$H^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$ Reactions

H. D. HOLMGREN AND R. L. JOHNSTON
Nucleonics Division, United States Naval Research Laboratory, Washington, D. C.
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The cross sections for the $H^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$ reactions have been measured at bombarding energies of 480, 720, 940, 1130, and 1320 kev. The cross sections at the lower bombarding energies may be fitted within the experimental uncertainties by the expressions $\sigma=0.12(1-0.00051E_\alpha)E_\alpha^{-1}\exp(-125E_\alpha^{-\frac{1}{2}})$ b for the H^3 reaction and $\sigma=2.8(1-0.00055E_\alpha)E_\alpha^{-1}\exp(-250E_\alpha^{-\frac{1}{2}})$ b for the He^3 reaction, with E_α in kev.

INTRODUCTION

THE $H^3(\alpha,\gamma)Li^7$ and the $He^3(\alpha,\gamma)Be^7$ reactions are of interest in astrophysics and nucleogenesis.[1–3] On the basis of the calculations of Cameron[1] and Fowler[2] the second reaction may be very important in the energy production of many stars during certain periods of their lifetimes. Our sun appears to be in just such a period. In addition they represent a means of bypassing the mass-5 barrier in the production of elements and may account for the anomalous over-abundance of certain light elements in some stars.[2]

The pp-reaction chains in hydrogen-burning stars which contain sufficient quantities of He^4 may proceed in the following ways[1,2]:

$$H^1(p,\beta^+\nu)H^2(p,\gamma)$$
$$He^3(He^3,2p)He^4, \quad (1)$$
$$\searrow (\alpha,\gamma)Be^7(e^-,\nu)Li^7(p,\alpha)He^4, \quad (2)$$
$$\searrow (p,\gamma)B^8(\beta^+\nu)Be^{8*}(\alpha)He^4, \quad (3)$$

where the following amounts of energy are released on the average, exclusive of the neutrino energy losses, in the conversion of 4 protons into an α particle: (1) 26.2 Mev, (2) 25.6 Mev, and (3) 19.1 Mev. The relative importance of each chain will depend upon the temperature, the densities of the constituents, the ratio of the cross section for the $He^3(He^3,2p)He^4$ reaction to that for the $He^3(\alpha,\gamma)Be^7$ reaction, and the ratio of the $Be^7(e^-,\nu)Li^7$ cross section to the $Be^7(p,\gamma)B^8$ cross section.

Due to the astrophysical interest an attempt was made to measure the cross sections for these reactions at as low a bombarding energy as possible. The reactions were found to proceed by nonresonant capture, thus making it possible to extrapolate the cross sections to very low energies with reasonable accuracy.

PROCEDURE

One of the 2-Mv Van de Graaff accelerators of the Naval Research Laboratory was used as a source of singly-ionized α particles[4] for these studies.

The H^3 and He^3 gases were contained in a small gas-target chamber, shown in Fig. 1. The beam of α particles entered the target chamber through a 25-μin. nickel window and were stopped at the other end of the chamber by a gold disk. The target chamber was filled with 94% He^3 to a pressure of 85 mm of Hg in order to study the $He^3(\alpha,\gamma)Be^7$ reaction and with 99% H^3 to a pressure of 20 mm of Hg for the $H^3(\alpha,\gamma)Li^7$ reaction. The number of α particles incident upon the gas was determined by measuring the charge collected in the chamber.

At the highest bombarding energy, 1320 kev, the yield of γ rays from these reactions was measured with a 3-in. diam by 3-in. long NaI (Tl) crystal placed at 90° to the axis of the beam and at a distance of 1 in. from the axis of the target chamber. The absolute cross sections were determined from the calculated efficiencies[5,6] for NaI crystals under these conditions. Since the yields decrease very rapidly with bombarding energies, it was necessary to use the 5-in. diam by 3-in. NaI (Tl) well crystal, shown in Fig. 1, in order to determine the yield at lower energies.

