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DELAYED NEUTRON SPECTRA FROM SHORT PULSE FISSION OF URANIUM-235

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ABSTRACT

Delayed neutron spectra from individual short pulse (~ 50 μs) fission of small ^{235}U samples (50 mg) were measured using a small (5 cm OD x 5 cm length) NE 213 neutron spectrometer. The irradiating fast neutron flux ($\sim 10^{13}$ neutrons/cm^2) for these measurements was provided by the Godiva fast burst reactor at the Los Alamos Critical Experiment Facility (LACEF). A high speed pneumatic transfer system was used to transfer the 50 mg ^{235}U samples from the irradiation position near the Godiva assembly to a remote shielded counting room containing the NE 213 spectrometer and associated electronics. Data were acquired in sixty-four 0.5 s time bins and over an energy range 1-7 MeV. Comparisons between these measurements and a detailed model calculation performed at Los Alamos is presented.

I. INTRODUCTION

Very little is known about delayed neutron spectra above 1 MeV neutron energy and practically nothing above 2 MeV. This situation exists for two reasons: 1) ~ 90% of the delayed neutrons have energies less than 1 MeV and 2) neutron detector efficiencies tend to decrease with increasing energy. These two features make experiments of this nature difficult at best. However, there have been neutron emitters identified with possible available energies of 6 MeV and above. Thus, we have embarked on a program to extend the measured delayed neutron spectra to as high a neutron energy as possible. At present, most of our measurements have been made on irradiated ^{235}U foils in which all of the delayed neutron precursors were present. A few measurements on separated precursors, made at the Tristan isotope separator facility at Brookhaven, will be mentioned.

II. EXPERIMENTAL SETUP

The source of the burst neutrons was the Godiva Fast Burst Reactor (FWHM ≈ 50 μs)at the Los Alamos Critical Experiment Facility[1]. These neutrons were moderated in a 1 cm polyethylene cylinder surrounding the irradiation sample. The neutron spectra with and without the moderating cylinder are shown in Fig. 1. The irradiation samples were Al-^{235}U alloy containing 50 mg of ^{235}U. Figure 2 shows the contribution to the number of fissions by each neutron group. Following the neutron burst, the irradiated sample was transported to a shielded counting room by a pneumatic transfer system. The system was constructed so

that the sample arrived in the counting room within 0.5 s after the neutron burst. The experimental setup is shown in Fig. 3.

The neutron spectrum measurements were made with an NE 213 scintillator spectrometer. A schematic of the electronics diagram is shown in Fig. 4. To separate the neutrons from the γ-rays, a pulse shape discrimination (PSD) circuit was used. It consisted of a zero crossing discriminator and fast amplifier purchased from Oak Ridge National Laboratory.[3] This circuit makes use of the longer decay time of pulses produced by neutron interactions in the scintillator. After impedance matching and integration in a preamplifier, the dynode pulse is double differentiated in a fast amplifier to produce a bipolar pulse and a zero-crossing discriminator is used to find the zero crossing time which is related to the pulse decay time.[2] All other modules are commercially available. Since we wish to reject any piled up pulses, there is a pile-up rejection circuit incorporated into the electronics. This circuit resolves pulse pairs of $\sim$ 5 ns and vetos any pairs up to 500 ns separation, the integration time of the PSD circuit.

The data were acquired with LeCroy Research Systems 3512 ADCs located in a CAMAC crate in the counting room. The pulse-height spectra were in sixty-four 0.5 s time bins of 1024 channels each, and the pulse-shape discrimination spectra were acquired in sixteen 2.0 s time bins of 1024 channels each. Figure 5 shows typical pulse shape discrimination spectra. In order to reduce the γ flux to reasonable levels, 10 cm of lead shielding was placed around the sample.

To correct for dead time and pile up rejections, the event rate, TAC starts, TAC valid starts, and ADC gates were scaled in 4096 channels of 10 ms wide time bins. Table I shows the event rates, deadtime correction, and neutron/gamma ratio as a function of time.

In addition to the eight data samples we have recorded, we have several measurements of the background from Godiva alone and also a measurement of the γ spectrum from the sample. In an effort to assess the γ contamination underneath the neutron peak in the PSD spectrum, we used a ^{60}Co source at various count rates. The number of events mislabeled as neutrons by the PSD electronics were measured. The results are shown in Table II.

III. DATA ANALYSIS

The background consists of three components. The neutron background from Godiva, the gamma-ray background from the sample itself, and the prompt fission neutrons from sample self-interaction. We have measured the Godiva background by using a rabbit containing no ^{235}U and have found it negligible. The gamma-ray background has been estimated, using the method mentioned previously, and found to be 2% of the early time spectrum. This background has been subtracted from the pulse height spectrum. The fission contribution has been calculated and found to contribute less than 0.2% of the total number of neutrons emitted from the foil.

We have evaluated the lead attenuation by measuring the pulse height spectrum of a ^{252}Cf source. First, the source is measured in a "good" geometry 1m from the detector. This pulse height distribution is unfolded to verify that the source strength and the energy spectrum is correct. Secondly, the source is placed in the sample position and a second pulse height spectrum obtained. The ratio of these two pulse height spectra then gives the attenuation correction factors.

The data are corected for dead time and pile up losses and summed into three time bins, 1-5 s, 5-10 s, and 10-20 s to achieve greater statistics. Presently we have approximately 10^6 counts per time bin. The data were then unfolded.

Because an NE 213 scintillator is essentially a proton recoil spectrometer, a monoenergetic source of neutrons yields a continuum of pulse heights as illustrated in Fig. 6. Thus, to obtain an energy spectrum, the detector response matrix must be unfolded from the pulse-height distribution. We obtained the detector response function matrix, the neutron energy vs. pulse height distributions, from measurements at the Oak Ridge Electron Linear Accelerator neutron-time-of-flight facility. The pulse heights were stored in 64 neutron energy bins from $\sim$500 keV to 25 MeV. For the present analysis, we are using only 9 of these bins between 730 keV and 5 MeV. The unfolding technique is the "least-squares" method detailed elsewhere.[4]

IV. RESULTS

Figures 7, 8, and 9 show the delayed neutron energy spectra for the three time bins. As the threshold for the neutron detector was 700 keV, the unfolded data start at 1 MeV. The curve shows the calculations of Tal England[5] where the histogram is the experimental data. The total number of fissions in the sample was determined by counting the gamma rays from ^{138}Cs and ^{90}Rb. Values[6] for the thermal chain yields for ^{235}U and gamma ray branching ratios for the fission products[7] were used to calculate the gamma-ray output per fission during the measurement interval. The number of fissions was also determined by chemically dissolving the sample and separating the ^{99}Mo fission product. The 140.5 keV gamma ray from ^{99}Tc daughter was counted with a germanium detector in a standard geometry. The results agreed to within 15%. The early time data suggest a distribution that falls less steeply with energy than the calculations indicate. Further analysis will be done where the calculated energy distribution will be folded with the response function matrix and compared directly with the measured pulse height distributions. This will allow us to compare data at higher neutron energies where the sparse statistics do not allow unfolding.

