Low-energy ^{7}Li(t,α)^{6}He cross sections

F. E. Cecil and R. F. Fahlsing
Department of Physics, Colorado School of Mines, Golden, Colorado 80401

Nelson Jarmie, R. A. Hardekopf, and R. Martinez
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 26 August 1982)

The thick target yield of the reaction ^{7}Li(t,α) has been measured to the ground and first excited states of ^{6}He for bombarding energies between 70 and 110 keV. These yields are used to deduce the reaction cross sections and astrophysical S factors at intermediate values of energy. The zero energy S factor $S(0)$ for ^{7}Li(t,α)^{6}He*(1.81) is 14±2.5 MeV b. Applications of the measured values of the cross section for this reaction to the diagnostics of high temperature tritium plasmas are discussed. Efforts to detect alphas from induced reactions on other light targets ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B are discussed.

[NUCLEAR REACTIONS ^{7}Li(t,α)^{6}He, ^{9}Be(t,α)^{8}Li, ^{11}B(t,α)^{10}Be; $E_t=70-110$ keV, $\theta=150°$. Measured thick target yields. Deduced $\sigma(\theta,E)$, $S(\theta,E)$.]

I. INTRODUCTION

Measurements of nuclear reactions at very low bombarding energies are increasing in number.[1] In addition to the intrinsic physics interest, cross sections measured below 1 MeV and in particular below 100 keV bombarding energy are of interest to astrophysicists and to designers of controlled thermonuclear devices for energy production.[2] Since some early fusion reactors are expected to use tritium in part, the present study investigates tritium-initiated nuclear reactions in light nuclei that might be useful as a plasma diagnostic. In particular we used a target of beryllium and natural targets of lithium and boron, concentrating on the (t,α) reaction since they have large positive Q values. As will be seen, only the ^{7}Li(t,α)^{6}He reaction appears to be of use. We measured thick target yields for this reaction to the ground and first excited state (1.81 MeV), extracted cross sections and astrophysical S factors, and describe how this information might be used to measure the ion temperature in energetic tritium plasmas. Lithium is especially appropriate as it has been suggested for beam heating of a plasma in tokamaks.[3]

Information on the ^{7}Li(t,α) reaction below 1.0 MeV bombarding energy is sparse (Refs. 4 and 5), and published values of the absolute cross section do not exist in this energy region. The (t,α) Q values for ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B are 15.2, 2.9, 13.2, and 8.6 MeV, respectively, and again low energy information about these reactions is limited or nonexistent (Refs. 4—6).

II. EXPERIMENTAL EQUIPMENT AND PROCEDURE

Our measurements were carried out at the Los Alamos National Laboratory using the low-energy fusion cross section facility accelerator.[7] This device accelerates positive or negative hydrogenic ions from 10 to 120 keV. We used typically 10 μA of negative tritium ions. The use of a negative-ion beam eliminated many unwanted molecular species that would otherwise contaminate the beam. Reaction products from the bombardment of a thick target of LiF were detected in reflection geometry (150°) with a 1-mm surface-barrier silicon charged-particle detector. The detector had a solid angle of 10 msr. The accumulated beam charge was measured with a Brookhaven Industries model-100 current integrator. A small bias voltage on the target suppressed secondary-electron escape. Measurements were done at laboratory triton energies of 70, 90, 100, and 110 keV. The beam energies were accurate to 25 eV.

A typical thick target raw-data spectrum is shown in Fig. 1. Particles from ^{19}F are not expected because of the high Coulomb barrier, and the particles rate from ^{6}Li has been oberved to be small.[5] Also,