Because the yields from these reactions are very low, it was necessary to determine the background under conditions as similar as possible to those under which the actual runs were made. This was accomplished by first taking a background run with the chamber filled with He^4; then a second run was taken for the same length of time and for the same amount of charge with the chamber filled with H^3 or He^3 to the same pressure as the background run. The H^3 or He^3 gas was then recovered; the chamber was again filled with He^4 and another identical background run was made. Two examples of the γ-ray spectra obtained with a 20-channel differential pulse-height analyzer in the above manner are shown in Figs. 2 and 3. Each run took about

[1] A. G. W. Cameron, Bull. Am. Phys. Soc. Ser. II, 3, 227 (1958), and private communication.
[2] W. A. Fowler, Astrophys. J. 127, 551 (1958), and private communication.
[3] A. G. W. Cameron, Atomic Energy of Canada, Limited, Report AECL 454 (unpublished).

[4] α particles were chosen as the bombarding particles rather than He^3 and H^3 ions because they produce fewer γ rays when they strike most other nuclei.
[5] Lazar, Davis, and Bell, Nucleonics 14, 52 (1956).
[6] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report NRL-4833 (unpublished).

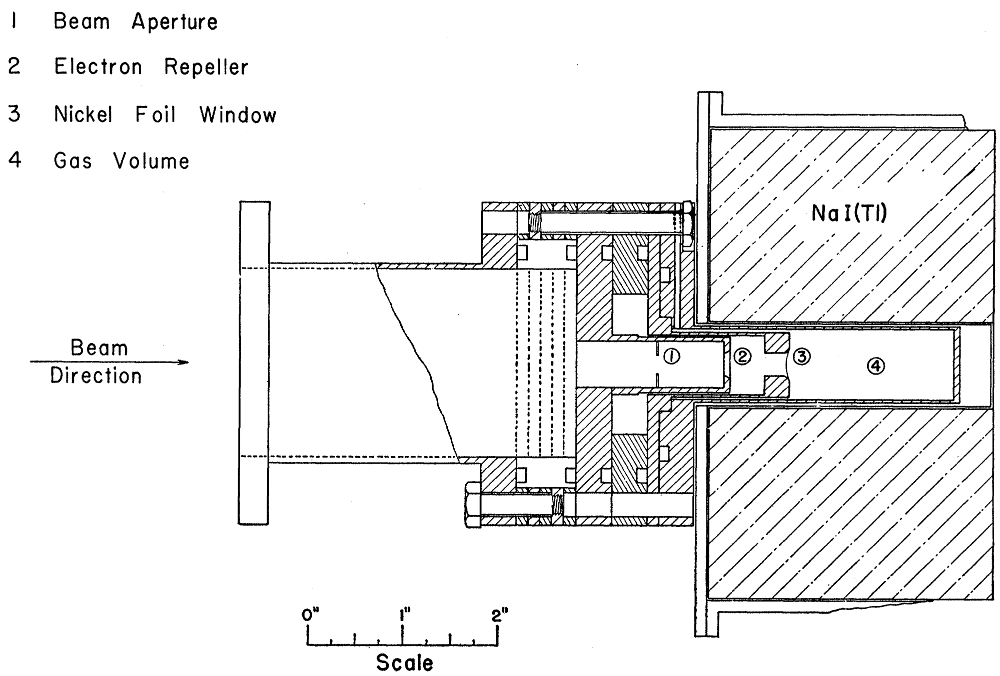

FIG. 1. Schematic diagram of the experimental apparatus.

one hour. The beam currents were limited to 0.2 or 0.3 μa because of the fragility of the nickel window.

In order to determine if the difference in charge of the H^3 and He^3 nuclei would produce any effect on the background due to differences in the Coulomb scattering, the chamber was filled with H^1. It may be seen in Fig. 2 that the background with the chamber filled with H^1 was essentially the same as with the chamber filled with He^4. The background runs were normally taken using He^4 instead of H^1 throughout the H^3 experiment in order to reduce the dilution of the H^3. The backgrounds obtained with He^4 in the chamber were not significantly different from that obtained with the beam off except at the highest bombarding energy. This increase in background was probably due to the interactions in the NaI crystal of neutrons from $C^{13}(\alpha,n)O^{16}$ reactions.[7]

