Cluster structures in ^{10}Be from the ^{7}Li$(\alpha, p)^{10}$Be reaction

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Three-nucleon transfer by the ^{7}Li$(\alpha, p)^{10}$Be reaction at 65 MeV has been carried out with good resolution. A cluster model is compared to the data with the aid of zero-range distorted wave Born approximation reaction calculations, finding consistent spectroscopic factors for low-lying $K = 0^+$ and 1^- bands. Large cluster spectroscopic factors are found for the states at 17.74 and 18.54 MeV that serve as resonances for reactions between ^{3}H and ^{7}Li at low energies of astrophysical importance. A search for states very near threshold found no transitions that significantly alter the important astrophysical reaction rate.

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I. INTRODUCTION

Cluster structures in light nuclei have often been noted by multinucleon transfer reactions [1], by a direct transfer of a cluster containing several nucleons. Cluster states of particular interest in mass 10 have long been noted in the compilation [2], where strong resonances are shown for the ^{3}H + ^{7}Li and ^{3}He + ^{7}Li reactions at low energies. Resonances such as these should also be prominent in the ^{7}Li$(\alpha, p)^{10}$Be reaction, and this seems to be the case in low-resolution spectra [3]. These states could be important for astrophysical reactions between masses 3 and 7 [4], where new work has shown the importance of reactions between ^{7}Li and ^{3}H to deplete ^{7}Li in certain environments [5], and to begin the generation of heavier elements. New measurements of reactions between ^{3}H and ^{7}Li have pursued this question to center-of-mass energies near 200 keV [6–9,12].

We report here a high-resolution study of the ^{7}Li$(\alpha, p)^{10}$Be reaction over a wide range of excitations to determine the cluster nature of states in ^{10}Be, including a search for transitions below the energy range of ^{3}H + ^{7}Li reactions, using a beam energy high enough to provide a direct reaction mechanism.

II. THE EXPERIMENT AND DWBA METHODS

The 65 MeV alpha beam was provided by the cyclotron at the Institute for Nuclear Study at the University of Tokyo. The target was a 97% enriched self-supporting foil of ^{7}Li metal, 2.3 mg/cm^2 thick. The beam intensity was limited to 50 nA to prevent evaporation of the target material. Scattered particles were detected in a quadrupole-dipole-dipole spectrograph [10] with particle identification at the focal plane [11], yielding an energy resolution of 100 keV for sharp final states at low excitations in ^{10}Be. Elastic scattering showed the oxygen and carbon thicknesses in the target to be 0.18 and 0.10 mg/cm^2, respectively.

The thickness of the ^{7}Li target was determined by comparison of measured elastic scattering to an optical model calculation. Figure 1 shows the measured elastic and the inelastic scattering to the first excited state of ^{7}Li, after normalizing to the optical model calculations. The curves shown are the result of an optical model optimization for the elastic scattering, which also determined the normalization to an accuracy of ±20%. A first-order distorted wave Born approximation curve for the $\frac{1}{2}^-$ 0.477 MeV transition is also shown, with a quadrupole deformation β=0.24, without including spins for the odd target. Optical model parameters are listed in Table I.

Two spectrometer settings were used to obtain the complete proton momentum spectrum shown in Fig. 2. The energy calibration at high excitations was obtained by the reaction on a carbon target, and is accurate to ±70 keV at 18 MeV excitation. At low excitation the calibration was determined by known ^{10}Be states [2] and is accurate to ±50 keV. The prominent peaks we locate at 17.79 and 18.55 MeV correspond to those found by a resonant reaction at 17.74 and 18.54 MeV [8].

Reaction calculations for the ^{7}Li$(\alpha, p)^{10}$Be analysis used the zero-range distorted wave Born approximation

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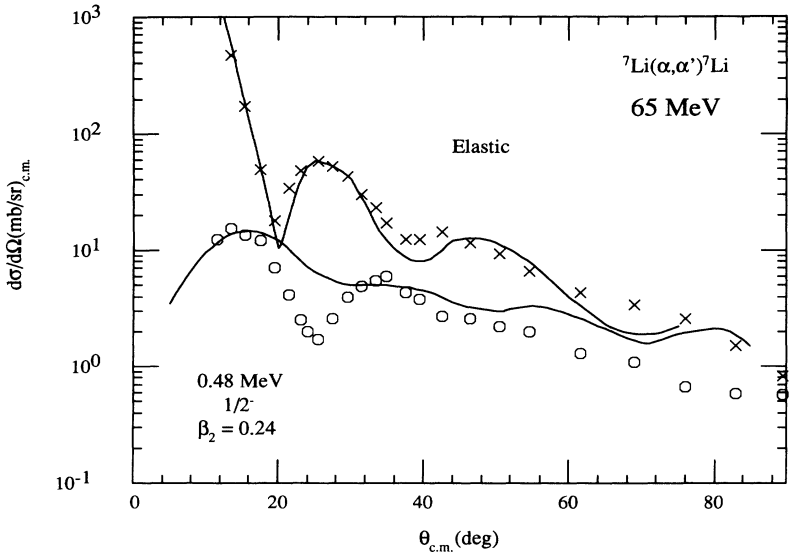

