where all quantities are known except $\epsilon(E_2)$. Because of the high efficiency of the NaI(Tl) detector for the low-energy E_2 photons, $\epsilon(E_2)$ is determined primarily by the ability of the fast coincidence circuit to accept the photomultiplier pulses resulting from these photons. To measure this efficiency, a source of annihilation photons was placed between the two detectors and the pulse-height distribution from the E_2 detector was observed with and without gating the 20-channel analyzer from the output of the fast coincidence circuit. After normalization the ratio of these two pulse-height distributions gives $\epsilon(E_2)$ as shown in Fig. 8. Upon integration, the predicted rates for $\theta_1=\theta_2=60°$, $\phi=96°$ and $\theta_1=\theta_2=40°$, $\phi=120°$ are 1.2×10^{-3}/sec and 1.8×10^{-3}/sec, respectively.

The corresponding observed rates were 3.0×10^{-3}/sec and 4.4×10^{-3}/sec. Residual bremsstrahlung counts and the assumption that $\epsilon(E')\approx\epsilon(E_2)$ most probably account for the difference.

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Cross Section for the $Be^9(n,\alpha)He^6$ Reaction

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The cross section for the reaction $Be^9(n,\alpha)He^6$ has been measured for neutron energies of 0.7 Mev (threshold) to 4.4 Mev. The cross section exhibits a smooth rise from less than 0.1 mb at the expected threshold to a broad maximum of 104±7 mb at 3.0 Mev, followed by a gradual decrease to 70 mb at 4.4 Mev.

INTRODUCTION

THE endoergic reaction $Be^9(n,\alpha)He^6$ is conveniently studied by the use of a pulsed neutron source since the radioactive He^6 decays to Li^6 by β^- ($E_{max}=3.5$ Mev) with an 0.8-second half-life. Allen, Burcham, and Wilkinson[1] determined the cross section by counting the activation of Geiger counters with walls made of beryllium metal when the counters were subjected to periodic fast-neutron irradiation. The cross section for neutron energies of 2 to 4 Mev showed no large variation and was in absolute value about 50 millibarns. An estimate of the uncertainty in absolute cross section was not given. Battat and Ribe,[2] performing a similar activation experiment, found the cross section to be 10±1 millibarns for 14-Mev neutrons. A preliminary report on the shape of the cross-section curve for neutron energies of 3.3 to 6.1 Mev has been given by Sattar *et al.*[3] We wish to report the measurement of the absolute cross section for neutron energies of 0.7 Mev (threshold) to 4.4 Mev.

EXPERIMENTAL METHOD AND RESULTS

Monoenergetic neutrons were produced by the use of the $T(p,n)$ and $Li(p,n)$ reactions. Protons of variable energy were obtained from the ORNL 5.5-Mv Van de Graaff generator. An electronic timer and an electrostatic proton beam deflector provided a repetitive cycle for short neutron bombardment and beta-ray counting of the beryllium sample. Further details of the method have been given in a report of a similar experiment on the excitation of the 0.8-second isomeric state in Pb^{207} by inelastic neutron scattering.[4]

A new timing sequence, which resulted in higher counting rates, was used for some of the measurements reported here.[5] This sequence was a continuous repetition of cycles in which the sample was alternately irradiated for a time T and counted for a time T. The interval T was made quite short (~10 milliseconds) compared to the half-life. In this case the average counting rate is independent of T, being equal to one-fourth the saturated counting rate. The anthracene scintillation counter for detecting the β particles and its amplifier were on continuously and this resulted in extremely high counting rates during the neutron irradiation intervals. In order to insure that rapid recovery would be made by the amplifier between the high counting rates associated with the beam-on period and the moderate to low counting rates of the beam-off

[1] Allen, Burcham, and Wilkinson, Proc. Roy. Soc. (London) **A192**, 114 (1947).
[2] M. E. Battat and F. L. Ribe, Phys. Rev. **89**, 80 (1953).
[3] Sattar, Morgan, and Hudspeth, Phys. Rev. **100**, 960 (1955).
[4] P. H. Stelson and E. C. Campbell, Phys. Rev. **97**, 1222 (1955).
[5] See Oak Ridge National Laboratory Progress Report ORNL-1879 (unpublished), p. 19 and Oak Ridge National Laboratory Progress Report ORNL-2076 (unpublished), p. 32.