Also, we have recently embarked on a program of delayed neutron spectral measurements of separated isotopes. In general, the same detection and analysis philosophy was adopted. Figures 10 and 11 show the preliminary analysis for ^{96}Rb and ^{97}Rb. For ^{97}Rb, there is also an

indication of steeper fall off with neutron energy than indicated by theory. These data await further experiments to verify this trend.

REFERENCES

1. T. F. Wimett, R. H. White, R. G. Wagner, Proceedings of the National Topical Meeting on Fast Burst Reactors, January 28-30, 1969.

2. M. L. Roush, M. A. Wilson, and W. F. Hornyak, Nuclear Instruments and Methods 31, 112-124 (1964).

3. J. K. Dickens, et al., Oak Ridge National Laboratory Report, ORNL/TM-9561.

4. B. C. Cook, Nuclear Instruments and Methods 24, 256 (1963).

5. T. R. England, M. C. Brady, E. D. Arthur, R. J. LaBauve, and F. M. Mann, Contribution to this conference.

6. E. A. C. Crouch, "Fission Product Yields from Neutron-Induced Fission," Atomic Data and Nuclear Data Tables 19, 417 (1977).

7. V. Reus and W. Westminister, "Catalog of Gamma Rays from Radioactive Decay," Atomic Data and Nuclear Data Tables 29, 1 (1983).

TIME (s)	EVENT RATE (KHz)	PILE UP FRACTION	TAC LIVE TIME	ADC LIVE TIME	NEUTRON FRACTION	NORMALIZATIO
1	140	0.20	0.74	0.63	0.21	2.70
2	90	0.14	0.80	0.71	0.20	2.05
5	42	0.07	0.89	0.80	0.18	1.53
10	20	0.04	0.94	0.86	0.16	1.28
15	12	0.03	0.96	0.85	0.10	1.19
20	9	0.02	0.97	0.85	0.10	1.17

TABLE 2

EVENT RATE (KHz)	ERROR PROBABILITY
400	5.4×10^{-3}
60	7.4×10^{-4}
22	3.5×10^{-4}
2	3.6×10^{-4}

FIGURE CAPTIONS

Fig. 1. Neutron energy distribution from Godiva with and without CH_2 sleeve.

Fig. 2. Fission contribution for the neutron spectra with and without sleeve.

Fig. 3. Experimental schematic layout.

Fig. 4. Electronics diagram.

Fig. 5. Pulse shape distribution.

Top Figure: 2-4 seconds after Godiva burst.

Middle Figure: 8-10 seconds after Godiva burst.

Bottom Figure: 14-16 seconds after Godiva burst.

Fig. 6. Neutron detector response function. The pulse height response of the NE 213 detector to 5 MeV neutrons.

Fig. 7. Neutron spectrum. 1-5 seconds after Godiva burst.

Fig. 8. Neutron spectrum. 5-10 seconds after Godiva burst.

Fig. 9. Neutron spectrum. 10-20 seconds after Godiva burst.

Fig. 10. ^{96}Rb pulse height specturm. Theory has been folded with measured response functions to generate a "theoretical" pulse height distribution.

Fig. 11. ^{97}Rb pulse height spectrum. The experimental data has been normalized to the theoretical calculation.