FIG. 1. Measured cross sections for 65 MeV elastic scattering in ^{7}Li and inelastic scattering to the 0.48 MeV first excited state. An optical model calculation gives the compared elastic cross sections, with parameters including the normalization obtained by a least-squares fit. Parameters are listed in Table I. A first-order quadrupole deformation β=0.24 was used in a DWBA calculation for the inelastic curve shown, assuming a zero-spin Li target.

(DWBA) code DWUCK4 [12] for a triton stripping reaction, although the reaction model contains assumptions which are in doubt for such a light target. For instance, knock-on scattering to cluster states of the form ^{6}He+α are not unlikely on the light target, but these are not treated. The knock-on process was found to predominate over the stripping for the ^{7}Li(^{3}H,n) reaction at a beam energy of 2.5 MeV [7], but is not included here at 65 MeV. We use the DWBA primarily to relate transitions one to another, rather than for absolute predictions. Proton optical parameters were taken from Ref. [13], as listed in Table I. The cluster formulation of Ref. [14] was used for the (α,p) reaction, transferring 3 nucleons to the p^3 configuration for $2N+L=3$, to the $p^2(s-d)$ configuration with $2N+L=4$, to the $p(sd)^2$ configuration with $2N+L=5$, or to the $(sd)^3$ configuration with $2N+L=6$. Here, $2N+L=\sum(2n_i+l_i)$ for the three transferred nucleons to oscillator shells, with n_i the number of single-particle radial nodes and l_i the orbital quantum number, N the number of nodes in the

TABLE I. Optical model parameters are listed as used in the present analysis. The results for alpha particle elastic scattering on ^{7}Li are shown in Fig. 1, with the fit giving the parameters listed.

	α+^{7}Li	t+^{7}Li	p+^{10} Be [a]	
V_0	122	Fit	53.73	MeV
r_0	1.648	0.88	1.108	fm
a	0.396	0.65	0.57	fm
W_v	13.24	–	7.5	MeV
r_v	1.652	–	1.108	fm
a_v	1.168	–	0.50	fm
r_c	1.3	1.3	1.25	fm

[a] Reference [13].

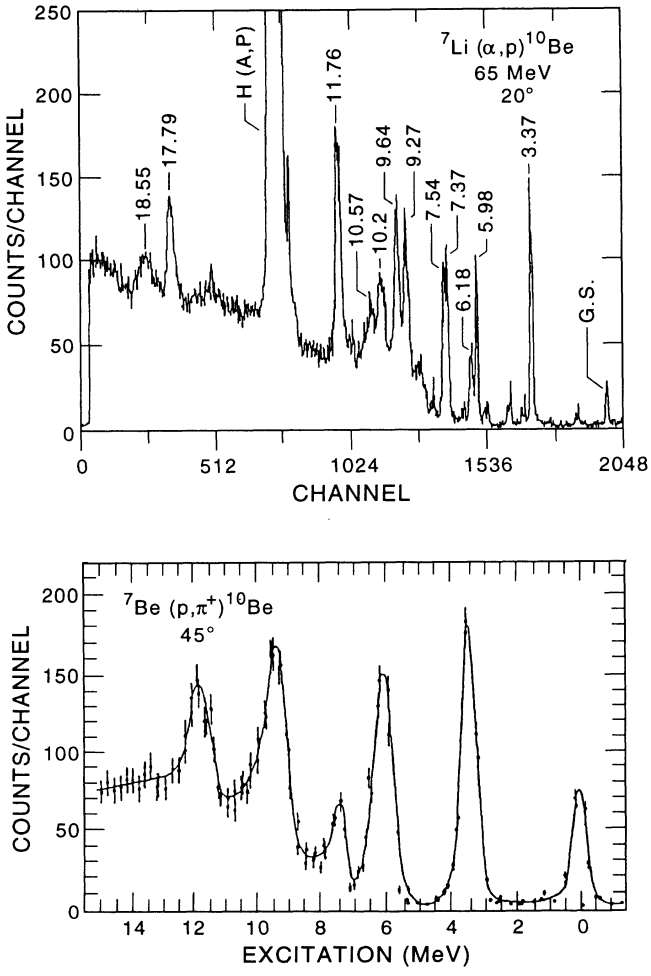

FIG. 2. A sample spectrum for the ^{7}Li(α,p)^{10}Be reaction, with prominent peaks labeled by excitation energy. Below is shown a spectrum from the ^{9}Be(p,π^+)^{10}Be reaction at 185 MeV [20].

cluster wave function, and L the cluster orbital angular momentum. In this cluster model L is the cluster orbital angular momentum. In this cluster model there is no distinction among the j components of a major shell, and only angular momentum constraints limit the L, J for the transfer.

