Formation of He^6 by 14-Mev Neutron Bombardment of Li and Be*

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Formation of He^6 by bombardment of Li^6, Li^7, and Be^9 with 14-Mev neutrons has been observed. The He^6 was identified by its known half-life and the decay rate observed on a ten-channel time-delay analyzer. Beta-rays from the He^6 were detected by means of a thin-walled proportional counter, and the over-all counting efficiency was determined by using the $Cu^{63}(n,2n)Cu^{62}$ reaction. Cross sections determined for the $Li^6(n,p)$, $Li^7(n,d)$, and $Be^9(n,\alpha)$ reactions were 6.7 ± 0.8, 9.8 ± 1.1, and 10 ± 1 millibarns, respectively. The half-life of He^6 was found to be 0.83 ± 0.03 second.

INTRODUCTION

IN the course of an investigation of the disintegration of Li^6 by 14-Mev neutrons[1] a large cross section was found for the sum of the (n,d) and (n,p) reactions. A large fraction of this cross section could be attributed to the (n,d) reaction, but it was impossible to obtain the magnitude of the smaller (n,p) cross section. Since the latter reaction yields beta-active He^6 (end point=3.5 Mev, half-life$\sim$0.82 sec),[2] it was feasible to measure its cross section by an activation method. The $Li^7(n,d)$ and $Be^9(n,\alpha)$ reactions, yielding the same radioactive nucleus, were also investigated. The $Be^9(n,\alpha)$ cross section has been measured for the neutron energy range from 2 to 4 Mev by Allen *et al.*[3] The $Li^6(n,p)He^6$ reaction for fast neutrons has been most recently observed by Poole and Paul.[4]

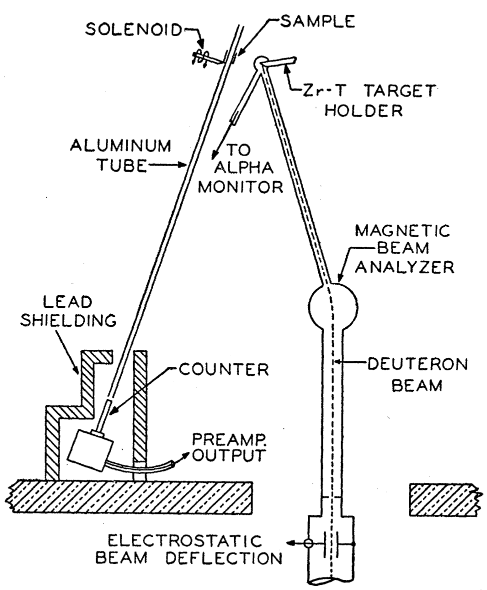

FIG. 1. Experimental arrangement for (n,He^6) cross-section measurements.

APPARATUS

The neutrons used in this experiment were obtained from the $H^3(d,n)He^4$ reaction, by bombarding a zirconium-tritium target[5] with the 250-kev diatomic deuteron beam of the Los Alamos Cockcroft-Walton accelerator. The angular position of the sample was 90 degrees with respect to the deuteron beam, corresponding to a neutron energy of 14.1 Mev. The number of neutrons from this reaction was measured by counting the accompanying alpha-particles emitted in a well-defined solid angle. For the He^6 activation it was necessary to know the instantaneous values of the neutron source strength Q. The Q values were obtained from a counting-rate meter, connected to the output of the alpha-monitor, calibrated under steady beam conditions, in terms of a known number of alphas emitted in a given time interval.

In order to determine the activation cross sections, it was necessary to identify the He^6 by means of its half-life and to determine the initial (saturated) activity of the irradiated samples at the instant the neutron irradiation stopped. Use was made of an automatic timing arrangement, consisting mainly of a time-delay analyzer. The time-delay analyzer, designed by C. W. Johnstone and O. L. Stone of this Laboratory, consisted of ten scales of 100 which were opened successively to the beta-ray pulses by means of a gate at intervals of 0.4 or 1.0 sec after initiation of the gate. Pulses derived by frequency division from a crystal-controlled 100-kc oscillator were used to control the timing of the gate. Such a gating arrangement was used earlier by Cassels and Latham[6] in their measurement of the He^6 half-life.