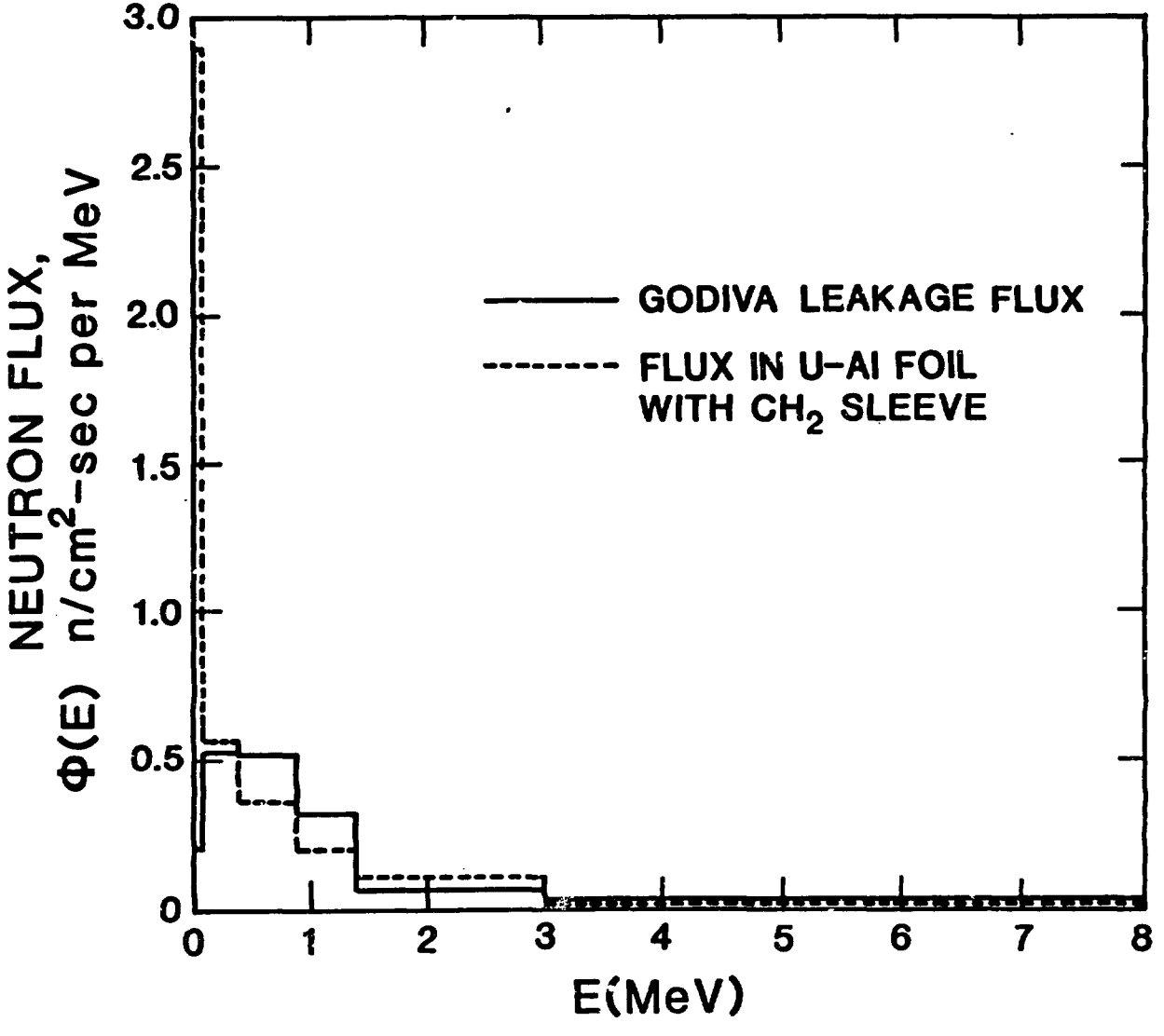

NEUTRON FLUX,
Φ(E) n/cm²-sec per MeV
3.0
2.5
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
E(MeV)
GODIVA LEAKAGE FLUX
FLUX IN U-Al FOIL
WITH CH2 SLEEVE

Fig. 1.

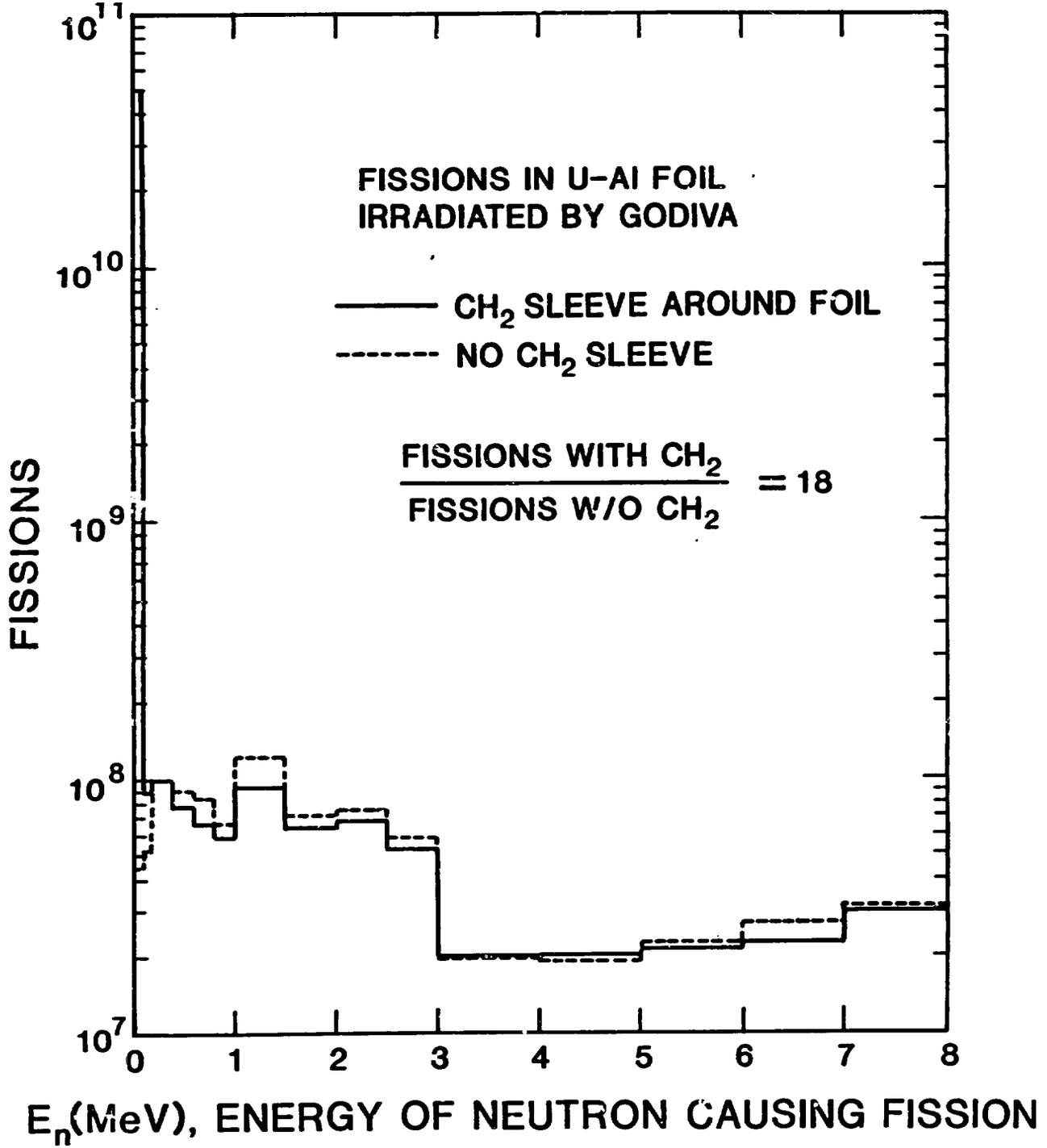
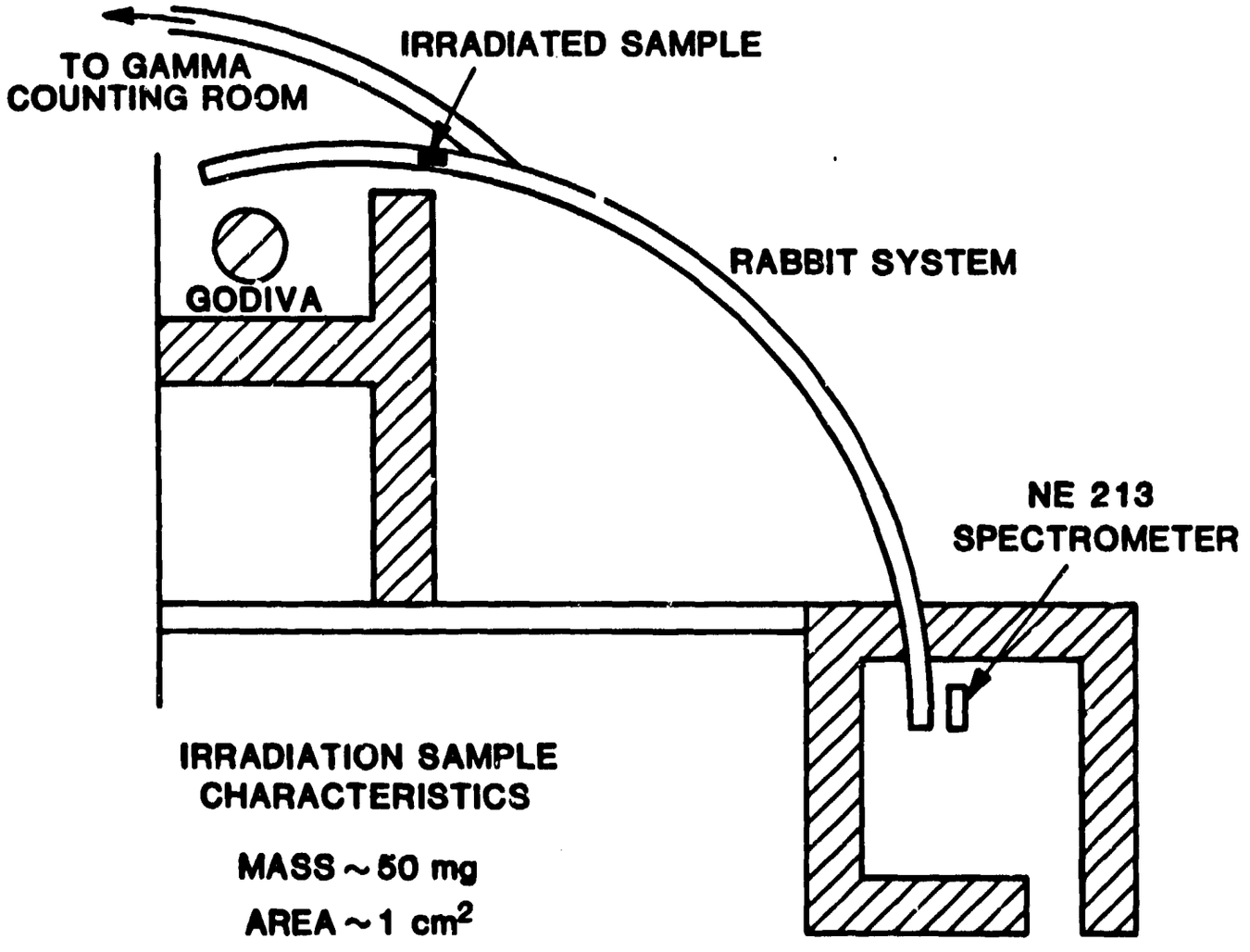

