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Technical Note 1

A DOUBLE-PULSE TOTAL-ABSORPTION FAST NEUTRON SPECTROMETER

U. S. DEPARTMENT OF COMMERCE
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NATIONAL BUREAU OF STANDARDS
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1

APRIL 24, 1959

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ABSTRACT

A fast neutron spectrometer utilizing the double-pulse total-absorption technique has been developed for use in the energy range 1 - 20 Mev. The total absorption spectrometer uses a hydrogenous scintillator, in which a fast neutron may lose all its energy, together with a detector for slow neutrons. Scintillation detection of the disintegration caused by absorption of a slow neutron in an element of high reaction cross section serves to identify those neutrons which lost essentially all their energy in the hydrogenous scintillator.

Various organic liquid scintillators loaded with natural methyl borate, and a plastic scintillator with a boron-10 or lithium-6 slow neutron scintillation detector nearby were all tested with mono-energetic neutrons obtained from the D(d,n) He^3 and T(d,n) He^4 reactions. The best experimental results were obtained with a plastic scintillator and a $Li^6I(Eu)$ crystal. Representative data for this spectrometer are given below. For comparison purposes, the results of Monte Carlo calculations, made by Leiss[1/] for a phenylcyclohexane liquid scintillator loaded with methyl borate (B^{10} enriched), are also included.

[1/] J. E. Leiss, Summary Technical Report for the Atomic Energy Commission NBS Project No. 3152, 1955.

1. INTRODUCTION

This report describes an attempt to develop a double-pulse total-absorption fast neutron spectrometer with moderately good energy resolution (30% at 2 Mev to 10% at 15 Mev) and moderately good detection efficiency (10^{-3} at 2 Mev to 10^{-4} at 15 Mev). This spectrometer was designed to measure the energy distribution of neutrons in the energy range 1 - 20 Mev.

There has been a need for such an instrument in the field of neutron physics for some time. Swartz[2/] has given a review of the fast neutron spectrometers that have been used by various investigators. Swartz found that the spectrometers commonly in use have either moderately good energy resolution or moderately good detection efficiency, but not both.

Recently, however, Murray[3/] has developed a fast neutron spectrometer with moderately good energy resolution and moderately good detection efficiency. His spectrometer, developed at about the same time as the spectrometer reported here, has the additional advantage that it is non-directional, that is, it is not necessary to know the direction from which the neutrons are coming. Murray's device employs a Li^6I (Eu) crystal, and depends on the $Li^6(n,\alpha)T$ reaction. Since this reaction has a Q of 4.78 Mev, the disintegration products share the energy of the incoming neutron plus 4.78 Mev. The pulse height is therefore a measure of the neutron energy. Murray's instrument is probably the most successful fast neutron scintillation spectrometer developed to date using pulse-height analysis.

Beghian, et al[4/] have used a scheme similar to the one reported here. Their spectrometer accepted only neutrons which were scattered near 90° and had undergone a single collision. A time-of-flight technique was utilized to identify these neutrons.

McCord[5/] also has attempted to develop a double-pulse total-absorption fast neutron spectrometer. His instrument, which utilizes a small plastic scintillator for the neutron energy absorption and a BF_3 proportional counter surrounding the plastic scintillator for the identification process, does not give peaks of measurable resolution for monoenergetic neutrons.

[2/] C. D. Swartz, NYO-3863 (1954).

[3/] R. B. Murray, Nuclear Instruments 2, 237 (1958).

[4/] Beghian, Allen, Calvert, Halban, Phys. Rev. 86, 1044 (1952).

[5/] J. W. McCord, UCRL-3411, (1956).

2. THE TOTAL ABSORPTION METHOD

A fast neutron incident on a hydrogenous medium usually loses most of its energy in elastic collisions with hydrogen nuclei, although other elastic and inelastic collisions may occur. In a hydrogenous scintillator the amplitude of the resultant light pulse will, under appropriate conditions, be a measure of the neutron energy absorbed.

When a large enough scintillator is used, practically all the neutrons incident on it will have their energy completely absorbed. If only elastic collisions are considered, the scintillation response of the detector is due to the recoil nuclei. However, the response of scintillation detectors to the recoil nuclei is not a linear function of energy, but depends on both the energy and mass of the nucleus, (Birks[6/]). Therefore, even though a neutron may lose all its energy in the scintillator, the amplitude of the light pulse will not be a measure of the energy lost.

In order to obtain a scintillation response which is related to the energy lost, Cleland[7/] proposed a spectrometer of such small dimensions that only those neutrons which lose a large fraction of their energy in the first collision will have a large probability of having their energy totally absorbed. In this case, only a few of the incident neutrons will lose all their energy, and most of these will be neutrons which lose a large fraction of their energy in the first collision. The rest of the neutrons, after a few collisions, will leave the spectrometer. Therefore, the scintillation response will approach a known functional relation to the energy lost. The relation between scintillation response and energy for protons is given by Birks[6/].

Since any neutron which loses energy in the scintillator will make a pulse, there must be some method to identify the pulses associated with neutrons which have lost all their energy. The absorption of slowed down neutrons in B^{10} or Li^{6}, and the detection of the subsequent disintegration products or the detection of a gamma ray associated with the disintegration process was the method used to identify neutrons which lost essentially all their energy. The elements B^{10} and Li^{6} have high absorption cross sections for low energy neutrons, negligibly small absorption cross sections for high energy neutrons, and disintegrate following the absorption event.

[6/] J. B. Birks, Phys. Rev. 84, 364 (1951); 86, 569 (1952).

[7/] M. R. Cleland, NBS Report 2036.

A delayed coincidence technique is employed to identify events in which the proton recoil pulse is followed by the identification pulse. When a proton recoil pulse, delayed by the proper amount of time, coincides with an identification pulse, the height of the proton recoil pulse is analyzed and is a measure of the neutron energy.

3. THE SPECTROMETER

Several liquid scintillator cells were prepared, all of which contained 50 percent natural methyl borate, $B(OCH_3)_3$; (18.8 percent of the boron is B^{10}). The scintillator cells were prepared with 50 percent phenylcyclohexane ($C_{12}H_{16}$), 50 percent xylene (C_8H_{10}), or 50 percent toluene (C_7H_8) as the organic liquid. The primary organic solute which gives the highest maximum relative pulse height, 2 - phenyl-5(4 - biphenylyl) - 1,3,4 - oxadiazole (PBD)[8], and the most efficient secondary solute, 1,4 - di 2 - (5 - phenyloxazolyl) benzene (POPOP)[9], were used as the scintillating materials. The concentration of these solutes in the particular liquids was the optimum as given by Hayes, et al[8,9].

These scintillators were loaded with a fairly high percentage of B^{10}, so that the reaction, $B^{10}(n,\alpha)Li^7$, could be used to identify those neutrons which lose most of their energy in the scintillator. At thermal neutron energies, this reaction proceeds in two ways: In 5.8 percent of the disintegrations, the Li^7 nucleus is left in the ground state and the alpha particle has an energy of 1.77 Mev; in the other 94.2 percent of the disintegrations, the Li^7 nucleus decays to the ground state by the emission of a 478 kilovolt gamma ray and the alpha particle has an energy of 1.46 Mev.

There are three methods by which the disintegration event can be distinguished. After the initial large pulse in the spectrometer caused by the slowing down of the neutron, the disintegration event may be observed as: (a) a small delayed pulse in the spectrometer due to the 1.46 or 1.77 Mev alpha particle, (b) a delayed pulse in the spectrometer due to the 478 kilovolt gamma ray, (c) a delayed pulse in a closely adjacent NaI(Tl) scintillator due to the 478 kilovolt gamma ray. The schematic diagrams of Figure 1 illustrate these three methods. The unloaded hydrogenous scintillator with nearby slow neutron detector is also illustrated. In all cases only one proton recoil is shown, although there may be several.

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[8] Hayes, Otto, Kerr, Rogers, Nucleonics 13, No. 12 (1955).

[9] Hayes, Otto, Kerr, Nucleonics 14, No. 1 (1956).

The above methods were tried with essentially the same electronic set-up shown in Figure 2. Cleland's calculations showed that for neutrons which lose essentially all their energy in the liquid scintillator loaded with 50 percent natural methyl borate, the disintegration event occurs at an average time of two microseconds after the initial large pulse. Therefore, a three microsecond gate was used. Monoenergetic neutrons were obtained from the $D(d,n)He^3$ and $T(d,n)\ He^4$ reactions. Severe electronic and background difficulties were encountered, however, and none of these methods was very successful in giving consistent results in the experimentally determined monoenergetic neutron spectra. It was found in methods (a) and (b) that the electronic apparatus used could not be made fast enough to observe the small disintegration pulse within three micro-seconds after the large initial pulse. The electronic difficulties encountered in methods (a) and (b) did not arise in method (c) but the large number of chance coincidences due to the high background in the NaI(Tl) crystal, which is highly sensitive to all kinds of radiation, obscured true coincidences that may have been present.

Instead of developing fast electronics, it was decided that the simpler approach would be to use an unloaded hydrogenous scintillator for the slowing down process and a nearby low energy neutron detector for the identification process (See Figure 1). This scheme removed the electronic difficulties of the previous approach, and also made it possible to use solid hydrogenous scintillators in place of inconvenient liquid scintillators. The background difficulty encountered previously could also be removed by the proper choice of slow neutron detector.

