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# CLOUD-CHAMBER AND PHOTOPLATE MEASUREMENTS OF THE FISSION-NEUTRON SPECTRUM OF 49



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## Abstract

The high-energy portion of the neutron spectrum from fast fission of 49 has been measured by the use of recoil protons in photographic emulsions. The result is identical within statistics to the 25 fast-fission-neutron spectrum (LA-200). A hydrogen-filled cloud chamber has been used to extend the photoplate data to low neutron energies (200 Kev). The resulting data when joined to the photoplate data indicate: (a) the maximum of the distribution is between 1 and 2 Mev; (b) that some 17% of the neutrons are above 4 Mev; (c) that the average energy is about 2.6 Mev; (d) that the high-energy spectrum is not incompatible with the assumption that the neutron energy distribution is Maxwellian in the moving fragment system; (e) to explain the shape of the low-energy end it may be necessary to assume that not all the neutrons are emitted from a moving spherical fragment.




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## Introduction

Photographic emulsions have been used by the present workers to examine the neutron specta of various sources especially the spectra of fission neatrons [1) 2)]. While this method has proved quite satisfactory for high-energy neutrons, grain straggling and other factors limit its usefulness to neutron energies greater than 1.0 to 1.5 Mev. At one time, concern was expressed that there might be a considerable group of fission neutrons with energy below 1 Mev. Furthermore, it can be shown that if neutron emission on a simple evaporation picture is spherically symmetric in the moving-fragment system, then the observed laboratory distribution should go to zero with decreasing E as $E^{1/2}$. Therefore, there is considerable interest in the shape of the fission spectrum in the low-energy region. For this reason a cloud chamber of very light construction (to minimize scattering) and designed for operation at very low stopping powers has been constructed and used to examine the fission neutron spectrum of 49 for energies less than 1.0 Mev.

## Experimental Arrangements

(a) For photoplate data: The experimental arrangements are similar to those described for the measurement of the neutron spectra from the fast fission of 25 [3)] except that the 25 disk was replaced by a 0.9" O.D. hemispherical shell of 49 weighing about 60 grams which Hanson had used earlier in his multiplication experiments. This hemispherical shell had a thickness of 0.74 cm. The front edge of the photoplates was about 9 cm from the 49.

1) H. T. Richards Phys. Rev., 59, 796 (1941)
2) H. T. Richards et al, LA 60, LA 66, LA 84, LA 85, LA 111, LA 200, LA 201
3) H. T. Richards, LA-200

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(b) For the cloud-chamber data: The cloud chamber and auxiliary equipment will be described in a forthcoming report. The experimental set up for this measurement is sketched in Fig. 1. Protons of energy but slightly greater ( 10 Kev) than the threshold value for the $Li^7(pn)Be^7$ reaction hit the rotating lithium target. Because of momentum considerations under these conditions all of the neutrons from the $Li^7(pn)Be^7$ reaction are confined to a cone of half angle 30 degrees to the proton beam hence no unscattered primary neutrons could reach the cloud chamber. These primary neutrons ($E \approx 70$ Kev) impinged upon a disk of 49 which was 1" in diameter and 0.5 cm thick. These neutrons cause fission in the 49 the fission neutrons from the plutonium disc are spherically symmetric in distribution so some will pass through the cloud chamber and be detected by the recoil protons which result from collisions of the neutrons with nuclei of the hydrogen gas in the chamber. The proton beam is only allowed to hit the lithium target for a few hundreds of a seconds after the cloud chamber has been expanded. If the beam hits the lithium before the chamber is sensitive, then the ions from the recoil protons have time to diffuse and the observed tracks will be quite diffuse. The pulsing of the proton beam is accomplished by momentarily shorting some electrostatic deflector plates which were about two meters before the target.

Because of the large size of the chamber and the large number of tacks (which because of the rapid fall in hydrogen of the vapor droplets carried down a large portion of the vapor at each expansion), it was necessary to run at a cycle time greater than one minute in order that the chamber return to equilibrium conditions.

