α breakup of ^{6}Li and ^{7}Li near the Coulomb barrier

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Angular distributions of the α-particle production differential cross section from the breakup of ^{6}Li and ^{7}Li projectiles incident on a ^{208}Pb target have been measured at seven projectile energies between 29 and 52 MeV. The α-breakup cross section of ^{6}Li was found to be systematically greater than that of ^{7}Li across the entire energy range. These data have been compared with previously reported results and with the predictions of continuum-discretized coupled channels (CDCC) calculations including resonant and nonresonant projectile breakup. The present data compare well with previous measurements, while the CDCC calculations provide a reasonable prediction of the relative α-breakup cross sections but underpredict their absolute values. The calculations confirm that a major factor in the enhancement of the ^{6}Li to ^{7}Li α-breakup cross section is the difference between the α-breakup thresholds of the two isotopes. These results have implications for structural studies of light exotic nuclei based on elastic scattering.

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I. INTRODUCTION

Over the past several years, developments in theoretical techniques for performing detailed coupled-reaction-channels calculations have led to significant advances in our understanding of the way the structures of colliding nuclei influence the course of the collision process itself. The overall effect of the couplings can be usefully described in terms of an energy dependent, complex polarization component of the nuclear potential, the details of which depend on the nature of the reaction processes involved. Channel coupling effects appear to be manifested particularly strongly at energies close to the Coulomb barrier. This is seen most clearly in the enhancement of near-barrier and sub-barrier fusion and in the appearance of a so-called *threshold anomaly* in the optical potential [1]. At energies near threshold, the number of significant contributing channels becomes relatively small and it becomes possible to examine in some detail the influences of the various reaction mechanisms arising from differences in the nuclear structure. It is this fact which makes the interplay of different nuclear processes at near barrier energies such a fruitful area for investigation.

In a previous analysis [2] of the elastic scattering of ^{6}Li and ^{7}Li by ^{208}Pb it was found that at energies just above the Coulomb barrier the polarization contribution to the real potential is of opposite sign for the two isotopes. The results are consistent with the existence of a threshold anomaly for ^{7}Li but not for ^{6}Li. The strengths and energy variation of the imaginary potentials are also considerably different. This is in contrast to the results at higher energy, where the double-folded potential (generated from the M3Y nucleon-nucleon interaction) of both projectiles must be scaled by a factor of about 0.6 in order to describe the elastic scattering.

Certain consequences for some of the unobserved reaction processes are implied by these findings. The existence of a threshold anomaly for ^{7}Li suggests, for example, that the relative importance of breakup for the two projectiles, which is similar at high energies, changes dramatically when the bombarding energy is reduced to near the Coulomb barrier. Indeed, Keeley *et al.* [2] suggested that the quasielastic scattering cross section σ_{qe} may be two to three times greater for ^{6}Li at near-Coulomb barrier energies than for ^{7}Li and, if it is the case that breakup dominates σ_{qe} for ^{6}Li, as expected, the ratio of the breakup cross sections would be even greater.

Although many studies of the α-breakup of ^{6}Li and ^{7}Li

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after an interaction with a heavy target have been published, only that of Pfeiffer *et al.* [3] compared the breakup of the two isotopes, populating channels including an α particle, at the same center-of-mass energies in the vicinity of the Coulomb barrier. Their results for a ^{118}Sn target show a consistent enhancement of the α-breakup cross section of ^{6}Li over that of ^{7}Li at the same center-of-mass energy and particularly so near the Coulomb barrier (around 17 MeV). The α-breakup cross section for ^{6}Li was found to be approximately $\sim$1.5 to $\sim$4 times that for ^{7}Li.

