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THE FISSION NEUTRON SPECTRUM OF 25

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ABSTRACT

Photographic plates have been used to measure the energy of neutrons from the fission of 25. The spectrum as inferred from the ranges of 850 protons recoiling in the forward direction shows a very wide maximum at ~1.5 Mev with an exponentially decreasing high energy tail which extends beyond 7 Mev. The minimum energy neutrons recorded were ~700 kv. If the spectrum is extrapolated to zero, one finds that the average neutron energy is about 1.85 Mev. The stopping power of the plates was calibrated by the use of monochromatic neutrons from the $Li^7(pn)\ Be^7$ reaction and the d-d reaction.

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THE FISSION NEUTRON SPECTRUM OF 25

The neutron fission neutron spectrum has been quantitatively measured by cloud chamber technique at Rice,[1] by photographic emulsion technique at Liverpool,[2] and by ionization chamber technique at Stanford.[3] Since these methods gave discrepant results, more work on the fission neutron spectrum seemed desirable. The photographic emulsion technique appeared to be the most promising method for covering a wide range of neutron energies in one run and keeping scattering material to a minimum.

<u>Exposure Arrangement</u>

Neutrons of energy $\leq$ 250 kv energy from the $Li^7(pn)Be^7$ were slowed down by ~60 gm paraffin in front of the Li target of the Minnesota Van de Graaff. The thermalized neutrons produced fissions in a cylinder of uranium metal (weight 330 grams, size approximately 3/4" x 1¼") in front of the paraffin (see Fig. 1). The plates were then placed ~15 cm from the uranium so that the fission neutrons would be well collimated. The plates were 100μ thick Ilford Special Halftone plates, and were wrapped first in thin aluminum foil and then in black paper. The aluminum foil serves to retard drying and stripping of the thick emulsions used and prevents proton recoils from the paper wrapping from entering the emulsion. A 30μ ampere hour bombardment of the Li target with ~ 2.0 Mv protons gave on the plates a

1) W. E. Bennett and H. T. Richards, CF-325
2) J. Rotblat, T. Pickavance, S. Rowlands, J. Holt and J. Chadwick, B-86
3) F. Bloch and H. Staub, LA-17 and LA-17A.

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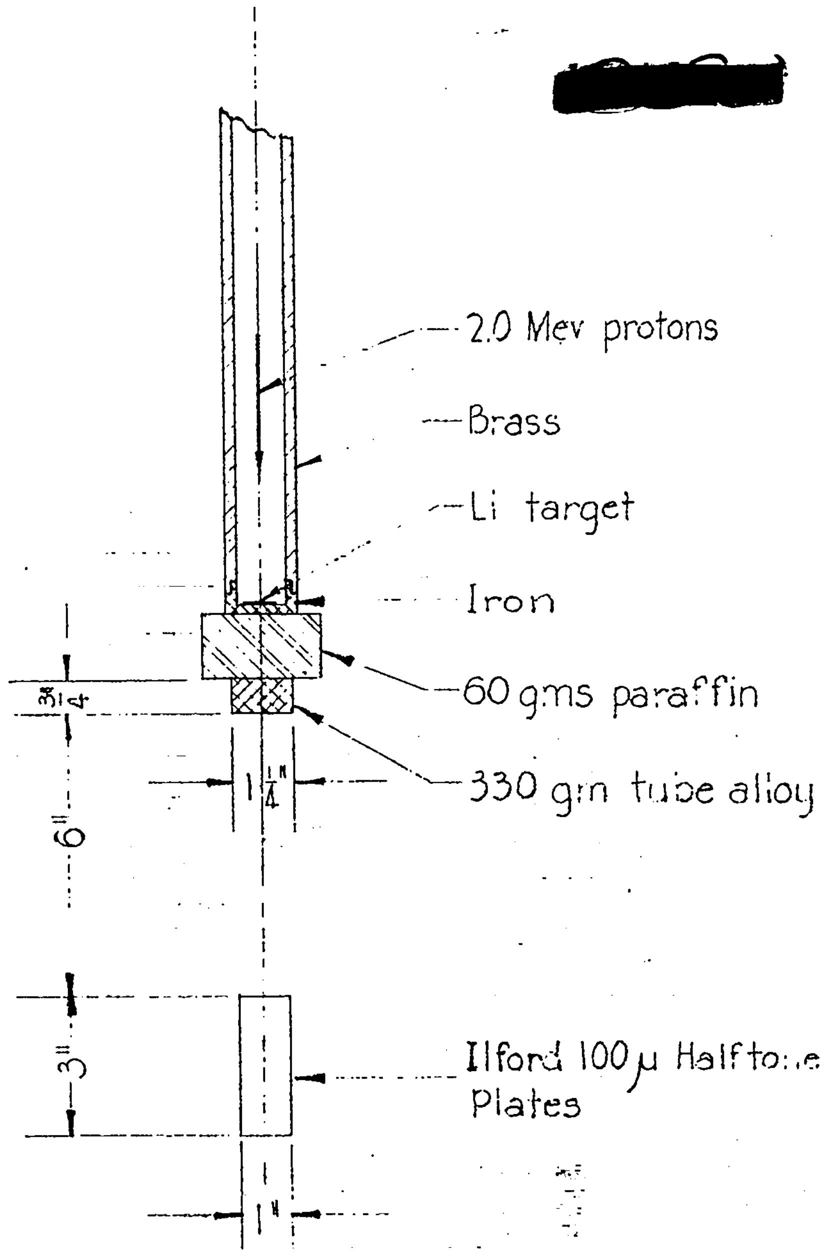