Calibration of the chamber

The stopping power of the hydrogen gas plus alcohol-water vapor can be computed from the pressure of the gas and the vapor pressure of the liquid. As

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a check upon the calculated stopping power and gas purity and also a check upon systemic errors of measurement of track lengths, it was considered worthwhile to determine experimentally the stopping power of the mixture by irradiating the chamber with monochromatic neutrons of known energy from the Li(pn)Be reaction. This was done before and after the fission neutron measurements to check whether the stopping power changed during the run. This experimental determination of the stopping power by use of monochromatic neutrons is also useful because of the information which it gives concerning the resolution of the measurements and the number of scattered neutrons present. The experimental stopping powers (about 0.2 that of air) agreed with the computed values in all cases. Once the stopping power is known, then the calibration data can be plotted in energy intervals to exhibit the energy resolution and the size of the tail caused by scattered neutrons or errors of measurement. This has been done in Fig. 2. The half width of recoil proton groups agree satisfactorily with that to be expected from measuring recoils out to 15 degrees and from the thickness of the lithium target.

Measuring Criteria

(a) Photoplate data: The measuring criterion for the photoplate data is the same as that described in earlier reports.[1) 2)]

(b) Cloud-chamber data: The illuminated portion of the chamber was a rectangular parallelipiped 12 x 10 x 30 cm. However, the useful sensitive region of the chamber does not extend clear to the walls so that the effective length of the parallelepiped was taken as 20 cm. Only recoil protons making an angle -15 degrees with the incident neutron beam were considered for measurement. Furthermore, to eliminate as far as possible the various geometric corrections

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arising from the longer tracks having a greater probability of leaving the illuminated area, tracks were considered acceptable for measurement only if they started in a truncated cone of the illuminated area whose position and size were so chosen that (a) there was no inverse $r^2$ correction for tracks starting at different distances from the source, (b) that all recoil protons of energy less than 700 Kev would end within the illuminated area of the chamber and hence have no geometrical correction, (c) that all recoil protons of energy greater than 700 Kev and to the maximum energy measured could only leave the illuminated area at one end and then only if they started in the half of the truncated cone nearest that end of the chamber. For these conditions, the geometrical correction factor was of an exceedingly simple form and was only a factor of two for the 1.2 Mev point.

With these criteria the number of acceptable tracks was of course but a small fraction of the total this was especially true because most of the recoil protons were too energetic to be stopped wholly within the chamber.

Results

(a) Photoplate: About 1000 tracks were measured on the photoplates. These have been plotted in energy intervals by means of the calibration data of LA-60, corrected for the n-p scattering cross section, and corrected for a geometrical factor arising from the fact that the slightly inclined long tracks have a larger probability of leaving the emulsion (see references 1 and 2). The inferred neutron spectrum is given in Fig. 3 by the solid points.

(b) Cloud chamber: Slightly over 500 tracks have been measured which satisfy the above cirteria. These have been plotted in energy intervals by means of the calibration data mentioned above, and corrected for the n-p scattering cross section. The points above 700 kv had also to be corrected for the finite chance which these longer recoils had of not being wholly contained in the chamber.

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The resulting distribution was normalized to the photoplate data in the region 1.0 to 1.5 Mev and is shown by the open circles of Fig. 3. It is to be regretted that the region of overlap of the two sets of data is not larger. It was planned to take cloud chamber data with a gas of higher stopping power (methane) but gamma ray background from the electrostatic generator was too high to make this possible until better shielding is arranged and the chamber redesigned to have a shorter sensitive time.

The average energy is about 2.6 Mev.



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Discussion

The simplest and most attractive hypothesis concerning the mechanism of neutron emission is based upon Bohr and Wheeler's description of the fission process.[4] Neutron emission is assumed to occur by evaporation from the moving fragments after they have separated appreciable. The energy distribution $I(E')$ of the evaporated neutrons in the moving-fragment system should be Maxwellian[5] i.e.

$$I(E')dE' = \text{const.}\ E'\ e^{-E'/kT}\ dE' \tag{1}$$

or in terms of velocities of emission

$$f(u)du = I(mu^2/2)\ u\ du = \text{const.}\ u^3\ e^{-mu^2/2kT}\ du \tag{2}$$

The above distribution, however, will not be the observed distribution in the laboratory system because the velocities of the fragements are comparable to e velocities of the emitted neutrons.

