Reexamination of ^{6}Li + p elastic scattering in inverse kinematics

V. Soukeras,[1] A. Pakou,[1,*] F. Cappuzzello,[2,3] L. Acosta,[4,5] C. Agodi,[2] N. Alamanos,[6] M. Bondi,[2,3] D. Carbone,[2] M. Cavallaro,[2] A. Cunsolo,[2] M. De Napoli,[5] A. Di Pietro,[2] J. P. Fernández-García,[2] P. Figuera,[2] M. Fisichella,[2] A. Foti,[3,5] N. Keeley,[7] G. Marquinez-Duran,[8] I. Martel,[8] M. Mazzocco,[9,10] D. Nicolosi,[2] D. Pierroutsakou,[11] K. Rusek,[12] O. Sgouros,[1] E. Stiliaris,[13] E. Strano,[9,10] and D. Torresi[9,10]

[1]*Department of Physics and HINP, The University of Ioannina, 45110 Ioannina, Greece*
[2]*INFN Laboratori Nazionali del Sud, via S. Sofia 62, 95125, Catania, Italy*
[3]*Dipartimento di Fisica e Astronomia, Universita di Catania, via S. Sofia 64, 95125, Catania, Italy*
[4]*Instituto de Fisica, Universidad Nacional Autonoma de Mexico, Mexico Distrito Federal 01000, Mexico*
[5]*INFN-Sezione di Catania, via S. Sofia 64, 95125, Catania, Italy*
[6]*CEA-Saclay, DAPNIA-SPhN, 91191, Gif-sur-Yvette, France*
[7]*National Center for Nuclear Research, A. Soltana 7, 05-400, Otwock Warsaw, Poland*
[8]*Departamento di Fisica Aplicada, Universidad de Huelva, E-21071 Huelva, Spain*
[9]*Departimento di Fisica e Astronomia, Universita di Padova, via Marzolo 8, I-35131 Padova, Italy*
[10]*INFN-Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy*
[11]*INFN-Sezione di Napoli, via Cinthia, I-80126 Napoli, Italy*
[12]*Heavy Ion Laboratory, University of Warsaw, Pasteura 5a, 02-093 Warsaw, Poland*
[13]*Department of Physics, Institute of Accelerating Systems and Applications, University of Athens, Greece*

Elastic-scattering measurements have been performed for the $^6\mathrm{Li} + p$ system in inverse kinematics at the energies of 16, 20, 25, and 29 MeV. The heavy ejectile was detected by the large acceptance MAGNEX spectrometer at the Laboratori Nazionali del Sud in Catania, Italy. The results are considered in a Jeukenne-Lejeune-Mahaux and a continuum discretized coupled-channel calculation framework.

Introduction. In principle nucleon scattering is the most favorable and simplest tool for probing the potential and/or the structure of a nucleus. For radioactive nuclei the method is adopted in inverse kinematics, and the halo or skinlike nature of the projectile is probed as long as the potential is known or vice versa. For example for energies well above $E_{\mathrm{proj.}} = 10$ MeV/u, the microscopic approach of the Jeukenne, Lejeune, and Mahaux (JLM) potential was the basis for several such studies [1–9]. This potential was derived by Jeukenne-Lejeune-Mahaux [10] and applied in Refs. [11–13] for medium- and heavy-mass stable nuclei and for energies above 10 MeV/u with slight adjustments only on the imaginary part. The applicability of the JLM method for lower energies ($7 \leqslant E/A \leqslant 24$) was tested in Ref. [14] while for lower mass numbers in Refs. [12,15], where the validity of the local density approximation is under a severe test. Both these issues were confronted in our recent work of proton elastic scattering in inverse kinematics with the radioactive nucleus ^{17}F [16]. The measurements were performed off-resonance, and the JLM standard potential was proven valid under various assumptions of the density distribution of this radioactive nucleus. However, no further consideration of its weakly bound nature via couplings to continuum was taken into account and of implications for measurements at energies on-resonance. In this respect we will present herewith our new study of $^6\mathrm{Li} + p$ in inverse kinematics.

