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Energies of Neutrons from MsTh-D, La-D, Y-Be, and Sb-Be Photo-Neutron Sources*

A. O. HANSON**
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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The energies of neutrons from several neutron sources have been compared with those of neutrons of calculable energies from the Li(p,n) reaction by observing the maximum pulse heights of proton recoils in a hydrogen filled proportional counter. The values found for the average neutron energy from the various sources are: MsTh-D, 197±10 kev; MsTh-Be, 827±30 kev; Y-Be, 158±5 kev; La-D, 151±8 kev; and Sb-Be, 24±3 kev.

These values are consistently lower than those expected from the measured gamma-ray energies and the usually accepted photo-neutron thresholds. Better agreement could be obtained if the photo-neutron thresholds of deuterium and beryllium were taken as 2.23 and 1.68 Mev.

The energies of the effective gamma-rays from Y^{88} and La^{140} are obtained from the neutron energies and are found to be 1.86 Mev and 2.53 Mev, respectively.

INTRODUCTION

ALTHOUGH a considerable amount of work has been reported on the measurement of neutron energies from photo-neutron sources, certain discrepancies have appeared and it was considered worth while to determine these energies with a somewhat different technique.[1,2] The present method consists of measuring the maximum pulse heights of neutron-produced proton recoils in a hydrogen-filled proportional counter which was calibrated by using neutrons of accurately known energies from the Li(p,n) reaction. Since the energies of the neutrons from the various photo-neutron sources lie within the range of energies obtained from the Li(p,n) reaction, the problem is simply that of matching the photo-neutron energies with known neutron energies.

SOURCES AND INSTRUMENTS

The gamma-ray sources used were: (1) A 500-mc MsTh source which was prepared commercially. (2) A radiolanthanum source made of barium fission products which is the parent of the 40-hour La^{140}. Its half-life is essentially that of the 12.2-day barium. (3) A 200-mc yttrium source (Y^{88}) prepared from strontium bombarded by deuterons in the Berkeley cyclotron.[3] Its half-life is approximately 105 days. (4) A 300-mc antimony source (Sb^{124}) which was prepared by exposing antimony to neutrons in the Argonne pile. It has a half-life of about 60 days.

The photo-neutrons were produced by placing the gamma-ray sources at the center of a deuterium sphere 2.5 inches in diameter and of a beryllium sphere 1.5 inches in diameter. In most of the runs these sources were placed inside a lead shield about 1.25 inches thick in order to reduce the number of low energy gamma-rays incident on the counter.

The proportional counter used was a rather large one. It was three inches in diameter and had a 0.010-inch central wire which had an active length of 3 inches. A guard ring which defined the active length of the 10-mil wire was made of $\frac{1}{16}$th-inch O.D. boron-free glass which was coated with Aquadag. This exterior conducting coating was connected to ground. The general construction of the counter is shown in Fig. 1. For most of the work the counter was filled with hydrogen or deuterium through a palladium leak to a pressure of about 50 cm. It was operated with about −3000 volts on the outer electrode. This voltage gave a gas multiplication of about a factor of five or more.

The counter was connected to a model 100 amplifier which had a rise time of about 1 microsecond and a minimum RC coupling which had a decay time of 5 microseconds. The counter and analyzing system were tested by filling the counter with nitrogen and observing the pulse height distribution due to the protons released by the capture of slow neutrons in N^{14} as described by Koontz and Hall.[4] In all cases the output of the amplifier was connected to a 10-channel pulse height analyzer so that all pulses in a small pulse height range were recorded in a single channel.[5] The relative magnitudes of the pulses recorded in the different channels, as well as the channel widths, were determined by using small pulses of known magnitudes fed into the first stage of the amplifier.

The neutrons of known energies which were used for calibrating the counter were obtained from the

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* This article is based on work which was described in a declassified document LADC 63 and MDDC 149 December 10, 1945. The document has been revised and is presented for wider publication at this time because of its bearing on the values of the deuterium and beryllium neutron binding energies.

