Comparison of the Effects of Couplings to Breakup Channels in Reactions Induced by ^{6}Li and ^{6}He on the Same ^{64}Zn Target.

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Abstract. The experimental elastic scattering angular distributions for the weakly bound nuclei ^{6,7}Li and for the halo nucleus ^{6}He on the same ^{64}Zn target at several energies around the Coulomb barrier were measured at the Laboratori Nazionali del Sud (LNS, Italy) and at the Cyclotron Research Center, Louvain La Neuve (Belgium), respectively. The measured elastic scattering angular distributions of these three systems at the same center of mass energy have been compared. The experimental data of the ^{6,7}Li+ ^{64}Zn systems have been analyzed within the CDCC method, while the ^{6}He+^{64}Zn data have been compared with both both CDCC and CRC calculations.

INTRODUCTION

The study of collisions induced by halo and weakly bound nuclei had a considerable interest in the last decade. In fact, due to the coupling to breakup channels, strong effects on the elastic scattering and fusion have been predicted and observed [1, 2, 3, 4]. In the case of the two stable lithium isotopes, ^{6,7}Li, elastic scattering angular distributions on different targets have been extensively measured and analyzed within the Continuum-Discretized Coupled-Channel (CDCC) method, showing that the couplings to the breakup process have a significant effect on the elastic scattering [5].

One of the most studied exotic nuclei has been ^{6}He [6, 7, 8, 9, 10, 11, 12], since intense beams of such isotope are available at different Radioactive Ions Beams (RIB) facilities. This nucleus has a tightly bound core (α particle) and two loosely bound neutrons (S_{2n}=0.97 MeV). These two neutrons have a large probability of being far away from the core, producing the so-called nuclear halo. The ^{6}He nucleus constitutes an archetype of Borromean nucleus, since the α-neutron and neutron-neutron systems are unbound. In Refs. [8, 9, 10, 11, 12, 13, 14], a long range effect on the optical potential was observed, which can be explained in terms of strong couplings to the breakup channels.

Recently, a systematic study of ^{6,7}Li + ^{64}Zn reactions at energies around the Coulomb barrier was carried out at LNS. The elastic scattering angular distributions were measured for both systems at different energies [15, 16]. We present results concerning the elastic scattering for the ^{6,7}Li+^{64}Zn reactions at the same center of mass energies. In addition, new preliminary experimental data for the collision ^{6}He+^{64}Zn are presented and compared with three-body CDCC calculations, which assume a simple di-neutron model of the projectile ^{6}He.

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EXPERIMENTAL SETUPS

The ^{6,7}Li beams were produced by the SMP Tandem Van de Graaff accelerator and transported to the CT2000 scattering chamber at center of mass energies of 11.7, 12.4, 13.5, 15.0, 16.3 and 18.1 MeV. The experimental setup was composed by five silicon telescopes situated on a rotating plate, in order to cover a wide angular range. The telescope systems consisted in a 10 μm detector plus a 200 μm detector. A ^{64}Zn target of 400 μg/cm^2 was used for the ^{6}Li+^{64}Zn reactions [15], while a 70 μg/cm^2 target for the ^{7}Li+^{64}Zn collisions.

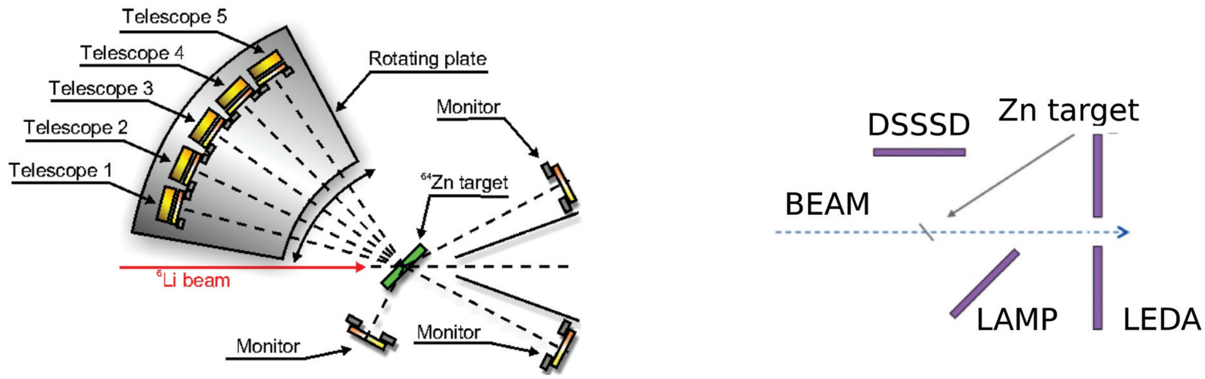

FIGURE 1. Sketches of the experimental setups of the ^{6,7}Li+^{64}Zn (on left) and ^{6}He+^{64}Zn (on right) measurements.