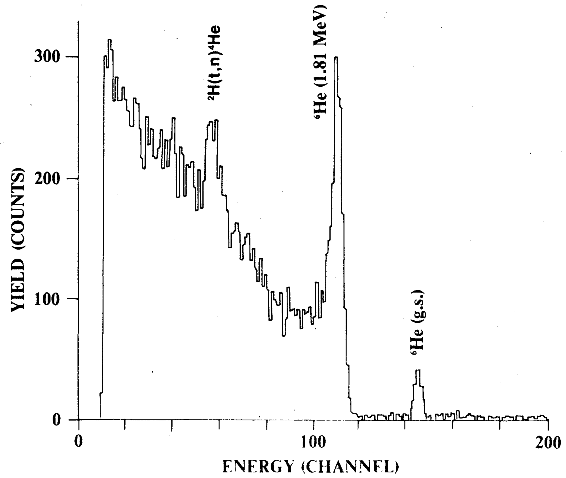

FIG. 1. Charged particle energy spectrum measured during the bombardment of a LiF target with a 110 keV triton beam.

the abundance of ^{6}Li in natural lithium is only 7.5%, the final state (^{5}He) is broad, and the energetics are such that the ^{6}Li reaction should not have interfered. It is possible that some of the low background under the ground state is due to the ^{6}Li in the target.

As the bombardment proceeds, a "self" target of tritium builds up in the LiF target and is responsible for the alpha continuum seen up to the 1.81 MeV ^{6}He peak; both the $^7Li(t,\alpha)\alpha 2n$ and $^3H(t,\alpha)2n$ reactions contribute. In addition, one sees in the spectrum the alpha yield peak due to minute amounts of deuterium in the beam bombarding the self-target of tritium. Such a peak is expected since the $^3H(d,\alpha)n$ cross section is roughly 10^5 larger (near 100 keV) than the ones under study here.

III. DATA REDUCTION AND RESULTS

The differential thick-target reaction yield $Y(\theta,E)$ is determined from the background subtracted peak counts, together with the measured charge and known solid angle of the detector. The resulting yields for the reaction $^7Li(t,\alpha)^6He$ to the ^{6}He ground and 1.81 MeV excited states are shown in Fig. 2. The laboratory differential cross section $\sigma_L(\theta,E)$ is related to the yield as follows:

$$Y(\theta,E_0)=\int_{E_0}^{0}\frac{\sigma_L(\theta,E)}{\epsilon(E)}f\,dE\ , \qquad (1)$$

where $\epsilon(E)$ is the stopping power (in keV cm^2 atom^{-1}) for the triton in the target material LiF. $\epsilon(E)$ is taken as the sum of the stopping powers of

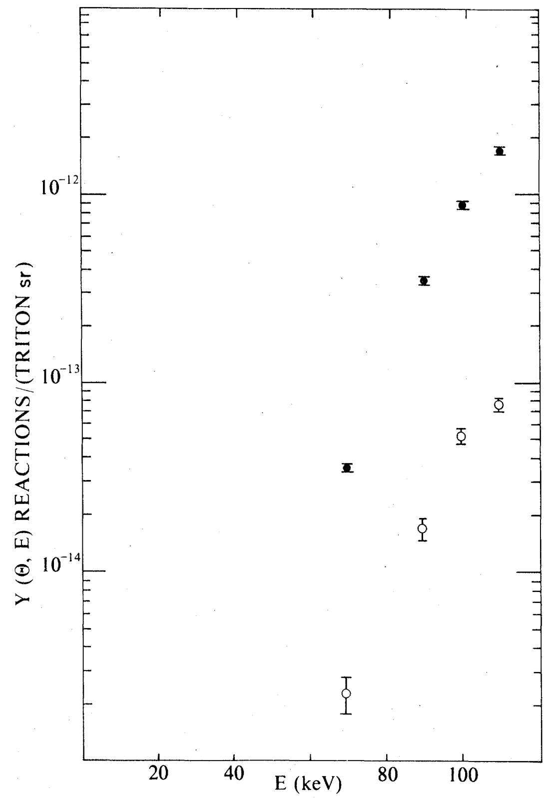

FIG. 2. Thick target yields at $\theta=150°$ of the $^7Li(t,\alpha)^6He$ reaction to the ground state (open circles) and 1.81 MeV 2+ excited states (filled circles) of ^{6}He as a function of the laboratory energy of the incident triton.

lithium and fluorine [the Bragg rule, which is expected to hold within 10% (Ref. 8)]. The constituent stopping powers were taken from the recent compilation of Andersen and Ziegler.[9] The isotropic abundance of ^{7}Li, f, in the target, is assumed to be 92.5%.

