$Li^6(n,\alpha)H^3$ Cross Section as a Function of Neutron Energy*†

F. L. Ribe
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received April 16, 1956)

The total $Li^6(n,\alpha)H^3$ cross section has been measured absolutely over the range of neutron energies from 0.88 to 14.1 Mev, with errors varying from 11 to 18%. At its low-energy end, the curve $\sigma(E_n)$ joins smoothly with an extension of the curve of earlier data of Blair and Holland, for which the maximum neutron energy was 0.62 Mev. A log-log plot of $\sigma(E_n)$ for the present data shows a variation approximately as E_n^{-1} for the high-energy portion of the curve with a break to greater flatness at the lower energies, resulting in a broad hump in the cross-section curve at about 2 Mev. This hump is believed to be due to competition from deuteron-producing reactions.

INTRODUCTION

When lithium is bombarded by low-energy neutrons, nearly all of the absorption takes place in the 7.5%-abundant Li^6 isotope by means of the (n,α) reaction. From its thermal value of 945 barns, the cross section for this reaction decreases with increasing neutron energy according to the $1/v$ law until it first exhibits a resonance in the region of 250 kev.[1] The cross section in the resonance region was measured by Blair and Holland[2] for neutron energies between 20 kev and 620 kev. They observed a strong resonance at 250 kev with a peak cross section of 3.4 barns, corresponding to a 7.46-Mev state in Li^7 with $J=5/2^-$.[3] Weddell and Roberts[4] have extended the measurements of cross-section and angular distribution up to a neutron energy of 2.0 Mev by means of track measurements in lithium-six loaded nuclear emulsions, using monoenergetic $Li^7(p,n)Be^7$ neutrons. Absolute differential cross sections for all of the reactions yielding charged particles when both isotopes of lithium are bombarded with 14-Mev neutrons have been measured by Frye,[5] using nuclear plate techniques. In what follows we shall report absolute measurements of the $Li^6(n,\alpha)H^3$ total cross section as a function of monoenergetic neutron bombarding energy in the region from 0.88 to 14.1 Mev.

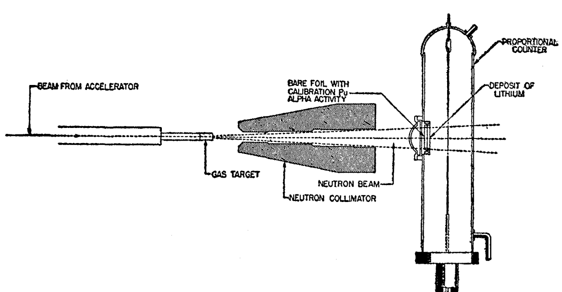


Fig. 1. Experimental arrangement for $Li^6(n,\alpha)H^3$ cross-section measurements.

APPARATUS AND EXPERIMENTAL METHODS

1. General Considerations

Since the $Li^6(n,\alpha)H^3$ reaction proceeds with an energy release $Q=4.78$ Mev, both the alpha particle and the triton resulting from the disintegration are quite energetic and hence are easily detected and counted. This feature of the reaction allows one to measure the total reaction cross section in 2π geometry by a procedure similar to that used in fission-cross-section measurements without recourse to the more usual process of measuring the differential cross section as a function of angle and then integrating over the total solid angle.

The apparatus is illustrated in Fig. 1. Neutrons produced in an accelerator target (illustrated as a tritium or deuterium gas target used with a Van de Graaff accelerator) were collimated and used to bombard a thin lithium target which was placed inside a 3-in.-diameter high-pressure proportional counter with sufficient gas filling to stop all charged reaction products inside the counting volume. All alpha particles and tritons ejected into the forward hemisphere with respect to the neutron beam were thus detected, and each disintegration event was represented either by a detectable alpha particle or a triton. There would appear to be a problem in detecting the heavier alpha particles when they are ejected at nearly 90 degrees with respect to the neutron beam and hence have their energy degraded in a nearly tangential path through the lithium foil. However this difficulty is alleviated by the center-of-mass motion at the neutron energies

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Preliminary reports of the work described in this paper were given at the Washington, D. C. meetings of the American Physical Society in 1952 and 1953. See F. L. Ribe, Phys. Rev. **87**, 205(A) (1952) and **91**, 462(A) (1953).

[1] For a compilation of the low-energy data see D. J. Hughes and J. A. Harvey, "Neutron Cross Sections," Brookhaven National Laboratory Report, BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955). A plot of the cross-section results of the present paper, in the medium energy region, is also given in this compilation.

[2] J. M. Blair and R. E. Holland (unpublished). These results are given in the compilation of reference 1.

[3] For a review of the work on the properties of this state in Li^7 see F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[4] J. B. Weddell and J. H. Roberts, Phys. Rev. **95**, 117 (1954).

[5] G. M. Frye, Jr., Phys. Rev. **93**, 1086 (1954).

used in this experiment. When the alpha particle enters the counter at an angle of greater than about 60 degrees it is accompanied by a triton of relatively negligible energy loss in the foil. On this basis one might also expect a small fraction of "doubles" pulses in the energy spectrum corresponding to simultaneous detection of the triton and alpha particle. The energies associated with these pulses would be greater than those of the forward tritons and equal to the sum of the incident neutron energy and the Q value of the reaction.