The solid hydrogenous scintillator used for the slowing down process was a plastic scintillator, Pilot Scintillator B. This plastic is 100 percent hydrocarbon and contains diphenylstilbene as the scintillating material.

Two different slow neutron detectors were used for the identification process: a boron polyester and a lithium iodide crystal.

The boron polyester, Slow Neutron Detector NE 401, was obtained from Nuclear Enterprises Limited. This detector, 1.2 mm thick by 2 inches in diameter, is a milky white, opaque solid which contains 55 percent B^{10} by weight and ZnS(Ag) for the scintillating material. The detection of slow neutrons by this scintillator depends on the $B^{10}(n,\alpha)Li^7$ reaction, which has already been described. By testing the boron polyester with a thermal neutron source, it was found that the pulse height distribution of the disintegration products had no peak, most of the pulses being at low pulse height.

When testing the boron polyester with Pilot Scintillator B, essentially the same electronic set-up as that shown in Figure 2 was used except that an integral discriminator took the place of the single channel analyzer, since the disintegration pulse events could not be resolved. A gate of three microseconds was used. The separation of the scintillators was one centimeter.

The results showed a distinct peak in the experimental energy spectrum of monoenergetic neutrons (2.5 Mev) obtained from the $D(d,n)He^3$ reaction. However, the background in the boron polyester was very high, and therefore many of the coincidences were chance coincidences, which had to be subtracted out of the spectrum. The boron polyester contains a high percentage of hydrogen, so that the high background could have been due to proton recoil pulses. For higher energy neutrons (14.1 Mev) obtained from the $T(d,n)He^4$ reaction, the background difficulty became more severe, and a peak in the experimental energy distribution was not observed.

The second slow neutron detector, a three mm thick by 1.5 inch diameter $Li^6I(Eu)$ crystal, was obtained from the Harshaw Chemical Company. Since the detection of slow neutrons by this crystal depends on the $Li^6(n,\alpha)T$ reaction, the crystal obtained was one in which the lithium was enriched to 96 percent lithium - 6. This reaction has a Q of 4.78 Mev. At thermal neutron energies the disintegration products share this much energy. But, like B^{10}, Li^6 has a high absorption cross section for low energy neutrons and a low absorption cross section for high energy neutrons. $Li^6I(Eu)$, a transparent crystal, was also tested with a thermal neutron source. With this crystal, the pulse height distribution of the disintegration products had a fairly well resolved peak, (14 percent full width at half maximum).

The experimental arrangement of detectors and the electronic set-up for a double-pulse total-absorption spectrometer utilizing Pilot Scintillator B and a $Li^6I(Eu)$ crystal are shown in Figure 2. The details of the electronic equipment and typical experimental data are given in the following two sections.

4. APPARATUS

Shown in Figure 2 is the block diagram of the apparatus used for the spectrometer. Two Pilot B plastic scintillators were employed in various tests (see Figure 2). One of these plastic scintillators, 1 inch thick by 4 inches in diameter, was optically coupled to a five inch diameter, Dumont Type 6364, photomultiplier tube. The second plastic scintillator, 1 inch thick by 1-3/4 inches in diameter, was optically coupled to a two inch diameter, Dumont Type 6292, photomultiplier tube. The $Li^6I(Eu)$ crystal, 3 mm thick by 1.5 inches in diameter, was optically coupled to a two inch diameter, Dumont Type 6292, photomultiplier tube. The coupling fluid was Dow Corning Silicone Grease. Each photomultiplier tube was followed by a cathode follower, and a Chase-Higinbotham type non-overloading linear amplifier with an integral pulse height selector (PHS). RG 65/U delay cable of the proper length (23.45 feet per microsecond delay) was used to obtain the indicated delays. The linear gates were coincidence circuits, which gave an output pulse proportional to the input pulse when a coincidence between input and trigger pulses occurred. If either an input or a trigger pulse went into the linear gate without making a coincidence, there was no output pulse. The single channel analyzer, a Hamner Differential Discriminator, was followed by a decade scaler, which counted the pulses that went through the differential discriminator window. Pulse height analysis of the proton recoil spectrum was done with a University of Denver Model 103 10-channel pulse height analyzer.

Pieces of apparatus with critical settings were set as follows:

The $Li^6I(Eu)$ crystal, mounted on a two inch diameter photomultiplier tube, was calibrated by placing it close to a thermal neutron source. Pulse height analysis gave a resolution of 14 percent full width at half maximum for the disintegration spectrum. The window of the differential discriminator was then set so that all pulses in the entire "thermal" peak, and disintegration pulses caused by neutrons with energies up to about 5 kev would pass through the window. When taking a "fast" neutron spectrum, the $Li^6I(Eu)$ crystal was placed with respect to the plastic scintillator as shown in Figure 2. Between the face of the crystal and the edge of the plastic there was a separation of one-quarter inch.

PHS No. 1 and PHS No. 2 were used to indicate that pulses coming from the two amplifiers were in the proper time sequence. Since the integral discriminators operate on the pulse rise time, PHS No. 1 and PHS No. 2 were set at zero volts discrimination level. This choice of discrimination level was made so that the time delay of pulses going to Linear Gate No. 1 was not variable. However, constant time delays were introduced by the various pieces of apparatus, and in order to obtain the proper time sequence between proton recoil pulses and disintegration pulses, the delay of 0.4 microsecond connecting PHS No. 1 and the trigger

of Linear Gate No. 1 had to be inserted. The overall time delay was such that, if a pulse occurred in the plastic scintillator, and at 0.1 microsecond later a second pulse occurred in the $Li^6I(Eu)$ crystal, the two pulses arrived at Linear Gate No. 1 at the same time.

The resolving time τ of the electronics was determined by the gate length of Linear Gate No. 1. By feeding pulses to the amplifiers which were completely unrelated, this gate length was determined experimentally.

5. DATA

The data presented here were obtained by allowing monoenergetic neutrons to fall on the spectrometer. The sources of monoenergetic neutrons were the $D(d,n)He^3$ and $T(d,n)He^4$ reactions. For these data, the scintillators were set with respect to the incident neutrons as shown in Figure 2. The neutrons incident on the spectrometer were those that leave the target at an angle of 90° with respect to the deuteron beam. In each case the bombarding deuterons were accelerated through a potential difference of 300 kev by a 2 Mev High Voltage Engineering Corporation Van de Graaff accelerator. At this deuteron energy, the neutrons that leave the target at an angle of 90° with respect to the deuteron beam have an energy of 2.5 Mev for the $D(d,n)He^3$ reaction and 14.1 Mev for the $T(d,n)He^4$ reaction.

Chance coincidences, calculated from the relation

$$C_P C_D \tau = C_C,$$

have been subtracted from the spectra. C_P(proton recoil count rate) is the count rate in the 10-channel analyzer with the analyzer gate out of the circuit, C_D(disintegration event count rate) is the count rate of pulses that get through the single channel analyzer window, τ is the resolving time of the electronics, and C_C is the calculated count rate of chance coincidences. With the analyzer gate in the circuit, the coincidence spectrum, C_{Co}, was obtained. The difference between C_{Co} and C_C gives the pulse height spectrum of true coincidences. The ratio of true coincidences to chance coincidences for 2.5 Mev neutrons was about 7 to 1, while for 14.1 Mev neutrons it was about 1 to 1.

The experimental results will be compared with calculations made by Leiss[1/]. It should be noted, however, that the calculations by Leiss were performed for a right circular cylinder, 2 cm thick by 8 cm in diameter composed of 50 percent phenylcyclohexane and 50 percent methyl borate, the boron being enriched to 94 percent B^{10}. In the experiment, Pilot Scintillator B was used in place of the liquid scintillator. Although these are two different spectrometers, they are comparable in many respects. For example, the plastic scintillator has approximately

the same hydrogen to carbon ratio and gives approximately the same pulse height for various radiations as the liquid scintillator. The dimensions of the large plastic scintillator, 1 inch thick by 4 inches in diameter, were slightly larger than those used in the calculations for the liquid scintillator. Important differences between the two spectrometers are: The Pilot B-Li^6I spectrometer is expected to have lower efficiency; the time delay between the initial large pulse and the detection of the slowed down neutron is much shorter in the B^{10} loaded liquid scintillator.

5.1 Resolution: Percent Full Width at Half Maximum

Typical experimental pulse height spectra obtained with the spectrometer are plotted as relative number versus channel in Figures 3, 4, 5 and 6. With each figure the neutron producing reaction, the neutron energy, the resolution and the diameter of the Pilot B plastic scintillator, are given.

Figures 3 and 4 are experimental pulse height spectra obtained with 2.5 Mev neutrons. For the first curve, the 4" diameter Pilot Scincillator B was used, while for the second the 1-3/4" diameter Pilot Scintillator B was used. It is seen from these two figures that the curves have essentially the same shape and resolution. Figures 5 and 6 are experimental pulse height spectra obtained with 14.1 Mev neutrons. The 4" diameter Pilot Scintillator B was used for the first curve, while the 1-3/4" diameter Pilot Scintillator B was used for the second curve. Again it is seen from these two figures that the curves have essentially the same shape and resolution. One of the results of Leiss' calculations was that the resolution of the spectrometer would be relatively independent of the area on which the neutrons were incident. The experimental data indicate this same result.

