Elastic scattering measurement for the system $^{17}$O + $^{58}$Ni at Coulomb barrier energies with silicon strip detectors exploiting ASIC electronics

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Abstract The quasi elastic scattering of a $^{17}$O projectile from a $^{58}$Ni target has been studied at beam energies ranging from 42.5 to 55.0 MeV in 2.5 MeV steps. The total reaction cross sections were derived from the measured angular distributions by using an optical model fit within the coupled-channel code FRESCO. These cross sections are very similar to those measured for $^{17}$F (loosely bound by 0.6 MeV), mirror nucleus of $^{17}$O (tightly bound by 4.14 MeV). This outcome points out that, in this energy range, the small binding energy of the $^{17}$F valence proton has negligible influence onto the reactivity of such a loosely bound projectile, contrary to simple expectations, and to what observed for other loosely bound nuclei. The reaction dynamics seems to be influenced mainly by the Coulomb interaction which is similar for both mirror projectiles.

1. Introduction
The present paper reports on the investigation of the scattering of a $^{17}$O projectile by a $^{58}$Ni target at several projectile energies around the Coulomb barrier. This work had two main motivations that will be illustrated in the following paragraphs.

1.1 The physics case
Over the last 10 years our group has been studying the dynamics of the reactions induced by loosely bound light projectiles, both stable and radioactive, on medium and heavy mass targets at energies around the Coulomb barrier [1]. Most of these studies has been undertaken at the Tandem Van de Graaff accelerator of the INFN Laboratori Nazionali di Legnaro (LNL) near Padova, Italy, where a beam line was installed for the in flight production of Radioactive Ion Beams (RIB) [2,3].
Such nuclei are produced via inverse kinematics on gas targets, namely: $^1$H, d, $^3$He. The radioactive beams produced up to now are listed in Table 1. The main goal was the extraction of the reaction cross section from the elastic scattering angular distributions and its comparison to those extracted for “similar” well bound nuclei (mostly stable) on the same targets. Indeed such RIB projectiles are very loosely bound, typically with binding energies a factor around 10 smaller than those of the stable nuclei. This calls “a priori” for more reactivity, i.e. larger reaction cross sections.

The Fig.1 we present a comparison between reaction cross sections around Coulomb barrier energies induced by loosely bound nuclei namely: $^6$He+$^{64}$Zn [4], $^7$Be+$^{58}$Ni, $^8$B+$^{58}$Ni and $^6$Li+$^{58}$Ni [5], $^{17}$F+$^{58}$Ni [6] and by well bound nuclei $^{16}$O+$^{64}$Zn [7], $^{16}$O+$^{58}$Ni [8]. In this figure the $y$ ($\approx \sigma_{\text{reaction}}$) and x axes ($\approx E_{\text{cm}}$) are normalized to the different radii and Coulomb barriers, respectively, of the various systems in order to make a more meaningful comparison. The general trend is that the reaction cross sections induced by the most loosely bound nuclei, such as $^6$He, $^6$Li, $^7$Be, $^8$B, are larger than those induced by the well bound one $^{16}$O. The behavior of $^{17}$F, with $S_n = 0.6$ MeV, is anomalous because it is more similar to that of $^{16}$O. To further investigate this point we decided to perform the same experiment by using a $^{17}$O projectile, that has a similar nuclear structure to that of $^{17}$F but it is well bound with $S_n = 4.14$ MeV.

| Table 1 |  |  |
|---|---|---|
| Radioactive ion beams produced at the beam line EXOTIC at the LNL laboratories |  |  |
| Beam | Intensity | Production reaction | Primary beam intensity (pnA) |
|---|---|---|---|
| $^{17}$F | $10^5$ Hz | $p(^{16}$O,$^{17}$F)n | $\sim 70$ |
| $^7$Be | $2.3 \times 10^5$ Hz | $p(^{6}$Li,$^7$Be)n | $\sim 100^*$ |
| $^8$B | $1.5 \times 10^3$ Hz | $^3$He ($^6$Li,$^8$B)n | $\sim 150$ |

*the primary beam intensity was limited by the radiation dose produced in the gas target in order to limit n-radiation damages to the neighboring Ge detectors of the AGATA – demonstrator.*

1.2 The detection technique

It is well known that the RIBs produced so far have intensities lower by many orders of magnitude than those of stable beams, requiring therefore the design of high efficiency detection techniques (ideally with $4\pi$ geometry) connected to high granularity. Large area, high granularity Si detectors are being manufactured by Micron Semiconductor Ltd, UK. The detector type BB7(DS)-300 $\mu$m thick is well suited for our measurements: it has a large area (64 x 64 mm$^2$) and a high segmentation with 32 strips, each 2 mm wide, per side. Each detector would require 64 conventional electronics channels. If a large solid angle coverage is needed (i.e. 8 such detectors at a distance of 10 cm from the target to ensure a 10% solid angle coverage ) connected, for example, with Z identification via a thin $\Delta E$ detector with similar strip structure, one ends up to 1024 conventional electronic channels. This number can be significantly reduced if ASIC type electronics is adopted.