FIG. 1
EXPOSURE ARRANGEMENT

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satisfactory number of proton recoils from fission neutrons. A background run with the uranium replaced by an equivalent lead cylinder was also made, and no recoil protons were observed.

Measuring Technique

The viewing and measuring techniques and criteria for measurable tracks are essentially those described in earlier neutron measurements by the photographic emulsion technique.[4] All actual track measurements were made by I. H. Perlman.

Calibration of Plates

Careful calibration of the stopping power of the Ilford 100μ halftone plates had been done earlier at Rice Institute.[4,5] A heavy paraffin target 20 kv thick was bombarded by magnetically analyzed 700 kv deuterons, and plates were placed at 0° and 90° to the target. The mean ranges of 200 recoil protons measured on each plate were $135 \pm 2\mu$ and $72 \pm 1\mu$. (The error is an estimated error which depends upon how the curve can be drawn through the experimental points.) Since recoils up to 12° angle with the incident neutron were measured, these mean ranges correspond to neutron energies $(1/2)E_n\theta_o^2$ less than the neutron energy calculated from Bonner's $Q = 3.31$ Mev.[6] Therefore $6.6 \pm 0.1\mu$ of emulsion was equivalent to 1 cm of air for stopping 3.73 Mev protons and $6.5 \pm 0.1\mu$ of emulsion was equivalent to 1 cm of air for stopping 2.60 Mev protons.

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4) H. T. Richards, Phys. Rev., 59, 796 (1941).
5) H. T. Richards and E. Hudspeth, Phys. Rev., 58, 382 (1940).
6) T. W. Bonner, Phys. Rev., 59, 237 (1941).

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This calibration was checked for later batches of Ilford plates by exposing plates at 90° to the d-d source in "Z". This agreed with the earlier Rice value, giving in this case a relative stopping power of 6.7 ± 0.2μ of emulsion equivalent to 1 cm air for $2.50-(1/2)E\theta_0^2 = 2.39$ Mev protons.

Since it was desired to measure the fission neutron spectrum to as low energies as possible and since energy is such a sensitive function of range in the low energy region, it was also desirable to have calibration points for lower energy neutrons. Therefore the $Li^7(pn)Be^7$ source was used to give monochromatic calibration neutrons of ~ 0.6, 0.9, 1.3, and 1.8 Mev. About 200 tracks were measured on each of these last three calibration plates. The stopping power results (except for the 0.6 Mev point) are given in Table I. (See page 7).

From Table I we see that experimentally there is no significant change as a function of energy for the stopping power of the emulsion relative to air. This result is as one would expect since the stopping power of the emulsion depends both on the heavy Ag and Br atoms and the light C, H, O and N atoms of the gelatin. The changes in relative stopping power with energy are in opposite directions for the light and heavy atoms and for reasonable guesses as to AgBr concentration, etc., should just about cancel each other. The stopping power of the emulsion was therefore taken as 6.6μ equivalent to 1 cm air independent of the energy of the neutron.

