Scattering process for the system \(^7\text{Be}\) + \(^{58}\text{Ni}\) at 23.2 MeV beam energy

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Abstract. We measured for the first time the scattering process of \(^7\text{Be}\) nuclei from a \(^{58}\text{Ni}\) target at 23.2 MeV beam energy. The experiment was performed at the Laboratori Nazionali di Legnaro (LNL, Italy), where the \(^7\text{Be}\) Radioactive Ion Beam was in-flight produced with the facility EXOTIC. Charged reaction products were detected by means of the detector array DINEX, arranged in a cylindrical configuration around the target to ensure a polar angle coverage in the ranges \(\theta_{\text{cm}} = 40^\circ - 80^\circ\) and \(110^\circ - 150^\circ\). The scattering differential cross section was analyzed within the optical model formalism with the coupled-channel code FRESCO to extract the total reaction cross section. The result was compared with those obtained at lower beam energies in an earlier experiment performed at the University of Notre Dame (USA). At the present stage of our analysis, the two data sets were found to be not fully consistent each other.

1. Introduction
The reaction dynamics induced by light weakly-bound Radioactive Ion Beams (RIBs) in the energy range around the Coulomb barrier has been one of most debated topics in the Nuclear Physics community for the last twenty years at least. These nuclei could have some very peculiar features, such as, for instance, (i) radial extensions much larger than those observed for stable well-bound nuclei close to the \(\beta\)-stability valley, (ii) very low binding energies (typically, \(S_{p,n,\alpha} \leq 1.0\) MeV) and (iii) very high surface densities of neutrons. All these phenomena are strongly interconnected to each other and they can sometimes generate conflicting effects. The situation
is particularly remarkable in the energy range around the Coulomb barrier, where for stable nuclei a strong enhancement of the sub-barrier fusion cross section was observed [1].

The question whether the low binding energies of the valence nucleon(s) as well as the halo properties of many of these light nuclei could enhance or hinder the fusion probability have triggered quite some effort both from a theoretical and an experimental point-of-view. Despite early measurements, it is now rather clear that breakup related effects mainly enhance the reaction probability rather than the fusion cross section, especially in the sub-barrier energy regime. Several review paper have been recently published on this subject [2, 3, 4, 5].

Now the key question has moved toward understanding which direct processes (among transfer channels, breakup processes or inelastic excitations) are the main responsible of the reaction cross section enhancement. In a series of experiments performed at Notre-Dame in the first half of the last decade, it was found that for the reaction $^6$He + $^{209}$Bi at 21.5 MeV, the contribution of the 2n-transfer was $\sim 55\%$ [6], that of the 1n-transfer ca. 20% [7] and about 25% of the enhancement was due to the breakup process $^6$He $\rightarrow$ $^4$He + 2n [8]. A similar series of measurements was carried out at GANIL for the system $^6$He + $^{63}$Cu at 19.5 and 30 MeV. In this case it was established that 90% of the enhancement was due to the 2n-transfer process [9], about 10% to the 1n-transfer [10], leaving essentially no room for the breakup process. Therefore, we can conclude that for the weakly-bound 2n-halo $^6$He ($S_{2n}$ = 0.972 MeV), the largest contribution to the reaction cross section at near-barrier energies is given by the 2n-transfer, whose relevance is increasing going from the heavy target mass region (i.e., $^{209}$Bi) down to medium-mass targets (such as $^{63}$Cu).

More recently, new experimental data on the reaction dynamics induced by the 1p-halo $^8$B ($S_p$ = 0.1375 MeV) [11] and by the 1n-halo $^{11}$Be ($S_n$ = 0.504 MeV) [12]. In both cases, reaction cross sections up to a factor 2 larger than those observed for reactions induced by the corresponding stable (more bound) isotopes were observed. A tentative analysis indicates the breakup channel as the main responsible for the enhancement of the reaction probability for $^8$B, while the origin of the large amount of $^{10}$Be observed for the system $^{11}$Be + $^{64}$Zn is still under evaluation. If this scenario is confirmed, n-rich nuclei and p-rich nuclei would show different behaviors, with the predominance of transfer channels for the former and of the breakup process for the latter.