Let $v$ = velocity of the fragment
$u$ = velocity of the emitted neutron in the fragment system
$V$ = velocity of the neutron in the laboratory system

then

$$V^2 = v^2 + u^2 + 2uv\cos\Theta \tag{3}$$

and hence for a given $u$, ($v$ is of course constant)

$$d(V^2) = 2\,dE/m = 2uv\,d(\cos\Theta) = -2uv\sin\Theta\,d\Theta \tag{4}$$

4) N. Bohr and J. Wheeler, Phys. Rev. 56, 426 (1939)



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where E is the energy of the neutron in the laboratory system.

Now f(u)du is the number of neutrons emitted with velocity between u and u + du in the fragment system. Hence for a given direction in the laboratory system the number of particles emitted with velocity between u and u + dd is

$$f(u)\, du \sin\theta\, d\theta \tag{5}$$

but by (4) this is

$$f(u)\, du\, (dE/4muv) \tag{6}$$

Now a given energy in the laboratory system between E and E- dE may result from various velocities and angles of emission in the fragment system hence

$$dN = \text{const.} \int_{u_{min}}^{U_{max}} f(u) du/u \quad dE \tag{7}$$

where

$$u_{min} = V - v$$

$$u_{max} = V + v$$

Dividing through by x dE and transforming the integral by means of (1) and (2) we have

$$dN/dE = \text{const.} \int_{E_1'}^{E_2'} \sqrt{E'}\; e^{E'/kT}\; dE' \tag{8}$$



6) V. F. Weisskopf, LA-24 (36) p. 15. The coefficient of the exponential involves e to the first power instead of $e^{1/2}$ as for the distribution of molecular energies in a gas this is because one is interested in the number of particles striking unit area per second, and hence the fast particles are weighted by their velocity.

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where

$$E'_1 = (\sqrt{E'/E_o} - 1)^2$$

$$E'_2 = (\sqrt{E'/E_o} + 1)^2$$

$$E_o = 1/2 \, mv^2$$

The integral must be evaluated numerically for given values of kT and $E_o$. $E_o$ is known from the experiments on the kinetic energies of fission fragments and is different for the two fragments. If the total kinetic energy of both fragments is 160 Mev and the fragment energies are in the ratio 3/2, then the energy of the neutron resulting from the motion of the light fragment is 1.0 Mev and is 0.5 Mev if resulting from motion of the heavy fragment. Further since $\nu \simeq 3$ for 49 fission, one fragment probably emits two of the neutrons. This is most likely to be the light fragment for the following reasons: (1) If we assume homogeneous mixing of neutrons and protons, then the light fragment will have the greater neutron excess relative to the stable nuclei and hence a lower neutron binding energy. (2) The lighter fragment will have a lower density of energy levels and hence for a given excitation energy will have a higher nuclear temperature.

It is difficult to calculate theoretically what the nuclear temperature of the fragments should be. However, an estimate can be made from our knowledge of level densities and from the maximum neutron energies observed in the spectrum. The method is described in reference (5). The result in Mev units of nuclear-temperature energy kT for the fission fragments is as follows:

| Wright of Fragment | Nuclear-temperature energy kT for Maximum Neutron energy of | |
|---|---|---|
| | 5 Mev | 10 Mev |
| 96 | .90 | 1.26 |
| 144 | .77 | 1.08 |



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If the light fragment does emit two neutrons and the binding energy of the first is of the order of 5 Mev then reasonable choices for the nuclear-temperature energy kT of the light fragment would appear to be kT 1.2 Mev for the first neutron emitted and perhaps 0.9 Mev for the second neutron. The heavy fragment somewhat arbitrarily may be assumed to have a kT of about 1.0 Mev.