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TABLE I

Av. neutron energy-$\bar{E}_n$	Av. recoil proton energy $\bar{E}_p = \bar{E}_n - (1/2)E_n\theta_o^2$	Mean emulsion range in microns R_{em}	Relative stopping power $\frac{R_{em}(\text{microns})}{R_{air}(\text{cm})}$
.864 MV	.825	10.8 ± 1	6.7 ± 0.6
1.285	1.230	21 ± 1	6.8 ± 0.4
1.79	1.71	34 ± 2	6.3 ± 0.4
2.50	2.39	64 ± 2	6.7 ± 0.2
2.66	2.60	72 ± 1	6.5 ± 0.1
3.81	3.73	135 ± 2	6.6 ± 0.1

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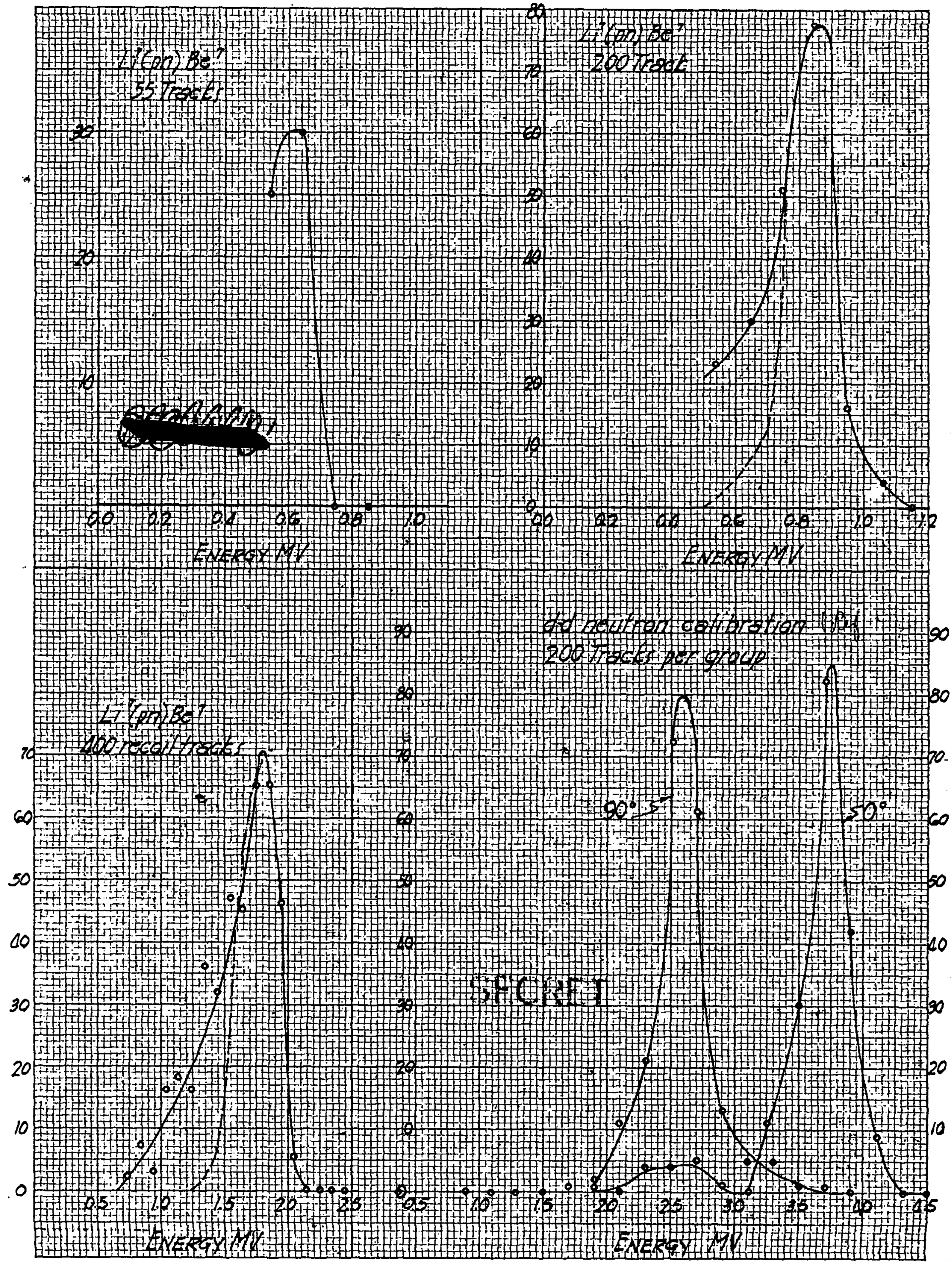