Within this framework, we undertook the study of the reaction $^7$Be + $^{58}$Ni. $^7$Be is a quite interesting radioactive nucleus, since it is rather weakly-bound ($S_\alpha$ = 1.586 MeV) and it has a well pronounced $^3$He + $^4$He cluster structure. Therefore this projectile has a large probability to breakup into its constituent clusters, while approaching the Coulomb or nuclear field of a target nucleus, or to transfer just one of the two clusters to the target. In addition, $^7$Be represents, among all light nuclei, the cleanest case where the breakup/transfer interplay into the reaction dynamics can be investigated. In fact the two $^7$Be inner clusters are very stable fragments with similar masses, while all breakup studies previously performed always involved the complicated and low-efficiency detection of neutrons (like in the case of the $^6$He and $^9,^{11}$Be breakup processes), the emission of a weakly-bound fragment (e.g., the deuteron emission in the $^6$Li breakup), the emission of a radioactive fragment (as for the triton emission in the $^7$Li breakup), or a very small breakup probability, as in the case of the $^{17}$F breakup process into $^{16}$O + p.

So far, very little is known for the system $^7$Be + $^{58}$Ni, since only the scattering process in the energy range $E_{lab}$ = 15.1-21.4 MeV [11] was measured. With our experiment we aimed (i) at improving the accuracy of the total reaction cross section data at two energies in the above-barrier energy domain and (ii) at measuring the cross sections for the $^7$Be most relevant transfer channels and breakup processes.
2. RIB production

2.1. The facility EXOTIC

The $^7$Be radioactive beam for this experiment was produced with the facility EXOTIC [13] at the Laboratori Nazionali di Legnaro (LNL, Italy) of the Istituto Nazionale di Fisica Nucleare (INFN). This facility was laid out for the production of light weakly-bound RIBs, employing two-body reactions induced from high intensity heavy-ion beams delivered from the LNL-XTU Tandem Van de Graaff accelerator on light gas targets. The gas cell is 50 mm long, doubly walled with 2.2-µm thick Havar foils and can be filled with $^2$H$_2$, $^3$H$_2$, $^3$He and $^4$He gases up to an operative pressure of 1 bar. Selection, separation and focusing of the secondary beam are performed by means of eight ion-optical elements (a first quadrupole triplet, a 30°-bending magnet, a 1 m long Wien Filter and a second quadrupole triplet) and four slit sets located at suitable positions along the beam line [14]. The facility EXOTIC is briefly sketched in Fig. 1.

The facility is presently undergoing an upgrade phase. In fact we first installed two Parallel Plate Avalanche Counters (PPACs) at the exit of the second quadrupole triplet to provide an event-by-event reconstruction of the position hit on the secondary target. More recently we located two $y$-steerers at the exit of the first quadrupole triplet to compensate a possible vertical misalignment in the secondary beam trajectory due to a misalignment in primary beam hitting the production target. So far, this problem was in case circumvented by a fine adjustment of the magnetic field of the Wien filter, usually at the cost of a smaller purity of the secondary beam. The possibility to re-align the secondary beam trajectory upstream the dipole magnet and the Wien filter will help to produced RIBs with better transmission and separation quality.

Finally, we are upgrading the power supplies of the middle quadrupoles of both quadrupole triplets. This project, financed by both INFN and MIUR, will increase the maximum current circulating in both quadrupoles by 10%, which corresponds to an increase of about 15% in the maximum magnetic rigidity of the RIB under production. It will be possible, therefore, to produce secondary beams with higher energy and better transmission through the facility and also to have a global $B$-scaling of all ion-optical elements.
2.2. \(^{7}\)Be secondary beam production

In this experiment we used a 34.2 MeV \(^{7}\)Li\(^{3+}\) primary beam with intensity around 100 pnA impinging on a H\(_2\) gas target. The production reaction was \(^{1}\)H\((^{7}\)Li,\(^{7}\)Be\))n \((Q_{value} = -1.64\) MeV\)). The target station was operating at a pressure of about 950 mbar and at cryogenic temperature (90 K), corresponding to an equivalent H-target thickness of \(\sim 1.3\) mg/cm\(^2\). The outcoming \(^{7}\)Be secondary beam energy was (after passing both PPACs) 23.3 \(\pm\) 0.4 MeV. A second \(^{7}\)Be beam energy of 19.0 \(\pm\) 0.5 MeV was obtained by inserting a 10-\(\mu\)m thick aluminum degrader between the two PPACs. Figure 2 shows the \(^{7}\)Be energy spectra measured with a 300-\(\mu\)m thick silicon detector placed at the secondary target position. The beam purity, as clearly visible in Fig. 2, was nearly 100\% for both beam energies. The radioactive beam intensity was around 3\(\times\)10\(^{5}\) pps for the higher energy and about 30\% lower for the 19.0 MeV beam. However we should remark that, in both cases, the \(^{7}\)Li primary beam intensity had to be kept below a safe value of about 100 pnA to avoid damages to the AGATA demonstrator (located downstream our facility) by fast neutrons produced in the target area and in the shielding surrounding the primary beam stopper. The full-width-at-half-maximum of the \(^{7}\)Be beams at the target position (reconstructed by means of the two PPACs) was about \(\sim 8\) mm and \(\sim 9\) mm in the horizontal and vertical axis, respectively.