The He^6 beta-rays were detected by means of a thin-walled aluminum proportional counter filled to a pressure of 65 cm Hg with a Kr-CO_2 (7 percent CO_2) mixture. The normal lithium and beryllium samples were in the form of cylindrical shells which fitted closely around the counter, giving nearly 2π counting

* This work performed under the auspices of the AEC.
[1] F. L. Ribe, Phys. Rev. **87**, 205 (1952).
[2] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 303 (1950); R. K. Sheline, Phys. Rev. **87**, 559 (1952); Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).
[3] Allen, Burcham, and Wilkinson, Proc. Roy. Soc. (London) **A192**, 114 (1948).
[4] M. J. Poole and E. B. Paul, Nature **158**, 482 (1946).
[5] Graves, Rodrigues, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).
[6] J. M. Cassels and R. Latham, Nature **159**, 367 (1947).

geometry. The counting system was biased to record pulses resulting from beta-ray energy losses in the counter of 0.3 kev or greater. With this bias the counter efficiency was approximately 100 percent.

EXPERIMENTAL PROCEDURE

The experimental arrangement is shown in Fig. 1. The sample was supported on an aluminum tube by means of a solenoid plunger about 15 cm from the neutron source. After an irradiation (to near saturation) of about 10 seconds, the deuteron beam was deflected and the solenoid energized, causing the sample to slide down the tube to a position around the counter. The counter was housed in lead shielding 150 cm from the neutron source.

Initiation of the first channel of the time-delay analyzer coincided with the deflection of the deuteron beam. It was not possible to observe the activity during the first second or so after the irradiation stopped; however, the number of channel intervals elapsed before useful counts were obtained provided a precise time interval for extrapolation to saturated activity. The initial decay of each sample was observed with channel widths of 0.4 and 1.0 sec, and further data were obtained by successively reinitiating the analyzer until the only counts obtained were due to normal background. Before and after each sample run, similar measurements were made with no sample to determine the background. These backgrounds were found to be quite reproducible.

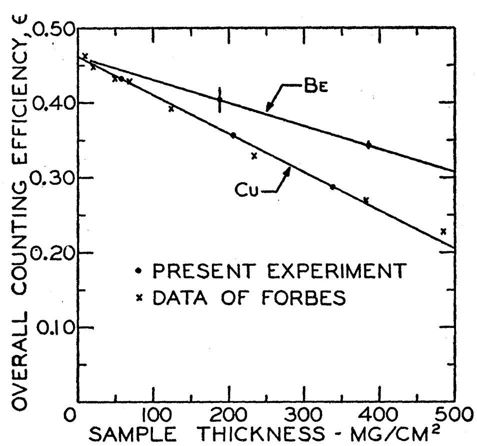

FIG. 2. Variation with sample thickness of the effects of self-scattering and absorption of beta-rays in copper and beryllium.

DETERMINATION OF THE CROSS SECTIONS

If one bombards a sample with a steady flux of f neutrons/cm²/sec, then the activity A at time t after the beginning of the irradiation is

$$A=f\sigma n[1-\exp(-\lambda t)], \qquad (1)$$

where σ is the activation cross section, n the number of atoms of the sample, and λ the disintegration constant of the resulting radioactive nucleus. For $t\gg 1/\lambda$ the cross section is given in terms of the counting rate N_0, corresponding to A, by

$$N_0=f\sigma n\epsilon, \qquad (2)$$

where ϵ is a factor which takes into account geometry, self-scattering and absorption of the sample, and counter efficiency.

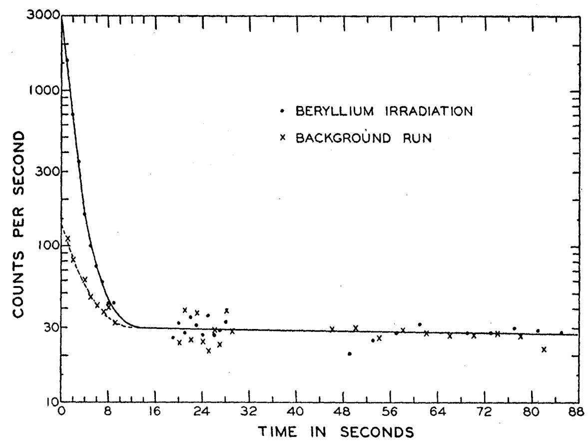

FIG. 3. Upper curve: Decay of He⁶ activity induced in Be by 14-Mev neutrons, background included. Lower curve: Decay of background activity.