Thompson and Nagarajan [4] first demonstrated that the breakup of ^{6}Li into $\alpha+d$ plays a highly important role in the elastic scattering of ^{6}Li. Nishioka *et al.* [5] then demonstrated that calculations of analyzing powers for polarized ^{6}Li and ^{7}Li scattering were highly sensitive to couplings between the ground and resonant excited states of the projectile. Many studies have used this technique to analyze polarization data for lithium scattering [6]. More recently, couplings to nonresonant excited states in the projectile have been shown to be just as important as couplings to resonant states [7,8]. In particular, Rusek *et al.* [8,9] have used the continuum-discretized coupled channels (CDCC) technique to demonstrate that the inclusion of nonresonant breakup permits the reproduction of ^{6}Li elastic scattering data using cluster-folding potentials without the introduction of renormalization factors. However, a question mark still remains over the CDCC technique as only the work of Davis *et al.* [10], over a small angular range and at a single bombarding energy, has compared CDCC predictions with empirical breakup cross sections.

The CDCC technique has recently been applied to the study of the elastic scattering of ^{6}He [11]. The ^{6}He nucleus is very similar to ^{6}Li and ^{7}Li. These three nuclei are weakly bound, have relatively large matter radii, have no (^{6}He and ^{6}Li) or few (^{7}Li) bound excited states and exhibit strong cluster structure ($\alpha+2n$ in ^{6}He, $\alpha+d$ in ^{6}Li, and $\alpha+t$ in ^{7}Li). Ter-Akopian *et al.* [12] obtained data for the elastic scattering of ^{6}He by ^{4}He at 151 MeV and inferred a strong dineutron configuration for ^{6}He from that data. The principal evidence for this structure was that an optical model analysis failed to describe the large angle scattering data. Ter-Akopian *et al.* obtained a satisfactory description of these data at all angles only after the calculations were extended to include dineutron exchange using the distorted wave born approximation. The most appropriate spectroscopic factor for the dineutron cluster was found to be unity. Rusek and Kemper [11] reanalyzed the data taken by Ter-Akopian *et al.* using the CDCC technique and found that the effects of breakup on the elastic scattering observables were at least as great as the effects of dineutron transfer. Rusek and Kemper concluded that the elastic scattering contains a much smaller dineutron transfer component than that derived by Ter-Akopian *et al.*

The present work describes an experiment similar to that of Pfeiffer *et al.* [3] measuring the α-particle yield from ^{6}Li and ^{7}Li breakup following scattering by a ^{208}Pb target over a range of bombarding energies similar to that of Keeley *et al.* [2]. Given a sufficiently wide angular range, the total (angle integrated) α-breakup cross section can be obtained as a function of bombarding energy for both ^{6}Li and ^{7}Li. The data are then compared with the predictions of CDCC calculations with a view to the following:

(1) Testing the predictions of Keeley *et al.* that the ^{6}Li α-breakup cross section is systematically enhanced over that of ^{7}Li [2].

(2) Testing the proposed energy dependence of this enhancement, based on the enhancement originating from the difference in the α-breakup thresholds [13].

(3) Comparing CDCC predictions with empirical breakup cross sections obtained at several bombarding energies, thereby establishing (or otherwise) the validity of the CDCC technique in the analysis of elastic scattering data.

II. EXPERIMENT

The experiment was performed at the Florida State University Tandem Accelerator Laboratory using ^{6}Li and ^{7}Li beams. Data were taken at seven bombarding energies between 29 and 52 MeV. Beam energies up to 35 MeV were provided by the tandem Van de Graaff accelerator alone, while the higher energy beams were prepared using the tandem Van de Graaff and a superconducting linear post accelerator. The targets used were self-supporting ^{208}Pb foils with nominal thicknesses of 250 μg cm^{-2} and the typical beam current was 20 nA (electrical). Data were taken over a period of approximately 10 days.

