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Physics - Fission

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A STUDY OF THE SPECTRUM OF THE NEUTRONS OF LOW ENERGY FROM THE FISSION OF U^{235}

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ABSTRACT

A cloud chamber has been used to determine, in the energy range 0.05 to 0.7 Mev, the distribution of prompt neutrons produced by the fissions of U^{235} in a thermal neutron beam. The ratio of proton recoils in the energy range 0.05 to 0.6 Mev to the recoils in the energy range 0.6 Mev to infinity was also determined. The data are compared with two formulas, and are found to fit one which also fits the data obtained by D. Hill and B. Watt.

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A Study of the Spectrum of the Neutrons of Low Energy from the Fission of U^{235}

The neutron spectra of the fission of U^{235} and Pu^{239} have been extensively studied by various techniques[1]. The photographic plate technique and the ionization chamber method were the first to be widely used to study the spectra. Both of these methods have limitations with regard to minimum energy of neutrons which may be detected. For example, the photographic plate method is limited to recoil-proton energies which give of the order of ten or more developable grains. With the emulsions available at the time the experiments were carried out (1942-1945), this restriction limited the detectable energy to above 1 Mev; actually it seems likely that reliable detection could not be made below 1.5 Mev. This may be partly due to the fact that very low energy protons in a photographic emulsion do not travel in straight lines but suffer considerable scattering by the heavy atoms which are present.

In 1945, Richards[2] carried out experiments from which he hoped to obtain information on the neutrons below 1.5 Mev. He used a cloud-chamber filled with hydrogen gas and alcohol vapor, and obtained data down to 250 kev. These rather preliminary experiments were interrupted by the end of the war. However, his data indicated a very strange neutron distribution -- very few neutrons at 250 kev , in fact only about 1/10 as many as at 1 Mev. This result is quite contrary to an evaporation model where at very

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low energies the number of neutrons should increase as $E_n(\frac{1}{2})$.

In view of these puzzling results, it was considered desirable to look at the energy distribution of neutrons from about 50 kev to 600 kev , using cloud-chamber techniques. In order to get longer proton tracks for a given energy in the cloud-chamber, hydrogen gas was used at a pressure of 1/3 of an atmoshere; and water vapor was used in place of alcohol, reducing the stopping power of the vapor by a factor of about three. With this mixture, a stopping power of 0.10 was obtained and a recoil proton with an energy of 50 kev , has a track length of 7 mm. Under the experimental conditions, tracks of this length were believed to be the shortest tracks that could be reliably measured, both with regard to length and direction, although shorter tracks were easily observable on the photographs.

The experimental set-up is shown in Fig. 1. The source of neutrons was the thermal column of the Water Boiler. The neutrons were collimated by cadmium so that a beam of thermal neutrons with a 4" by 4" cross section was obtained at the front of the thermal column. Since the neutrons had a cadmium ratio of 400 under the conditions of the experiment, there were only 0.25 percent with energies over a few volts. This beam of thermal neutrons had a flux of 5×10^5 neutrons per cm^2 per sec at a distance of 6 ft from the face of the pile, where the U^{235} foil was placed. The foil was 3 cm by 10 cm by .010 inches thick, making the source strength of fission neutrons approximately equal to $5 \times 10^5 \times 30 \times 2.5 = 3.7 \times 10^7$ neutrons per sec. The cloud-chamber was placed well outside the

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beam of neutrons, at a distance of 35 cm from the U^{235} sample. The cloud-chamber, about 12" in diameter and about 9" deep, was especially designed to have as small an amount of scattering material in it as possible. To this end, the cloud-chamber was placed 49½ inches above the floor and the chamber walls were made of 3/16 inch pyrex glass. The walls and roof of the room were negligible scatterers because of their large distance from the chamber. A fast-acting, mechanical cadmium shutter was placed at the opening of the thermal column to allow synchronization of the flux of neutrons on the U^{235} sample with the expansion of the cloud-chamber. Excessive general fogging of the cloud-chamber was caused by the large number of hard gamma rays coming from the cadmium plates of the shutter. A thick collimator of lead was effective in reducing the intensity of gamma-radiation in the chamber to a level sufficiently low that it did not cause troublesome fogging in the cloud-chamber. A somewhat better method of eliminating gamma-radiation would be to use a shutter made of enriched boron of mass 10, which gives off fewer gamma rays than cadmium. Even more important, these gamma-rays only have a quantum energy of 470 kev , and can easily be absorbed by a small amount of lead. A shutter of this type was not used because of the prohibitive fabrication time.