2. Electronic Detection

The pulses from the counter were detected by means of a Los Alamos Model 101 preamplifier and amplifier system, and the pulse-height spectrum was presented on a Johnstone-type 18-channel analyzer.[6] The decay time of the amplifier system was set, by means of an *R-C* clipper, at 32 microseconds. This rather long decay time was necessary, for the pure noble gas fillings which were generally used, in order that the pulse heights of the tritons and alpha particles should be accurately proportional to the particle energies regardless of their differences in range and angle with respect to the center wire of the counter.

The linearity of the amplifier-analyzer system was checked by means of a Los Alamos Model 500 mercury-relay pulser fed through an attenuator into the Model 101 preamplifier and found to be exact to within about two percent.

3. Proportional Counter

The proportional counter used in this experiment has been extensively studied[7] and found to provide pulse heights accurately proportional to particle ionization and also independent of the location of the ionizing event in the counter, for purified noble gases at the pressures and gas multiplications used in this experiment. In the present case a 300°C calcium purifier was used; pressures of krypton were of the order of 100 psi, requiring a few thousand volts on the two-mil center wire; and the gas multiplication was always chosen to be between 10 and 15.

The lithium target foils were mounted on one side of a rotatable "pancake" on the wall of the counter as shown in Fig. 1. On the other side was a tantalum blank which could be made to face the counter volume by tilting the counter, in order that background runs could be made to determine the pulse spectrum due to gas disintegrations and other sources. A weak deposit of $Pu^{239}(NO_3)_2$ on the tantalum blank provided a 5.16-Mev alpha-particle source for energy calibration of the pulse-height spectrum.

The entire counter was covered with $\frac{1}{16}$-inch cadmium to reduce the number of disintegrations of the Li^6 caused by thermal background neutrons. In some cases, at the lower neutron bombarding energies, further shielding of boron was also used to help eliminate epithermal neutrons which might otherwise produce disintegration pulses of heights comparable with those to be observed. In addition a gold liner was used in the counter.

4. Counter Fillings and Neutron Collimators

At the higher neutron energies used, it was found that the krypton counter filling was appreciably disintegrated, providing a troublesome background. A comparison study was undertaken to determine this disintegration background with argon, krypton, and xenon fillings. In each case the filling was bombarded with 14-Mev neutrons, and pulse-height spectra were taken. The pressure of the filling was increased for each gas until no further changes in the spectrum occurred with increased pressure, indicating that the ranges of all disintegration products were reasonably short compared to the counter dimensions. The resulting energy distributions are shown in Fig. 2. On the basis of these graphs krypton was chosen as the most suitable counter gas.

The neutron collimators were used in order to reduce this gas-disintegration background with respect to the desired signal from the lithium foil by insuring that the neutrons irradiated only that portion of the gas filling which lay behind the foil.

Two collimators were used, one made of brass (Fig. 1) and the other of iron. Their behavior was checked at the neutron energies used in the experiment as follows: First, the neutron beam from the collimator was scanned by moving a small Np^{237} (threshold = 400 kev) or U^{238} (threshold = 1 Mev) spiral fission chamber in small steps across the output aperture and plotting the counts per neutron *versus* distance perpendicular to the collimator axis. The results showed well-defined geometrical shadows, with shadow counts which were about 5% of those at the center of the aperture. Second, a stilbene scintillator one inch in diameter and

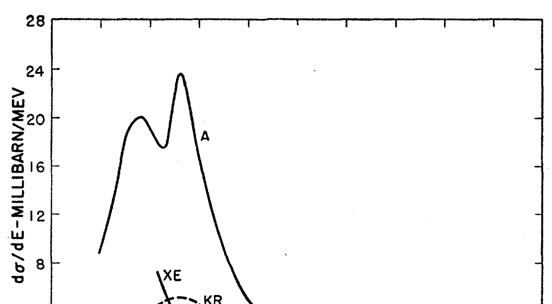


FIG. 2. Energy spectra of disintegration particles produced by 14-Mev neutrons in noble-gas counter fillings.

[6] C. W. Johnstone, Nucleonics 11, No. 1, 36 (1953).
[7] John Wahl, Los Alamos Report, LA-1135, August 1, 1950 (unpublished).

one inch long was exposed to the beam at the center of the aperture, and its pulse-height spectrum was measured. The results showed that no degraded neutrons were present in the neutron spectra down to the lower limit of measurement, e.g., 0.6 Mev in the case of 5.5-Mev incident neutrons. By comparing the heights of the spectra at their end points both with and without the collimator in place it was found that the elastic in-scattering due to the collimator was, e.g., 9% in the case of 5.5-Mev incident neutrons. In each case the flux measurements were corrected for this in-scattering.

