A new experiment on $^{19}F(p,\alpha)^{16}O$ reaction at low energies.

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Abstract. $^{19}F(p,\alpha)$ reactions are important both in nuclear astrophysical field and for the study of the inner structure and the cluster behaviour in light nuclei. The available cross section data on such reaction, although being in reasonable agreement over a wide energy range, still show some discrepancies for both α_0 and α_π channels. In this work we discuss the preliminary results of a new experiment aimed to solve the disagreement around 1.6 MeV for the $^{19}F(p,\alpha_0)$ absolute cross section. The excellent resolution of the detection device allowed us also to resolve the α_π peak in the spectra obtained in the 1.0-1.5 MeV beam energy range, where very few data where previously reported in the literature.

1 Introduction

High excitation energy states in self-conjugate nuclei, as ^{16}O and ^{20}Ne, could bring up clues of their α-cluster structure when suitable spectroscopy studies are performed; this is especially important in energy regions close to the cluster decomposition thresholds indicated in the Ikeda diagram [1,2]. For the case of ^{20}Ne, this study can be profitably performed by analysing p+^{19}F induced reactions at energies close to the Coulomb barrier [3-5].

Furthermore, understanding the magnitude of the competition between the $^{19}F(p,\alpha)$ and $^{19}F(p,\gamma)$ reactions at sub-coulomb energies is crucial to determine possibly escape mechanisms and pathways from the ordinary CNOF cycle [6]. In this proceeding, we will show some preliminary results aiming at removing some disagreement, in both the shape and the magnitude, of different data sets. The detailed search for normalization factors between various data sets that would lead to a common behaviour of the S-factor for this reaction is discussed in [7], but while for all the other energy regions this common trend was found, a disagreement of a factor about 1.5 is still persisting for the $^{19}F(p,\alpha_0)$ reaction in the region $E_{cm} \simeq 1.5 - 1.7$ MeV between the data sets of Refs. [8,9]. Such disagreement prevents an accurate knowledge of the spectroscopical properties of 14.35 MeV (1^-) and 14.47 (0^+) excited states in ^{20}Ne (see Ref. [10] for further details). Similarly, very few and sparse data concerning the $^{19}F(p,\alpha_\pi)$ reaction channels are reported in the literature in the region around 1.1 and 1.3 MeV, preventing the accurate knowledge of the partial decay widths towards this channel of states at about 14 MeV [10,11]; this point is particularly important in the framework of the cluster structure in the nucleus, having a strongly pronounced $\alpha \oplus {}^{12}C$ structure.

2 Experimental setup

The experiment has been performed using a proton (^1H) beam accelerated at laboratory energies between 1.130-1.300 MeV and 1.620 -1.720 MeV, with 20 keV steps.

The beam was delivered by the Singletron accelerator at the Physics Department of the University of Catania (Italy). The beam energy stability was better than 1 keV; the typical beam intensity used in the experiment was $\simeq$ 100 nA. The calibration of the beam energy was carefully checked by the analysis of well-known proton elastic scattering resonances in ^{12}C. The target was made by a CaF_2 film of 30 μg/cm^2 thickness, deposited over a 10 μg/cm^2 carbon backing. Data from elastic scattering and alpha-particles emission have been collected via a movable high resolution silicon detector, similar to the ones used in [12], that was placed at laboratory angles of 115°, 125°, 135°, 145°, 155° and 165°, with angular opening of about 1°. The vacuum level of the scattering chamber was of the order of 10^{-7} mbar: this strongly prevents carbon build-up effects on the target.

2.1 Preliminary analysis and background

For every energy and every angle, we measured counts due to elastic scattering events on carbon, oxygen, fluorine, calcium and tantalum, and reaction particle counts (for α_0, α_π, and α_1 particle emissions). They have been extracted from the measured ejectile spectra by means of a multi-gaussian fit. As shown in Figure 1 for a typical spectrum taken at backward angles, the achieved energy resolution is several times better than the state of art one [13]. This feature is particularly

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important especially for the study of α_π channel, whose peak is in close vicinity with the α_1 peak: in this case, we got a peak to background ratio of ~12.5, with respect to the factor ~3 reported by Ref. [13].

For the elastic scattering peaks, we also included a polynomial function allowing for the reproduction of the small background in such energy region of the spectrum.

