Probing the cluster structure of ^{7}Li via elastic scattering on protons and deuterons in inverse kinematics

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Elastic scattering measurements were performed for the ^{7}Li + p system in inverse kinematics at energies of 16, 25, 35, and 38.1 MeV and for the ^{7}Li + d system at 38.1 MeV. The heavy ejectiles were detected by the large acceptance MAGNEX spectrometer at the Laboratori Nazionali del Sud in Catania, Italy. The results are analyzed using the Jeukenne-Lejeune-Mahaux and continuum discretized coupled channel frameworks. In the latter case the cluster structure of ^{7}Li proves to be critical for the theoretical interpretation of the experimental results.

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I. INTRODUCTION

Continuing our systematic study of nucleon scattering on light weakly bound nuclei in inverse kinematics [1], we present new elastic scattering results for the ^{7}Li + p and ^{7}Li + d systems at near barrier energies [$\sim$(3–7)V_C]. As is well known, nucleon scattering is one of the most favorable and simple tools for probing the structure of a nucleus. The idea of clustering in light nuclei like ^{6,7}Li has been investigated in several articles (e.g., Refs. [2–6]) with regard to its application to both nuclear properties and reaction dynamics. In this respect, it is the goal of this work to highlight proton elastic scattering in inverse kinematics as a means for probing the cluster structure of the projectile.

The ^{7}Li nucleus exhibits a pronounced cluster structure similar to that of ^{6}Li, but with the following difference. The ^{7}Li binding energy in the α-t channel is 2.47 MeV instead of 1.47 MeV for the α-d channel of ^{6}Li, and the first unbound resonant level of ^{7}Li is at 4.630 MeV instead of 2.186 MeV for ^{6}Li. Therefore, couplings to the continuum and resonance states are less favored here, and elastic scattering, especially at the lower energies, can be used as a tool for probing the cluster structure of the projectile ground state. This is extended to our experimental results with a deuteron target, where couplings to the deuteron n-p continuum are also considered.

We studied proton elastic scattering for radioactive nuclei in inverse kinematics at near barrier energies with ^{17}F [7], probing both the potential and the neutron skin structure of the projectile. It was shown that for off-resonance energies even well below the limit of $E_{\mathrm{proj}} = 10$ MeV/nucleon, that is, 4–5 MeV/nucleon, the microscopic approach of the Jeukenne-Lejeune-Mahaux (JLM) [8] potential can be the basis for interpreting the elastic scattering. This potential was applied in Refs. [9–11] to medium and heavy mass stable nuclei at energies above 10 MeV/nucleon, with only slight adjustments to the imaginary part. It should be noted that Jeukenne, Lejeune, and Mahaux parametrized their numerical results for the real and imaginary parts of the optical potential in an analytical form. For that they took into consideration calculated values over the energy interval $10 \leqslant E \leqslant 160$ MeV. Additionally, since the calculations were performed for infinite nuclear matter and used the local density approximation to obtain optical potentials for finite nuclei, their application to light nuclei constitutes a severe test of this assumption. A comprehensive discussion of these points can be found in Ref. [12]. The applicability of the JLM method at lower energies ($7 \leqslant E/A \leqslant 24$) was tested in Ref. [13] and for low-to-high mass numbers in Refs. [10,14]. These issues were tested simultaneously for the first time in our recent work [1] on the elastic scattering of ^{6}Li + p, where the JLM potential was applied both to a low mass projectile and at low energies, 2.7–4.8 MeV/nucleon. Optical model calculations with the JLM potential were found inadequate to describe these data. On the other hand, continuum discretized coupled channel (CDCC) calculations were very successful. With the same motivation, we have extended our study to the ^{7}Li + p and ^{7}Li + d elastic scattering. Some inelastic scattering results are also considered.

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Several articles exist in the literature concerning measurements of elastic scattering of protons and deuterons from ^{7}Li in direct kinematics. Detailed compilations may be found in Refs. [15–17], where elastic scattering data are used for global potential studies in conventional phenomenological frameworks as well as in a CDCC context.

