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^{8}Li from the ^{9}Be(t,α)^{8}Li reaction

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The ^{9}Be(t,α) reaction has been used to populate states in ^{8}Li. Angular distributions were measured for four low-lying narrow states, and distorted-wave Born approximation calculations (including coupled channels) were used to analyze the data. The results are compared with results of a ^{9}Be($d,{}^3$He) reaction and with Cohen-Kurath shell-model predictions.

I. INTRODUCTION

The nucleus ^{8}Li has been the object of many experimental and theoretical studies. Experiments on ^{6}Li(t,p)^{8}Li,[1] ^{7}Li(d,p)^{8}Li (Ref. 2), and other reactions[3,4] helped to establish its level diagram. It has only two bound states [ground state (g.s.) and 0.981-MeV state], but another two narrow low-lying states (2.255 and 6.53 MeV) and several broad states are known. Nuclear structure information concerning ^{8}Li is summarized in a recent compilation.[5] As for the 6.53-MeV state, its width is remarkably small (35±15 keV) for a state at this excitation, and a 4^+ assignment for it was suggested by Barker.[6] Arnold *et al.*[7] support this assignment based on their measurement of polarized (t,α) reaction and a theoretical analysis. The current experiment was performed in order to obtain absolute cross section for both the suggested 4^+ state and the lower-lying levels. An additional aim was a search for previously unidentified narrow states at low excitation. Schwinn *et al.*[8] studied the ^{9}Be($d,{}^3$He) reaction and performed single-step distorted-wave Born approximation (DWBA) calculations for $l=1$ transfer. They extracted spectroscopic factors (normalized to the ground-state value from Cohen-Kurath) for the three lowest states and compared them with predictions from the Cohen-Kurath intermediate-coupling shell-model calculations.[9] However, they did not measure absolute cross sections for these states, and they presented no analysis for the 6.53-MeV state (which they did observe). Oothoudt and Garvey[10] did a similar study on ($d,{}^3$He) and extracted spectroscopic factors for the mentioned four states ($\Sigma C^2S=2.812$). But they did not make any assignment for the 6.53-MeV state. (They, in fact, analyzed it as $l=1$ transfer.) Although Arnold measured an absolute cross section for (t,α) to the 6.53-MeV state, they did not give any data for the other low-lying states. In the present work, we have measured absolute cross sections and angular distribution for all four narrow low-lying states and have extracted absolute spectroscopic factors for the three lowest states based on DWBA single-step fits. A two-step analysis was carried out for the 6.53-MeV state, based on coupled-channel Born-application (CCBA) calculations, and the present results were compared with previous data.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 15.0-MeV triton beam from the University of Pennsylvania tandem accelerator. The target was 65 μg/cm^2 natural Be foil. Outgoing particles were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Data were recorded in 7.5° steps beginning at 7.5°. Forward-angle data were scanned for α particles. In order to get data at backward angles for outgoing α particles, a different wrinkle was used. Data at $(\pi-\theta)$ in the ^{9}Be(t,α)^{8}Li reaction correspond to data at θ in a complementary reaction of ^{9}Be($t,{}^8$Li)^{4}He. After outgoing ^{8}Li nuclei stopped in the nuclear emulsion, they decayed to ^{8}Be ($\tau_{1/2}=838\pm6$ ms), and then ^{8}Be decayed into two back-to-back α particles. This process creates a characteristic track (so-called "hammer" track) in the nuclear emulsion. In this way, two kinds of tracks (normal α track and the hammer track created by ^{8}Li nucleus) were scanned at forward angles, and angular distributions at both forward and backward angles of ^{9}Be(t,α)^{8}Li reaction were obtained. Of course, this method works only for the two bound states of ^{8}Li, i.e., the ground state and the first-excited state (0.981 MeV).