Particles were detected using two 10×50 mm^2 position-sensitive detector telescopes located in an 85 cm diameter scattering chamber. Each telescope consisted of a 70 μm ΔE and a 500 μm E detector. Each telescope was fitted with a 10 slit mask, where each slit measured 3.7 mm in the reaction plane and 8.7 mm normal to the reaction plane. The centers of the masks were positioned 150 mm from the target, such that each slit subtended an angle of approximately 1.41° in the reaction plane (equivalent to a solid angle of 1.43 msr). The error in the position of the detected particles was less than $\pm0.9°$ (given the slit width and a beam spot

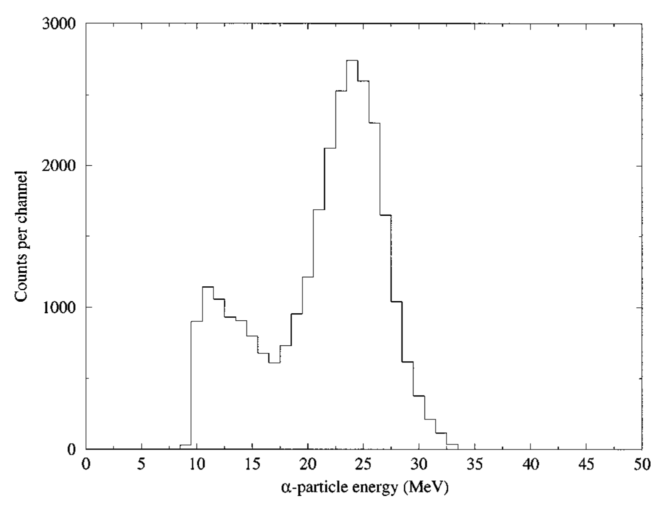

FIG. 1. Typical α-particle energy spectrum from the breakup of ^{6}Li incident on a ^{208}Pb target, obtained at 35 MeV bombarding energy and a laboratory angle of $\sim$59°.

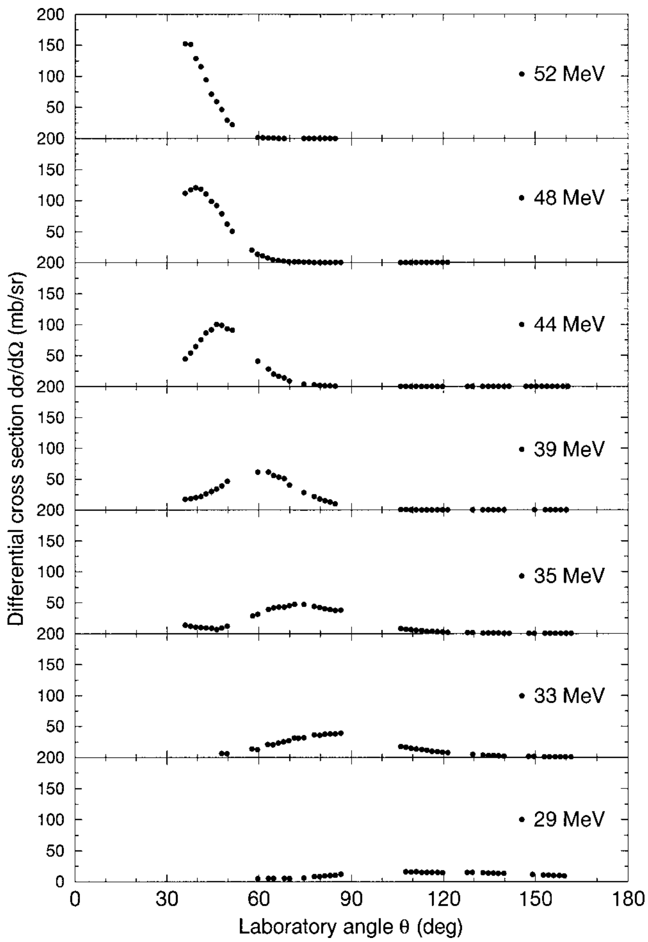

FIG. 2. Angular distributions of the differential cross section for α-particle production from ^{6}Li incident on a ^{208}Pb target at bombarding energies between 29 and 52 MeV. The error associated with each datum is smaller than the symbol.