In order to determine the over-all counting efficiency ϵ, the 2.9-Mev, 10-minute beta-activity induced in copper by 14-Mev neutrons was used. The $Cu^{63}(n,2n)Cu^{62}$ cross section for normal copper as determined by Forbes[7] for 14-Mev neutrons is 350±25 millibarns. Cylindrical copper samples of thicknesses 56.9, 205, and 338 mg/cm² were bombarded for a few seconds with the 14-Mev neutrons, and the resulting activities were measured in the counting geometry which was used in the He⁶ activation runs. In this case $t\ll 1/\lambda$, and the counting rate N_0 is given by

$$N_0=(ft)\sigma n\lambda\epsilon. \qquad (3)$$

The integrated flux ft was known accurately from the total alpha-monitor count for the irradiation. The values obtained for ϵ are plotted in Fig. 2. Data obtained by Forbes for plane samples in 46-percent counting geometry are also given for comparison. The value of ϵ obtained for zero thickness of copper is assumed to apply also to the cases of lithium and beryllium, although a smaller slope of the curve of ϵ *versus* sample thickness is to be expected for the lighter elements and the He⁶ beta-activity.

A. The $Be^9(n,\alpha)He^6$ Cross Section

Data were obtained for beryllium samples of thicknesses 189 and 385 mg/cm². Figure 3 shows the data for a typical run on the 189-mg/cm² sample using a 1.0-sec analyzer channel width. The background in this case is 5 percent of the initial activity, and it was of

[7] S. G. Forbes (private communication).

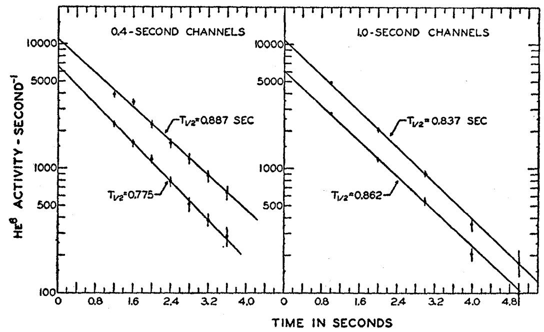

FIG. 4. Decay of He^6 activity induced in Be by 14-Mev neutrons.

roughly the same magnitude for all of the beryllium and lithium runs. He^6 decay curves for both beryllium samples are given in Fig. 4 (background subtracted). The lines drawn through the experimental points were fitted by the method of least squares, weighting the points inversely as their statistical errors. Values of ϵ for the two sample thicknesses, normalized to the value 0.463 for zero thickness are plotted in Fig. 2. This curve is taken, within the error of the present experiment, to apply also to lithium. The error in extrapolation of the values of ϵ to zero sample thickness is ± 5 percent. The data of Fig. 4 provided four determinations of the He^6 half-life which were 0.862, 0.837, 0.887, and 0.775 sec. The $Be^9(n,\alpha)$ cross section determined from these data is 10 ± 1 millibarn.

B. The (n,He^6) Cross Section for Normal Lithium

Three runs were made with a normal lithium sample of 191 mg/cm^2 thickness, two with 0.4-sec and one with 1.0-sec channels. The three values obtained for the He^6 half-life were 0.773, 0.811, and 0.822 sec. The cross section for the production of He^6 in normal lithium was determined as 9.5 ± 1.0 millibarn. This represents a combination of the $Li^6(n,p)$ and $Li^7(n,d)$ cross sections, weighted according to their normal isotopic abundances (92.6 percent lithium 7).

