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Reaction $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ for 12- to 20-Mev Neutrons*

ALICE H. ARMSTRONG AND GLENN M. FRYE, JR.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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Ilford 200-μ C-2 plates loaded with B^{11} were exposed to monoenergetic neutrons produced at nine angles to a 3.5-Mev deuteron beam incident upon a tritium gas target. Mesurements of range and space angles were made upon 450 "hammer stars" which were found to result from the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ reaction. The cross sections in mb as a function of energy in Mev are as follows: 12.6 Mev, 27.0±6.5 mb; 13.0, 38.4 ±7.4; 14.7, 30.9±6.3; 15.4, 36.9±7.0; 16.9, 21.9±3.6; 17.6, 23.7±4.8; 18.9, 19.7±3.7; 19.8, 16.3±3.1; 20.0, 15.8±3.1. The angular distribution of the alpha particles from the (n,α) reaction is obtained at each energy. In nearly all cases the Li^8 is left in the ground state or in the first excited state of 1 Mev. The Be^8 disintegration goes through the broad 3-Mev level and possibly a lower level near 2 Mev. A range-energy relation is found for Li^8 in Ilford C-2 emulsion. Comparison with previous experimental results shows closest agreement with Barkas.

I. INTRODUCTION

THE individual reactions comprising the steps in the fast-neutron disintegration of B^{11} by way of the reaction $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ have been studied by various observers. The half-life of the β decay of Li^8 has been well established,[1] and the final states of the transitions to Be^8 investigated.[2] The disintegration of Be^8 into two alpha particles has been used for determination of the energy levels of Be^8. The evidence for and against the existence of the low-lying levels furnished by other reactions as well as by this one has been summarized by Titterton[3] up to February 1954, and augmented by a number of more recent investigations.[4–17] In addition, the cross section for the (n,α) reaction has been measured at 14 Mev.[18]

Nuclear emulsions loaded with B^{11} and bombarded by high-energy neutrons make it possible to observe the reaction chain in its entirety except for the decay of the Li^8. In the present experiment measurements have been made of the (n,α) cross sections and of the angular distribution of the alphas from the (n,α) reaction as a function of neutron energy. The low-lying energy levels of Li^8 and of Be^8 and the range-energy relation for Li^8 in boron-loaded emulsion in the energy region between 1.5 and 7.5 Mev have been investigated.

II. EXPERIMENTAL PROCEDURE

Ilford C-2 nuclear emulsion plates, 200 μ thick, loaded with 23 mg/cm³ of B^{11}, were exposed to neutrons from the $T(d,n)He^4$ reaction, produced by 3.50-Mev deuterons from the large Los Alamos electrostatic accelerator incident upon a tritium-gas target. The plates were placed at nine different angles with respect to the incident deuteron beam, corresponding to neutrons of energy 12.6, 13.0, 14.7, 15.4, 16.9, 17.6, 18.9, 19.8, and 20.0 Mev. The experimental arrangement has been described in detail elsewhere.[19]

III. PLATE ANALYSIS AND CALCULATIONS

Of the neutron-induced reactions which can occur in B^{11}, the most distinctive is $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$, as the Li^8 does not decay until after it has come to rest in the emulsion and the breakup of Be^8 into two alphas gives rise to the characteristic "hammer star." Two such stars are shown in Fig. 1. Since C-2 emulsion

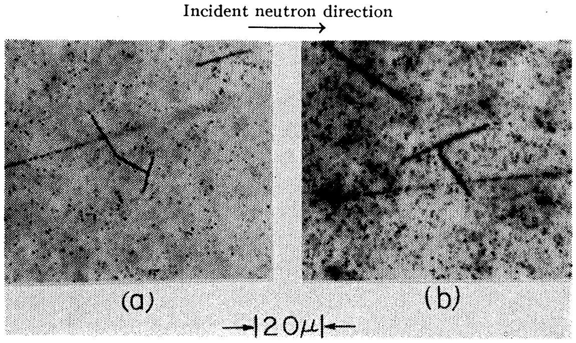

FIG. 1. Two typical "hammer stars." In (a), $E_n=16.9$ Mev, $E_{ex}(Be^8)=3.31$ Mev, and $Q_1=-7.52$ Mev; in (b), $E_n=12.6$ Mev, $E_{ex}(Be^8)=7.75$ Mev, and $Q_1=-6.91$ Mev.

