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Abstract. The elastic scattering process for the nuclear reactions induced by the Radioactive Ion Beams ^{7}Be and ^{8}B on a ^{208}Pb target was measured for the first time in the energy range around the Coulomb barrier. Extensive theoretical calculations within the framework of the optical model were performed. An excellent agreement between experimental data and theoretical predictions was achieved for the reaction ^{7}Be + ^{208}Pb, while a comprehensive understanding of the reaction dynamics induced by the more exotic projectile ^{8}B is still far to be reached. Predictions of the cross section for the breakup for both systems will also be given.

1. Introduction
The reaction dynamics induced by light weakly-bound nuclei in the energy range around the Coulomb barrier is a quite interesting research topic in present-day nuclear physics. These studies was originally motivated by the expectation that the peculiar properties of many light exotic nuclei, such as halo structure, neutron skin structure or very weak binding energy, could magnify the strong enhancement of near-barrier fusion cross section observed in collisions between stable nuclei. Despite earlier measurements, it was soon realized that the unusual features of exotic nuclei tend to increase the total reaction probability rather than the fusion cross section. The investigation then moved to try to shed some light on which reaction channels were mainly responsible for the enhancement of the total reaction probability, whether this effect was mainly related to transfer channels or to the breakup process. Several review articles have been written over the past 15 years on this topic [1, 2, 3, 4, 5, 6, 7, 8, 9].

These studies are usually very complicated and typically suffer of low statistical accuracy. In fact, these exotic projectiles are generally radioactive and short-lived, therefore we need first a nuclear reaction between stable nuclei to occur, in order to produce the radioisotopes, and then a suitable device to select and purify the secondary beam. As a consequence, Radioactive Ion Beams nowadays available still have rather low intensities. Thus, the first series of experiments performed with exotic beams in the energy range around the Coulomb barrier are typically addressed to the investigation of the most probable reaction mechanism, i.e. the elastic scattering process. The analysis of the elastic scattering angular distribution within the framework of the optical model can provide a first indication about the overall reactivity of an exotic projectile and (possible) modification on the shape the experimental data with respect to the theoretical predictions for the scattering process can give some hints on the magnitude of cross sections for other nuclear processes and their influence on the scattering channel.

2. Experiments
2.1. Production of the secondary beams
Both Radioactive Ion Beams used in these studies were produced by means of the in-flight technique.

The ^{8}B experiment was performed with the CRIB facility [10, 11], located inside the RIKEN campus in Japan. We started with a 11.2 MeV/u $^{6}Li^{3+}$ primary beam with an average intensity of about 1 pμA impinging on a 8-cm long gas target, filled with ^{3}He gas at a pressure of about 1 bar and kept at cryogenic temperature. The ^{8}B was then selected and purified by means of the ion-optical elements of CRIB and impinged on a 2.2 mg/cm^2 ^{208}Pb target with an energy of 50 ± 1 MeV, an average intensity of 10^4 pps and a purity around 20%.

The ^{7}Be experiment was carried out at the Laboratori Nazionali di Legnaro (LNL, Italy), where the radioactive ion beam was produced with the facility EXOTIC [12]. In this case, we used a ^{7}Li^{3+} beam with an energy of 48.8 MeV and an intensity of 50-60 pnA. The primary beam was hitting a 5-cm long gas target, filled with H_2 at a pressure of about 1 bar. The outgoing ^{7}Be secondary beam was selected with the facility EXOTIC and delivered with at intensity of 2-3 × 10^5 pps and a nearly 100-% purity on a 1 mg/cm^2 ^{208}Pb target. Three different secondary beam energies were obtained by operating the target at room and cryogenic temperatures and by inserting a 12.5-μm thick aluminum degrader at a suitable position along the beam line. The ^{7}Be energies on target were: 42.2 ± 0.4 MeV, 40.5 ± 0.4 MeV and 37.4 ± 0.5 MeV.

2.2. Detector set-up

In both experiments, six modules of the detector array EXPADES [13] were employed for the detection of charged particles. Each module was composed by two Double-Sided-Silicon-Strip-Detectors (DSSSDs), the inner one with a thickness of 43-57 μm, while the outer one had a thickness of 300 μm. Each DSSSD had an area of 64.0 mm × 64.0 mm and the front and back sides were segmented into 32 vertical and horizontal strips, respectively. Details on the electronic chains used for both detector stages can be found in [13].

The six modules of EXPADES were arranged in a cylindrical configuration around the target position ensuring a solid angle coverage of about 14 % of 4π sr. A symmetrical displacement, covering the angular range θ_{lab} = [52°, 167°], around the beam axis was chosen for the ^{7}Be experiment. On the other hand, for the ^{8}B experiment a slight asymmetrical arrangement of the EXPADES modules was preferred in order to enlarge the polar angle coverage θ_{lab} = [8°, 166°]. More details on the detector geometry are given in the recent publication [14].

