STUDY OF THE $^6\mathrm{Li} + p$ AND $^7\mathrm{Li} + p$ SYSTEMS IN THE CONTINUUM DISCRETIZED COUPLED CHANNELS APPROACH*

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A complete study of the $^{6,7}\mathrm{Li} + p$ reactions was performed by measuring the complete net of reaction channels at the energy range of ~ 2 to 5 MeV/nucleon. The experiments were performed at the MAGNEX facility of the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS) in Catania. The breakup channel was identified by means of a new algorithm, MULTIP, which gives the possibility of following up the decay of the nucleus into two or more constituent particles from the rest frame of the nucleus itself to the laboratory frame. Angular distributions were obtained for all reaction products and were considered within the Continuum Discretized Coupled Channels (CDCC) framework. The results of the CDCC calculations were found in a very good agreement with the experimental data presenting a strong evidence for the important influence of coupling to breakup on the elastic channel.

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1. Introduction

Elastic scattering measurements are a well-established tool for probing coupling channel effects at energies around the Coulomb barrier. However,

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elastic scattering remains a complex many-body problem for the projectile-target interaction, while the level of complexity may be reduced in the case of the nucleon–nucleus scattering. In this way, the study of coupling channel phenomena is still feasible, and furthermore, the nucleon scattering allows investigating the nuclear structure of a nucleus. A particularly interesting case is when weakly bound nuclei are involved, since they are characterized by relatively small binding energies and thus they breakup easily in the field of the target nucleus. Therefore, nucleon–nucleus elastic scattering measurements coupled with the breakup ones present a unique tool for probing the cluster structure of the nucleus, if analyzed using an appropriate theoretical approach. The most successful theoretical model which has been developed so far for the description of the breakup couplings on the elastic channel is CDCC [1–4]. In the CDCC formalism, both coupling to resonant and non-resonant breakup are taken into account, and thus the coupling influence for each of the breakup modes can be quantitatively determined. From the experimental point of view, it is not always easy to obtain a clear signature of the breakup mechanism by studying only the energy spectra, since due to their continuous shape they may contain events originating from various sources of background like the target contamination or even with events triggered by a different reaction mechanism. In this context, coincidence measurements together with Monte Carlo simulations present a valuable tool as they may provide a basis for disentangling the different reaction channels.

Considering all the above, elastic scattering and exclusive breakup measurements were performed with the stable, but weakly bound, ^{6,7}Li nuclei on a proton target at the energy range of ~ 2 to 5 MeV/nucleon. The goal of this study is twofold. First, we aim to verify how realistic the discretization of the continuum phase space is, by comparing the experimental and simulated energy spectra. In this respect, the CDCC reaction model is coupled to a recently developed simulation algorithm, named MULTIP [5]. Second, we aim at a global study of all the involved reaction channels using this approach.

2. Experimental details

The experiments were performed at the MAGNEX facility [6, 7] of the INFN-LNS in Catania. The $^{6}Li^{3+}$ and $^{7}Li^{3+}$ ion beams were delivered by the TANDEM accelerator onto a CH_2 target. A ^{12}C target of an appropriate thickness was also used in order to estimate the background in the data due to the presence of carbon in the CH_2 target. The MAGNEX spectrometer is a large acceptance device covering a solid angle of 50 msr. Moreover, its Focal Plane Detector (FPD) guarantees an excellent mass, energy and angular resolution [8, 9]. Therefore, taking into account that the reaction under

study is in inverse kinematics, MAGNEX is the most suitable tool for the detection and identification of the reaction products. For the elastic scattering measurement [10, 11] the ^{6}Li (^{7}Li) ejectiles were momentum analyzed by the MAGNEX spectrometer and they were detected by the FPD, while for the breakup measurement [12–14], the heavy fragment (*i.e.* an α particle) was detected by the MAGNEX FPD ($0^\circ \leq \theta_{\rm lab} \leq 10^\circ$) in coincidence with the light ^{2}H(^{3}H) particle which was detected by a Surface Barrier Silicon (SBS) detector 2000 μm thick. The angular range covered by the SBS detector was $4^\circ \leq \theta_{\rm lab} \leq 6^\circ$. It should be noted that during the breakup measurements, a Ta foil was placed in front of the SBS detector in order to prevent the detector deterioration from the elastic scattering high counting rate. Finally, our experimental setup included also a ΔE–E telescope from the GLORIA array [15], in order to measure other available reaction channels.

