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Does the breakup process affect the reaction dynamics for the systems ^{17}O,^{17}F + ^{58}Ni at Coulomb barrier energies?

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Abstract. The scattering processes of two mirror projectiles, the well bound ^{17}O (S_n = 4.143 MeV) and the loosely bound radioactive ^{17}F (S_p = 0.600 MeV), on the proton closed shell target ^{58}Ni were measured at several energies around the Coulomb barrier. The experimental data were analyzed within the framework of the optical model to extract the reaction cross section and to investigate the role played by direct reaction channels at near-barrier energies. The comparison shows a similar behaviour for the two A = 17 projectiles despite their very different binding energies and suggests a rather small effect of the ^{17}F breakup channel on the reaction dynamics.

1 Introduction

Breakup related effects on the reaction dynamics induced by light weakly bound Radioactive Ion Beams (RIBs) at near-barrier energies has been the subject on an intense scientific activity from both an experimental and a theoretical point of view. In particular, it has been largely discussed whether the low binding energy and the halo structure of some of these light RIBs should increase the fusion probability or rather the reaction cross section (see [1] and references therein).

Within this framework we undertook the study of the ^{17}F reaction dynamics on a ^{208}Pb and, more recently, on a ^{58}Ni target. This projectile has a very low binding energy (S_p = 0.600 keV) and its nuclear structure could be nicely described as a single (loosely bound) proton orbiting around a well bound ^{16}O core. In addition, the ^{17}F first excited state is located just 106 keV below the breakup threshold and it is a well known proton halo state.

Our first experiment with a ^{17}F secondary beam was performed at the Argonne National Laboratories (USA) in 2002 [2], while the subsequent series was carried out starting from 2006 at the Laboratori Nazionali di Legnaro (Italy), after the commissioning of facility EXOTIC [3] for the in-flight production of light RIBs.

The results obtained in the latest experiments for the system ^{17}F + ^{58}Ni [4] were compared with those gathered for the reference system ^{16}O + ^{58}Ni [5] and for reactions induced by other loosely bound light projectiles (^{6}He [6], ^{7,11}Be [7,8], ^{8}B [7]) on a ^{58}Ni or ^{64}Zn target at near-barrier energies. With the aim of adding a new

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benchmark reaction to the present scenario, in April 2011 we measured the scattering process for the system ^{17}O + ^{58}Ni in a wide energy range around the Coulomb barrier. ^{17}O is indeed the mirror nucleus of the radioactive weakly-bound ^{17}F. The two isobars have similar shell model configurations with $d_{5/2}$ ground states and low-lying $s_{1/2}$ first excited states, but very different binding energies (i.e. breakup thresholds): S_p = 0.600 MeV for ^{17}F and S_n = 4.143 MeV for ^{17}O. Thus, nuclear structure related effects on the reaction dynamics should be more easily decoupled from breakup related effects for ^{17}O- than for ^{17}F-induced reactions.

The present paper is organized as follows: Sec. 2 briefly summarizes the results recently obtained for the system ^{17}F + ^{58}Ni (and already published in [4]), Sec. 3 describes the experimental set-up used for studying the reaction ^{17}O + ^{58}Ni and presents the preliminary results of the data analysis. The two systems are compared in Sec. 4 and some concluding remarks are finally drawn in Sec. 5.

2 The system ^{17}F + ^{58}Ni

2.1 Experiment

The ^{17}F beam for this experiment was delivered by the facility EXOTIC [3] at the Laboratori Nazionali di Legnaro of the INFN. A $^{17}O^{6+}$ primary beam with an energy of 100 MeV was impinging on a gas target filled with molecular hydrogen and producing the $^{17}F^{9+}$ RIB via the two-body reaction p(^{17}O,^{17}F)n. Starting from a 100 pnA primary beam, a secondary beam intensity of about 10^5 pps was achieved. Two ^{17}F energies were obtained by operating the target at different gas pressures and temperatures: 54.1 and 58.5 MeV. Additional details on the ^{17}F secondary beam production at the facility EXOTIC can be found in Ref. [4].

Charged reaction products originated by the interaction with a 1.0 mg/cm^2 thick ^{58}Ni target were detected by means of the detector array EXODET [9]. It essentially consisted of eight 50 x 50 mm^2 ΔE-E silicon telescopes, arranged along the faces of two cubes closely packed around the target: one located at forward angles and the other in the backward hemisphere.