The laboratory cross section $\sigma_L(\theta,E)$ may be unfolded from the integral expression of the yield given in Eq. (1) by applying the mean-value theorem to the yields measured at adjacent energies:

$$Y(\theta,E_1)-Y(\theta,E_2)=\frac{\sigma(\theta,\bar{E})}{\epsilon(\bar{E})}(E_1-E_2)f\ . \qquad (2)$$

This procedure is described in a recent Colorado School of Mines report of (d,p) and (d,n) reactions for light nuclei at low bombarding energies.[10,11] The mean intermediate laboratory energies $\bar{E}$ were determined by assuming that the differential cross sections are proportional to the Coulomb barrier penetration probability.[12] The differential cross sections thus determined are transformed to the center of mass and given in Table I. The value for the cross section at a center-of-mass energy of 38.5 keV

TABLE I. Differential cross sections and S factors for the reaction ^{7}Li$(t,\alpha)^6$He to the ^{6}He ground and 1.81 MeV first excited states at a center-of-mass scattering angle of 151° and total cross section for the 1.81 MeV first excited state for center-of-mass initial energies from 38 to 73 keV. The cross sections are measured in μb/sr and μb, and the S factors in MeV b/sr.

E_c (keV)	σ_c(g.s.)	$\sigma_c(1.81)$	$\sigma_T(1.81)$	S(g.s.)	S(1.81)
38.5	0.0008(3)	0.008(2)	0.10(3)	0.10(3)	1.05(25)
56.7	0.015(4)	0.29(03)	3.64(37)	0.061(16)	1.17(11)
66.5	0.065(20)	1.04(09)	13.1(11)	0.077(24)	1.23(11)
73.5	0.054(10)[a]	1.67(20)	21.0(25)	0.031(07)	0.97(11)

[a]The numbers in parentheses give the relative standard deviation and refer to the two least significant digits in the analyzing power. For example, the fourth entry in column 2 is to be read 0.054±0.010.

(corresponding to a mean laboratory energy of 55 keV) was deduced using the measured yield at a laboratory energy of 70 keV and assuming that the yield at a energy $E=0$ would be zero.

The uncertainties of the differential cross section given in Table I are relative uncertainties derived from the statistical uncertainties in the measured yields and backgrounds and range from 9% to 37% for the lowest yield. In addition, there is an absolute scale error of 15% that is derived from (1) uncertainties in the method of data reduction, (2) errors in the stopping power used in Eq. (2), and (3) a geometric uncertainty of the position of the beam spot relative to the detector. The total absolute error may be calculated by adding the relative and scale error in quadrature.

The Coulomb barrier penetrability and the de Broglie wavelength factor $1/E$ may be divided out of the differential cross section values to determine a center-of-mass differential astrophysical S factor $S(\theta_c,E_c)$:

$$\sigma_c(\theta_c,E_c)\equiv S(\theta_c,E_c)\frac{1}{E_c}\exp[-136.2E_c{}^{-1/2}] , \tag{3}$$

where E_c is the center-of-mass energy measured in keV. The resulting values of the S factor for the g.s. and 1.81 MeV states in ^{6}He are given in Table I.

Total cross sections for the ^{7}Li(t,α) reaction to the 1.81-MeV excited state of ^{6}He can be found by multiplying the differential cross section $\sigma_c(1.81)$ given in Table I by 4π. This assumption of center-of-mass spatial isotropy is supported by the measured isotropy of the angular distribution for this reaction by Almqvist *et al.* at a laboratory bombarding energy of 240 keV.[5] This isotropy is likewise consistent with the dominant S wave nature expected of the reaction to the 1.81 state at low energies. Such isotropy is not expected of the transition to the 0^+ ^{6}He ground state nor does the measured angular distribution at 240 keV indicate isotropy; rather the measured angular distribution is strongly peaked at 90°, suggesting that $4\pi\sigma_c$(g.s.) would underestimate the actual values of the total ground-state cross sections by 20 to 30%.