3. Data reduction: The algorithm MULTIP

In the breakup measurement, the α particles were detected in MAGNEX in coincidence with deuterons (tritons) in the SBS detector. The resulting α–$d(t)$ correlation plots were analyzed by means of a Monte Carlo simulation algorithm, MULTIP [5], which was employed in order to identify the fingerprint of the breakup mechanism in the experimental spectra. As an example, the philosophy of the simulation of the ^{6}Li breakup by a proton target is illustrated below and can be divided into three stages. A similar procedure was followed for the breakup of ^{7}Li.

The first step in the simulation of the ^{6}Li breakup is the determination of the momentum modulus of the parent nucleus in the laboratory reference frame, before it breaks into its cluster constituents. For this, the continuum excitation is treated as a 2-body-like reaction $^6\text{Li}+p \rightarrow {}^6\text{Li}^*+p$. The kinetic energies of the simulated ^{6}Li* nuclei are determined via the adopted energy bins of the continuum. In our Monte Carlo simulation the choice of these bins (energy levels) is based on the continuum level scheme as specified in the CDCC calculations. Details of these calculations are given in the following section.

In the second step of the sequence, the breakup of the excited ^{6}Li nucleus is considered in its rest frame, where the excitation energy of the ^{6}Li* above the breakup threshold is shared among the breakup fragments, the α particle and the deuteron. In our simulation, it was assumed that the generated α particle acquires randomly a fraction of the ^{6}Li* nucleus excitation energy, while its angular distribution was assumed to be isotropic. On the other hand, the energy and the momentum of the deuteron were determined by applying the energy and momentum conservation laws in the rest frame of the ^{6}Li* nucleus.

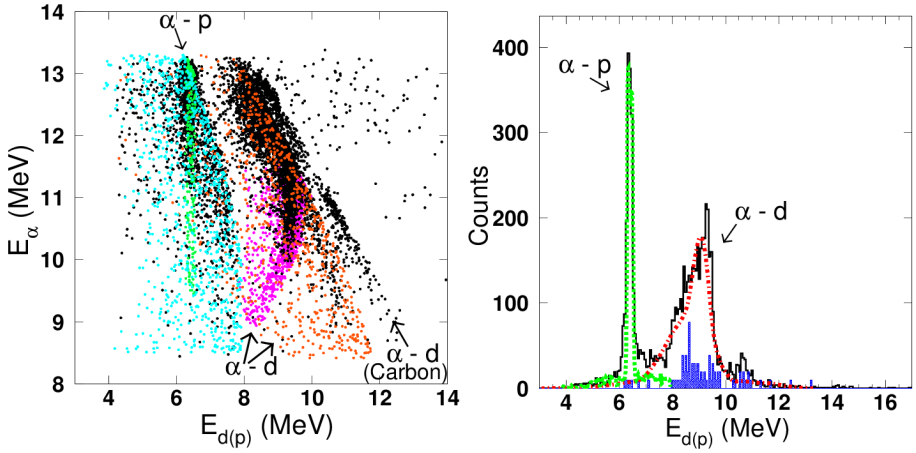

Fig. 1. (Color online) Left panel: E_α–$E_{d(p)}$ correlation plot at the energy of 25 MeV for the α particles detected in MAGNEX in coincidence with deuterons (protons) detected in the SBS detector. Superimposed on the experimental spectrum, which is denoted in black, are the α–d simulated events for the resonant and non-resonant breakup, denoted in magenta and orange, respectively, as well as the α–p simulated events for the resonant and non-resonant breakup, denoted in green and cyan, respectively. Right panel: Projection of the bi-dimensional correlation plot on the horizontal axis $E_{d(p)}$. The experimental spectrum, which is denoted in black, is compared with the α–d and α–p simulated spectra (resonant+non-resonant contribution), which are denoted with the red dot-dashed and green dashed lines, respectively. An exclusive breakup spectrum, obtained with a pure carbon target, is also appropriately normalized and presented with the filled blue histogram. Data are also reported in Ref. [12].