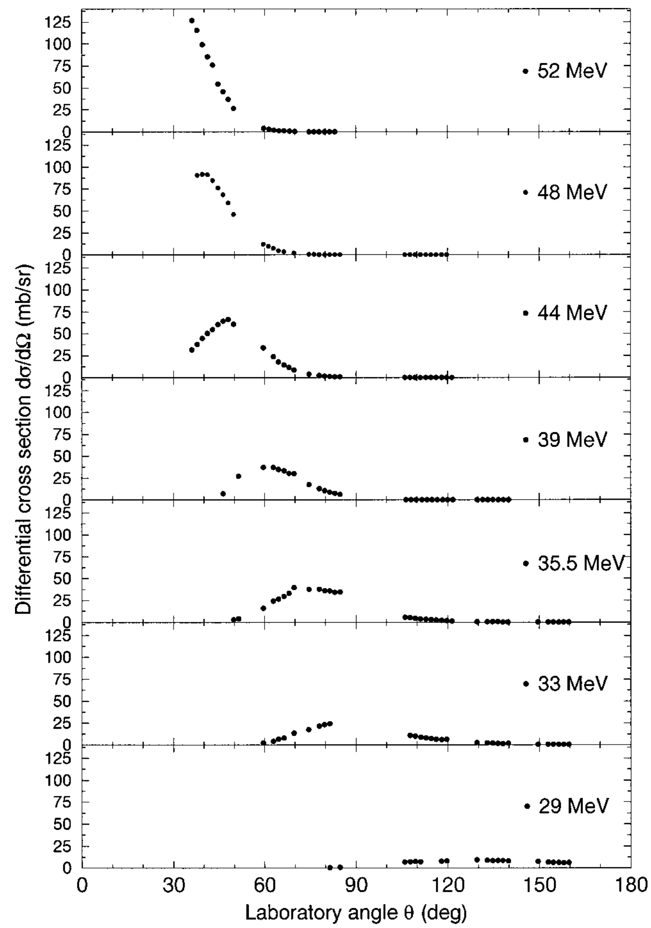

FIG. 3. Angular distributions of the differential cross section for α-particle production from ^{7}Li incident on a ^{208}Pb target at bombarding energies between 29 and 52 MeV. The error associated with each datum is smaller than the symbol.

size of 3×3 mm^2). The design of the scattering chamber enabled the acquisition of data in the interval $34°\leqslant\theta\leqslant160°$, where θ is the scattering angle measured in the laboratory frame.

III. DATA REDUCTION AND DISCUSSION

A. α-particle energy spectra

Figure 1 shows a typical α-particle energy spectrum obtained using a 35 MeV ^{6}Li beam. Maximum yield was observed at an α-particle energy $E_\alpha\approx24$ MeV, where the kinetic energy per nucleon of the α-particle is approximately equal to that of the projectile. Similar spectra were obtained at the other beam energies and with a ^{7}Li projectile. A background of low-energy α particles is visible beneath the peak in Fig. 1. This is perhaps attributable to deuteron capture by the ^{208}Pb target. For ^{7}Li, the spectra were further complicated at forward angles by the ^{1}H(^{7}Li, α)α reaction, arising from hydrogen contamination in the target. The effect of this background on the measured α-breakup cross sections is discussed in Sec. III C.

B. Differential cross sections

The peak in Fig. 1 was integrated for each slit position using a χ^2-minimization routine incorporating background subtraction. To eliminate the effect of deadtime in the detector or data-acquisition system, each α-particle yield Y_α was normalized with respect to the elastic scattering yield $Y_{\rm el}$ within the same slit. The α-breakup differential cross section $d\sigma/d\Omega$ was then calculated by multiplying the resulting quotient by the elastic scattering differential cross section, that is,

$$\frac{d\sigma}{d\Omega}=\frac{Y_\alpha}{Y_{\rm el}}\left(\frac{d\sigma}{d\Omega}\right)_{\rm el}, \tag{1}$$

where $(d\sigma/d\Omega)_{\rm el}$ is the elastic scattering differential cross section calculated using phenomenological optical model parameters determined by Keeley *et al.* [2].