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[*] Work performed under the auspices of the U. S. Atomic Energy Commission.

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

[2] W. F. Hornyak and T. Lauritsen, Phys. Rev. **77**, 160 (1950).

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[18] S. A. Heiberg, Phys. Rev. **96**, 856(A) (1954).

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is insensitive to electrons, the track of the electron from the beta decay of the Li^8 is not observed. No advantage would have been gained by the use of electron-sensitive G-5 emulsion, for loading with boron appears to destroy the sensitivity to electrons.

A minimum of seven different scanners analyzed separate regions on each plate. Detailed measurements[19] of projected length, horizontal angle and dip were made on the tracks of each of the other four particles, i.e., the alpha and the Li^8 from the (n,α) reaction and the two alphas from the Be^8 disintegration. From these three measurements on each track its true range and hence energy were determined. The range-energy relation used for the three alpha particles was obtained from data given by Wilkins[20] for boron-loaded Ilford C-2 emulsions. For the Li^8 particle a range-energy curve was obtained from data given by Barkas[21] at four energies between 4.3 and 10.7 Mev and the two low-energy points obtained by Faraggi[22] for Li^7 and transformed to Li^8.

The Q of the (n,α) reaction was calculated in two different ways: (1), from the energy and direction of the incident neutron and the energy and direction of the first alpha particle; and (2), from the energies of the incident neutron, the first alpha particle, and the Li^8 particle. Conservation of energy and momentum leads, in the first case, to the relation

$$Q_1 = 1.5E_\alpha - 0.5(E_n E_\alpha)^{\frac{1}{2}} \cos\psi_\alpha - 0.875E_n, \qquad \text{(A)}$$

where all quantities are in the laboratory system. Q, by the second calculation based on conservation of energy, is

$$Q_2 = E_\alpha + E_{Li^8} - E_n. \qquad \text{(B)}$$

Since the percentage error in the conversion of range to energy is greater for Li^8 than for an alpha particle and, furthermore, the range-energy relation for Li^8 was not well established, particularly at low energies, the calculated value of Q_2 was not considered as reliable as that of Q_1 and was accordingly given less weight in setting up criteria for the identification of a star as one resulting from a neutron of proper energy and direction. In most cases, a satisfactory momentum balance and reasonable values of both Q_1 and Q_2 left no doubt concerning the identification of such a star. In the less obvious cases, a maximum acceptable value of $\Delta Q = |Q_1 - Q_2| = 1.40$ Mev was determined from examination of the ΔQ distribution of all events. In addition, an arbitrary upper limit of -5.0 Mev was imposed on both Q_1 and Q_2. A higher Q was invariably found to indicate a poor momentum balance. No lower limit was set on the value of Q, since the Li^8 might be left in an excited state. All stars, however, for which the calculated Q was less than -9.0 Mev, were also calculated as carbon stars. The emulsion has an appreciable carbon content, and many neutron-induced C^{12} disintegrations into three alpha particles proceed via Be^8.[18] A carbon star in which two alphas are colinear and the third scatters could thus have the appearance of a hammer star. A number of such cases, in which the calculated Q agreed closely with the value of -7.28 Mev for C^{12} disintegration, were discarded.

Since the electron emitted from the Li^8 leaves no track in the type of emulsion used, allowance for its momentum as well as for that of the neutrino had to be made in the criteria of colinearity and equality of range which would otherwise be imposed on the two alphas by conservation of momentum. Thus, a maximum divergence of about 20% from equality of range of the two alphas would occur if both the electron and the neutrino were emitted in the same direction as one of the alphas.[23] Similarly, a maximum divergence of 6° from colinearity would occur if the electron and neutrino were emitted in the same direction but at right angles to that of the alphas. The tolerances permitted were somewhat larger than these values, to allow for errors in measurement or for scattering of one or both of the alphas immediately after emission. About fifty "good" stars were obtained at each energy.