5. Lithium Target Foils

The target foils were made from lithium enriched to 90–95% in Li^6. For some of the first lower-energy runs lithium fluoride was used. However, at the higher energies the fluorine disintegrations provided prohibitive competition to the lithium signal. Therefore lithium-metal targets were used in most of the runs. They were made by evaporating the metal onto a cooled tantalum backing, and the total weight of the deposit was determined by weighing the tantalum piece in a dry helium atmosphere before and after the evaporation. The deposited lithium-six foils had surface densities of the order of one mg/cm^2 and covered a circular area $1\frac{1}{4}$ inches in diameter.

6. Neutron Sources

In making the cross-section measurements, both a Cockcroft-Walton and a Van de Graaff accelerator were used to provide sources of monoenergetic neutrons. In the case of the Cockcroft-Walton machine, neutrons of energies 2.50 Mev and 14.1 Mev were derived from the $D(d,n)He^3$ and $T(d,n)He^4$ reactions, respectively, by bombarding thick zirconium-deuterium and zirconium-tritium targets[8] with the 250-kev deuteron beam and making use of the neutrons emitted at 90 degrees with respect to the deuteron beam. In the case of the Van de Graaff machine, neutrons of energies between 0.88 and 2.90 Mev were derived from the $T(p,n)He^3$ reaction by bombarding a thin tritium-gas target with a proton beam. Similarly, neutrons of energies 4.44, 5.53, and 6.52 Mev were produced by the $D(d,n)He^3$ reaction by bombarding thin deuterium-gas targets with a deuteron beam. The Van de Graaff beam energy was accurately determined by means of a 90-degree bending magnet with a proton-moment magnetometer, and corrections were made for energy loss in the 0.0001-inch nickel foil which sealed the gas target as well as for energy loss in the half-thickness of the gas target itself. Neutrons emitted at zero degrees with respect to the Van de Graaff beam were used in the measurements.

[8] Graves, Rodrigues, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).

DATA AND EXPERIMENTAL PROCEDURE

1. Van de Graaff Measurements Using *p*-T Neutrons

In this case the experimental arrangement was that shown in Fig. 1, with the exception that no collimator was used. The tritium-gas target had a length of one inch and was filled to an absolute pressure of 18.5 cm Hg. With an average beam current of about 1.5 microamperes and 17.0 cm spacing between the tritium target and the lithium foil, the average neutron flux at the foil was about 7×10^7 neutrons/cm^2/sec.

A long counter,[9] whose energy response was approximately independent of neutron energy over the energy range used, was used as a neutron monitor. The procedure followed in one cycle of a run at a given neutron energy was as follows: The 3-inch proportional counter was removed, and the count of the long counter corresponding to one or more clicks of the gas-target current integrator was determined. A paraffin shadow cone was then interposed, and the long-counter background determined. The counter was then put in place with the lithium foil facing the counter volume and irradiated, using the current integrator as a monitor, and the pulse-height spectrum from the counter was measured. The pancake inside the counter was rotated to expose the tantalum blank to the counter, and a background pulse-height spectrum taken. Concurrently the weak source of plutonium provided a spectrum peak of about 7% resolution, due to the 5.16-Mev alpha particles, over the relatively smooth background pulse-height distribution. The counter was again removed and another long-counter monitor count was taken.

The long counter was calibrated absolutely at the end of a series of runs, each day, by removing the lithium counter and exposing the long counter, with and without the shadow cone, to the neutrons from a standard one-gram Po-Be neutron source calibrated absolutely to ±6%. In this way the absolute flux determinations were made within an accuracy of about 7.5%. Care was taken to choose the neutron energies so as to avoid those energy regions where the carbon resonances affect the smoothness of the long-counter response.[10]

Possible effects of thermal and epithermal neutrons were determined to be negligible by noting that the numbers of pulses in the pulse-height spectra followed an inverse-square distance relationship between neutron source and lithium-target foil.

The lithium metal deposit used in these runs had a total weight of 5.4±0.2 mg.

Figure 3 shows the data for the five runs made with *p*-T neutrons. In each case the net counts due to the lithium disintegration (tantalum-blank background

[9] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[10] Nobles, Day, Henkel, Jarvis, Kutarnia, McKibben, Perry, and Smith, Rev. Sci. Instr. **25**, 334 (1954).

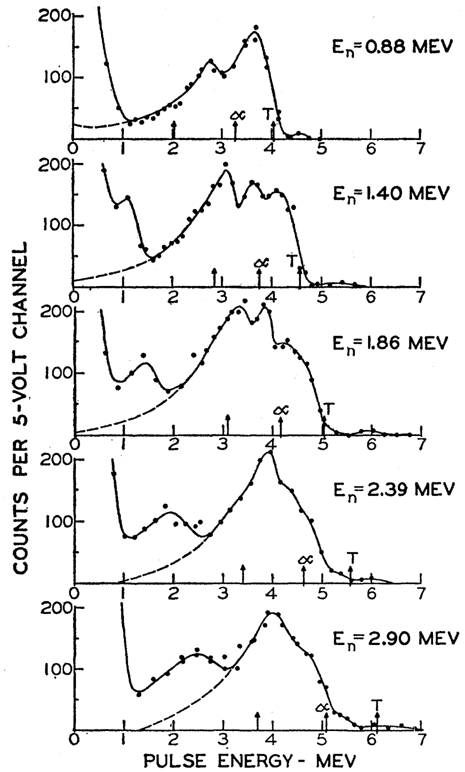


FIG. 3. Pulse-height spectra of tritons and alpha particles from the disintegration of Li^6 by thin-target p-T neutrons.

subtracted) are plotted against pulse height in Mev. The alpha-particle and triton groups, as well as small high-energy tails due to the doubles pulses can be seen. On each graph the energy values calculated for the forward tritons, forward alpha particles, and single alpha particles of maximum angle with respect to the neutron beam are indicated on the axis of abscissas.

