Elastic scattering for the system ^{6}Li + p at near barrier energies with MAGNEX

V. Soukeras[*], A. Pakou[*], F. Cappuzzello[†,**], L. Acosta[‡], C. Agodi[†], N. Alamanos[§], M. Bondi[†,**], D. Carbone[†], M. Cavallaro[†], A. Cunsolo[†], M. De Napoli[¶], A. Di Pietro[†], J. P. Fernández-García[†], P. Figuera[†], M. Fisichella[†], A. Foti[**,¶], N. Keeley[‖], G. Marquinez-Duran[‡], I. Martel[‡], M. Mazzocco[††], D. Nicolosi[†,**], D. Pierroutsakou[‡‡], K. Rusek[§§], O. Sgouros[*], E. Stiliaris[¶¶], E. Strano[††] and D. Torresi[††]

[*] *Department of Physics and HINP, The University of Ioannina, 45110 Ioannina, Greece*
[†] *INFN Laboratory Nazionali del Sud, via S. Sofia 62, 95125, Catania, Italy*
[**] *Dipartimento di Fisica e Astronomia, Universita di Catania, via S. Sofia 64, 95125, Catania, Italy*
[‡] *Departamento di Fisica Aplicada, Universidad de Huelva, E-21071, Huelva, Spain*
[§] *CEA-Saclay, DAPNIA-SPhN, 91191, Gif-sur-Yvette, France*
[¶] *INFN - Sezione di Catania, via S. Sofia 64, 95125, Catania, Italy*
[‖] *National Center for Nuclear Research, A. Soltana 7, 05-400, Otwock Warsaw, Poland*
[††] *Departimento di Fisica and INFN - Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*
[‡‡] *INFN - Sezione di Napoli, via Cinthia, I-80126, Napoli, Italy*
[§§] *Heavy Ion Laboratory, University of Warsaw, Pasteura 5a, 02-093, Warsaw, Poland*
[¶¶] *Institute of Accelerating Systems and Applications and Department of Physics, University of Athens, Greece*

Abstract. Elastic scattering measurements have been performed for the ^{6}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 (LNS) in Catania, in the angular range between $\sim 2^0$ and 12^0 in the laboratory system, giving us the possibility to span almost a full angular range in the center of mass system. Results will be presented and discussed for one of the energies.

Keywords: elastic scattering, coupling channel calculations, compound versus direct
PACS: 24.10.Ht, 25.40.Cm, 25.70.Bc, 27.20.+n

INTRODUCTION

In a long term plan, we have undertaken in this laboratory systematic work [1, 2, 3, 4, 5, 6, 7, 8, 9], concerning the optical potential or/and the structure of nuclei via A+p elastic scattering and reactions (A: weakly bound stable or radioactive light nucleus). All these studies but the [9], were performed at energies well above $E_{proj.}$=10MeV/A. In [9] we have performed measurements with the radioactive nucleus ^{17}F at E$\sim$ 4MeV/A putting on stake the validity of the microscopic JLM potential. This potential was derived by Jeukenne, Lejeune and Mahaux [10] and applied for stable nuclei by Mellema et al. [11], Hansen et al. [12] and Petler et al. [13] for medium and heavy mass stable nuclei and for energies above 10MeV/A, with slight adjustments only on the imaginary part. In this respect, herewith, the elastic scattering and reactions were studied for ^{6}Li+p in inverse kinematics at near barrier energies with possible relevant interest on astrophysical problems. While for the ^{17}F study measurements were performed off resonance, for ^{6}Li we have gone a step forward, performing the measurement on resonance, and exploring the case of compound versus direct couplings to continuum.

The reactions of nucleons and light nuclei with ^{6}Li are of great practical and theoretical importance, with serious consequences on astrophysical problems. The determination of low-energy cross sections, which belong to a deep sub-barrier region is a difficult task both from the theoretical and experimental point 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.

The ^{6}Li nucleus exhibits a pronounced cluster structure with a very small binding energy in the α-d channel and a low density of its excited states up to excitation energy of 16 MeV. Under these conditions, the choice of a

Exotic Nuclei and Nuclear/Particle Astrophysics (V). From Nuclei to Stars
AIP Conf. Proc. 1645, 406-409 (2015); doi: 10.1063/1.4909611

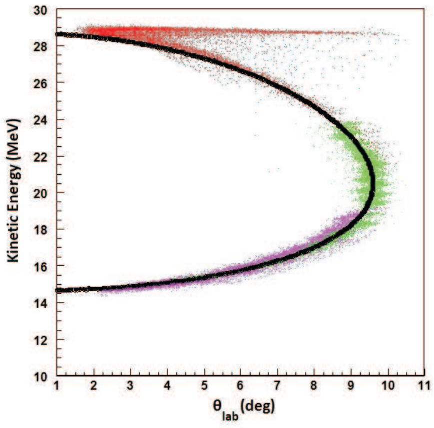

FIGURE 1. A reconstructed ^{6}Li+p spectrum. The two kinematical solutions of the reaction, were obtained in 3 different runs with 3 sets of magnetic fields. The plot shows the superposition of these runs, designated with different colors. The black solid line represents the theoretical prediction which seems to describe perfectly well the data, giving further support to the accurate spectrum reconstruction.

standard optical potential is inapplicable. Therefore, in principle, elastic scattering measurements and induced reaction measurements as well as total reaction cross sections at low energies for a detailed CRC approach could be very useful.

