EPJ Web of Conferences **117**, 06003 (2016) DOI: 10.1051/epjconf/201611706003
NN2015

Reaction studies with low-energy weakly-bound beams at INFN-LNS

A. Di Pietro[1], J.P. Fernandez-Garcia[1], P. Figuera[1], M. Fisichella[1], M. Lattuada[1,2], D. Torresi[1,2] and M. Zadro [3]

[1] INFN-Laboratori Nazionali del Sud, Catania, Italy
[2] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
[3] Ruđer Bošković Institute, Bijenička cesta 54,HR-10000 Zagreb, Croatia

Abstract

The reaction dynamics of collisions involving halo or weakly bound nuclei, at energies around the Coulomb barrier, can be strongly affected by the structure of such nuclei. Very strong entrance channel effects have been observed on various reaction pocess such as, elastic scattering, fusion and direct reactions when comparing collision induced by the ^{6}He and ^{11}Be halo nuclei with the ones induced by their cores ^{4}He and ^{10}Be. Collisions induced by the stable weakly bound nuclei ^{6}Li, ^{7}Li show also some peculiarities in comparison to the ones induced by well bound nuclei; coupling with the break-up channel is in fact very important in reproducing low energy data. In this contribution an overview of our present understanding of the discussed topic will be given along with the discussion of some new preliminary results.

1 Introduction

The study of nuclear collisions around the Coulomb barrier induced by halo and, more in general, weakly bound nuclei such as the stable ^{6}Li, ^{7}Li, ^{9}Be, has been widely investigated over the last twenty years. Results have shown that the very low breakup threshold of such nuclei, combined with the halo or cluster structure of the ground state, will strongly affect the reaction

dynamics around the Coulomb barrier. A recent overview can be found in [1]. A complete theoretical description of such collisions requires a reaction theory which includes all of the structure and dynamic effects. This is partially done in Continuum Discretized Coupled Channels (CDCC) calculations. However such calculations include only coupling with elastic break-up and other effects such as coupling to inelastic breakup or transfer must be included with a different approach. Recently, coupling with excited states of the core have also been included in the CDCC in the case of collisions induced by the 1n-halo ^{11}Be [2]. For the 2n-halo nuclei the inclusion of coupling with core excitation is still beyond reach.
Fusion excitation functions may also be affected both by static and/or dynamic effects being due respectively to the diffuse surface of the halo and to the coupling effects also to the continuum. Moreover, fusion reactions in collisions induced by weakly bound nuclei are complicated by the fact that, owing to the large breakup probability, in addition to complete fusion (CF) one can have a non negligible contribution of incomplete fusion (ICF) following breakup of the projectile or transfer see e.g. [3, 4, 33].

2 Elastic scattering

Elastic scattering with halo nuclei, ^{6}He, ^{11}Be and ^{11}Li, at energies around the Coulomb barrier has been measured by different authors mostly on heavy targets [6–13]. In collisions induced on heavy nuclei the data showed a suppression of the elastic cross-section in the region of the Coulomb-nuclear interference peak when compared with the scattering induced by the corresponding stable isotope at similar c.m. energies. Optical Model (OM) analysis allowed to reproduce the data only using very large imaginary diffuseness, indicating the presence of long range absorption [8–10, 13]. Recently, the ^{11}Li+^{208}Pb elastic scattering around the Coulomb barrier was reported and compared with the scattering of ^{9}Li on the same target [13]. A huge suppression of the ^{11}Li elastic cross-section was found with respect to the ^{9}Li one, much larger than the one observed in the case of ^{6}He on similar mass targets [8–10]. CDCC calculations show that coupling to continuum via the Coulomb-dipole interaction gives an important contribution to the disappearance of the Coulomb-nuclear interference peak. Results are somehow different on medium mass and light targets.
On medium mass targets very few experiments have been performed. The measurement of elastic scattering of ^{6}He+^{64}Zn was reported in [6, 7]. Although the elastic cross-section is overall suppressed when compared to the