V. RESULTS

A. Energy Levels of Li^8

Figure 2 shows that in nearly all events the Li^8 was left in the ground state or in the first excited state of

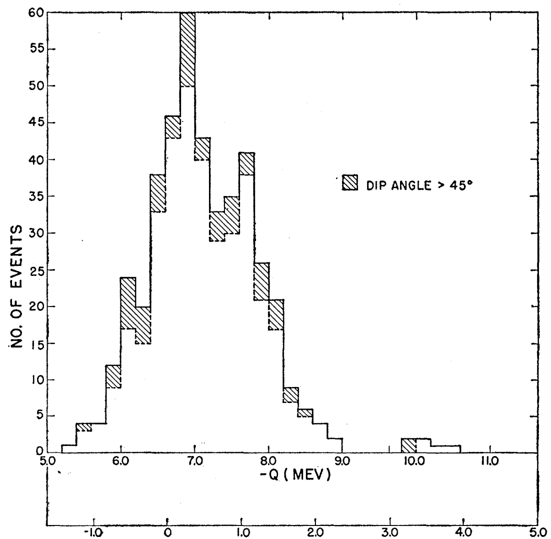

FIG. 2. Q_1 for the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ reaction calculated from the energy and direction of the incident neutron and the alpha particle.

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[20] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report G/R 664, 1951 (unpublished).

[21] W. H. Barkas, Phys. Rev. **89**, 1019 (1953); UCRL-1937, August 29, 1952.

[22] H. Faraggi, Compt. rend. **229**, 1223 (1949).

[23] Christy, Cohen, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **72**, 698 (1947).

1.0 Mev, which is here only partially resolved from the ground state. There is no indication of the 2.28-Mev level; and none should be expected, since this level is unstable against decay by neutron emission.

B. Cross Section for the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ Reaction

The neutron energy and the energy spread at each of the different angles of exposure were the same as those calculated for the experiment on C^{12} disintegration which was performed simultaneously with this experiment.[19] The attenuation of the neutron flux in boron-loaded emulsion was measured and included in the calculation of the absolute flux at each region of the plates analyzed. In the evaluation of the cross section stars were included in which the alpha particle had gone out the top or bottom of the emulsion, provided $-5.0>Q_1>-9.0$ Mev and the calculated energy of the alpha gave $\Delta Q\leq 1.4$ Mev.

Table I and Fig. 3 show the variation of cross section with incident neutron energy for the (n,α) reaction.

TABLE I. The cross sections for the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ reaction.

Incident neutron energy in Mev	Cross section and total error in mb
12.6	27.0±6.5
13.0	38.4±7.4
14.7	30.9±6.3
15.4	36.9±7.0
16.9	21.9±3.6
17.6	23.7±4.8
18.9	19.7±3.7
19.8	16.3±3.1
20.0	15.8±3.1

These values are a lower limit, since they do not include those reactions in which the Li^8 is left excited above 2.04 Mev where it decays by neutron emission rather than by beta emission. Nor do they include the beta decay of Li^8 to the ground state of Be^8, since the disintegration energy of 0.10 Mev for Be^8 is too small for the resulting alpha particles to leave tracks of perceptible length. The multiple reaction would thus appear simply as the two-pronged (n,α) reaction which could not be resolved from the multitude of other two-prong events occurring in the emulsion. The transition to the ground state of Be^8 has been found experimentally to be less than 2 percent of the entire β decay of Li^8.[2]

Absolute errors in the determination of cross section are estimated as follows: determination of neutron flux, 5%, except at 12.6 Mev where it was 15%[19]; B^{11} content of the emulsion, 10%; emulsion thickness and area scanned, 5%; star recognition, 5%; statistical uncertainty, 13% to 17%, as indicated in Fig. 3. Total errors range from 19% to 23%.