Angular distributions of the α-particle production differential cross section for ^{6}Li and ^{7}Li projectiles are shown in Figs. 2 and 3, respectively. With the exception of the 52 MeV data, a clear maximum is observed in each of the distributions, which, as one would expect, shifts to lower laboratory angles at higher beam energies. Comparison of Figs. 2

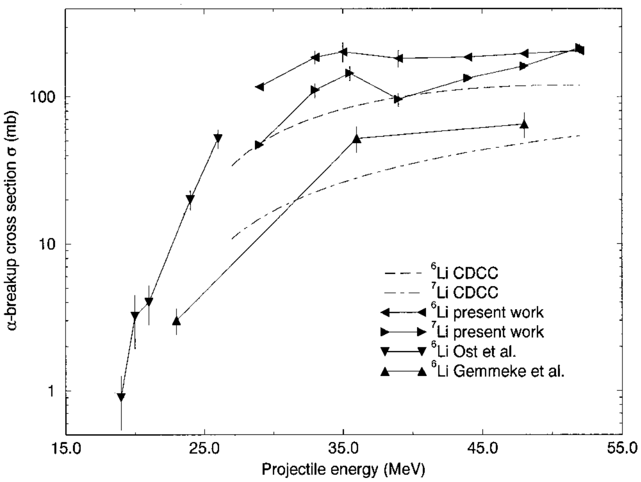

FIG. 4. Excitation function of the α-particle production cross section for lithium isotopes incident on a ^{208}Pb target. Also shown are the data of Ost *et al.* [14] and Gemmeke *et al.* [16] and the results of CDCC calculations. The lines between the data points are to guide the eye.

and 3 shows that, at each energy, the maximum value of $d\sigma/d\Omega$ is greater for ^{6}Li than for ^{7}Li, implying that the total α breakup is greater for ^{6}Li than for ^{7}Li.

C. Angle-integrated cross sections

To extract the angle integrated (i.e., total α breakup) cross section, each differential cross section angular distribution was fitted with a skew Gaussian function $f(\theta)$ using a χ^2-minimization routine. The *goodness of fit* parameter χ^2_ν (i.e., the χ^2 per degree of freedom) emerging from this process varied from just over zero to just below 17. The total α-breakup cross section σ was then calculated using

$$\sigma=\int_0^{2\pi} d\Omega \int_0^{\pi} f(\theta)\sin\theta d\theta \qquad (2)$$

for both lithium isotopes at each beam energy. The forward peaking of differential cross sections for transfer reactions and the $\sin\theta$ weighting mean that the background due to transfer reactions mentioned in Sec. III A introduces only a slight systematic error into the integration procedure.

The total α-breakup cross sections obtained are plotted in Fig. 4 and tabulated in Table I (along with the χ^2_ν values emerging from the fitting procedure). The α-breakup cross section of ^{6}Li is systematically greater than that of ^{7}Li, with the greatest difference being observed at low beam energies, i.e., closest to the Coulomb barrier. Figure 4 also demonstrates that the present lower-energy ^{6}Li measurements compare very well with an extrapolation of the data taken by Ost *et al.* [14].

Finally, Fig. 5 shows a comparison of the ratio of the ^{6}Li to ^{7}Li α-breakup cross sections, obtained from the present experimental data, with the results of Pfeiffer *et al.* [3]. In order to provide a fair comparison, this ratio has been plotted for each ^{6,7}Li + target combination as a function of the ratio of the approximate center-of-mass energy $E_{\mathrm{c.m.}}$ to the respective Coulomb barrier E_C. The ratio of ^{6}Li to ^{7}Li α-breakup cross sections is around 2.5 at the Coulomb barrier, but generally decreases with increased beam energy. The total cross sections in the present measurement are equal at a bombarding energy of 52 MeV. Apart from the single ^{6,7}Li+^{208}Pb datum at $E_{\mathrm{c.m.}}/E_C=1.43$, which corresponds to the dip in the ^{7}Li α-breakup cross section shown in Fig. 4, the present data are in good agreement with the general trend of the results of Pfeiffer *et al.* [3]. Figure 5 also shows that the enhancement of the ^{6}Li α breakup to that of ^{7}Li is independent of the target species.