one for ^{4}He+^{64}Zn, the Coulomb-nuclear interference pattern is not as much reduced as it was observed in the case of heavy targets. More recently, the ^{4,6}He+^{64}Zn measurements were extended to higher c.m. energies $E_{c.m.}$=13.5 and 16.5 MeV and compared with CDCC calculation [14] . These calculations underestimate the experimental data (see figure 1 of [14]), therefore, other effects than coupling to the break-up channel must be into play in the energy range explored in that study. To investigate on that, Coupled Reaction Channel (CRC) calculations were performed in order to include coupling to the one-neutron transfer to bound and unbound states of the target. Such calculations described the elastic, break-up and fusion cross section [15] of the ^{6}He+^{64}Zn reaction at lower energy $E_{c.m.}$=12.4 MeV [6,7]. It is found that coupling to the one-neutron transfer reproduces better the data than when coupling to the two-neutron transfer to bound and unbound states of the target is considered.
At the REX-ISOLDE facility of CERN, scattering and direct reactions for collisions induced by the 1n halo nucleus ^{11}Be and its core ^{10}Be at the same center of mass energy $E_{c.m.}$ = 24.5 MeV [11,12] were measured. As shown in figure 1, in the ^{11}Be case it was found a suppression of the elastic angular distribution in the region of the Coulomb-nuclear interference peak which is not present in the ^{6}He case on the same target at similar $E_{c.m.}/V_C$. The Coulomb-nuclear interference seems to be constructive in the case of ^{6}He and distructive in the case of ^{11}Be. The difference observed could be the result of the lower binding energy of ^{11}Be compared to the one of ^{6}He and the consequent more extended halo, in addition the effect of Coulomb-dipole coupling is weaker in the ^{6}He case.
The ^{11}Be elastic scattering angular distribution has been reproduced within the OM, using as bare potential the one that reproduces ^{10}Be scattering, and adding a phenomenological surface Dynamic-Polarization-Potential (DPP). A good fit was obtained with a DPP having a large diffuseness of the order of 3.5 fm in agreement with [16]. The ^{11}Be data were also reproduced within the CDCC frame, showing that the suppression of the Coulomb nuclear interference peak is due to the combined effect of Coulomb and nuclear couplings to continuum.

Core excitation effects have been found to be important in the scattering and break-up of ^{11}Be on the heavy Au target [17].
Although scattering data in collision induced by halo nuclei around the Coulomb barrier start to show some common features, most of those data have been obtained with ^{6}He beams and, in some cases, the results are limited by the poor beam quality. Therefore, additional data, including the ones obtained with p-halo nuclei, are needed to build a wider systematics

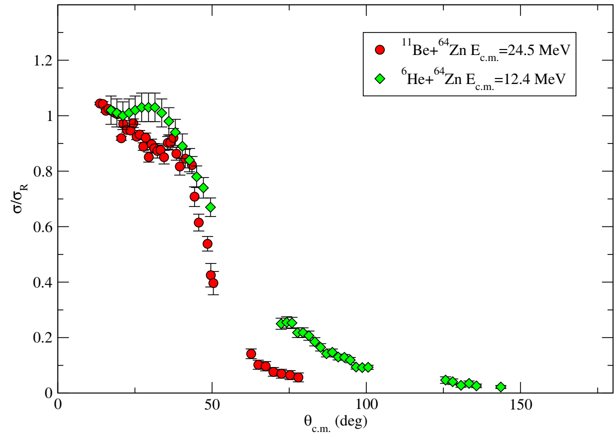

Figure 1: (Color online) Comparison of scattering angular distribution for ^{11}Be (red circles) and ^{6}He (green diamonds) on a ^{64}Zn target at similar energies with respect to the Coulomb barrier.

and allow a deeper understanding of the different effects involved.
The study of collisions induced by stable weakly bound nuclei such as ^{6}Li, ^{7}Li and ^{9}Be, which do not have a halo structure, has also a considerable interest to investigate on the problems related to the presence of the continuum in the vicinity of the ground state. When compared with halo nuclei, they have larger breakup thresholds and do not show the same extended mass distribution. However, coupling to continuum effects are still expected to be important and, since beams of such stable nuclei are available with high currents, high quality data can be gathered.
For weakly bound nuclei the projectile breakup channel is expected to be important even at energies below the Coulomb barrier. In fact, breakup is an open reaction channel also at energies much below the barrier. Coupling to the breakup produces a repulsive polarization potential (e.g. [18]) which is responsible for the disappearance the usual threshold anomaly (TA) in the OP.
At Laboratori Nazionali del Sud in Catania elastic scattering angular distributions were measured at several energies around and below the barrier for the systems ^{6,7}Li+^{64}Zn [19,20]; clear absence of the usual threshold anomaly has been observed in the case of ^{6}Li+^{64}Zn. Absence of the usual threshold anomaly in the OP, in collisions induced by weakly bound nuclei both stable and radioactive has been observed also for other systems (e.g. [21–25]). The ^{6,7}Li+^{64}Zn elastic scattering data have been also analised within the CDCC approach. In figure 2 it is shown a comparison between the ^{6}Li+^{64}Zn data