The elastic scattering of protons by ^{7}Li is revisited in this article in inverse kinematics using the MAGNEX spectrometer [18–23] as part of our systematic research into nucleon elastic scattering. The focus in this study is on a precise elastic scattering measurement avoiding the normalization uncertainties possibly associated with previous data, with the final goal, as in the ^{6}Li study, of a measurement of the breakup. This can be more easily accomplished in inverse kinematics, since all the ejectiles are confined to forward angles and MAGNEX is capable of detecting them with good angular and energy resolution. The elastic scattering measurement is an essential part of this study, probing the potential under the same conditions. Moreover, by setting the spectrometer close to zero, and thanks to its large acceptance, we can span almost the full angular range for the elastic scattering in the center of mass frame in a single setting, facilitating normalization via Rutherford scattering at the most forward angles. In this way we may verify the normalizations adopted in the previous direct kinematics measurements and remove possible uncertainties.

In the following sections we first present the experimental details and the data reduction method with comparisons to previous data (Sec. II); then we describe the theoretical calculations (Sec. III) and finally make some concluding remarks (Sec. IV).

II. EXPERIMENTAL DETAILS AND DATA REDUCTION

The experiment was performed at the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. Beams of ^{7}Li^{3+} were accelerated by the TANDEM Van de Graaff to energies of 16, 25, 35, and 38.1 MeV and impinged on a 240 μg/cm^2 CH_2 target. At the highest energy of 38.1 MeV a measurement was also performed with a 260 μg/cm^2 CD_2 target. Measurements were repeated with a ^{12}C target of similar thickness to estimate the carbon background. The elastically scattered lithium ions were momentum analyzed by the MAGNEX spectrometer [19,22,23], whose optical axis was set at $\theta_{opt} = 4^\circ$, and were detected by its focal plane detector [21]. The spectrometer worked with full horizontal angular acceptance but with reduced vertical acceptance to protect the focal plane detector from the high elastic scattering counting rate. For the elastic scattering on deuterons the optical axis of MAGNEX was set at $\theta_{opt} = 6^\circ$ and 12° to obtain a full angular distribution measurement.

Our data reduction technique, based on the differential algebraic method [24], and the performance of the whole system are described in Refs. [20,25]. The two kinematical solutions of the ejectiles were measured by the application of three different magnetic fields. The beam charge was collected by a Faraday cup set at the entrance of MAGNEX and its absolute value was cross checked via the measurements at the very forward angles, where the elastic scattering is Rutherford. The counts were integrated over an angular step of $\sim 0.5^\circ$ and the solid angle, defined by four slits located 250 mm downstream of the target, was calculated taking into account the contour of the reconstructed (θ_i, ϕ_i) locus [26]. The solid angle uncertainty is estimated to be $\sim$2%. Our results for ^{7}Li + p elastic scattering are compared with previous data,

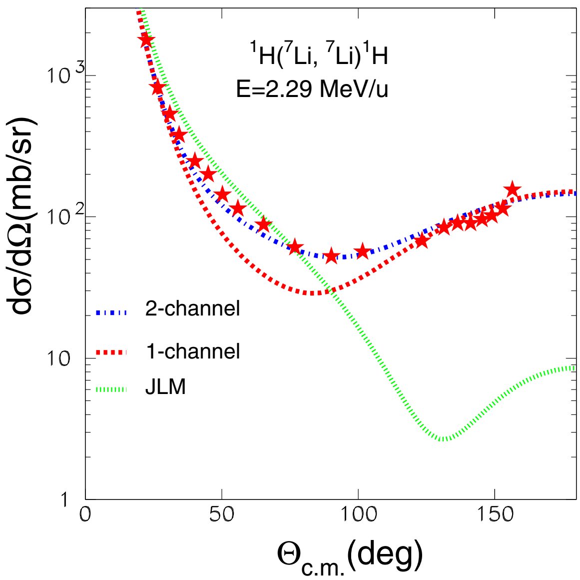

FIG. 1. Elastic scattering of ^{7}Li + p at 16 MeV (2.29 MeV/nucleon). The type of calculation compared with the data is indicated on the figure. No CDCC calculation was performed in this case since the available energy was insufficient to excite the continuum.