TABLE I. Empirical α-breakup cross sections for ^{6}Li and ^{7}Li after interaction with a ^{208}Pb target. The parameter χ^2_ν, measuring the *goodness of fit* between the function $f(\theta)$ and the angular distribution of the differential cross section, is also shown.

	σ (mb)		χ^2_ν	
E (MeV)	^{6}Li	^{7}Li	^{6}Li	^{7}Li
29.0	117±1	47±2	0.08	0.49
33.0	186±19	111±13	11.11	16.57
35.0	203±31		8.40	
35.5		145±17		7.52
39.0	183±25	96±10	5.90	5.25
44.0	187±4	134±6	7.23	4.36
48.0	197±5	162±8	5.11	4.43
52.0	206±9	216±13	4.06	3.29

IV. CDCC CALCULATIONS AND DISCUSSION

A. Model space

Figure 4 shows CDCC α-breakup cross section predictions for ^{6}Li and ^{7}Li projectiles incident upon a ^{208}Pb target. These calculations were obtained using version FRXP15 of the

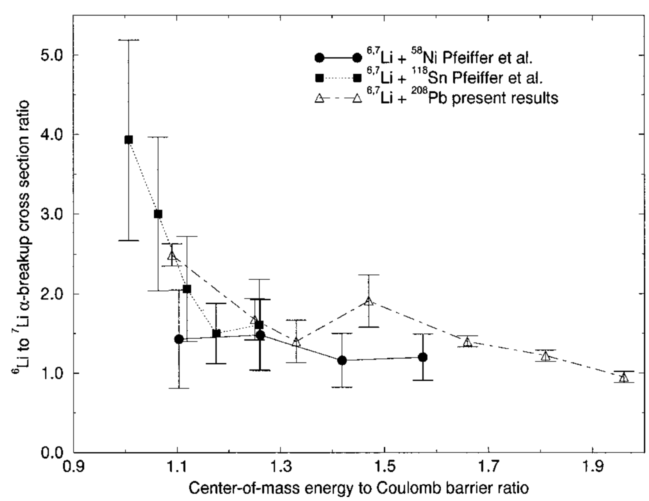

FIG. 5. A comparison of the present results with those of Pfeiffer *et al.* [3]. The ratio of the ^{6}Li to ^{7}Li α-breakup cross sections is plotted for each ^{6,7}Li + target combination as a function of the ratio of the center-of-mass beam energies to their respective Coulomb barriers.

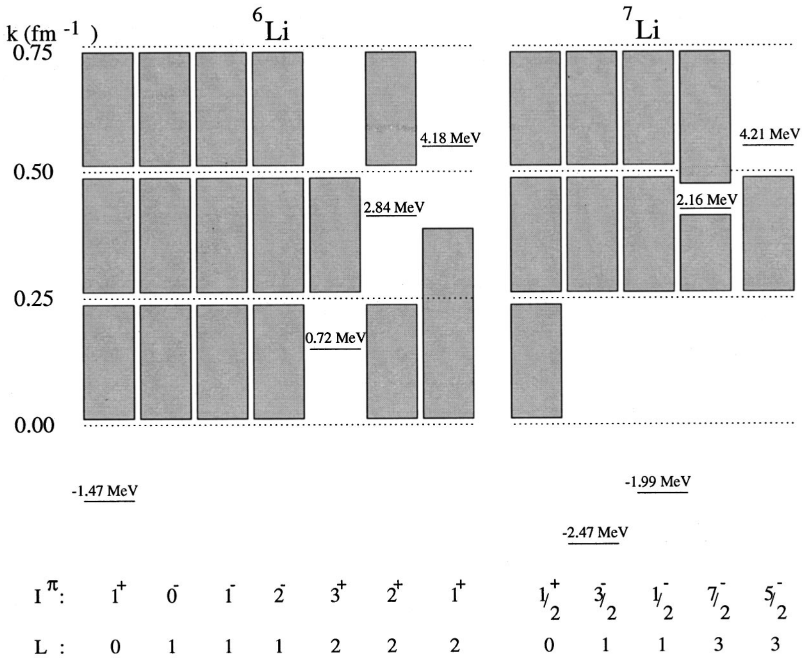

FIG. 6. The $^{6}\mathrm{Li}=\alpha+d$ and $^{7}\mathrm{Li}=\alpha+t$ model spaces used in the CDCC calculations. Excitation energies are measured relative to the projectile breakup thresholds at 1.47 and 2.47 MeV for ^{6}Li and ^{7}Li, respectively.

