showed that the variation in the dose monitoring was less than 1.5%.

The cross section obtained was compared with cross sections computed on the basis of two models for the Li^6 nucleus.[19,20] One model considered Li^6 as an alpha-particle core with a neutron and proton independently bound, the other with a deuteron bound to the alpha-particle core. Both of these calculations are based on the general phenomenological formulation of the interaction between the nuclear fields and the electromagnetic field.[21] The calculations considered electric and magnetic interaction contributions to the cross section. Neither of the models gives a cross section which agrees with the experimental results.

[19] G. E. Bing, Ph.D. thesis, Case Institute of Technology, 1954 (unpublished).

[20] E. F. Corome, Ph.D. thesis, Case Institute of Technology, 1954 (unpublished).

ACKNOWLEDGMENTS

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[21] L. L. Foldy, Phys. Rev. 92, 178 (1953).

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$C^{12}(n,p)B^{12}$ Cross Section for 14.9- to 17.5-Mev Neutrons

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The cross section for the $C^{12}(n,p)B^{12}$ reaction has been measured for 14.9- to 17.5-Mev neutrons. The neutrons were obtained from the $T(d,n)He^4$ reaction and their flux density was determined by counting the recoil alpha particles or by counting the neutrons directly with a $Li^6I(Eu)$ scintillation counter. A cylindrical plastic scintillator 5 inches in diameter and 3 inches in length served as the carbon-containing target and permitted the counting of the B^{12} decay beta rays in nine consecutive 7-msec intervals during the "beam off" period of a pulsed neutron beam cycle. The cross section rises from slightly above the reaction threshold of 13.6-Mev to a value of 29.09±4.36 millibarns at 17.5-Mev. The B^{12} beta-decay half-life has been redetermined as 18.87±0.50 milliseconds.

INTRODUCTION

Boron-12 has been observed to decay by emission of beta particles having a maximum energy of 13.4 Mev and a half-life whose measured values have ranged from 18 to 27 milliseconds.[1,2] Detailed studies[3] of the decay have shown that 97% of the beta transitions go directly to the ground state of C^{12}. For most of the studies of this decay, the B^{12} has been formed by the $B^{11}(d,p)B^{12}$ reaction. However, it is also possible to form the radioactive B^{12} by the $C^{12}(n,p)B^{12}$ reaction, and the cross section for this reaction is of some general theoretical interest. Mass determinations ascribe a Q value of -12.5 Mev for this reaction and a neutron energy threshold of 13.6 Mev. An attempt to observe this reaction has been made by Jelley and Paul,[4] who used the neutrons from 0.9-Mev deuterons on a lithium target; the occurrence of the reaction was not established with certainty. An earlier measurement at this laboratory[5] determined the cross section as 29±23 millibarns for neutrons of energy 17.3-Mev, but the method used the inefficient detection of the 4.43-Mev gamma rays from the de-excitation of the first excited state of C^{12} and it was not possible to obtain satisfactory accuracy. The present report describes a measurement of the cross section at several neutron energies using a method in which the beta rays are detected with high efficiency. In the course of this work the half-life for the beta decay has been redetermined.

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

[2] B. C. Cook, Phys. Rev. 106, 300 (1957).

[3] Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. 107, 508 (1957).

[4] J. V. Jelley and E. B. Paul, Proc. Cambridge Phil. Soc. 44, 133 (1948).

EXPERIMENTAL APPARATUS AND TECHNIQUES

It was decided to measure the $C^{12}(n,p)B^{12}$ cross section by counting the energetic beta particles in the time interval from 7 to 70 milliseconds after the bombardment of a carbon-containing target with monoenergetic neutrons. The carbon was contained in a solid plastic scintillator, which as a component of a scintillation spectrometer made it possible to record the pulse-height distribution with a 100-channel pulse-height analyzer and also to record the integral counts

[5] Kreger, Bolotin, and Edelsack, Bull. Am. Phys. Soc. Ser. II, 1, 325 (1956).