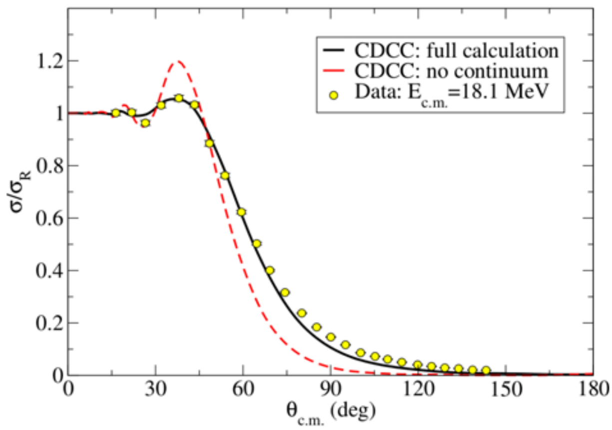

Figure 2: (Color online) Elastic scattering angular distribution for ^{6}Li+^{64}Zn at $E_{c.m.}$=18.1 MeV. Symbols are the experimental data, the full line represent the CDCC calculation with full coupling while the dashed line represent the calculation with no-continuum coupling.

and the CDCC calculation both, with and without coupling with the continuum; it can be seen that continuum coupling is essential to reproduce the data. In addition, coupling to resonances in the continuum is also found to be important in collisions induced by ^{6}Li at the barrier energies [20].

3 Fusion reactions

Recently, a complete review on different fusion data for collisions induced by halo and weakly bound nuclei has been published [1]. Systematic studies suggests that, for collisions induced by halo nuclei, once static effects are removed, the residual effect of coupling to continuum or to transfer is a suppression of fusion above barrier and, possibly, a small enhancement of fusion below the barrier. Unfortunately most of presently available data do not explore the sub-barrier region with reasonable errors and new data would be necessary for a complete understanding of this topic.
Fusion excitation functions in collisions induced by stable weakly bound nuclei have been measured for several systems in a wide target mass range [e.g. [3, 26–32]. For fusion-evaporation reactions induced on heavy targets (e.g. [3, 26–28]), where the emission of charged particles is hindered by the presence of a strong Coulomb barrier, complete (CF) and incomplete fusion (ICF) contributions can usually be clearly separated. The main finding for

such systems is that CF is suppressed above the barrier by about 30% with respect to the prediction of Single Barrier Penetration calculations or Coupled Channel calculations not including coupling to continuum effects.
For fusion of weakly bound nuclei on medium mass or light targets (e.g. [29–32]), the compound nucleus can evaporate charged particles; therefore, the same residues can be populated by the CF and ICF mechanisms, making their separation much more difficult. For this reason, most of the fusion data for light and medium mass systems refer to total fusion (TF) cross section. However, also the single nucleon transfer could populate the same heavy fragments and therefore the measured cross-section could contain contributions of direct processes. In the case of collision on medium mass targets no effects on TF are observed at energies above barrier, whereas below the barrier not much data are available.
Recently, in Catania, the excitation functions for heavy residue (H.R.) production was measured, in the collisions ^{6,7}Li+^{64}Zn around the Coulomb barrier, with the aim to extract some information on the competition between CF, ICF and other reaction mechanisms in the H.R. production [33]. It was found that, at energies below the barrier, the H.R. cross-section measured in the ^{6}Li collision is larger than for ^{7}Li, in agreement with [31]. Since ^{6}Li and ^{7}Li have weakly bound cluster structures of the ground state, ICF reactions, where only an alpha particle, a deuteron or a tritium are captured by the target, are expected to contribute to the H.R.. Moreover, as it has been shown in [34, 35], transfer triggered breakup is an important reaction channel in ^{6,7}Li induced reaction, in some cases even more important than direct breakup. Those type of processes would contribute to the production of the same H.R. as for CF and ICF. In [33] it is shown that at energies above the barrier CF is the dominant mechanism; however, at energies below the barrier the H.R. experimental relative yield is rather different than the one expected for CF, showing that CF is no longer the dominant reaction mechanism while other processes such as ICF, direct cluster transfer (DCT) or single nucleon transfer become very important. The present results suggest that, in order to study fusion below the barrier in collisions induced by weakly bound nuclei on medium mass targets, the simple integration of the H.R. yield is not giving the TF cross-sections since direct processes may give an important contribution to the cross-section. Therefore, one needs to find experimental techniques allowing to properly separate the different reaction mechanisms contributing to the H.R. yield.