In the LIPMAGNEX experiment we have proposed the study of ^{6}Li+p, in a full angular distribution measurement to probe both the elastic scattering in a precise way and also the direct (breakup) and compound reactions. This give us the opportunity to explore coupling effects on the compound as well as to direct contributions in a more detailed way. We have planned our experiment in the MAGNEX facility [14, 17, 18], which is a powerful tool for detecting both heavy and light ejectiles with a very good angular and energy resolution. As it will be shown later in another article the MAGNEX spectrometer was inevitably a very appropriate solution for the breakup measurement.

In the present article we present a preliminary analysis of the first part of this study, referring to the elastic scattering at the highest energy of 29MeV. A detailed compilation of elastic scattering measurements for p+^{6}Li can be found in [24]. Measurements in a wide energy range (E$_p$=1.8 to 12MeV) and a rather wide angular range θ_{lab}=30^0 to 160^0 are found in [25] while polarisation and phase shift measurements in [26] for E$_p$=0.5 to 5.6MeV. The difficult experimental problem of these measurements to determine the thickness of a lithium target, results in relative measurements and absolute only via normalisation to previous ones introducing large errors. Furtheron, due to single stage silicon detectors used, elastic events are not separated from reaction events, the last ones creating a continuum background which has to be subtracted from the total rate. Finally all these measurements are mainly focused on the ^{7}Be structure and not on the potential but the Haller et al. [25], where an optical potential is used to fit the data allowing the various parameters to strongly depend on energy. The polarisation 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 CC context are found in [27, 28, 29], but they deal with data at rather high energies above E$_p$=25 MeV. Interest present two recent articles [21, 22] with CDCC calculations (Continum Discretized Coupled Channel) and calculations with a microscopic M3Y potential respectively from rather low to higher energies (∼5 to 25MeV/A). The first calculations show unexpectedly that couplings to continumm without considering any compound contribution can describe adequately well previous experimental results.

Within our experimental approach we focus on a precise, clear from the above described uncertainties, elastic scattering measurement, predesessor to measurements on MAGNEX with radioactive projectiles in inverse kinematics. This measurement will be the first step for obtaining the optical potential and subsequently for describing the various reaction processes.

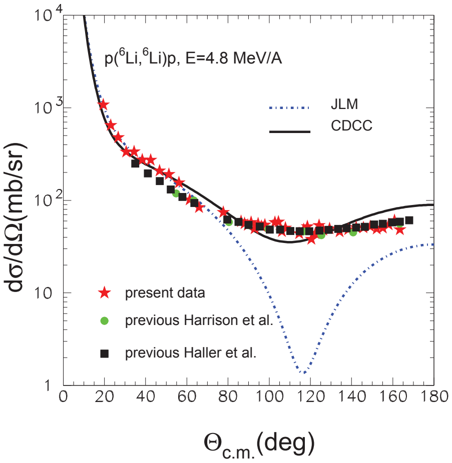

FIGURE 2. Present elastic scattering data for ^{6}Li+p at 29MeV are compared with previous values as well as with JLM and CDCC calculations.

THE EXPERIMENT: RESULTS AND DISCUSSION

The experiment was performed at (LNS - INFN) Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud in Catania, Italy. Beams of $^6Li^{3+}$ were accelerated at the energies 16, 20, 25 and 29MeV 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 [14, 17, 18], set at θ_{opt}=4^0, working in the total horizontal angular acceptance and detected by its focal plane detector [16]. The vertical acceptance of MAGNEX was reduced for protecting the focal plane detectors from the elastic high counting rate. Our data reduction technique, based on a differential algebraic method [19] and the performances of the whole system are described in Refs [15, 20]. The two kinematical solutions of the ejectiles were measured by the application of three different magnetic fields. A typical reconstructed spectrum at projectile energy of 29 MeV, is displayed in Figure 1. In this Figure, the reconstructed kinematical spectrum was obtained with the superposition of the 3 different sets, which are designated with different colors. Overlapping regions between sets I, II and 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 re-confirmed via the measurement at the very forward angles, where the elastic scattering is Rutherford. For an angular step of $\sim$0.5^0, the counts were integrated and the solid angle, defined by 4 slits located at 250mm from the target, was calculated taking into account the contour of the reconstructed (θ_i, ϕ_i) locus [30]. The solid angle uncertainty is estimated to be $\sim$2%. The differential cross sections, obtained at the projectile energy of 29 MeV are compared in Figure 2 with previous measurements as well as with JLM and CDCC calculations. For the CDCC calculation we follow the same technique as in [31], where we present calculations for the same system but at a much higher energy, 155MeV/A. A cluster $\alpha + d$ model of ^{6}Li was adopted, with all the parameters of the model including discretization and truncation described in detail in [32]. The central potential in the ^{6}Li + p entrance channel as well as all the coupling potentials used in the calculations were derived from empirical p - α and d - p potentials by means of a single - folding method. For that the data sets of Hinterberger *et al.* [33] for $d + p$ elastic scattering at E_d = 52 MeV and by Plummer *et al.* [34] for $p + \alpha$ elastic scattering at E_p = 26.1 MeV were used. It should be noted however that the depth of the imaginary part of the input $d + p$ potential was multiplied for the 155MeV data by a normalization factor N_i=1.7, simulating the strong contribution of the transfer channel. In the present case however for this low projectile energy this normalization was set equal to N_i=0.1 according to the systematic study of nucleon scattering from ^{6}Li with the CDCC method by Matsumoto, Guo [21, 23]. In these studies the authors have revealed the strong dependence of the input optical potentials on the energy of the neutron/proton beam.