The energy of the γ rays corresponding to the ground-state transition was found to increase continuously with the bombarding energy in agreement with the

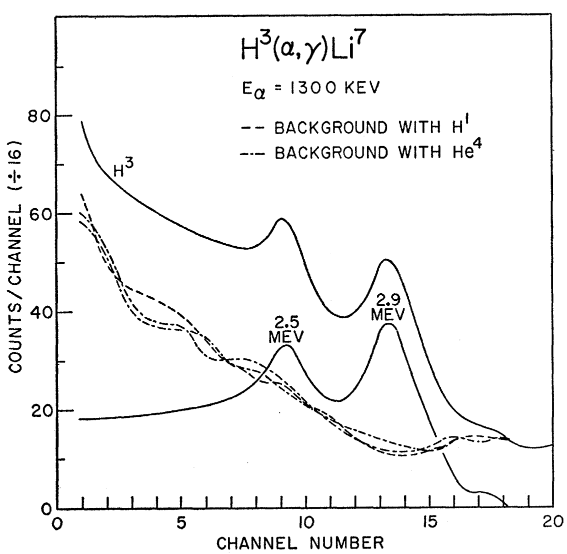

FIG. 2. γ-ray spectra observed with H^3, H^1, and He^4 as target gases. Lower solid curve is with the average background subtracted from the gross spectrum. Of importance is the similarity of background with H^1 and He^4 as target gases. Data points are omitted for clarity.

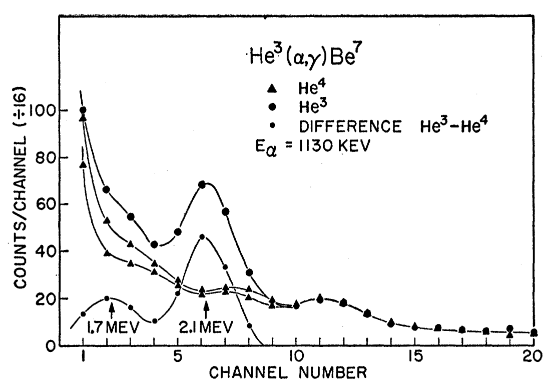

FIG. 3. γ-ray spectra observed with He^3 and He^4 as target gases. Lower curve is with the average background subtracted from spectrum with He^3 as target gas.

[7] The 1% of C^{13} in the very thin layers of normal C which accumulated upon the collimating apertures, window, and beam stopper would probably be sufficient to account for this observed increase in the background. Since this background was subtracted out in the procedure described above, it did not affect the data.

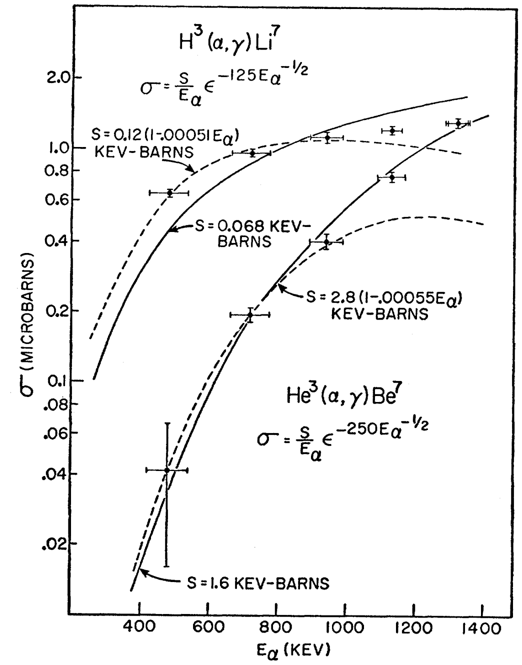

FIG. 4. The total cross sections for the $H^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$ reactions as a function of energy. The solid curves are for S, a constant in the expression. The dashed curves are for S energy-dependent, as indicated.

following relationship:

$$E_\gamma = Q + (3/7)E_\alpha,$$

where Q is 1.583 Mev for the $He^3(\alpha,\gamma)Be^7$ reaction and 2.465 Mev for the $H^3(\alpha,\gamma)Li^7$ reaction. This continuous change in γ-ray energy confirmed the identification of these γ rays with the reactions studied.

