Cloud-Chamber Energy Measurement of Photo-Neutron Sources*

D. J. HUGHES AND C. EGGLER
Argonne National Laboratory, Chicago, Illinois

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The energy distributions of the neutrons from several photo-neutron sources have been measured by means of the range distribution of recoil protons produced in a hydrogen-filled cloud chamber. It is shown that slowing-down in the source itself produces a broad spread in energy instead of the almost monoenergetic spectrum to be expected from a single γ-energy. The values of the mean neutron energy, E, and the maximum energy, E_M, for the sources measured are as follows:

Source	E (kev)	E_M (kev)
Na−Be	800	1020
Na−D_2O	220	320
Mn−Be	300	375
	<150	<150
In−Be	300	400
	<150	<150
Sb−Be	35	68

As the E_M values should be directly related to the energies of each of the γ-sources, they are compared to the γ-energies as reported by different observers for each source.

I. INTRODUCTION

THE advent of chain-reacting piles has made available intense γ-sources which can be used to produce photo-neutrons by the photo-disintegration of the deuteron or of beryllium. Such photo-neutron sources have proved to be extremely useful and convenient neutron sources in the region 30 kev to 1 Mev. If only a single γ-ray above the photo-disintegration threshold is present and the amount of deuterium or beryllium is very small, then the emitted neutrons show practically no spread in energy. Such a monoenergetic neutron source is, of course, much superior to the usual Ra (α) Be source with its great spread in neutron energy. Actually, in order to obtain sufficient intensity the amount of deuterium or beryllium which must be used is large enough so that significant moderation of the neutrons occurs by elastic scattering, and a broad band of energies results.

During the year 1944 Wattenberg[1] investigated the production and calibration of photo-neutron sources, using various γ-emitters produced in the Argonne pile. The γ-sources were surrounded by amounts of deuterium or beryllium about one centimeter in thickness in order to obtain sufficient intensity, and, as a result, the nearly monoenergetic neutrons emitted in the photo-disintegration were slowed down appreciably in the surrounding material. Wattenberg estimated the average energy of his sources by measuring the average scattering cross section of hydrogen for the neutrons of each source. The energy corresponding to the observed hydrogen cross section was then obtained from the curve of Bohm and Richman.[2] The energies as determined from the hydrogen scattering were always less than that expected from the γ-energy, thus showing that the moderator did have a definite effect in lowering the average neutron energy.

In order to aid in the understanding of the actual energy distribution of the neutrons emitted by the sources it was decided to measure the neutron energies by means of recoil protons in a hydrogen-filled cloud chamber. In addition, it was hoped that investigation of the actual energy distribution would show whether some of the sources consisted of several neutron groups instead of a single one. Some of the γ-sources had been reported as having more than one

* This document is based on work performed in 1945 under Contract No. W-31-109-eng-38 for the Atomic Energy Project at the Argonne National Laboratory. It was submitted for declassification June 6, 1947.

[1] A. Wattenberg, Phys. Rev. 71, 497 (1947).

[2] D. Bohm and C. Richman, Phys. Rev. 71, 567 (1947).

γ-energy above the photo-disintegration threshold, but it was impossible to ascertain from the average energy, as measured by the hydrogen scattering, whether multiple groups were present or not.

II. METHOD

The main difficulty in the measurement of the neutron energies with the cloud chamber is caused by the fact that while the sources are only moderate in neutron strength, they are intense in γ-activity. Thus a source strong enough to give one recoil proton per expansion when placed about two feet from the chamber must be several curies in γ-strength. Such an intense γ-activity near the chamber makes it rather difficult to obtain clear proton tracks. It was found, however, that if the photo-neutron source was surrounded by several inches of lead to reduce the γ-activity to some extent, and if the expansion ratio of the chamber was kept quite low (which emphasizes proton over beta-tracks), it was possible to obtain quite sharp contrast between the protons and the intense background of beta-tracks. The presence of the lead does not change the neutron energy spectrum appreciably because energy losses for elastic scattering with lead are small, and inelastic scattering does not take place at photo-neutron energies.

The apparatus is shown diagrammatically in Fig. 1. It was placed on supports about 6 ft. above the floor in a large room to reduce the scattering of neutrons from walls and floor. The γ-source could be lowered by remote control into a large lead pot on the floor while the chamber was being adjusted, film changed, etc. Then it could be replaced in operating position and several hundred pictures taken without the necessity of approaching the apparatus. The photo-neutron source itself is of the same construction as those described by Wattenberg, that is, a tube 2 cm in diameter and 5 cm long, containing the γ-source, located in a cylinder of beryllium or a deuterium-filled cylindrical can 3.8 cm in diameter and 5.1 cm long with a 2.2-cm diameter axial hole.