FIG 2-CALIBRATION DATA

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In Figure 2 some of the calibration data have been plotted in energy intervals to indicate the resolving power of the emulsion method for different energy neutrons. The 1.8 Mev calibration point has an experimental half width of ~0.50 Mev. Target thickness, pure range straggling, and measuring recoils out to 17° should account for ~ .25 Mv half width. The other .25 Mv straggling is to be attributed to the inhomogeneous character of the photographic emulsion. This inhomogeneity (colloidal AgBr in gelatin) increases straggling for two reasons. First, one estimates that about half the stopping power of the emulsion is due to the heavy AgBr colloidal particles dispersed through the emulsion. These are of the order 1μ in diameter spaced of the order of 1μ apart, and hence for 10-30μ tracks fluctuations in the number of colloidal AgBr particles may considerably increase the true range straggling. This straggling should be symmetric. The second straggling effect introduced by the AgBr particles is an asymmetric straggling and results from the fact that not all AgBr grains through which the proton passes become developable. Hence, if there are several insensitive grains at the beginning or end of the recoil proton's range, the <u>measured</u> range will be too short. That such insensitive regions exist is shown in the photomicrograph (Figure 3), Ref 7 of a 78μ recoil proton track from a 2.6 Mev neutron used for calibration. Such insensitive regions are much less rare for alpha-particle tracks since the specific ionization is several times larger, and for the same reason are less common near the end of the proton range (peak of Bragg curve). However, this still results in a much larger proportional straggling for short tracks.

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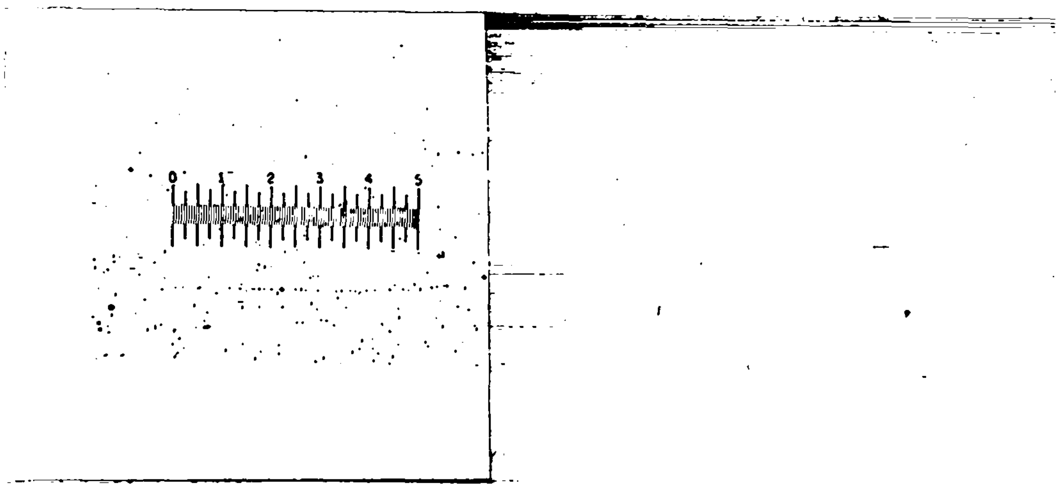

Figure 3

Background grains which may be mistaken for part of the track also contribute to straggling. These various factors definitely prevent the application of the method for very low energies (ranges in emulsion $\ll 10\mu$, i.e., $E \ll 800$ kv). However, the calibration data at 900 kv (see Figure 2) still gives a symmetric group with a small enough half width that measurements in this region may still be useful.

A calibration point was attempted for 600 kv neutrons (range in emulsion $\sim$ 6-7 microns i.e. $\sim$ 4-6 grains), but the straggling is here so important that no complete group can be found (see Figure 2). Hence, one concludes from the calibration data that the emulsion method may be useful

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down to energies of about 900 kv but not very much lower.

For accurate energy-spectrum measurements it is of course important that there be no preferential selection of short or long tracks for measurement. This was tested in two ways. Two observers (I. H. Perlman and H. T. Richards) independently examined the same area of a plate. The number of tracks of a given range reported by each observer checked within a few per cent. The other check consisted in experimentally determining the number of acceptable tracks per unit area on the 1.9 and 0.9 Mev calibration plates which had been exposed to neutron flux of different energy and magnitude. If correction is made for the different flux and neutron-proton scattering cross section, the number of tracks per unit area on the two plates should have been 1.98. The experimentally observed ratio was 2.08, which is probably a fortuitously good check since the hydrogen content of the plates may be expected to vary appreciably with the humidity of the air. This point is being checked by chemical analysis of the hydrogen content of the plates. Also if one knows the hydrogen content of the plate one can estimate the absolute expected track density. This has not yet been done pending an analysis of the plates for H_2.