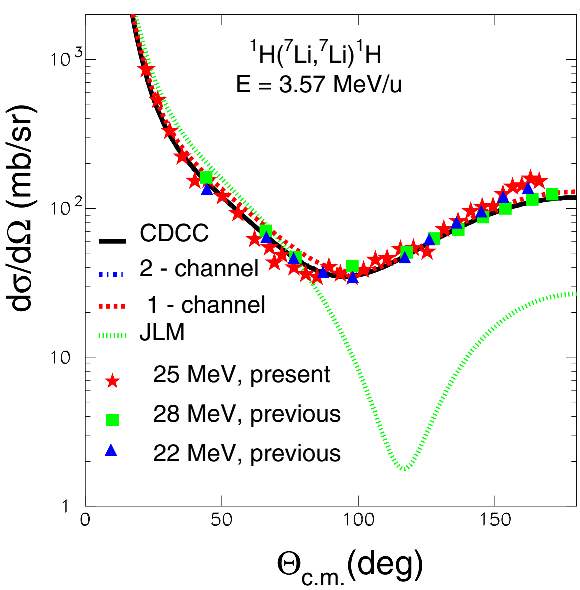

FIG. 2. Elastic scattering of ^{7}Li + p at 25 MeV (3.57 MeV/nucleon). The type of calculation compared with the data is indicated on the figure. The CDCC calculation includes couplings to the continuum but they are very weak, since the CDCC and two-channel calculations coincide. Previous data are from Ref. [27].

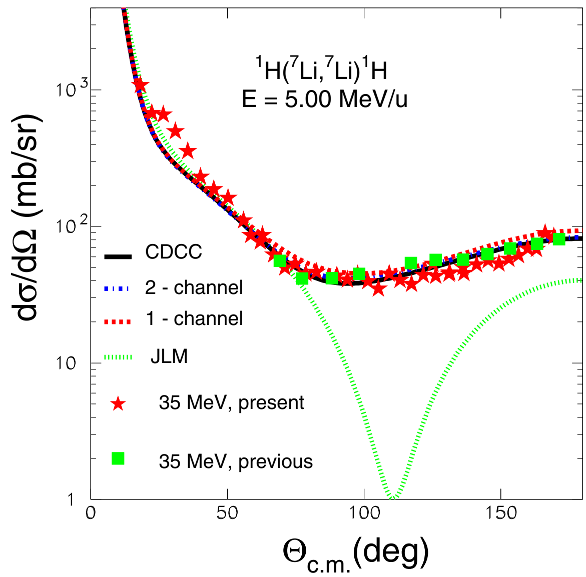

FIG. 3. Elastic scattering of ^{7}Li $+ p$ at 35 MeV (5 MeV/nucleon). The type of calculation compared with the data is indicated on the figure. The CDCC calculation includes couplings to the continuum but they are very weak, since the CDCC and two-channel calculations coincide. Previous data are from Ref. [27].

where they exist, in Figs. 1–4 from the lower to the higher bombarding energy, and in Fig. 5 for the 38.1 MeV ^{7}Li $+ d$ elastic scattering. Total uncertainties were less than 8% which includes the statistical uncertainty (less than 5%), an error due to the beam flux, solid angle, and thickness of the target. As can be seen, the agreement between the previous and the present