During the last years our group has been developing home-made electronics based on ASIC chipsets [9]. The first approach was by using the ASIC chipset AToM-II [10] for single sided strip detectors. This chipset was originally developed for high energy physics, i.e. for minimum ionizing particles. Our current approach has been based onto commercial chipsets, better tailored for nuclear physics experiments involving heavily ionizing particles.
The aim of the experiment we are presenting in this contribution was motivated by a significant physics case, the $^{17}$O scattering from a $^{58}$Ni target at Coulomb barrier energies, while performing the in-beam commissioning of our ASIC based electronics.

![Fig. 1. Comparison of reaction cross sections from loosely bound and well bound light projectiles on medium mass targets. See text for more details about the chosen axes.](image)

1– The experiment

1.1– Detectors.

The elastic scattering differential cross section for the reaction $^{17}$O+$^{58}$Ni was investigated with the $^{17}$O beam delivered by the Tandem Van de Graaff accelerator of the INFN Laboratori Nazionali di Legnaro (Padova, Italy). The data were collected at beam energies from 42.5 up to 55.0 MeV in 2.5 MeV steps, for a total amount of 6 energies. The $^{17}$O beam current was ranging from 1 to 5 enA. The target consisted of a layer of $^{58}$Ni 150 $\mu$g/cm$^2$ thick, backed by a $^{208}$Pb layer 50 $\mu$g/cm$^2$ thick for normalization purposes. Two double sided Si strip detectors with a thickness of 300 $\mu$m were used. The detectors had an active area of 64 x 64 mm$^2$ and were segmented on both sides with 32 strips, each 2 mm wide, with strips perpendicular to each other. The two detectors were located at a distance of 100 mm from the target and spanning polar angles $\theta_{lab}$ ranging from 32° to 68° and from 82° to 118°, respectively. In addition two monitors were located at ± 20°.

1.2- The ASIC electronics.

The 32 signals out of each detector side were read by a couple of ASIC chipsets: (i) a slow shaper VA (for the processing of the energy signals) and (ii) a fast chipset TA, including a leading edge discriminator for timing purposes. This allows us to have only one signal out of the 32 strips to be processed by a suitable sampling ADC, instead of 32 signals needed for conventional electronics. The chipsets used were: VA32HDR14.2 and TA32CG.3 manufactured by Gamma Medica IDEAS (Norway). All the electronics has been developed in our INFN laboratories between Milano, Napoli and Padova. The system is schematized in Fig. 2. The main features of the different elements are the following: (i) the linear...
shaper chip VA, (ii) the leading edge fast discriminator chip TA for timing purposes, (iii) the motherboard (MB in Fig. 2) delivers the appropriate polarizations and controls to the all the chips, (iv) the 12-bit multisampling ADC with 50 MHz sampling rate, v) the Trigger Supervisor Interface (TSI) provides the appropriate trigger signals, (v) the data acquisition (DAQ) and run control system.

This set up gives an energy resolution of ~ 85 keV for 5.48 MeV alpha particles and can run with a data rate up to ~ 1 kHz, fully suited for RIB experiments where the beam intensities are orders of magnitude lower than for stable beams.

Fig. 2. Scheme of the readout electronics for the silicon detectors based onto two ASIC chipsets: the linear shaper VA and fast-leading edge discriminator TA for triggering purposes. See text for additional details.

1.3 - Experimental results.

In this conference proceeding we report on the results of the analysis of the data collected by detector vertical strips. More details about the electronics and the pixel-by-pixel analysis of the gathered data will be reported in a forthcoming paper.

Fig. 3 shows, as an example, the energy spectra collected for all 6 energies in the strip nr. 4 of the detector located at more backward angles. From these spectra, recorded at an angle where the kinetic energy spread over all the vertical strip is negligible, an overall resolution of the detection system $\Delta E/E \sim 1.2\%$ has been evaluated. Consequently the $^{17}\text{O}$ first excited state at 0.87 MeV could not be resolved in a strip-by-strip analysis, and the scattering data have to be considered as quasi-elastic. We will come back to this point later, when discussing the optical model fit to the data. Please note also that the energy of the particles detected increases “unusually” with decreasing ADC channel number. This originates from the fact that the signals of the two detector sides, one with positive polarity and one with negative polarity are simultaneously analyzed by the same multisampling ADC, which locates zero amplitude signals at about channel 2048, so that positive (negative) signals are stored from channels 2048 to 4096 (2048 to 0) and consequently the energy increases with increasing (decreasing) ADC channel number.
Fig. 3. – Energy spectra at the 6 beam energies of the strip nr. 4 of the detector located at more backward angles.