TABLE I. Information on the spread of the neutron energies used to measure the $Be^9(n,\alpha)$ cross section.

Source	Neutron energy (Mev)	Energy spread (kev)
$T(p,n)$	1.7	70
	4.4	55
$Li(p,n)$ first run	0.7	100
	3.0	70
$Li(p,n)$ second run	0.5	50
	2.2	40

period, a fast Fairstein double-delay-line amplifier[6] was used. An electronic gate prevented amplifier pulses from reaching the scaler during the beam-on period. To insure that no counts associated with neutron bombardment of the crystal were recorded, the pulse gate remained closed for several microseconds after the end of the beam-on interval. In addition, background runs were made by removing the beryllium sample and the background counting rate, normalized to standard neutron flux, was subtracted from the observed normalized counting rate with the Be sample in place.

A beryllium metal sample in the form of a cylinder $\frac{3}{16}$ inch in length and $1\frac{1}{8}$ inches in diameter was used to study the shape of the cross section curve. Both the target thickness and the finite solid angle subtended by the sample contributed to the energy spread of the neutrons passing through the sample. Two lithium targets and a tritium gas target were used in the experiment and information on the neutron energy spread for these targets (including the finite solid angle contribution) is given in Table I.

To obtain the absolute cross section it is necessary to know the neutron flux passing through the sample and the efficiency with which the subsequent β particles are detected. Two methods were used to determine the flux and two types of β counters were employed.

In one arrangement, a thin disk of beryllium foil was placed directly against the end of an anthracene scintillation counter to give 2π counting geometry. The anthracene crystal was a cylinder $1\frac{1}{2}$ in. in diameter and $\frac{3}{4}$ in. in length. A 3-mil aluminum foil covered the crystal to serve as light shield and light reflector. The beryllium disk (29.1 mg/cm^2 thick and $1\frac{1}{8}$ in. in diameter) was thin enough so that self-absorption was negligible ($<1\%$). The pulse-height spectrum of the β particles is shown in Fig. 1. The shape of the β spectrum of He^6 has been studied by Wu *et al.*[7] They observed a linear Kurie plot with an end point of (3.50 ± 0.05) Mev. Therefore, for comparison, the calculated shape of $N(E)$ *vs* E for an allowed transition is also shown in Fig. 1.[8] As is to be expected, the observed spectrum is somewhat degraded. While a small part of this degradation results from energy losses suffered by the β particles in the Be foil and Al foil, most of it arises from β particles which are scattered out of the crystal before expending all of their energy. The background counting rate caused by activities generated in the target rises rapidly below 0.5 Mev. For this reason, the cross-section measurements were made with the bias set to accept all pulses larger than 0.60 Mev. Still, the shape of the spectrum below 0.60 Mev must be known to obtain the fraction of the pulses recorded. Because of the high background the data in this region are poor. The solid curve is our best estimate of the shape. The dashed curves are taken as upper and lower limits for the shape in this region. Integration of the areas gives the result that $(83\pm3)\%$ of the pulses are counted with a bias setting of 0.60 Mev. With this bias setting, the background counting rate is approximately 5% of that with the Be foil.