The data of Figures 3, 4, 5 and 6 are plotted in Figure 7 as resolution, percent full width at half maximum versus neutron energy. The circles on the graph represent the experimental points. For the purpose of comparison, the variation of resolution with neutron energy, as calculated by Leiss, is shown by the solid line, it is seen that the energy resolution obtained experimentally is not as good as might be expected from calculations. Experiments done by allowing Po^{210} alpha particles (alpha particle energy 5.3 Mev) to fall on Pilot Scintillator B also indicated that the energy resolution should have been better.

In the alpha particle tests, the Po^{210}, plated on a silver planchet, was placed as close as possible to the face of the plastic scintillator. With identical conditions of photomultiplier tube high voltage and amplifier gain, pulses from the 5.3 Mev alpha particles had approximately the same height as the highest proton recoil pulses obtained with 2.5 Mev neutrons incident on the plastic scintillator. However, the energy resolution for the alpha particles was 16 percent full width at half maximum, while for 2.5 Mev neutrons the energy resolution was 50 percent full width at half maximum. Such a difference in resolution for pulses of approximately the same height is unexpected.

The data of Figure 4 are plotted again in Figure 8 as relative number versus relative pulse height. Also plotted is the pulse height distribution calculated by Leiss for the boron-10 loaded liquid scintillator and 2 Mev neutrons. The histograms have been normalized to the same area and an attempt has been made to put the peaks of the two distributions at the same relative pulse height. In the same manner, the data of Figure 6 and the pulse height distribution calculated by Leiss for the boron-10 loaded liquid scintillator and 10 Mev neutrons have been plotted in Figure 9 as relative number versus relative pulse height. It is seen from these two figures that the experimental and calculated pulse height distributions are not as dissimilar as Figure 7 indicates.

Possible sources of the excessive broadening of the experimental neutron pulse height spectra are as follows: (a) the targets used were thick targets, and therefore a spread in the energy of the neutrons leaving the target at a particular angle resulted. At an angle of 90° with respect to the deuteron beam, calculations done by Seagrave[10] show that the energy spread for neutrons from the $D(d,n)He^3$ reaction is 4 percent, and for neutrons from the $T(d,n)He^4$ reaction is 1 percent. However, Seagrave points out that his calculations did not take into account multiple scattering of deuterons in thick targets, which would considerably broaden the energy spectra. It would be a major undertaking to attempt to estimate the magnitude of this effect. (b) Since the target was necessarily in a vacuum system, the neutrons had to go through the walls of the vacuum system. It is expected that the additional spread in energy caused by this factor was small. (c) The plastic scintillator was fairly close to the target (77 cm), so that neutrons incident on it have left the target at an angle of 90° ± 3.5° with respect to the deuteron beam. The results of Seagrave show that the energy spread due to this cause is about 2 percent for neutrons from the $D(d,n)He^3$ reaction and about 0.5 percent for neutrons from the $T(d,n)He^4$ reaction.

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[10] Seagrave, LAMS-2162, 1958.

(d) The calculations of Leiss showed that the resolution of the spectrometer would become poorer with increasing scintillator thickness. The experimental pulse height distributions for a 2.5 cm thick scintillator have been compared with the calculated pulse height distributions for a 2 cm thick scintillator, and the extra thickness may be a source of excessive broadening of the experimental pulse height spectra. (e) All neutrons arriving at the plastic scintillator are not incident normal to its face. For neutrons not arriving at normal incidence, the effective thickness of the detector is increased. The spread in pulse height due to this cause is expected to be small. (f) Many of the neutrons which lost essentially all of their energy were not identified as totally absorbed neutrons. This came about because neutrons which are slowed down to fairly low energy (10 ev or below) will take a relatively long time (depending on where the neutron initially lost its energy in the plastic scintillator) to reach the $Li^6I(Eu)$ crystal. By the time many of these neutrons diffuse to the crystal, the gate they originally opened will have closed. With the electronic set-up that was used, the length of this gate (which is the resolving time of the electronics) could be made no longer than three microseconds. On the other hand, neutrons that have been slowed down to energies between 10 ev and 5 Kev have a much better chance of reaching the $Li^6I(Eu)$ crystal while the gate is open. The result is that many neutrons are slowed down to fairly low energy (10 ev or below), but only the neutrons which are slowed down to these energies in the part of the plastic scintillator that is relatively near to the $Li^6I(Eu)$ crystal are detected effectively. Since these neutrons are the best ones to count, not counting most of them may have the effect of broadening the observed pulse height spectra.

5.2 Efficiency

Efficiency is defined here as the number of true coincidence counts in the coincidence spectrum divided by the total number of neutrons incident on the Pilot Scintillator B during the time the coincidence spectrum was being taken. This latter quantity was obtained by measuring the total neutron flux during a run by means of a calibrated "long counter". With the total neutron flux known, the total number of neutrons incident on the plastic scintillator during the run could be calculated.

The efficiencies obtained with the spectrometer under various conditions are given in Table 1. If lines 1 and 2 of Table 1 are compared, it is seen that the efficiency obtained for the 1-3/4" diameter Pilot Scintillator B is about twice that of the 4" diameter Pilot Scintillator B. However, if the differences in resolving time and fraction of area of plastic scintillator covered by $Li^6I(Eu)$ crystal are taken into account, the 4" diameter Pilot Scintillator B is about three times more efficient

than the 1-3/4" diameter Pilot Scintillator B. The same holds true if lines 3 and 4 of Table 1 are compared. Another result of Leiss' calculations was that the efficiency of the spectrometer would increase with increasing area on which the neutrons were incident. The experimental data indicate this same result.

The efficiency of the spectrometer is plotted against neutron energy in Figure 10. The circles represent the data of lines 2 and 4 of Table 1. Shown by the solid line is the variation of efficiency with neutron energy as calculated by Leiss. It is seen from the figure that the detection efficiency obtained experimentally was not as good as the calculated efficiency. However, it has been mentioned already that many of the neutrons which lost essentially all of their energy were not identified as totally absorbed neutrons. A crude calculation was performed to estimate the number of these neutrons. The 4" diameter plastic scintillator, with the $Li^6I(Eu)$ crystal next to it, was considered to be broken down into several sections. In the calculation, the following were taken into consideration: the probability that a neutron would be slowed down in a certain section; the probability that a neutron, slowed down in a certain section, would reach the $Li^6I(Eu)$ crystal; the probability that the gate (a 1.48 microsecond gate was considered), originally opened by the slowing down pulse, was still open by the time the slowed down neutron reached the $Li^6I(Eu)$ crystal. The results of this crude calculation showed that only 10.6 percent of the neutrons that could be identified as totally absorbed neutrons by the single $Li^6I(Eu)$ crystal were put in the coincidence spectrum. Therefore, the efficiency could be made a factor of 9.4 higher if the gate were long enough. (It has been mentioned already that the length of the gate could be made no longer than 3 microseconds with the electronic set-up that was used.) That the result of the crude calculation may be reasonable is shown in Figure 11 where the data of lines 4, 5 and 6 of Table 1 are plotted as efficiency versus resolving time. It is seen that the curve is still going up fast at a resolving time of 2.76 microseconds.

The efficiency of the spectrometer can also be increased by placing more $Li^6I(Eu)$ crystals around the Pilot Scintillator B. It is given in Table 1 that 3.45 percent of the area of the plastic scintillator was covered by the $Li^6I(Eu)$ crystal. The efficiency calculated by Leiss and shown by the solid line in Figure 10 was based on 30 percent of the slowed down neutrons being identified. If 30 percent of the area of the 4" diameter Pilot Scintillator B were covered by $Li^6I(Eu)$ crystals, the efficiency would be increased by a factor of 8.7. This means nine $Li^6I(Eu)$ crystals would have to be used.

The efficiencies that would be expected of the Pilot B - Li^6I spectrometer with a long enough resolving time and nine $Li^6I(Eu)$ crystals are represented by the squares in Figure 10. It is seen that under the proper conditions the efficiency of the Pilot B - Li^6I spectrometer will approach the efficiency curve calculated by Leiss for a boron-10 loaded liquid scintillator.

6. CONCLUSIONS

It has been mentioned that the efficiency of the Pilot B - Li^6I spectrometer can be improved by the use of longer resolving time and more $Li^6I(Eu)$ crystals. It should be pointed out, however, that although the efficiency of the Pilot B - Li^6I spectrometer in its present form is low, it possesses the advantage that very large area detectors may be used with consequent gain in count rate.

The most important drawback of the Pilot B - Li^6I spectrometer as it now stands is the relatively poor energy resolution. The calculations of Leiss and the Po^{210} alpha particle experiments indicate that the resolution should be better. Probably the most important sources of excessive broadening of the observed pulse height spectra are: use of thick targets, multiple scattering of deuterons in the thick targets, and counting only a few of the neutrons which have been slowed down to fairly low energy (10 ev or below). With the Pilot B - Li^6I spectrometer as it is, the first and second possible sources of broadening can be eliminated by making use of thin gas targets. The third possible source of broadening can be eliminated by making the resolving time of the electronics longer. (This also is necessary to increase the efficiency.)