A typical spectrum of α particles is displayed in Fig. 1. The resolution is about 28 keV FWHM. The four narrow states are clearly present in the figure, but other known

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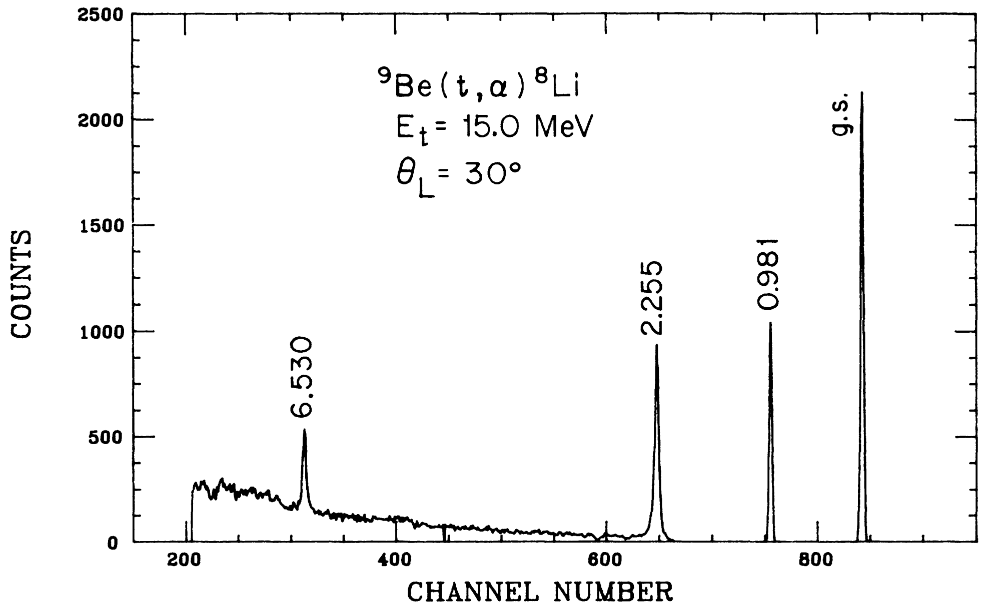

FIG. 1. Spectrum of alpha particles from the reaction ^{9}Be(t,α)^{8}Li at $E_t = 15.0$ MeV and a laboratory angle of 30.0°. States in ^{8}Li are labeled by their excitation energies.

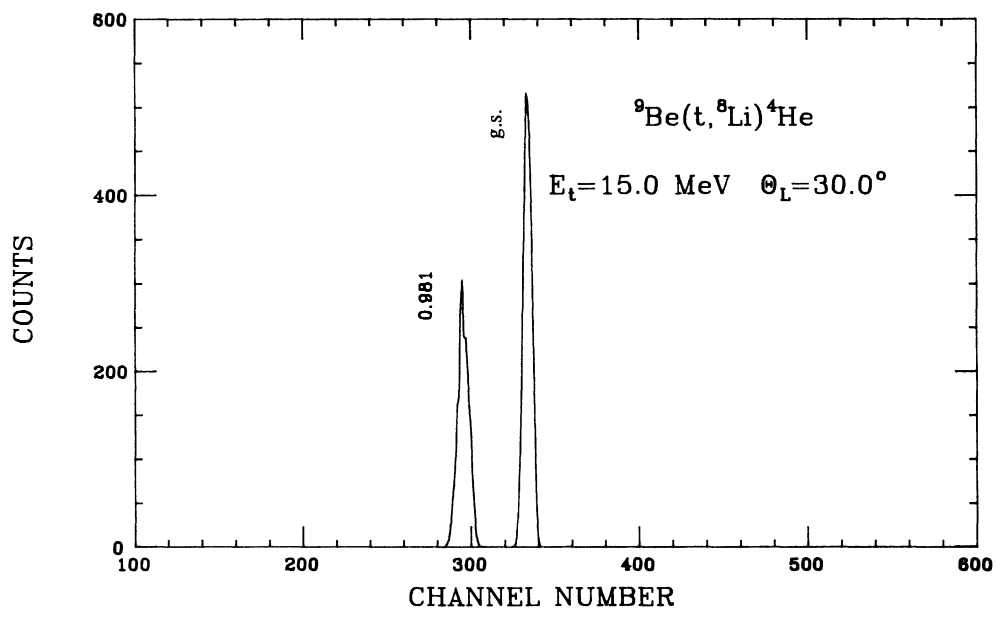

FIG. 2. Spectrum of ^{8}Li from the reaction ^{9}Be(t,^{8}Li)^{4}He at a laboratory angle of 30.0°. States in ^{8}Li are labeled.