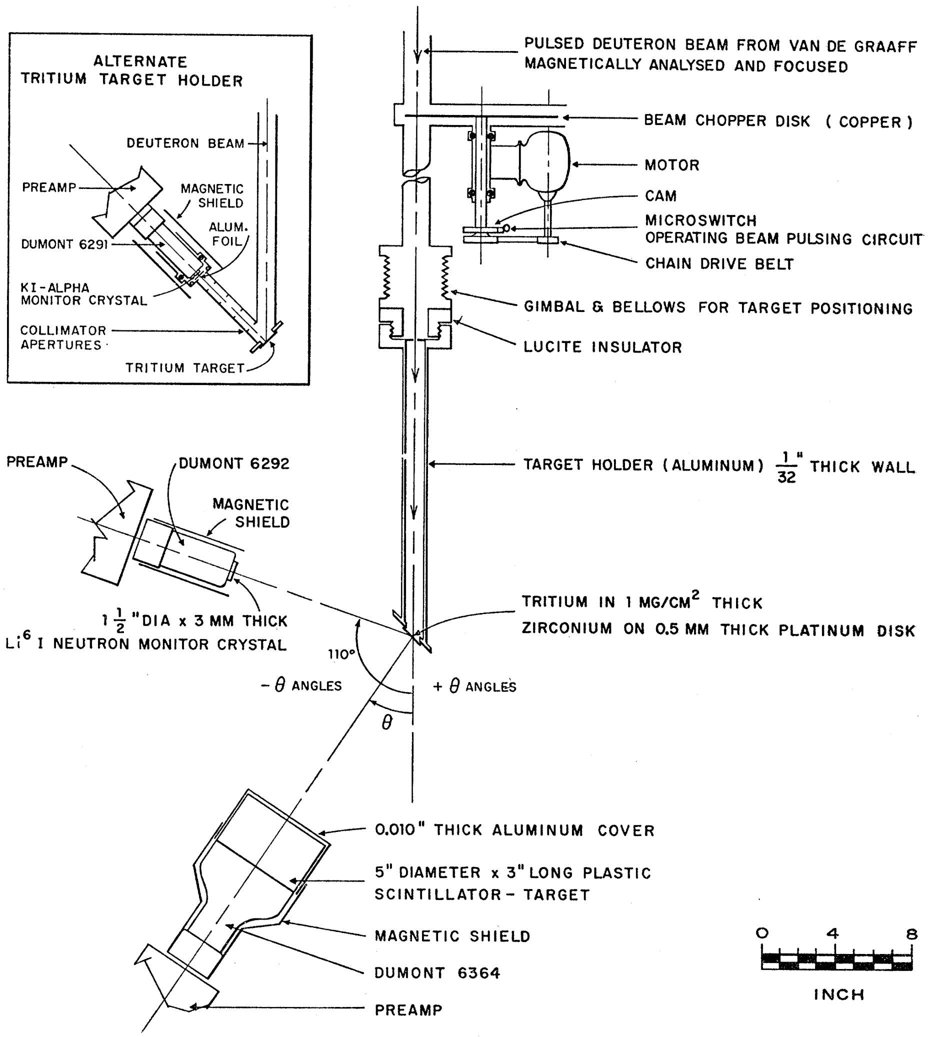

FIG. 1. Arrangement of the neutron source and counters. The higher neutron energies were obtained with the scintillator at 0° and one lower energy with it at the "$+\theta$" angle of 60°. The insert shows the target holder as used with the KI recoil alpha particle counter. The beam chopper disk has a round opening near its periphery which allows the beam to pass uninterrupted for 4.7 msec of each 131.7-msec interval.

with a nine-channel time analyzer. Figure 1 shows a plan view of the experimental arrangement.