It is felt, however, that probably the best approach for further work would be to use a boron-10 loaded plastic scintillator. A system such as this would involve the use of fast electronics to detect the alpha particle from the disintegration event. This method would have the advantages of the boron-10 loaded liquid scintillator, such as high probability of absorption of slowed down neutrons by B^{10} and short resolving time, but would not have the disadvantages of preparing and containing boron-10 loaded liquid scintillators. This method would also remove the disadvantages of the Pilot B - Li^6I spectrometer, such as the necessity of having a long resolving time and using several $Li^6I(Eu)$ crystals. Surrounding the Pilot Scintillator B with several $Li^6I(Eu)$ crystals could also result in a spreading of the pulse height

spectra because of elastic scattering from the large amount of matter in the vicinity of the plastic scintillator. To test a boron-10 loaded plastic scintillator, it would be best to use thin gas targets, so that any spreading of the pulse height spectra due to the sources themselves would be eliminated.

7. ACKNOWLEDGMENT

The authors wish to express their gratitude to L. Costrell, Chief of the Nucleonic Instrumentation Section, for his assistance with the many electronic problems that were encountered in this work.

Table 1

Pilot Scintillator B Diameter (inches)	Neutron Energy (Mev)	Resolving Time (microseconds)	Efficiency	Fraction of area of plastic scintillator covered by $Li^6I(Eu)$ crystal
1-3/4	14.1	1.85	1.85×10^{-6}	.18
4	14.1	1.48	1.01×10^{-6}	.0345
1-3/4	2.5	1.85	4.04×10^{-5}	.18
4	2.5	1.48	1.58×10^{-5}	.0345
4	2.5	1.41	1.52×10^{-5}	.0345
4	2.5	2.76	2.59×10^{-5}	.0345

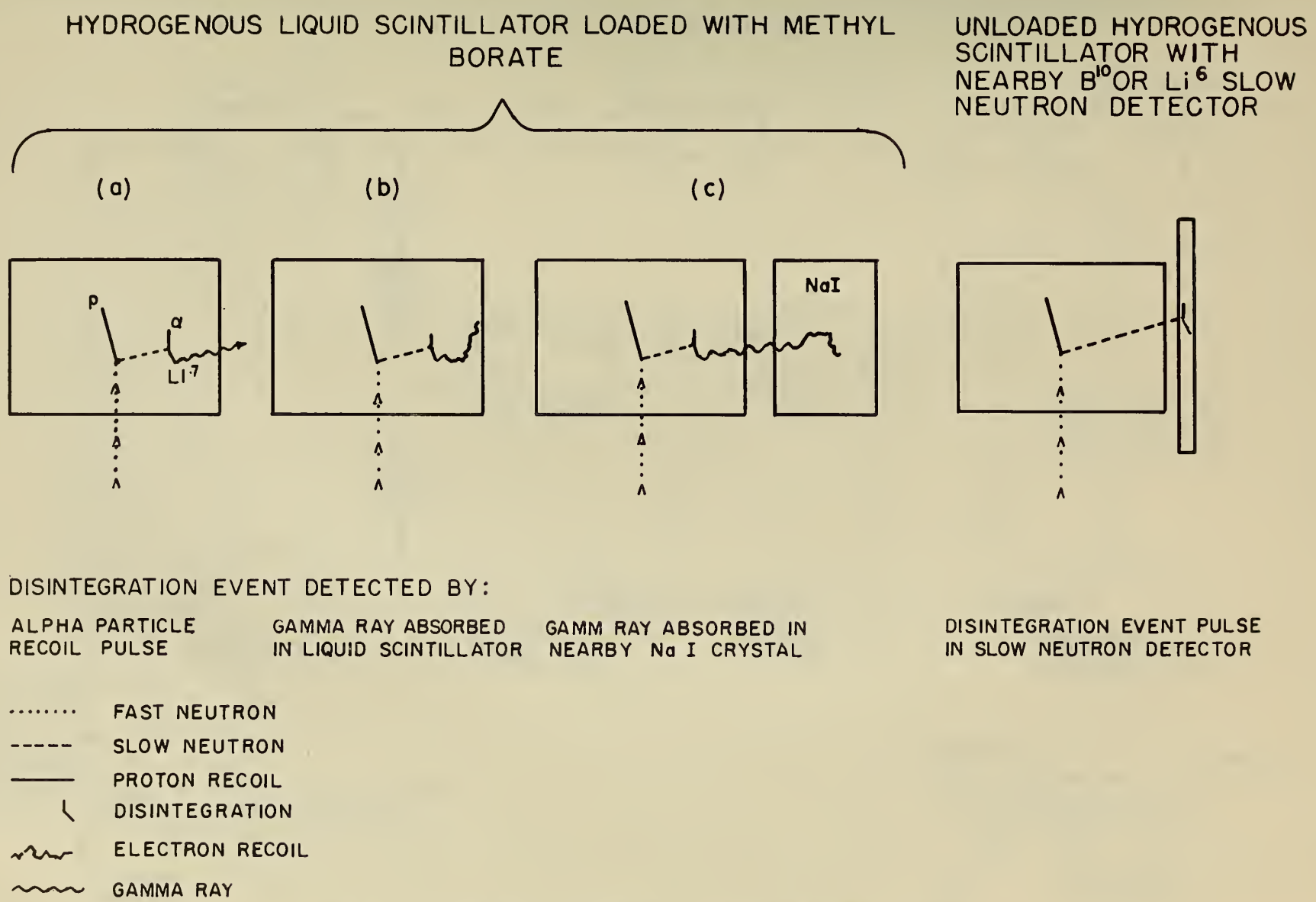

Fig. 1. Schematic diagrams of various forms of the spectrometer.

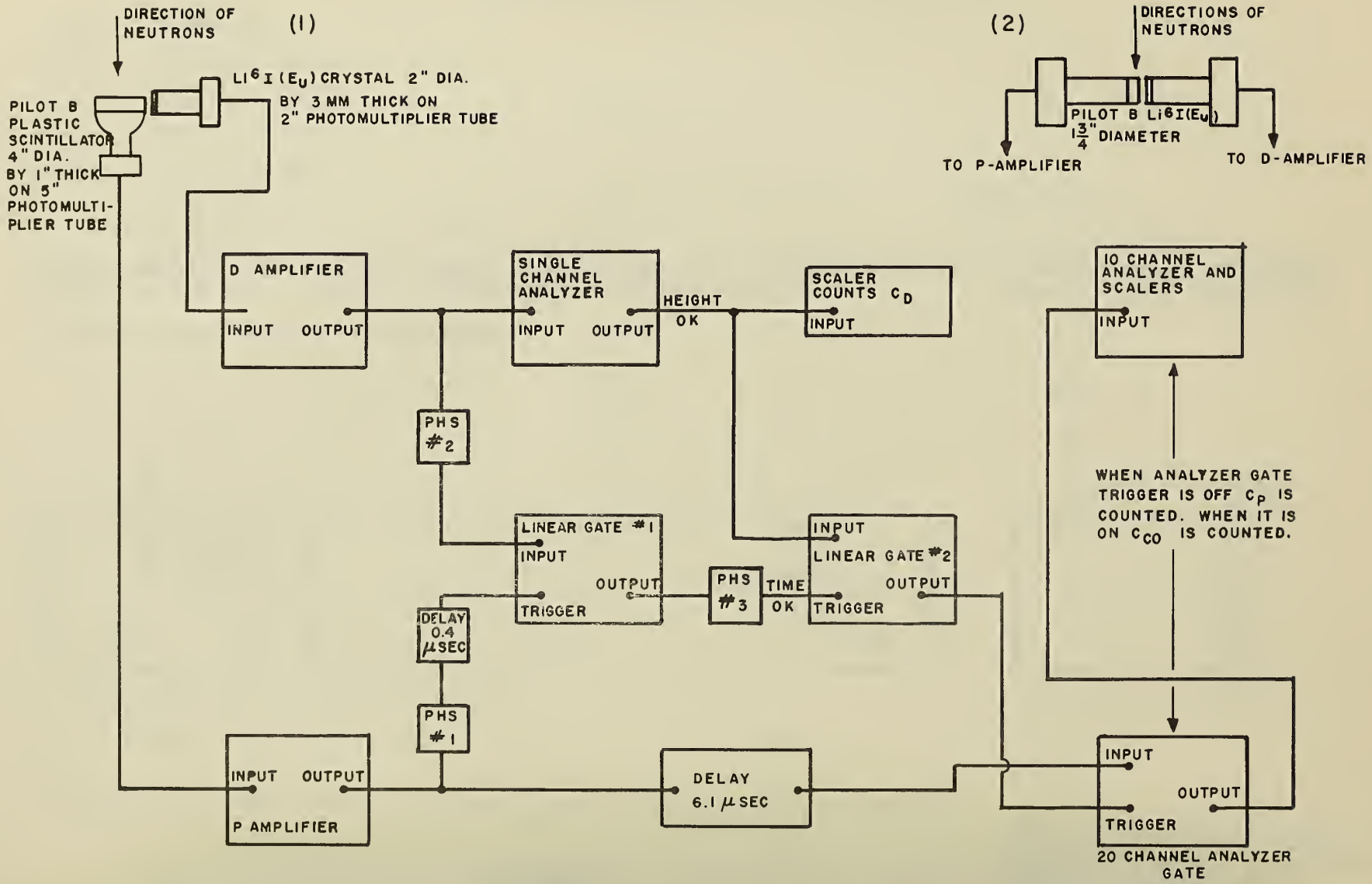

Fig. 2. Block diagram apparatus.