DWBA calculations for the ^{9}Be$(\alpha,p)^{12}$B reaction at 65 MeV were carried out in such a cluster model with an exact finite range code [15], in contrast to the zero-range model used here. The angular distributions predicted and observed for the ^{9}Be target show less structure than those found in the present work, where we see several cases of final states of the same known angular momentum that give very similar experimental shapes for their angular distributions.

The large deformations known for ^{7}Li and ^{10}Be engender strong inelastic scattering, such that a coupled-channel analysis would be a preferred description for the reaction. Many unknown quantities would be needed, and the model would still be unreliable. Our use of the α+^{7}Li optical potential from a fit to elastic scattering data effectively includes some second-order effects in our first-order analysis.

Only for 0^+ final states may we specify the transferred J uniquely. Figure 3 shows the data for the ground state and the 6.18 MeV 0^+ excited state of ^{10}Be. The radius of the potential binding the cluster had to be 0.88 fm to match the shapes observed, as shown in Fig. 3. The well depth to bind the triton cluster with the geometrical parameters listed in Table I was 51.5 MeV, with $N = 1, L = 1$ for transfer to the p^3 configuration for the ground state. The small radius for the potential binding the cluster indicates a small radius difference between ^{7}Li and ^{10}Be. Since the rms charge radii of ^{7}Li and ^{10}B are nearly the same [16], this is not unreasonable.

For states below the triton separation energy of 17.251 MeV, the triton binding energy was used to determine the potential depth for the cluster. Above this excitation a constant 0.3 MeV binding was used. A finite-range correction term was used, with a Gaussian form and a range parameter of 1.42 fm [12]. Shapes and magnitudes of computed cross sections varied smoothly with excitation energy for each multipolarity with this method.

Computed cross sections were greater for higher values of the transferred orbital angular momentum L, because of the large momentum mismatch for the (α,p) reaction. At 20° the ground state transition with our beam has a center-of-mass momentum transfer of 234 MeV/c, increasing to 287 MeV/c for the 17.79 MeV transition. At 3 fm the grazing angular momentum is thus four units.

Rather than rely on the DWBA for an accurate description to extract spectroscopic factors, we shall use it only to relate data at different excitations, populated by a range of quantum numbers. From the cluster model of Ref. [14], the cluster spectroscopic factors for excited states (ex) relative to that of the 0^+ ground state (g.s.) of ^{10}Be are found by

$$R(\text{ex}) \equiv \frac{d\sigma(\text{ex})}{d\sigma(\text{g.s.})} \frac{d\sigma_{DW}(\text{g.s.})}{d\sigma_{DW}(\text{ex})} \frac{2J+1}{4(2J_B+1)} \quad (1)$$

for an excited state J_B, excited by transfer J. Momentum matching tends to drive the reaction by the highest L, as found for the observed shapes of our angular distributions. For simplicity, only $J = L+1/2$ was used unless disallowed by the angular momentum couplings.

III. RESULTS

Since it is expected that ^{10}Be is deformed, we first examine the known [2] states and our data for a ground state $K = 0$ rotational band. The rotational spacing, based on the 3.37 MeV 2_1^+ state, leads us to assign the strong peak seen in Fig. 2 at 11.76 MeV to be the 4_1^+ state. Cross sections for the (α,p) reaction are shown in Fig. 4, along with the DWBA shapes. For the 2^+ transition $L = 1$ or 3 ($J = 3/2$ or $7/2$) are allowed, while $L = 3$ ($J = 7/2$) alone is suited to the 4^+ transition for a cluster to the p^3 configuration. Both observed angular distributions have shapes more similar to

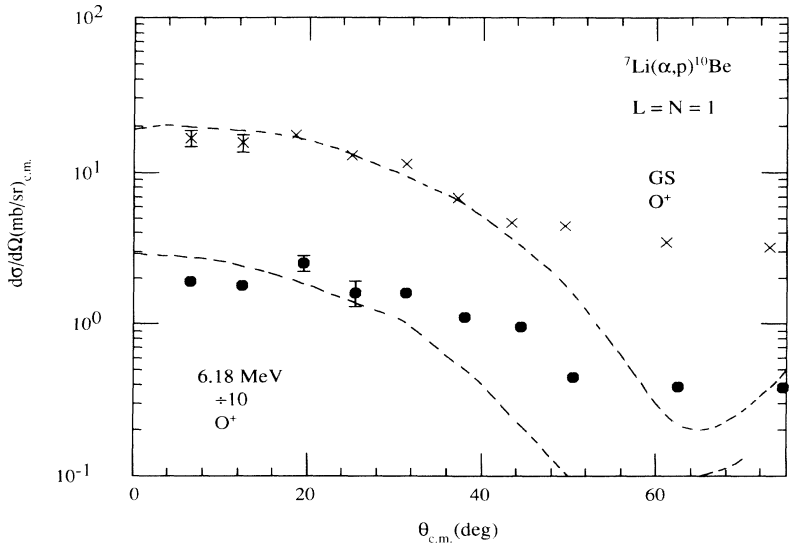

FIG. 3. Cross sections for the known 0^+ states of ^{10}Be are compared to $N = L = 1$, $J = 3/2^-$ DWBA calculations, uniquely required by the quantum numbers. The radius for the potential binding the triton was found to be 0.88 fm to yield these shapes.