FISSIONS IN U-Al FOIL
IRRADIATED BY GODIVA
CH2 SLEEVE AROUND FOIL
NO CH2 SLEEVE
FISSIONS WITH CH2 / FISSIONS W/O CH2 = 18
FISSIONS
10^11
10^10
10^9
10^8
10^7
0
1
2
3
4
5
6
7
8
En(MeV), ENERGY OF NEUTRON CAUSING FISSION

Fig. 2.



EXPERIMENTAL GEOMETRY

Fig. 3.

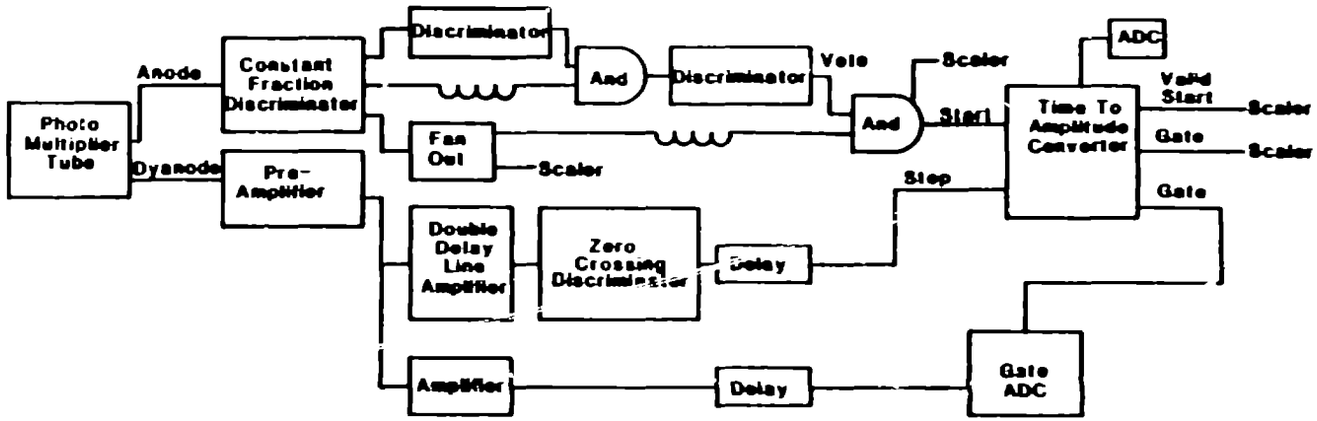
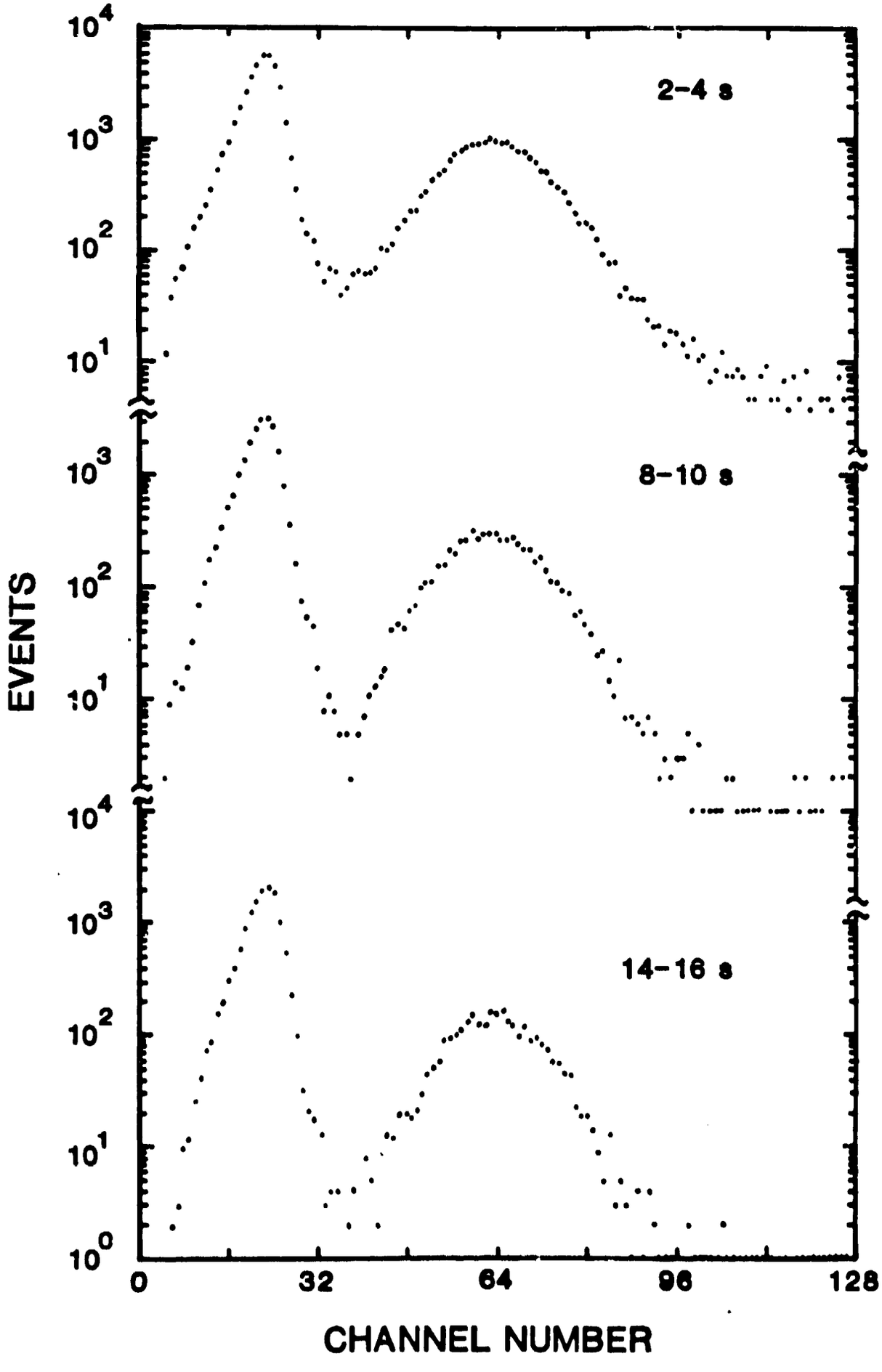