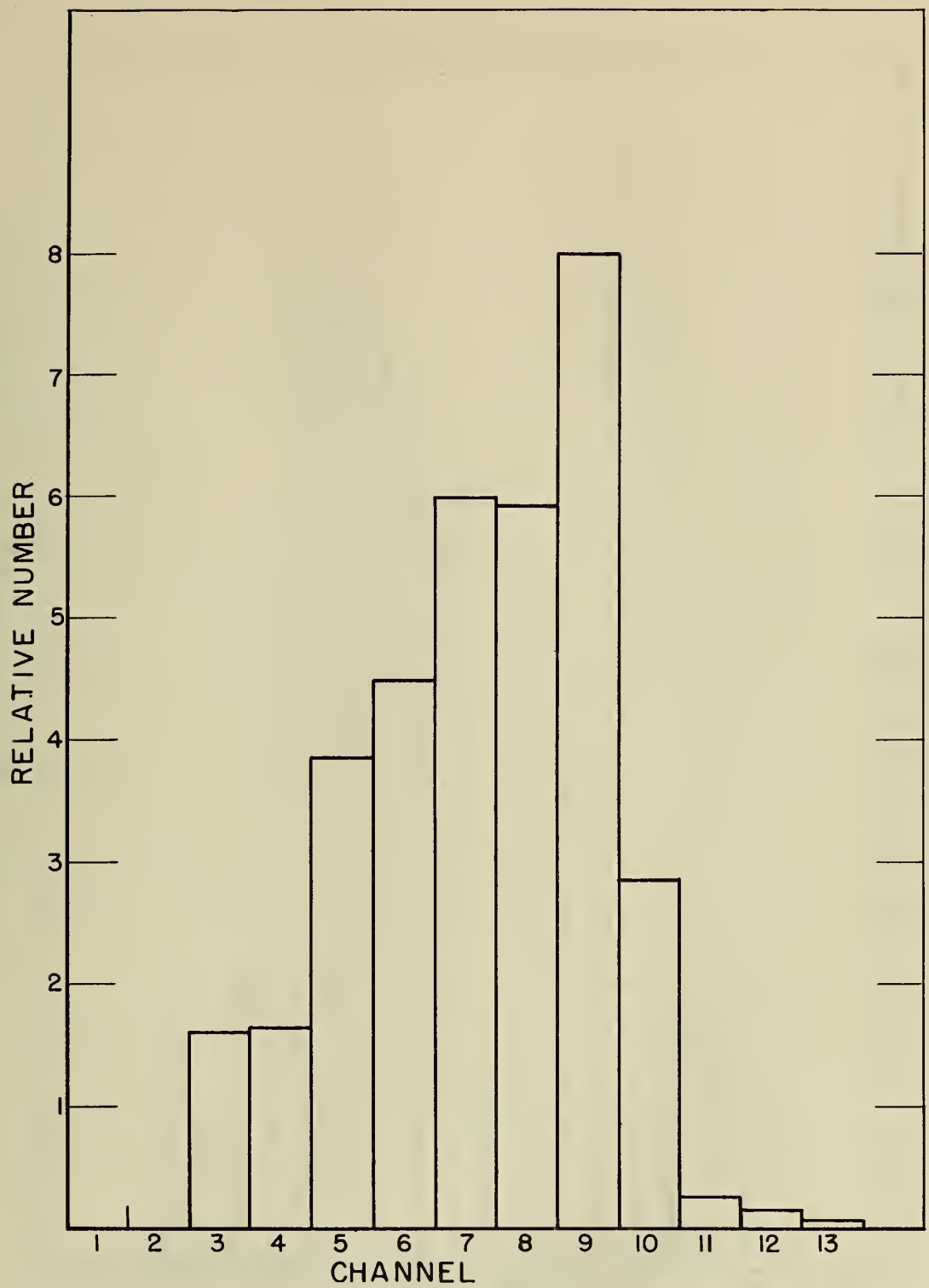

Fig. 3. $D(d,n)He^3$, 2.5 Mev neutrons, resolution 50%, 4" diameter Pilot Scintillator B.

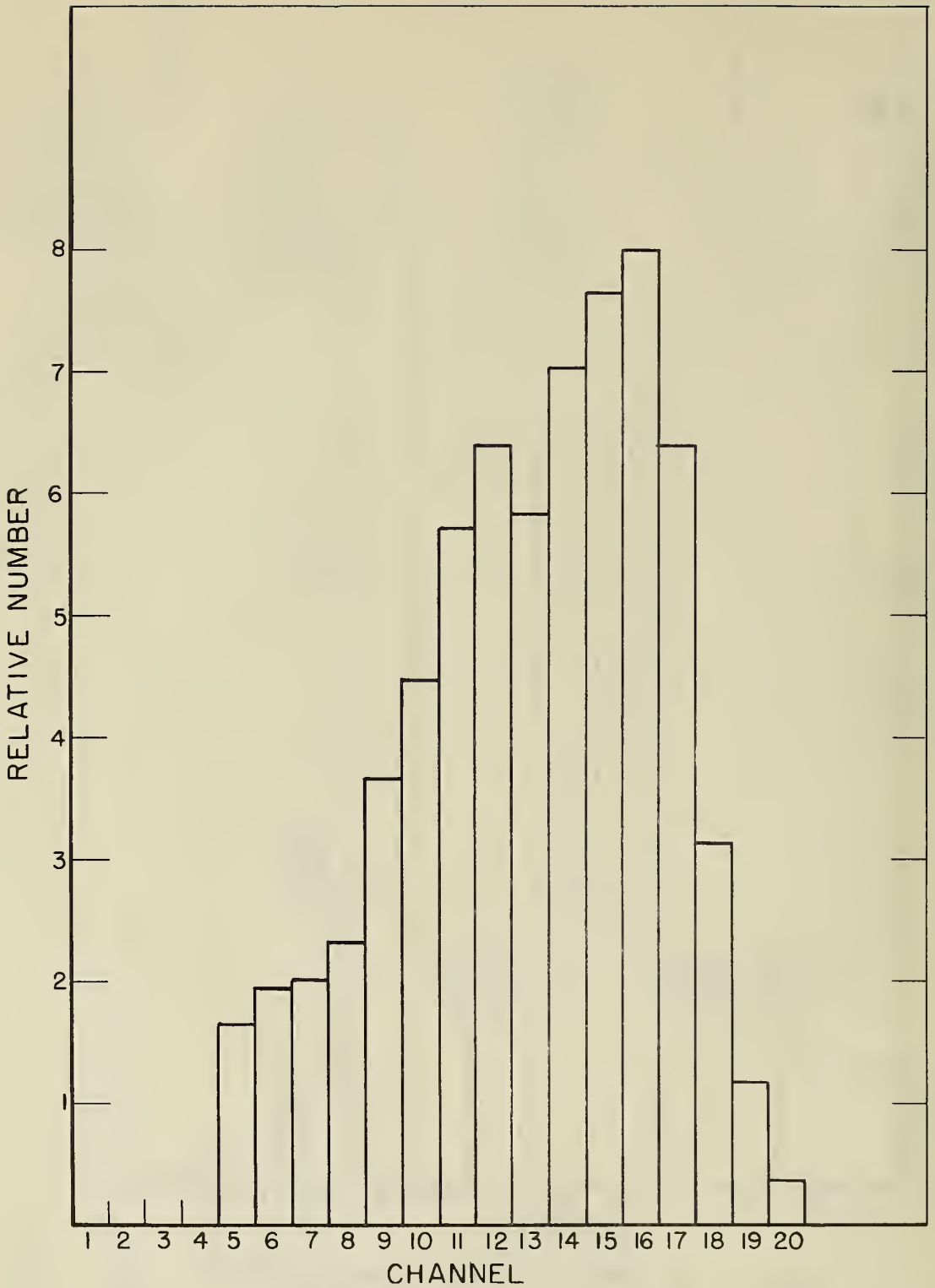

Fig. 4. $D(d,n)He^3$, 2.5 Mev neutrons, resolution 50%
1-3/4" diameter Pilot Scintillator B.

