New direct measurement of the $^{19}F(p,\alpha_0)^{16}O$ reaction at very low energies

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Abstract

The $^{19}F(p,\alpha_0)^{16}O$ reaction has been studied with two different experiments in Naples (0.6–1.0 MeV) and Legnaro (0.2–0.6 MeV). In this way a comprehensive view of the *S*-factor at low energy has been obtained. This reaction is relevant in Nuclear Structure, to study the ^{20}Ne compound nucleus, and in Nuclear Astrophysics, because is an important fluorine destruction channel in hydrogen rich stellar environments. Our works points out the role played by several low-energy resonances and confirms the presence of direct components in the *S*-factor. The *R*-matrix fit of experimental data allows us to perform the spectroscopy of ^{20}Ne excited states and to extrapolate the reaction rate at temperatures typical of the basis of the convective envelope of AGB stars.

1 Introduction

The first, pioneering, studies of α-particle emission in proton induced nuclear reactions on ^{19}F can be found in very old papers in Nuclear Physics [1-5]. These reactions can be distinguished in $^{19}F(p,\alpha_0)^{16}O$ (Q=8.114 MeV), $^{19}F(p,\alpha\pi)^{16}O_{6.05}$ (Q=2.06 MeV) and $^{19}F(p,\alpha\gamma)^{16}O$ (E_γ = 6.13, 6.92, 7.13 MeV) [6]. The low energy (E_p=0.5-2.0 MeV region) cross sections for all these three reaction branches show the presence of several resonances, testifying a quite large level density in the 13-15 MeV excitation energy region of the compound nucleus [5,6]. Typically, a state observed in the α_0 channel is also seen in the $\alpha\pi$ one, with some exceptions [6]. Despite the experimental efforts made in past times, the present knowledge of these reactions is still lacking in several parts. It is mainly based on the experimental works of Isoya et al [7], Clarke and Paul [5], Breuer [8], Ranken et al [9], Caracciolo et al [10], De Rosa et al [11], Cuzzocrea et al [12], Ouichaoui et al [13], Spyrou et al [14] A review on the spectroscopy of ^{20}Ne based on these and other works can be found in Tilley et al [6]. As pointed out by [6], ambiguities are still present in the spectroscopy of some natural parity states (for example the 13.522, 13.645 and 14.85 MeV states have uncertain J^π assignments).

Furthermore, the NACRE collaboration [15] has discussed the presence of discrepancies between the various data sets reported in the literature concerning the absolute cross section data of this reaction [16]. At low energies ($E_p \approx 0.5 - 0.7$ MeV), the data by Isoya *et al* and Breuer show discrepancies at 30% level or more; these discrepancies heavily influence the uncertainty level of low energy *S*-factor extrapolations and the consequent reaction rate determination, that is of the order of 50%, as discussed in Ref. [15]. Indeed, the accurate knowledge of this reaction cross section is important for Nuclear Astrophysics purposes. The nucleosynthesis of fluorine is an open problem in Astrophysics [17], and

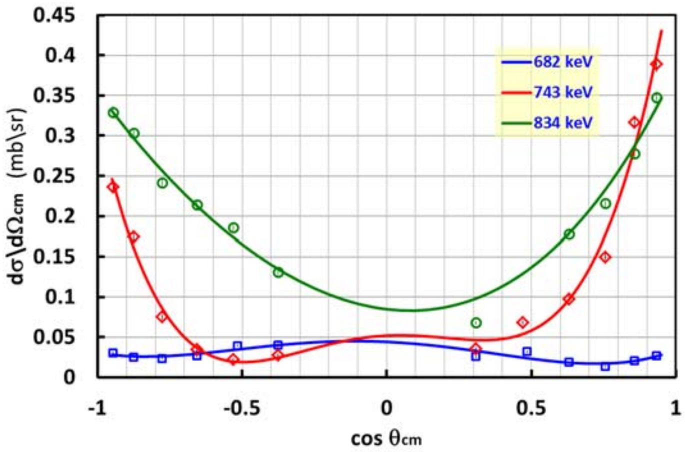

Fig. 1: Examples of three angular distributions obtained for the $^{19}F(p,\alpha_0)^{16}O$ reaction at E_p= 0.682, 0.743 and 0.834 MeV. Lines represent the results of Legendre Polynomial fits of data.

recent papers suggested that, in hydrogen-rich environments at the basis of the convective envelope of AGB stars, the $^{19}F(p,\alpha)^{16}O$ reaction can play a role in the destruction of fluorine by means of deep mixing processes [18-21].