With these assumptions the above intergral has been evaluated numerically. The result is represented by the solid line of Fig. 4. At high energies the fit if roughly satisfactory. The low-energy end shows considerable deviation from that which would be expected from a Maxwellian distribution in the fragment system. Furthermore, this deviation from a Maxwellian distribution on the low-energy end does not result simply from a poor choice of kT since it may be shown that the distribution should go to zero with decreasing E as $E^{1/2}$ independent of the particular values assigned to kT and or $E_o$. The present low-energy data do not appear to approach zero as $E^{1/2}$. This disagreement of the low-energy data with the evaporation hypothesis is quite similar to the results which Staub and Nicodemus found from ionization-chamber measurements of the low-energy portion of the fission-neutron spectrum.[6]

If the present low-energy data are to be believed, it may indicate that not all of the prompt neutrons are emitted by evaporation from the moving fragments. Bohr and Wheeler[4] consider it not unreasonable that some neutrons may be emitted at the moment of fission in a manner analogous to the creation of tiny droplets in the space where the original enveloping surface of a liquid drop was torn apart. The dynamics of such a fission process are very complicated and hence it is difficult to predict theoretically what energy and angular dis-

6) Private communication of some unpublished results

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tribution the neutrons emitted by this process might possess. If future experiments on the correlation of neutron and fragment directions be inconsistent with the hypothesis that the neutron emission in the fragment system is isotropic, this might be further evidence against assuming that all of the neutrons are evaporated from the moving spherical fragments.

One might perhaps modify the evaporation model by postulating that the evaporation occurs before the moving fragments have assumed a spherical form. By properly choosing the shape of the fragment at the time of neutron emission, one might obtain a non-isotropic distribution in the fragment system which would give the observed laboratory neutron spectrum.

Before adopting such complicated models of neutron emission it would be desirable to have considerable better experimental data on the fission neutron spectrum, particularly in the very-low-energy region (E 300 Kev).

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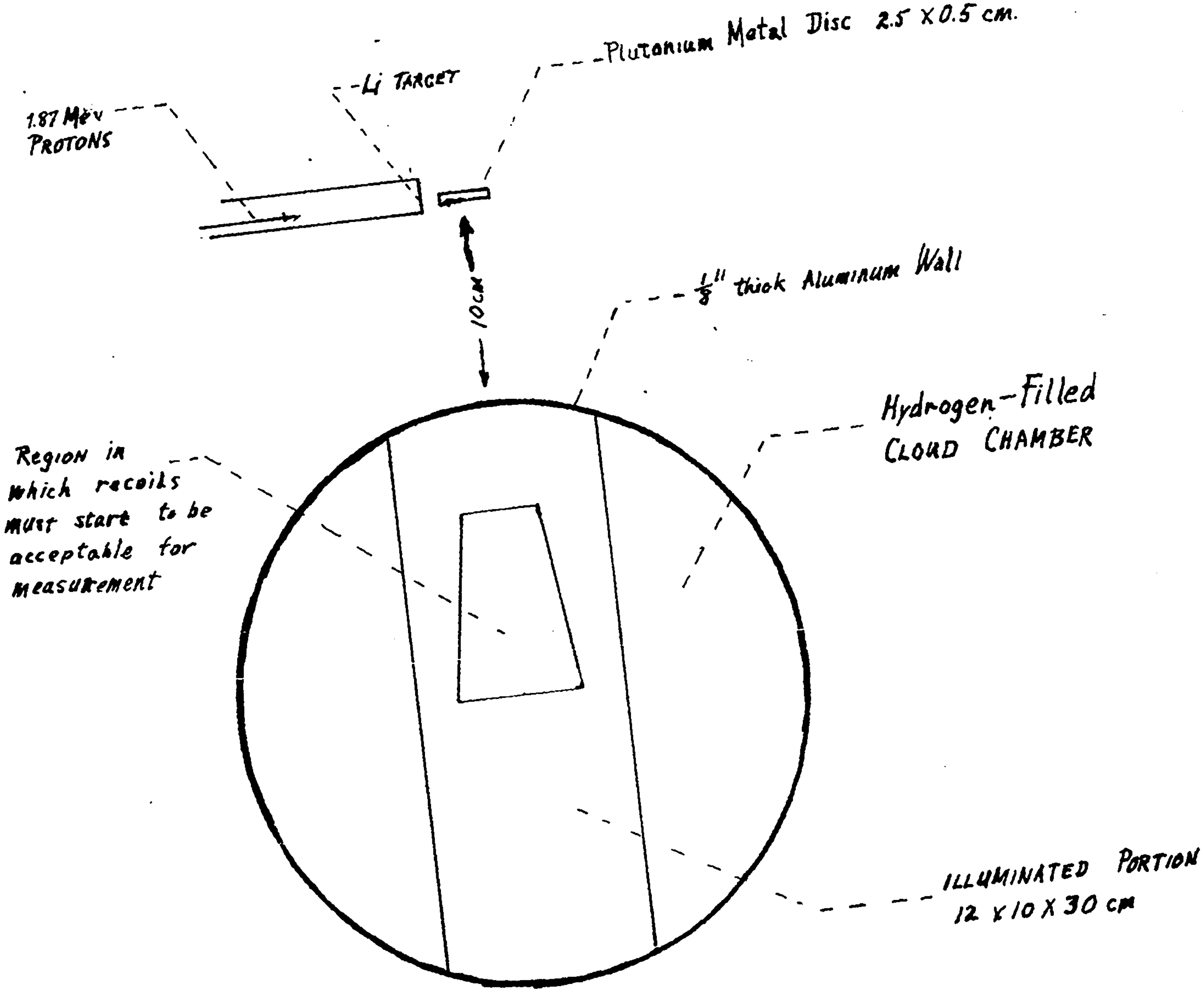