TABLE I. Optical-model parameters used in analysis of ^{9}Be(t,α)^{8}Li (strengths in MeV, lengths in fm).

Channel	V	r_0	a_0	W	r_0'	a_0'	V_{SO}	r_c
^{3}He	149.3	1.10	0.733	12.00	1.98	0.700	5.00	1.40
α	212.1	1.373	0.520	14.00	1.699	0.563		1.345
Bound state		1.26	0.60	$\lambda=25.0$				1.20

TABLE II. Relative spectroscopic factors of the reaction ^{9}Be$(t,\alpha)^8$Li compared with results from $(d,{}^3$He$)$.

E_x (MeV)	Present J^{π}	l	C^2S	$(d,{}^3$He$)$[a] C^2S
0.000	2+	1	0.843	1.000
0.981	1+	1	0.506	0.423
2.255	3+	1	0.552	0.333
2.4–2.8		1	0.099	
Total			2.000	1.756

[a]Reference 8.

broad states are difficult to identify. Below 7.7 MeV excitation energy, our data allow us to place an upper limit of 50 μb/sr (0.5% of g.s. cross section) for any possible missing narrow state. In Fig. 2 a spectrum of outgoing ^{8}Li is shown, and two peaks corresponding to ground state and 0.981-MeV state of ^{8}Li are clearly seen. Typical resolution of ^{8}Li spectra is 87 keV. A solid-state detector was placed at a scattering angle of 40°, and the calculated triton elastic peak was used to check absolute cross section. The elastic cross section from the monitor detector yield and the nominal target thickness is only 3% different from the value with the optical potential that was used in the DWBA calculations.

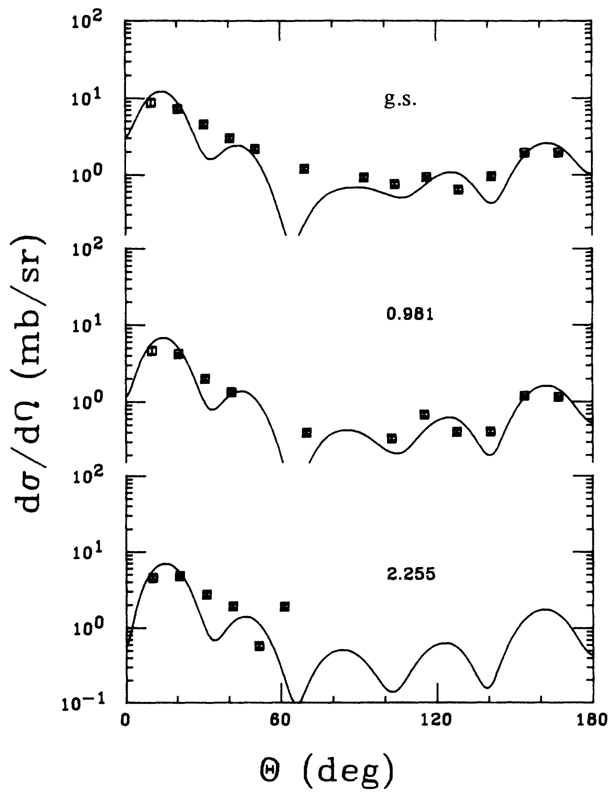

FIG. 3. Angular distributions for the reaction ^{9}Be$(t,\alpha)^8$Li, compared with DWBA calculations for $l=1$ transfer.

III. RESULTS AND ANALYSIS

Local, zero-range distorted-wave Born approximation calculations, using the code DWUCK4,[11] were performed for the first three states (g.s., 0.981-, and 2.255-MeV states). The optical-model parameters used in the calculations are listed in Table I. They are similar to those of Ref. 12, but with some adjustments of potential depths for both t and α particle.

