Strong reaction channels for the system $^{17}\text{F} + ^{58}\text{Ni}$ at Coulomb barrier energies

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Abstract. The reaction dynamics induced by the $^{17}\text{F}$ Radioactive Ion Beam on the proton-shell closed $^{58}\text{Ni}$ target was studied at two colliding energies slightly above the Coulomb barrier. Charged reaction products were detected at forward angles and the quasi-elastic differential cross section was analyzed within the framework of the optical model in order to extract the reaction cross section and to investigate the relevance of direct reaction channels (inelastic scattering, breakup and transfer) at near-barrier energies. The comparison with the reaction induced by double-magic tightly-bound $^{16}\text{O}$ projectiles on the same target showed that the $^{17}\text{F}$ reaction cross section is moderately enhanced at the lower secondary beam energy. Direct reaction channels were also found to be more relevant than for the corresponding $^{16}\text{O}$-induced reaction.

1. Introduction

Scattering experiments, more than 100 years after Rutherford’s experiment, are still very useful tools to investigate some basic features of atomic nuclei. The advent of Radioactive Ion Beams (RIBs) has recently opened the gates to the study of exotic nuclei under extreme conditions of shape deformations, large neutron-to-proton and proton-to-neutron ratios, weak binding energy, low density nuclear matter distribution and neutron skin structure. Considering the still limited intensity of RIBs, scattering experiments are often the first (and sometimes the only available) source of information for the reaction dynamics induced by an exotic projectile.
First reaction dynamics experiments with light RIBs (nicely summarized in several recent reviews [1, 2, 3, 4, 5]) evidenced that the low binding energy of these projectiles has rather moderate effects on the fusion probability whereas it rather increases the reaction cross section with respect to reactions induced by well-bound projectiles. Within this framework we undertook the study of the scattering process for the system $^{17}\text{F} + ^{58}\text{Ni}$ at near-barrier energies. $^{17}\text{F}$ is a rather exotic nucleus: it has a very low breakup threshold $(S_p = 0.600 \text{ MeV})$ and its first excited state at 0.4935 MeV has a well known proton-halo character [6]. The main aim of the experiment was to extract the reaction cross section and to compare it with that measured for the reaction induced by tightly-bound $^{16}\text{O}$ ions on a $^{58}\text{Ni}$ target in the same energy range.

2. Experiment

The $^{17}\text{F}$ RIB was produced with the facility EXOTIC [7] at the Laboratori Nazionali di Legnaro (Italy) of the Istituto Nazionale di Fisica Nucleare. The production reaction was induced by a 100 MeV $^{17}\text{O}^6+$ beam impinging on a $^1\text{H}_2$ gas target. The primary beam intensity was about 100 pnA. Two secondary beam energies were obtained operating the target station at different conditions: the former, $54.1 \pm 1.1 \text{ MeV}$, with a 750 mbar gas pressure at liquid nitrogen temperature, and the latter, $58.5 \pm 1.0 \text{ MeV}$, warming up the target to room temperature and increasing the gas pressure up to 950 mbar. In both cases the secondary beam intensity was around $10^5 \text{ pps}$, with purities around 96% and 93% at the higher and lower energy, respectively. The main contaminant was the $^{17}\text{O}^{8+}$ scattered beam with an energy $\sim 14 \text{ MeV}$ smaller than that of the RIB under production. Additional details concerning the radioactive beam production technique at the facility EXOTIC can be found in Refs. [8, 9, 10, 11].

Charged reaction products originated from the interaction of the $^{17}\text{F}$ RIB with a 1.0 mg/cm$^2$ thick $^{58}\text{Ni}$ target were detected with the array EXODET [12]. This set-up consists of 8 $\Delta E - E$ telescopes, arranged along the faces of two cubes: one located at forward angles and the other one in the backward hemisphere with respect to the target position. Each detector has an active area of $50 \times 50 \text{ mm}^2$ and is single-sided segmented into 100 0.5-mm wide strips. In the present experiment the thickness of the $\Delta E$ layers (40-70 $\mu\text{m}$) was enough to completely stop $^{17}\text{F}$ scattered ions and $^{16}\text{O}$ reaction products. Therefore, quasi-elastic events, i.e. $^{17}\text{F}$ elastically/inelastically scattered ions, transfer products and $^{17}\text{F}$ breakup fragments, were selected according to their energy deposit into the $\Delta E$ layer. For statistical purposes the collected data were grouped into bins of 4-6 strips, hereafter called multistrips.