Fig. 4.


2-4 s
8-10 s
14-16 s
EVENTS
CHANNEL NUMBER
0
32
64
96
128

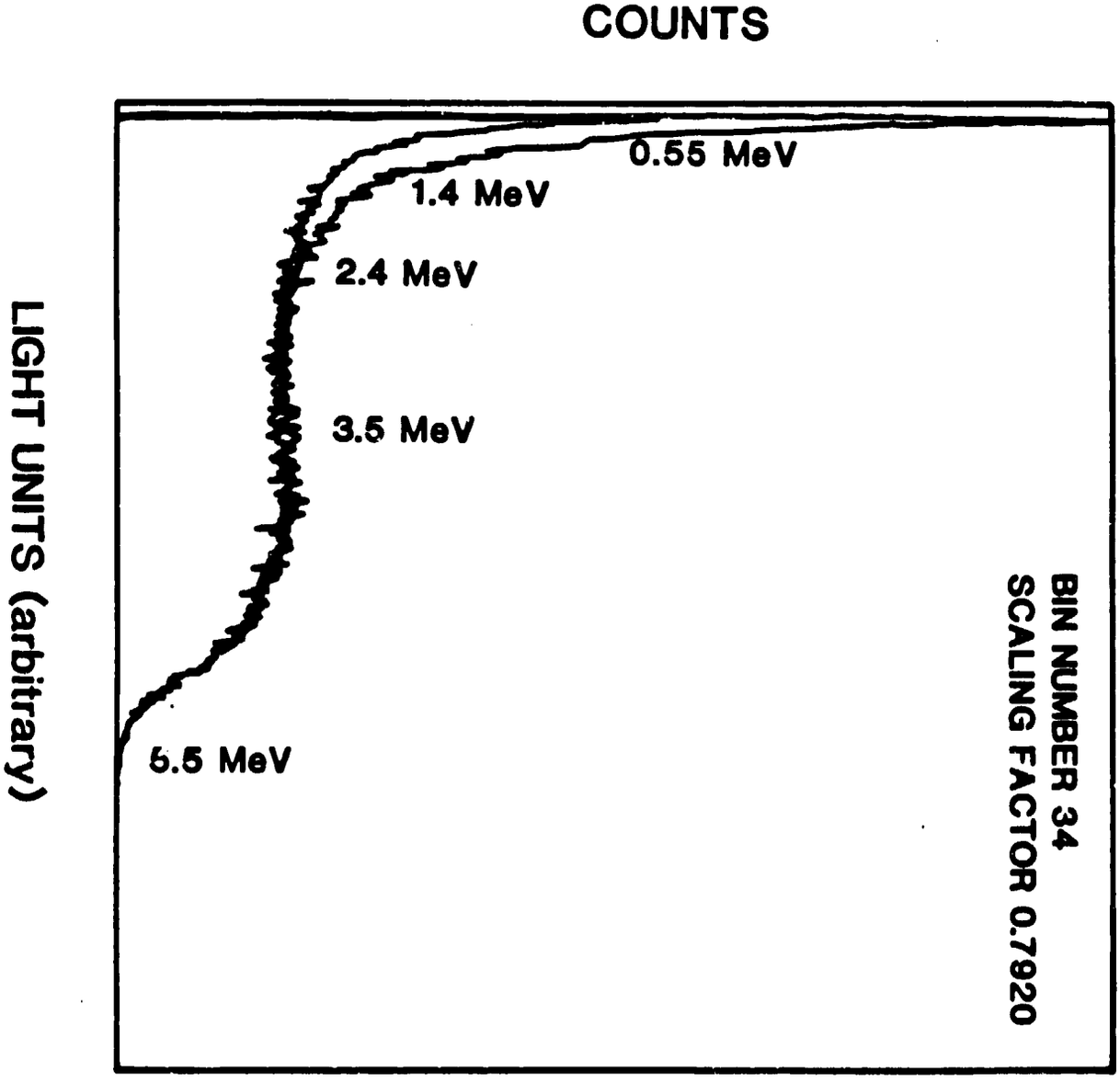

COUNTS
0.55 MeV
1.4 MeV
2.4 MeV
3.5 MeV
5.5 MeV
LIGHT UNITS (arbitrary)
BIN NUMBER 34
SCALING FACTOR 0.7920

Fig. 6.