The experimental angular distributions were compared with the DWBA calculations by use of the relation

$$\sigma_{\rm expt}(\theta)=\frac{1}{2j+1}NC^2S(l,j)\theta_{DW}(\theta)\ ,$$

where l and j are the transferred orbital and total angular momentum, respectively, $\sigma_{DW}(\theta)$ is the theoretical pickup cross section calculated by the code DWUCK4, S the spectroscopic factor, C is an isospin-coupling Clebsch-Gordan coefficient ($C^2=\frac{2}{3}$ here), and N is the overall normalization factor. A value of $N=18.2$ for the (t,α) reaction[12] was used in the present analysis.

In Fig. 3 the experimental angular distributions for the lowest three states are shown together with the one-step DWBA calculations. From the figure, we see that the DWBA calculations with $l=1$ transfer fit the data for the first two states reasonably well. Data for the third state exist only at a few forward angles, but all three states are known to be populated via $l=1$ pickup. Normalizing the curves to the data at the forward-angle maximum provides spectroscopic factors. In Table II we list relative spectroscopic factors from our (t,α) data and from the $(d,{}^3$He$)$ experiment.[8] In Table III we compare the abso-

TABLE III. Absolute spectroscopic factors of the reaction ^{9}Be$(t,\alpha)^8$Li compared with $(d,{}^3$He$)$ results and theoretical predictions.

E_x (MeV)	Present J^{π}	$C^2S(p\frac{3}{2})$	$(d,{}^3$He$)$[a] $C^2S(p\frac{3}{2})$	Theoretical calculations[b] E_x (MeV)	Theoretical calculations[b] $C^2S(p\frac{3}{2}+p\frac{1}{2})$
0.000	2+	1.059	1.63	0.0	0.90+0.10
0.981	1+	0.636	0.61	1.08	0.21+0.20
2.255	3+	0.693	0.48	1.69	0.35
Total		2.388	2.72		1.46+0.30

[a]Reference 10.
[b]Reference 9.

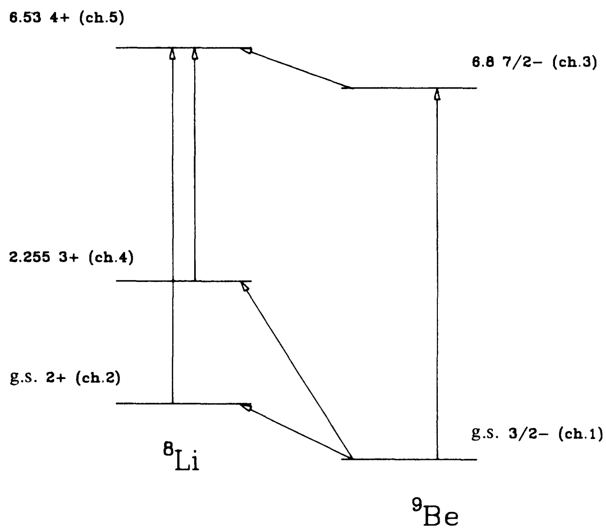

FIG. 4. The level diagram with the channels included in the CCBA calculations for both (t,α) and $(d,{}^3\mathrm{He})$ reactions.

lute spectroscopic factors from our data with results from another $(d,{}^3\mathrm{He})$ measurement[10] and with theoretical values from Cohen-Kurath calculations (Ref. 9). Because the theoretical elastic cross section of the triton can differ by $\pm 20\%$ for different optical potentials and the value of C^2S extracted from one-step DWBA calculations can differ by about $\pm 12\%$, our absolute C^2S's can be uncertain by $\pm 30\%$. Of course, this uncertainty does not affect the relative cross sections of the various states.