FIG 1

EXPERIMENTAL ARRANGEMENT FOR CLOUD-CHAMBER DATA

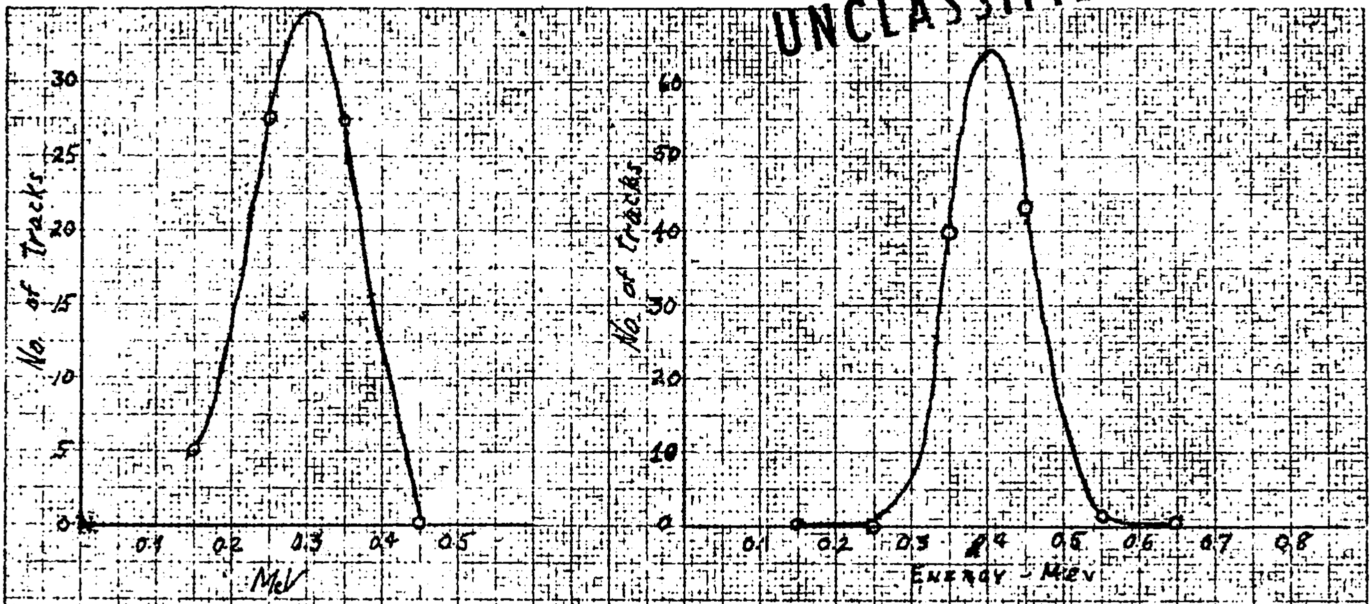
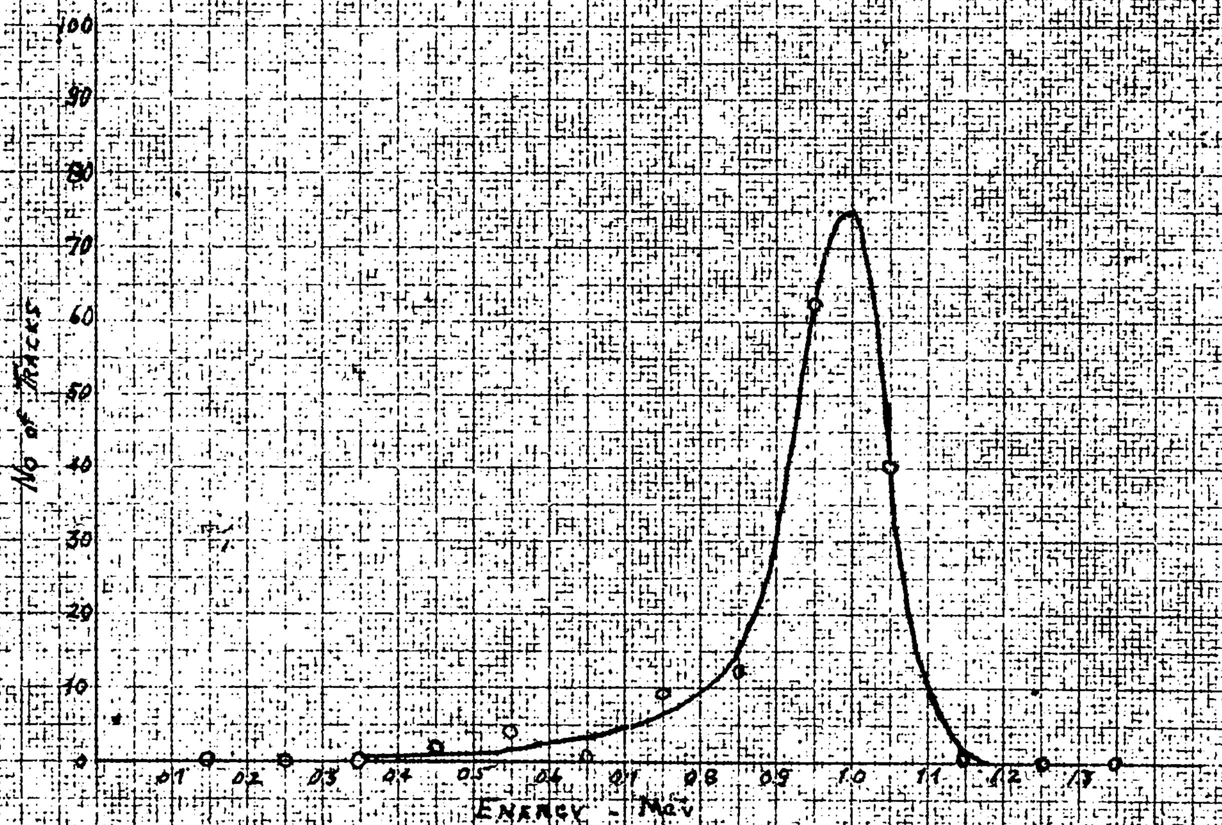



