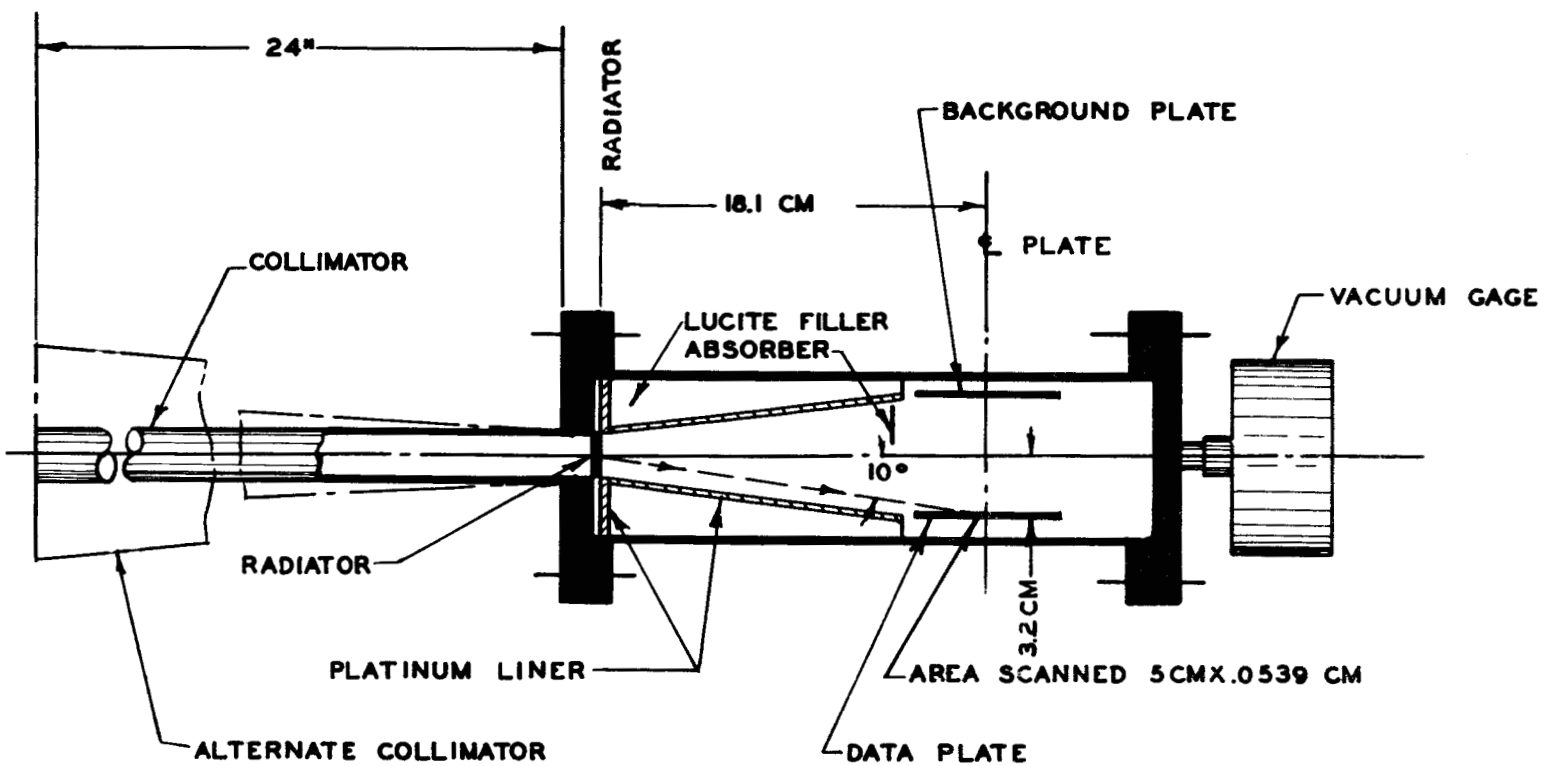

NUCLEAR PLATE CAMERA
BULK SHIELDING FACILITY
FIG. 1

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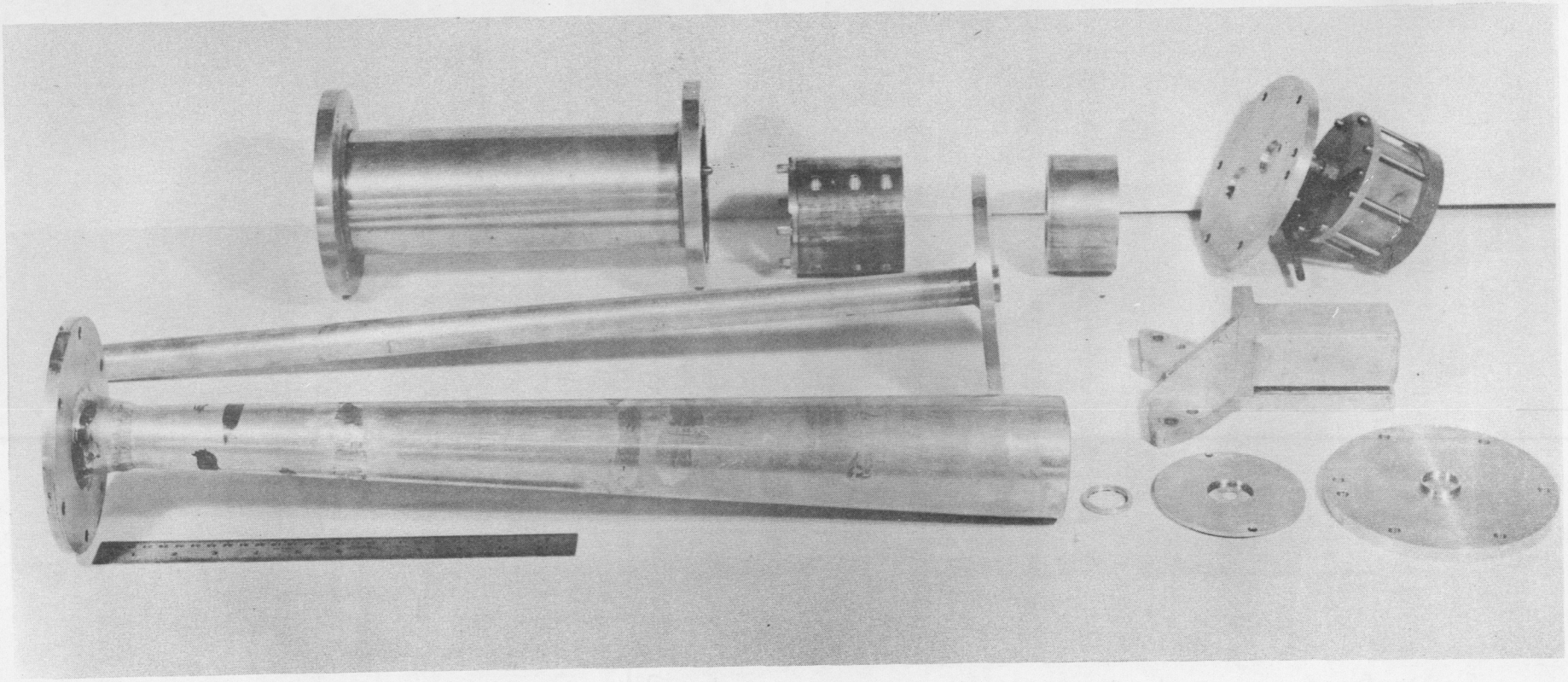

Fig. 2
NUCLEAR PLATE CAMERA DISASSEMBLED