The reaction calculations for the 6.53-MeV final state were performed using the coupled-channel Born-approximation (CCBA) code CHUCK.[11] Optical-potential parameters used in this calculation were the same as those used in the DWBA calculations. In Fig. 4 channels included in the CCBA calculations are displayed. The transition coupling strengths β for three inelastic excitations (β_{13}, β_{25}, and β_{45}) were all set to be 0.3. This seems reasonable if the states form a rotational band. In any case, using other values in the neighborhood of these will not greatly affect the results. β_{12} for the transfer process from channel 1 to channel 2 was obtained from the ground-state normalization factor needed to fit the ground-state data. The value of β_{14} was obtained in the same way as β_{12} but to fit data of 2.255-MeV state. The strength β_{35} was chosen to be equal to β_{12}. In the right top part of Fig. 5, we show the 6.53-MeV data of this work and coupled-channels contributions through ground state (solid curve) and 2.255-MeV state (dashed curve). In the right bottom, we compare our data with the full CCBA calculations and previous data.[7] From the figure, it appears that the two-step process dominates the excitation of the 6.53-MeV state in the (t,α) reaction.

Of course, another possible contribution to excitation of the 6.53-MeV state could be from a compound process. In the ${}^9\mathrm{Be}(d,{}^3\mathrm{He}){}^8\mathrm{Li}$ reaction,[8] because of higher incoming energy ($E_d = 52$ MeV), the compound cross section is expected to be small. The data of Ref. 8 are not useful for extracting absolute spectroscopic factors C^2S, but they could be used to assess the magnitude of a coupled-channels effect, because the unknown factor is identical for all states. We have carried out the same procedure of CCBA calculations as we did for (t,α) reaction. Figure 6

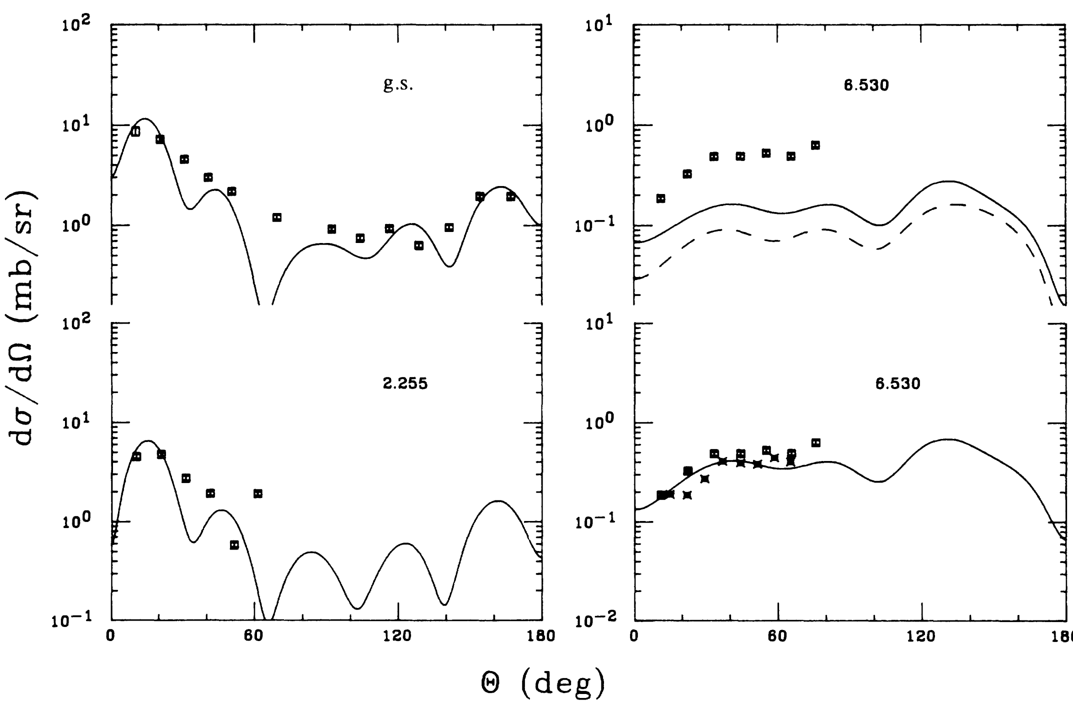

FIG. 5. The angular distributions for ${}^9\mathrm{Be}(t,\alpha){}^8\mathrm{Li}$, compared with CCBA calculations. In the left top, data of ground state with CCBA fit and in the left bottom, data of 2.255-MeV state and CCBA fit. In the right top, data of 6.53 MeV with CCBA calculations through ground state (solid curve) and 2.255-MeV state (dashed curve). In the right bottom, the present data (squares) and previous data from Ref. 7 (crosses) of 6.53-MeV state with full CCBA calculations.