Starting at the lowest bombarding energy, it is seen that the alpha peak and triton peak are well separated. As the neutron energy increases the alpha particles are more able to overcome the energy loss in the lithium foil, and the leading edge of the alpha group moves toward that of the tritons. At 1.40 and 1.86 Mev it is seen that the alpha and triton groups overlap to the extent that there is an extra peak between the two groups due to addition of the leading edge of the alpha group and the trailing edge of the triton group. Above 1.86 Mev the alpha group merges with the triton group, and the latter appears merely as a bump on the leading edge of the composite group.

There are also some proton-recoil pulses in these spectra, due most likely to the deposition of pump oil on the tantalum backing during the long process of evaporating the lithium. The proton-recoil spectra are seen to be roughly rectangular energy distributions superimposed on the trailing edges (dashed curves) of the alpha-particle groups, with end points equal to the neutron bombarding energy. At the higher neutron energies they cover some of the low-energy tail of the alpha-particle group. However, a dependable method for extrapolating the low-energy tail, as shown by the dashed lines in Fig. 3 was found. The smearing of the alpha-particle groups due to energy loss in the lithium foil was calculated numerically, assuming an isotropic alpha energy distribution for an infinitely thin foil. At the lower neutron energies where almost all of the alpha-particle groups are visible the method was tested, and a good fit was obtained to the whole alpha group. In addition it was shown that varying the shape of the assumed angular distribution for zero foil thickness from one peaked strongly forward to that of one peaked strongly backward, changed the area under the low-energy tail by only 10%, introducing a negligible error into the integrated area under the whole triton-alpha spectrum. The total disintegrations of Li^6 were thus obtained from the areas under the curves of Fig. 3, with the low-energy tails as indicated.

The spectra of Fig. 3 also show a low-energy "wall" of pulses in the vicinity of one Mev. This is believed to be at least partly due to Li^6 recoil nuclei.

2. Van de Graaff Measurements Using *d*-D Neutrons

These measurements were carried out in a manner nearly identical with those described above with, however, a few exceptions. In the case of the p-T neutron bombardments, the neutron energy was either less than the thresholds for all competing reactions in Li^6 (and Li^7) or else so slightly above threshold that competing reaction products had negligible energies. In the present case, however, the thresholds of the following competing reactions were exceeded: $Li^6(n,d)He^5$ ($Q=-2.35$ Mev), $Li^6(n,p)He^6$ ($Q=-2.43$ Mev), and $Li^6(n,dn)He^4$ ($Q=-1.48$ Mev). The bombarding neutrons had energies of 4.44, 5.53, and 6.52 Mev, and it was observed that the spectra of Li^6 reaction products repeated all the features shown in Fig. 3 with the exception there were many pulses of small pulse height due to low-energy deuterons. These were identified by their energy end point and by observing the pressure of counter gas at which the forward reaction products in this group had a range equal to the diameter of the counter. It was determined roughly that the yield of deuterons from the two-body reaction $Li^6(n,d)He^5$ was about 200 millibarns for each of the neutron energies 5.53 and 6.52 Mev.

A check was made to see if any $Li^6(n,\alpha)$ reaction products were being produced by stray *d*-D neutrons produced in parts of the beam tube other than the deuterium-gas target, by making irradiations with the gas target filled with H_2 gas. It was found that the yield of pulses in the region of the normal triton-alpha groups was only one percent of that of the normal groups. There was a small yield in the region of the Li^6-recoil "wall," due to essentially thermal neutrons, which had no effect on the cross-section determinations.

Flux determinations were again made with the long counter and PoBe neutron source. The lithium metal target foil had a total weight of 14.6±0.3 milligrams. The brass collimator was used.

3. Cockcroft-Walton Measurements Using *d*-D Neutrons

Two separate runs were made, using two methods for the flux determination. In the first run, the counter was placed with its target foil 11.4 cm from the neutron source in the plane at 90 degrees with respect to the deuteron beam of the accelerator. No collimator was used. In the same plane, at an equal distance on the opposite side of the neutron source, was placed a U^{235} fission chamber which provided a monitor for the neutrons. Absolute flux determinations were made by using a *d*-T source as a primary standard as follows: The Zr-D target was replaced by a Zr-T target, and the fission chamber was bombarded with 14-Mev *d*-T neutrons. The flux from the Zr-T target (again in the 90-degree plane) was measured absolutely to within three percent by counting the associated alpha particles from the $T(n,d)He^4$ reaction in a proportional-counter monitor of accurately known solid angle. By comparing the fission-chamber counting rates for the *d*-T and *d*-D neutrons and using the known ratio of the U^{235} fission cross sections at 14 and 2.5 Mev, the flux of *d*-D neutrons was then determined to within seven percent.