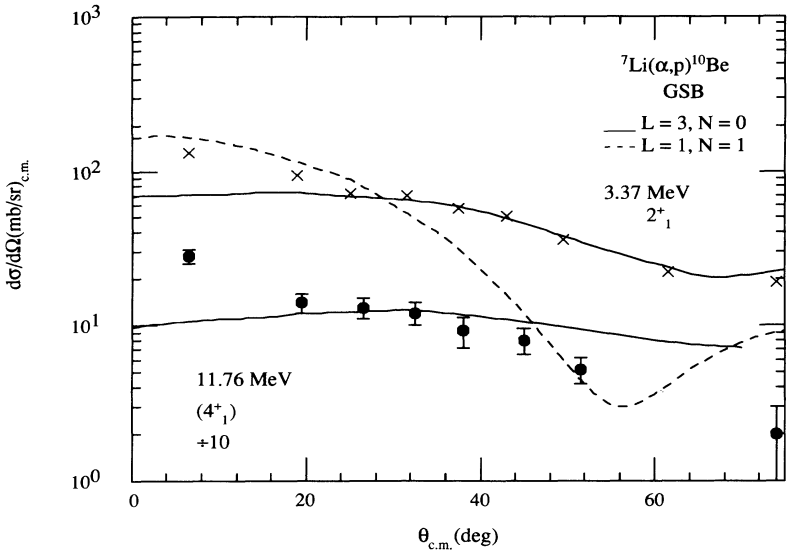

FIG. 4. Cross sections for candidates of a ground state band in ^{10}Be are compared to DWBA calculations. The momentum mismatch in the (α, p) reaction favors the $L = 3$ transfer. Spectroscopic factors relative to the ground state are obtained from the comparison of data to these $L = 3$ calculations.

the $L = 3$ curves, as expected from the momentum mismatch, which enhances the cross sections for higher values of L.

Relative to the ground state, the cluster spectroscopic factors are $R(3.37) = 0.067$ and $R(11.76) = 0.049$ for the $L = 3$ comparisons shown in Fig. 4 and Table II. The $L = 3$ DWBA cross sections are much larger than the $L = 1$ results used for the ground state, and since the DWBA model may be inadequate to compare results for $L = 3$ to those for $L = 1$, the small cluster spectroscopic factors for the 2^+ and 4^+ band members may be misleading. The close similarity of the $L = 3$ strengths for the latter two states is, however, a sign that we have located the 4^+ rotational state in ^{10}Be.

The cluster calculation of Furutani *et al.* [17], with a structure of two alpha particles and two neutrons for ^{10}Be, also finds a sequence of 0^+, 2^+, and 4^+ states in a rotational band, with the same cluster separation for these band members. Another $K = 0^+$ band is based on the 6.18 MeV excited 0^+ state, but the present experiment is not able to locate its members.

The low-lying negative parity states of ^{10}Be may be organized into a $K = 1^-$ rotational band, but the 5.96 MeV 1^- state is not resolved from the second 2^+ state at 5.96 MeV [2]. Observed cross sections are shown in Fig. 5, compared to DWBA shapes. No $L = 0$ transition is possible to the 3^- and 4^- members, and the $L = 2$ shapes are seen to account for the data. This is consistent with a transferred cluster with p^2 neutrons paired and a proton to the d shell. Both the 1^- and 2^- data show a small angle rise, indicating some $L = 0$ strength, as allowed.

Relative spectroscopic factors, using only the $L = 2$ comparisons as shown, are $R(1^-) \leq 2.0$ (since this is an unresolved doublet), $R(2^-)$=0.53, $R(3^-)$=0.64, and $R(4^-)$=0.84. Given the accuracy available, these relative strengths are nearly in agreement, as would be expected for a rotational band of the same intrinsic structure.

This $K = 1^-$ band is also found in the cluster calculation of Furutani *et al.*, with a larger cluster separation than for the ground state band [17]. The rotational spacing for the band found in the present work also indicates a larger moment of inertia for the 1^- band than for the ground state band.