3. Detection set-up: the detector array DINEX

\(^{7}\)Be scattered ions and other charged reaction products, originated from the interaction with a 1.0-mg/cm\(^2\) \(^{58}\)Ni target, were detected by means of the array DINEX [15]. Four \(\Delta E - E\) telescopes were located around the target in a cylindrical configuration. The thickness of the \(\Delta E\) layers was 40 \(\mu\)m, while the \(E_{res}\) stages were 1000 \(\mu\)m thick. Each detector had an active

![Energy spectra measured with a silicon detector placed at the secondary target position. The black continuous and red dotted lines refer to the higher and lower \(^{7}\)Be secondary beam energy, respectively.](image-url)
Figure 3. Energy spectra measured for the reaction $^7$Be + $^{58}$Ni at 23.2 MeV. Panel a shows the spectrum collected by the left monitor, while panels b-d display the energy spectrum gathered by the vertical strip number 1, 8 and 15, respectively, of the $\Delta E$ stage of telescope T1. Strip number 1 is that at the forwardmost polar angles covered by telescope T1.

area of 48.5 mm × 48.5 mm and both the p-side and the n-side were segmented into 16 strips, allowing a pixel definition of about 3 mm × 3 mm. The minimum distance between the inner detector of each telescope and the target position was about 70-72 mm. Two telescopes were located at forward (backward) angles, one in the left (in a upstream view of the reaction plane) hemisphere, T1 (T2), and one in the right hemisphere, T3 (T4). The mean polar angles in the laboratory frame were $\theta_{lab} = +55^\circ$, $+120^\circ$, $-65^\circ$ and $-140^\circ$ for the telescope T1, T2, T3 and T4, respectively. The overall solid angle coverage of this configuration was about 15% of $4 \pi$ sr.

Two additional silicon detectors were located at $\theta_{lab} = \pm 20^\circ$ for beam monitoring. The thickness of these detectors was 300 µm and a 5-mm collimator was placed in front of each of them. For normalization purposes a pulser with a constant frequency of 2 Hz was sent to all preamplifiers. The data acquisition system was triggered by the “OR” of the DINEX telescopes and the two silicon monitors. Trigger rates of about 20-30 Hz were typically recorded during the experiment.

4. Data analysis

Fig. 3 shows the experimental energy spectra collected by the monitor detectors located at $\theta_{lab} = 20^\circ$ (panel a) and by three vertical strips (panels b-d) of the $\Delta E$ layer of telescope T1 for the reaction $^7$Be + $^{58}$Ni at 23.2 MeV. Strip no. 1 (panel b) and no. 15 (panel d) corresponds to the T1 strip located at forwardmost and backwardmost angles, respectively, while strip no. 8 (panel c) is one of the middle strips of the detector. One can clearly appreciate the evolution
Figure 4. Counting statistics of the elastic scattering peak for the reaction $^7\text{Be} + ^{58}\text{Ni}$ at 23.2 MeV beam energy. Each point of the histogram refers to a vertical $\Delta E$ strip of telescope T1 (forward angles) and T4 (backward angles). The mean polar angle of each strip was assigned to the relative point in the drawing.

of the high-energy peak in the spectra while increasing the polar angles $\theta_{\text{lab}}$. The peak shifts toward lower energies, gets broader and broader and its intensity decreases. This behavior is fully compatible with the kinematics and the cross section of the Rutherford scattering process. Other events are clearly visible at intermediate energies in the $\Delta E$ spectra of Fig. 3. These events will be subject of a further detailed $\Delta E - E$ and $E$-Time-of-Flight analysis. For the moment we concentrated on the scattering process at the higher beam energy.