Fig. 1 shows the experimental energy spectra collected at the higher secondary beam energy for 4 multistrips located at average polar angles $\theta_{cm} = 34^\circ-87^\circ$. Due to the cubic configuration of EXODET, the geometrical efficiency of each multistrip had to be evaluated with an ad-hoc Monte-Carlo code. The results of the simulation are displayed with continuous lines in the four panels of Fig. 1. Simulated events were generated according to the Rutherford differential cross section and taking into account the secondary beam spot on target, the beam energy resolution, the energy lost into the target thickness and the detector energy resolution. The simulated curves were normalized to the experimental data collected by the multistrips located at scattering angles $\theta_{cm}$ smaller than 41$^\circ$, where the cross section is expected to be purely Rutherford at both secondary beam energies. The quasi-elastic differential cross sections (see Fig. 2) were extracted for each multistrip from the ratio between the integral of experimental and simulated data over the same energy interval. For additional details concerning the data analysis please refer to Refs. [9, 11].

3. Optical model analysis

Due to the limited energy resolution, projectile and target inelastic excitations, transfer processes and the breakup channel $^{17}\text{F} \rightarrow ^{16}\text{O} + p$ ($S_p = 600 \text{ keV}$) could not be distinguished experimentally from pure elastic scattering events. Therefore all these direct processes were
simultaneously included into the fitting procedure of the experimental data. The theoretical analysis was performed within the framework of the optical model with the coupled-channel code FRESCO [13]. We described the interaction potential between $^{17}$F and $^{58}$Ni with an Akyüz-Winther [14] parametrization. The real part was a Woods-Saxon well with initial values: $V_0 = 52.24$ MeV, $r_0 = 1.18$ fm and $d_0 = 0.63$ fm. For the imaginary part we also assumed a Woods-Saxon well with starting values $W_0 = V_0/2$, $r_i = r_0$ and $a_i = a_0$. In this section we briefly summarized the scheme adopted to select the direct reaction channels to include all of them simultaneously into the formalism of FRESCO. More details can be found in [11].

We included into the coupled-channel calculations inelastic scattering processes leading to the first (and only one bound) excited state of $^{17}$F at 0.4935 MeV and to the first excited state of $^{58}$Ni at 1.454 MeV. Excitations of target excited levels at excitation energies higher than 2 MeV were not taken into account since their contributions are presumably negligible with respect to that arising from the first excited state. We considered also p-stripping processes $^{17}$F + $^{58}$Ni → $^{16}$O + $^{59}$Cu ($Q_{pp} = 2.88$ MeV) leading to three $^{59}$Cu negative parity levels up to an excitation energy of about 1 MeV. These states can be nicely described as single-particle states with spectroscopic factors equal to 1. At higher excitation energies the $^{50}$Cu level scheme becomes very complicated and such a description is not possible. Other stripping channels were not considered since they all involve the rather unfavorable breaking of the $^{16}$O core in $^{17}$F. Pick-up reactions were also disregarded following $Q_{opt}$-arguments based on the semi-classical model of Brink [15]. Finally the breakup process was described according to a single-particle model [16, 17], where the $d_5/2$ bound valence proton in $^{17}$F, moving with respect to the $^{16}$O core, is promoted to continuum states. Electric dipole (quadrupole) transitions to $p_{3/2}$, $f_{5/2}$ and $f_{7/2}$ ($s_{1/2}$, $d_{3/2}$, $d_{5/2}$, $g_{7/2}$ and $g_{9/2}$) continuum states were considered. Magnetic and higher order electric transitions were not taken into account since they should provide quite small contributions. In order to include the breakup process into the formalism of FRESCO, the continuum above the $^{17}$F breakup threshold was discretized into 0.5-MeV (0.3-MeV) bins for dipole (quadrupole) excitations up to $E_x =$

**Figure 1.** Charged reaction product energy spectra measured for the system $^{17}$F $+ ^{58}$Ni at 58.5 MeV beam energy. Each panel refers to a multistrip located at different average polar angle $\theta_{cm}$. Experimental data are drawn with histograms, while continuous lines are the results of Monte-Carlo simulation performed assuming a pure Rutherford scattering process.