Cross sections for other known [2] and new states of ^{10}Be are shown in Figs. 6 and 7. Positive parity states are at 6.18 MeV (0^+), 5.96 MeV (2^+, unresolved doublet), and 7.54 MeV(2^+) [2]. Using $L = 3$ DWBA comparisons for the 2^+ states and $L = 1$ for the 0^+ state, all with $2N + L = 3$ for a p^3 cluster, relative cluster spectroscopic factors are $R(6.18) = 0.86, R(5.96) < 0.061$, and $R(7.54) = 0.10$. The $L = 3$ shape for the 7.54 MeV 2^+ state seems appropriate, and the $L = 3$ relative spectro-

TABLE II. Results of the present analysis, where shapes of the zero-range DWBA calculations with transferred L were selected from comparison to the observed shapes. The ratios R are cluster spectroscopic factors relative to the ^{10}Be ground state.

E_x (MeV)	J^π	L	R
0	0^+	1	(1.00)
3.37	2^+	3	0.067
5.96	$2^+, 1^-$	–doublet	–
6.18	0^+	1	0.86
6.26	2^-	2	0.53
7.37	3^-	2	0.67
7.54	2^+	3	0.10
9.27	(4^-)	2	0.84
9.64	(2^+)	3	0.13
10.57	≥ 1	0,1	0.08,0.035
11.76	$(4^+)^a$	3	0.049
17.12	(2^-)	0	0.3
17.79	$(2^-)^b$	2	1.0
18.55	$(2^-)^b$	2	1.0

[a] Assigned from the present work.

[b] Assumed by analogy to ^{10}B, as in Ref. [2].

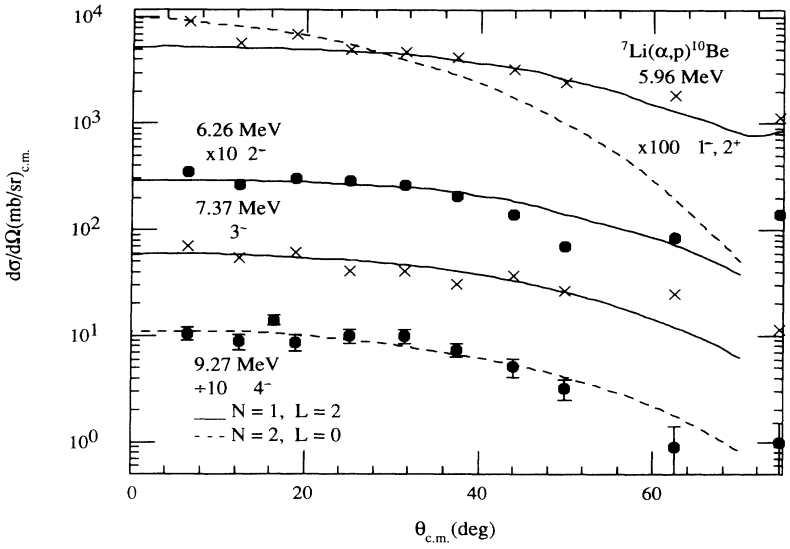

FIG. 5. Cross sections for candidates of a $K = 1^-$ band in ^{10}Be are compared to DWBA computed shapes. The 1^- member is not resolved from a 2^+ state. The (α, p) reaction favors the $L = 2$ mechanism over that for $L = 0$.

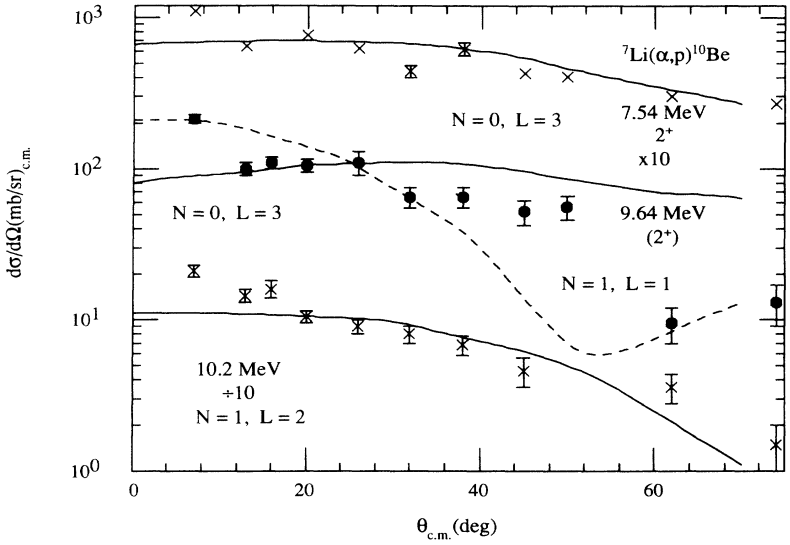

FIG. 6. Cross sections for several known and new states in ^{10}Be are compared to DWBA shapes. The $L = 3$ transfer to 2^+ states is emphasized by the reaction.