code FRESCO [15]. The parameters of the input potentials were the same as in the calculations published Keeley and Rusek [13]. The model spaces used for each projectile are shown schematically in Fig. 6. The continua were binned in terms of wave number k from 0 to 0.75 fm^{-1}, in bin widths of $\Delta k=0.25\ \mathrm{fm}^{-1}$. This width was suitably modified in the presence of the resonant states in order to avoid double counting. In the calculations, each momentum bin was treated as an excited state of either ^{6}Li or ^{7}Li, at an excitation energy equal to the mean energy of the bin and having spin $\vec{I}$ and parity $\pi=(-1)^{L}$, where $\vec{L}$ is the relative angular momentum between the α-particle core and the deuteron or triton, respectively.

The $^{6}\mathrm{Li}+{}^{208}\mathrm{Pb}$ calculation included sequential α-breakup from the first three resonant states plus $L=0,1,2$ nonresonant (continuum) α breakup. The $^{7}\mathrm{Li}+{}^{208}\mathrm{Pb}$ calculation included α breakup from the first excited state plus the first two unbound resonant states and $L=0,1,3$ nonresonant breakup. Test calculations, similar to those described by Rusek *et al.* [8], indicated that the $L=2$ contribution to ^{7}Li breakup was minimal, as were contributions from k bins missing from Fig. 6.

B. Discussion

The calculations showed that the $^{6}\mathrm{Li}\rightarrow\alpha+d$ breakup proceeds mainly via the $\alpha+d$ cluster states with angular momentum $L=2$. Since the ground state of ^{6}Li is $L=0$, the breakup corresponds to transitions with multipolarity $\Delta L=2$. In the case of $^{7}\mathrm{Li}\rightarrow\alpha+t$, the breakup proceeds mainly via the $L=0$ states, so the multipolarity is $\Delta L=1$. Table II details how contributions to the total α-breakup cross sections at 48 MeV bombarding energy depend on the angular momentum of the cluster state through which the breakup proceeds.

Figure 4 demonstrates that the predicted ^{6}Li α-breakup cross sections are systematically larger than the predicted ^{7}Li α-breakup cross sections across the entire projectile energy range. However, the enhancement of the ^{6}Li α-breakup cross section over that of ^{7}Li is greatest near the Coulomb barrier, decreasing smoothly from a factor of 3.3 at 29 MeV to a factor of 2.2 at 52 MeV. Thus, the energy variation of the predictions qualitatively matches that of the present data.

It is clear from Fig. 4 that the calculations under-predict the data across the entire range of bombarding energy. It is,

TABLE II. Contributions to the α-breakup cross section from cluster states with angular momentum L at 48 MeV bombarding energy. The final column shows the effect of artificially reducing the ^{7}Li α-breakup threshold to 1.47 MeV, i.e., equal to that of ^{6}Li.

$L(\hbar)$	$\sigma(^{6}\mathrm{Li}\rightarrow\alpha+d)$ (mb) $Q=-1.47$ MeV	$\sigma(^{7}\mathrm{Li}\rightarrow\alpha+t)$ (mb) $Q=-2.47$ MeV	$\sigma(^{7}\mathrm{Li}\rightarrow\alpha+t)$ (mb) $Q=-1.47$ MeV
0	18.5	26.3	82.5
1	27.7	6.0	17.9
2	69.4		
3		15.9	31.4
Total	115.6	48.2	130.8

however, reassuring that the ^{6}Li calculations overpredict the data taken by Gemmeke *et al.* [16], also shown in Fig. 4, who measured the resonant α breakup of ^{6}Li through the 3^{+} excited state via an $\alpha+d$ coincidence experiment. Several possible causes exist for the discrepancy between the present data and the calculations.