Results

About 850 recoil proton tracks have been measured on the plates exposed at Minnesota. The range intervals were converted to energy intervals by use of the Cornell range-energy relation and the experimentally determined

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stopping power of the emulsion. Each energy interval was decreased by $(1/2)E\theta_o^2$ ($\theta_o = 17^\circ$) because recoils out to $\theta_o = 17^\circ$ were measured. The resulting recoil proton distribution was then corrected for variation of the neutron-proton scattering cross section with energy[7] and for a geometry correction arising from the fact that slightly inclined long tracks are much more likely to leave the emulsion (and hence not be acceptable for measurement) than short tracks. The geometry correction factor[4] is of the form

$$W(s) = 1 - \frac{S \sin \theta_o}{2d}$$

where W(s) is the probability that a track of length (s) be acceptable for measurement, d is the depth of the emulsion, and θ_o is the maximum acceptable angle that the recoil proton can make with the incident neutron direction. 1/W(s) is plotted for various energies in Figure 4 (see page 13) to indicate the magnitude of the correction.

The inferred neutron spectrum after these corrections have been made is given in Figure 5 (see page 14). The probable error of each point is 0.67 times the error indicated on the curve.

Discussion

The neutron spectrum appears to have a rather flat maximum from ~0.8 - 2.0 Mev. Above that energy it drops exponentially, decreasing roughly by a factor of two for each 1 Mev increase in energy. A few per