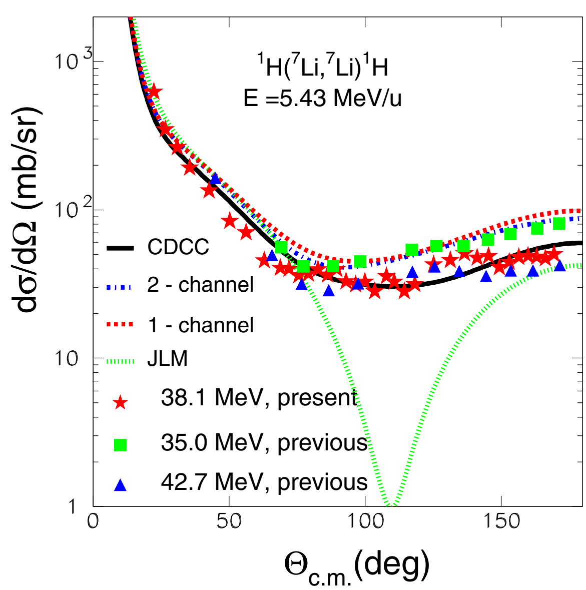

FIG. 4. Elastic scattering of ^{7}Li $+ p$ at 38.1 MeV. The CDCC calculation includes couplings to the continuum as well as the resonant state, although coupling to the resonance alone was found to be adequate. The difference between the CDCC and two-channel results is obvious here. The type of calculation compared with the data is indicated on the figure. Previous data are from Ref. [27].

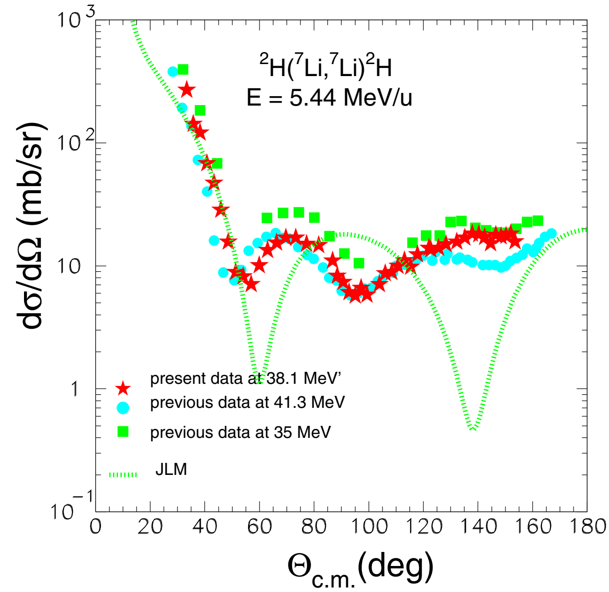

FIG. 5. The present 38.1 MeV ^{7}Li $+ d$ elastic scattering data compared with previous data at similar energies and a JLM calculation. Previous data are from Refs. [28,29].

data is in most cases good, within an uncertainty band of 15%. However, the previous data for ^{7}Li $+ d$ at 35 MeV [29] require a renormalization of 30%. It should be noted that our data extend to forward angles where the scattering is Rutherford, thereby validating the normalization.

III. CALCULATIONS

To interpret our data we initially adopted the microscopic JLM model [8] according to the code developed by Dietrich, with the "standard" renormalization [11] of the imaginary part for light nuclei of $\lambda_W = 0.8$. The ^{7}Li density was taken from Hartree-Fock calculations performed by Trache *et al.* [30]. Our calculations are compared with the experimental data in Figs. 1–4 for ^{7}Li $+ p$ and Fig. 5 for ^{7}Li $+ d$ (dotted green lines) and it is clear that they fail to reproduce the data.