In the energy range of the experiment, the ranges in silicon of elastically/inelastically scattered ^{17}F nuclei as well as of ^{16}O ions, produced via the 1p-stripping transfer $^{17}F + ^{58}Ni \rightarrow ^{16}O + ^{59}Cu$ or via the breakup process $^{17}F \rightarrow ^{16}O + p$, were shorter than the thickness of the ΔE layer (40 μm). Charged reaction products could be selected only according to their energy deposited in the first detector layer. Therefore, it was not possible to separate the contribution arising from the elastic scattering from those originated by inelastic scattering processes, the 1p-stripping transfer and the breakup channel. Hereafter we will refer to all these events together with the name of "quasi-elastic" events. Additional details about the data reduction are addressed in Ref. [4].

2.2 Optical model analysis

To partially overcome the lack of experimental discrimination between different direct reaction mechanisms, we analyzed the quasi-elastic differential cross sections within the framework of the optical model by means of the coupled-channel code FRESCO [10]. Inelastic excitations leading to the first projectile and target excited states were included in the theoretical calculations with their experimental transition probabilities, the breakup process was described according to the single-particle model of Fortunato and Vitturi [11], while for transfer processes we followed the formalism of Brink [12]. The experimental data were fitted with the sum of the differential cross sections for all these direct channels. A more detailed description of this procedure can be found in Ref. [4].

As a result, we computed a reaction cross section of 510.5 mb and 559.7 mb at the lower and higher secondary beam energy, respectively. The contribution of inelastic excitations was estimated to be about 67-74 mb, while the breakup process accounted for 11-14 mb. Particular care was paid to the p-stripping process, since only excited states up to 3 MeV below the Q_{opt}-window could be included in the calculations. For this process, the evaluated cross sections of 7-15 mb had therefore to be considered as lower limit estimates. We noticed furthermore that the reaction cross section increases only by 10% between the two ^{17}F energies, while for the system ^{16}O + ^{58}Ni [5] the reaction cross section increases by 55% over the same energy range. This outcome fuels some suspicions that the "degree of contamination" of pure elastic scattering events could be somewhat larger at the higher ^{17}F secondary energy, being the contribution of direct processes other than the elastic scattering (especially of the p-stripping transfer) underestimated.

3 The system ^{17}O + ^{58}Ni

3.1 Experimental set-up

The reaction ^{17}O + ^{58}Ni has been investigated very recently (April 2-5, 2011) at the Laboratori Nazionali di Legnaro in the framework of the commissioning of the new detector array EXPADES [13]. Each module of EXPADES consists of a 64 x 64 mm^2 silicon detector with a thickness of 300 μm. Each detector side is segmented into 32 strips and the readout electronics is based on an innovative 32-channel ASIC chipset, manufactured by IDEAS-GM (Norway). The valuable advantage of this readout system is that only one signal contains the energy loss information for all the strips of one detector side (namely 32 channels) and therefore a strongly reduced number of electronic chains is required for the readout of the entire apparatus. This reduction is particularly suited when highly segmented detectors have to be used to ensure a large solid angle coverage still keeping a good granularity, i.e. especially for experiments involving low intensity RIBs.

3.2 Experiment

In this experiment we used two modules of EXPADES, one located at forward angles (covering the angular range $35° \leq \theta_{lab} \leq 70°$) while the other in the backward hemisphere ($80° \leq \theta_{lab} \leq 110°$).

A $^{17}O^{4+}$ beam, with intensity about 1-4 enA and energy varying with 2.5-MeV steps from 42.5 to 55 MeV was impinging on a 0.15 mg/cm^2 ^{58}Ni foil, tilted by 45° with respect to the beam axis. A thin ^{208}Pb layer (0.05 mg/cm^2) was evaporated downstream the ^{58}Ni target material for normalization purposes.

Fig. 1 shows the experimental energy spectra collected by 5 vertical strips of the EXPADES module located at backward angles. Each panel corresponds to a different strip. The peaks at higher and lower energies arise from the elastic scattering process ^{17}O ions on the ^{208}Pb and the ^{58}Ni target layer, respectively.