C. Ratio of the (n,He^6) Cross Sections of Li^6 and Li^7

Enriched samples of lithium 6 (90.94 percent) and lithium 7 (99.90 percent) in the form of cylindrical slugs 7.8 mm in diameter, of weights 0.793 and 0.964 gram, respectively, were used. These slugs were irradiated in turn in a thin polyethylene container which fitted around the counter. The He^6 activity from each slug was counted with the axis of the slug parallel to that of the counter. Since the activities were counted in identical geometry, the ratio of the $Li^6(n,p)$ and $Li^7(n,d)$ cross sections could be determined independently of the over-all counting efficiency. The background runs for this part of the experiment were made with the empty polyethylene container. There was no discernible contribution by the container to the background. Runs on each slug were made, using 0.4- and 1.0-sec channel widths. The four values obtained for the He^6 half-life were 0.806, 0.817, 0.830, and 0.911 sec, and the ratio of cross sections was found to be

$$\sigma_6(n,p)/\sigma_7(n,d)=0.69\pm 0.03.$$

D. The $Li^6(n,p)$ and $Li^7(n,d)$ Cross Sections

Combining the results of the measurements of $\sigma_6(n,p)/\sigma_7(n,d)$ and of the (n,He^6) cross section for normal lithium, one obtains for the isotopic cross sections: 9.8 ± 1.1 millibarn for $Li^7(n,d)He^6$ and 6.7 ± 0.8 millibarn for $Li^6(n,p)He^6$.

E. The He^6 Half-Life

The value of the He^6 half-life obtained from the 11 determinations of this experiment is 0.83 sec with an error of ± 0.03 sec, estimated from the statistical spread of the data.

EVALUATION OF ERRORS

A. Experimental Errors

Among the sources of experimental error in the determination of the cross sections were those arising from the flux measurements and the background determinations. In each of the measurements involving beryllium, normal lithium, and isotopic lithium the saturated activities were determined several times. In all cases, these measurements agreed among themselves to within ± 5 percent; this is taken as the error arising from both of the above sources. In addition, there was the 5 percent error in the extrapolation of the over-all counting efficiency to zero thickness, 7 percent error in the $Cu^{63}(n,2n)Cu^{62}$ cross section, and a 4 percent error in the calibration of the alpha-monitor. These errors account for the uncertainties quoted in the final cross section values.

B. Possible Formation of Li^8

If Li^8 (half-life$=0.83$ sec)[2,8] were formed, either by the $Be^9(n,d)$ or the $Li^7(n,\gamma)$ reaction, its activity would not have been distinguished from that of He^6. The $Be^9(n,d)$ reaction, however, does not occur at 14-Mev neutron energy, since its threshold is 16.3 Mev. The $Li^7(n,\gamma)$ cross section for thermal neutrons is 33 millibarns.[9] Measurements made with a U^{235} fission chamber, at 15 cm from the neutron source, showed that the thermal and epicadmium (less than 14-Mev) neutron fluxes were 0.03 percent and ≤ 3 percent of the 14-Mev component, respectively. The activity of Li^8 due to

[8] W. Rall and K. G. McNeill, Phys. Rev. **83**, 1244 (1951). This paper also contains references to previous measurements of the Li^8 half-life.

[9] Hughes, Hall, Eggler, and Goldfarb, Phys. Rev. **72**, 646 (1947).

thermal and epithermal neutron capture was therefore negligible. It is reasonable to assume that the $Li^7(n,\gamma)$ reaction also gives a negligible contribution for 14-Mev neutrons, since at these energies particle emission from the compound nucleus is generally much favored over gamma emission. This assumption is borne out by the fact that even at the resonance peak of about 10 barns in the total cross section at 0.256-Mev neutron energy the $Li^7(n,\gamma)$ cross section is less than 0.1 millibarn.[10]

The authors are pleased to acknowledge the helpful interest of Dr. J. H. Coon and Dr. E. R. Graves throughout this investigation.

[10] Rose, Bayly, and Freeman, AERE, Harwell (private communication).

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The Beta-Decay Interaction*

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The recent identifications of two beta-decays as 0-to-0 transitions proves that the beta-decay interaction must contain a component obeying Fermi selection rules. Evidence is presented regarding the relative strengths of the Fermi- and Gamow-Teller interactions, and experiments are suggested to improve our knowledge of these strengths. It is pointed out that the He^6 *ft* value does *not* give significant information about the beta-decay interaction. An experiment is proposed to determine the nature (scalar or polar vector) of the Fermi interaction.