In recent times, the need of new data has driven different groups to perform new experiments, by using both direct and indirect techniques. For example, a new measurement performed by using the Trojan Horse method [21,22] has suggested the presence of various low energy resonances. In particular, the E_{cm}=113 keV one is believed to highly influence the reaction rate value at temperatures near 0.6 GK, typical of AGB environments.

Considering all these discrepancies and the lack of low energy data, we performed two new direct measurements of the $^{19}F(p,\alpha_0)^{16}O$ reactions in the bombarding energy regions E_p≈0.6–0.1 MeV (experiment performed at the TTT3 tandem in Naples, Italy) and E_p≈0.2–0.6 MeV (experiment performed at the AN2000 Van de Graaf accelerator in Legnaro, Italy). In these proceedings we report some results of both experiments. The reader is referred to the more extended Refs. [23] and [24] for further details.

2 The E_p≈0.6-1.0 MeV experiment in Naples

The first of the two $^{19}F(p,\alpha_0)^{16}O$ cross section measurement was performed in Naples by using the TTT3 tandem [23,25,26]. The beam energy was varied from about 1.0 MeV down to 0.6 MeV in 10 keV steps. The accuracy in the beam energy determination was better than 0.2%, and the diameter of the beam spot on the target was less than 3 mm. The beam energy calibration was checked by investigating resonances in the elastic scattering of proton and α particles on ^{12}C and ^{16}O nuclei. A LiF layer (94 μg/cm^2 thick) evaporated on a thin carbon backing (18 μg/cm^2 thick) was used as target. The beam intensity was measured by means of a Faraday cup and the collected charge was determined with a digital current integrator. The detection system was made by an array of 12 silicon detectors, placed at 10-15 cm from the target centre. The detection system covered a broad range of polar angles in the laboratory frame, both in the forward and backward hemisphere (20°–70° and 110°–160° in 10° steps). To suppress the high flux of elastically scattered protons we used thin Al absorbers (14.5 μm thick) in front of detectors. Because of the high reaction Q-value (8.114 MeV), α particles emitted in the $^{19}F(p,\alpha_0)^{16}O$ reaction punch through the Al foils and are detected with 100% efficiency. The measured yields is transformed into absolute cross sections using standard equations. Examples of angular distributions obtained at various angles are reported in Figure 1.

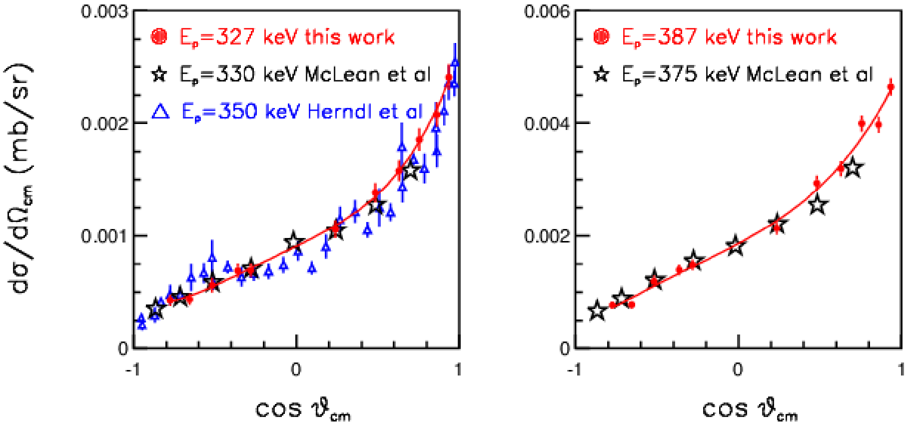

Fig. 2: Examples of angular distributions obtained for the $^{19}F(p,\alpha_0)^{16}O$ reaction at $E_p \approx$ 0.330, 0.380 MeV. Full dots: results of the LNL experiment [24]. Triangles: data reported in [27]. Stars: data reported in Ref. [4]. Lines represents results of Legendre Polynomial fits of our data.