2 – Reaction cross sections and discussion.

The differential cross section can be evaluated from the present experimental data according to the following well known formula:

$$N_i = B_i T_i \frac{d\sigma}{d\Omega}(\theta) \Delta\Omega_i$$

$N_i$ are the counts measured in the detector, or detector portion, 

$$\frac{d\sigma}{d\Omega}(\theta)$$

is the differential cross section at angle $\theta$, 

$\Delta\Omega_i$ is the related detector covered solid angle,
B, and T, are, respectively, the total number of beam particles and the number of target particles per surface units.

The data normalization of the quasi-elastic scattering distributions for the system $^{17}$O + $^{58}$Ni was performed by using the elastic scattering events from the $^{208}$Pb target, with the incoming beam energy range 42.5-55.0 MeV well below the Coulomb barrier for the system $^{17}$O + $^{208}$Pb ($V_c \approx 80$ MeV). Therefore, the elastic cross section for the reaction $^{17}$O + $^{208}$Pb is purely Rutherford over the entire angular range covered by the two DSSS detectors. The actual target thickness ratio between the $^{58}$Ni and $^{208}$Pb layers was deduced from the ratio between the $^{58}$Ni and $^{208}$Pb elastic scattering peaks in the energy spectra collected by the monitor detectors, where the elastic scattering cross section is purely Rutherford for both systems. We proceeded to a strip-by-strip normalization of the experimental data. The ratios of the elastic scattering angular distributions to the Rutherford differential cross sections for all 6 beam energies are depicted in Fig. 4.

The data have been fitted in the framework of the optical model formalism by using the subroutine SFRESCO within the coupled-channel code FRESCO [11]. A standard Woods-Saxon potential was adopted. In the fit only the potential depths V and W were let free to vary and the remaining parameters were kept fixed to the following values: $r_i = r_0 = 1.18$ fm and $a_i = a_0 = 0.63$ fm. The best fit values resulted to be $V = 55.96$ MeV, $W = 25.71$ MeV. Fig. 4 shows the results of the fitting procedure.

The reaction cross sections extracted from the fits are reported in Table 2. As stated in the previous section, the $^{17}$O data have to be considered quasi-elastic, since the excitation of the $^{17}$O first excited level at 0.87 MeV could not be experimentally resolved. The contribution of this inelastic excitation to the total reaction cross section was also estimated with code FRESCO and turned out to be about 2 mb at all energies in the range 42.5-55.0 MeV.

**Table 2**

| E (MeV) | 42.5 | 45.0 | 47.5 | 50.0 | 52.5 | 55.0 |
|--------|------|------|------|------|------|------|
| $\sigma$ (mb) | 253 | 452 | 590 | 694 | 779 | 869 |

**Fig. 4** – Angular distributions measured for the quasi-elastic scattering process for the system $^{17}$O + $^{58}$Ni. Continuous lines are the results of optical model fits of the collected data.

**Fig. 5** – Reduced reaction cross sections for the loosely bound $^{17}$F and the well bound $^{17,16}$O projectiles interacting with $^{58}$Ni target nuclei.
In Fig. 5 we compare the reduced reaction cross sections for the three systems $^{17}\text{F}, ^{16,17}\text{O} + ^{58}\text{Ni}$. The reduction procedure was adopted to account for the different radii and Coulomb barriers of the various systems. It is somehow unexpected that the $^{17}\text{F}$ ($S_p = 0.6\text{ MeV}$) reaction cross sections are:

i) nearly identical to the $^{17}\text{O}$ ones at the lower energy and

ii) even lower at the higher energy.

In order to confirm the trend in the point ii) other measurements are required, as already discussed in [6]. However, if we assume that the $^{17}\text{O}$ and $^{17}\text{F}$ reaction cross sections are essentially similar, the (unexpected) conclusion is that in this energy range the effect of the $^{17}\text{F}$ small binding energy on the reaction dynamics is very small, practically negligible. We might conclude that breakup process is mostly triggered by the Coulomb interaction (quite similar for both nuclei) rather than by the nuclear interaction (which could be affected by small binding energies). We also remark that an additional Coulomb barrier of about 2 MeV should be considered for the $^{17}\text{F}$ valence proton and this feature can somewhat counteracts the effects of the projectile very low binding energy.

It would be challenging to extend this investigation at lower as well as at higher bombarding energies.

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