Under the experimental conditions outlined above, from 5 to 15 recoil-protons were obtained each time the cloud-chamber expanded. As a check to make sure that fast neutrons from the

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pile were not causing recoil-protons in the cloud-chamber, expansions of the cloud-chamber were observed without opening the cadmium shutter. Under these conditions less than 1 percent as many tracks were observed.

Results

2800 pairs of stereoscopic pictures were taken with the apparatus and approximately 25,000 recoil protons were observed. In order to obtain the energy distribution of the neutrons, only recoil protons which made angles of less than 15° with the direction of the incident neutron were measured, ensuring that essentially all the energy of the neutron was transferred to the proton. In order to minimize the geometrical correction for the probability of observing tracks of different lengths, only tracks were measured which began in region A of the cloud-chamber as indicated in Fig. 1. Thus tracks with lengths up to 13 cm have almost as great a probability of ending in the illuminated section of the cloud-chamber as tracks of much shorter length. The tracks which were measured fell into two categories - those that ended in the gas, and those that continued into the wall of the chamber. A total of 437 tracks were measured which began in region A and made angles less than 15° with the direction of the primary neutrons. Of these tracks, 237 ended in the gas and 200 continued into the walls of the chamber.

The data on these recoil-protons is given in Table 1, in the form of the relative number of recoil-protons in a given