7) Minnesota measurements - LA 11 and CF 599

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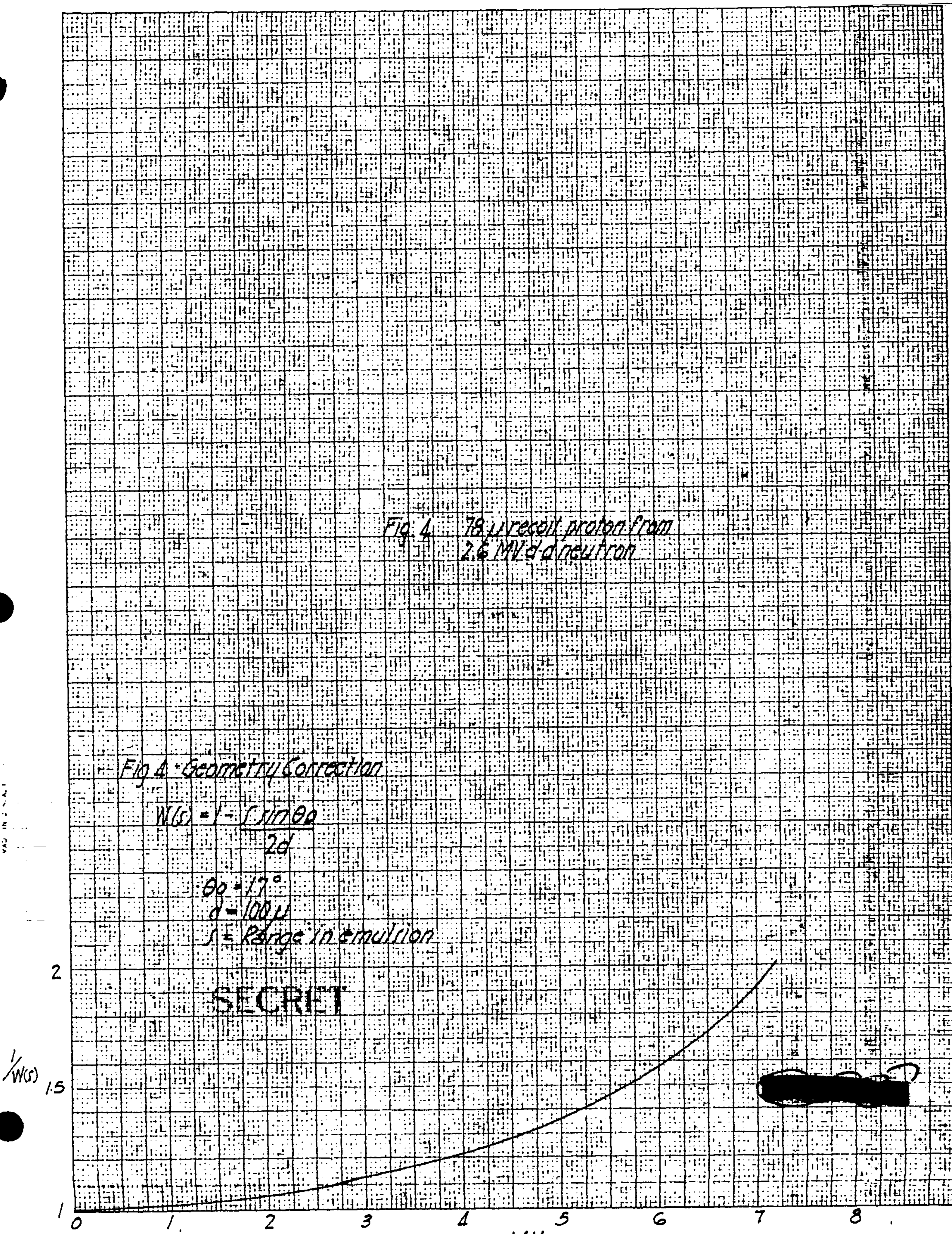
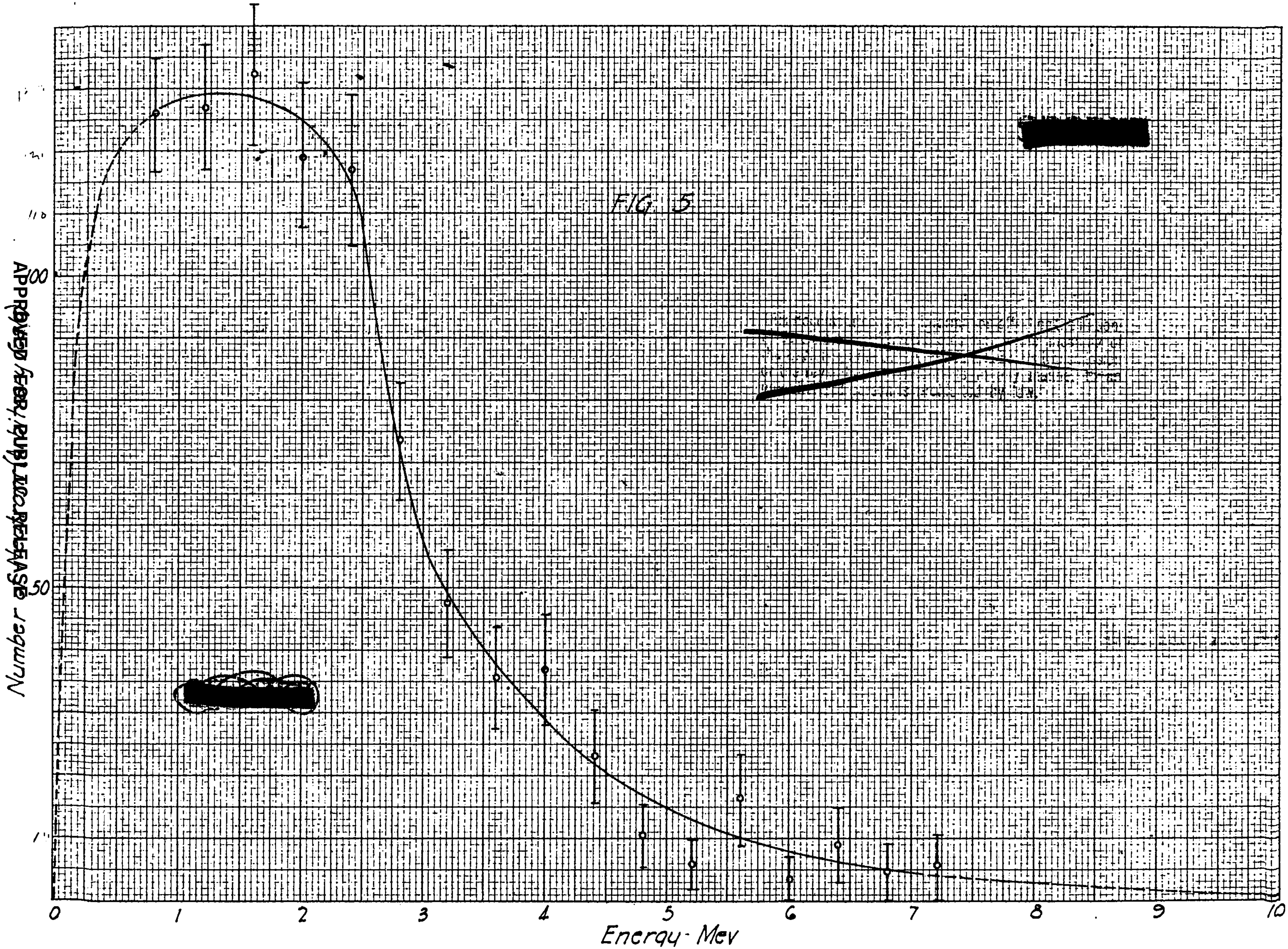