On the other hand, the experiment corresponding to the collisions ^{6}He on ^{64}Zn was performed at the Cyclotron Research Center of Louvain La Neuve, Belgium. The reactions ^{6,4}He+^{64}Zn at center of mass energies of 13.5 and 16.5 MeV were measured to complement old measurements performed by our group on the same systems at different energies [3, 6]. The experimental setup was composed by an array of 4 LEDA detectors [17] covering the forward angles 5° < θ_{lab} <12°. Another array of 3 LEDA detectors (so-called LAMP detector), placed at 45° with respect to the beam axis, covered the angular range 22° < θ_{lab} <65°. Finally, two double sided silicon strips detectors (DSSSD) were used to cover the backward angles, between 67° and 120° (see Fig. 1). For additional details see Refs. [3, 13].

In Fig. 2, the preliminary elastic scattering angular distributions of the ^{6,7}Li and ^{6}He on ^{64}Zn systems at the same center of mass energy ($E_{c.m.}$=13.5 MeV) are presented.

THEORETICAL CALCULATIONS

In the last years, the CDCC method has been successfully applied to describe collisions induced by halo and weakly bound nuclei, such as ^{6,7,11}Li, ^{11}Be and ^{6}He [1, 2, 6, 9, 18, 19, 20]. This formalism uses the coupled channel method to solve the scattering problem. It is known that for weakly bound and halo nuclei it is important to take into account the continuum states of the projectile. These states are included and discretized by means of the so-called *binning* method [21]. The calculations were performed using the code FRESCO [22], in which both nuclear and Coulomb effects were considered.

The CDCC method is based on a elastic direct breakup mechanism, where the breakup process is considered as a inelastic excitation of the projectile to its continuum states. We would like to emphasize that this calculation do not consider the non-elastic breakup, i.e, breakup processes accompanied of target excitation or neutron absorption.

In this framework, we have analyzed the reactions induced by ^{6,7}Li and ^{6}He on the same ^{64}Zn target.

^{6,7}Li+^{64}Zn reactions

The ^{6}Li nucleus was described as an α+d structure, with a break-up threshold at 1.47 MeV above the ground state. The resonances 3^+, 2^+, 1^+, corresponding to the coupling between the angular momentum ℓ=2 and the spin of the deuteron s=1, and the non-resonant states were included in the calculations. On the other hand, the ^{7}Li isotope was described as an α+t system, with a break-up threshold at 2.47 MeV. The excited state $1/2^-$, the resonances $7/2^-$, $5/2^-$ (ℓ=3 coupled to the tritium spin s=1/2) and the non-resonant states were considered.

In Fig. 2, the solid blue lines represent the CDCC calculations, while the dotted red lines correspond to the calculations without couplings to the continuum states of the projectile. A good agreement between the predictions of the CDCC calculations and the experimental data was observed. In the case of the ^{6}Li induced collisions, it was necessary to include the couplings to the breakup channels to reproduce the experimental data, while for the ^{7}Li reactions these couplings were less important. Similar results were observed at the other bombarding energies. This behavior could be linked to the fact that the breakup threshold of ^{6}Li (S_α=1.47 MeV) is smaller than that of ^{7}Li (S_α =2.47 MeV).