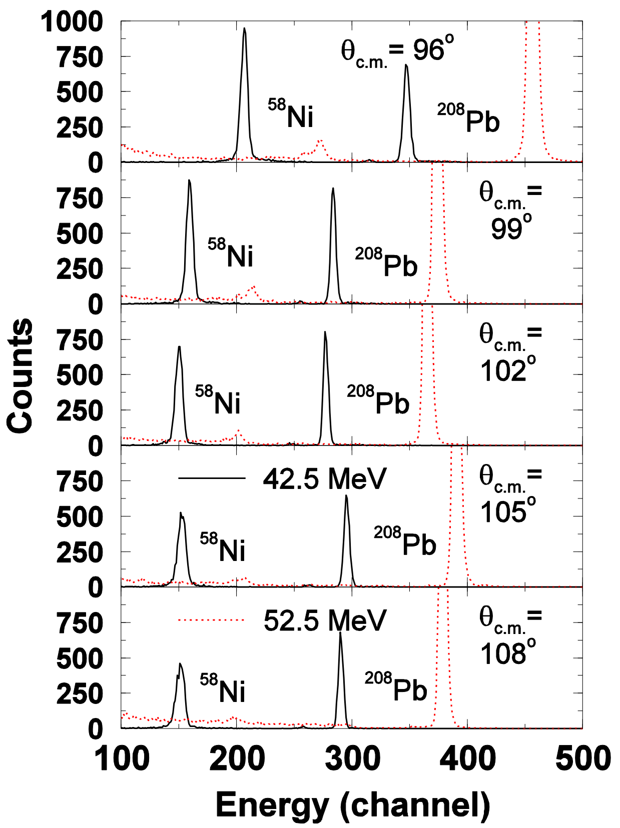

Fig. 1. Energy spectra for the reactions ^{17}O + ^{58}Ni,^{208}Pb at 42.5 (black solid line) and 52.5 MeV (red dotted line). Each panel corresponds to a different vertical strip of the EXPADES module located at backward angles. The angles refer to mean $\theta_{c.m.}$ of each strip for the ^{17}O + ^{58}Ni system.

We displayed in Fig. 2 a preliminary evaluation of the elastic scattering differential cross sections for the six bombarding energies of our experiment. So far the data analysis has been limited to the energy spectra measured by the vertical strips. Each point in Fig. 2 corresponds to the (properly normalized) strip-by-strip ratio between the areas of the ^{17}O peaks due to the elastic scattering process on a ^{58}Ni and a ^{208}Pb target, being the cross sections for the latter case a purely Rutherford cross section. The data reduction is particularly critical for the strips located at very forward angles, where each strip covers a wider range of polar angles and the two elastic peaks nearly overlap. As a consequence, the experimental points at $\theta_{c.m.} < 65°$ exceed in several cases the unity. This excess is somewhat larger than that expected for a strong Fresnel peak. The data evaluation will be improved in the next future by performing a pixel-by-pixel analysis for the strips at the most forward angles.

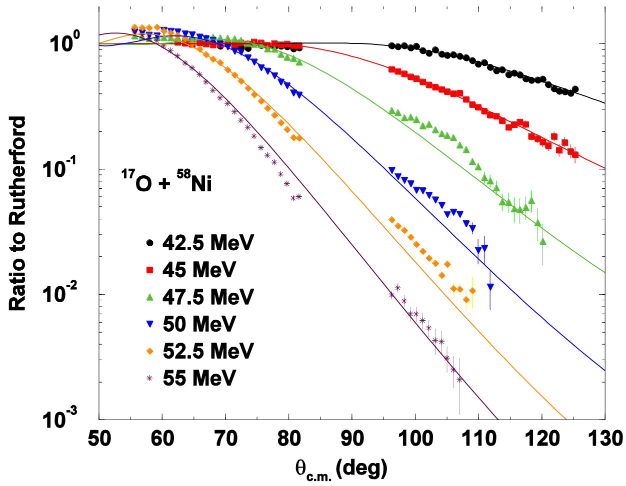

Fig. 2. Elastic scattering differential cross sections for the reaction ^{17}O + ^{58}Ni. The data evaluation is still preliminary. Errors bars include statistical accuracy and a 5%-systematical uncertainty related to data normalization procedure. Continuous lines are the results of optical model fits of the experimental data performed using the coupled-channel code FRESCO [10].

3.3 Optical model analysis

A very preliminary optical model analysis of the experimental data has been also performed. The interaction potential between the ^{17}O and ^{58}Ni nuclei was described according to a standard Akyüz-Winther [14] parameterization. The real and imaginary parts were Woods-Saxon wells with the following parameters V_0 = 51.70 MeV, W_0 = 25.85, $r_0 = r_i$ = 1.18 fm and $a_0 = a_i$ = 0.63 fm. These values were used as starting points for fitting the experimental data. Only the real and imaginary depths of the potential were let free to vary, while all others parameters were kept fixed to the initial values. The fits were performed with the SFRESCO subroutine of the main coupled-channel code FRESCO [10] and are displayed in Fig. 2 with lines. For the moment we assumed all events as originating from a pure elastic scattering process, even if the experimental energy resolution (~1%) and the energy straggling due to the angular range covered by each vertical strip did not allow to separate the events leading to the excitation of the ^{17}O first excited state at E_x = 0.871 MeV.