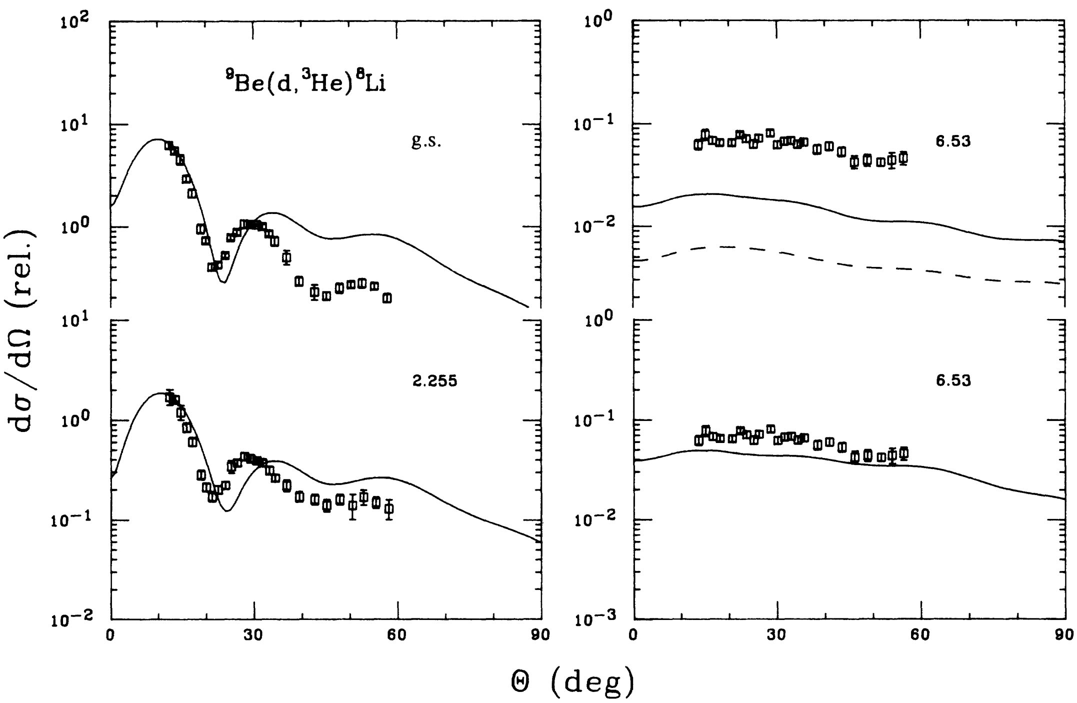

FIG. 6. The angular distributions for ^{9}Be(d,^{3}He)^{8}Li (Ref. 8), compared with CCBA calculations.

displays (d,^{3}He) data from Schwinn[8] and our CCBA calculations, which included the same five channels (Fig. 4). From the figure we conclude that two-step excitations dominate the population of the 6.53-MeV state in the (d,^{3}He) reaction.

IV. CONCLUSION

In the present study of ^{9}Be(t,α) at 15.0 MeV, we have measured differential cross sections for the four narrow states of ^{8}Li (g.s. and at $E_x = 0.981$, 2.255, and 6.53 MeV). One-step DWBA calculations for the first three states give a reasonable description of the data, and the extracted spectroscopic factors are comparable with (d,^{3}He) results and with Cohen-Kurath shell-model calculations as well. For the 6.53-MeV state, two-step excitations based on CCBA calculations fit the (t,α) data well, and the same procedure works for the (d,^{3}He) reaction. We thus conclude that a two-step excitation process dominates the population of 6.53-MeV state in proton pickup from ^{9}Be.

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