3. Results

3.1. Elastic scattering and total reaction cross section

The first step of the data analysis was the evaluation of the elastic scattering angular distributions for both systems and the extraction, via an optical model fit of the experimental data, of the total reaction cross sections. All the steps of the data evaluation and of the fitting procedure are described in [14] and here we discuss the results and the comparison with similar mass systems.

When comparing different systems, both bombarding energies and cross sections need to the normalize in order to account for the different Coulomb barrier and the different geometrical size of the colliding nuclei. In doing that, we used the formalism suggested by L.F. Canto and collaborators [15]. This method was originally developed and works pretty nicely for the comparison of fusion cross section data, but can also be employed, paying some attention [16], also to reaction cross section data. In our case, we are going to compare reactions induced by projectiles with similar masses (in the range A = 6-8) and all interacting with the same target nucleus (^{208}Pb).

It has been discussed for a long time whether, from the point of view of the reaction dynamics, the ^{7}Be behavior would have resembled more that of ^{6}Li, which has a separation energy very similar (within 100 keV) to that of ^{7}Be, or that of its mirror nucleus ^{7}Li, with an analogue nuclear structure but a separation energy 60% larger. Our study provides a first answer to this question, at least for the interaction with a very massive target such as ^{208}Pb, since the three data points we measured for the system ^{7}Be + ^{208}Pb follow essentially the trend of the reaction ^{6}Li + ^{208}Pb [17]. This result suggests that nuclear binding energy plays a major role than nuclear structure in collisions involving weakly-bound nuclei, at least in the energy range around the Coulomb barrier.

If we now add to the comparison also the mirror nuclei of mass A = 8, i.e. ^{8}Li [18] and ^{8}B, again interacting with a ^{208}Pb target, we observed in [14] that, in both cases, the "'normalized"' total reaction cross section data are enhanced with respect to region of the graph where projectiles with mass A = 6-7 are located. A simple argument related only to the projectile binding energy would not stand in this occasion, since the ^{8}Li separation energy is exactly in between those of ^{6}Li/^{7}Be and ^{7}Li. The actual reason for the ^{8}Li enhancement has therefore to be searched elsewhere and, most likely, relies on the large probability, i.e. cross section, for the n-stripping process (leading to ^{7}Li in the reaction exit channel) to occur. Specific experimental measurements for this process are therefore needed in order to confirm this scenario.

Even more striking is the comparison of ^{8}B with all other light projectiles. In fact, its reaction cross section is enhanced by a factor 3-4 with respect to that measured for the reaction induced by its core ^{7}Be. Following the analogies with the system ^{8} + ^{58}Ni [19], the enhancement should be due to the extremely weak binding energy of ^{8}B ($S_p = 137.5$ keV) and consequently the very high probability for this nucleus to break up while approaching a target nucleus. To this extend, we performed extensive Coupled-Channel calculations in order to provide an estimate of the cross section for the breakup process ^{8}B $\rightarrow$ ^{7}Be + p.

3.2. Breakup process
Theoretical calculations were performed for both systems. Being both projectile very weakly-bound, we described the breakup projectile by means of a discretization of the (continuous) energy spectrum above the breakup threshold in bins equally spaced in the momentum space. Also in this case, the procedure adopted for the calculations is fully described in [14] and here we summarize the main details important for the subsequent discussion.

The ^{7}Be nucleus was modelled using an ^{3}He + ^{4}He cluster folding model. In the calculations, we included also the possibility to excite the ^{7}Be first excited state at 0.429 MeV ($J^{\pi} = 1/2^{-}$), the two $l = 3\hbar$ resonances at 4.57 ($7/2^{-}$) and 6.73 ($5/2^{-}$) MeV, the non resonant continuum up to multipolarity $\lambda = 4$ and up to an excitation energy of 9.88 MeV above the breakup threshold. The calculations were performed by using the coupled channel code Fresco [20]. First of all, we remark that we were able to reproduce the experimental elastic scattering angular distribution without any free parameter, providing an additional confirmation of the validity of the adopted approach. The calculations predict a breakup cross section of 20-38 mb in the range of energies covered by our experiment. These values correspond approximately to about 10% of the overall reaction cross section for the system ^{7}Be + ^{208}Pb, strongly indicating that the breakup process does not dominate the reaction dynamics for this system, in a qualitative agreement with our previous observation for the reaction ^{7}Be + ^{58}Ni [?]. We also had an additional confirmation of this outcome from the preliminary analysis of the production cross section of the reaction products ^{3}He and ^{4}He. The heavier isotopes is indeed 4-5 times more abundant than the lighter counterpart, suggesting that there are many other reaction channels (such as, for instance, n-pickup or p-stripping) open in this energy range and leading to extra-production of ^{4}He with respect to ^{3}He.