The preliminary results for the reaction cross sections for the system ^{17}O + ^{58}Ni are the following: 253 mb at 42.5 MeV, 452 mb at 45 MeV, 590 mb at 47.5 MeV, 694 mb at 50 MeV, 779 mb at 52.5 MeV and 869 mb at 55 MeV.

4 Discussion

A comparative analysis of the reaction cross section data for reactions induced by light projectiles on medium-mass targets, such as ^{58}Ni and ^{64}Zn, is displayed in Fig.3. The data were reduced according to the formalism of Shorto et al. [15] with dimensionless variables defined as follows:

$$x = (E_{c.m.} - V_B)/\hbar\omega \quad (1)$$

$$F(x) = 2E_{c.m.}\, \sigma_R /(\hbar\omega\, R_B^2) \quad (2)$$

R_B, V_B and ħω being the potential barrier radius, height and curvature and $E_{c.m.}$ being the bombarding energy in the center-of-mass reference frame. This reduction eliminates all static effects, i.e. the system geometrical size and the Coulomb barrier height, and those related to bound states, leaving thus only the effects of breakup couplings [16].

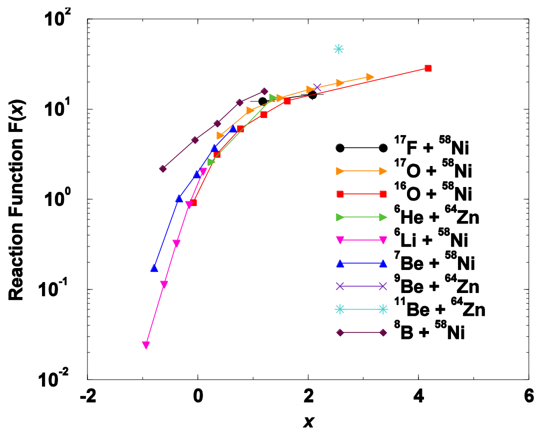

Fig. 3. Total reaction function F(x) for reactions induced by light projectiles on medium-mass targets. F(x) and x are calculated according to the formalism of Ref. [16].

The comparison between the systems ^{17}F + ^{58}Ni and ^{16}O + ^{58}Ni immediately shows an inconsistency of the data for the reaction induced by the radioactive projectile. In fact, at the lower ^{17}F secondary beam energy *F(x)* is about 50% larger than for ^{16}O, while at the higher energy the ^{17}F value falls nearly below the ^{16}O curve. This outcome suggests that the quasi-elastic scattering data at 58.5 MeV have a larger degree of contamination from direct processes, leading to an underestimation of the reaction cross section, as already described in Section 2.2.

An even more meaningful comparison is provided by the preliminary results obtained for the system ^{17}O + ^{58}Ni. These two projectiles have similar nuclear structures, but very different binding energies: 0.600 MeV for the ^{17}F and 4.143 MeV for the ^{17}O. Therefore, any difference in the reaction dynamics between the two isobars should be, in a first approximation, ascribed to the different binding energy of the valence nucleon. Considering that the data reduction should account for all static effects and for dynamical effects related to bound states, the tiny difference between the ^{17}F data point at the lower secondary beam energy and the ^{17}O curve leaves very small room to the breakup channel.

An overall comparison of reactions induced by light loosely bound projectiles shows that the ^{11}Be [7], bound by S_n = 0.504 MeV, exhibits by far the largest reactivity among all light projectiles. On the other side it should be very interesting to extend the measurements performed with the proton halo ^{8}B [8], bound only by S_p = 0.1375 MeV, to the same energy range covered for the system ^{11}Be + ^{64}Zn.

5 Concluding remarks

The scattering process of the mirror projectiles ^{17}F and ^{17}O on a ^{58}Ni target has been measured in the energy range around the Coulomb barrier. The data have been analyzed within the framework of the optical model to extract the reaction cross section and to investigate the relevance of direct reaction channels at near-barrier energies. The data point at the ^{17}F higher energy exhibits an anomalous behaviour, probably related to the fact that the direct channels (especially the p-stripping) were not properly described in the theoretical approach. At the lower ^{17}F secondary beam energy, the reduced reaction cross section is nearly superimposed to the curve obtained from the preliminary analysis of the system ^{17}O + ^{58}Ni. Since the reduction procedure should account for all static effects and for dynamical processes related to bound states, this similarity suggests a small influence of the breakup channel in the ^{17}F reaction dynamics. These issues should be explicitly verified experimentally. Future measurements involving the ^{17}F nucleus should foresee the possibility to unambiguously distinguish between different reaction channels and, moreover, an improved theoretical description, especially for transfer processes, would be very welcome.

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