Fig. 4 78 μ recoil proton from
2.6 MV d-d neutron
Fig 4 - Geometry Correction
W(s) = 1 - s sin θo / 2d
θo = 17°
d = 100 μ
s = Range in emulsion
SECRET
[redacted]
1/W(s)
2
1.5
1
0
1
2
3
4
5
6
7
8
Energy MV



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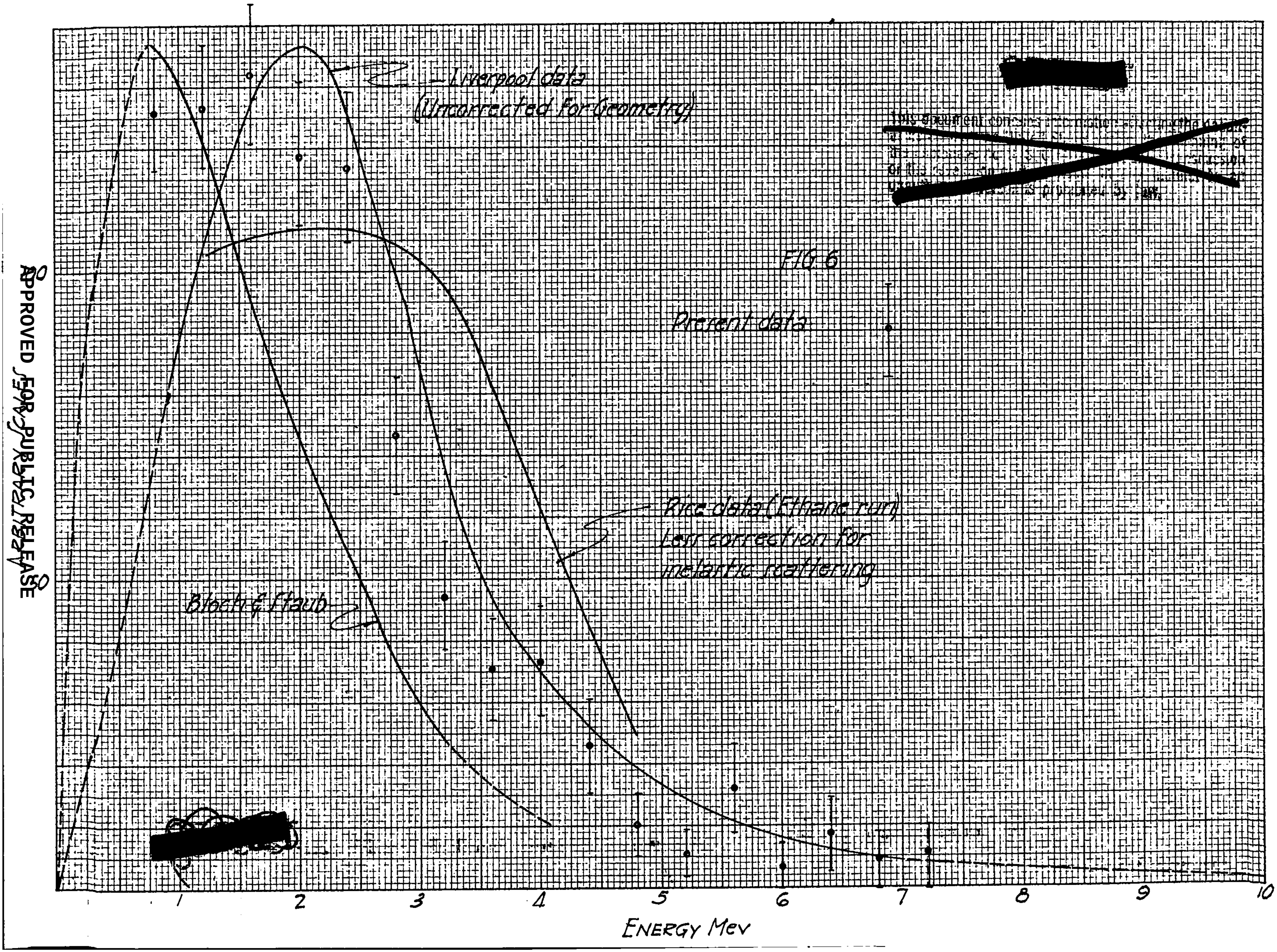