In order to determine the mean energy of the α particles in the reaction chamber, a thick Li^7 target was placed at the center of the chamber. The chamber was then filled to the normal pressure of He^4 used in taking the background runs. (The stopping powers of He and H do not differ sufficiently so that a correction need be made for this effect.) The shifts in the positions of the 400-, 820-, and 960-kev $Li^7(\alpha,\gamma)B^{11}$ resonances were then measured, as well as their apparent widths. These three resonances provided an energy calibration curve by which the mean energy of the α particles in the chamber could be determined to an accuracy of about 20 kev. In addition, the observed width of the resonances gave an indication of the straggling of the beam of α particles. The α particles were found to lose on an average of 720 kev before reaching the center of the chamber (most of this loss was due to the Ni window) and the beam energy spread was about 120 kev at lowest bombarding energy (1200 kev incident on the window). The energy spread was only about 70 kev at the higher resonances.

Due to this observed large straggling at low bombarding energy, the measurements were limited to a lower

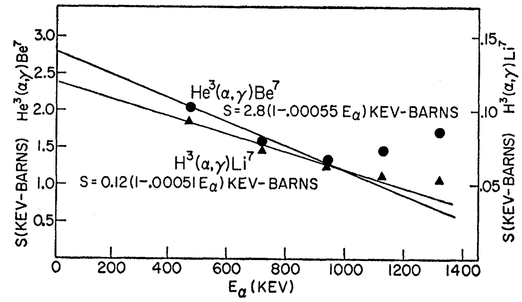

FIG. 5. The experimental values of the cross-section factor, S, as a function of the bombarding energy for the $H^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$ reactions.

bombarding energy of 480 kev. In addition, at this bombarding energy it was difficult to identify the γ rays originating from the reaction due to the rapid decrease in the cross section with energy.

RESULTS

The cross sections for the $H^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$ reactions are shown in Fig. 4. The uncertainties indicated in the values of the cross sections are due primarily to the statistical uncertainties and thus indicate only the relative uncertainties of the data. The absolute uncertainties of the data which arise from the uncertainties in the gas pressure, gas purity, solid angle, and crystal efficiency are estimated to be of the order of 30%.

The horizontal bars indicate the spread of the beam energy in the target chamber due to the straggling caused by the nickel window and the energy loss in the gas.

The curves in Fig. 4 represent two attempts to fit each set of data with an expression of the form[8–10]

$$\sigma = \frac{S}{E_\alpha} \exp\left(\frac{2\pi e^2 Z_1 Z_2}{\hbar v}\right),$$

where v is the velocity of relative motion of the two particles (E_α is measured in kev throughout this paper). This expression is based on an approximation to the barrier penetration calculation for a nonresonant capture cross section. A theoretical expression may be obtained for S of the following form:

$$S = \tfrac{1}{2}\pi R^2 \left(\frac{M_1+M_2}{M_2}\right) \Gamma \exp[(32R/a)^{\frac{1}{2}}],$$

where

$$a = \hbar^2/(M Z_1 Z_2 e^2) = 4.25\times 10^{-13} \text{ cm},$$

R is the radius of interaction, and Γ is the radiation width for γ rays. Assuming $R \approx 4\times 10^{-13}$ cm, we find $S \approx 160\Gamma$ (kev-barns) for the $He^3(\alpha,\gamma)Be^7$ reaction.

[8] Burbidge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 560 (1957).
[9] H. A. Bethe, Revs. Modern Phys. **2**, 186 (1957).
[10] H. A. Bethe, Phys. Rev. **55**, 436 (1939).