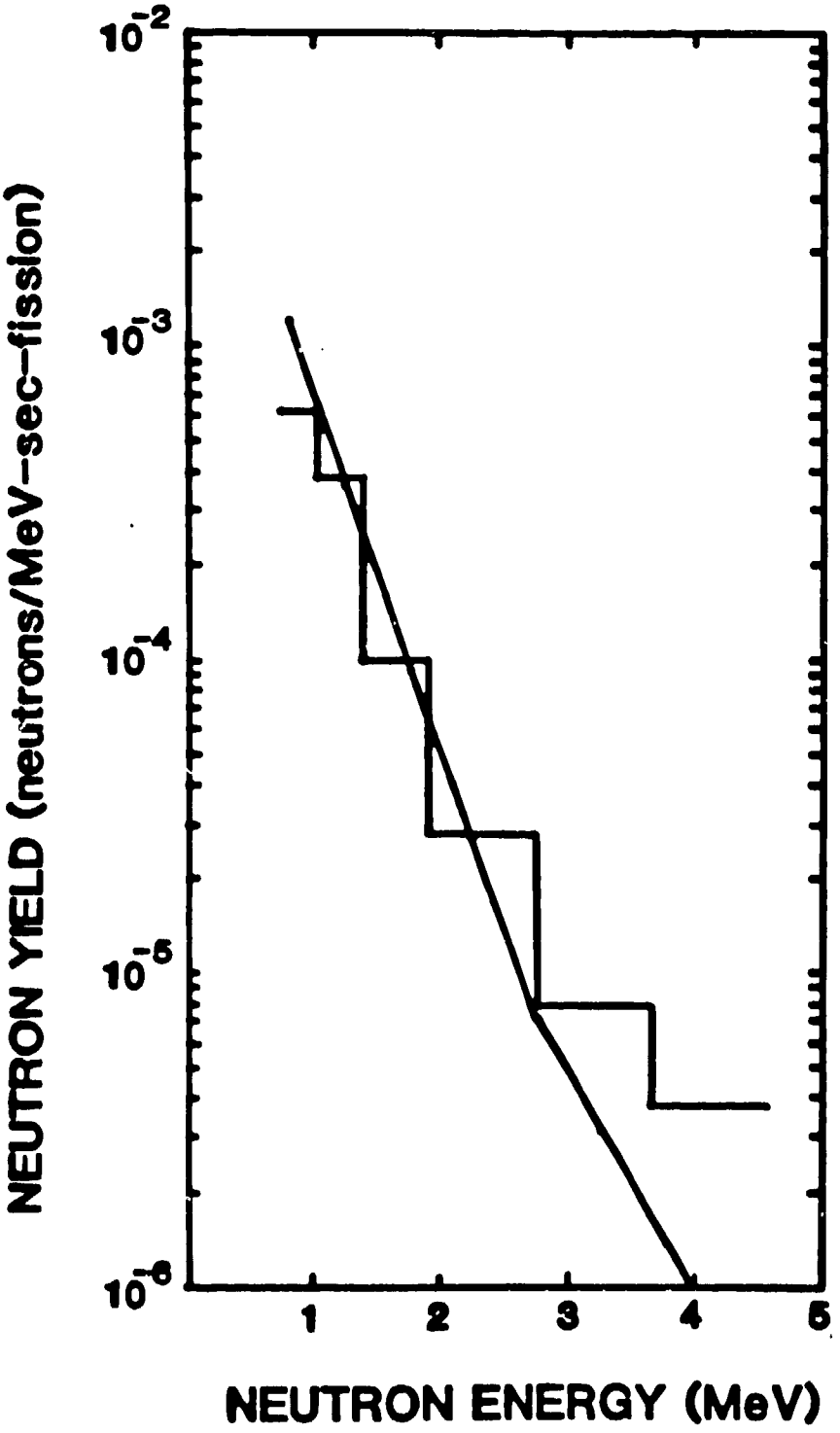

NEUTRON YIELD (neutrons/MeV-sec-fission)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5
NEUTRON ENERGY (MeV)