The Conical collimator is in the foreground with the one inch diameter collimator immediately behind it

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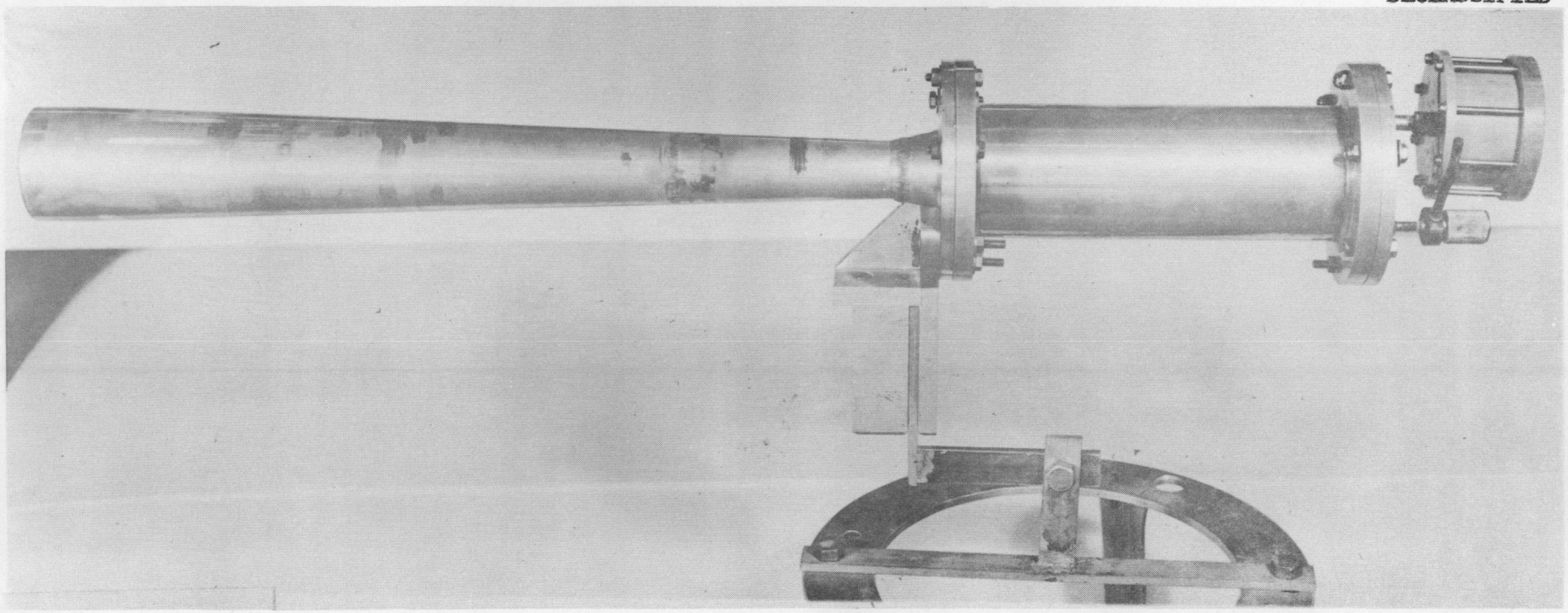