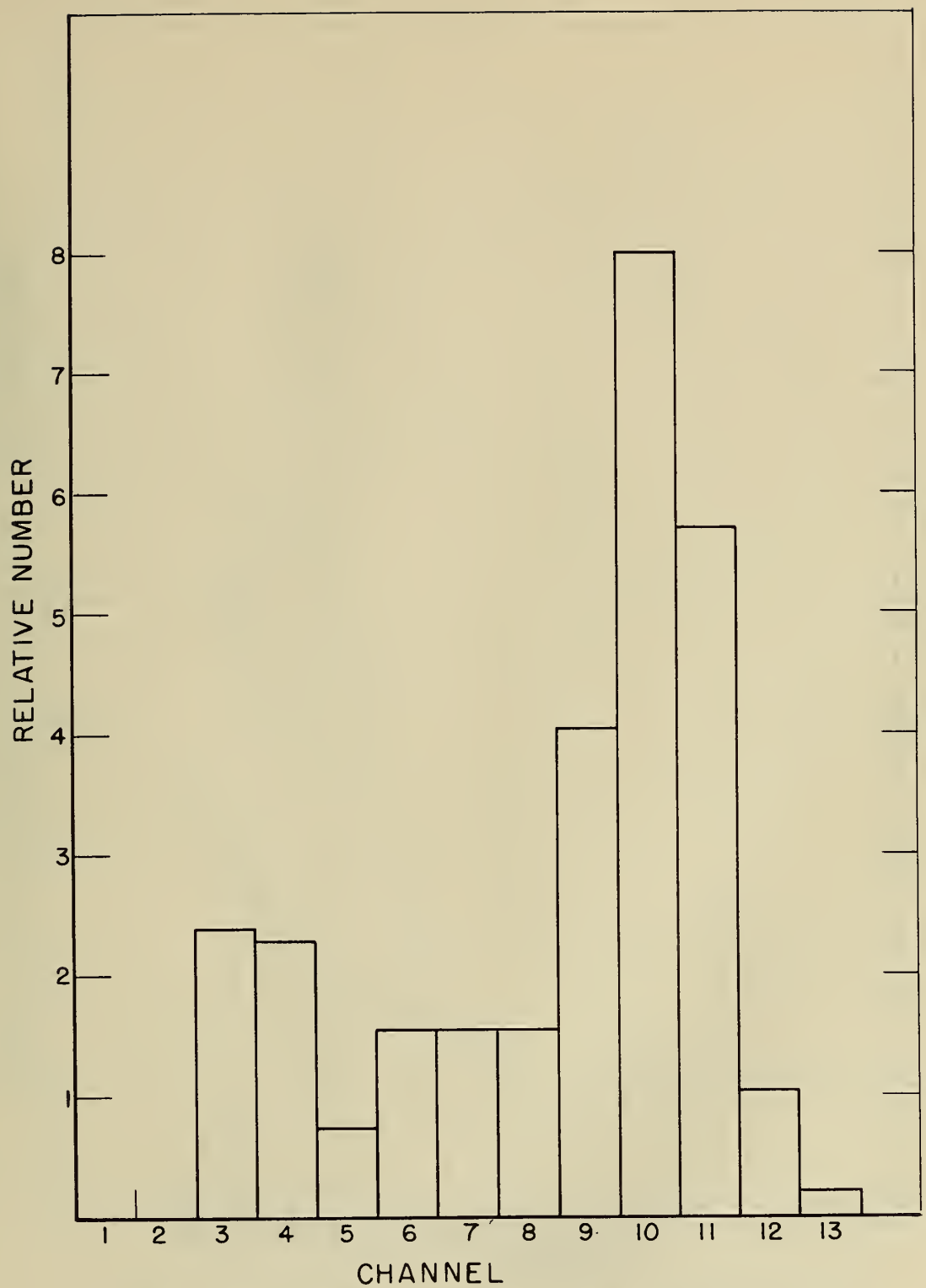

Fig. 5. $T(d,n)He^4$, 14.1 Mev neutrons, resolution 22%, 4" diameter Pilot Scintillator B.

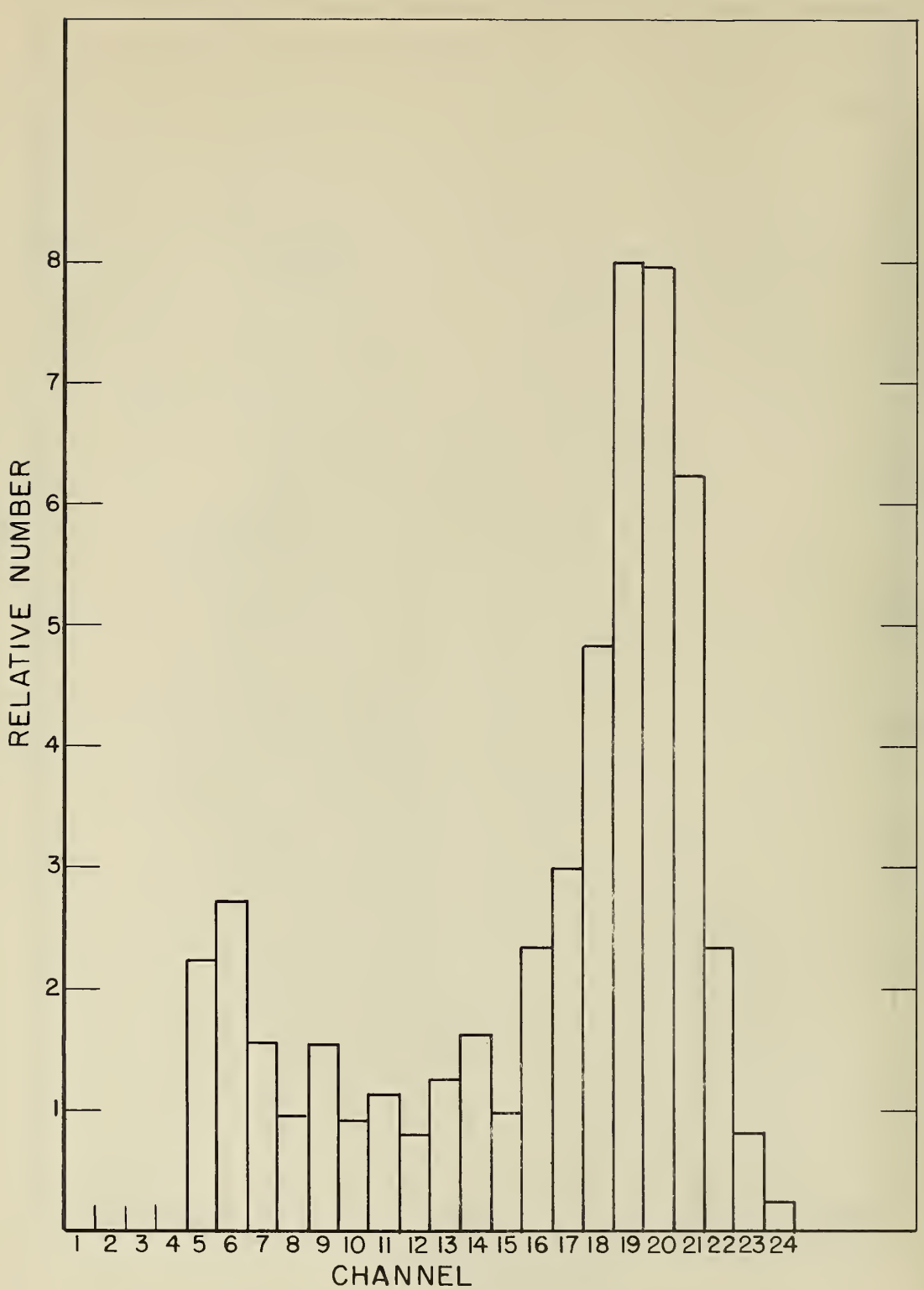

Fig. 6. $T(d,n)He^4$, 14.1 Mev neutrons, resolution 20%, 1-3/4" diameter Pilot Scintillator B.