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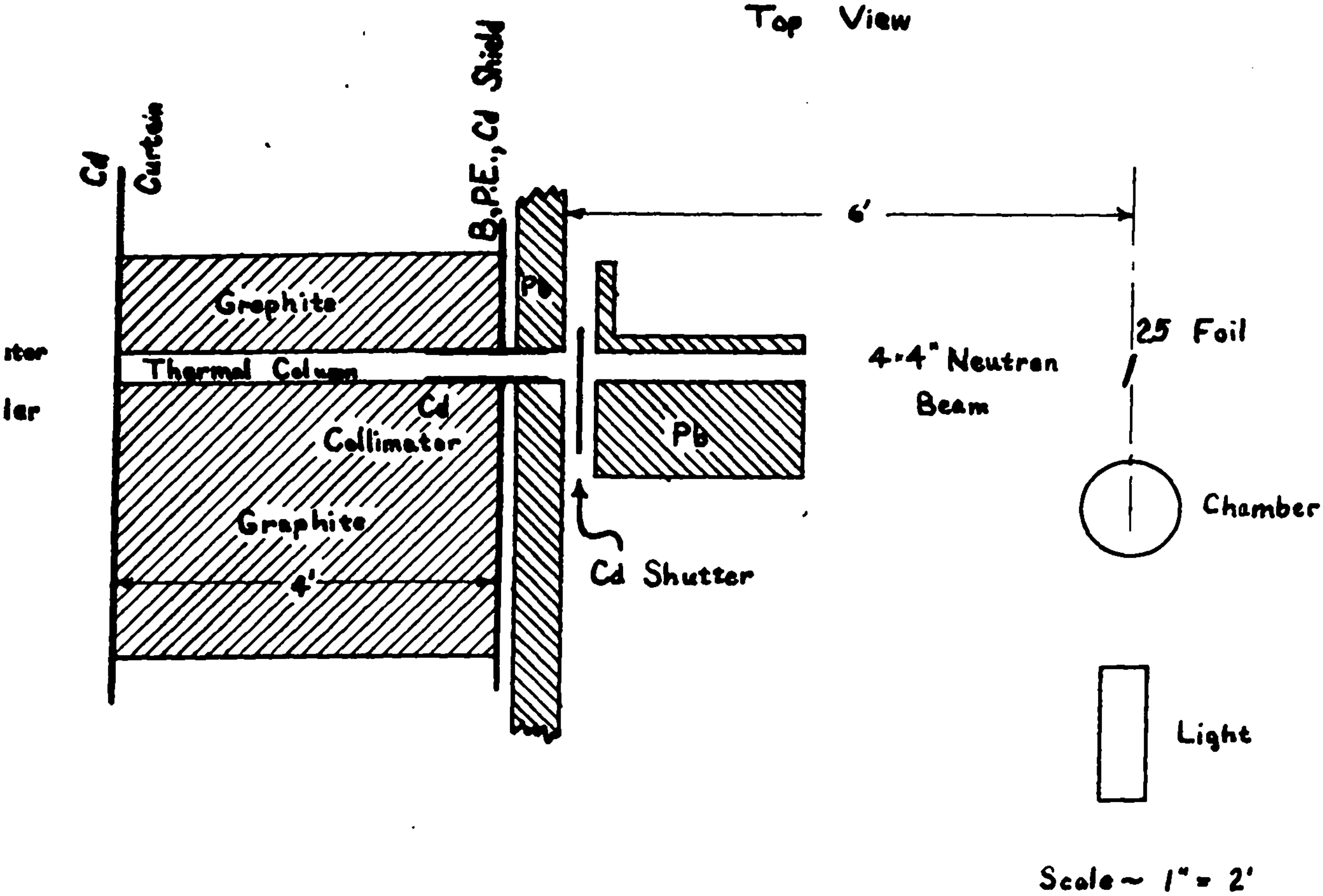
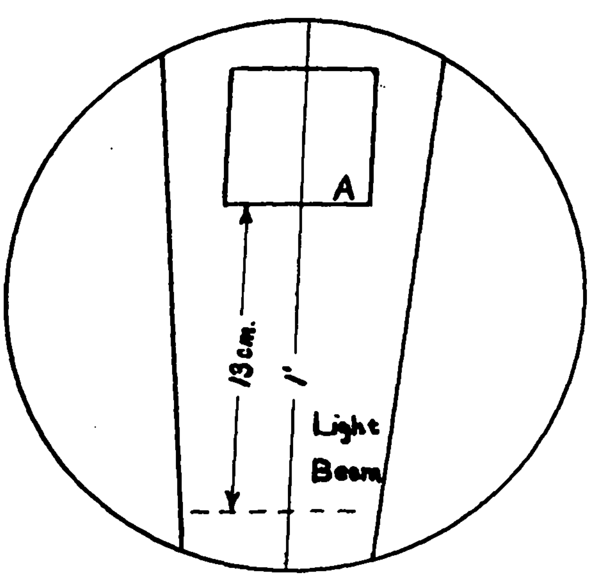
Fig. 1. Cloud Chamber Position

Top View





Enlarged Top View of Cloud Chamber

Recoil Proton Tracks Must

1. originate within region A
2. end in the light beam
3. point within 15° of dir. of foil

To Be Counted.

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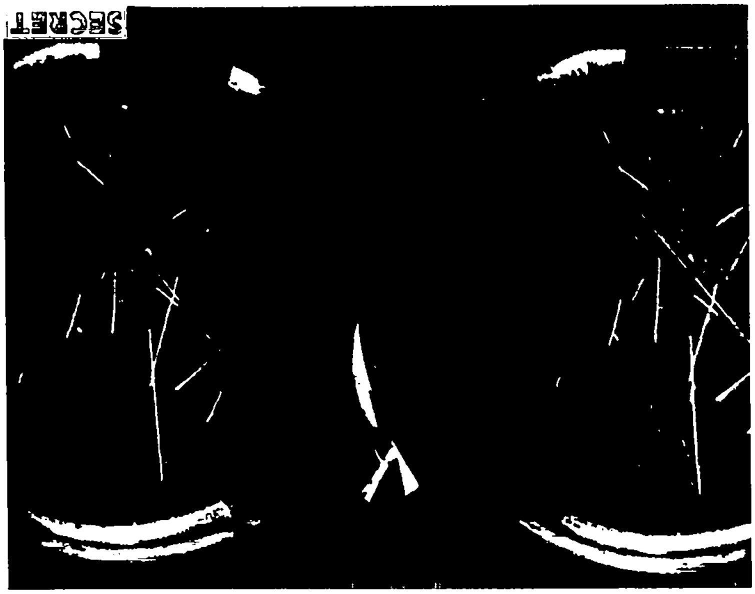