** Present address: Department of Physics, University of Illinois, Urbana, Illinois.

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

[2] William E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).

[3] M. Kahn, La225.

[4] P. G. Koontz and T. A. Hall, Rev. Sci. Inst. **18**, 643 (1947).

[5] The ten-channel pulse height analyzer was one designed at Los Alamos by Dr. K. I. Greisen.

Li(p,n) reaction.[6] The protons were furnished by the Wisconsin electrostatic generators then at Los Alamos. The energies of the protons are given in terms of the Li(p,n) threshold which is taken as 1.88 Mev.[7] The automatic regulators kept the voltages constant to about 2 kilovolts so that the error in the neutron energies is of the order of a few kev.

The neutrons from the various photo-neutron sources are fairly monoergic but there is a small distribution in energies due to the momentum carried into the system by the incident gamma-ray.

In general the energy of the emitted neutron depends on the angle (θ) between the direction of the emitted neutron and the direction of the incident gamma-ray. This energy is given approximately by the following relation:

$$E_n=\frac{A-1}{A}(E-Q)+\frac{E}{A}\left[2\left(\frac{A-1}{A}\right)\frac{(E-Q)}{931}\right]^{\frac{1}{2}}\cos\theta,$$

where E is the energy of the gamma-ray in Mev, Q is the neutron binding energy in Mev, and A is the mass number of the initial nucleus. The first term in the equation represents the average energy of the emitted neutrons (and protons in the case of deuterium). The second term gives the variation in the neutron energy as a function of the angle. The neutrons from the MsTh-D source are found to have energies distributed between 170 kev and 224 kev. In this case the maximum energies measured in this work must be reduced by 27 kev in order to obtain the average energy of the emitted neutrons or protons. The number of neutrons per unit energy interval within the above range can be represented approximately by a parabola with its vertex at the average energy.[8]

RESULTS

The relative pulse height distributions in the proportional counter when exposed to the neutrons from the Y-Be source and to neutrons of various energies from the Li(p,n) reaction are shown in Figs. 2 and 3. The abscissa on all graphs is the relative pulse height as determined by pulses of known magnitudes fed into the amplifier and the ordinate is the number of pulses in each given pulse height interval. The points are plotted to correspond to the average value of the pulse height range accepted by each channel. The data in Fig. 2 were obtained with the counter in front of the Li target while those in Fig. 3 were obtained with the counter at an angle of 120° from the forward direction. In the latter run the tail of large pulses is due to higher energy neutrons which were emitted in the forward direction but which have been scattered back by material around the target. Both runs indicate a value of 160 kev for the energy of the Y-Be neutrons. Since the protons from the generator are not strictly monoergic and since the counter subtends a finite angle, one would estimate that the maximum energies of the neutrons incident upon the counter from the Li(p,n) source would be about 2 kev greater than the energy indicated. The maximum energy of the Y-Be neutrons may, therefore, be specified as 162 kev with an error which may be estimated as about 5 kev.

The pulse height distributions with the same counter exposed to the neutrons from the MsTh-D, La-D, and Y-Be sources are shown in Fig. 4. If one assumes that the maximum neutron energies are proportional to the maximum pulse heights, the maximum energy of the neutrons from the MsTh-D and La-D sources are found to be 220 kev and 171 kev, respectively. A direct check on the proportionality between the pulse height and the neutron energy can be obtained from the data shown in Fig. 2. These data indicate that the proportionality is satisfactory within the accuracy of the measurements. They also indicate that the spread in the pulse height distribution introduced by the proportional counter is essentially a certain fraction of the pulse height. The preliminary experiments with nitrogen as well as the data shown in Fig. 5 indicate that this spread in pulse height is about ±5 percent.