Fig 2

CLOUD - CHAMBER CALIBRATION DATA

$Li^7(p,n)Be^7$ neutrons

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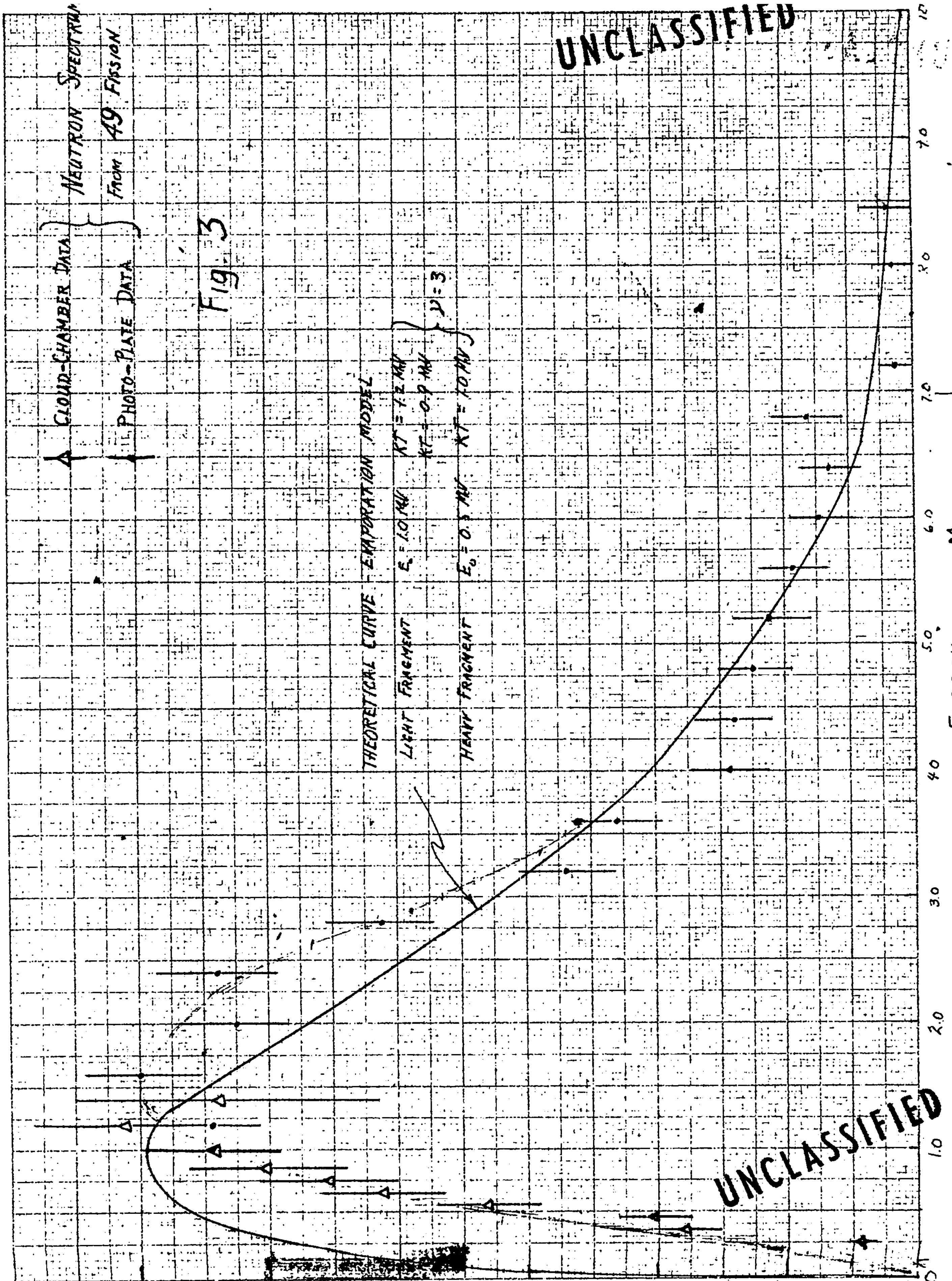
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CLOUD-CHAMBER DATA
PHOTO-PLATE DATA
NEUTRON SPECTRUM FROM 49 FISSION
Fig. 3
THEORETICAL CURVE - EVAPORATION MODEL
LIGHT FRAGMENT $E_0$ = 1.0 Mev KT = 1.2 Mev
HEAVY FRAGMENT $E_0$ = 0.5 Mev KT = 1.0 Mev
ν = 3
ENERGY - Mev
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