Suitable neutrons for bombarding the carbon target for a length of time which is short compared to the 18.87-msec half-life (the value obtained in this work) were obtained from the $T(d,n)He^4$ reaction using the magnetically-deflected, pulsed deuteron beam from the N.R.D.L. Van de Graaff accelerator. The deuteron beam was pulsed electronically at the ion source at the rate of approximately 7 times per second, and a small residual beam which persisted during the "beam off" time was eliminated by the mechanical "chopper" whose open period was synchronized with the "beam on" interval. The variation of neutron energy was obtained by changing the incident deuteron energy from 0.61 to 1.58 Mev and the angle of observation relative to the deuteron beam's axis from 0° to 60°. The differential cross section values for the $H^3(d,n)He^4$ reaction of Bame and Perry[6] were used to correlate the data at different angles. The tritium target consisted of approximately 0.4 curie of H^3 in a 1-mg/cm^2 layer of zirconium, circular in form with a radius of 0.5 cm. The zirconium was evaporated onto a 0.25-mm thick foil of platinum. The deuteron beam struck the target at an angle of 45 degrees, so that the effective thickness of the tritium-bearing layer was 1.41 mg/cm^2. The deuteron energy loss in passing through the zirconium layer varied from 360 to 190 kev and was taken into account in determining the average deuteron energies given in Table I. The beam pulse on the tritium target was determined to be of about 1-msec duration and the current was approximately 30 microamperes.

The time-integrated neutron flux density was determined for the average value of the deuteron energy of 0.43 Mev by counting the recoil alpha particles from the $T(d,n)He^4$ reaction. This method is described in detail elsewhere.[7] At higher deuteron energies, it was not possible to monitor the alpha particles and the

[6] S. J. Bame, Jr., and J. E. Perry, Jr., Phys. Rev. **107**, 1616 (1957).

[7] B. D. Kern and W. E. Kreger, Phys. Rev. **112**, 926 (1958).

TABLE I. Summary of data and results.

E_n(aver.) (Mev)	ΔE_n (Mev)	E_d(aver.) (Mev)	Angle (degrees)	Time-integrated neutron flux density at midplane (n/cm^2)	Correction factor	No. of β's/7 msec at $t=0$	Discriminator setting (volts)	Fraction of β's counted	Cross section (mb)
14.92	$+0.48$, -0.47	0.43	60	3.110×10^5	0.79	2030	40	0.334	1.93 ± 0.25
15.68	$+0.38$, -0.47	0.43	0	2.924×10^5	0.77	5530	40	0.334	5.69 ± 0.68
16.54	$+0.21$, -0.29	0.87	0	1.471×10^5	0.77	2360	65	0.082	19.56 ± 2.74
17.51	$+0.14$, -0.20	1.48	0	1.041×10^5	0.81	2480	65	0.082	29.09 ± 4.36

neutrons were counted directly with a $Li^6I(Eu)$ scintillation detector. It was possible to count the pulses in the scintillator due to the $Li^6(n,t)He^4$ reaction for which the cross section has been measured[7] in the energy range used in this experiment. Using the $T(d,n)He^4$ differential cross sections,[6] it was then possible to calculate the time-integrated neutron flux density at the midplane of the plastic scintillator.

The plastic scintillator was composed mainly of polystyrene[8] and was in the form of a cylinder 5 inches in diameter and 3 inches in length. It was supported with its nearer face 11.4 inches from the tritium target, as shown in Fig. 1. It has the advantage of containing no materials which, when bombarded by high-energy neutrons, produce radioactivities with half-lives in the millisecond region where they might be confused with B^{12}. The scintillator was optically coupled to a DuMont 6364 photomultiplier tube which was supported by a light weight arm mounted on a turntable which permitted rotation of the scintillator about the tritium target in a plane containing the deuteron beam's axis. The large size of the plastic scintillator was chosen since the path length of beta rays of maximum energy (13.4 Mev) is 2.34 inches and it is desired that the output pulse-height distribution be as much like the actual beta-ray spectrum as possible. The carbon content of the scintillator was calculated from the dimensions, the density, the formulas for the constituent hydrocarbons, and the C^{12} percentage abundance in carbon.