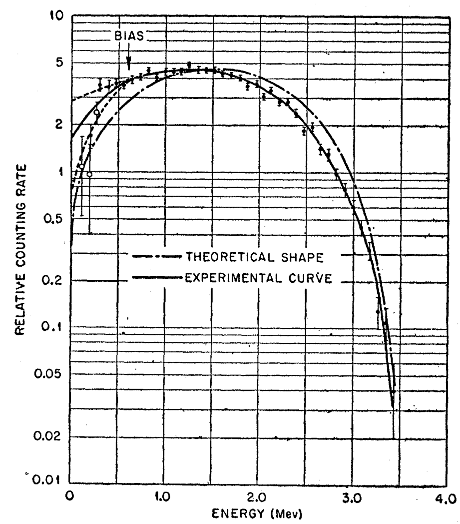

FIG. 1. The pulse-height spectrum of β particles from decay of He^6 observed with a 2π-geometry anthracene scintillation counter. The theoretical shape is also shown. The solid curve is the best estimate of the experimental shape. The dashed curves at low pulse heights are taken as upper and lower limits to the shape in this region.

Fast neutrons which traverse the thin Be foil enter the thick anthracene crystal. This gives rise to a reflected neutron flux of somewhat degraded energy which may contribute to the activation of the Be foil. This "albedo" effect is largest at the higher neutron energies where the cross section is decreasing with increasing neutron energy. A rough estimate which considered only the reflection caused by single collisions with the carbon atoms of the crystal gave a few percent contribution to the activation of the Be foil. To determine this albedo correction experimentally, a mechanical flip-flop device, driven by a solenoid and spring combination, was built. This device quickly moved the foil back and forth between an exposure position close to the target and a counting position several inches

[6] E. Fairstein, Revs. Sci. Instr. **27**, 475 (1956).
[7] Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).
[8] Dismuke, Rose, Perry, and Bell, Oak Ridge National Laboratory Report ORNL-1222 (unpublished).

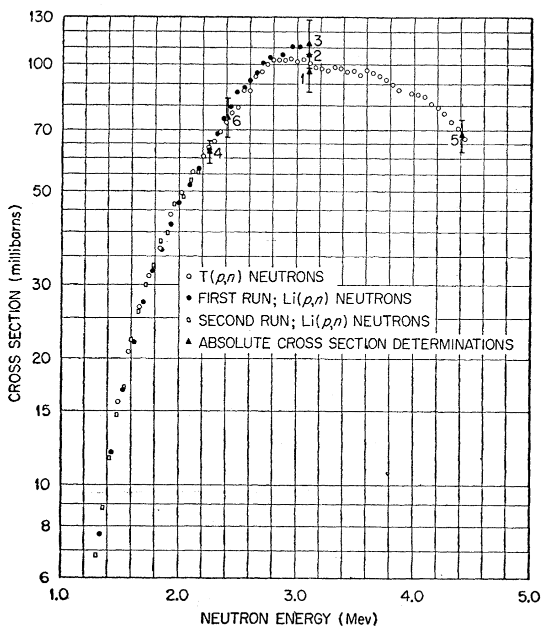

FIG. 2. The cross section for the $Be^9(n,\alpha)$ reaction as a function of neutron energy. The points identified by numbers are absolute cross-section measurements which are summarized in Table II. Information on the neutron energy spread for the points which determine the shape of the curve is given in Table I.

away. The movement of the foil was synchronized with the beam deflector and counting time control circuits with $T=1$ sec. It was then possible to expose the foil in its usual location to the fast-neutron flux but without the anthracene crystal behind it. The foil was quickly moved and counted at the new location several inches away. When this counting rate was compared to that observed when a "dummy" anthracene crystal of the same size as the detector crystal was placed directly behind the foil during the exposure, it was found that the albedo correction was $(5\pm1)\%$ for incident neutrons of 3.11-Mev energy. An albedo correction which varied from 2% at $E_n=2.0$ Mev to 9% at $E_n=4.4$ Mev was applied to the shape of the cross-section curve.