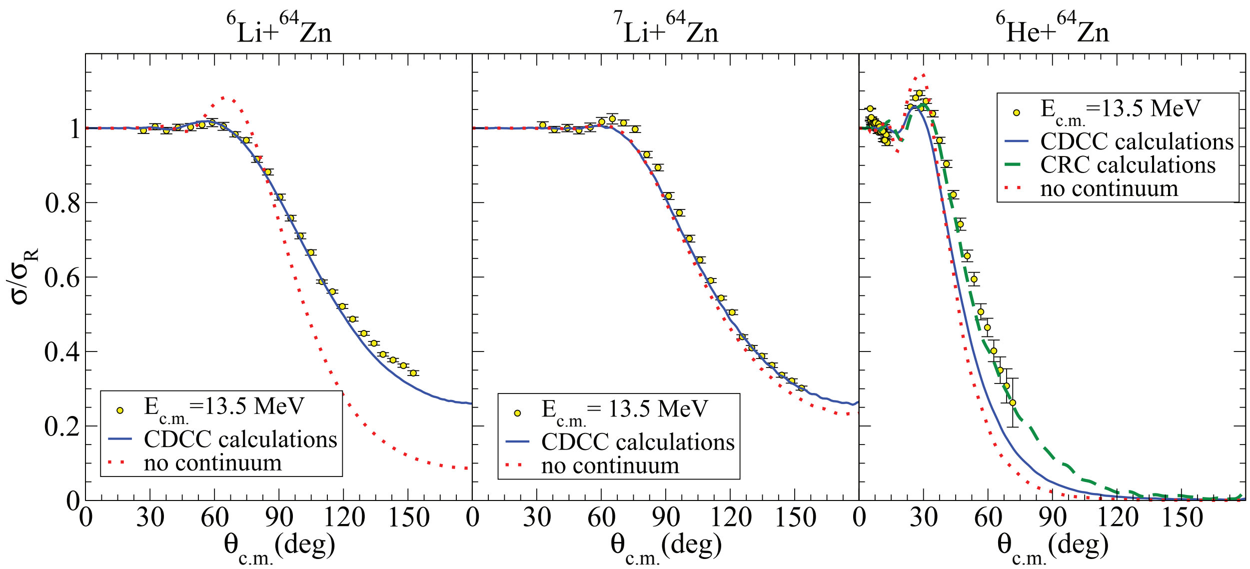

FIGURE 2. Preliminary elastic scattering angular distributions for the ^{6,7}Li and ^{6}He + ^{64}Zn collisions at the same center of mass energy ($E_{c.m.}$=13.5 MeV). The CDCC calculations are represented by solid blue lines, while the same calculation without the continuum couplings are shown by dotted red lines. In the case of the ^{6}He + ^{64}Zn reaction. The CRC calculation considering one-neutron transfer mechanism is represented by the dashed green line.

^{6}He+^{64}Zn reaction

The ^{6}He+^{64}Zn reaction has been analyzed within the three-body (α+2n+^{64}Zn) CDCC method. The improved di-neutron model for ^{6}He (α+2n) of Ref. [23] was used. This model, which assumes a two-neutron cluster with spin zero bound to the α core with an effective separation energy of 1.6 MeV, was applied to describe several reactions involving ^{6}He nucleus [23].

In Fig. 2, the CDCC calculation of the elastic scattering angular distribution for the ^{6}He+^{64}Zn system is represented by the solid blue line. To study the effects of the coupling to the continuum states of the projectile, we have included the calculations without such couplings, represented by the dotted red line. Comparing both calculations we see that the inclusion of the breakup channels has a strong effect on the elastic cross section and a reduction of the Coulomb-nuclear interference peak is observed.

The CDCC calculation underestimates the experimental data of the ^{6}He+^{64}Zn reaction. Therefore, additionally to this calculation, a Coupled Reaction Channel (CRC) calculation considering the one-neutron transfer to bound and unbound states of the target has been performed, since this calculation described the elastic cross section of the ^{6}He+^{64}Zn reaction at $E_{c.m.}$=12.4 MeV [24]. In Ref. [24], the one-neutron transfer mechanism was found to be a more suitable representation than that considering two-neutron transfer to bound and unbound states of the target. In addition, the CRC calculations, performed in [24], were an useful method to describe the experimental fusion excitation function reported in Ref. [6].

To include the final states of ^{65}Zn* the same procedure of Ref. [24] has been considered, where the final states include the single-particle states of Ref. [25] and some *door-way states*.

The calculated elastic scattering angular distribution is represented by the green dashed line in Fig. 2. Unlike to the CDCC result, a good agreement between the prediction of the CRC calculation and the experimental data is observed.

The obtained results suggest that the elastic direct breakup process (CDCC calculation), where the core and the target are considered as inert particles, is not a good approach to describe the elastic scattering of the ^{6}He+^{64}Zn reaction at $E_{c.m.}$=13.5 MeV. On the other hand, the CRC calculation, based on a breakup process in which one neutron is transferred to bound and unbound states of the target, reproduces the experimental data. This result is different from that obtained in Ref. [24], where both CDCC and CRC calculations were in reasonable agreement with the experimental data at $E_{c.m.}$=12.4 MeV, which could indicate a possible energy dependency of the different breakup mechanisms in the collisions induced by ^{6}He on ^{64}Zn.