To avoid errors deriving from the variation of the Calcium vs Fluorine stoichiometry in the CaF_2 target under bombardment, we adopted an internal normalization technique by using, as reference, the counts under the elastic peak of fluorine. Similar normalization protocols were used also in [14] to derive absolute cross sections with the OSCAR hodoscope [15].

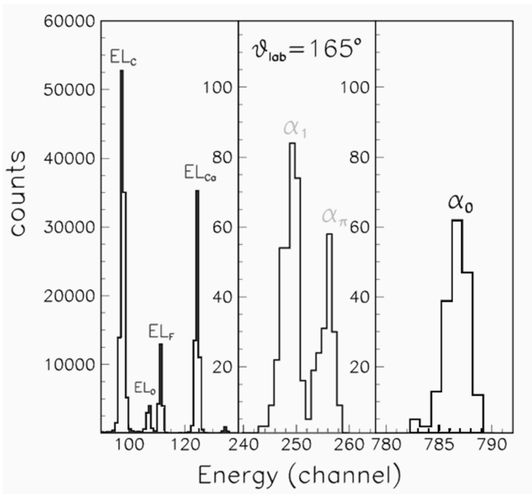

Fig. 1. Ejectile spectrum collected from the experiment at 165° detection angle in the laboratory system, at 1.3 MeV bombarding energy. Elastic scattering peaks on fluorine and other nuclides present in the target are labelled, together with peaks due to the emission of $\boldsymbol{\alpha}$ particles.

Absolute scattering cross section were deduced from *R*-matrix calculations at all the studied angles, by using the resonance parameters from [10], that describe very well elastic scattering data at backward angles. The number of detected particles for α_0 (and α_π) and elastic scattered protons ($N_{\alpha_{0,\pi}}$ and $N_{p,ela}$, respectively) are related to the corresponding cross sections as follows:

$$N_{\alpha_{0,\pi}} = N_i \mathcal{N} \frac{d\sigma^{\alpha_{0,\pi}}}{d\Omega}(\theta, E)\Delta\Omega \qquad (1)$$

$$N_{p,ela} = N_i \mathcal{N} \frac{d\sigma^{p,ela}}{d\Omega}(\theta, E)\Delta\Omega \qquad (2)$$

Here N_i is the number of incident particles, $\mathcal{N}$ the number of target atoms per unit area, θ the polar detection angle and ΔΩ the solid angle covered by the detector. By dividing eq. (1) to eq. (2) and knowing the proton scattering cross sections from the *R*-matrix calculations, we can simplify several factors and obtain the α_0 (and α_π, in the same way) differential cross section as follows:

$$\frac{d\sigma^{\alpha_0}}{d\Omega}(\theta, E) = \frac{N_{\alpha_0}}{N_{p,ela}} \cdot \frac{d\sigma^{p,ela}}{d\Omega}(\theta, E) \qquad (3)$$

To estimate the uncertainty level of the $\frac{d\sigma^{p,ela}}{d\Omega}$ *R*-matrix extrapolations, we compared published data of $p+^{19}F$ elastic scattering at backward angles (>135°) with such extrapolations, and we find on the average an agreement better than 10%. We then assumed conservatively a 10% error on the estimate of the $\frac{d\sigma^{p,ela}}{d\Omega}(\theta, E)$ absolute differential cross section. The total uncertainty was then obtained by including also statistical uncertainties on counts in the error propagation.

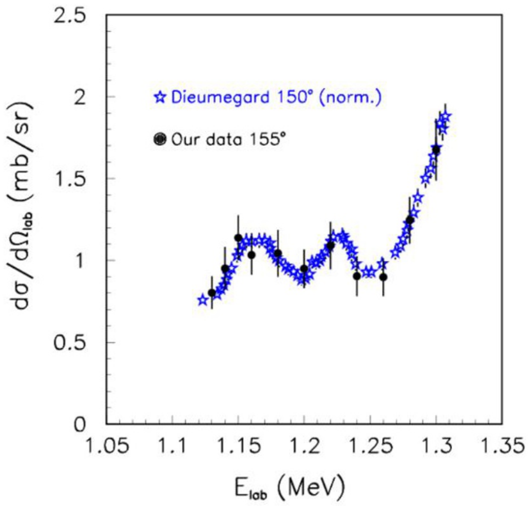

Fig. 2. Comparison of the excitation function at θ_{lab} = 155° between present work and data from Ref. [16] normalized by a factor 2.