Salpeter[11] has assumed that Γ is about 0.1 ev, which gives a value of $S=0.016$ kev-barn for this reaction. This theoretical estimate appears to be too small by about a factor of 100. From the present experiment the best experimental estimate of S (for S a constant) is 1.6 kev-barns. On the basis of a more refined expression[8] for S, one expects S to vary with the bombarding energy according to $S=S_0(1-\alpha E_\alpha)$. In Fig. 5, S has been plotted as a function of the bombarding energy (note different ordinates for the two reactions). It may be seen that for both reactions S appears to vary in a linear manner for low bombarding energies and departs from this line at higher energies. In the above expression it has been assumed that only s-wave α particles contribute to the reaction; thus this departure of the cross-section factor from a straight line at higher bombarding energies may be due to the onset of p-wave α-particle contributions. A reasonable fit to the experimental data is obtained when S_0 equals 0.12 kev-barn and $\alpha=0.00051$ kev^{-1} for the $H^3(\alpha,\gamma)Li^7$ reaction, and when $S_0=2.8$ kev-barns and $\alpha=0.00055$ kev^{-1} for the $He^3(\alpha,\gamma)Be^7$ reaction.

On the basis of these estimates of S for the $He^3(\alpha,\gamma)Be^7$ reaction and the calculations of Cameron[1,3] and Fowler,[2] it appears that chain (2) or (3) could compete very favorably with chain (1) at temperatures above 10×10^6 °K.

[11] E. E. Salpeter, Phys. Rev. 88, 552 (1952).

From the spectra of γ rays taken with the 3-in. diam by 3-in. NaI crystal it is estimated that at a bombarding energy of 1320 kev about 50% of the time both reactions proceed through the first excited states, that is the 478 kev state of Li^7 and 431 kev state of Be^7. In the present experiment it was difficult to estimate how the branching ratio changed with energy; since with the 5-in. diam by 3-in. NaI crystal used to measure the yield curves there was a large probability of stopping both γ rays from the cascade.

Riley[12] has found a cross section of 0.2 μb/sterad at 90° for the $H^3(\alpha,\gamma)Li^7$ reaction at 1640 kev and a branching ratio of 5 to 2 for the ground state to first excited state transitions. On the basis of the combined uncertainties this is in reasonable agreement with the present work.

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[12] Riley, Warren, and Griffiths, Bull. Am. Phys. Soc. Ser. II, 3, 330 (1958).

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Phase-Shift Analysis of Proton-Proton Scattering Experiments below 40 Mev*†

MALCOLM H. MACGREGOR
Radiation Laboratory, University of California, Livermore, California

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A phase-shift analysis has been made of p-p angular distribution measurements at 1.855, 4.203, 9.68, 9.73, 18.2, 19.8, 31.8, and 39.4 Mev. At 1.855 Mev, Coulomb effects plus the nuclear S-wave phase shift are sufficient to give agreement within experimental errors. At 10 Mev, S-, P-, and D-wave effects are apparent. At 40 Mev, F-wave components are also necessary. With the aid of the Clementel-Villi parametrization method, it has been possible to determine all of the least-squares fits to the angular distribution data in the S, P, D approximation. Polarization measurements and potential model calculations can be used to further restrict the allowable phase-shift sets. It is shown that angular distribution measurements with an accuracy of 0.1% would not lead to a unique set of phase shifts. Both double- and triple-scattering experiments are necessary in order to remove the ambiguity.

I. INTRODUCTION

THE spin-space scattering matrix for p-p elastic scattering contains, as is well known, five independent complex amplitudes. Puzikov, Ryndin, and Smorodinsky[1] have shown that, in view of the unitarity conditions on the elastic scattering matrix, only five independent experiments are necessary to specify the matrix. As an example of a set of five such experiments, they list angular distribution cross section, polarization, normal component of the polarization correlation tensor, and normal components of the triple scattering tensor (depolarization) for each of the protons participating in

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† Preliminary accounts of this work were presented at the 1958 Cornell meeting of the American Physical Society [Bull. Am. Phys. Soc. Ser. II, 3, 268 (1958)], and at the Congrès International de Physique Nucléaire in Paris, France, July, 1958; published in Compt. Rend. Congrès intern. Phys. Nucleaire, Dunod, 92 Rue Bonaparte, Paris.

[1] Puzikov, Ryndin, and Smorodinsky, Nuclear Phys. 3, 436 (1957).