It is obvious that for this weakly bound projectile, the description of the experimental data can not be done simply adopting the microscopic JLM potential as in the ^{17}F case [9]. Couplings in the continuum are strong and reproduce in principle the trend of the data, but still they leave space to compound contributions. Calculations taking into account the compound couplings, are under progress and will be presented in our next publication. Also the analysis of the breakup channel data is under progress and it could reveal the validity of the CDCC calculations.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007- 2013 under Grant Agreement No. 262010-ENSAR.

REFERENCES

1. N. Alamanos et al., *Nucl. Phys. A* **660**, 406 (1999).
2. A. Pakou et al., *Nucl. Phys. A* **691**, 661 (2001).
3. N. Alamanos et al., *J. Phys. G* **24**, 541 (1998).
4. A. de Vismes et al., *Phys. Lett. B* **505**, 15 (2001).
5. A. Lagoyiannis et al., *Phys. Lett. B* **518**, 27 (2001).
6. V. Lapoux et al., *Nucl. Phys. A* **722**, 49c (2003).
7. F. Skaza et al., *Phys. Lett. B* **619**, 82 (2005).
8. A. Gillibert et al., *Nucl. Phys. A* **787**, 423c (2007).
9. N. Patronis et al., *Phys. Rev. C* **85**, 024609 (2012).
10. J. P. Jeukenne, A. Lejeune, C. Mahaux, *Phys. Rev. C* **16**, 80 (1977).
11. S. Mellema, R. W. Finley, F. S. Dietrich, F. Petrovich, *Phys. Rev. C* **28**, 2267 (1983).
12. L. F. Hansen et al., *Phys. Rev. C* **31**, 111 (1985).
13. J. S. Petler, M. S. Islam, R. W. Finley, F. S. Dietrich, *Phys. Rev. C* **32**, 673 (1985).
14. A. Cunsolo et al., *Eur. Phys. J. Special Topics* **150**, 343 (2007).
15. F. Cappuzzello et al., *NIM A* **621**, 419 (2010).
16. M. Cavallaro et al., *Eur. Phys. J. A* **48**, 59 (2012).
17. A. Cunsolo et al., *NIM A* **484**, 56 (2002).
18. A. Cunsolo et al., *NIM A* **481**, 48 (2002).
19. F. Cappuzzello et al., *NIM A* **638**, 74 (2011).
20. M. Cavallaro et al., *NIM A* **648**, 46 (2011).
21. H. Guo et al., *Phys. Rev. C* **87**, 024610 (2013).
22. M.Y.H. Farag et al., *Phys. Rev. C* **88**, 064602 (2013).
23. T. Matsumoto et al., *Phys. Rev. C* **83**, 064611 (2011).
24. M. Skill et al., *Nucl. Phys. A* **581**, 93 (1995).
25. W. D. Harisson and A. B. Writehead, *Phys. Rev* **132**, 2607 (1963); M. Haller et al., *Nucl. Phys. A* **496**, 189 (1989).
26. C. Petitjean, L. Brown, R. G. Seyler, *Nucl. Phys. A* **129**, 209 (1969); M. Haller et al., *Nucl. Phys. A* **496**, 205 (1989).
27. K. H. Bray et al., *Nucl. Phys. A* **189**, 35 (1992).
28. B. A. Mughrabi, Z. El Itaoui, P. J. Ellis, Y.C. Tang; *Phys. Rev. C* **29**, 29 (1984).
29. F. Petrovich et al., *Nucl. Phys. A* **563**, 387 (1993).
30. M. Cavallaro et al., *NIM A* **637**, 77 (2011).
31. K. Rusek, K.W. Kemper, R. Woslki, *Phys. Rev. C* **64**, 044602 (2001).
32. K. Rusek, P.V. Green, P.L. Kerr, K.W. Kemper, *Phys. Rev. C* **56**, 1895 (1997).
33. F. Hinterberger, G. Mairle, U. Schmidt-Rohr, G.J. Wagner, *Nucl. Phys. A* **111**, 265 (1968).
34. D.J. Plummer, K. Ramavataram, T.A. Hodges, D.G. Montague, A. Zucker, N.K. Ganguly, *Nucl. Phys. A* **174**, 193 (1971).