Fig. 7

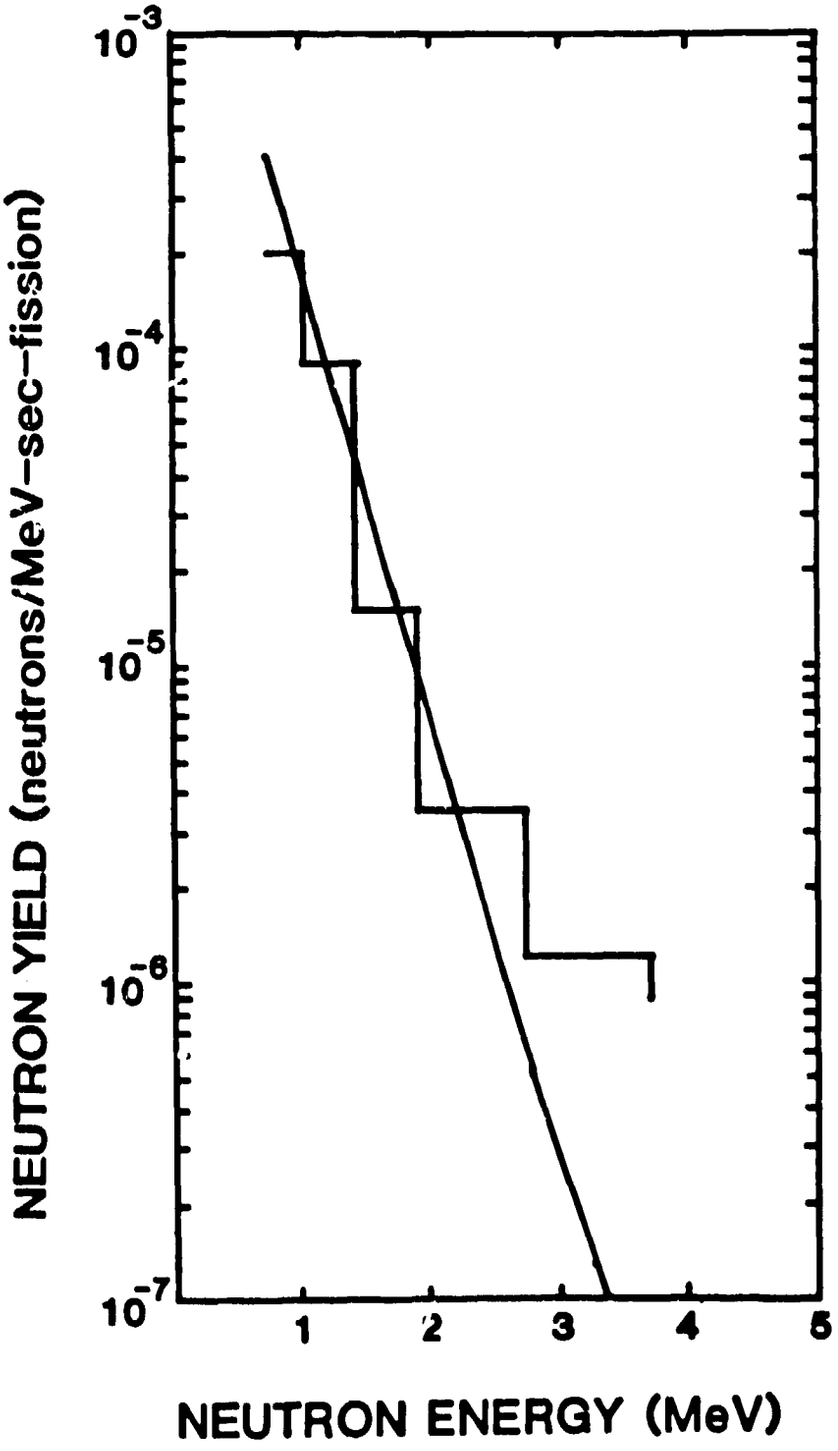

NEUTRON YIELD (neutrons/MeV-sec-fission)
10^-3
10^-4
10^-5
10^-6
10^-7
1
2
3
4
5
NEUTRON ENERGY (MeV)

Fig. 8.

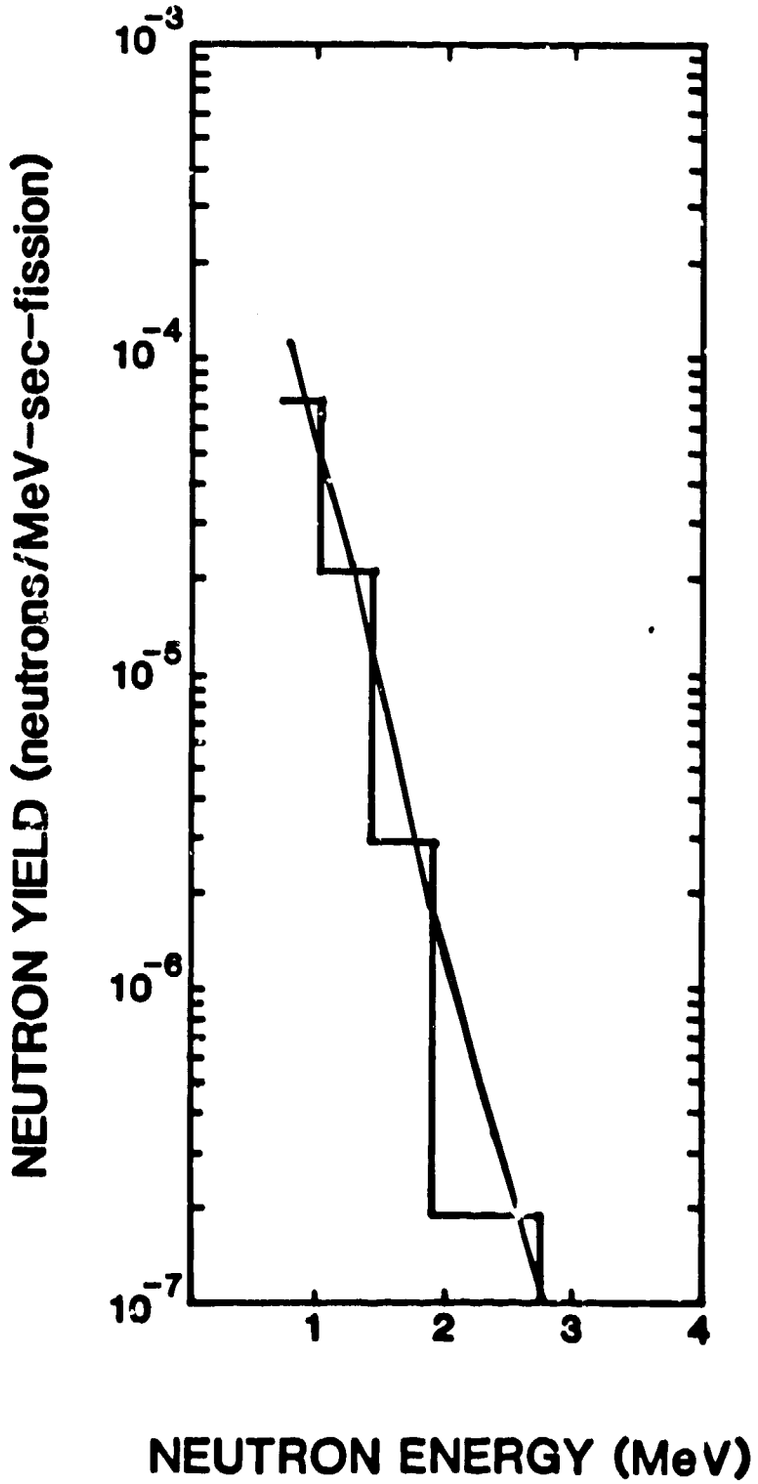

NEUTRON YIELD (neutrons/MeV-sec-fission)
10^-3
10^-4
10^-5
10^-6
10^-7
1
2
3
4
NEUTRON ENERGY (MeV)

Fig. 9.