The cross section at 3.11-Mev neutron energy determined by the use of the 2π anthracene counter was about a factor of two larger than that found in the early work of Allen *et al.*[1] Although, as previously mentioned, no estimate is given of the uncertainty of their determination so that a factor of two might not be unreasonable, it was thought desirable to use a different type of β detector to serve as a check on the anthracene counter results. A cylindrical gas proportional counter, similar to that used by Battat and Ribe, was built. The counter, with o.d. of 0.70 inch and active length of 3 inches, had thin glass walls of 20 mg/cm^2 thickness. It was filled to approximately one atmosphere pressure with a gas mixture of 90% argon–10% methane. A cylindrical Be metal sleeve of length $\frac{3}{4}$ inch and thickness of 95 mg/cm^2 was fitted over the counter. According to the results of Battat and Ribe,[2] the self-absorption of the β particles for this thickness of Be sample should be small. The efficiency for detection of the β particle is judged to be known to an accuracy of $\pm10\%$. The result with this counter confirmed our 2π anthracene counter result (see Table II).

The initial determinations of the neutron flux passing through the Be sample were made by the well-known procedure of measuring the neutron yield from the target with a neutron long counter which was calibrated with a standard Po-Be source. The accuracy of this method is thought to be $\pm10\%$; the error being made up of the errors in the source strength of the Po-Be source and the uncertainty in the energy response of the long counter.[9]

In order to measure the neutron flux more accurately and to have an independent check on the long-counter results, the neutron flux was also measured by counting the number of fissions in U^{238} foils. For this purpose we used the fission counter built and described by Lamphere.[10,11] Although this fission counter was designed for comparison of fission cross sections rather than for absolute measurements, the constructional mass was small enough so that in-scattering of neutrons by components of the counter did not cause serious uncertainties. An estimate, involving crude assumptions about the angular distribution and energy distribution of neutrons scattered by the components of the counter, gave 3% contribution to the counting rate in the U^{238} foils from the in-scattered flux. Since the primary flux

TABLE II. Summary of information on the six determinations of the absolute cross section for the $Be(n,\alpha)$ reaction. The errors given are considered to be standard deviations.

Identification No.	Neutron source	Neutron energy (Mev)	Determination of neutron flux	Detection of β rays	Cross section (millibarns)
1	$T(p,n)$	3.11	Calibration of long counter with standard Po-Be source; $\pm10\%$	2π geometry anthracene crystal; $\pm4\%$	96 ± 10
2	$T(p,n)$	3.11	U^{238} fission counter; $\pm5\%$	2π geometry anthracene crystal; $\pm4\%$	105 ± 7
3	$T(p,n)$	3.11	Calibration of long counter with standard Po-Be source; $\pm10\%$	Thin wall cylindrical gas proportional counter; $\pm10\%$	113 ± 15
4	$T(p,n)$	2.26	U^{238} fission counter; $\pm5\%$	2π geometry anthracene crystal; $\pm4\%$	62 ± 4
5	$T(p,n)$	4.41	U^{238} fission counter; $\pm7\%$	2π geometry anthracene crystal; $\pm5\%$	68 ± 6
6	$Li(p,n)$	2.41	Calibration of long counter with standard Po-Be source; $\pm10\%$	2π geometry anthracene crystal; $\pm4\%$	75 ± 9

[9] See W. D. Allen, Atomic Energy Research Establishment Report AERE NP/R 1667 (unpublished).

[10] R. W. Lamphere and R. E. Green, Phys. Rev. **100**, 763 (1955).

[11] We wish to thank R. W. Lamphere for lending us his counter, foils, and associated circuitry and for instructing us in the use of the equipment.

was attenuated by about 1% before reaching the fission foils, a net correction of 2% was applied to the flux measurements. The principal error in measuring the flux by this method is that caused by the error in the cross section itself. We estimate that the neutron flux was determined to $\pm 5\%$ for neutron energies 2.26 and 3.11 Mev and to $\pm 7\%$ for $E_n = 4.41$ Mev.

Table II contains a summary of information on six determinations of the absolute cross section. The three values at $E_n = 3.11$ Mev, obtained by different methods of β counting and flux measurements, are in satisfactory agreement. The value at 2.41 Mev obtained by the use of the Li(p,n) source has been corrected for the presence of the second, lower energy group of neutrons from the Li(p,n) reaction on the assumption that the intensity of this group is 10% of the primary group.