Since stars may have been missed, any of the cross-section values are more likely to be low than high; and stars at low energy can be missed more easily than those at high energy. The larger uncertainty in the neutron flux at 12.6 Mev[19] is further reason for the apparent slighting of this point. The decrease in cross section at higher energies may be due in part to competing reactions which may occur at these energies. At 14 Mev there is agreement, within statistical limits, with the results of Heiberg,[18] who reports a cross section of the order of 30 mb for the (n,α) reaction at this energy.

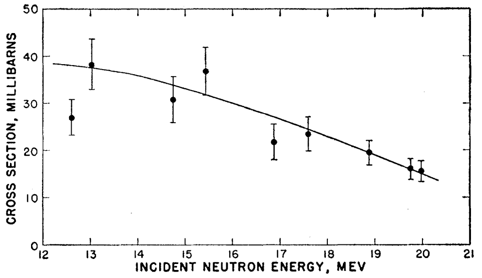

FIG. 3. The cross section for the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ reaction for incident neutron energies from 12.6 to 20.0 Mev. The errors shown are statistical.

C. Angular Distributions of the Alpha Particle in the (n,α) Reaction

The angular distributions, in the center-of-mass system, of the alpha particle from the (n,α) reaction at each energy are shown in Fig. 4. Although there appears to be slight peaking in the forward direction at several of the higher energies, the divergence from symmetry about 90° lies within the statistical error except at 20 Mev.

D. Energy Levels of Be^8

The excitation energy of Be^8 is obtained by subtracting the binding energy of the ground state of Be^8 from the sum of the energies of the two breakup alphas, i.e., $E_{\mathrm{ex}}(Be^8)=E_{\alpha 1}+E_{\alpha 2}-0.10$ Mev. No stars in which either alpha left the emulsion were included in the determination of the excitation energy of Be^8, although they were used for the (n,α) cross section and the energy levels of Li^8.

The excitation energies of Be^8 are shown in Fig. 5. The broad 3-Mev level is clearly indicated. On the low-energy side of the peak there is a shoulder which could correspond to the 2.2-Mev level reported by several observers.[3,9,10] There is only slight indication of the 4.0-Mev level found in these as well as in other investigations,[3–6,11,12] and even less corroboration of levels reported at 5.3 Mev[3,9,14] and at 7.5 Mev.[3–6,11,14] In fact, within the limits of the statistics a smooth curve can be drawn representing the events of Fig. 5 and showing only the broad 3-Mev level. Although a 10% branching to the 10-Mev level has been observed,[2] there is no indication of this level in the present study. The observations of Gilbert[24] and of Frost and Hanna[7] confirm

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[24] F. C. Gilbert, Phys. Rev. **93**, 499 (1954).