Fig. 3
NUCLEAR PLATE CAMERA ASSEMBLED USING CONICAL COLLIMATOR

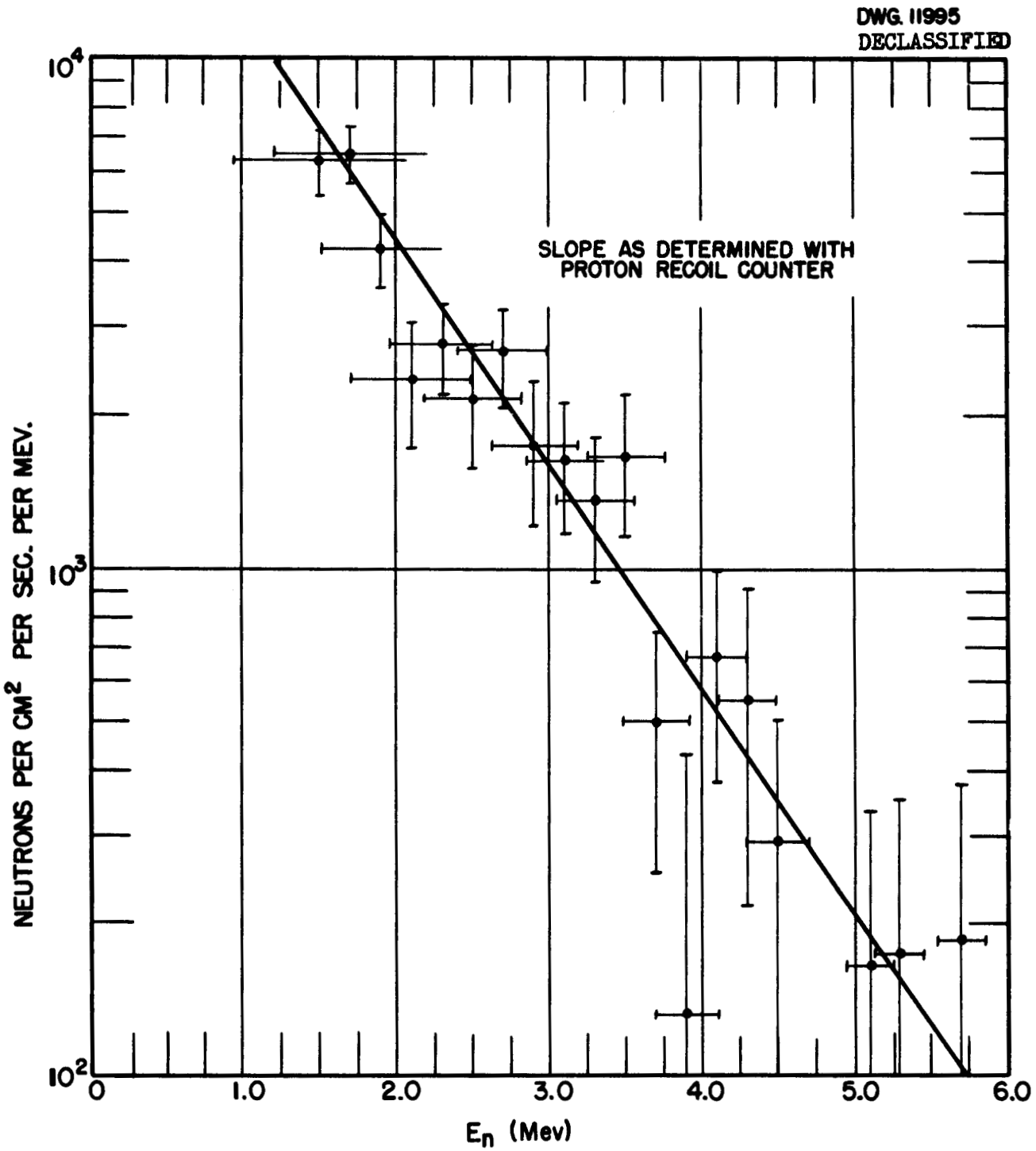

FIG. 4

FAST NEUTRON SPECTRUM FROM U^{235} FISSION