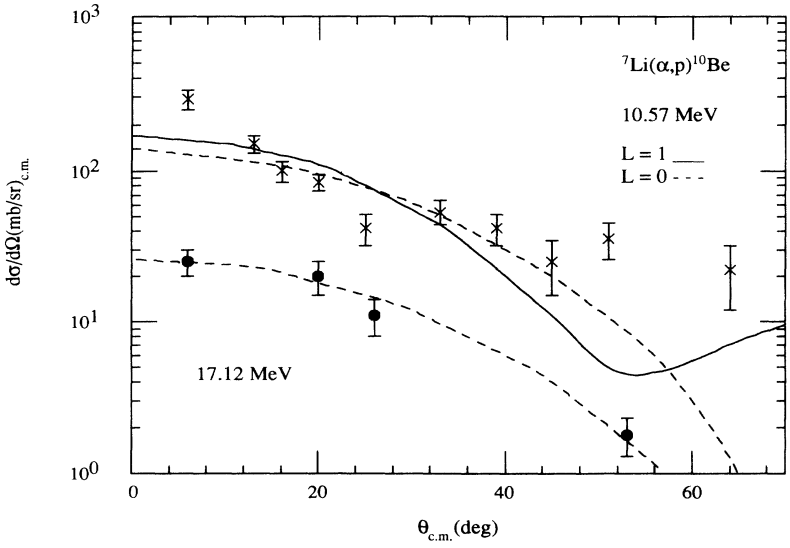

FIG. 7. Cross sections for two states of ^{10}Be are compared to $L = 0$ and $L = 1$ DWBA calculations. The 10.57 MeV state is known to have spin ≥ 1. The 17.12 MeV state could be important for astrophysical reactions between ^{7}Li and ^{3}H.

scopic factor is somewhat larger than that for the first 2^+ state.

A peak calibrated by us at 9.64±0.1 MeV excitation in ^{10}Be is probably that compiled at 9.4 MeV [2], without information on its spin. Our data are shown in Fig. 6, compared to a $L = N = 1$ DWBA shape. A possible 2^+ spin assignment is compiled [2], and the 9.64 MeV data have a shape similar to that for the 11.74 MeV 4^+ transition. If we use $J_B = 2, N = 0, L = 3$, we find $R(9.64) = 0.13$. A known state of ^{10}Be with spin ≥ 1 at 10.57 MeV yields the (α, p) cross sections shown in Fig. 7. Both $L = 0$ and $L = 1$ DWBA shapes could be taken to agree with the data. If this state has $J_B = 1^-(L = 0)$, $R = 0.08$, while if it has $J_B = 1^+(L = 1), R = 0.035$.

Figure 8 shows an enlarged view of the ^{7}Li(α,p)^{10}Be spectrum summed over ten channels for the two prominent peaks just above the threshold for ^{7}Li + ^{3}H. Our fits give excitations of 17.79 and 18.55 MeV, compared to 17.74 and 18.54 MeV from Ref. [8]. The fits use the Breit-Wigner shapes, with laboratory widths at 25° of 228 and 410 keV. After unfolding a resolution of 150 keV, these correspond to center-of-mass widths of 170 and 380 keV. The width of the 17.79 MeV is a bit wider than the compiled result from a resonant reaction [2], but within the range of widths for the astrophysical S factors in Ref. [7]. The width we obtain for the 18.55 MeV peaks agrees with that compiled. No interference between these peaks is noted. There is no sign of a 2^+ peak near channel 93, as needed to fit the astrophysical S factor in Ref. [7]. The small peak near channel 90 in Fig. 8 does not have the kinematics needed for the ^{7}Li(α,p)^{10}Be reaction.

A narrow resonance corresponding to our 17.79 MeV peak generates a sharply energy-dependent astrophysical S factor, as shown in Fig. 5 of Ref. [7]. At very low triton energies, the S factor is constant for the ^{7}Li(^{3}H,α)^{6}He reaction [18], indicating that this width is not as low as 60 keV.

Triton single-particle widths for the t+^{7}Li states may be estimated from the equations of Ref. [19], neglecting spin and charge. As compared in Table III, only triton $L = 0$ decay can reasonably account for the observed widths. Angular distributions from the present work are similar to the calculation for $L = 2$ transfer, and the 17.79 and 18.55 MeV shapes are very similar, in spite of the different strengths of the partial waves responsible for the widths. Single-neutron decay from the 17.79 MeV state, estimated as above, leads to widths of tens of MeV to the ground state of ^{9}Be. The narrow width observed requires an exceedingly small single neutron spectroscopic factor. A cluster state readily accounts for this, and we conclude that these peaks are due to $L = 2$ triton cluster transfer to states with widths determined by the $L = 0$ component, which is not the important term in our reaction.