Moving now to ^{8}B, we used a ^{7}Be + p cluster folding model to describe this very exotic projectile. To reduce the computation time, ^{7}Be was assumed to be spinless and inert and the proton to be in a pure $p_{3/2}$ state. The non resonant continuum up to a multipolarity $\lambda = 5$ and up to an excitation energy of 11.7 MeV above the breakup threshold was included. Due to assumed spinless nature of ^{7}Be, no ^{8}B resonances were considered in the theoretical calculations. The predicted differential cross section for the elastic scattering process failed to reproduce satisfactory the experimental data, already indicating that our model to describe ^{8}B might be too simplistic. Being the ^{8} core, i.e. ^{7}Be, also a weakly bound nucleus, perhaps a 4-body approach, including also the possibility of core excitation, should be more adequate for this reaction.

Nevertheless, coupled channel calculations predict an extremely large breakup cross section of around 600 mb, which corresponds to more than 50% of the total reaction cross section. We are presently working to extract the angular distribution for the ^{7}Be reaction product. A preliminary evaluation shows a differential cross section strongly peaked at forward angles, with a large tail extending up to very backward angles, in qualitative agreement with the earlier observations by V. Guimarães and collaborators for the reaction ^{8}B + ^{58}Ni [22, 23].

4. Outlook

The elastic scattering process for the systems ^{7}Be, ^{8}B + ^{208}Pb has been measured for the first time in the energy range around the Coulomb barrier. The experimental data have been analyzed within the framework of the optical model in order to extract the total reaction cross section. The ^{8}B + ^{208}Pb reactivity resulted to exceed by far those reported for projectiles of masses in the range A = 6-8 and interacting with the same target nucleus. Theoretical calculations indicate that this enhancement might be due to the breakup process $^8 \rightarrow {}^7$Be + p and we are presently working to extract the experimental differential cross section for the ^{7}Be reaction product.

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References

[1] Canto L F, Gomes P R S, Donangelo R and Hussein M S 2006 *Phys. Rep.* **424** 1
[2] Liang J F and Signorini C 2005 *Int. J. Mod. Phys.* E **14** 1121
[3] Keeley N, Raabe R, Alamanos N and Sida J L 2007 *Prog. Part. Nucl. Phys.* **59** 579
[4] Keeley N, Alamanos N, Kemper K W and Rusek K 2009 *Prog. Part. Nucl. Phys.* **63** 396
[5] Mazzocco M 2010 *Int. J. Mod. Phys.* E **19** 977
[6] Back B B, Esbensen H, Jiang C L and Rehm K E 2014 *Rev. Mod. Phys.* **86** 317
[7] Keeley N, Kemper K W and Rusek K 2014 *Eur. Phys. J.* A **50** 145
[8] Canto L F, Gomes P R S, Donangelo R, Lubian J and Hussein M S 2015 *Phys. Rep.* **596** 1
[9] Kolata J J, Guimarães V and Aguilera E F 2016 *Eur. Phys. J.* A **52** 123
[10] Yanagisawa Y *et al* 2005 *Nucl. Instrum. Methods Phys. Res.* A **539** 74
[11] Yamaguchi H *et al* 2008 *Nucl. Instrum. Methods Phys. Res.* A **589** 150
[12] Farinon F *et al* 2008 *Nucl. Instrum. Methods Phys. Res.* B **266** 4097
[13] Pierroutsakou D *et al* 2016 *Nucl. Instrum. Methods Phys. Res.* A **834** 46
[14] Mazzocco M *et al* 2019 *Phys. Rev.* C 100 024602
[15] Canto L F, Gomes P R S, Lubian J, Chamon L C and Crema E 2009 *J. Phys.* G **36** 015109
[16] Canto L F, Mendes Junior D R, Gomes P R S and Lubian J 2015 *Phys. Rev.* C **92** 014626
[17] Keeley N, Bennett S J, Clarke N M, Fulton B R, Tungate G, Drumm P V, Nagarajan M A and Lilley J S 1994 *Nucl. Phys.* A **571** 326
[18] Kolata J J, Goldberg V Z, Lamm L O, Marino M G, O'Keeffe C J, Rogachev G, Aguilera E F, García-Martínez H, Martinez-Quiroz E, Rosales P, Becchetti F D *et al* 2002 *Phys. Rev.* C **65** 054616
[19] Aguilera E F, Martinez-Quiroz E, Lizcano D, Gomez-Camacho A, Kolata J J, Lamm L O, Guimarães V, Lichtenthaler R, Camargo O, Becchetti F D *et al* 2009 *Phys. Rev.* C **79** 021601(R)
[20] Thompson I J 1988 *Comput. Phys. Rep.* **7** 167
[21] Mazzocco M, Torresi D, Pierroutsakou D, Keeley N, Acosta L, Boiano A, Boiano C, Glodariu T, Guglielmetti A, La Commara M *et al* 2015 *Phys. Rev.* C **92** 024615
[22] Guimarães V, Kolata J J, Peterson D, Santi P, White-Stevens R H, Vincent S M *et al* 2000 *Phys. Rev. Lett.* **84** 1862
[23] Kolata J J, Guimarães V, Peterson D, Santi P, White-Stevens R H, Vincent S M *et al* 2001 *Phys. Rev.* C **63** 024616