In the third step of the algorithm, the momenta of the breakup fragments are transformed from the rest frame of the ^{6}Li* nucleus to the laboratory one, after applying a Galilean transformation together with the appropriate axis rotation, following the prescription of Ref. [16]. Finally, the energy loss of the protons and deuterons inside the Ta foil (see Sec. 2) was taken into account. The resulted simulated energy spectra are compared with the experimental ones in Fig. 1 at the energy of 25 MeV. Here, for the first time, the simulations for the α–p coincidences are also presented. One can see that the simulation describes in an excellent way the experimental data. The simulated locus associated with the resonant breakup follows closely the trend of the experimental data, while in the mono-dimensional spectrum, the agreement between experimental and simulated data is even more evident. An excellent agreement between simulation and data was also obtained for the $^7\mathrm{Li}+p$ system [13, 14]. Hence, adopting in our Monte Carlo simulations

the same continuum level scheme as the one specified in the CDCC calculation, we were able to reproduce in a very good way the experimental energy spectra. Therefore, we may conclude that discretization of the continuum phase space in the CDCC approach presents a realistic model of the continuum excitation. MULTIP was also used in order to determine the detection efficiency of the exclusive measurement.

4. The CDCC calculations

The CDCC model was invoked for the interpretation of the elastic scattering data, by taking into account couplings to the continuum states of the weakly bound nucleus, in our case, the ^{6,7}Li nuclei. For the easiness of the reader, below are presented details of the CDCC calculations for the $^6\mathrm{Li} + p$ system which were performed adopting the same technique as the one reported in Ref. [3]. The CDCC calculations were performed using the code FRESCO [17], where the cluster structure of the projectile was explicitly introduced in the calculation. Considering the excited ^{6}Li nucleus as a composite system of a valence deuteron particle and an α-particle core, the α–p and d–p potentials were introduced. These potentials were determined by fitting previously measured p–d [18–22] and p–α [23, 24] elastic scattering data. Furthermore, these potentials were used in the calculation in order to "construct" the $^6\mathrm{Li} + p$ diagonal potential as well as the coupling potentials by means of the single folding method [3]. A proton spin-orbit potential of Thomas form was also added to the diagonal $^6\mathrm{Li} + p$ potential. More details are given in Refs. [12, 14].

The most common methods for the discretization of the continuum phase space are the continuum bins and the pseudo-states methods. The pseudo-states method is favorable in the case of a four-body breakup process [4, 25]. In our case, we adopted the continuum bins method, in which the available momentum phase space above the α–d separation threshold was discretized into a finite number of momentum bins of a certain width, following the prescription of Ref. [26]. The width of each continuum state was modified accordingly in the case of a resonant continuum state. In our case, the only excited resonance was the 3^+_1 one of ^{6}Li, which lies ~ 0.7 MeV above the α–d separation threshold and it was treated as a momentum bin with a width corresponding to 0.1 MeV. Moreover, the continuum phase space was truncated in terms of the relative α–d angular momentum $\boldsymbol{L}$. Consequently, by providing the details mentioned above as an input for the FRESCO code, the theoretical angular distributions for the elastic scattering as well as for the breakup were deduced. A similar procedure was followed for the ^{7}Li case [13, 14].

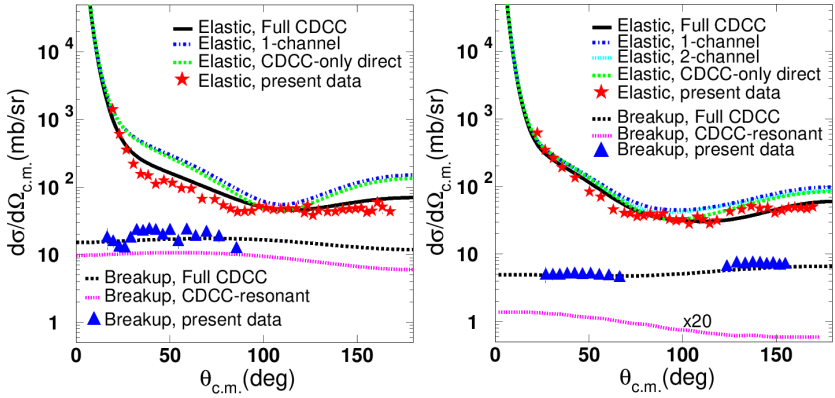

Fig. 2. Left panel: A comparison between experimental and theoretical angular distribution data of elastic scattering and breakup for the $^6\mathrm{Li} + p$ reaction at the energy of 25 MeV. Right panel: The same as the figure on the left, but for the $^7\mathrm{Li} + p$ reaction at the energy of 38.1 MeV. Experimental data and calculations were taken from Refs. [11–14].