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cent of the neutrons may still have energies > 7.0 Mev. In shape the high-energy end of the spectrum (i.e. E_n > 2.5 Mv) agrees satisfactorily with the results of Bloch and Staub, and with the British results. (See Figure 6, page 15.) On the low-energy side of the spectrum the results disagree with both Bloch and Staub and the British. Bloch and Staub report that the spectrum continues to rise exponentially with decreasing neutron energy down to a million volts, while the British have a pronounced maximum at ~2.0 Mev, the number of neutrons falling to half value by .8 Mev. Since the Stanford method obtains the spectrum from differentiating the integral distribution of recoils at all angles, the differential spectrum is a very sensitive function of the observed integral distribution. Hence, as Bloch and Staub have pointed out,[8] part of the discrepancy between the present measurements (available to them in a preliminary form) can arise from the fact that their observed integral distribution may be too high on the low-energy end because of piling up of small pulses from gamma rays and because of the fact that their modulation scheme biased their results in favor of the delayed neutrons which presumably are of low energy.

The disagreement with the British may in part be statistical since they only observed 200 tracks and may in part be due to their measuring recoils out to 30°. A recoil proton at 30° gets but ~3/4 the energy of the neutron and hence for less than 1 Mev energy neutrons, the ranges of part of the recoils are quite short. Our present calibration studies with

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8) Bloch and Staub, LA 17A.

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monochromatic neutrons indicate that these very low energies ($<$ 800 kv) may occasionally be missed particularly because inhomogeneities in the emulsion introduce large additional straggling which throws some ranges to below detectable values. Also the use of 3 kg. of U_3O_8 instead of 330 gms of the metal for the fission source may account for part of the difference.

For comparison, part of the cloud chamber data at Rice[1)] is included. The run taken in C_2H_6 is chosen, because the geometry corrections for it are smallest, since ethane has a high stopping power. Also the Rice data here reported do not include their inelastic scattering correction, the magnitude of which is very doubtful. At the low-energy end $<$ 2.5 Mev (where the cloud chamber data are best) the agreement is satisfactory. Above 2.5 Mev the Rice statistics are so poor and the geometry corrections become so large that little weight can be given to the Rice data. However, the flatness of the cloud chamber data in the region 1.0 - 2.5 Mev does lend support to the present spectrum as compared with the sharp rise reported by Bloch and Staub.

It is difficult to say much about the shape of the spectrum below 1 Mev since the calibration exposures with monochromatic neutrons indicates that the photographic method loses its reliability in the region $<$ 800 kv. By the use of hydrogen in the cloud chamber the Rice group extended their spectrum to 0.4 Mev energy and their results indicated that the number of neutrons was decreasing in this region. Therefore it seems reasonable to extrapolate the present spectrum to zero. If this is done, one estimates that the average energy of the neutrons is $\sim$ 1.85 Mev which checks only

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roughly the value (~2.2 Mev) which Christy and Manley[9)] report from the water absorption curve of the fission neutrons.

The fact that the calibration proton recoil groups from the $Li(pn)Be^7$ source are not quite symmetric may also indicate that the low-energy end of the present spectrum has too high an amplitude. If one knew that all the neutrons incident upon the calibration plates were really monochromatic, then a correction for this asymmetry could be calculated. However, it is possible that a significant part of the excess number of low-energy recoil tracks may actually represent neutrons which were either originally non-homogeneous in energy or which had been degraded in energy. At any rate the correction would only be of importance for the low-energy end of the spectrum (<~2 Mv) since the d-d spectrum at 2.60 Mev is quite symmetric.

Recently Fermi's group[10)] at Chicago has done careful experiments on the slowing down of fission neutrons in carbon and in H_2O. They find a $\bar{r^2}$ in carbon of 1856 cm^2 and $\bar{r^2}$ in H_2O of 174 cm^2. Richman[11)] has calculated the $\bar{r^2}$ to be expected from the present spectrum and finds values of 1958 cm^2 and 177 cm^2 for the two respective cases. The sign of the small discrepancies is such as to indicate that the present spectrum gives slightly too high an average value. However, there are three other facts to indicate that actually the converse is true. First, the asymmetry of

9) R. F. Christy and J. Manley, CF-209.
10) E. Fermi, J. Marshall and L. Marshall, CP-1084.
11) Richman, LAA-L1

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the calibration neutron groups may mean the photographic method is weighting the low energy neutrons. Secondly, the normal alloy fission source was thick enough that as high as 15% of the fission neutrons from the far side of the fission source may have been inelastically scattered before reaching the plate. Thirdly, the average neutron energy of the present spectrum (1.85 Mv) is significantly less than the water absorption value (2.2) observed by Christy and Manley.[9)]

It is hoped soon to resolve these difficulties by more careful calibration studies and by repeating the spectrum measurement with an enriched 25 source which can be small enough that inelastic scattering will be negligible.