The cloud chamber, 30 cm in diameter, is very similar to that described by Jones and Hughes.[3] For most of the sources measured it was filled with hydrogen gas and water vapor to a pressure of 82 cm of mercury. The stereoscopic pictures were taken with a standard mirror arrangement, using 35-mm Eastman *XX* film and an f:3.5 lens. The light source was a xenon-filled capillary, flashed by discharging a 50 μf condenser bank at 2000 volts. The xenon lamp is a General Electric "Flashtube FT 26" and has proved to be an extremely convenient cloud-chamber light source.

The lengths of the recoil protons, and their direction of motion relative to the incident neutrons, were determined by a stereoscopic reprojection of the negatives. The proton ranges in standard air were obtained by comparison with the observed range in the chamber of the alphas from a plutonium source mounted in the chamber. In the comparison, a correction was made for the fact that the stopping power of the chamber for alphas relative to protons is a function of the proton range. The proton range in air was converted to energy units, using the range-energy curves given by Livingston and Bethe,[4] and the neutron energy calculated from the proton energy and the angle, θ, between the neutron and proton directions. The energy spectrum of the neutrons from the source could then be plotted from the observed numbers of recoil protons as a function of energy. A correction must be made, of course, for the effect of the change in the scattering cross section of hydrogen with neutron energy, but because of the nearly monochromatic nature of the sources such a correction is small.

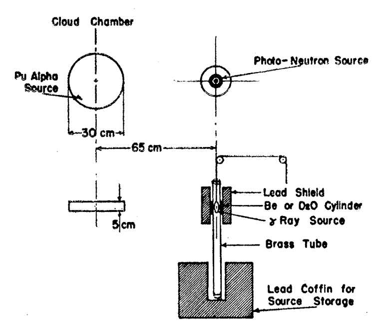

FIG. 1. Experimental arrangement of source and cloud chamber for the measurement of photo-neutron energies.

[3] H. Jones and D. Hughes, Rev. Sci. Inst. 11, 79 (1940).

[4] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 245 (1937).

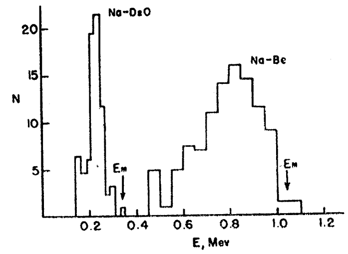

FIG. 2. Measured spectra of the photo-neutrons from Na−Be and Na−D_2O. E_M denotes the maximum neutron energy calculated from a γ-energy of 2.76 Mev.

III. RESULTS

If no slowing down takes place in the deuterium or beryllium of the source itself, then the energy spread in the emitted neutrons should be very small. The energy spread in this ideal case is caused by the difference in direction, θ, of the neutron and the γ-ray and is given by

$$\delta = E_\gamma \cos\theta \left(\frac{2(A-1)(E_\gamma - Q)}{931A^3} \right)^{\frac{1}{2}},$$

where δ is the deviation from the average energy, E_γ the γ-energy, A the mass of the target nucleus, and Q the threshold energy (all energies in Mev). The value of this energy spread is usually of the order of one percent, which is much less than the energy spread caused by slowing down in an actual source. Because of the low atomic weight of deuterium and beryllium they are excellent moderators and distort the neutron energy spectrum even when present in small amounts. The resulting energy spectrum is expected to have a maximum neutron energy corresponding to that given by the γ-energy but an average energy somewhat lower. The actual energy spectra were measured for several photoneutron sources of interest, and the findings will be discussed separately for each source.

Na−Be

The spectrum obtained from 106 recoil protons which were within 30° of head-on collisions is shown by the block diagram of Fig. 2. It is seen that the distribution, while showing no great spread in energy similar to a Ra−Be source, is by no means monoenergetic. The spectrum is, of course, distorted to some extent by errors of measurement. However, if only those recoils are chosen which are within 20° of head-on, the spectrum does not narrow appreciably, the full width at half-maximum, which is 33 percent of the maximum energy in Fig. 2, changing only to 31 percent in the 20° case. The true width is probably slightly less than the latter value, say about 25 percent.