Stereoscopic photograph of recoil-protons. The neutron source is beyond the top of the photograph. Recoil-protons of energies 170, 280, and 500 kev point in the direction of the source.

Stereoscopic photograph of recoil-protons. The neutron source is beyond the top of the photograph. A long proton track with an energy of 750 kev points at the neutron source. This proton has been scattered through an angle of about 20 degrees near the middle of the track.

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energy interval. To convert from the number of recoil-protons to the number of primary neutrons one must take into account the varying cross section for neutron-proton scattering, which is indicated by σ in Table 1. As a final correction one must multiply by the geometrical correction factor for the probability of measuring tracks of different lengths. This factor varied from 1.04 for tracks with a length of 1.1 cm to 1.56 for tracks with a length 12.2 cm. The relative number of neutrons with different energies N is obtained from these calculations.

Table 1.

Energy Interval in kev.	Track Length in cm.	No. of Tracks	σ in barns	Track-length Correction	Relative no.(N) of neutrons per 100 kev. interval
50-99	0.7 - 1.4	24	14.5	1.04	34.2 ± 5.0
100-199	1.5 - 2.8	43	11.6	1.09	40.3 ± 4.1
200-299	2.9 - 4.5	41	9.3	1.15	50.6 ± 5.3
300-399	4.6 - 6.4	34	7.6	1.23	55.3 ± 6.5
400-499	6.5 - 8.5	29	6.6	1.33	58.6 ± 7.2
500-699	8.6 - 13.5	51	5.6	1.50	68.0 ± 6.5

The relative numberof neutrons N is plotted in Fig. 2 as a function of the energy of the neutrons. The experimental curve indicates that at 100 kev , there are approximately one-half as many neutrons as at 600 kev. The solid curve shown in Fig. 2 is given by the relation: $N = \sinh\left(\frac{E_n}{0.487}\right)^{\frac{1}{2}} e^{-\left(\frac{E_n}{0.974}+\frac{1}{2}\right)}$ which is a semi-empirical relation obtained by Watt to describe the energy distribution from 0.6 Mev to 15 Mev. This relation