**Figure 2.** Quasi-elastic differential cross sections for the system $^{17}$F $+ ^{58}$Ni at near-barrier energies. Plotted errors include both statistical and systematical accuracies. Solid and dashed lines are results of the theoretical analysis performed within the framework of the optical model, as described in Sect. 3.
The results of the optical model analysis are displayed with solid and dashed lines in Fig. 2. The curves are the sum of the calculated differential cross sections for the elastic scattering process, the inelastic excitations of the projectile and target first excited states, the breakup channel and p-stripping processes leading to the first three states of $^{59}$Cu. The angular distributions for direct processes other than elastic scattering are individually depicted in Fig. 3, while the breakup differential cross section with respect to the continuum energy broken down into components is shown in Fig. 4. Both Figs. 3 and 4 refer to a RIB energy of 58.5 MeV.

From the performed analysis, we extracted a reaction cross section of 510.5 mb and 559.7 mb at the lower and higher secondary beam energy, respectively. Direct processes accounted for a quite relevant portion of the whole reaction cross section. Target and projectile inelastic excitation had cross sections of 46-53 mb and 21-22 mb, respectively, while smaller contributions were computed for the breakup channel (11-14 mb) and for the p-stripping process (7-17 mb). The last process has to be considered with a particular care, since the semi-classical model of Brink predicts that final states with excitation energy around 6.0-6.3 MeV should be preferably populated, whereas our calculations stopped at $E_x < 1.0$ MeV. In addition the p-stripping cross section increases with the excitation energy of the $^{59}$Cu final state and explorative calculations indicated that transfer processes leading to $^{59}$Cu positive parity states in the energy range $E_x = 1.0-3.4$ MeV ($S_p$ ($^{50}$Cu) = 3.414 MeV) could globally account for even 50-75 mbar. Thus, the computed values of 7-15 mb have to be considered as lower limits for the the (whole) p-stripping process. Finally, if we add up the contributions calculated for all direct processes, we get a cumulative cross section of (at least) 85-106 mb, which corresponds to 17-19% of the whole reaction cross section. This percentage is 50% larger than that for the benchmark reaction $^{16}$O + $^{58}$Ni [18], guiding to the conclusion that direct reaction channels are more strongly populated in the $^{17}$F-induced reaction. This feature could be strongly related to the low binding energy of the $^{17}$F valence proton.
4. Discussion
The reaction cross sections extracted from the present analysis are plotted in Fig. 5 together with the data for five other reactions induced by weakly-bound ($^6$He [19], $^6$Li, $^7$Be, $^8$B [20]) and tightly-bound ($^{16}$O [18]) projectiles on medium-mass targets at Coulomb barrier energies. The data were plotted according to the formalism suggested by Shorto et al. [21] with dimensionless variables defined as follows:

$$F(x) = \frac{2E}{\hbar \omega R_B^2} \sigma_{TR} \quad \text{and} \quad x = \frac{E - V_B}{\hbar \omega}$$

where $R_B$, $V_B$ and $\hbar \omega$ are the potential barrier radius, height and curvature, respectively, and $E$ is the bombarding energy in the center-of-mass frame. This reduction of the cross section data eliminates all static effects, i.e. system size and barrier height, and those related to couplings to bound states, leaving only the effects of breakup couplings [22].

Fig. 5 shows that two conflicting conclusions can be drawn for the system $^{17}$F + $^{58}$Ni according to the projectile bombarding energy. At the lower secondary beam energy $^{17}$F appears as “exotic” as the 2n-halo $^6$He, while at the higher secondary beam energy it seems to be as “standard” as the doubly-magic $^{16}$O. This unexpected behavior could be ascribed to the underestimation of the contribution of direct channels, especially of the p-stripping process, to the reaction cross section at the higher secondary beam energy. Coupled-channel calculations showed that the p-stripping cross section has the steeper dependence on the bombarding energy among all direct processes and that it also rapidly increases with the excitation energy of the target-like nucleus. Our analysis stopped at $E_x < 1.0$ MeV and the explorative calculations performed up to $E_x = 3.4$ MeV (still 3 MeV below the $Q_{opt}$-window!) indicated possible additional contributions of at least 50-75 mb. On the experimental side, Fig. 2 shows that the data points in the range $\theta_{cm} \sim 60^\circ$-$65^\circ$ exceed the predictions of the coupled-channel approach and Fig. 3 displays that this angular range is particularly close to the maximum of the angular distribution predicted for the p-stripping process. These outcomes confirm this direct process as the main responsible for the conflicting behavior of the reaction cross section at the two bombarding energies.