The ^{6}Li nucleus exhibits a pronounced cluster structure with a very low binding energy in the α-d channel and a low density of its excited states up to an excitation energy of 16 MeV. Under these conditions, the choice of a standard optical potential is inapplicable. The reactions of nucleons and light nuclei with ^{6}Li are of great practical and theoretical importance with serious consequences on astrophysical problems [17] and applications in fusion reactors [18]. The determination of low-energy cross sections, which belong to a deep sub-barrier region, is a difficult task both from the theoretical and from the experimental points of view and the possible approach relies on extrapolations. The latter is based on the exact form of the potential barrier, the potential penetrability, and the extrapolation of S factors to zero energy.

Therefore, elastic-scattering and reaction measurements as well as total reaction cross sections at low energies could be very useful for a detailed theoretical approach.

Several articles exist in the literature concerning measurements on elastic scattering of protons from ^{6}Li in direct kinematics, and a detailed compilation can be found in Ref. [19]. All measurements are taken at energies near and on-resonance [20] due to the particular structure of ^{6}Li as was mentioned above. Measurements in a wide energy range ($E_p = 1.6$–12 MeV) and a rather wide angular range of $\theta_{\mathrm{lab}} = 30^\circ$–$165^\circ$ are found in Refs. [20,21] whereas polarization and phase-shift measurements are found in Refs. [22,23] for $E_p = 0.5$–5.6 MeV. It should be mentioned that all these measurements are relative measurements, and the normalization is obtained via a thick target study [24]. The theoretical analysis of these data is mainly focused on the ^{7}Be structure

*apakou@cc.uoi.gr

and not on the potential, except for Haller *et al.* [21] where an optical potential is used to fit the data allowing the various parameters to strongly depend on energy. The polarization measurements fail to give a clear analysis due to several parameters which have to be determined. Between these parameters we note the unknown total reaction cross section needed to fit absorption. Theoretical approaches to probe the potential in a folding and coupled-channel (CC) context are found in Refs. [15,25,26], but they deal with data at rather high energies above $E = 25$ MeV/u. Four recent interesting articles [27–30] present continuum discretized coupled-channel calculations (CDCC) and calculations with a microscopic M3Y potential, respectively, from rather low to higher energies ($\sim$5–155 MeV/u).

The elastic scattering of protons by ^{6}Li is revisited in this Brief Report in inverse kinematics and by using the MAGNEX spectrometer [31–35] on the following grounds. This will be considered as a predecessor measurement to one with radioactive projectiles, such as ^{8}Li. The final goal, for both stable and radioactive projectiles, will be the breakup measurement, which can be easily accessible in inverse kinematics since all the ejectiles are confined at forward angles and MAGNEX is a powerful tool, capable of detecting them with good angular and energy resolutions. The elastic-scattering measurement is then an inevitable study for probing the potential at the same conditions. Moreover by setting MAGNEX close to zero, and thanks to its large acceptance, we can span almost a full angular range in the center-of-mass frame, all in one go, facilitating our normalization via Rutherford scattering at the most forward angles. This can validate or not the normalization adopted in the previous data and remove possible uncertainties.

That is, within our experimental approach we focus on a precise, clear from previous data ascribed uncertainties, elastic-scattering measurement, predecessor to measurements on MAGNEX with radioactive projectiles in inverse kinematics. This measurement will be the first step for obtaining the optical potential and subsequently in a future work for describing the various reaction processes. Another goal of this Brief Report is to establish the reliability of the CDCC method at lower energies than in previous studies [27,28] for a safe prediction of cross-section data.

In the following sections we will first present the experimental details and the data reduction with comparisons with previous data (Sec. II), then we will proceed with details of our theoretical calculations (Sec. III), and we will finalize with the concluding remarks.