Other comparisons of the MsTh-D and La-D neutron energies with that from Y-Be were obtained by observing the protons from the disintegration of deuterium in the proportional counter. The data shown in Fig. 5 were taken with the counter filled with 30 cm of deuterium and 25 cm of hydrogen and those in Fig. 6 with 55 cm of deuterium in the counter. If we again use the maximum pulse heights as a measure of the maximum energies these data indicate that the maximum energies of the neutrons from MsTh-D and La-D are 226 and 174 kev. If it is assumed that the maximum pulse heights are

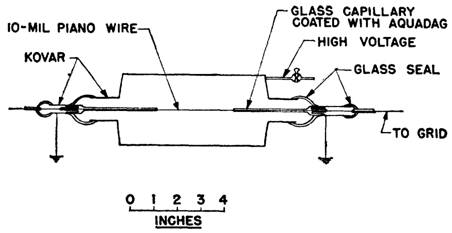

FIG. 1. Proportional counter.

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[6] R. F. Taschek and A. Hemmendinger, Phys. Rev. **73**, 373 (1948).

[7] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944); Shoupp, Jennings, Jones, and Garbuny, Phys. Rev. **75**, 336 (1949); Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).

[8] J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938).

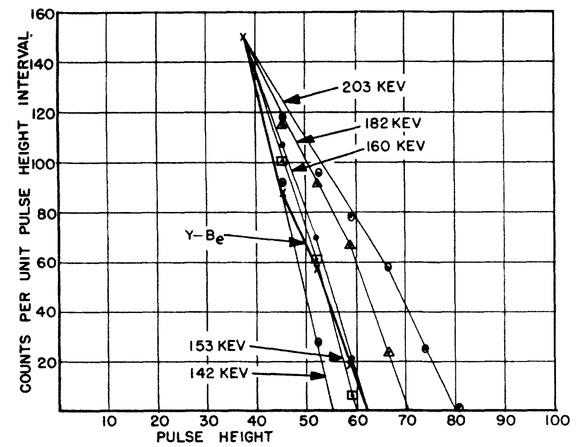

FIG. 2. Pulse height distributions due to Y-Be neutrons and Li(p,n) neutrons at 0°.

increased by the spread of 5 percent but that this pulse spread does not affect the position of the maximum in the observed pulse height distribution curve, the position of the maximum can be used to estimate the average neutron energies from MsTh-D and La-D sources. The average energies estimated in this way are found to be 195 kev and 151 kev. If one uses the values of 224 and 173 for the observed maximum energies reduced by the calculated energy spreads the corresponding average energies are 197 kev and 151 kev. These values are thought to be the most reliable but the uncertainty is difficult to estimate. The measurements seem to be consistent to within about 5 kev but the error could be as large as 10 kev.

A comparison of the pulse height distribution due to 890-kev Li(p,n) neutrons with that due to MsTh-Be neutrons is shown in Fig. 7. The data were taken with the counter filled with 20 cm of hydrogen and 50 cm of argon. The maximum energy of MsTh-Be neutrons can be estimated to be about 840 kev which gives an average energy of 827 kev.

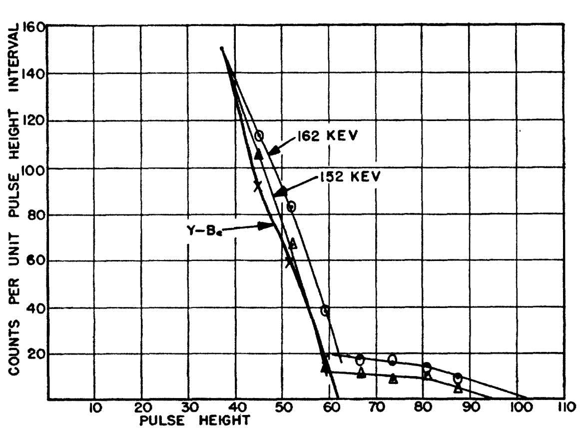

FIG. 3. Pulse height distributions due to Y-Be neutrons and Li(p,n) neutrons at 120°.