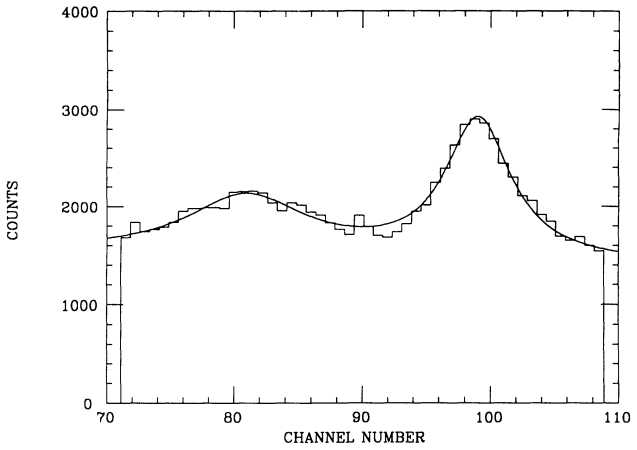

FIG. 8. An amplified view of the ^{10}Be spectrum found at 20°, with Breit-Wigner fits as shown giving the widths and shapes discussed in the text. The right-hand edges of the data boxes line up with the channel numbers and are to match the fit.

Observed cross sections for the 17.79 and 18.55 MeV peaks are shown in Fig. 9. The shapes of these two distributions are identical, consistent with having the same angular momentum, and they have almost identical magnitudes. The shapes are also identical at 50 MeV [3]. DWBA calculations shown use $2N + L = 6$, as for the $(sd)^3$ configuration, but calculations with $2N + L = 4$, as for the $p^2(sd)$ configuration, have almost the same shapes, and larger magnitudes. The $(sd)^3$ structure is used for this comparison since the low-lying cluster states of negative parity in Ref. [17] use the $p^2(sd)$ structure, but this theory does not predict the two high-lying states. They may thus be inferred to be of explicit three-nucleon cluster appropriate to the $(sd)^3$ configuration. The spins of these states are assumed to be 2^- by analogy with the similar region in ^{10}B [2] and the analysis in Ref. [7], and thus require $L = 0, 2, 4$ shapes. The $L = 2$ shapes shown provide a suitable shape but the $L = 0$ shape is not much different. For the $L = 2$ comparison, the relative spectroscopic factors R are 1.0 for both peaks, taken

TABLE III. Measured and estimated single-particle widths for the triton decay of two highly excited states in ^{10}Be, in MeV. Ratios assuming each multipole accounts for the observed width give the spectroscopic factors listed, indicating that $L = 0$ triton decay needs only a small spectroscopic factor S to account for the width.

E_x (MeV)	Γ(data)[a] (MeV)	Γ_s (MeV)	Γ_d (MeV)	Γ_g (MeV)	S_s	S_d	S_g
17.79	0.11	13.8	.021	6.6 E-4	0.008	5.3	170
18.55	0.35	21.5	.092	3.5 E-2	0.016	3.8	10

[a] Reference [2].

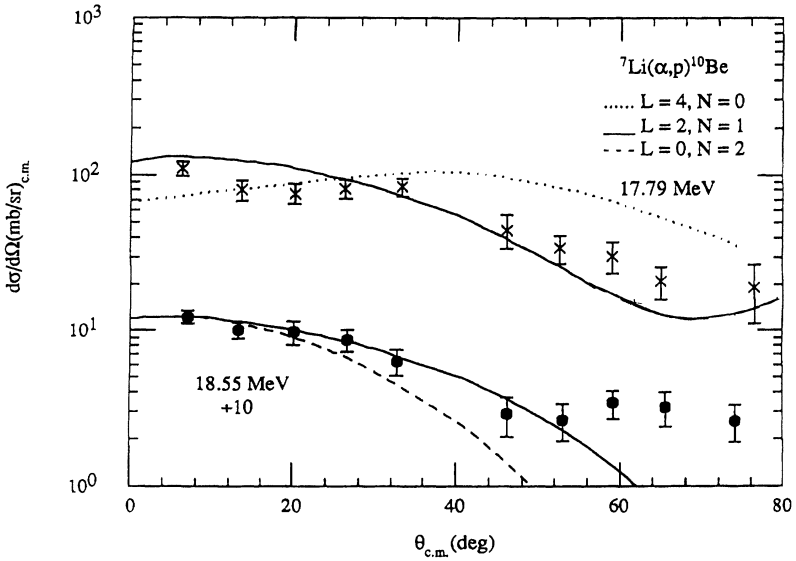

FIG. 9. Cross sections for the two sharp states at high excitation in ^{10}Be are compared to DWBA calculations with $2N+L = 6$ for a cluster of three nucleons in the s-d shell. The $L = 0$ and $L = 2$ shapes are too similar to be selected by the data. The widths for these states preclude an exclusive $L = 4$ transition. The comparisons shown indicate large triton cluster structures for these two states.

as 2^- states. If the $L = 0$ shape is used, both peaks yield $R = 1.4$. The larger $L = 4$ DWBA calculated cross section would yield $R = 0.4$ for both peaks, but does not match the observed shape, and is not allowed in the model discussed below. These relative cluster spectroscopic factors for $L = 2$ are the largest found for any peaks in the ^{10}Be spectrum, and surely indicate a substantial cluster structure. A large $L = 0$ spectroscopic factor would yield a much greater peak width than is observed, but the present experiment is not sensitive to such a term due to the momentum mismatch in the reaction.