Experimental Details and Data Reduction. The experiment was performed at the MAGNEX facility of the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. Beams of ^{6}Li^{3+} were accelerated by the Tandem accelerator at the energies of 16, 20, 25, and 29 MeV and impinged on a 240-μg/cm^2 CH_2 target. Measurements were repeated with a ^{12}C target of similar thickness for estimating the carbon background. The elastically scattered lithium ions were momentum analyzed by the MAGNEX spectrometer [31,34,35], whose optical axis was set at $\theta_{\rm opt} = 4^\circ$ and were detected by its focal plane detectors [33]. MAGNEX worked in a full horizontal angular acceptance but with a reduced vertical acceptance for protecting the focal plane detectors from the elastic high counting rate.

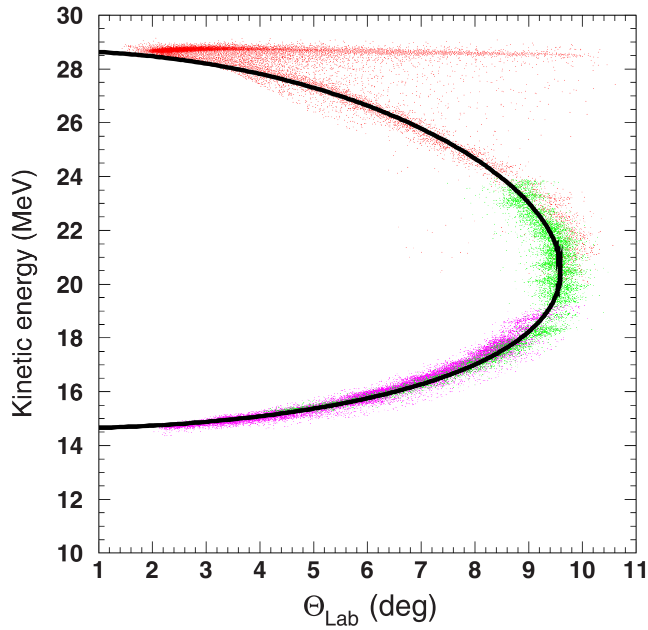

FIG. 1. (Color online) A reconstructed E-θ correlation plot for ^{6}Li + p at a projectile energy of 29 MeV. The two kinematical solutions of the reaction were obtained in three different runs with three sets of magnetic fields. The plot shows the superposition of these runs, designated with different colors. The black solid line represents the theoretical prediction which seems to describe perfectly well the data, giving further support to the accurate spectrum reconstruction.

Our data reduction technique, based on a differential algebraic method [36] and the performances of the whole system are described in Refs. [32,37]. The two kinematical solutions of the ejectiles were measured by the application of three different magnetic fields. A typical reconstructed E-θ correlation plot at a projectile energy of 29 MeV is displayed in Fig. 1. In this figure, the reconstructed kinematical plot was obtained with the superposition of the three different magnetic sets, which are designated with different colors. Overlapping regions among sets I–III ensured the consistency between the different sets. The beam charge was collected by a Faraday cup, set at the entrance of MAGNEX, and its absolute value was cross-checked via the measurement at the very forward angles where the elastic scattering is Rutherford. For an angular step of $\sim$0.5°, the counts were integrated, and the solid angle, defined by four slits located at 250 mm from the target, was calculated taking into account the contour of the reconstructed (θ_i,ϕ_i) locus [38]. The solid angle uncertainty is estimated to be $\sim$2%. Our results are shown in Figs. 2–5 from the lower to the higher bombarding energy.

Present and previous data are compared as an example at 29 MeV in Fig. 6. As can be seen, the agreement between themselves is very good. It should be noted here, that our data are extended to smaller angles than the previously measured ones where the scattering is Rutherford, validating the normalization. Similar conclusions can be drawn for the lower-energy data.