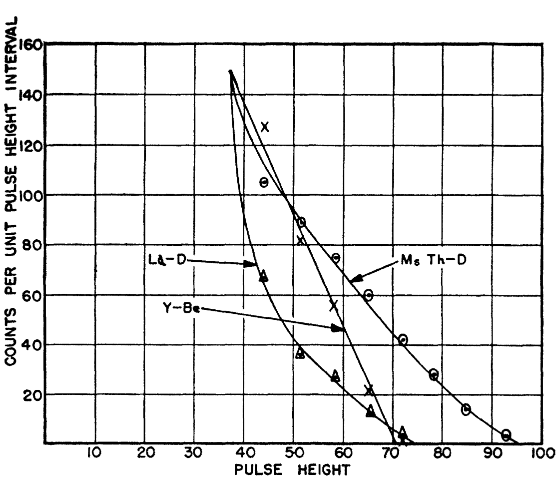

FIG. 4. Pulse height distributions due to neutrons from Y-Be, MsTh-D and La-D sources.

The data on the Sb-Be source were obtained with the same counter filled with 3 cm of hydrogen and ½ cm of methane. With only pure hydrogen in the counter at this pressure, the gas multiplication in the counter was very unstable. The addition of a small amount of methane greatly increased the stability.

A comparison of the pulse heights due to Sb-Be neutrons and those from the Li(p,n) reaction just at threshold is shown in Fig. 8A. The energy of the neutrons from this reaction at the threshold is 29.6 kev. For protons just 1 kev above the threshold, however, the energy turns out to be 40 kev. It is therefore difficult to estimate the effective energy with any accuracy. We have used a value of 35±5 kev, which would give a value of 25 kev for those from Sb-Be. The minimum value for these threshold neutrons would give an energy of 22 kev.

The dependence of the energy of the neutrons on that of the incident protons is much less critical at 120°. At this angle (for 30-kev neutrons) the neutron energy will change by only 1 kev for a 2-kev change in the proton energy. The spread in the neutron energy due to the finite solid angle subtended by the counter (3°) is about 3 kev. The results of the comparison at 120° is shown in Fig. 8B. It appears that the maximum energy of the Sb-Be neutrons is slightly lower than that of the 23 kev neutrons from Li. If one tries to take into account the spread in the energies from the Li(p,n) source one should increase these energies by about 3 kev. The maximum energy of the Sb-Be neutrons can therefore be specified as 25±3 kev and the average energy as 24±3 kev.

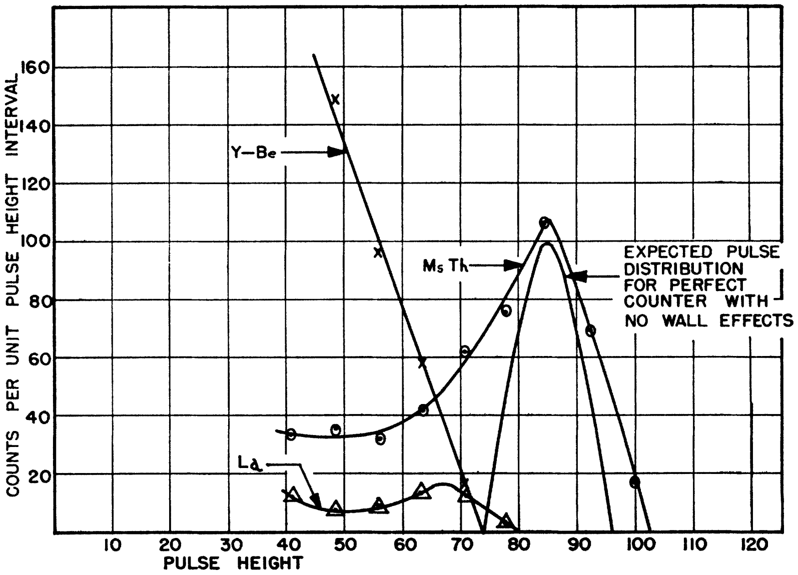

Fig. 5. Pulse height distributions due to Y-Be neutrons and the photo-protons from MsTh and La gamma-rays. The proportional counter was filled with 25 cm of hydrogen and 30 cm of deuterium.