Consistent with the errors in Table I, it is appropriate to assume that $S(E)(1.81)$ is constant; indeed, if one computed the mean $\overline{S(E)}$ from the four values, the internal and external errors of $\overline{S(E)}$ are roughly equal. We conclude that the total S factor $S_T(E)\simeq S_T(0)=14\pm2.5$ MeV b, where the error given is now the total absolute error (with the scale error folded in).

In the course of our measurements on ^{7}Li, we therefore attempted to measure the thick target of the (t,α) reactions on ^{9}Be and a natural boron target (^{10}B,^{11}B). The ^{9}Be$(t,\alpha)^8$Li reaction resulted in an alpha particle that was not observable due to the background of degraded alpha particles from the ^{3}H$(d,\alpha)n$ reaction (recall Fig. 1). The ^{11}B$(t,\alpha)^{10}$Be reaction was observed. However, the yield of this reaction to the ^{10}Be ground state at a triton bombarding energy of 110 keV was about 2×10^{-15} reaction/(triton sr), roughly three orders of magnitude below the ^{7}Li$(t,\alpha)^6$He yield reported in Fig. 2, a result due to the larger Coulomb barrier. We also did not observe with any persuasion any other energetically allowed reactions, such as ^{10}B$(t,p)^{12}$B ($Q=+6.3$ MeV), in the course of our measurements. Thus of the targets that were bombarded (^{6}Li, ^{7}Bi, ^{9}Be, ^{10}B, and ^{11}B), the only reaction for which we measured a relatively large yield, and that yielded a discrete final state, was the ^{7}Li$(t,\alpha)^6$He ground and first excited state (1.81 MeV).

IV. DISCUSSION AND APPLICATION

The total cross section for the reaction to the 1.81 MeV excited state can be used to predict the ^{7}Li(t,α)

reaction rate R when a small component of ^{7}Li is in thermal equilibrium with a high temperature tritium plasma:

$$R = n_t n_7 \langle \sigma v \rangle \text{cm}^{-3}\,\text{sec}^{-1} , \qquad (4)$$

where n_t and n_7 are the triton and ^{7}Li densities, respectively, and the reactivity $\langle \sigma v \rangle$ is the product of the total cross section σ_T and relative velocities averaged over the velocity distribution of the plasma. Assuming this distribution to be Maxwellian,

$$\langle \sigma v \rangle = \left[\frac{2}{M} \right]^{1/2} (kt)^{-3/2} S(E_0) 4 \left[\frac{E_0 kT}{3} \right]^{1/2} \times \exp\left[\frac{-3E_0}{kT} \right] , \qquad (5)$$

where E_0 is the centroid of the Gamow peak[13] and is given by

$$E_0 = \left[\frac{\pi e^2 Z_1 Z_2 kT}{\hbar c} \left[\frac{Mc^2}{2} \right]^{1/2} \right]^{2/3} . \qquad (6)$$

E_0 is given in Table II as a function of the temperature T. M is the triton-^{7}Li reduced mass. The total S factor $S(E_0)$ is $4\pi\, S(1.81)$. The values of $S(E_0)$ are deduced from the measured value of $S(1.81)$ in Table I by interpolation or extrapolation. The fact that $S(E)$ is a slowly varying function of E allows the extrapolation, particularly to low temperature, to be carried out with confidence. We emphasize that this analysis for the ground-state reaction would be uncertain, as we have no reliable estimate of the ground-state total cross section.

From Eqs. (5) and (6), and the values of $S(1.81)$ in Table I, the reactivity $\langle \sigma v \rangle$ is calculated as a function of T for energies up to 200×10^6 K and is given in Table II. The absolute error of $\langle \sigma v \rangle$ is 15%, and the relative error may be inferred from the error in $S(1.81)$ in Table I.

The values of Table II together with Eq. (4) may be used to measure the ion temperature of a tritium plasma if the densities of tritium and ^{7}Li are known

TABLE II. Gamow peak centroids E_0 and velocity averaged cross sections (reactivities) for the reaction ^{7}Li(t,α)^{6}He to the ^{6}He 1.81 MeV excited state.