5. Summary and future
The reaction dynamics induced for the $^{17}$F RIB on the proton-shell closed target $^{58}$Ni was investigated at two secondary beam energies around the Coulomb barrier. The experimental
data were analyzed within the framework of the optical model in order to extract the reaction cross section and to study the relevance of direct reaction processes at near-barrier energies. The comparison with the benchmark reaction induced by the doubly-magic tightly-bound $^{16}\text{O}$ on the same target nucleus, shows that the contribution of direct process to the reaction cross section is at least 50% higher than for the $^{17}\text{F}$-induced reaction. This feature could be strongly related to the low binding energy of the $^{17}\text{F}$ valence proton.

The reaction cross section data exhibited an anomalous behavior according to the bombarding energy. At the lower secondary beam energy the “reduced” reaction cross section is moderately enhanced with respect to the system $^{16}\text{O} + ^{58}\text{Ni}$, and $^{17}\text{F}$ appears as “exotic” as the 2n-halo $^6\text{He}$. On the contrary, at the higher beam energy of our experiment, no enhancement is evident and the loosely-bound $^{17}\text{F}$ seems to behave like the doubly-magic $^{16}\text{O}$. Our investigation indicates the p-stripping process as the main responsible for this contradictory effect since its cross section has the steeper dependence on the incoming energy among all direct processes and it most likely provides at the higher secondary beam energy a contribution to the reaction cross section larger than predicted. Moreover, from a theoretical point-of-view, our calculations stopped at a final state excitation energy smaller than 1.0 MeV, while the population of states with $E_x \sim 6.0 - 6.3$ MeV is suggested by the the semi-classical model of Brink. Explorative calculations performed up to $E_x = 3.4$ MeV indicates that the cross section for the p-stripping process could have been underestimated by at least a factor 5-8.

Future experiments should foresee not only the possibility to unambiguously distinguish between $^{17}\text{F}$ scattered ions and $^{16}\text{O}$ reaction products, but also the coincidence measurement of $^{16}\text{O}$ and protons, to unravel whether the reaction mechanism triggering the $^{16}\text{O}$ production is mainly a p-stripping process or a breakup reaction. On the theoretical side, developments are needed in order to provide a more comprehensive description of the breakup reaction mechanism, for instance by including the continuum-continuum couplings into the optical model calculations, and the p-stripping process to p-unbound states of the target-like nucleus at excitation energies around the $Q_{val}$-window.

References

[1] J.F. Liang and C. Signorini, Int. J. Mod. Phys. E 14, 1121 (2005).
[2] L.F. Canto, P.R.S. Gomes, R. Donangelo and M.S. Hussein, Phys. Rep. 424, 1 (2006).
[3] N. Keeley et al., Prog. Part. Nucl. Phys. 59, 579 (2007).
[4] N. Keeley et al., Prog. Part. Nucl. Phys. 63, 396 (2009).
[5] M. Mazzocco, Int. J. Mod. Phys. E 19, 977 (2010).
[6] R. Morlock et al., Phys. Rev. Lett. 79, 3837 (1997).
[7] F. Farinon et al., Nucl. Instrum. Meth. B 266, 4097 (2008).
[8] M. Mazzocco et al., Nucl. Instrum. Meth. B 266, 4665 (2008).
[9] M. Mazzocco et al., Nucl. Phys. A 834, 488c (2010).
[10] C. Signorini et al., Eur. Phys. J. A 44, 63 (2010).
[11] M. Mazzocco et al., Phys. Rev. C 82, 054604 (2010).
[12] M. Romoli et al., IEEE T. Nucl. Sci. 52, 1860 (2005).
[13] L.J. Thompson, Comput. Phys. Rep. 2, 167 (1998).
[14] R. Broglia, A. Winther, Heavy Ion Reactions (Addison-Wesley, 1990) p. 113.
[15] D.M. Brink, Phys. Lett. B 40, 37 (1972).
[16] L. Fortunato and A. Vitturi, Eur. Phys. J. C 26, 33 (2005).
[17] A. Mason et al., Eur. Phys. J. 39, 107 (2009).
[18] N. Keeley et al., Nucl. Phys. A 582 (1995) 314.
[19] E. Di Pietro et al., Phys. Rev. C 69, 044613 (2004).
[20] E. Aguilera et al., Phys. Rev. C 79, 021601(R) (2009).
[21] J.M.B. Shorto et al., Phys. Lett. B 678, 77 (2009).
[22] L.F. Canto et al., J. Phys. G 36, 015109 (2009).