DISCUSSION

Since the neutron energies depend on the difference between the gamma-ray energies and the binding energies of deuterium and beryllium, the present results can be used to obtain additional information about one or the other. The energy of the gamma-ray from MsTh is 2.623±0.005 Mev[9] and has long been considered one of the most accurately known gamma-ray energies. The energy of the strong gamma-ray from the 60-day antimony has recently been measured and found to be 1.708±0.010 Mev.[10] These two sources can be used with the present data on neutron energies to obtain values for the deuterium and beryllium binding energies. The average neutron energies from the Y-Be and the La-D sources can be used to obtain more accurate values for the energies of the effective gamma-rays from these sources. The data on the neutron energies and these simple correlations are summarized in Table I.

The value obtained for the deuterium binding energy (2.229 Mev) is much higher than the usually accepted value of 2.187 Mev and agrees reasonably well with the value (of 2.237 Mev) reported by Bell and Elliott for the energy of the gamma-rays due to the capture of slow neutrons by hydrogen.[11]

The value of 1.681 Mev for the binding energy of beryllium, obtained from the data on the anti-

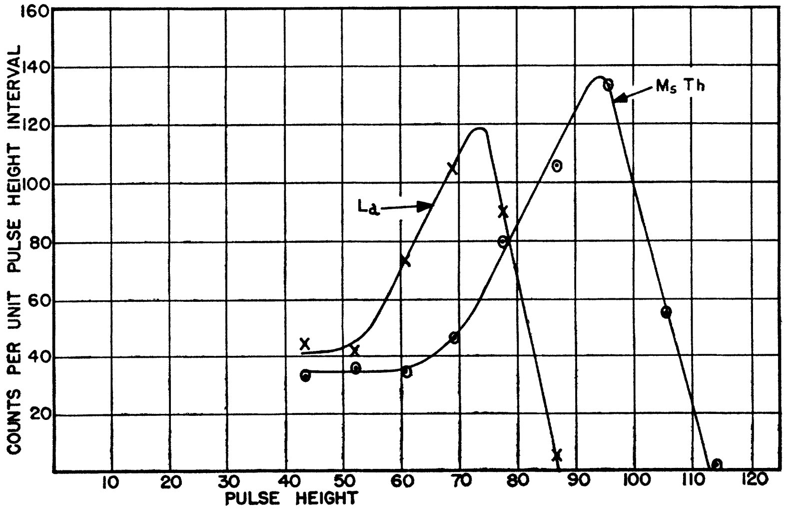

Fig. 6. Pulse height distributions due to photo-protons from MsTh and La gamma-rays with 55 cm of deuterium in the counter.

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[9] C. D. Ellis, Proc. Roy. Soc. **138**, 318 (1932).
[10] C. S. Cook and L. M. Langer, Phys. Rev. **73**, 1149 (1948).
[11] R. E. Bell and L. G. Elliott, Phys. Rev. **74**, 1553L (1948).

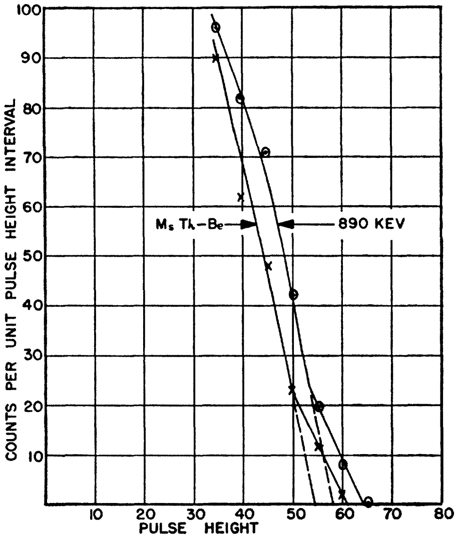

FIG. 7. Pulse height distributions due to MsTh-Be and 890-kev Li(p,n) neutrons.

mony source, is at first rather startling since it represents a difference of about 3 percent from the usually accepted value of 1.63 Mev.[2] It should, however, be more precise than the value obtained for the deuterium threshold.