The most probable neutron energy from Fig. 2 is about 825 kev, while the arithmetic mean energy is 800 kev. Wattenberg finds a mean energy for this source from the mean hydrogen scattering cross section of 830 kev. It seems then that the spectrum of Fig. 2 is a good representation of the actual neutron distribution of a source made according to Wattenberg's method.

The maximum energy in the spectrum can, of course, be identified with those neutrons which are unmoderated and which should therefore correspond to the energy calculated from the Na γ-energy. The Na γ-energy has been measured as 2.76 Mev recently by Siegbahn,[5] in agreement with an earlier measurement of Elliot, Deutsch, and Roberts.[6] Other measurements have given values for the energy ranging as high as 2.94 Mev. The maximum neutron energy (including the energy spread δ) to be expected, assuming E_γ to be 2.76 Mev, is marked as E_M in Fig. 2. Considering the inevitable straggling of the experimental points, it is seen that the agreement between E_M and the observed upper limit is quite satisfactory. A γ-ray has been reported of energy higher than that of the γ-ray of energy 2.76 Mev, but no tracks were found in the present spectrum (or in the Na−D_2O spectrum), to indicate the presence of such a γ-ray. If it exists, it does not contribute an appreciable number of neutrons in the photoneutron source.

Na−D_2O

The spectrum based on 75 recoils is shown in Fig. 2. The theoretical maximum, based on a γ-energy of 2.76 Mev and a D_2O threshold of 2.18 Mev is indicated (E_M), and it is seen that the maximum neutron energy corresponds quite well with the theoretical value. The most prob-

[5] K. Siegbahn, Phys. Rev. **70**, 127 (1946).
[6] Elliot, Deutsch, and Roberts, Phys. Rev. **67**, 273 (1945).

able value of the distribution and the average are at about 220 kev (70 percent of E_M) which is the same as the mean energy which Wattenberg finds for this source by the hydrogen cross section method. The width of the energy distribution at half-maximum for the $Na-D_2O$ source is 20 percent of E_M.

Mn—Be

Gamma-ray measurements[7,8] for Mn^{56} had shown two γ-rays of energy 1.81 and 2.13 Mev. As both these energies are higher than the threshold in Be, one would expect two groups of photo-neutrons. Wattenberg actually found from the scattering cross section of hydrogen that the photo-neutrons he observed were due to a γ-ray of energy 1.83 Mev. (He also found an extremely weak group of photo-neutrons in deuterium which would indicate a γ-ray of energy 2.7 Mev.) As his method of estimating energies from the hydrogen scattering cross section gives only the mean energy of the neutron group, it was impossible for him to say whether there were any neutrons from the 2.1-Mev γ-ray.

The energy spectrum of the Mn—Be neutrons was measured in the cloud chamber to determine whether only one group of neutrons was present, as seemed likely from Wattenberg's result, or if two groups were present, as would be indicated by the γ-ray energies. The results are shown in the lower curve of Fig. 3. It was found that two groups of neutrons were definitely present (no effort was made to study the small number of neutrons which would be caused by the 2.7-Mev γ-ray). The energy of the most abundant group was too low to be measured accurately as the recoil protons were of such short range. The energy is roughly 100 kev, which would give an approximate γ-ray energy of 1.8 Mev. The higher energy group has an average energy of 300 kev, and it is possible to estimate the energy of the γ-ray causing the group. The maximum energy, E_M, is chosen as 375 kev, by taking E_M slightly less than the apparent maximum energy in analogy with the spectra of Fig. 2. A value of 375 kev for E_M then gives 2.05 ± 0.03 Mev for the γ-ray energy. This energy is somewhat less than the earlier value 2.13 Mev, but agrees extremely well with a recent determination of this γ-ray by Siegbahn[9] of 2.06 Mev. It is definite then that the 2.06-Mev γ-ray produces photo-neutrons in addition to the 1.81-Mev γ-ray.

The relative numbers of photo-neutrons in the low and high energy groups are about 90 percent and 10 percent, respectively, as determined by counting recoil protons and correcting for the change of hydrogen cross section with energy. Because of the low intensity of the high energy group, it was not indicated as a discrete group by Wattenberg but probably increased his average energy slightly. Thus the 1.83-Mev γ-ray energy that he inferred is probably high for this reason. Siegbahn's[9] recent determination of the low energy γ-ray is 1.77 Mev.