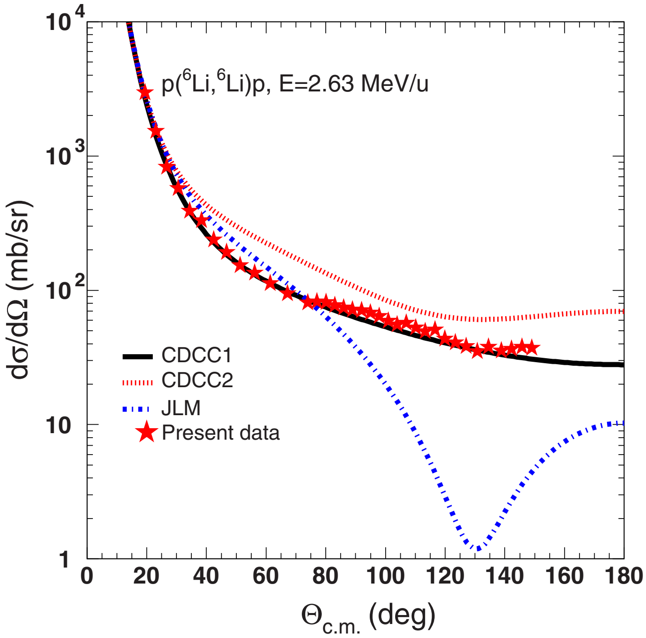

FIG. 2. (Color online) Present elastic-scattering data for ^{6}Li + p at 16 MeV are compared with JLM and CDCC calculations (see the text). The uncertainty in the data points is between 8% and 10%. This error includes the statistical error, errors due to the target thickness, the beam flux measurement, and the solid angle determination.

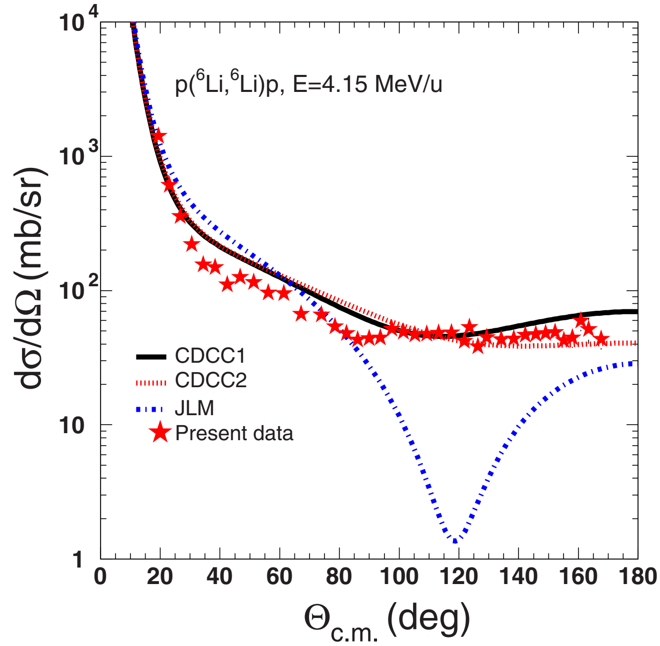

FIG. 4. (Color online) The same as in Fig. 2 but for a projectile energy of 25 MeV.

Theoretical Details. For the microscopic JLM approach the Jeukenne-Lejeune-Mahaux model [10] is adopted according to the code developed by Dietrich *et al.* [14] at a standard normalization ($\lambda_V = 1.0$ and $\lambda_W = 0.8$). The density for ^{6}Li is derived from Ref. [25]. Our calculations are compared with the experimental data in Figs. 2– 5 (dot-dashed line), and it is obvious that they fail to reproduce the data.

For the CDCC calculation we follow the same technique as in Ref. [27] where we present calculations for the same system but at a much higher energy of 155 MeV (25.8 MeV/A).