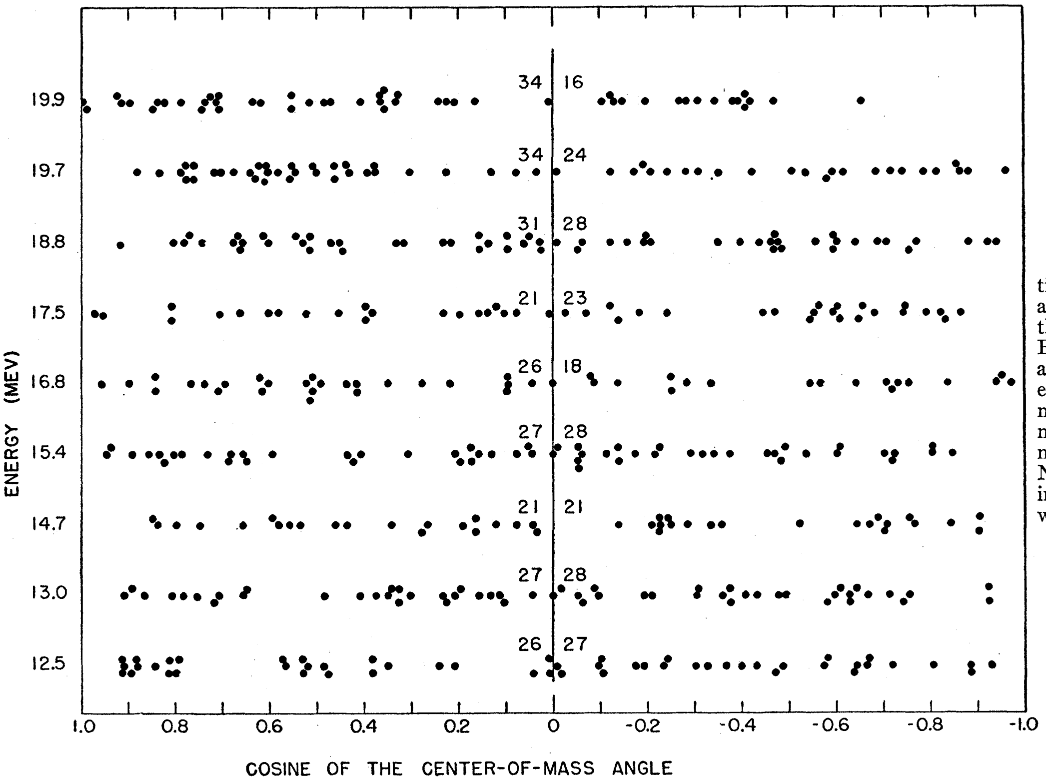

FIG. 4. Distribution of individual alpha particles from the $B^{11}(n,\alpha)Li^8(\beta^-)Be^{8*}(2\alpha)$ reaction as a function of energy in the center-of-mass system, parametric in incident neutron energy. Numbers are totals in forward and backward hemispheres.

the absence of any level above 8 Mev, at least up to an energy of 12 Mev.

E. Range-Energy Relation for Li^8

Previous investigations[21,22,25–27] of the range-energy relation for Li have shown discrepancies in the low-energy region. The present experiment provides data for an empirical Li^8 range-energy relation throughout the low-energy region, since the Li^8 particles originating from the (n,α) reaction are emitted with all energies up to a maximum of 9 Mev for a bombarding energy of 20 Mev. The energy of each measured Li^8 can be obtained from the energy of the incident neutron, the energy of the alpha particle, and Q_1. The range-energy plot of the data from all the stars showed a large spread of the calculated energies corresponding to any given

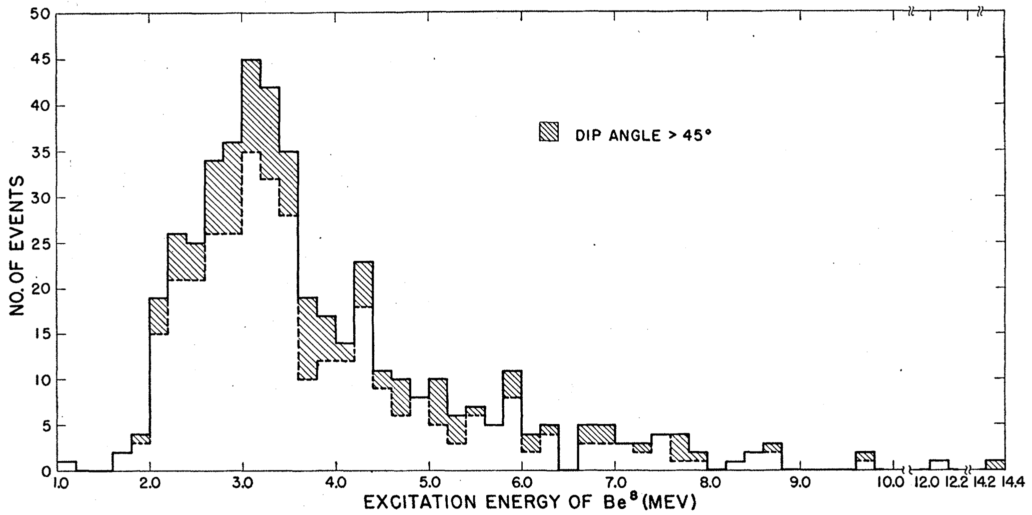

FIG. 5. Excitation energy of Be^8 calculated from the sum of the two hammer-alpha energies.