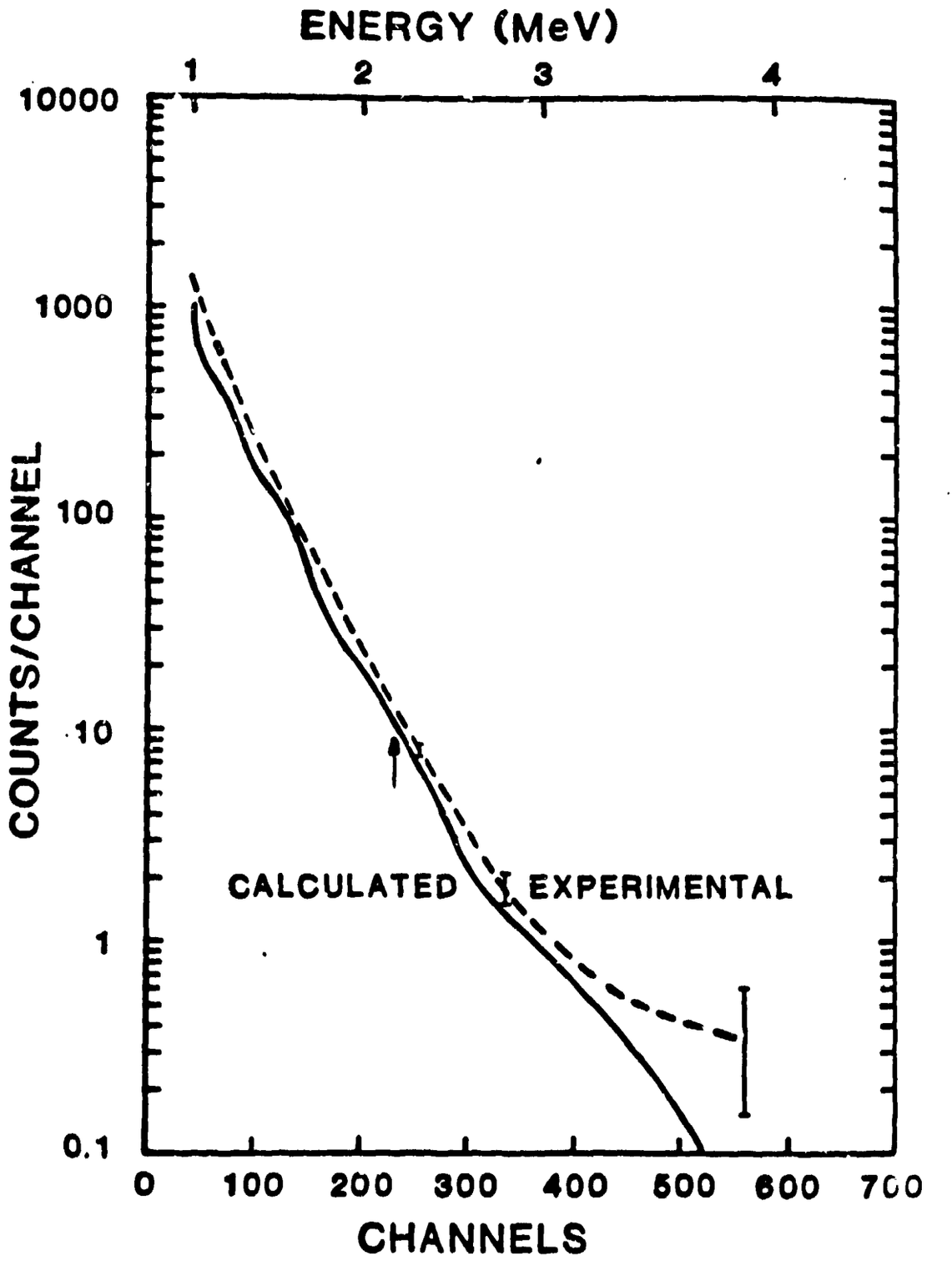
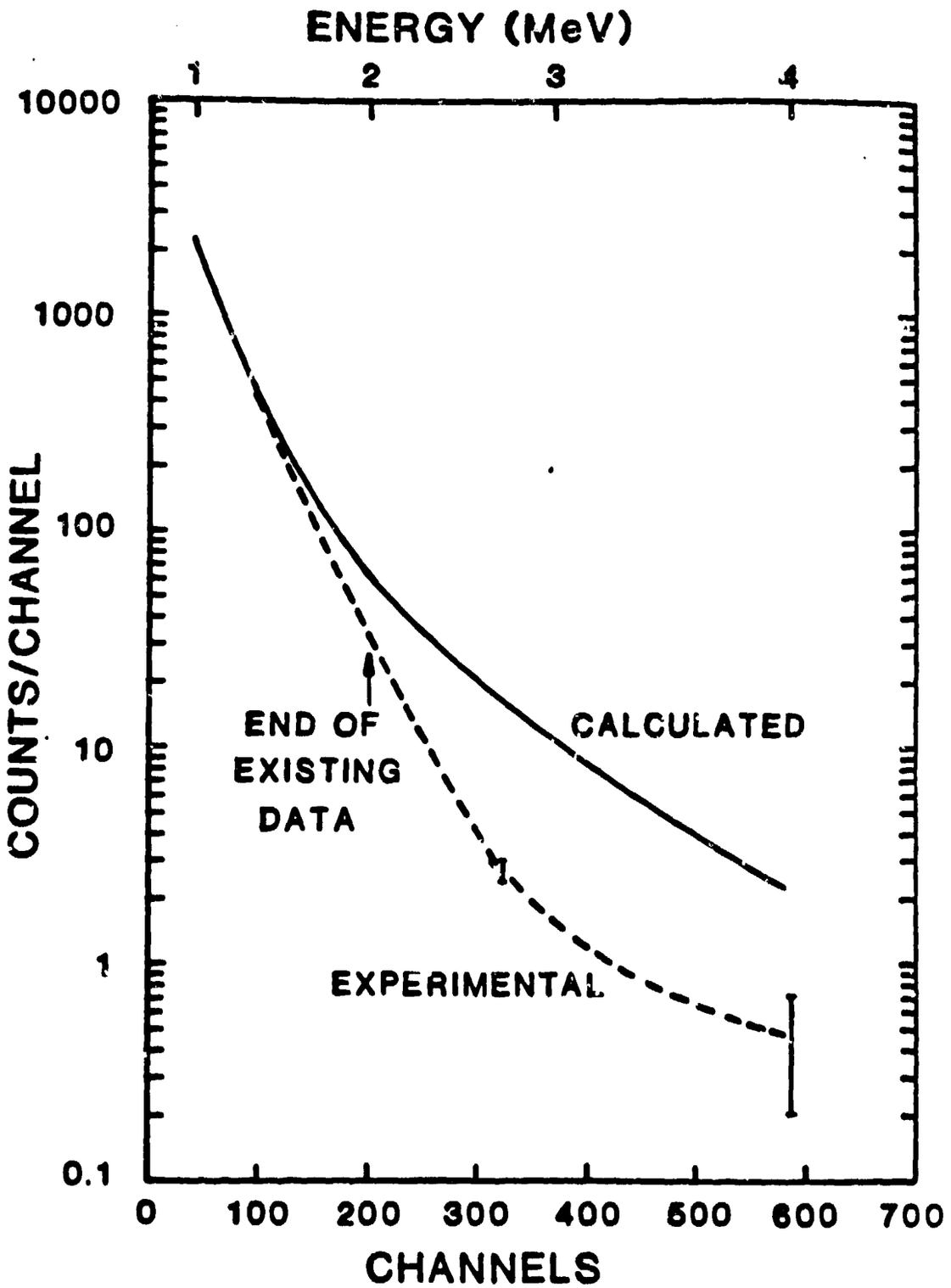

ENERGY (MeV)
1
2
3
4
10000
1000
100
10
1
0.1
COUNTS/CHANNEL
CALCULATED
EXPERIMENTAL
0
100
200
300
400
500
600
700
CHANNELS
96 RUBIDIUM DELAYED NEUTRON SPECTRUM

Fig. 10.



^{97} RUBIDIUM DELAYED NEUTRON SPECTRUM

Fig. 11.