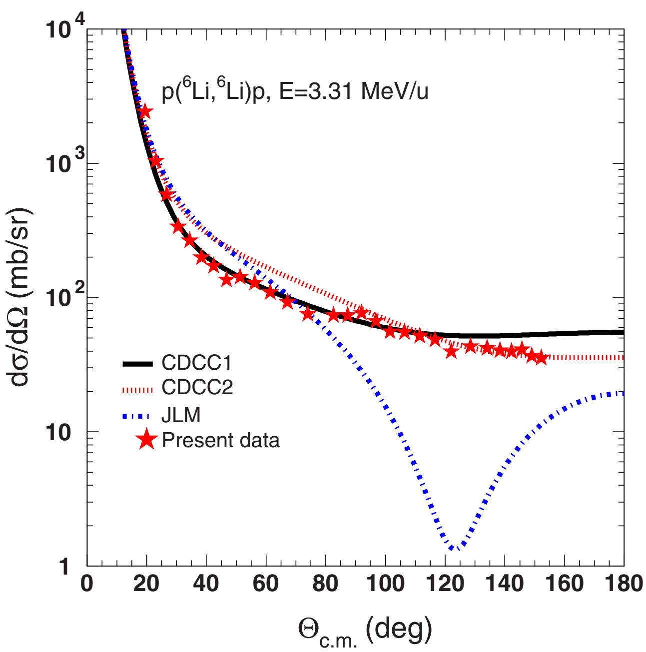

FIG. 3. (Color online) The same as in Fig. 2 but for a projectile energy of 20 MeV.

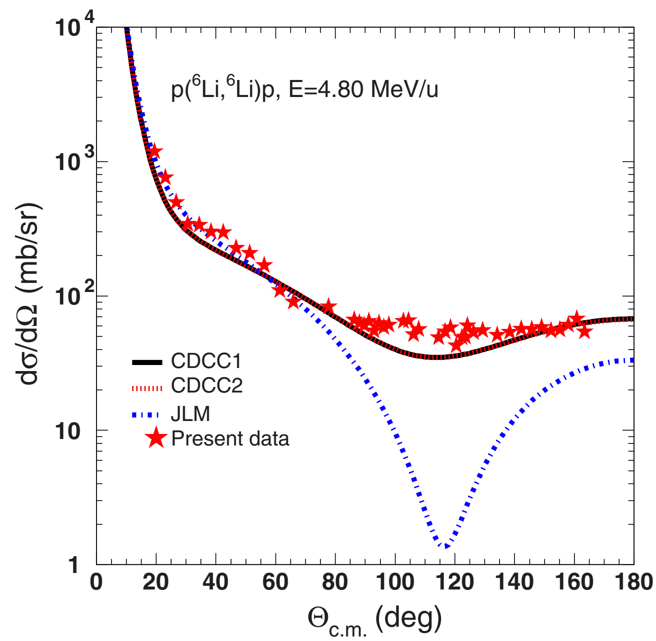

FIG. 5. (Color online) The same as in Fig. 2 but for a projectile energy of 29 MeV. It should be noted that for this energy, the calculations CDCC1 and CDCC2 gave the same results therefore lines are not distinguished one from the other.

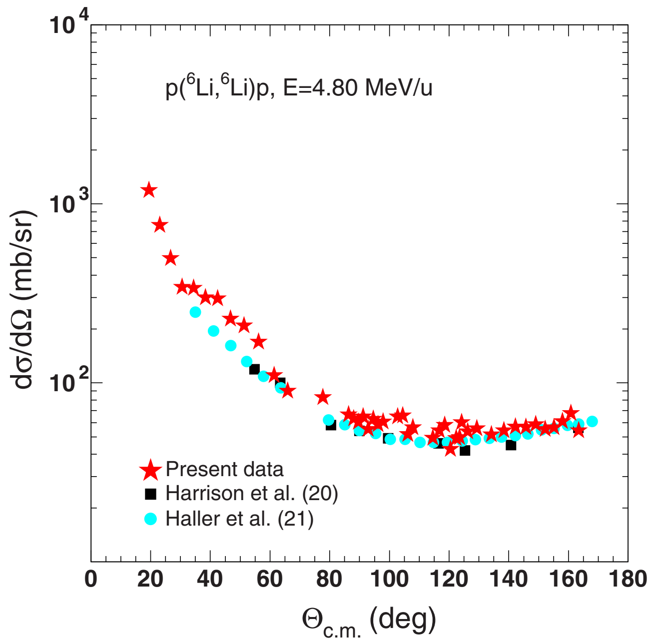

FIG. 6. (Color online) Comparison between present and previous data ([20,21]) at 4.8 MeV/u.