The beta rays from the decay of B^{12} were counted to determine the number of $C^{12}(n,p)B^{12}$ reactions which occurred when a monitored number of neutrons passed through the sample. The schematic diagram of the electronic apparatus is shown in Fig. 2. The bombardment and counting cycle, shown in the lower left hand

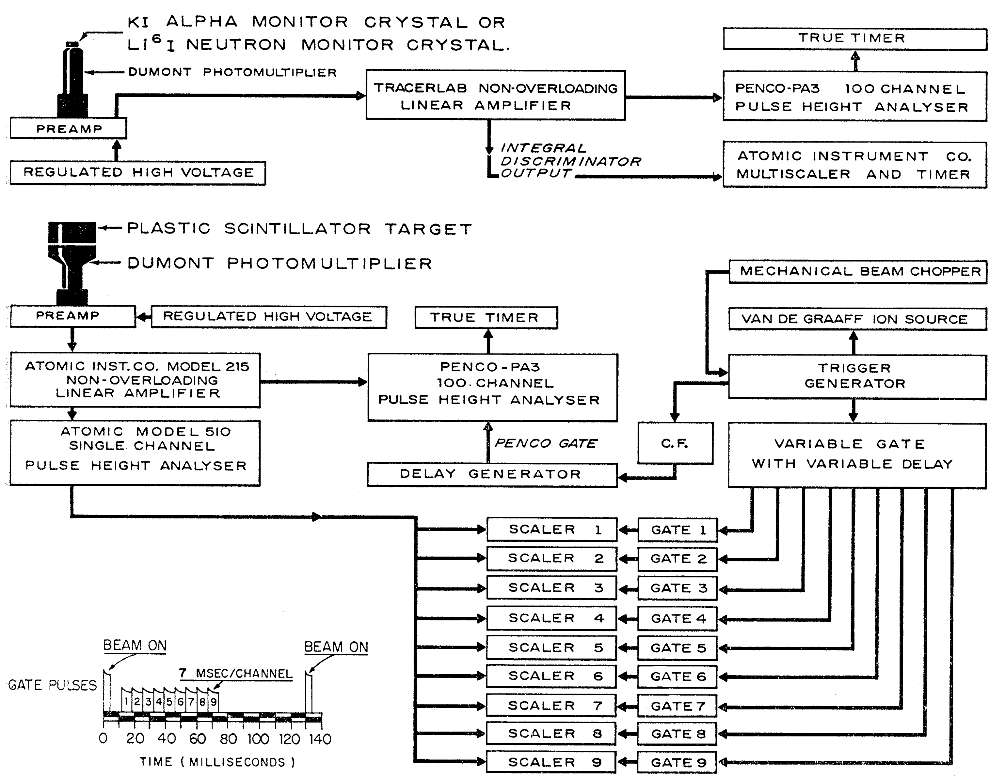

FIG. 2. Block diagram of the electronic circuits. The lower left hand corner diagram illustrates the time intervals in the "irradiate, then count" cycle which was repeated 7.59 times per second.

[8] L. F. Wouters, University of California Radiation Laboratory Report UCRL-4516, 1955 (unpublished).

corner of this figure, made possible the integration of counts over a large number of "irradiate, then count" cycles. The beta-ray pulse-height distribution in the plastic scintillator was determined with the 100-channel pulse-height analyzer, which was calibrated so that 13.4-Mev beta rays produced pulses of approximately 95 volts. In each of many repeated cycles, the analyzer received pulses starting 15 msec after the deuteron beam was turned off, and the pulse-height distribution due to the B^{12} beta rays and background was recorded for a 15-msec interval. In order to determine the fraction of this distribution, shown in Fig. 3, which was due to the background, a 5-volt differential pulse-height count was taken in the nine-channel time analyzer for consecutive pulse-height intervals from 6.5 to 31.5 volts. The fraction of the total count which decayed with the 18.9-msec activity was found for the mean time of the interval in which the pulse-height distribution (Fig. 3) had been obtained, and the ordinates of Fig. 3 then were reduced by this factor. The results are indicated by the squares in Fig. 3. For the lowest setting at 6.5 volts, the background was so high that the decay could not be observed. The corrected curve has been extrapolated to the left without change of slope. This seems a reasonable assumption as those beta rays which do not lose all of their energy in the scintillator tend to increase the number of pulses in the low-energy end of the distribution. With the background correction and the extrapolation having been made, the pulse-height distribution was taken as including all of the B^{12} decay beta rays. At the higher pulse heights the background becomes nearly the same as that which was obtained by rotating the scintillator to an angular position at 130° relative to the deuteron beam where the neutron energy is below the threshold for this reaction. The pulse-height distribution at this position is shown in Fig. 3.