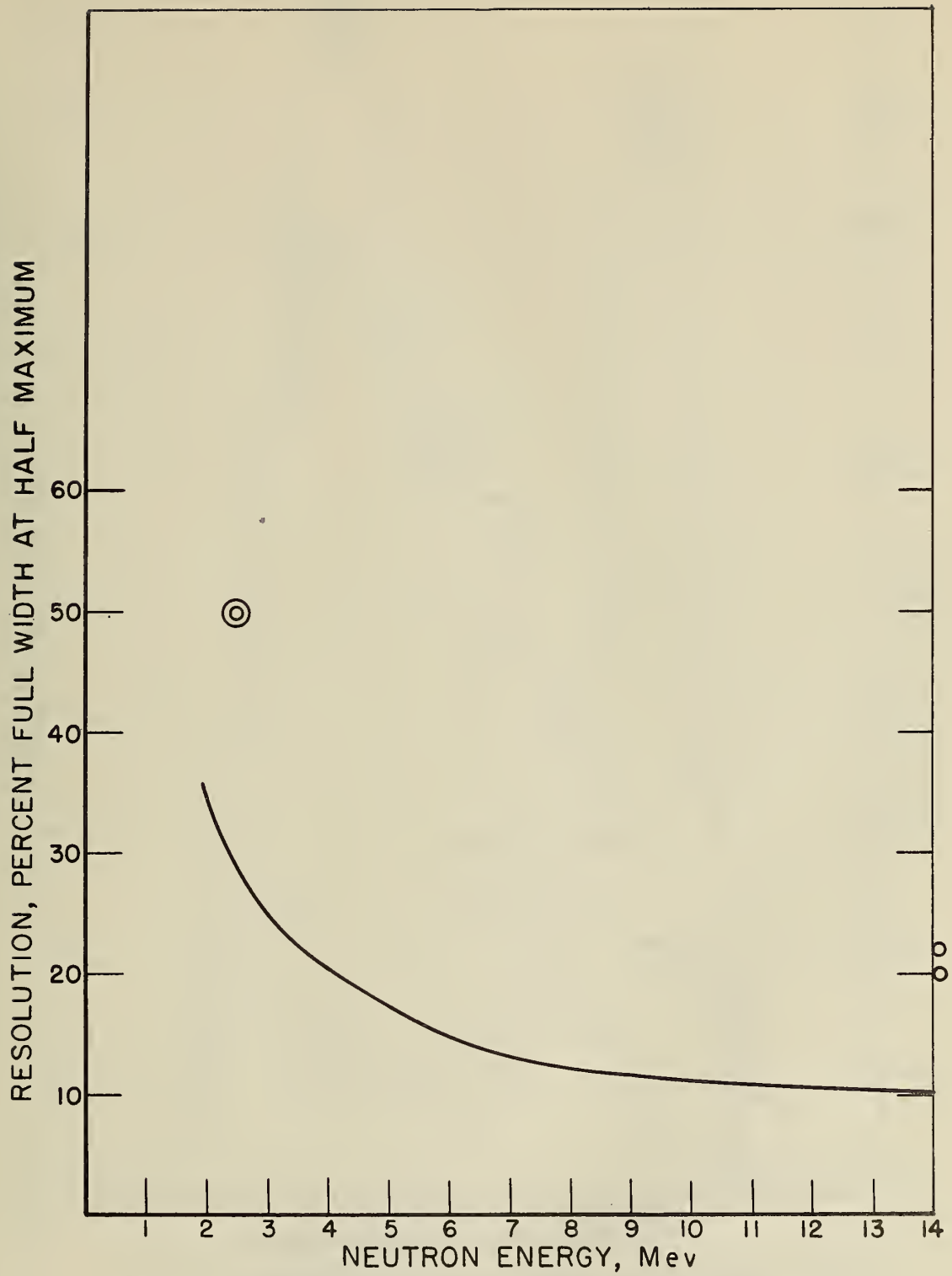

Fig. 7. Resolution vs. neutron energy, experimental and calculated.
O Resolution obtained experimentally with Pilot B-Li^6I spectrometer.
—— Resolution calculated by Leiss for Boron-10 loaded liquid scintillator.

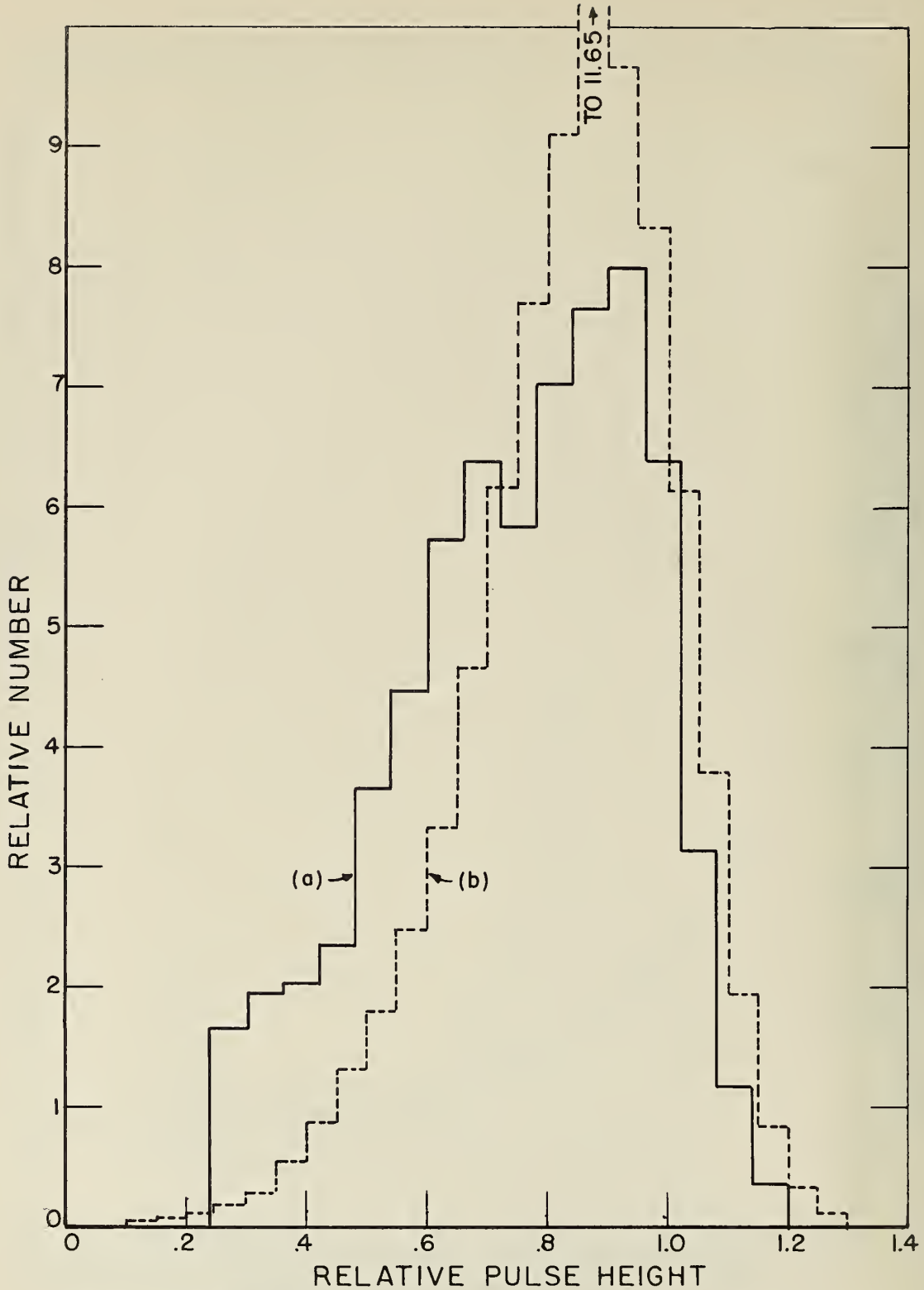

Fig. 8. Pulse height distributions, experimental and calculated.
Curve (a) Pulse height distribution obtained experimentally with Pilot B-Li^6I spectrometer and 2.5 Mev neutrons.
Curve (b) Pulse height distribution calculated by Leiss for Boron-10 loaded liquid scintillator and 2 Mev neutrons.

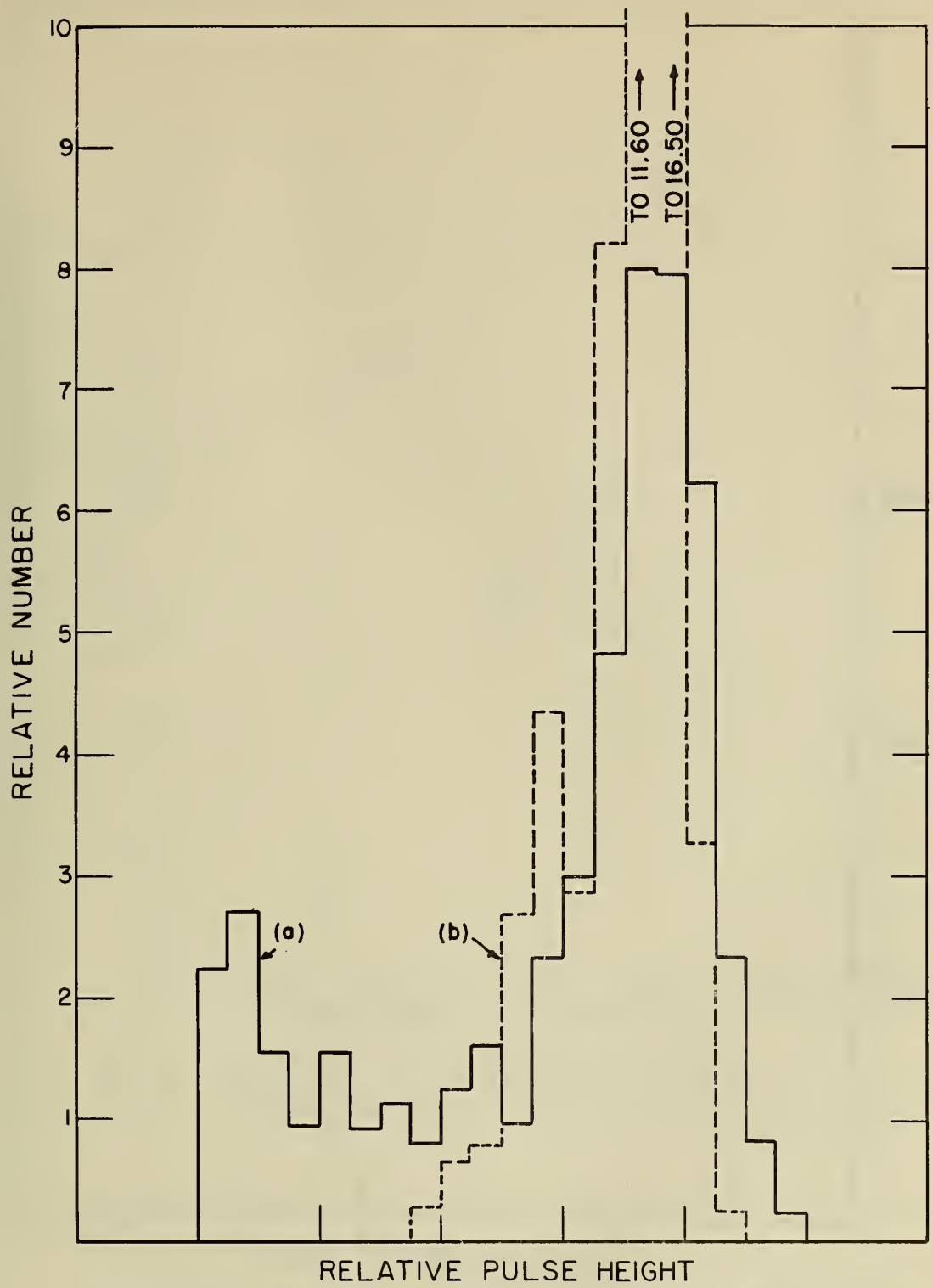

Fig. 9. Pulse height distributions, experimental and calculated.
Curve (a) Pulse height distribution obtained experimentally with Pilot B-Li^6I spectrometer and 14.1 Mev neutrons.
Curve (b) Pulse height distribution calculated by Leiss for Boron-10 loaded liquid scintillator and 10 Mev neutrons.