A cluster $\alpha + d$ model of ^{6}Li is adopted with all the parameters of the model including discretization and truncation described in detail in Ref. [39]. The 3^+ resonance was taken into account and was treated as a momentum bin with the width corresponding to 0.1 MeV. The central part of the entrance potentials for α-p and d-p has been derived as previously [27] from empirical p-α and p-d potentials by means of a single-folding method. The empirical potentials were obtained from $p + d$ and $p + \alpha$ elastic-scattering studies at $E = 2.52$–5 MeV/u measured previously [40–46]. These $p + d$ and $p + \alpha$ elastic-scattering data were fitted by simple Woods-Saxon form factors for both real volume and imaginary volume parts for the $p + \alpha$ system and a real volume and a surface imaginary term for the $p + d$ system. The so obtained input potentials were fed to a FRESCO calculation [47], and our results for ^{6}Li + p (CDCC1) are compared with the experimental data in Figs. 2– 5 (solid black line) exhibiting very good agreement with them. It should be noted here that for the higher-energy data at 155 MeV (25.8 MeV/u) the depth of the imaginary part of the input $d + p$ potential had to be multiplied by a normalization factor $N_i = 1.7$, simulating the strong contribution of transfer channels. Such a transfer effect was verified for ^{6}He + p in a subsequent paper [48]. No such case was observed here in this low-energy regime, and therefore no renormalization was adapted.

Further on, in order to verify the validity of the present data into the global CDCC framework applied by Guo *et al.* [28] and Matsumoto *et al.* [29] for ^{6}Li + p in the wide energy range from 5 to 72 MeV/u, we have adopted the input potentials from Ref. [27] adapted for the energy of 25.8 MeV/u scaling down the depths of the input potentials, according to the energy-dependent scaling procedure given in Ref. [28]. In this respect the normalization factors for the real part of the optical potentials were set close to 1, whereas for the imaginary part the normalization factors were set equal to 0.072, 0.062, 0.05, and 0.039 for the 29-, 25-, 20-, and 16-MeV data, respectively. The calculations with this new global approach (CDCC2) are compared with the data in the same figures (dotted red line), and fair agreement is seen for the lower energies and larger angles whereas good agreement is seen for the higher energies as before.

From both approaches one thing is evident. CDCC calculations are important and can adequately well describe at least in first order the data, although the chosen energy regime lies on a resonance region. Of course other mechanisms should also be taken into account in order to obtain a full description of the data. Data analysis of the breakup reaction and the reaction ^{6}Li + $p \rightarrow {}^3$He + ^{4}He is under progress, and it may shed more light in future papers.

Summary and Conclusions. Absolute differential cross sections for the elastic scattering of ^{6}Li + p were obtained at 16, 20, 25, and 29 MeV in inverse kinematics and are found to be in very good consistency with previous data in direct kinematics. Our technique, for measurements at a close to zero angle, obtained with the MAGNEX spectrometer, is well established, and it can be applied in future measurements with radioactive beams. JLM calculations fail to reproduce the data, whereas the validity of CDCC calculations is extended to a lower-energy regime (2.5–4.5 MeV/u) than before (5–72 MeV/u). It is proven that even in the present low-energy region CDCC calculations can be adapted for reproducing the data. However the degree of applicability of the CDCC will be tested in the future with the measurement of breakup and other direct and/or compound reaction measurements.

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