(1) Incorrect normalization of the present data. However, Fig. 4 demonstrates that the present lower-energy ^{6}Li measurements compare very well with an extrapolation of the data taken by Ost *et al.* [14], implying that the ^{6}Li data are normalized correctly. Since the same data reduction procedure was employed for the two lithium isotopes it is reasonable to infer that the present ^{7}Li data are also normalized correctly.

(2) The absence of significant elastic breakup channels from the CDCC calculations. The extensive test calculations [8] performed during the early stages of this analysis render this explanation unlikely.

(3) The absence of significant inelastic breakup channels from the CDCC calculations. However, mutual excitation of this kind was found by Rusek *et al.* [17] to have little effect on elastic scattering observables, perhaps implying that it is characterized by small cross section.

(4) Inappropriate results emerging from the cluster-folding technique used to generate the interaction and coupling potentials. However, the technique has been used with considerable success in earlier CDCC studies of elastic scattering [7–9].

(5) The absence of transfer breakup channels [10] from the CDCC calculations, since the kinematically incomplete experiment from which the data were derived was unable to differentiate between, for instance, $^{7}\mathrm{Li}^{*}\rightarrow\alpha+t$ and $^{8}\mathrm{Be}\rightarrow2\alpha$.

Table II demonstrates that artificial reduction of the α-breakup threshold of ^{7}Li from 2.47 to 1.47 MeV, equal to that of ^{6}Li, increased the predicted ^{7}Li α-breakup cross sections such that they were comparable to those of ^{6}Li at the same beam energy. This clearly shows that a major contribution to the enhancement of the ^{6}Li α-breakup cross section to that of ^{7}Li is the difference between the α-breakup thresholds of the two isotopes. As the beam energy is increased, the importance of this difference is reduced. This idea has been more thoroughly discussed by Keeley and Rusek [13].

V. CONCLUSIONS

Alpha breakup cross sections have been measured for ^{6}Li and ^{7}Li projectiles incident on a ^{208}Pb target at similar center-of-mass energies and compared with the results of CDCC calculations. With reference to the objectives articulated in Sec. I, from the analysis of these new data and comparison with similar breakup data the following conclusions can be drawn.

(1) The α-breakup cross section of ^{6}Li on ^{208}Pb is systematically enhanced over that of ^{7}Li, confirming the prediction of Keeley *et al.* [2]. This reinforces the indications from data for other targets [3]. The present analysis demonstrates that the cause of the enhancement is primarily the difference in the α-breakup thresholds of ^{6}Li and ^{7}Li.

(2) This cross section enhancement exhibits a significant energy dependence. It is most pronounced at low beam energies, i.e., near the Coulomb barrier, and is less at higher energies. The reason for this is that the difference in the breakup thresholds of the two lithium isotopes is proportionately less of the collision energy at higher beam energies, leading to the threshold difference being less significant, as predicted by Keeley and Rusek [13]. A montage of the present and previously reported results for α breakup of ^{6}Li and ^{7}Li scattering from a variety of targets [3] indicates that the ratio of the α-breakup cross sections is independent of the target species.

(3) CDCC calculations are shown to be a powerful tool. Resonant and nonresonant projectile excitations are included and the outcome is that the breakup cross section enhancement for ^{6}Li over ^{7}Li seen in the data is well produced by the calculations. The energy dependence of this enhancement is also reproduced. There does however remain a discrepancy between the observed and predicted magnitudes of the α-breakup cross sections. The existence of strong transfer breakup channels is believed to be the most likely cause of this discrepancy.

Rusek and Kemper [11] have already demonstrated that strong elastic breakup effects are seen in elastic scattering observables for light exotic nuclei. The present work indicates that the effects of transfer breakup are likely to be just as great. Taken together, these studies indicate that attempts to infer the structure of such nuclei from elastic scattering observables must include the effects of breakup if these studies are to be conclusive.

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