Fig. 4 shows the counting statistics collected for the elastic peak by each vertical $\Delta E$ strip of telescopes T1 and T4. The plot was obtained after correcting the relative efficiency of the two telescopes (estimated via the 2-Hz pulser constantly plugged during the experiment into all electronic chains). We assigned to each strip in Fig. 4 a mean polar angle in the center-of-mass reference system, which was computed by means of a Monte-Carlo simulation of the whole experimental set-up. The same simulation was also used to extract the differential cross section for the scattering process. The code took into account: (i) the kinematics of the elastic scattering process, (ii) the Rutherford cross section, (iii) the geometry of the detector array DINEX, (iv) the secondary beam energy spread ($\sigma_E = 0.4$ MeV, see Fig. 2), (v) the secondary beam spot on target ($\sigma_x = 3.4$ mm and $\sigma_y = 3.8$ mm, reconstructed with the PPAC detectors), (vi) the energy loss within the whole target thickness (evaluated with the code TRIM [16]) and (vii) the experimental energy resolution (0.7% and 1.4%, measured with 5.486 $\alpha$-particles, for the monitor and the DINEX $\Delta E$ strips, respectively).

In the simulation a random interaction point along the whole target thickness (1.12 $\mu$m) was assumed event-by-event and the kinetic energy of the incoming particle was decreased according to the distance traveled through the target. The simulated data were normalized by requiring
Figure 5. Scattering angular distribution for the system $^7\text{Be} + ^{58}\text{Ni}$ at 23.2 MeV beam energy. Plotted errors account only for the statistical accuracy of the collected data. The red dotted line is an optical model fit of the experimental data.

that the integrated areas under the elastic peak corresponded to the experimental values at the forwardmost angles ($\theta_{\text{c.m.}} \leq 55^\circ$), where the differential cross section is expected to be purely Rutherford at this bombarding energy. Fig. 5 shows the result of the normalization procedure and the outcoming differential cross section for the reaction $^7\text{Be} + ^{58}\text{Ni}$ at 23.2 MeV. Plotted errors account only for the statistical accuracy of the collected data.

5. Optical model analysis

The data shown in Fig. 5 were analyzed within the framework of the optical model by means of the coupled-channel code Fresco [17]. The interaction potential between $^7\text{Be}$ and $^{58}\text{Ni}$ used as starting point for the optical model analysis was described according to a standard Akyüz-Winther [18] parametrization. The real part was a Woods-Saxon well with the following parameters: $V_0 = 39.76$ MeV, $r_0 = 1.15$ fm and $a_0 = 0.63$ fm. For the imaginary part of the potential we also assumed a Woods-Saxon well with $W_0 = V_0/2$, $r_i = r_0$ and $a_i = a_0$. Only the depths of both real and imaginary part of the potential were let free to vary, whereas all other parameters were kept fixed to the initial values. To account for the energy lost by the $^7\text{Be}$ secondary beam into the target thickness ($\Delta E \approx 1.0$ MeV [16]), the optical model fit was performed at 22.7 MeV beam energy, instead of 23.2 MeV. A preliminary best-fit of the experimental data was obtained with the following parameters: $V_0 = 19.6 \pm 1.8$ MeV and $W_0 = 41.2 \pm 3.8$ MeV. The corresponding angular distribution for the scattering process was drawn in Fig. 5 with a red dotted curve. The total reaction cross section resulting from the fit was $\sigma_R = 480 \pm 20$ mb (see Table 1 and Fig. 6).
Figure 6. Total reaction cross section for the system $^7\text{Be} + ^{58}\text{Ni}$. Black squares are taken from Ref. [11], whereas the red circle is the result of the present work. Beam energies are considered at mid-target depths.

Table 1. Total reaction cross section for the system $^7\text{Be} + ^{58}\text{Ni}$. The values between $E_{\text{lab}} = 15.1$-21.4 MeV were taken from Ref. [11], whereas the point at $E_{\text{lab}} = 22.7$ MeV is the result of the present work. Beam energies are considered at mid-target depths.

| $E_{\text{lab}}$ (MeV) | $\sigma_R$ (mb) |
|-------------------------|-----------------|
| 15.1                    | 20.4 ± 10.0     |
| 17.1                    | 106 ± 30        |
| 18.5                    | 182 ± 26        |
| 19.9                    | 330 ± 103       |
| 21.4                    | 506 ± 97        |
| 22.7                    | 480 ± 20        |