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[25] F. C. Gilbert, University of California Radiation Laboratory Report 2771, 1954 (unpublished).

[26] P. Cüer and J. Lonchamp, Compt. rend. **232**, 1824 (1951).

[27] Neuendorffer, Inglis, and Hanna, Phys. Rev. **82**, 75 (1955).

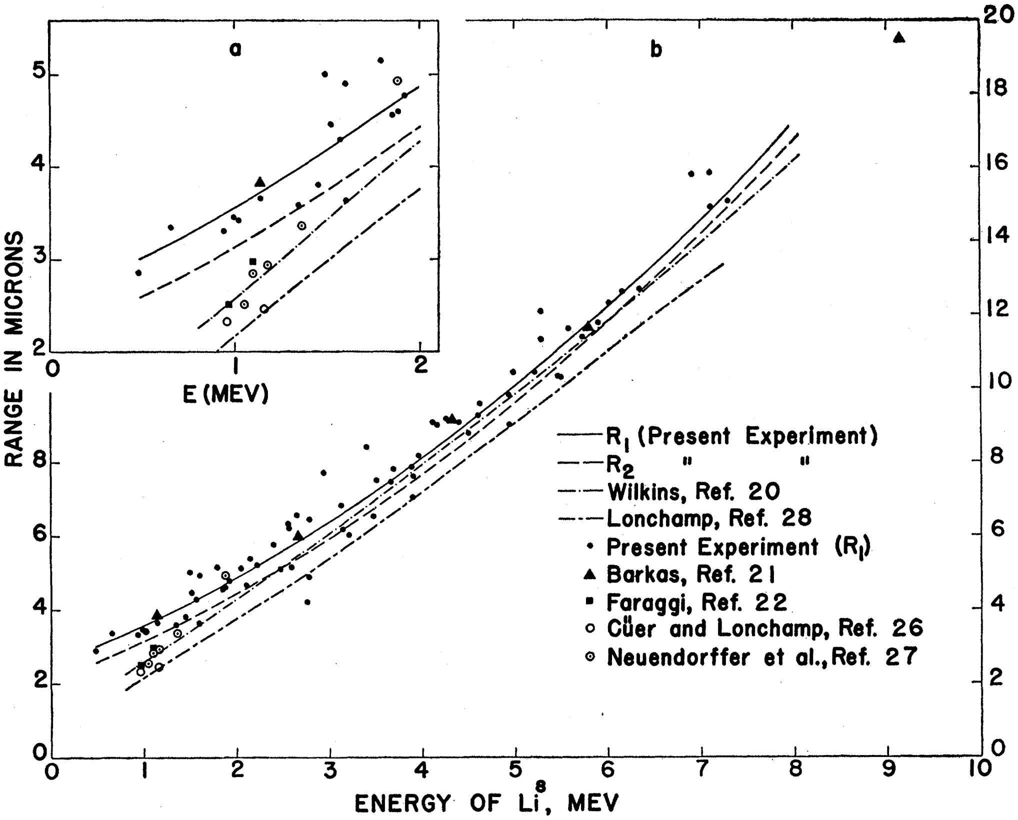

FIG. 6. The range-energy relation for Li^8 in Ilford C-2 emulsion. R_1 is a least squares quadratic fit to the solid circles, where the Li^8 range was measured from the α-Li^8 vertex to the farther edge of the hammer track. R_2 is a similar fit to the points (not shown) where the Li^8 range was measured only to the center line of the hammer track. The two conventions give approximately a 0.5 μ difference. The other two curves of Wilkins and Lonchamp are semitheoretical. The Li^6 points of Neuendorffer *et al.*, and the Li^7 points of Faraggi and Cüer and Lonchamp have all been transformed to Li^8.

range. This spread was due to the width in E_n, the inclusion of some steeply-dipping tracks, and the fact that no special precautions were taken to insure that uniform criteria were used by the various scanners in measuring the Li^8 projected range. To obtain the best data it was decided to use only the events where neither the first alpha nor the Li^8 dipped more than 45° in the unprocessed emulsion and where $|Q_1 - Q_m| \leq 0.3$ Mev. It was assumed that these reactions had actually proceeded via the ground state of Li^8, and hence $Q_m = -6.63$ Mev (determined from the masses) was used to calculate the energy of the Li^8.