In this measurement a 94.3% enriched Li^6F target foil with a total weight of 8.21±0.10 mg was used. The pulse-height spectrum of the Li^6 reaction products is shown in Fig. 4. Here it is seen that the peak of the lower energy alpha group is separated from that of the triton group in the vicinity of 5 Mev, in contrast to the situation of Fig. 3 for a bombarding energy of 2.39 Mev. This is due to the larger energy loss by the alpha particles in the LiF foil in the former case. The somewhat cruder aspect of the data of Fig. 4 is accounted for mainly by the fact that at the time this

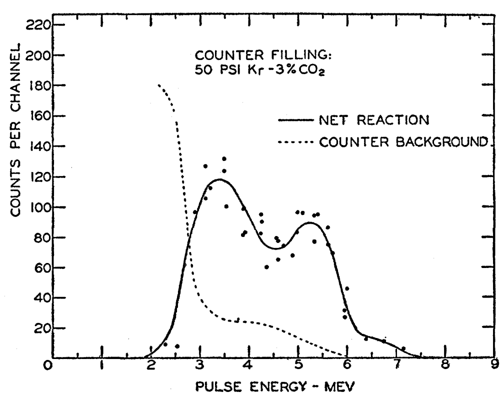


FIG. 4. Pulse-height spectrum of tritons and alpha particles from the disintegration of Li^6 by 2.5-Mev thick-target *d*-D neutrons.

run was made, an older model 10-channel pulse-height analyzer was used instead of the Johnstone-type 18-channel analyzer.

An analysis of the shape of the low-energy alpha-particle tail in the spectrum of Fig. 4 indicated that some of it was missed in subtracting the low-energy counter background. The counts which were missed amounted to about 6% of the total counts, and this fact was included in the error estimation.

In the second *d*-D run the metallic lithium-six foil was the same one used in the Van de Graaff *p*-T runs, and the pulse-height spectrum was practically identical to that shown in Fig. 3 for 2.39-Mev bombarding energy. In this case the neutron flux was monitored by means of a proportional counter which counted protons associated with the other branch of the *d*-D reaction, $D(d,p)H^3$. Tritons (and He^3 ions) were excluded from the monitor counter by means of a one-mil aluminum foil over its aperture. The proton monitor was calibrated absolutely by means of a Ra-Be neutron source and long counter.

The cross-section values obtained in these two runs at 2.50-Mev bombarding energy were 188±27 millibarns and 205±28 millibarns for the first and second runs, respectively.

4. Cockcroft-Walton Measurements Using *d*-T Neutrons

In this case one could expect all of the competing lithium reactions to be excited, giving reaction products of appreciable energies. This was indeed found to be the case. In particular there were many more deuterons from the (n,d) reaction than there were products from the (n,α) reaction. The target in this case was 90.9%-enriched Li^6 metal with a total weight of 18.6±1.5 mg. An iron collimator was used, and the neutron flux was measured absolutely to an accuracy of ±3% by means of the proportional alpha-particle counter mentioned in the last section.

For the 14.1-Mev bombarding energy the energy spectrum to be expected from the $Li^6(n,\alpha)H^3$ reaction is as follows: (1) a band of tritons from 12.9 Mev (53° laboratory angle) to 16.4 Mev (0°); (2) a band of alpha particles from 10.2 Mev (54°) to 14.2 Mev; and (3) a relatively narrow group of doubles pulses at 19.0 Mev.

The right-hand graph of Fig. 5 shows the energy spectrum (background subtracted) obtained with a counter filling of 201 psi of krypton, sufficient to stop all forward reaction products. The high-energy tail contains the triton and doubles pulses in the proper energy range. However, the alpha group is obscured by the large group in the vicinity of 12 Mev which, as will be shown, is due to deuterons. In order to eliminate these deuterons, the gas pressure was greatly reduced so that they could deposit much less energy in the counter than the alpha particles. The energy spectrum measured with a 41.6 psi filling is marked by the circles in the left-hand graph of Fig. 5. Here the alpha particles