4 Summary and conclusions

In this paper experimental results concerning the study of elastic scattering and reactions for halo and stable weakly bound nuclei around the Coulomb barrier have been summarized . We have shown that, in collisions induced by halo nuclei, a strong suppression of the elastic scattering cross-section and, correspondingly, a large enhancement of the total reaction cross-section has been observed. Core excitation effects and coupling with the 1n-transfer channel are also found to be important in the elastic scattering with halo nuclei.

In elastic scattering with weakly bound stable nuclei coupling to continuum effects are found to be very important.

Fusion excitation functions in collisions induced by halo nuclei suggest the presence of a fusion cross-section enhancement around the barrier which is due mainly (but not only) to static effects. Fusion with stable weakly bound nuclei on heavy targets shows at energies above the barrier a well established suppression of CF due to ICF following projectile breakup. In collisions with medium mass or light targets CF and ICF cannot be easily separated and most of available data refers to TF. ^{6,7}Li+^{64}Zn fusion data suggest that above barrier H.R. production is dominated by CF. Below the barrier, on the contrary, other processes such as ICF but also DCT or single neutron transfer are the dominating processes for H.R. production.

References

[1] L.F. Canto et al Phys. Rep. **596**, (2015) 1-86

[2] R. de Diego et al. Phys.Rev. C **89**, 064609 (2014)

[3] M. Dasgupta et al. Phys. Rev. C **70**, (2004) 024606

[4] V. Scuderi et al. Phys. Rev. C **84**, (2011) 064604

[5] A. Di Pietro et al. Phys. Rev. C **87**, (2013) 064614

[6] A. Di Pietro et al. Europhys. Lett. **64** (2003) 309

[7] A. Di Pietro et al. Phys. Rev. C **69** (2004) 044613

[8] L. Acosta et al. Phys. Rev. C **84** (2011) 044604

[9] A. M. Sanchez Benitez et al. Nucl. Phys. A **803** (2008) 30

[10] O. R. Kakuee et al. Nucl. Phys. A **765** (2006) 294

[11] A. Di Pietro et al. Phys. Rev. Lett. **105** (2010) 022701

[12] A. Di Pietro et al. Phys. Rev. C **85** (2012) 054607

[13] M. Cubero et al. Phys. Rev. Lett. **109** (2012) 262701

[14] J.P. Fernandez-Garcia et al. *Contribution to these proceedings*

[15] A. M. Moro et al. EPJ Web of Conferences **17** (2011) 08001

[16] A. Bonaccorso et al. Nucl. Phys. A **706** (2002) 322

[17] V. Pesudo et al. Act. Phys. Pol. B **45** (2014) 375

[18] Y. Sakuragi et al. Phys. Rev. C **35** (1987) 2161

[19] M. Zadro et al. Phys. Rev. C **80** (2009) 064610

[20] J.P. Fernandez-Garcia et al. *Accepted for publication Phys. Rev. C*

[21] A.M.M. Maciel et al. 1999 Phys. Rev. C 59 2103

[22] A. Pakou et al. 2004 Phys. Rev. C 69 054602

[23] H. Kumawat et al. 2008 Phys. Rev. C 78 044617

[24] J.M. Figueira et al. 2010 Phys. Rev. C 81 024613

[25] N.N. Deshmukh et al. 2011 Phys. Rev. C 83 024607

[26] P.R.S. Gomes et al. Phys. Rev. C **73** (2006) 064606

[27] Y.W. Wu et al. Phys. Rev. C **68** (2003) 044605

[28] Pradhan M K et al. Phys. Rev. C **83** (2011) 064606

[29] P.R.S. Gomes et al. Phys. Rev. C **71** (2005) 034608

[30] R.M. Anjos et al. Phys. Lett. B **534** (2002) 45

[31] M. Sinha et al. Eur. Phys. J. A **44** (2010) 403

[32] C. Beck et al. Phys. Rev. C **67** (2003) 054602

[33] A. Di Pietro et al. Phys. Rev. C **87** (2013) 064614

[34] D.H. Luong et al. Phys. Lett. B **695** (2011) 105

[35] D.H. Luong et al. Phys. Rev. C **88** (2013) 034609