A typical time analyzer count is shown in Fig. 4. All the counts above a discriminator setting of 40 volts are represented in each of the nine consecutive 7-msec time intervals described in Fig. 2. Having used the 130° counts as the background, in this sample the half-life was found to be 18.6 msec; the average for seven determinations similar to that of Fig. 4 is 18.87 ±0.50 msec, where the uncertainty is the mean deviation. By extrapolating the decay curve back to the end of the bombardment, the initial decay rate was found and the number of B^{12} nuclei whose decay produced pulses of voltage greater than 40 volts was calculated. This number, multiplied by the ratio of the total number of counts in the corrected distribution of Fig. 3 to the number of counts in the portion above 40 volts, is then the total number of B^{12} nuclei formed. At the higher deuteron energies, a discriminator setting of 65 volts was used in order to reduce the effect in the decay curve of an increase in the number of background pulses between 40 and 65 volts.

A typical data-taking cycle required 15 to 30 minutes time and resulted in about 150 000 counts in the recoil alpha particle counter and a mid-time (channel 4) time analyzer count of 1800 counts for the 40-volt discriminator integral count. The spread of neutron energies

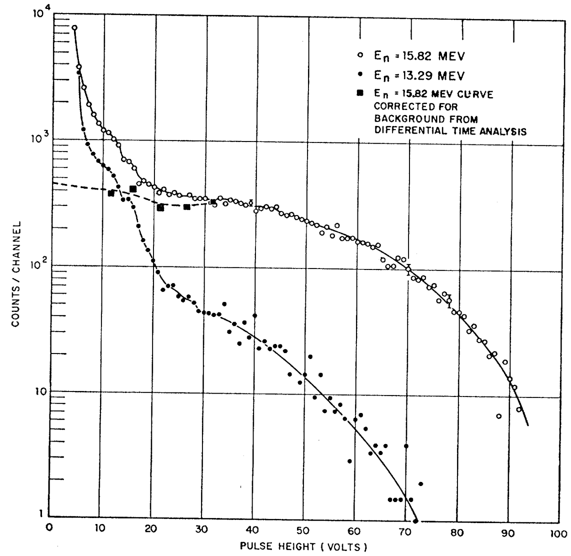

FIG. 3. The B^{12} beta-ray pulse-height distribution from the 5-in. diameter by 3-in. high plastic scintillator. The dots give the background distribution at the 130° angular position (E_n =13.29 Mev). The squares locate the points which have been corrected for the background by the time analysis method discussed in the text.