The two states at 17.79 and 18.55 MeV do not appear in the two-nucleon cluster model [17], and are thus likely to be due to a three-nucleon cluster structure closely matched to the (α, p) reaction. This model was used for the DWBA calculations in zero range. The lowest positive parity orbital available is the $K = 1/2^+$ band of the s-d shell, which drops very low in excitation for large positive deformations. For instance, the ground state of ^{11}Be is $1/2^+$. This $K = 1/2$ band for the cluster and the $K = 1/2^-$ nature of the target ground state limit ΔK to 0^+, 1^+ for populating the cluster states in ^{10}Be. Only ΔL=0 or 2 are allowed for lowest excitations to the s-d shell. Indeed, we see no need of a ΔL=4 shape for the high-lying states in Fig. 9, in spite of the strong preference for this high value from the momentum mismatch.

The $\Delta K = 0(\Delta J = 1/2)$ three-nucleon stripping cluster transition can populate only two states of ^{10}Be, with $J = 1^-, 2^-$ and is consistent with the observed widths of each. These appear to coincide with the states at 17.79 and 18.55 MeV. Evidence for a 2^- assignment for the 17.79 MeV state of ^{10}Be comes from analogy to the 18.43 MeV $T = 1$ state in ^{10}Be, where the lack of a seemingly allowed α decay leads to the spin assignment [2]. Both the 17.79 and 18.43 MeV states are assumed to be 2^- for computing the relative spectroscopic factor.

This demonstration of an important and spectroscopically reasonable $\Delta L = 0$ reaction mode to the two states of ^{10}Be just above threshold for ^{7}Li + ^{3}H surely makes further spectroscopic studies a high priority for consideration of nucleosynthesis reactions.

It is especially important to locate broad states near the threshold (17.251 MeV in excitation) for their role in low-energy resonant reactions between ^{3}H and ^{7}Li. Our spectra show a consistent peak at 17.12±0.2 MeV, with measured full width at half maximum of 200±50 keV at 25°. The intrinsic width thus cannot be much above 150 keV. The angular distribution shown in Fig. 7 is sharply forward peaked, consistent with the $L = 0$ shape shown. The high excitation side of this s-wave peak could be of importance for very low energy reactions. The relative $L = 0$ spectroscopic factor is $R = 0.3$ if this state has spin 2^-, and is again due to transfer of a cluster of three nucleons to the s-d shell.

A weak $L = 0$ transition such as this, 130±200 keV below threshold, will increase the thermonuclear reaction rate between ^{3}H and ^{7}Li, but the analysis of Ref. [8] shows that the Coulomb barrier makes energies very near threshold unimportant for the reaction leading to ^{9}Be. Thus the conclusions of Ref. [8], that the ^{3}H + ^{7}Li reaction is weaker than hypothesized by Boyd and Kajino [5] remains intact after our search by a direct reaction for states near or below threshold.

A large momentum mismatch is also required for the ^{9}Be$(p, \pi^+)^{10}$Be reaction, and for the 45° spectrum shown [20] in Fig. 2, this is q(c.m.)=501 MeV/c for the 12 MeV structures. For our 20° spectrum shown for comparison, q(c.m.)=267 MeV/c. The similarities are striking, with particular strength to the 9.27 (4^-) peak and the 11.76 MeV peak taken to be the 4^+ member of the ground state band in the present work. In general, the highest spins match the largest peaks. It is known that the (p, π^+) reaction preferentially excites two-particle–one-hole states. For the present case, these would become four-particle–one-hole states relative to ^{7}Li, with an obvious match to the cluster picture used for the present analysis of the (α, p) reaction. A similar comparison has been noted for high spin states in ^{14}C [21].

IV. CONCLUSION

The direct three-nucleon stripping reaction ^{7}Li(α,p)^{10}Be has been used to measure cross sections for known and new states of ^{10}Be. With the aid of a zero-range DWBA reaction model, cluster spectroscopic factors were found, relative to the ground state transition. A consistent result for the ground state band allows us to assign a 4^+ spin to the 11.76 MeV peak. Large relative spectroscopic factors are found for an $L = 1$ band, up to the 4^- member. Large relative spectroscopic factors are found for 2^- states just above the threshold for the ^{3}H + ^{7}Li system, and we ascribe their structure to be that of three nucleons in the lowest deformed orbital of the *s-d* shell.

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