3 Data analysis

As a first check on the data collected in the present experiment, we compared the excitation function for the α_0 channel at 155° with similar results reported by Ref. [16] at 150°. The shape of the two excitation functions is in excellent agreement, while the absolute cross section scale of data from Ref. [16] is a factor of 2 smaller than the present data. This scale factor is quite similar to the one used in Ref. [3] to compare their data and data from Ref. [16] in the 0.7-1.1 MeV energy region, pointing out a possible normalization problem in the data of [16]. At variance, the cross section scale reported by [17] at 150° in the 1.3 MeV region (not shown in Figure 2 for simplicity) is in close agreement with the one deduced in the present experiment.

To deduce the integrated cross section from the present data, that are measured only in the backward hemisphere, we need to know the trend of the angular distribution in the whole angular range. Fortunately, such trends are quite well known from the literature [8,18,19] in the energy ranges here investigated for the α_0 channel: 1.13-1.30 MeV and 1.62-1.72 MeV, and they are in good agreement. Similarly, the shapes of α_π angular distributions (and their expansion in Legendre polynomials) in the 1.13-1.30 MeV range have been reported in Ref. [20].

We performed spline fits of the Legendre polynomial coefficients (B_i) (in relative units and truncated to $\ell = 2$) as a function of energy, as taken from the literature. In this way, it was possible to interpolate the B_i values (in relative units) at the energy values of the present experiments. With such interpolations, we estimated, energy by energy, the trend of angular distributions; the absolute cross section scale was instead determined by fitting the backward angle cross section data collected in the present experiment with the estimated angular distributions. The integrated cross section and its uncertainty were then estimated analytically from the Legendre polynomial expansion of the angular distribution in absolute cross section units.

An example fit for the α_π angular distribution at the beam energy of 1.15 MeV can be seen in Figure 3. The presently measured data reproduce quite well the shape of the angular distribution interpolated from literature data at backward angles. Similar results have been deduced also for the other investigated energies and for the α_0 channel.

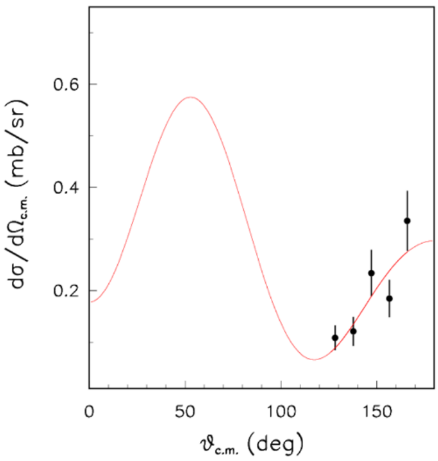

Fig. 3. Fit of the interpolated angular distribution for the ^{19}F(p,α_π)^{16}O reaction at E = 1.15 MeV with the experimental absolute cross section data coming from the present experiment. The interpolated curve is obtained by a spline fit of the coefficients of Legendre polynomial expansion reported at similar energies in Ref. [20].

The results of integrated cross sections data for both channels will be discussed in more details in forthcoming publications. As a preliminary observation concerning the ^{19}F(p,α_0) reaction in the region $E_{cm} \simeq 1.5 - 1.7$ MeV, the data obtained in the present work strongly agree, both in shape and in absolute values, with the [9] measurements. On the other hand, ^{19}F(p,α_π)^{16}O data in the region $E_{cm} \simeq 1.1 - 1.3$ MeV are in agreement, within the error bars, with the estimates reported in Ref. [10] based on unpublished results obtained during the '70s.

The impact of the new datasets here obtained on the spectroscopic properties of excited states in ^{20}Ne is currently under investigation and will be the subject of future publications.