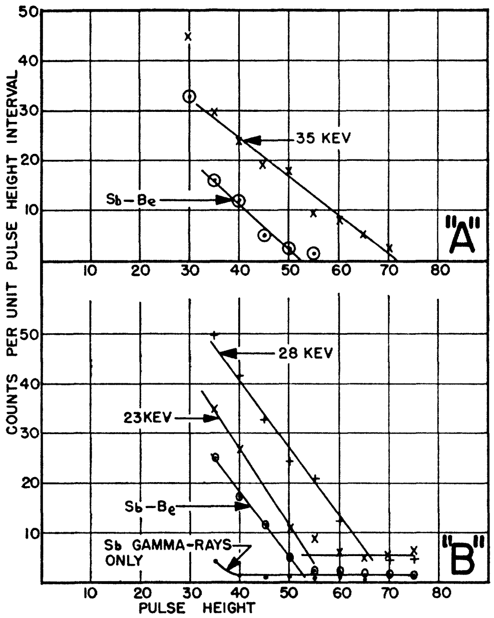

FIG. 8. Data on the comparison of the energy of Sb-Be neutrons with Li(p,n) neutrons at threshold (A), and with Li(p,n) neutrons at 120° (B).

TABLE I. Neutron energies.

Neutron source	Gamma-ray energy (Mev)	Average neutron energies (kev)				Thresh-olds
		Ref	This work	Other work	Ref	
MsTh-D	2.623 ±0.005	9	197 ±10	218	2	2.229 ±0.020
MsTh-Be	2.623		827 ±30			1.693 ±0.030
Sb-Be	1.708 ±0.010	10	24 ±3	29 ±15	1	1.681 ±0.013
Y-Be	1.92 ±0.03	a	158 ±5	220	c	1.74
	1.89 ±0.05	b				1.71
	1.859 ±0.015	†				
La-D	2.3	d	151 ±8	160 ±20	1	
	2.531 ±0.010	†				

† These gamma-ray energies are based on the present neutron measurements.
[a] J. Reginald Richardson, Phys. Rev. **60**, 188 (1941).
[b] Downing, Deutsch, and Roberts, Phys. Rev. **60**, 471L (1941).
[c] G. Scharff-Goldhaber, Phys. Rev. **59**, 937A (1941).
[d] W. Rall and R. G. Wilkinson, Phys. Rev. **71**, 321L (1947).

There are two other measurements which can be used to correlate these two binding energies. One is the difference between the binding energies as obtained from the reaction energy for the $Be^9(p,d)Be^8$ reaction. The most recent value reported for this energy is 0.555±0.003 Mev.[12] The present value of 1.681±0.013 for the beryllium binding energy would, therefore, lead to a value of 2.236±0.014 for the binding energy of deuterium which is essentially the same as that obtained by Bell and Elliott. The other measurement which seems to be well established is the ratio of the two thresholds. The value of this ratio is 1.338±0.004.[13] This ratio and the present value for the beryllium binding energy would give a value of 2.249 Mev for deuterium. Although this value seems somewhat high, it is in agreement with the preceding value within the probable experimental errors. It seems likely that the energy assigned to the antimony gamma-ray may be slightly high. Further measurements on this gamma-ray, as well as that from the yttrium, would be desirable in order to use the present neutron energies to establish the binding energy of beryllium with greater precision.

The difference in energy between the Y and Sb gamma-rays can be determined in terms of the difference between the energies of the neutrons from the Y-Be and the Sb-Be sources. The present neutron measurements indicate that the energy of the gamma-ray from Y is 0.151 Mev greater than that from Sb. The energy obtained in this way is, therefore, 1.859±0.015 Mev. Similarly the energy of the La gamma-ray is found to be 0.092 Mev less

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[12] Tollestrup, Lauritsen, and Fowler, Phys. Rev. **75**, 1463 (1949); Allison, Skaggs, and Smith, Phys. Rev. **57**, 550L (1940).

[13] B. Waldman and W. M. Miller, Phys. Rev. **74**, 122A (1948).

than that from MsTh and can be specified as 2.531 ± 0.010 Mev.