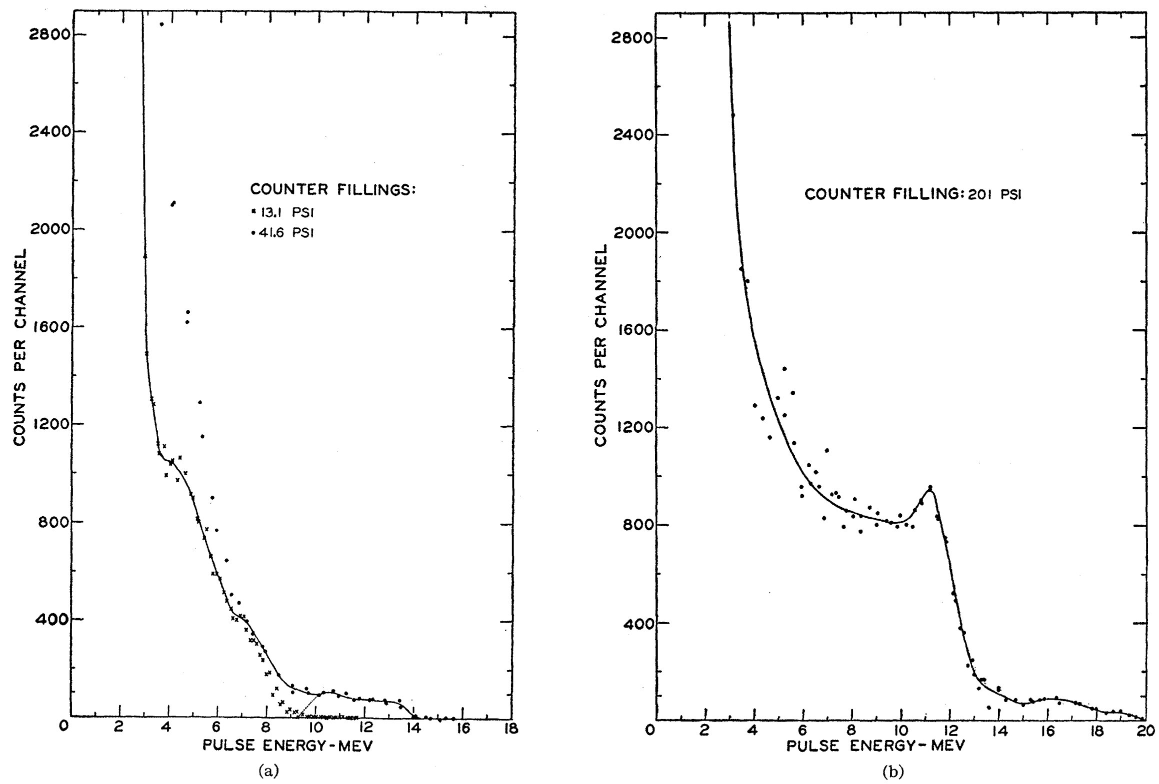


FIG. 5. Disintegration products of Li^6 produced by 14-Mev neutrons. (a) Heavy reaction products in the forward direction; (b) light and heavy reaction products in the forward direction.

can still deposit their full energy, and their spectrum can be seen as the high-energy tail with the proper 14-Mev end point. Further reducing the counter pressure to 13.1 psi gave the spectrum marked by the crosses in which the alpha particles no longer appeared with full energy, since their ranges were greater than the counter diameter. The solid line is the composite spectrum of multiply-charged reaction products comprised of the following components: (1) the alpha particles from the $Li^6(n,\alpha)H^3$ reaction; (2) alpha particles from the competing $Li^6(n,d)He^5(n)He^4$ and $Li^6(n,dn)He^4$ reactions; and (3) recoil Li^6 nuclei. The dotted line of the left-hand graph of Fig. 5 represents the low-energy tail of the alpha-particle group (1), calculated as has already been discussed in connection with the Van de Graaff p-T neutron experiments.

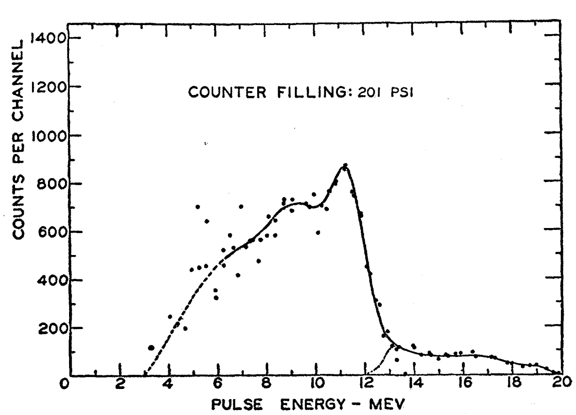


FIG. 6. Spectrum of tritons and deuterons and double (alpha+triton) events from the disintegration of Li^6 by 14-Mev neutrons.

In Fig. 6 is shown the spectrum of the tritons and deuterons and double (alpha+triton) events, obtained by subtracting the left-hand graph of Fig. 5 from the right-hand graph. The dotted line indicates the lower energy edge of the triton+doubles spectrum. By adding this spectrum to that of the alphas in the left-hand graph of Fig. 5, the total yield of the $Li^6(n,\alpha)H^3$ reaction was obtained.