4 Conclusions

The aim of this work was to improve our knowledge on the ^{19}F(p,α_0) and ^{19}F(p,α_π)^{16}O reactions at low energies, where the occurrence of contrasting data sets or energy regions with lacking or very sparse data have been reported. These reactions are important both for the spectroscopy of natural-parity states of the self-conjugate ^{20}Ne nucleus and to determine the behaviour of stellar nucleosynthesis beyond the CNOF cycle in various astrophysical contexts. In this proceeding we presented preliminary results on the new measured data, at various angles, in the 1.13-1.30 MeV and 1.5-1.7 MeV energy ranges for the α_0 and α_π channels coming from p + ^{19}F reactions. We described the internal normalization procedure that leads us to estimate the absolute cross sections for both reaction channels by avoiding any ambiguity due to target stoichiometry, beam current integration and solid angle measurements. The integrated cross section was then determined by coupling, through a fit procedure, the shape of angular distributions already reported in the literature in the full angular domain with the measured data obtained at backward angles. A further analysis is in progress to determine new spectroscopic parameters of ^{20}Ne states in the excitation energy region $\approx 14.0 - 14.4$ MeV from an R-matrix analysis of the present results and other data taken from the literature.

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References

1. W. von Oertzen, Martin Freer, Y. Kanada-En'yo, Phys. Rep., **432**, 43-113 (2006)
2. J. Bishop et al., Phys. Rev. C, **100,** 034320 (2019)
3. I. Lombardo, D. Dell'Aquila, L. Campajola, E. Rosato, G. Spadaccini, M. Vigilante, J. Phys. G: Nucl. Part. Phys., **40,** 125102 (2013)
4. I. Lombardo, L. Campajola, D. Dell'Aquila, M. La Commara, A. Ordine, E. Rosato, G. Spadaccini, M. Vigilante, J. Phys. Conf. Ser., **569**, 012068 (2014)
5. I. Lombardo, D. Dell'Aquila, L. Campajola, E. Rosato, G. Spadaccini, M. Vigilante, Bull. Russ. Acad. Sc., **78**, 1093-1096 (2014)
6. R. J. deBoer, O. Clarkson, A. J. Couture, J. Görres, F. Herwig, I. Lombardo, P. Scholz, M. Wiescher, Phys. Rev. C, **103,** 055815 (2021)
7. J. He, I. Lombardo, D. Dell'Aquila, Y. Xu, L. Zhang, W. Liu, Chin. Phys. G, **42,** 015001 (2018)
8. R. L. Clarke, E. B. Paul, Can. J. Phys., **35,** 155-164 (1957)

9. P. Cuzzocrea, A. De Rosa, G. Inglima, E. Perillo, E. Rosato, M. Sandoli, G. Spadaccini, Lett. Nuov. Cim., **28**, 515-522 (1980)
10. I. Lombardo, D. Dell'Aquila, J. He, G. Spadaccini, M. Vigilante, Phys. Review C, **100**, 044307 (2019)
11. D. R. Tilley, C. M. Cheves, J. H. Kelley, S. Raman, H. R. Weller, Nucl. Phys. A, **636**, 249-364 (1998)
12. I. Lombardo, L. Campajola, E. Rosato, G. Spadaccini, M. Vigilante, Nucl. Instr. Meth. Phys. Res. B, **302**, 19-23 (2013)
13. R. Caracciolo, P. Cuzzocrea, A. De Rosa, G. Inglima, E. Perillo, M. Sandoli, G. Spadaccini, Lett. Nuov. Cim., **11,** 33-38 (1974)
14. I. Lombardo et al., J. Phys. G: Nucl. Part. Phys., **48**, 065101 (2021)
15. D. Dell'Aquila et al., Nucl. Instr. Meth. Phys. Res. A, **877,** 227-237 (2018)
16. D. Dieumegard, B. Maurel, G. Amsel, Nucl. Inst. Meth., **168 (1-3),** 93-103 (1980)
17. I. Golicheff, M. Loeuillet, C. Engelmann, J. Rad. Chem., **22**, 113-129 (1974)
18. A. Isoya, H. Ohmura, T. Momota, Nucl. Phys., **7,** 116-125 (1958)
19. A. De Rosa, E. Perillo, P. Cuzzocrea, G. Inglima, E. Rosato, M. Sandoli, G. Spadaccini, Nuov. Cim., **44A,** 433-440 (1978)
20. A. Isoya, K. Goto, T. Momota, J. Phys. Soc. Jap., **11**, 899-906 (1956)