THERE are now two cases known of allowed and favored 0-to-0 transitions. One is a branch of the C^{10} decay;[1,2] the second is the decay of O^{14}.[1,3,4] Hence, the beta-decay interaction must contain a part leading to Fermi selection rules, i.e., an admixture of either the scalar or the polar vector interaction, or of both interactions.[5]

We wish to call attention to the fact that the O^{14} decay allows us to get more specific information about this Fermi component. First, we may ask for the relative strength of the Fermi and Gamow-Teller interactions. Let M_0^2 be the square of the nuclear matrix element for the Fermi interaction, M_1^2 be the corresponding quantity for the Gamow-Teller interaction (these quantities are often referred to as $(\int 1)^2$ and $(\int \boldsymbol{\sigma})^2$, respectively). We restrict ourselves to transitions for which these matrix elements can be computed theoretically without detailed knowledge of the nuclear wave functions.[6] For transitions within the same isotopic spin multiplet, between nuclei with neutron excesses T_ζ and T_ζ', respectively, we get

$$M_0^2 = T(T+1) - T_\zeta T_\zeta', \tag{1}$$

where T is the quantum number for the total isotopic spin. Formula (1) depends only upon the assumed charge independence of nuclear forces. In particular, it holds even in the presence of strong spin-orbit coupling, i.e., under conditions where the full supermultiplet theory of Wigner[7] is inapplicable.

Unfortunately, the determination of M_1^2 is not as clean-cut since the presence of spin-orbit coupling leads to appreciable corrections. For example, the 4 percent admixture of $^4D_{\frac{1}{2}}$ state to the $^2S_{\frac{1}{2}}$ ground state of H^3 leads to a 5 percent correction in M_1^2.[6,8,9] Since the D-state admixture is not very well known (it could be anywhere between 1 and 10 percent, if one takes into account the possibly quite large relativistic corrections to the magnetic moments of H^3 and He^3) the value of the beta-decay matrix element M_1^2 is correspondingly

* Work assisted by the joint program of the ONR and AEC.
[1] Sherr, Muether, and White, Phys. Rev. 75, 282 (1949).
[2] R. Sherr and J. Gerhart, Phys. Rev. 86, 619 (1952).
[3] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. 22, 291 (1950).
[4] The identification of the final state (a 2.3-Mev excited level of N^{14}) as having spin zero was made by Adair (private communication) by an ingenious application of the charge independence of nuclear forces, leading to a selection rule for the isotopic spin quantum number. In particular, Adair's argument shows that there cannot be an excited $^3S_1$ state of N^{14} close (in energy) to the $^1S_0$ "partner" of the O^{14} ground state. Previously the possibility (and even theoretical likelihood) of such a $^3S_1$ state close to the $^1S_0$ state had made it impossible to identify the beta-decay of O^{14} as a 0-to-0 transition. Dr. N. Kroll has kindly informed the writer that a weaker assumption about nuclear forces suffices to get the selection rule in the cases discussed by Adair. However, the identification of the 2.3-Mev level of N^{14} as a spin 0 state is not appreciably weakened by Kroll's argument; in particular, a $^3S_1$ state close by would have been observed in Adair's experiment even under Kroll's assumptions about nuclear forces.
[5] E. J. Konopinski, Revs. Modern Phys. 15, 209 (1943).
[6] E. P. Wigner, Phys. Rev. 56, 519 (1939); J. M. Blatt, Phys. Rev. 89, 86 (1953), following paper.
[7] E. P. Wigner, Phys. Rev. 51, 106 (1937).
[8] E. Gerjuoy and J. S. Schwinger, Phys. Rev. 61, 138 (1942); and experimental evidence from the magnetic moments of H^3 and He^3. A recent theoretical calculation by Pease and Feshbach (private communication) indicates an admixture of 3 percent rather than 4 percent.
[9] E. Feenberg, quoted by G. Trigg, Phys. Rev. 86, 506 (1952). An error of sign in the value quoted there was corrected in a private communication from Professor Feenberg to the writer. At the time Trigg's paper was written there was no experimental identification of the spins in the O^{14} decay. Thus Trigg's argument for the presence of a Fermi interaction was based primarily upon comparative half-lives rather than upon selection rules.