CONCLUSIONS

Experimental results for elastic scattering of the weakly bound nuclei ^{6,7}Li and the halo nucleus ^{6}He on ^{64}Zn at the same center of mass energy have been presented.

The ^{6,7}Li+^{64}Zn collisions have been reproduced within the CDCC framework. The calculated elastic scattering angular distributions are in good agreement with the experimental data. The couplings to the breakup channels have a significant effect in the case of the ^{6}Li scattering, whereas minor effects have been found for the ^{7}Li case. This behavior could be due to the smaller breakup threshold of the ^{6}Li (S_{α}=1.47 MeV) nucleus compared with ^{7}Li (S_{α}=2.47 MeV).

In the ^{6}He+^{64}Zn reaction, we have observed a strong effect of the coupling to breakup channels. Two different calculations, CDCC and CRC calculations, including couplings to the breakup channels have been performed within different breakup mechanism. The CDCC calculation fails to reproduce the experimental elastic scattering angular distribution. However, we have observed that the CRC method provides a more suitable approach to describe the elastic scattering angular distribution, where the ^{6}He breakup is treated within one-neutron transfer to the continuum picture.

REFERENCES

[1] A. Di Pietro *et al.*, Phys. Rev. Lett. **105**, p. 022701 (2010).
[2] M. Cubero *et al.*, Phys. Rev. Lett. **109**, p. 262701 (2012).
[3] V. Scuderi *et al.*, Phys. Rev. C **84**, p. 064604 (2011).
[4] L. F. Canto *et al.*, Nucl. Phys. A **821**, p. 51 (2009).
[5] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein, Phys. Rep. **424**, p. 1 (2006).
[6] A. Di Pietro *et al.*, Phys. Rev. C **69**, p. 044613 (2004).
[7] E. A. Benjamim *et al.*, Phys. Lett. B **647**, 30–35 (2007).
[8] A. M. Sánchez-Benítez *et al.*, Nucl. Phys. A **803**, p. 30 (2008).
[9] L. Acosta *et al.*, Phys. Rev. C **84** (2011).
[10] P. N. de Faria *et al.*, Phys. Rev. C **82**, p. 034602 (2010).
[11] E. F. Aguilera *et al.*, Phys. Rev. C **63**, p. 061603 (2001).
[12] O. R. Kakuee *et al.*, Nucl. Phys. A **728**, p. 339 (2003).
[13] A. D. Pietro *et al.*, Europhys. Lett. **64**, p. 309 (2003).
[14] J. P. Fernández-García, M. Rodríguez-Gallardo, M. A. G. Alvarez, and A. M. Moro, Nucl. Phys. A **840**, 19–38 (2010).
[15] M. Zadro *et al.*, Phys. Rev. C **80**, p. 064610 (2009).
[16] M. Zadro *et al.*, Phys. Rev. C **87**, p. 054606 (2013).
[17] T. Davinson *et al.*, Nucl. Inst. and Methods A **454**, 350–358 (2000).
[18] J. P. Fernández-García *et al.*, Phys. Rev. Lett. **110**, p. 142701 (2013).
[19] Y. Sakuragi, Phys. Rev. C **35**, p. 2161 (1987).
[20] C. Beck, N. Keeley, and A. Diaz-Torres, Phys. Rev. C **75**, p. 054605 (2007).
[21] N. Austern, Y. Iseri, M. Kamimura, M. Kawai, G. Rawitscher, and M. Yahiro, Phys. Rep. **154**, p. 125 (1987).
[22] I. J. Thompson, Comp. Phys. Rep. **7**, 167 (1988).
[23] A. M. Moro, K. Rusek, J. M. Arias, J. Gómez-Camacho, and M. Rodríguez-Gallardo, Phys. Rev. C **75**, p. 064607 (2007).
[24] A. M. Moro, J. P. Fernández-García, M. A. G. Alvarez, and M. Rodríguez-Gallardo, EPJ Web of Conferences **17**, p. 08001 (2011).
[25] E. K. Lin and B. L. Cohen, Phys. Rev. **132**, 2632–2638 (1963).