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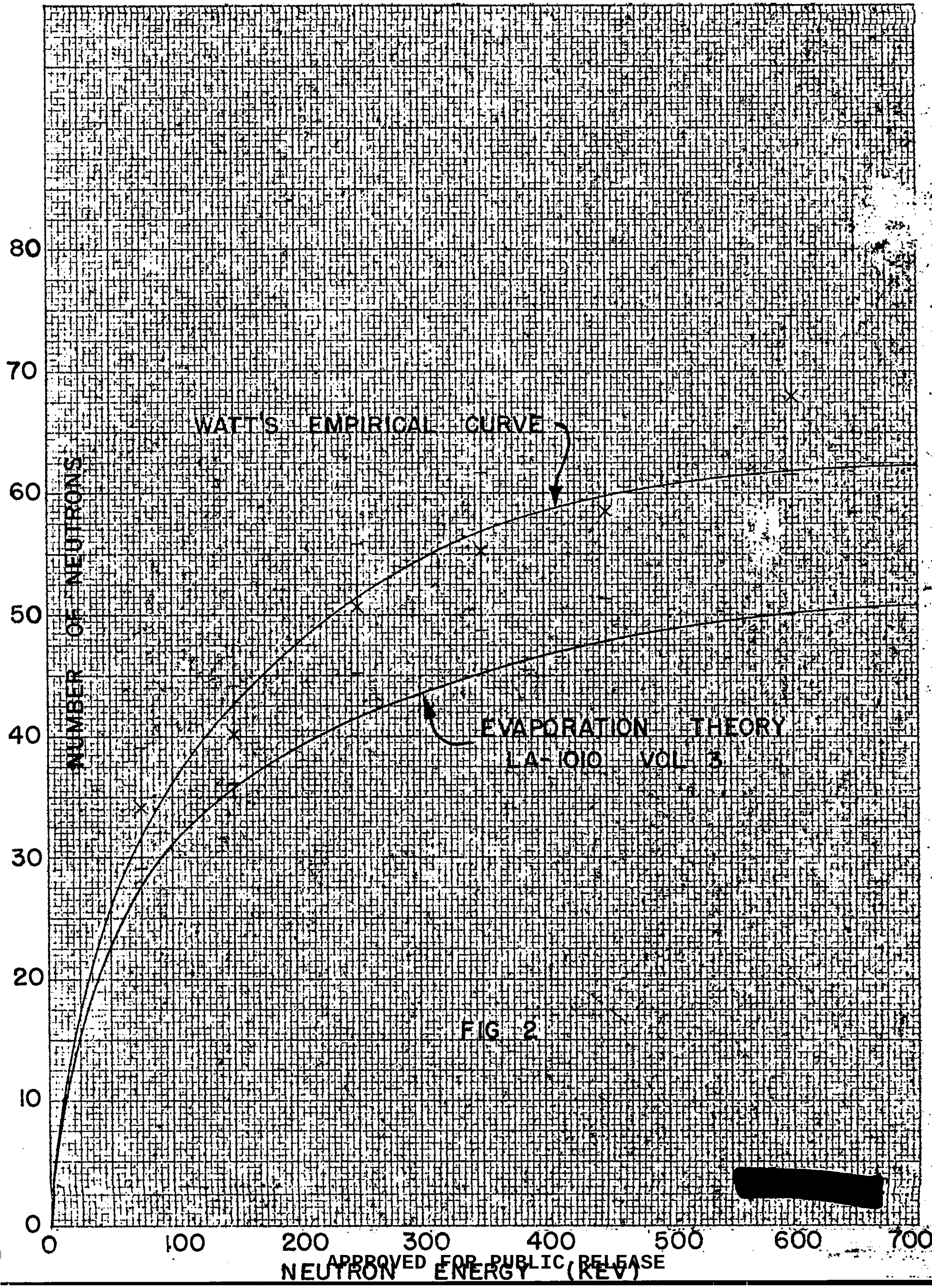
NUMBER OF NEUTRONS
NEUTRON ENERGY (KEV)
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
WATT'S EMPIRICAL CURVE
EVAPORATION THEORY
LA-1010 VOL. 3
[redacted]

FIG 2

[redacted]

fits our experimental data quite well over the 75 kev to 600 kev range. The shape of the neutron distribution curve predicted by the evaporation theory (LA 1010 vol. 3) also fits our data quite well, so we need to find another criteron to choose between the formulas.

Our experimental data gives more information than the shape of the curve from 0.05 to 0.6 Mev. Data on the relative number of recoil-protons with energy greater than 0.6 Mev, were also obtained, allowing a comparison of our data with any theoretical neutron distribution as regards the relative number of recoil-protons above and below 0.6 Mev. From our experimental data, we found the value of the ratio of the number of recoil-protons in the range 50 - 600 kev to that in the range 600 - ∞ to be 0.54 ± 0.05, compared to a value of 0.52 from Watt's formula and 0.42 from the evaporation model. The calculated values were obtained by numerical integration of the curves and from the known variation of the cross-section of neutron-proton scattering. This ratio fixes the scale factor used in comparing our results below 0.6 Mev with the two formulas, and in plotting both theoretical relations (Fig. 2). The agreement with Watt's formula is quite good and indicates that this relation fits the entire neutron spectrum from 75 kev up to 15 Mev.

(1) See LA-1010 Vol. 3 for a summary of the results.
(2) H. T. Richards, LA-556, (1946).

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