There remains the large group in Fig. 6 which peaks at about 11.3 Mev. This could be accounted for either by the 11.4-Mev forward deuterons from the (n,d) reaction or possibly the 10.9-Mev forward protons from the (n,p) reaction. However the latter reaction is excluded, since it has been shown[11] that it has a cross section of only 6.7 millibarns at 14-Mev neutron bombarding energy. As a further check on the identity of the deuterons, runs were made with a counter filling of 137 psi, at which pressure only the deuterons would have been stopped in the counter. It was ob-

[11] M. E. Battat and F. L. Ribe, Phys. Rev. **89**, 80 (1953).

served that the shape of the portion of the spectrum with its peak at 11.3 Mev was essentially unchanged. It should be noted that this part of the spectrum extends to too low an energy to be entirely due to the two-body reaction $Li^6(n,d)He^5$, leaving He^5 in its ground state. Apparently there are also reactions to an excited state of He^5 or contributions from the three-body $Li^6(n,dn)He^4$ reaction.

Various measurements of the deuterons and alpha particles in both the forward and backward hemispheres with respect to the neutron beam indicated about 200 millibarns of yield to be attributed to the (n,d) and (n,dn) reactions. From the spectra and the dynamics of the reactions it is estimated that of this, about 100 millibarns are due to the reactions leading to the ground state of He^5.

5. Correction for Response of Long Counter

In making flux determinations by the long-counter-standard-source method during the Van de Graaff runs, it was assumed that the long-counter response was the same for both the standard-source neutrons and those produced by the accelerator beam. Recently measurements[12] have been carried out with this accelerator in which absolute flux determinations were made by means of a proton-recoil counter telescope of accurately known radiator weight and solid angle. From these flux determinations it was possible to measure the long-counter sensitivity absolutely as a function of incident neutron energy. By simultaneously determining the long-counter sensitivity with a PuBe standard source it was possible to arrive at a correction factor, as a function of neutron energy, with which to correct the flux determinations made in this experiment. The long counter and geometry were the same as those used in the present experiment, and it was found that the amount of correction varied smoothly with energy with a maximum of about 11% correction over the range of neutron energies used in the present experiment. This correction factor has been applied to the cross sections measured with Van de Graaff p-T and d-D neutrons and with the Cockcroft-Walton neutrons in which use was made of a long counter.

TABLE I. Results of measurements of the cross section for the reaction $Li^6(n,\alpha)H^3$. Cross-section values in the third column were computed on the assumption of flat long-counter energy response. Values in the fourth column are corrected for actual long-counter response.

Neutron bombarding energy (Mev)	Neutron source	Total $Li^6(n,\alpha)H^3$ cross section (millibarns)	Total $Li^6(n,\alpha)H^3$ cross section corrected for long-counter response (millibarns)
0.88±0.01	Thin-target p-T	291±31	262±28
1.40±0.01		255±27	229±24
1.86±0.01		236±25	215±23
2.39±0.01		203±24	189±22
2.90±0.01		153±19	148±18
4.44±0.12	Thin-target d-D	97±14	97±14
5.53±0.07		71±13	72±13
6.52±0.04		57±10	59±10
2.50±0.03	Thick-target-90° d-D	188±27	188±27
2.50±0.03		205±28	192±27
14.1±0.08	Thick-target-90° d-T	26± 4	26± 4

[12] Haddad, Perry, and Smith (private communication).

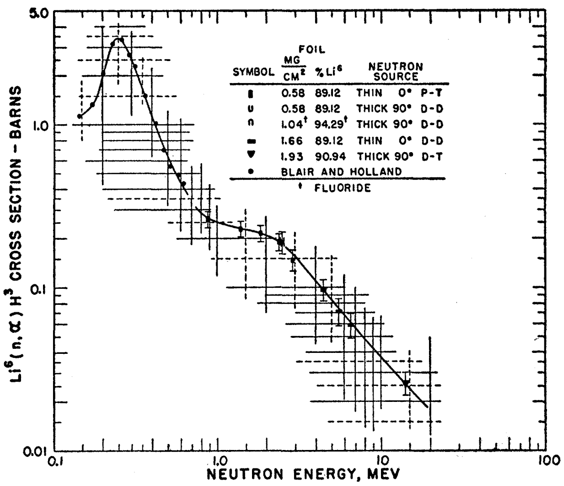


FIG. 7. Measured $Li^6(n,\alpha)H^3$ total cross section as a function of bombarding neutron energy.

RESULTS

The results of the $Li^6(n,\alpha)H^3$ cross-section measurements are given in Table I and plotted in Fig. 7. The graph also contains a plot of the results of Blair and Holland[2] in the resonance region.

In Table I the third column gives the cross sections determined on the assumption that the long-counter response was flat. These results have been corrected to the true long-counter response in the fourth column. The corrected results are plotted in Fig. 7.

The errors assigned to the cross-section values include all counting statistics, both in the reaction yield and the flux determinations, as well as estimates of systematic errors such as those in foil weights, those arising in estimating the lower limits of the alpha spectra, those introduced into the flux measurements by the collimators, and those in the calibrations of the standard sources.

There is fortuitously good agreement between the 26±4 millibarn value obtained here for the (n,α) cross section at 14.1 Mev and the identical value obtained by Frye[5] by nuclear plate methods. His value of 166±19 millibarns for the (n,d) cross section and the present value of about 200 millibarns are also in agreement.

