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A new experiment on ^{19}F(p, α)^{16}O reaction at low energies and the spectroscopy of ^{20}Ne at large excitation energies

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Abstract. In these proceedings, we present new data for the p + ^{19}F reaction, obtained for the ^{19}F(p, α_0)^{16}O$_{gs}$ and ^{19}F(p, α_π)^{16}O$_{6.05}$ channels. The experiment was performed at the Singletron accelerator in Catania, with proton beam energies in the 1.1-1.3 and 1.6-1.7 MeV energy regions. This allowed us to provide new data for the α_π channel around 1.3 MeV projectile energy and to shed light on the ambiguities existing between previous data sets in the absolute value and in the peak shape of a particular resonance, in the α_0 channel, at around 1.6 MeV projectile energy.

1 Introduction

The investigation of nuclear reactions at sub-barrier energies has paramount importance in the understanding of the spectroscopy of light nuclear systems, and its astrophysical relevance [1, 2]. In this framework, the ^{19}F(p, α_0)^{16}O reaction has a peculiar relevance, since cross section related data from the α_0 and α_π channels may generate information on the occurrence and the properties of excited cluster states in the spectroscopy of the ^{20}Ne compound nucleus at $E_x > 12.844$ MeV (i.e., the proton separation energy) [3–7], and may highlight unknown possibilities for fluorine nucleosynthesis in stars, deriving from possible escape pathways from the ordinary CNO cycle [8–10]. Following its formation, the ^{20}Ne compound nucleus can decay in various ways, but those that bring the most precious information, in the framework of this experiment, are the so-called α_0 and α_π channels. In these two cases, the residual ^{16}O nucleus is respectively left in the ground state or in the first excited state at 6.049 MeV. Since both these channels have $J^\pi = 0^+$, the decays from the first excited state to the ground state may only happen via pair emission (hence, the "π" label); furthermore, the ^{20}Ne states de-exciting via such two channels must have natural parity, because of parity and angular momentum conservation rules.

The main goals, in this experiment, were two: to provide new experimental points in the data-poor region around 1.1-1.3 MeV projectile energy in the α_π channel and to solve the large discrepancy between datasets obtained from experiments conducted by Cuzzocrea (1980) [11] and Clarke (1957) [12] around 1.6 MeV projectile energy in the α_0 channel.

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On the other hand, the correct detection of the α particles coming from the α_π channel is particularly challenging, since these counts are usually overwhelmed by those coming from the close-lying α_1 excited state, a γ-emitting state which is only 80 keV above the π-emitting state at 6.049 MeV of excitation energy: this means that the α_π particles could be detected only by using high resolution instrumentation.

2 Experimental procedure

The experiment, performed at the Singletron accelerator (Physics and Astronomy Department, University of Catania, Italy), exploited proton beams accelerated to energies of E_{lab} = 1.13-1.32 MeV and E_{lab} = 1.62-1.72 MeV (energy stability within 1 keV, beam intensity ~100 nA), with variations of 10 or 20 keV for each measurement step. We also verified the energy of the beam delivered by the accelerator by means of a second-level calibration using, as a reference, a dip at 165° in the elastic scattering cross section in the p + ^{12}C reaction. In verifying the calibration, we deduced the yields through two independent methods: (*i*) by normalization with the Rutherford prediction for elastic scattering of protons on calcium, assuming a fixed target stoichiometry and (*ii*) with respect to the charge collected on the Faraday Cup. The detection of charged particles was made through a state-of-the-art silicon detector, as in [2], with 0.3% energy resolution; its position was varied by 10° angular steps, in the range between 115° and 165° (in the laboratory coordinates system), with an accuracy on the angular position of about 0.1°. The calcium fluoride (CaF_2) target was prepared by depositing a film with a thickness of 30 μg/cm^2 over a 10 μg/cm^2 carbon backing. The vacuum level in the chamber was better than $\approx 10^{-7}$ mbar, in order to prevent carbon contamination by deposition on the target.

3 Results

As a first accomplishment we managed to get, compared to the state-of-the-art measurement [13], a considerable improvement in the energy resolution for the detection of charged particles, not only for the separation of α_π and α_1 particles, but also for all the other ejectiles related to various reaction channels, including the elastic ones. As it can be seen from figure 1, the α_π peak is very well defined, exhibiting a peak-to-background ratio of about 12, whereas that of the previous measurement was of $\sim$ 5. The various particle counts were obtained by estimating the area under every peak by means of a multi-gaussian fit, with polynomial functions to take into account the observed weak background.

The eventuality of errors deriving from the fluorine content variation inside the target due to the bombardment was overcome through the comparison of the data obtained in the α_π and α_0 channels with the respective data (i.e., obtained in the same experimental conditions) from the p + ^{19}F elastic scattering, in the framework of an internal normalization procedure [14]. The reliability of the fluorine elastic scattering cross sections was verified using well-known and bench-marked literature data for the 135° and 145° measurements [15], while extrapolated *R*-matrix calculation curves (with resonance parameters from [16]) were used at the other angles, that were further cross-checked within 5% error with data from [17] at 153°. This led us to the conservative assumption of a 10% relative error in the determination of the elastic cross section, that is comprehended inside the error budget for the estimate of the absolute reaction cross-section here measured. The differential cross section for α_0 and α_π particles, as a function of the angle θ and the energy E, was then determined in the following way:

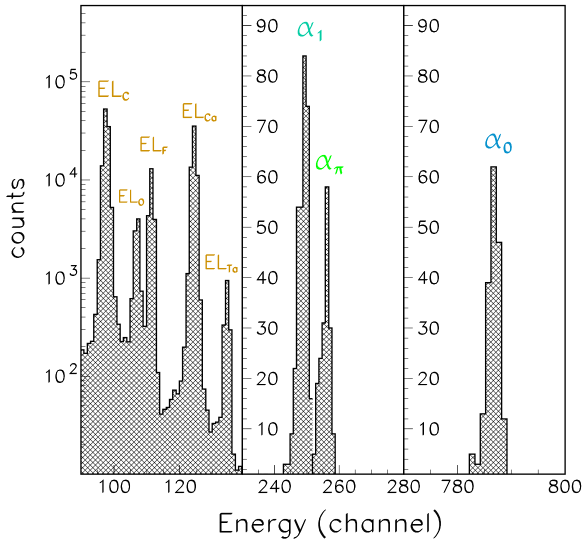

Figure 1. Count spectra at $E \simeq 1.2$ MeV and $\theta_{lab} = 165°$ for the various ejectiles related to the different channels, including elastic scattering channels (on the left, reported in logarithmic scale) and α-emitting reaction channels (center and right-hand panels, reported in linear scale).

$$\frac{d\sigma}{d\Omega}^{\alpha_{0,\pi}}(\theta, E) = \frac{N_{\alpha_{0,\pi}}}{N_{p,ela}} \cdot \frac{d\sigma}{d\Omega}^{p,ela}(\theta, E)$$

where the indexed N_i are the number of counts for a given type of detected particle (elastic scattered protons, α_0 or α_π particles). Through this procedure, our results do not depend anymore on the fluorine content and its variation.

Since the experimental data only cover the angular region between 115° and 165°, to obtain angular distributions in absolute units ranging from 0° to 180°, we fitted our results to the shapes of angular distributions, previously reported in arbitrary units in literature works ([18] for α_0 and [19] for α_π). From the so obtained angular distributions, we estimated the integrated cross section, for every channel, through the formula

$$\sigma(E) = 4\pi \cdot A(E) \cdot B_0$$

where A is a fitting parameter, i.e., the one needed to scale our absolute data to the curves obtained from Isoya's works, and B_0 is the zero-order Legendre polynomial coefficient. The results, for the α_π channel, were compared in figure 2 (left) with originally unpublished experimental data, already reported in Ref. [16].

We thus calculated, from the integrated cross section, the astrophysical factor $S(E_{c.m.})$. When our data are put alongside those from Refs. [11] and [12], for the α_0 channel at around $E_{lab} \approx 1.6$ MeV, the agreement with data from Ref. [11] is clearly better than that with data of Ref. [12], see figure 2 (right). In particular, on the average, the agreement is verified within 1.7 standard deviations σ for the first dataset [11], and only within 3.45 σ for the second one [12].

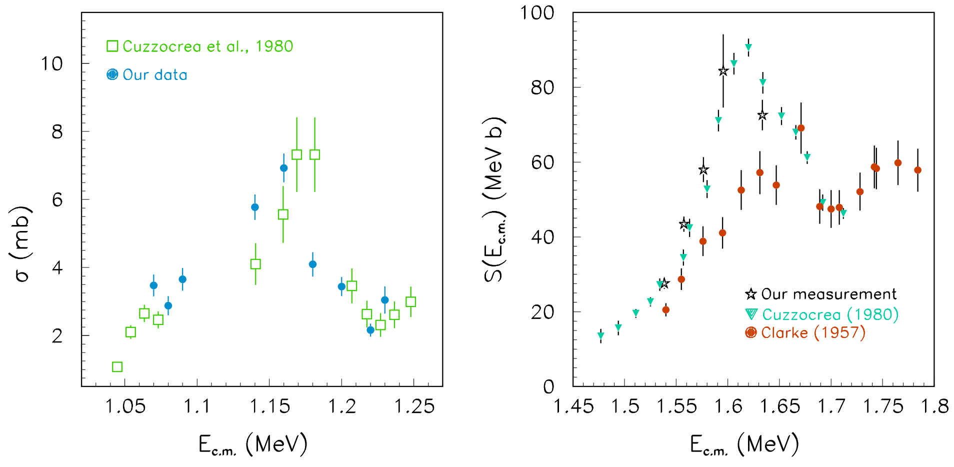

Figure 2. Left: Comparison between experimental results for the total cross-section of α_π particles obtained from this work and from an unpublished INFN activity report from Cuzzocrea et al., 1980. **Right**: Astrophysical Factor $S(E_{c.m.})$ comparison between the data from this experiment and those from Refs. [11] and [12].

The availability of the new data reported here will allow refining the spectroscopic parameters (in particular, the partial widths) for the 0^+ state at 14.47 MeV that is responsible for the strong peak in the α_0 channel cross section at $E_{lab} \approx 1.6$ MeV discussed above. We are currently performing a comprehensive *R*-matrix fit of data coming from both the α_0, α_π and elastic scattering channels to improve our knowledge of the spectroscopy of the 14.47 MeV excited state in ^{20}Ne states, for which the possible quartet nature was previously debated in the literature [11, 13, 20, 21].

4 Conclusions

The two main goals of the experiment, i.e., to fill in for the general lack of data in the α_π channel ($E_{lab} \sim 1.3$ MeV) and to solve the discrepancies existing in the α_0 channel ($E_{lab} \sim 1.6$ MeV), have been successfully achieved, thanks to a state-of-the-art experiment conducted at the Singletron accelerator in Catania. The resulting integrated cross sections have been fitted together with bench-marked literature data and included in the framework of a complete *R*-matrix fit, to progress in ^{20}Ne spectroscopy knowledge.

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