The CDCC calculations were performed using the code FRESCO [31]. Some nuclei, such as ^{6,7}Li, may be modeled as two inert clusters and the Coulomb and nuclear excitations can then be calculated from the interactions of each cluster with the target using Watanabe-type folding. We employed this technique here, following Ref. [32], where calculations for the ^{6}Li $+ p$ system at a much higher energy (150 MeV) were presented, and Refs. [1,33], where calculations at similar energies to those considered here were performed. In the latter case it was found that the calculation was very sensitive to the interactions between each cluster and the target. Couplings to the continuum were found to be weak, while couplings to the resonant states were strong, especially at the higher energies [33]. It should be noted here that strong couplings to resonance states were also reported previously for ^{6,7}Li scattering from heavy targets [34,35]. However, for our system, ^{7}Li $+ p$, we expect small contributions from couplings to both the continuum and the resonant states, as the available energy is insufficient for such excitations. In fact, by choosing the energies so as to minimize these couplings, we expect to reproduce the elastic scattering simply by describing in the most accurate way the interactions between each cluster and the target.

The $\alpha + t$ cluster model of ^{7}Li was therefore adopted, with all the parameters of the model including discretization and truncation of the continuum as described in detail in Ref. [36]. The α-t continuum was divided into bins in momentum (k) space of width $\Delta k = 0.125$ fm^{-1} and relative angular momenta $L = 0,1,2,3$ were included. The $7/2^-$ resonance at 4.631 MeV was taken into account and was treated as a momentum bin with a width corresponding to 0.1 MeV. Couplings to the first excited state at 0.478 MeV and ground state reorientation were also considered. Special care was given to the potentials between each cluster and the target, that is, the p-α and p-t potentials. Empirical potentials were obtained by fitting previous $p + \alpha$ and $p + t$ elastic scattering data at the appropriate energies, $E = \sim$2.5–6 MeV/nucleon [37–40]. These data were fitted with volume Woods-Saxon form factors for both real and imaginary parts for the $p + \alpha$ system and a volume real and a surface imaginary term plus a spin-orbit potential for the $p + t$ system. The input potentials thus obtained were fed into FRESCO calculations and the results for ^{7}Li + p are compared with the experimental data in Figs. 1–4 (solid black lines), exhibiting an excellent agreement. The calculations were repeated, omitting couplings to the continuum and the resonant state. As expected, the effect of couplings to the continuum was negligible at all energies, while the difference between the two-channel calculations and calculations where coupling to the resonance was also considered is significant only at the highest energy of 38.1 MeV where the available energy is enough to excite this state. Single-channel calculations were also performed, omitting all couplings including that to the first excited state of the projectile. The difference between the one- and two-channel calculations is small except at 16 MeV. Therefore, the important issue here is the correct description of the p-t and p-α potentials, indicating in a very clear way the cluster structure of ^{7}Li.

Bearing this result in mind and with the intention of probing further the cluster structure of ^{7}Li, we performed similar calculations for the ^{7}Li + d elastic scattering data. With FRESCO, couplings to the continuum can only be taken into account for one of the two colliding nuclei; mutual breakup couplings are not possible. Coupling to the deuteron continuum may be rather stronger than coupling to the ^{7}Li continuum, as the $n + p$ binding energy is 2.224 MeV, that is, $\sim$200 keV lower than the $\alpha + t$ binding energy in ^{7}Li. However, we initially assumed that the deuteron may be taken as the "stable" partner and ^{7}Li as the weakly bound one. This assumption was then reversed in a second set of calculations. For the first set of calculations where we took into account the breakup of ^{7}Li, we followed the same procedure as for the ^{7}Li + p case, the only difference being the choice of "cluster" potentials. For a deuteron target we fitted previous data [41,42] for d-α and d-t elastic scattering with volume Woods-Saxon form factors for both real and imaginary parts plus a spin-orbit term. The "cluster" potentials thus obtained were fed as input into FRESCO. Our results for ^{7}Li + d, under the notation "present CDCC1," are compared to the data in Fig. 6.