To conform as closely as possible to the convention of Wilkins,[20] whose range-energy data for boron-loaded emulsions were used, the length of the alpha-particle track should have been measured between the outer edges of the first and last grains of the track. Some question as to the identification of the first grain, however, arises from the fact that the grain of the α-Li^8 vertex may belong in some cases to the alpha and in others to the Li^8 particle. The same ambiguity applies to the Li^8 particle. To be consistent, therefore, the α-Li^8 vertex was defined as the intersection of the center lines of the alpha and Li^8 tracks, and this point was taken as the beginning of each track. The alpha-particle range was then measured from this point to the outermost edge of the last grain of the track.

Since the Li^8 ends in a hammer track, Wilkins' convention cannot be applied here. Furthermore, to determine if the discrepancies in published data might be due to different criteria for measurement, it was decided to measure the Li^8 range in two ways. In method (1) the range was measured from the α-Li^8 vertex to the outer edge of the hammer track; in method (2) the range was measured from the α-Li^8 vertex to the axis of the hammer track. The range found by this second method should be very close to the actual distance traveled by the Li^8, since the intersection of the first alpha and Li^8 axes establishes the point of origin of the Li^8, and the two alphas of the hammer track serve to locate the position of the Li^8 at rest.

The results are shown in Fig. 6. The individual points are those obtained by method (1). The solid curve is a least squares quadratic fit to the points from 2 to 16 μ whose equation is

$$R_1(Li^8) = 2.578 + 0.955E + 0.111E^2,$$

where E is in Mev and R in microns. The least squares fit to the points of method (2), which gives values about one-half micron shorter than (1), are shown in Fig. 6 by the dashed curve whose equation is

$$R_2(Li^8) = 2.120 + 0.928E + 0.114E^2.$$

The standard deviation of the experimental points from either curve is 0.6 micron, which corresponds approximately to an energy of 0.3 Mev. This energy is the maximum deviation from the value of $Q_m = -6.63$ Mev allowed for the selection of stars for remeasurement in this check of the range-energy relation.

$R_1(\mathrm{Li}^8)$ agrees, within our experimental error, with the points of Barkas,[21] whose criterion for the end of the Li^8 track was that of method (1). Although Gilbert[25] states that his results agree with those obtained by Barkas, his criterion for the end of the Li^8 track was that of method (2). In the experiments of Barkas and Gilbert the Li^8 tracks were surface ones and the range was measured from the point at which the Li^8 ion entered the emulsion; whereas in the present experiment all the tracks originated and ended in the emulsion.

$R_2(\mathrm{Li}^8)$, although still somewhat above them, is closer than $R_1(\mathrm{Li}^8)$ to the low-energy experimental points of Faraggi,[22] Cüer and Lonchamp,[26] and Neuendorffer, Inglis, and Hanna.[27] The semitheoretical curve of Wilkins, which was fitted to the two low-energy points of Faraggi, agrees quite well with the results of method (2), whereas that of Lonchamp[28] is somewhat low.

Equations (1) and (2) apply at 30% relative humidity. Although these results are for boron-loaded emulsion, the correction to normal emulsion is less than 1% at 30% relative humidity.[20] Therefore no correction was made.

ACKNOWLEDGMENTS

We extend our thanks to the members of the large electrostatic accelerator group for their assistance in exposing the emulsions; to the eighteen microscopists of the nuclear plate group who not only analyzed the plates but carried out some of the calculations; and to Mr. Robert Bergstresser for his invaluable aid in the analysis of the calculations. We are also happy to express our appreciation of Dr. Louis Rosen's interest in this work and his many helpful criticisms.