5. Results and discussion

The experimental elastic scattering and breakup data were analyzed in the CDCC framework. An extensive analysis for the $^6\mathrm{Li} + p$ system can be found in [12], while the corresponding results for the $^7\mathrm{Li} + p$ system are reported in Refs. [11, 13, 14]. As a representative case, the elastic scattering and breakup angular distribution data for the $^6\mathrm{Li} + p$ reaction at the energy of 25 MeV are presented in the left panel of Fig. 2, while the corresponding data for the $^7\mathrm{Li} + p$ reaction at 38.1 MeV are presented in the right panel of the same figure. Starting with the case of ^{6}Li, it is observed that in order to reproduce the shape and the magnitude of the elastic scattering data, the inclusion of the coupling to the $3_1{}^+$ resonance (Full CDCC) is important, as coupling only to the non-resonant continuum (direct breakup) has a smaller impact on the reproduction of the experimental data. The same conclusion can be also drawn by looking at the elastic scattering data for the $^7\mathrm{Li} + p$ system, where although due to the available energy of the system, the $7/2^-$ resonance is barely excited, the influence of its coupling on the elastic scattering data is dominant. Looking at the breakup data, the agreement between experimental and theoretical angular distributions is satisfactory for both systems. However, in the case of ^{6}Li, almost 50% of the breakup cross section is exhausted by the resonant breakup, while for ^{7}Li, the resonant breakup is very small. The latter observation, in conjunction with the results for the coupling strength of the resonant breakup on the elastic channel, suggests that the coupling to the continuum is not always correlated with the magnitude of the breakup cross section.

Finally, the CDCC calculation besides the elastic scattering and breakup angular distributions may also provide the absorption cross section, to account for the loss of flux from elastic to other reaction channels, different than breakup. The theoretical predictions for the absorption cross section were compared with the experimental values and were found to be in excellent agreement. In particular, for the $^6\mathrm{Li} + p$ system, the only available channel with a significant probability in our energy regime was the $^6\mathrm{Li} + p \rightarrow {}^3\mathrm{He} + {}^4\mathrm{He}$ reaction. The results of this analysis are reported in Ref. [27]. For the case of the $^7\mathrm{Li}+p$ system, the absorption cross section predicted by the CDCC calculation was found in very good agreement with the sum of the experimental cross sections for all the available reaction channels, namely single charge exchange and (p, α) reactions [14]. Thus, we concluded that for both the $^{6,7}\mathrm{Li} + p$ systems, the very good agreement between experimental data and theoretical predictions suggests the inter-consistency of all the measured reaction channels and their valid interpretation within the CDCC model.

In summary, a complete study of the $^{6,7}\mathrm{Li} + p$ reactions was performed by studying elastic scattering, breakup and other available reaction channels with significant probabilities under the same experimental conditions. The elastic scattering data were analyzed together with the breakup ones in the CDCC framework and it was found that the coupling strength of the continuum excitation does not depend on the magnitude of the breakup cross section. Furthermore, the absorption cross sections predicted by the CDCC model were compared with the sum of the experimental cross sections for the remaining reaction channels and were found to be in very good agreement for both systems. This fact gives further support to the analysis of all measured reaction channels and indicates a successful global interpretation of all the data sets within the CDCC approach. Finally, the breakup channel for both systems was identified by means of the Monte Carlo simulation algorithm named MULTIP, in which the continuum excitation of $^{6,7}\mathrm{Li}$ nuclei was simulated assuming the same continuum level scheme as the one specified in the CDCC model. The excellent agreement between the experimental and simulated energy spectra represents a strong evidence for the realism of the discretization of the continuum phase inside the CDCC approach.

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