In—Be

Indium is of doubtful value as a γ-emitter for photo-neutron sources because of its short half-life (54 min.). However, if only one group of neutrons were present then the difficulty caused by the short half-life would not be insurmountable. Gamma-ray measurements had indicated energies of 1.8 (spectrometer) and 2.3 Mev (cloud chamber) for those γ's higher than the Be threshold, so it was decided to measure the photo-neutron spectrum to see if several groups were actually present. The spectrum obtained, shown in the upper part of Fig. 3, contains two

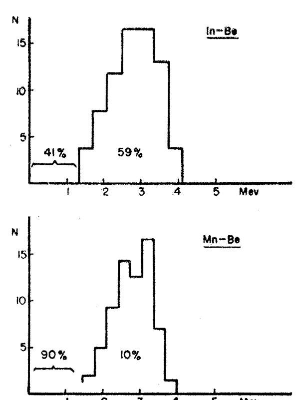

FIG. 3. Photo-neutron spectra of In—Be and Mn—Be.

[7] M. Deutsch and A. Roberts, Phys. Rev. **60**, 362 (1941).
[8] L. G. Elliot and M. Deutsch, Phys. Rev. **63**, 321 (1943).
[9] K. Siegbahn, Ark. Mat. Astr. Fys. **33A** (2), Paper 10 (1946).

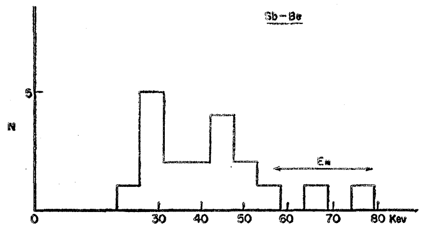

FIG. 4. Photo-neutron spectrum of Sb–Be. The energy range shown for E_M gives a value for the γ-energy of 1.70 ± 0.02 Mev.

groups of neutrons, one of mean energy about 300 kev, and a group of energy too low (about 100 kev) to be measured accurately. The higher energy neutron group comprises 59 percent of the total, and its E_M gives a value of 2.08 ± 0.04 Mev for the indium γ-ray. The low energy group cannot be measured accurately, but it indicates a γ-ray of roughly 1.8 Mev. It seems therefore that both energies are present in indium and in such intensities that they give roughly comparable groups of photo-neutrons. Because of the presence of the two neutron groups the value of In–Be as a photo-neutron source is much reduced.

Sb–Be

The highest energy γ-ray from Sb has been reported[10,11] as having energies ranging from 1.70 to 1.82 Mev. This discrepancy in the γ-ray energy is large enough so that the calculated photo-neutron energy is quite indefinite. Scharff-Goldhaber and Klaiber[12] measured the energy of the photo-neutrons from an Sb–Be source and found E_M to be 115 kev, which would indicate a γ-energy of about 1.75 Mev. Wattenberg's value for the average energy of the photo-neutrons is 24 kev, from which he obtains a γ-energy of 1.67 Mev. The spectrum of photo-neutrons was studied with the cloud chamber mainly in order to investigate the large discrepancies in both the γ-energy and neutron energy measurements.

Because the neutron energy is so low, the cloud chamber was modified to allow operation at low pressure and thus increase the range of the protons to a measurable value. The chamber could be operated with hydrogen at a minimum pressure of about 8 cm, using water as the vapor. Under such conditions the range is about 25 times the range in air and a 20-kev proton, which would have a range of about 0.3 mm in air, will have a range of almost a centimeter in the chamber. The observed ranges in the chamber could not be converted to energies by using the method described for the higher energy sources because the Pu α's would have ranges much greater than the chamber diameter. The stopping power of the chamber gas was therefore determined by measuring the range of the protons produced in the $N^{14}(n,p)C^{14}$ reaction which have an energy of 558 kev. The low energy proton ranges could then be obtained by taking into account the change of the stopping power of hydrogen and oxygen with proton energy.[13]