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[28] J. P. Lonchamp, J. phys. radium **14**, 89 (1953); Compt. rend. **239**, 877 (1954).

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Alpha and Spontaneous Fission Half-Lives of Plutonium-242*†

J. F. Mech, H. Diamond, M. H. Studier, P. R. Fields, A. Hirsch, C. M. Stevens,
R. F. Barnes, D. J. Henderson, and J. R. Huizenga
Argonne National Laboratory, Lemont, Illinois

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Measurements on Pu^{242} samples, highly enriched by neutron irradiation, resulted in the alpha half-life value of $(3.88\pm0.10)\times10^5$ years and in the spontaneous fission half-life value of $(7.06\pm0.19)\times10^{10}$ years.

I. ALPHA AND MASS MEASUREMENTS

The alpha half-life of Pu^{242} has been reported previously as 5×10^5 and 9×10^5 years.[1,2] We have recently redetermined this value by a combination of alpha energy and mass spectrographic analyses of plutonium samples enhanced in Pu^{242}.

This plutonium was principally Pu^{242} by mass and was made available through long neutron irradiation of Pu^{239} in the Materials Testing Reactor (MTR) at Arco, Idaho. More precise measurements of the spontaneous fission decay rate and more accurate evaluation of the alpha half-life were possible, since interfering plutonium activities are largely removed in the irradiation process.

Two plutonium samples were irradiated in the MTR with approximately 1.0×10^{22} and 1.2×10^{22} neutrons/cm^2, samples 1 and 2, respectively. After irradiation the plutonium was purified by chemical methods described elsewhere.[3,4] The isotopic compositions of these plutonium samples were determined mass spectrometrically and are compiled in Table I. Alpha pulse analyses of these samples are presented in Table II.

TABLE I. Mass spectrometric analyses of plutonium in mole percent.

Pu isotope	Sample 1	Sample 2
238	0.216±0.004	0.16 ±0.02
239	0.087±0.002	0.068±0.004
240	2.02 ±0.02	0.633±0.006
241	1.31 ±0.01	0.308±0.006
242	96.33 ±0.02	98.77 ±0.03
244	0.037±0.002	0.052±0.004

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* The α half-life was reported previously as Argonne National Laboratory Report ANL-5348.

† Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Thompson, Street, Ghiorso, and Reynolds, Phys. Rev. **80**, 1108 (1950).

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[3] P. R. Fields and C. H. Youngquist, *International Conference on the Peacetime Uses of Atomic Energy, Geneva, Switzerland, August, 1955* (United Nations, New York, 1956), Vol. 2, Paper No. 951.

[4] E. K. Hyde, *The Actinide Elements* (McGraw-Hill Book Company, Inc., New York, 1954), National Nuclear Energy Series, Plutonium Project Record, Vol. 14A, Div. IV, pp. 573–580.

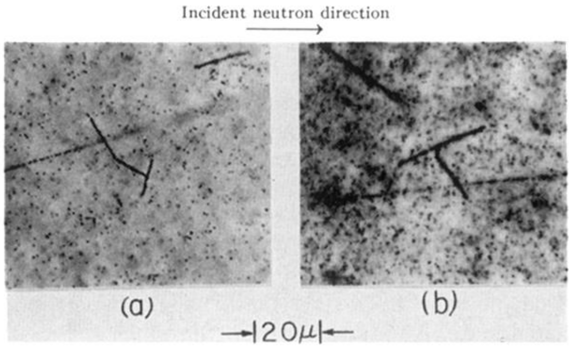

FIG. 1. Two typical "hammer stars." In (a), $E_n = 16.9$ Mev, $E_{ex}(\mathrm{Be}^8) = 3.31$ Mev, and $Q_1 = -7.52$ Mev; in (b), $E_n = 12.6$ Mev, $E_{ex}(\mathrm{Be}^8) = 7.75$ Mev, and $Q_1 = -6.91$ Mev.