6. Discussion
Fig. 6 and Table 1 summarize the total reaction cross sections measured for the system $^7\text{Be} + ^{58}\text{Ni}$ in the energy range $E_{\text{lab}} = 15.1$-22.7 MeV. The first five points were taken from the optical model analysis described in Ref. [11]. The comparison clearly shows that our result is not fully compatible with the trend individuated by the data points collected at the University of Notre Dame (Indiana, USA). According to the low-energy data trend, one would expect a total reaction cross section of about 650 mb at 22.7 MeV. Our value is 170 mb lower than this expectation and falls even below the point measured at 21.4 MeV. We should remark that our preliminary optical model analysis of the scattering data still does not include the possibility that the projectile could
excite to its first excited state (M1 transition leading to $E_x = 0.429$ MeV), which, due to energy straggling induced by the target thickness and to the limited detector energy resolution, we were unable to distinguish experimentally from pure elastic scattering events. This possibility will be included in the forthcoming theoretical analysis, after the final evaluation of the $^7$Be angular distributions at both beam energies and the overall estimate of the systematical uncertainty introduced by the Monte-Carlo simulation. However the large discrepancy between our data and those obtained by the other group cannot be entirely justified by this missing channel, since its cross section would be (at most) of the order of a few tens mb.

We should also underline that the two points at $E_{lab} = 19.9-21.4$ MeV have rather huge error bars of about 30% and 20%, respectively, whereas the statistical accuracy of our preliminary result is about 5%. Therefore we cannot exclude a priori that our measurement, even if not consistent with the low energy data trend, might fit with these rather large error bars. Only the final evaluation of our data, especially of those collected at the lower $^7$Be beam energy, will be helpful to shed more light on this issue.

7. Summary
We measured for the first time the scattering process of $^7$Be radioactive nuclei from the proton shell-closed $^{58}$Ni target at 23.2 MeV beam energy. The $^7$Be RIB was produced with the facility EXOTIC at the Laboratori Nazionali di Legnaro. The facility is now fully operational for the production of light weakly-bound RIBs and is even undergoing an upgrading process to increase the maximum energy and the intensity of the secondary beams. At the moment we analyzed the scattering process for the system $^7$Be + $^{58}$Ni, while a careful analysis of other direct reaction channels (i.e. transfer, breakup and inelastic scattering) was left to a forthcoming phase of the data analysis. The optical model analysis of the scattering differential cross section enabled us to evaluate the reaction cross section with a statistical uncertainty of about 5%. The result was compared with those obtained at lower beam energies at the University of Notre Dame. The two data sets were found to be, at this stage of the analysis, not fully consistent each other. Some tentative explanations of the origin of the discrepancy were given.

Acknowledgements
This work was partially supported by the Italian MIUR within the project RBFR08P1W2_001 (FIRB 2008).

References
[1] M. Dasgupta, D.J. Hinde, N. Rowley, A.M. Stefanini, Ann. Rev. Nucl. Part. Sci. 48, 401 (1998).
[2] J.F. Liang and C. Signorini, Int. J. Mod. Phys. E 14, 1121 (2005).
[3] L.F. Canto, P.R.S. Gomes, R. Donangelo and M.S. Hussein, Phys. Rep. 424, 1 (2006).
[4] N. Keeley et al., Prog. Part. Nucl. Phys. 59, 579 (2007).
[5] M. Mazzocco, Int. J. Mod. Phys. E 19, 977 (2010).
[6] J.P. Bychowski et al., Phys. Lett. B 506, 26 (2004).
[7] P.A. De Young et al., Phys. Rev. C 71, 051601(R) (2005).
[8] J.J. Kolata et al., Phys. Rev C 75, 033002(R) (2007).
[9] A. Navin et al., Phys. Rev. C 70, 044601 (2004).
[10] A. Chatterjee et al., Phys. Rev. Lett. 101, 032701 (2008).
[11] E. Aguiler et al., Phys. Rev. C 79, 021601(R) (2009).
[12] A. Di Pietro et al., Phys. Rev. Lett. 105, 022701 (2010).
[13] F. Farinon et al., Nucl. Instrum. Meth. B 266, 4097 (2008).
[14] M. Mazzocco et al., Nucl. Instrum. Meth. B 266, 4665 (2008).
[15] A.M. Sanchez-Benitez et al., J. Phys. G: Nucl. Part. Phys. 31, S1953 (2005).
[16] J.F. Ziegler et al., The Stopping and Range of Ions in Solids, Vol. 1, Pergamon Press, Oxford, 1984.
[17] I.J. Thompson, Comput. Phys. Rep. 2, 167 (1998).
[18] R. Broglia, A. Winther, Heavy Ion Reactions (Addison-Wesley, 1990) p. 113.