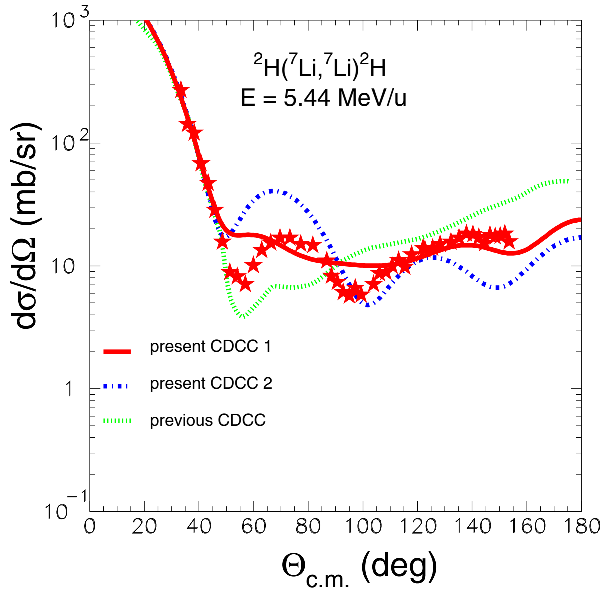

FIG. 6. The present 38.1 MeV ^{7}Li + d elastic scattering compared with CDCC calculations. The curve labeled "present CDCC1" corresponds to the calculation that takes into account excitations to the ^{7}Li α-t continuum only while the curve labeled "present CDCC2" corresponds to the calculation taking into account excitations to the n-p continuum of ^{2}H only. The curve labeled "previous CDCC" is taken from Ye *et al.* [16] and denotes a calculation that takes into account the breakup of ^{2}H only.

Second, a calculation was performed explicitly taking into account the breakup of the deuteron. Here the calculation is

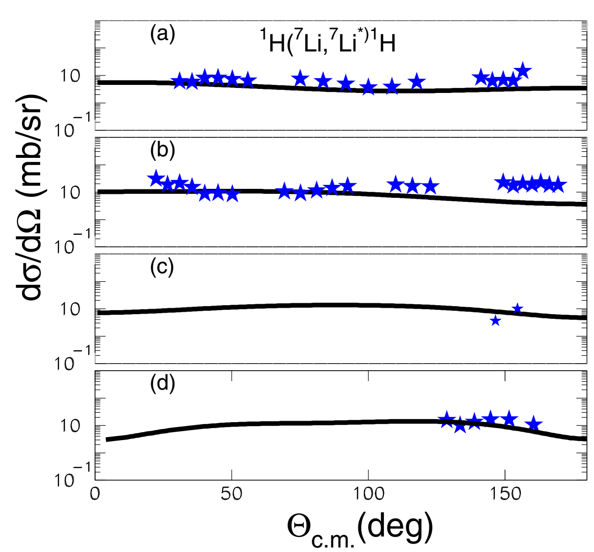

FIG. 7. Inelastic scattering data for ^{7}Li + p at (a) 16, (b) 25, (c) 35, and (d) 38.1 MeV. The solid curves represent two-channel FRESCO calculations for the lowest energy, and CDCC calculations for the higher energies with additional coupling to the first excited state of ^{7}Li.

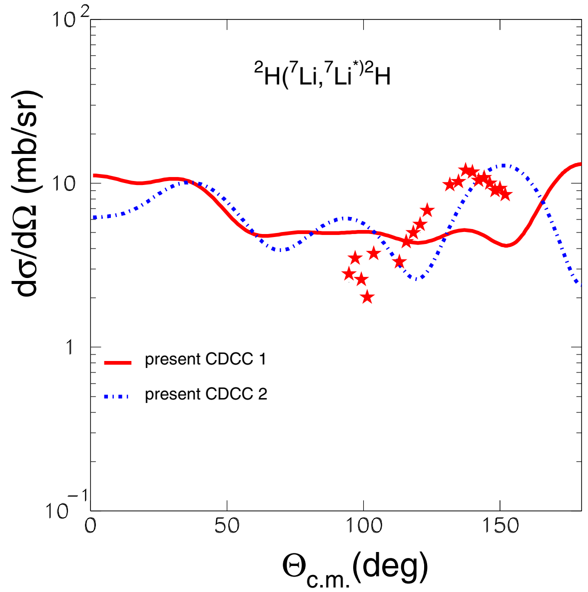

FIG. 8. Inelastic scattering results for ^{7}Li $+ d$ at 38.1 MeV (5.43 MeV/nucleon).