The source strength of Sb–Be is very low, so it was possible to obtain only 20 recoil protons caused by nearly head-on collisions. The distribution obtained is plotted in Fig. 4. In spite of the extremely small number of tracks it appears that a single group of neutrons of average energy of about 35 kev is present. This value is in rather good agreement with the mean energy of the photo-neutrons of 25 ± 15 kev measured by Wattenberg. Because the neutrons are of such low energy, it should be possible to use the photo-neutron energy to determine the γ-energy rather accurately. Unfortunately, the straggling at the upper end of the measured spectrum of Fig. 4 is quite large, and E_M cannot be determined very accurately. In fact, the possibility that two closely spaced groups might be present cannot be ruled out because of the small number of tracks. However, E_M seems to be within the range shown, that is, 68 ± 11 kev. The value of the γ-energy resulting from this E_M is 1.704 ± 0.012 Mev. The error in this determination of the γ-ray is actually somewhat greater than 12 kev because the error in the photo-neutron threshold should be included, as well as errors in the determination of the stopping power of the chamber gas. Inclusion of these two errors would probably increase the error in the γ-energy to about 20 kev. The γ-energy determined

[10] P. G. Kruger and W. E. Ogle, Phys. Rev. **67**, 273 (1945).
[11] Mitchell, Langer, and McDaniel, Phys. Rev. **57**, 1107 (1940).
[12] G. Scharff-Goldhaber and G. S. Klaiber, Phys. Rev. **61**, 733A (1942).
[13] J. Ashkin, Los Alamos Report 12-R (September 23, 1943). Also published as Manhattan District Declassified Document No. 276 (September 10, 1946).

from the present experiment agrees very well with the latest direct γ-energy determination of Kruger and Ogle[10] which gave 1.70 ± 0.02 Mev. It is somewhat higher than the value 1.67 Mev which Wattenberg obtains from the mean energy of the photo-neutron source.

We wish to extend thanks to Dr. A. Wattenberg for his help in preparation of the sources used and for valuable discussion, to T. Brill for the design of cloud-chamber control circuits, and to N. Goldstein and S. Jashemski for aid in taking data.

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Scattering of Neutrons in Polycrystals*

R. J. FINKELSTEIN**
Argonne National Laboratory, Chicago, Illinois
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Although elastic and first-order inelastic cross sections for a neutron against a Debye crystal have already been determined, expressions for higher order inelastic collisions have not been calculated, and would be very complex for the Debye model. The calculation of the total inelastic cross section involving the emission of an arbitrarily large number of phonons is here presented for a neutron against an Einstein polycrystal. The result, as one would expect, is essentially the same as that given by Fermi for amorphous scatterers, except at high neutron energies where we have calculated the cross section for the ejection of the struck nucleus from its lattice. The coherent elastic cross section is also determined; it is important for energies as high as 1 volt, and does not differ appreciably from that previously calculated for a Debye crystal. The total cross section, the sum of the coherent and incoherent parts, is compared with the experimental data on beryllium.

1. INTRODUCTION

THE scattering of a neutron by a crystal may be described qualitatively in the following manner. As long as its energy is large compared to the chemical binding energy of the lattice, the neutron is scattered as if the nuclei forming the lattice were free. A fast neutron therefore slows down by dislocating effectively free nuclei until its energy becomes of the order of the crystal bond. It then makes inelastic collisions with the lattice as a whole, until it loses so much more energy that its wave-length exceeds the amplitude of the temperature vibrations of the scattering nuclei. At this point elastic collisions with the lattice become the most probable process and further cooling of the neutron takes place very slowly. Finally, if the neutron energy is somehow made still lower, inelastic scattering becomes important again, since the neutron begins to absorb energy from the crystal.

In this paper the cross sections for these different kinds of scattering are calculated for the Einstein crystal. The elastic and first-order inelastic cross sections have already been determined for the Debye crystal.[1] The difference between our formula for elastic scattering and that deduced from the Debye model is insignificant. For first order inelastic collisions the Debye type of formula is to be preferred, but for higher order collisions, in which many phonons are exchanged, the equations of the Debye model become too complex. In these higher order collisions the cross section computed from the Einstein model is essentially identical with the cross section calculated by Fermi[2] to describe

* This work has been carried out under the auspices of the Atomic Energy Commission. It was submitted for declassification on March 10, 1947.

** Now at the Institute for Advanced Study, Princeton, New Jersey.

[1] I. Pomerantschuk, Physik. Zeits. d. Sowjetunion **13**, 65 (1938); R. Weinstock, Phys. Rev. **65**, 1 (1944). See also Halpern, Hamermesh, and Johnson, *ibid.* **59**, 981 (1941); Wick, Physik. Zeits. **38**, 403 (1937); Seeger and Teller, Phys. Rev. **62**, 37 (1942).

[2] E. Fermi, Ricerca Sci. **7**, 13 (1936); H. A. Bethe, Rev. Mod. Phys. **9**, 124 (1937).