The absolute cross section values are plotted in Fig. 2 and are identified by the corresponding numbers listed in Table II. The relative cross-section curve was normalized to give a good fit to the absolute cross section points. Figure 3 shows the data at lower neutron energies plotted on an expanded neutron energy scale. The expected threshold, based on the maximum energy of the β spectrum, is (0.705 ± 0.050) Mev. The cross section near threshold is too small to allow an accurate threshold determination. The shape of the curve is consistent with a threshold at the expected value of 0.70 Mev. A small residual counting rate, associated with neutron irradiation of the Be sample, persists below the threshold. The dashed curve shows the shape of the cross-section curve near threshold if it is assumed that the residual counting rate is constant with changing neutron energy and, therefore, may be subtracted out.

The salient feature of the (n,α) cross section is its smooth variation with neutron energy. No obvious resonances are observed. On the other hand, the total neutron cross section of Be exhibits resonances at 0.81 and 2.73 Mev.[12] However, it is probably not surprising that the resonance at 0.81 Mev is not observed since it is quite narrow (8 kev) compared to our neutron energy spread. The resonance in the total cross section at 2.73 Mev is relatively strong and broad ($\sim$100 kev) but it is, nevertheless, not directly discernible in the (n,α) cross section.

The $Be^9(n,2n)$ reaction has a threshold of 1.85 Mev and therefore above 1.85 Mev this mode of decay competes with the (n,α) process. However, there is no

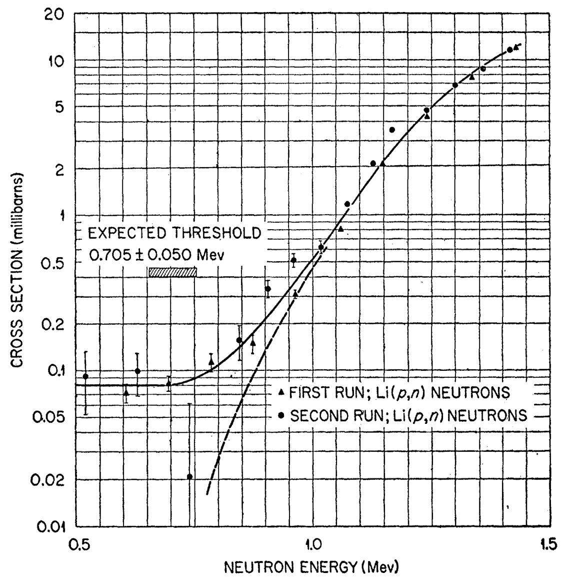

FIG. 3. The cross section for the $Be^9(n,\alpha)$ reaction. Information on the neutron energy spread is given in Table I. The dashed curve shows the shape of the cross-section curve near threshold if it is assumed that the residual counting rate below threshold is constant with changing neutron energy and, therefore, may be subtracted out.

published information on the $(n,2n)$ cross section for neutron energies below 4.0 Mev. At 4.0 Mev the cross section can be inferred from the measurement of Beyster *et al.*[13] of the nonelastic neutron scattering cross section of Be. This cross section is the sum of the $(n,2n)$, (n,α), and (n,n') cross sections. However, the (n,n') cross section should be negligible for Be because breakup into $Be^8 + n$ is energetically possible for excited states of Be^9 and this should overwhelm decay to the ground state by emission of γ rays. Beyster *et al.* found $\sigma_{\text{nonelastic}}$ was 620 ± 30 mb. Since the (n,α) cross section of 4.0 Mev is 85 mb, one sees that the $(n,2n)$ reaction is 6 times more likely than the (n,α) reaction. The competition offered by the $(n,2n)$ process probably accounts for the fall-off of the (n,α) cross section at the higher neutron energies.

We wish to thank Professor E. L. Hudspeth and his group at the University of Texas for the private communication of the results of their work on the Be(n,α) reaction.

[12] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).

[13] Beyster, Henkel, Nobles, and Kister, Phys. Rev. **98**, 1216 (1955).