more complicated. We performed a CDCC calculation for the deuteron and treated the ^{7}Li $1/2^-$ bound excited state at 0.478 MeV and the $7/2^-$ resonance at 4.631 MeV as members of a $K = 1/2$ rotational band. In more detail, the first step was to perform a CDCC calculation including deuteron breakup and adjusting the p-^{7}Li and n-^{7}Li "cluster" potentials to obtain the best fit to the elastic scattering data. The calculation was similar to that described in Ref. [43]. The deuteron potentials were obtained by Watanabe-type folding of the n- and p-^{7}Li optical potentials over the deuteron internal wave function calculated with the Reid soft core interaction [44]. The n-p continuum was divided into bins in momentum (k) space of width $\Delta k = 0.125$ fm^{-1}, and relative angular momenta $L = 0{,}2$ were included. The ^{7}Li excitations were then added by reading in the "bare" diagonal Watanabe deuteron potential for the entrance channel and deforming it in the usual way, with the Coulomb coupling strength derived from the measured $B(E2; 3/2^- \rightarrow 1/2^-)$ [45] and a nuclear deformation length $\delta_2 = 2.4$ fm. Any further adjustments required to recover the description of the elastic scattering data were made by renormalizing the cluster potentials. The target excitation could in this way be included consistently; N.B. "mutual excitation," i.e., inelastic breakup, was not included in these calculations. Our results are presented in Fig. 6 with the notation "present CDCC2." A third calculation performed by Ye *et al.* [16] taking into account the breakup of the ^{2}H in a similar way to our CDCC2 calculation and denoted "previous CDCC" is also presented. It is observed that both the "CDCC1" and "previous CDCC" curves describe the data adequately but do not reproduce the oscillatory nature of the scattering. However, the "CDCC2" calculation, where in the first stage of the calculation the "cluster" potentials were renormalized to fit the deuteron elastic scattering data and then couplings were taken explicitly into account, reproduces better the oscillatory nature of the experimental results.

In Figs. 7 and 8 we present our inelastic scattering results for ^{7}Li $+ p$ and ^{7}Li $+ d$, respectively. While these data are not complete, they further support the validity of our calculations. It should be noted that the uncertainty in these data is less than 14%, including the statistical error (less than 12%) as well as errors due to the integrated beam flux, solid angle, and thickness of the target.

IV. SUMMARY AND CONCLUSIONS

Absolute differential cross sections for the elastic scattering of ^{7}Li $+ p$ were obtained at 16, 25, 35, and 38.1 MeV and ^{7}Li $+ d$ at 38.1 MeV in inverse kinematics. The goal of this work was to highlight elastic scattering, especially from protons, as a means for probing the cluster structure of the projectile. ^{7}Li was chosen as an appropriate test case due to its well known ^{4}He$+^3$H cluster structure. This goal was accomplished as it was found that simple optical model calculations taking into account the cluster nature of ^{7}Li can give an excellent description of the scattering at the lowest energies. This is in accordance with similar calculations on heavy targets [5]. At higher energies, where resonant states are excited, CDCC calculations provide a basis for such studies, with the emphasis on the couplings to the resonances. The present limited inelastic scattering results further support this conclusion. The results of scattering from deuterons also support this view, although the number of degrees of freedom are enlarged here, and their full inclusion is necessary.

Furthermore it is found that, as in the ^{6}Li case, the JLM interaction is not able to provide a good description of the elastic scattering of nuclei with mass numbers as low as $A \sim 7$ at very low energies ∼2–5 MeV/nucleon.

The strong message of this work is that under the appropriate energy conditions the cluster structure of a nucleus can be clearly probed by elastic scattering from protons. Good indications in this direction can also be obtained by scattering from deuterons, although in this case other degrees of freedom play a crucial role.

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