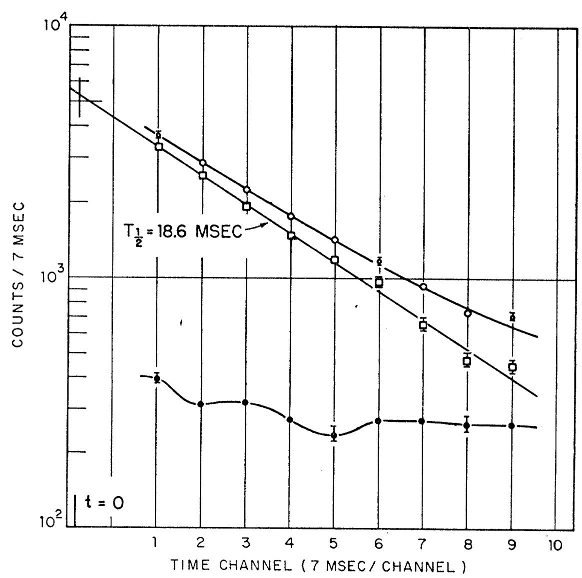

FIG. 4. Example of the decay of the B^{12} beta rays. The averaging of seven sets of data similar to this one gives the half-life as 18.87±0.05 msec. The circles in this figure represent the data from the nine-channel time analyzer for those beta rays with energies greater than approximately 5.5 Mev and producing pulses above the 40-volt discriminator level. The dots are the background taken at the 130° angular position and the squares give the decay rate corrected for this background.

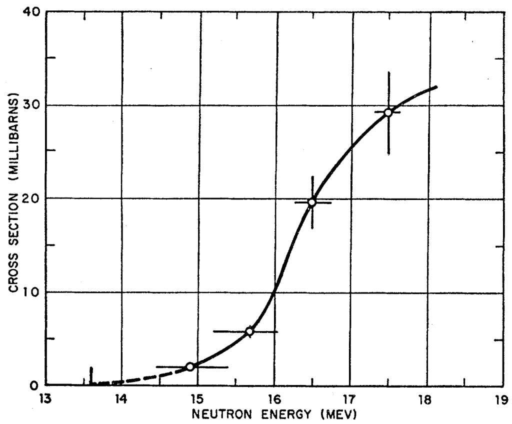

FIG. 5. Cross section for the $C^{12}(n,p)B^{12}$ reaction. The horizontal bars indicate the spread in neutron energy.

ranged from 0.34 to 0.95 Mev and was due partly to the deuteron energy loss in the zirconium target and partly to the angle subtended by the plastic scintillator.

RESULTS AND DISCUSSION

A summary of the data and the calculated cross-section values are listed in Table I. The cross sections are shown as a function of neutron energy in Fig. 5.

A significant correction has been made for the reduction of the neutron flux by scattering in the material of the plastic scintillator. Elastic scattering from carbon and hydrogen nuclei at certain angles, and inelastic scattering from carbon nuclei, can reduce the neutron energy to a value which is below the threshold for the $C^{12}(n,p)B^{12}$ reaction. Scattering cross sections[9–11] were used to calculate for each value of the incident neutron energy a correction factor by which the uncorrected time-integrated neutron flux density at the mid-plane of the scintillator should be multiplied. These are given in Table I.

The sources of uncertainty in the final cross section values and an estimate of their magnitudes are (1) geometry, 1%; number of C^{12} nuclei in the scintillator, 2%; statistical error in the monitor counts, 1 to 4%; extrapolated value of the B^{12} decay curve, 5 to 8%; fraction of the beta-ray pulse-height distribution counted, 10%; angular factor, from reference 6, 3.5%; correction for neutron scattering and absorption, 4%; and cross section for the $Li^6(n,t)He^4$ reaction, at the two higher deuteron energies, 5.7%. As these quantities all enter into the cross-section calculation in a multiplicative fashion, the resulting uncertainty was taken as the square root of the sum of the squares. The uncertainties range from 12 to 15%.

There are no other measurements of this cross section with which to compare the present value. It is interesting to note that a recent report[12] of the total cross section for the scattering and absorption of neutrons in this energy region indicates an increase in the cross section starting at 14 Mev. However, this total cross section goes up by 170 mb between 14.2 and 15.7 Mev, whereas the (n,p) cross section goes up only by 5 mb. Thus, there must be some cause for this increase in the total cross section other than the contribution from the (n,p) reaction.

Of the several previously obtained values for the B^{12} half-life, the present value of 18.87 ± 0.50 msec is in closest agreement with that of reference 1, which is $18_{-1.3}^{+1.5}$ msec.

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[11] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
[12] J. P. Conner, Phys. Rev. **109**, 1268 (1958).