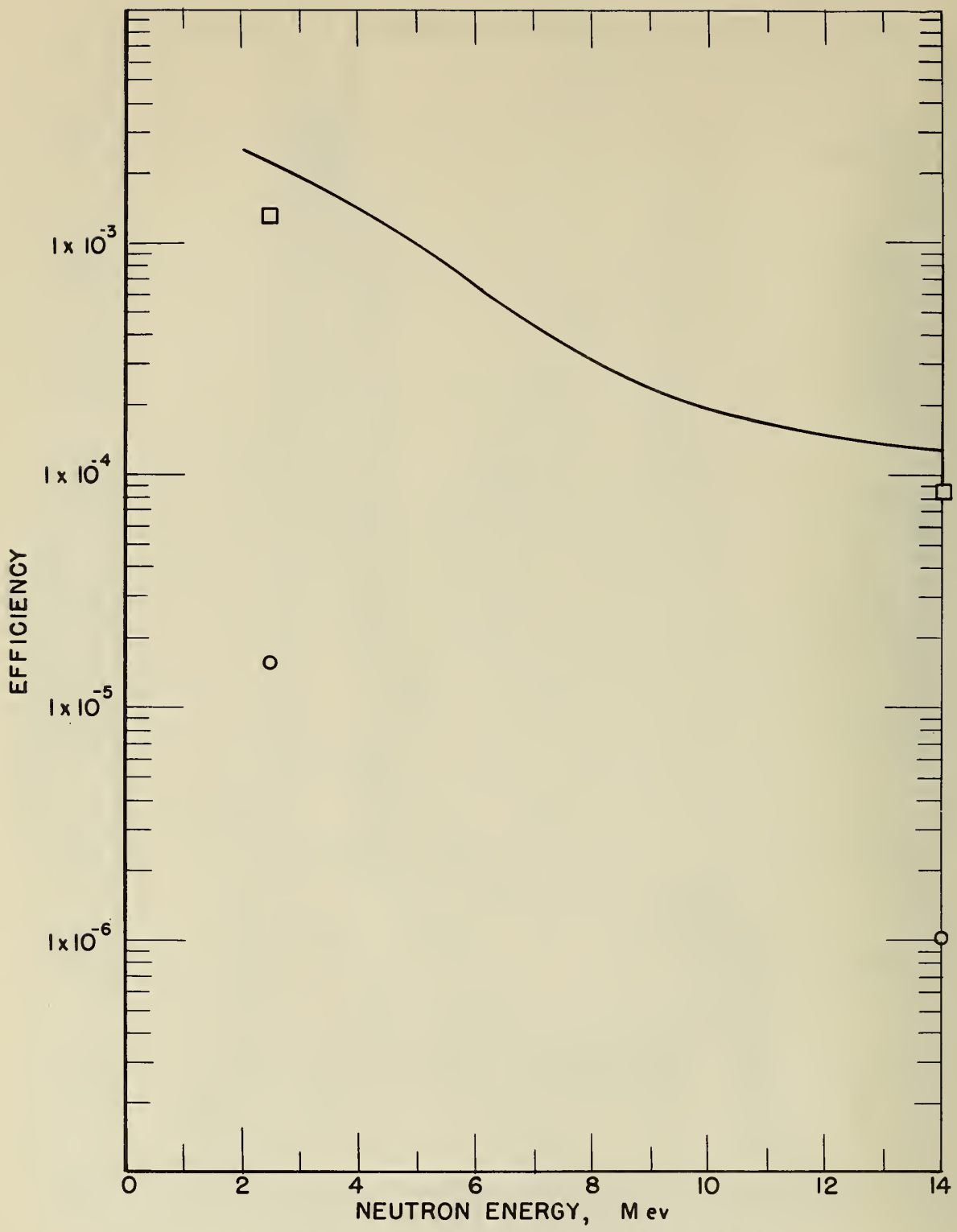

Fig. 10. Efficiency vs. neutron energy, experimental and calculated.
○ Efficiency obtained experimentally with Pilot B-Li^6I spectrometer, 5" diameter Pilot B, 1.48 microsecond resolving time.
□ Efficiency expected with Pilot B-Li^6I spectrometer with longer resolving time and more Li^6I crystals. See text for explanation.
—— Efficiency calculated by Leiss for Boron-10 loaded liquid scintillator.

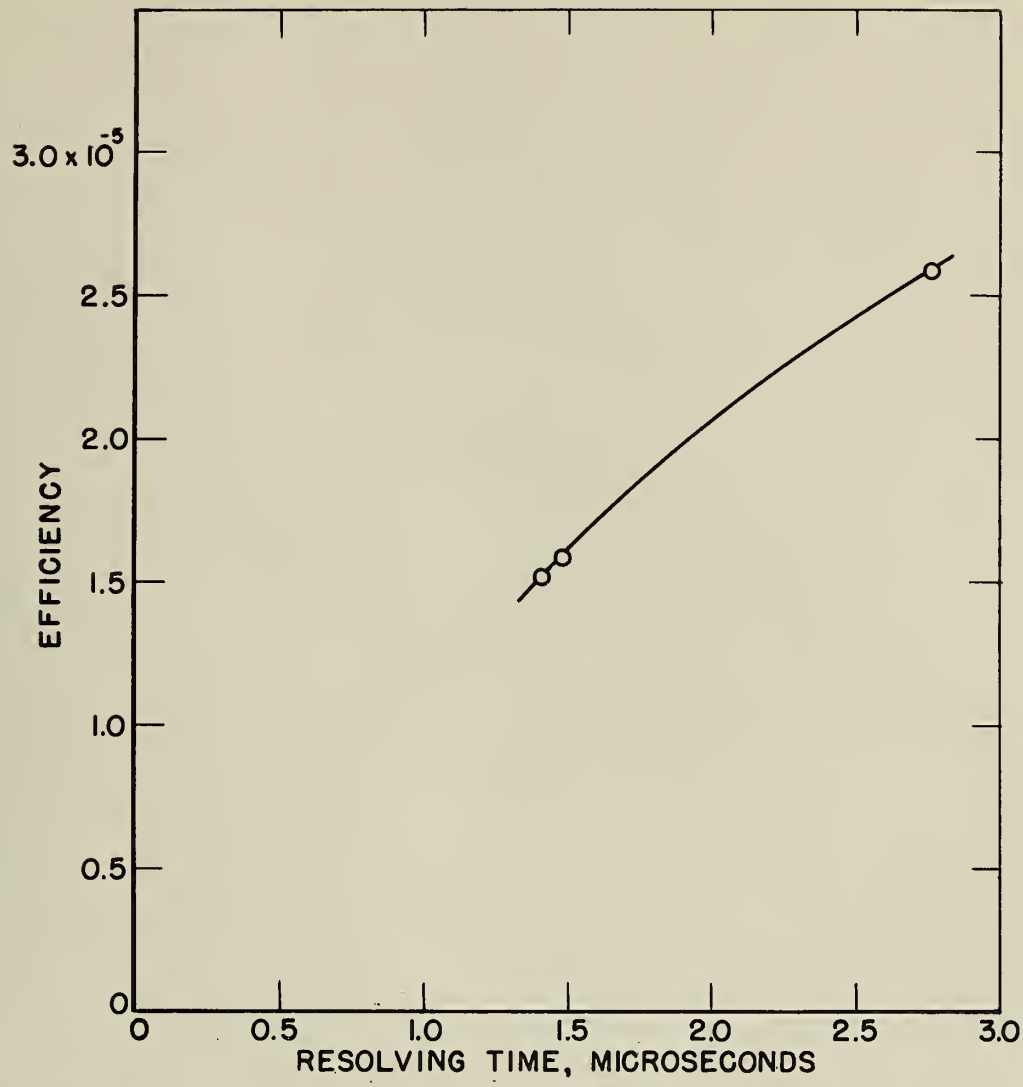

Fig. 11. Efficiency vs. resolving time, $D(d,n)He^3$, 2.5 Mev neutrons, 4" diameter Pilot Scintillator B.

February 26, 1959

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U. S. DEPARTMENT OF COMMERCE
Lewis L. Strauss, *Secretary*

NATIONAL BUREAU OF STANDARDS
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