Temperature ($\text{K}\times10^6$)	E_0 (keV)	$\langle \sigma v \rangle$ ($\text{cm}^3\,\text{sec}^{-1}$)
20	23.6	3.1×10^{-30}
40	37	1.1×10^{-26}
60	49	5.3×10^{-25}
80	60	6.4×10^{-24}
100	69	3.6×10^{-23}
120	78	1.3×10^{-22}
140	87	3.8×10^{-22}
160	95	8.9×10^{-22}
180	100	1.9×10^{-21}
200	110	3.5×10^{-21}

and if the production rate of the 8.1 MeV alpha particles corresponding to the ^{7}Li(t,α)^{6}He(1.81 MeV) reaction can be measured. For example, at a plasma temperature of 100×10^6 K, and with tritium and lithium densities of 10^{14} and 10^{13} cm^{-3}, respectively, the reaction rate [using Eq. (4) and Table II] is 3×10^4 cm^{-3} sec^{-1}. In tokamak fusion reactors attention must be paid to the energy losses and the helical paths of the alpha particles in magnetic fields. The use of this technique may be more applicable in inertial-confinement fusion where the reaction products may escape more easily.

V. CONCLUSION

Thick target yields, cross section, and S factors have been determined for the reaction ^{7}Li(t,α)^{6}He at low energies. A plan for using these values for determining the ion temperature of a Li-seeded tritium plasma is described. We were not able to determine with our apparatus the cross sections and other parameters for ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B.

This work supported by the U. S. Department of Energy, in part under Contract DE AC01 80ER10643.

[1]See, for example, R. E. Holland *et al.*, IEEE Trans. Nucl. Sci. NS-28, 1344 (1981); N. A. Roughton *et al.* At. Data Nucl. Data Tables 23, 177 (1979); F. E. Cecil and R. F. Fahlsing, Phys. Rev. C 24, 1769 (1981); T. P. Intrator *et al.* Nucl. Instrum. Methods 188, 347 (1981).
[2]F. E. Cecil, L. K. Len, and R. J. Peterson, Nucl. Instrum. Methods 175, 293 (1980); F. C. Young, J. Golden, and C. A. Kapetanakos, Rev. Sci. Instrum. 48, 432 (1977).
[3]L. R. Grisham, D. E. Post, H. P. Eubank, and W. C. Stwalley, Bull. Am. Phys. Soc. 25, 983 (1980).
[4]D. M. Ćirić, R. V. Popić, M. R. Aleksić, B. Z. Stepančić, and R. B. Žakula, Fizika (Zagreb), Suppl. 7, 64 (1975).
[5]E. Almqvist, T. P. Pepper, and P. Lorrain, Can. J. Phys. 32, 621 (1954).
[6]B. Ćirić, B. Stepančić, D. Stanojević, K. Subotić, and R.

Žakula, Fizika (Zagreb), Suppl. 1, 9, 39 (1977).
[7]R. A. Hardekopf, R. E. Brown, F. D. Correll, and N. Jarmie, IEEE Trans. Nucl. Sci. NS-28, 1339 (1981).
[8]J. F. Ziegler, private communication.
[9]H. H. Andersen and J. F. Ziegler, *Hydrogen Stopping Powers and Ranges in All Elements* (Pergamon, New York, 1977).
[10]F. E. Cecil and R. F. Fahlsing, Phys. Rev. C 24, 1769 (1981).
[11]F. E. Cecil, R. F. Fahlsing, and R. A. Nelson, Nucl. Phys. A376, 379 (1982).
[12]A discussion of this assumption in the context of low energy nuclear reactions may be found in many sources. See, for example, C. Rolfs and H. P. Trautvetter in *Annual Review of Nuclear and Particle Science,* edited by J. D. Jackson, Harry E. Gove, and Roy F. Schwitters (Annual Reviews, Palo Alto, California, 1978), pp. 115–160.
[13]C. Rolfs and H. P. Trautvetter, see Ref. 12.