ACKNOWLEDGMENTS

The author is indebted to Dr. E. Segrè and his group for making these sources available for this work, to Dr. A. Hemmindinger for his collaboration in the work with the Sb-Be source, and to Dr. J. H. Williams for his support and interest in this work.

Note added in Proof.—Peacock and Jones have reported a value of 1.853 ± 0.03 for the energy of the yttrium gamma-ray which is in agreement with the value deduced from the present work (W. C. Peacock and J. W. Jones, Plutonium Project Record CNL14 (February, 1948).

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Neutrinos from P 32

CHALMERS W. SHERWIN
Department of Physics, University of Illinois, Urbana, Illinois

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Sources of P 32 which come close to being true monolayers are prepared by evaporation in a vacuum. The characteristics of these sources are maintained for 5 to 10 days with the aid of radiant heating. Surface charges are neutralized by periodic "baths" of thermal electrons. The momentum of the electrons is measured with a magnetic spectrometer and the momentum of the recoil ions is measured by observing their time of flight in a field free space.

The momentum measurements show that the missing momentum disappears in one package. Separate energy measurements determine the amount of energy which disappears. The observed ratio of the missing energy to the missing momentum is equal to the velocity of light (±20 percent), as required by the hypotheses that one neutrino is emitted in beta-decay.

After experimentally determined corrections are made for the effects of surface scattering of the recoil ions, it is concluded that the missing momentum vector (i.e., the neutrino) most probably enters the same hemisphere as the electron. The experimental points fit best on a curve of the form, $(1+v/c\cos\theta)$. This is in disagreement with previous tentative conclusions by the author which are now shown to be in error due to surface losses and scattering of the recoil ions.

I. INTRODUCTION

In a recent review article, H. R. Crane[1] has described the search for the neutrino through its effect on the parent nucleus during the process of beta-decay. Experiments, performed over the past decade, have conclusively shown that momentum is not conserved in beta-decay, and there is some more or less tentative evidence[2,3] that the neutrino direction is either approximately random, or favors the opposite hemisphere with respect to the electron.

Both Crane[1] and Allen[2] point out that no recoil experiments have yet demonstrated that a single neutrino is emitted in beta-decay. However, in the Fermi theory[4] the bell shaped momentum distribution of the electrons is a consequence of the emission of two fast particles. The main factor which controls the shape of the electron momentum spectrum at high momenta is the number of cells in momentum space that are available to the electron and the neutrino.[5] If there were two neutrinos the electron spectrum would be quite different than observed.[6] Recoil experiments are also capable of giving information on this point, either by observing monoenergetic recoils from K capture as Crane[1] has suggested, or as in the present experiments, observing monoenergetic recoils associated with monoenergetic electrons.

An important objective of these experiments is to determine as much as possible about the angular correlation between the electron and the neutrino. Different forms of the neutrino-electron interaction predict different angular correlations.[7] Also the angular momentum change which determines the "forbiddeness" of the transition should affect the neutrino-electron angular correlation. Hamilton[7] shows that as the forbiddeness increases, the neutrino tends to go more and more in the same direction the electron, this correlation being greatest when the electron and neutrino momenta are equal. This effect can be visualized by the following simple classical picture. There is only a definite amount of energy available for the electron and the neutrino. Consequently, a limited amount of linear momentum can be carried by the two particles. If this linear momentum leaves the

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[1] H. R. Crane, Rev. Mod. Phys. **20**, 278 (1948).

[2] James S. Allen, Am. J. Phys. **16**, 451 (1948); Allen, Paneth, and Morrish, Phys. Rev. **75**, 570 (1949).

[3] Chalmers W. Sherwin, Phys. Rev. **73**, 216 (1948); **73**, 1173 (1948).

[4] Enrico Fermi, Zeits. Physik **88**, 161 (1934).

[5] Emil J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

[6] J. Blatt, private communication.

[7] Donald R. Hamilton, Phys. Rev. **71**, 456 (1947).