An interesting feature of the log-log plot of the cross section *versus* energy in Fig. 7 is the hump at about 2 Mev, indicating a break from a slow $E_n^{-0.1}$ variation to a faster E_n^{-1} variation of the cross section. Since no

similar anomaly appears in the total cross section[13] of Li^6, it is unlikely that this hump is due to another state in Li^7. A reasonable explanation is that the sudden decrease of the (n,α) reaction is due to the onset of the competing $Li^6(n,nd)He^4$ reaction which has its threshold at 1.72 Mev. The two-body reactions $Li^6(n,n')Li^{6*}$ and $Li^6(n,d)He^5$ also provide competition above their thresholds at 2.55 and 2.89 Mev.

[13] Johnson, Willard, and Bair, Phys. Rev. 96, 985 (1954).

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help and advice of Dr. J. H. Coon and Dr. E. R. Graves during the rather long course of this experiment. Indispensible aid was given by Dr. R. H. Henkel and Dr. J. E. Perry at the Los Alamos large Van de Graaff accelerator and by Mr. R. W. Davis at the 250-kev Cockcroft-Walton accelerator.

PHYSICAL REVIEW VOLUME 103, NUMBER 3 AUGUST 1, 1956

Three-Millimicrosecond Metastable State in Pb^{209}†

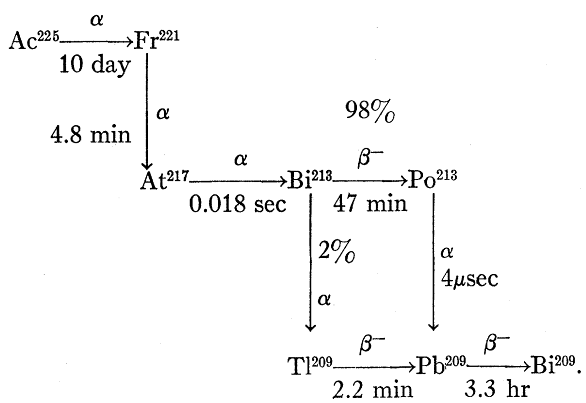
D. Strominger, F. S. Stephens, Jr., and J. O. Rasmussen
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

(Received April 17, 1956)

Coincidence studies of radioactive isotopes in the Ac^{225} decay chain were made. A metastable state of Pb^{209} with a half-life of (3.1 ± 1.0) millimicroseconds was observed. This delay following beta decay of Tl^{209} to Pb^{209} is exhibited by a 120-kev $E1$ gamma transition and other gamma transitions succeeding the 120-kev gamma transition. Upper limits are set for the lifetimes of several other gamma transitions present in the Ac^{225} chain. An explanation for the delayed nature of this 120-kev $E1$ transition is given in terms of parentage overlap. Some unusual features of the beta decay rates of Tl^{209} to Pb^{209} are discussed.

INTRODUCTION

THE 10-day alpha emitter Ac^{225} is followed by a chain of shorter-lived activities.



The decay properties of these activities have been the subject of several previous investigations.[1–4]

The present study was undertaken to investigate the lifetimes of various nuclear excited states by the delayed coincidence method, and γ-γ, β-γ, and α-γ coincidence measurements were made wherever possible.

A sample of Ac^{225} was chemically purified from its Th^{229} and Ra^{225} parents; however, daughter activities of Ac^{225} grow in so rapidly that all of the following measurements were done with a sample in transient equilibrium.

Scintillation detectors with RCA 5819 photomultiplier tubes were used, employing a Lucite disk impregnated with terphenyl, a thin layer of sublimed stilbene, or a sodium-iodide (thallium-activated) crystal as scintillators for beta particles, alpha particles, or electromagnetic radiation, respectively.

Delayed coincidences were measured with fast-slow coincidence pulse-height analysis equipment at resolving

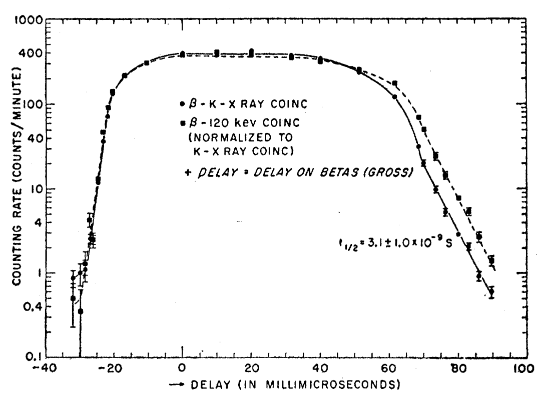


Fig. 1. Delay curves of beta-gamma coincidences. Delay curves of coincident K x-rays and 120-kev gamma rays are shown.

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

[2] Magnusson, Wagner, Engelkemeir, and Freedman, Argonne National Laboratory Report ANL-5386, January, 1955 (unpublished).

[3] F. S. Stephens, PhD. thesis, University of California Radiation Laboratory Unclassified Report UCRL-2970, June, 1955 (unpublished).

[4] Perlman, Stephens, and Asaro, Phys. Rev. 98, 262(A) (1955).