Examples of angular distributions are shown in Figure 1, where the continuous shape evolution as a function of energy testifies the contributions of different excited states in the compound nucleus. In particular, in the energy region here explored, large contributions are due to the E_p=842, 778, 733 keV resonances (corresponding to ^{20}Ne states at E_x=13.642, 13.586, 13.544 MeV, respectively). The analysis of angular distributions in terms of Legendre polynomials confirms the 2^+ assignment for the 778 and 733 keV resonances [6,7] and indicates $J^\pi=0^+$ assignment for the 842 keV resonance, for which two different J^π assignments (0^+ and 2^+) have been reported in the literature [6,7,10]. Furthermore, the shape of angular distributions in the 820-850 keV region can be well reproduced by considering the overlap between the 842 keV state and a newly reported state (with tentative $J^\pi=1^-$ assignment) at about 825 keV [23]. The integration of angular distributions allows us to derive the *S*-factor. Its behaviour as a function of energy is reported in Figure 3 as red triangles. The presence of resonant structures at energies corresponding to the previously mentioned excited states in ^{20}Ne can be recognized. In the E_{cm}=0.8 MeV region (E_x=13.642) our data are in good agreement with Caracciolo et al data [10] and Isoya et al data [7] as reported by NACRE [15]. In the $E_{cm} \approx$ 0.6-0.74 MeV region our data are ≈30% larger than the Isoya et al ones but matches well the absolute data by Breuer [8]. This last (and very old) data set pointed out (very tentatively) the possible existence of broad states at low energy ($E_{cm} \approx$ 0.4 MeV), which can have some influence in the reaction rate determination at 0.5-0.7 GK. Furthermore, recent results based on the use of the Trojan Horse indirect technique [21,22] pointed out the important contribution of other low energy states at 380 and 113 keV (E_x=13.226 and 12.957 MeV). Considering these suggestions, we decided to perform a new experiment aimed at exploring the low energy domain of this reaction, where very few results have been reported to date. The results of this experiment are discussed in the following section.

3 The $E_p \approx$0.2-0.6 MeV experiment at LNL

The second experiment on the $^{19}F(p,\alpha_0)^{16}O$ reaction was performed at Laboratori Nazionali di Legnaro (LNL) by using the AN2000 single–ended van de Graaf accelerator [24]. The beam energy was varied from about 0.6 MeV down to 0.2 MeV in ≈20 keV steps. The maximum beam energy spread was ±2.5 keV. The beam energy calibration was determined by scanning the 340 keV resonance in the $^{19}F(p,\alpha\gamma)$ reaction and the 992 keV resonance in the $^{27}Al(p,\gamma)$ reaction. CaF_2 layers (30 μg/cm^2 thick) evaporated on a thin carbon backing (20 μg/cm^2 thick) were used as reaction targets; they were frequently replaced to prevent degradation. Target thickness was estimated by means of the resonating quartz method; it was subsequently cross-checked with dedicated elastic backscattering analysis. These analyses also pointed out a natural stoichiometry of the CaF_2 layer, as seen in [28].

The detection system was an array of 12 silicon detectors (covering the 20°-160° polar angular range) and placed 10 – 12 cm far from the centre of the target. The detectors thickness was 300 μm. 8 μm thick aluminium absorbers were used to stop scattered protons. The detection system was operated in high vacuum (better than 10^{-6} mbar). Absolute cross section measurements were obtained by using a Faraday Cup equipped with an electrostatic suppressor ring (-300V bias). Absolute normalizations were checked by means of an unshielded silicon detector placed at 160° monitoring the p+Ca elastic scattering whose cross section follows the Rutherford prediction in this low energy domain. Examples of α energy spectra obtained with the present array are reported in Figure 1 of Ref. [24]. The large *Q*-value of this reaction allowed us to unambiguously identify the peak due to the $^{19}F(p,\alpha_0)^{16}O$ reaction.

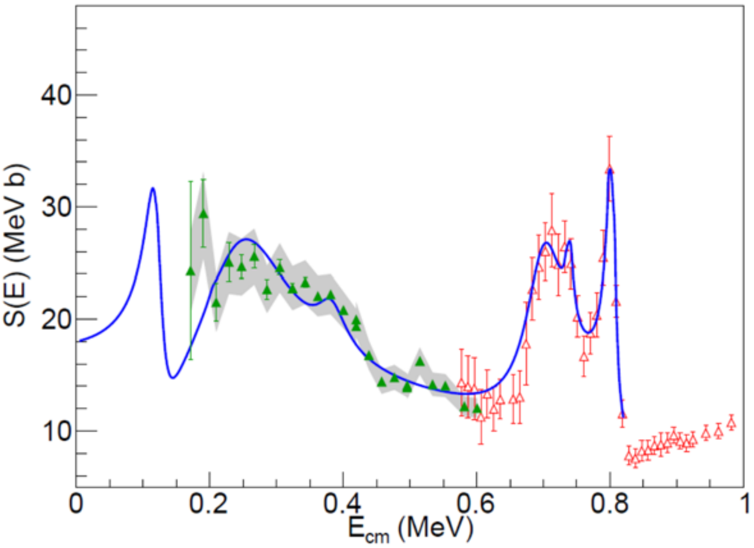

Fig. 3: $^{19}F(p,\alpha_0)^{16}O$ *S*-factor obtained in the first experiment in Naples (red open triangles) and in the second one in Legnaro (green filled triangles). For the LNL data, the grey band indicates non statistical errors. The blue line is the result of the *R*-matrix fit of the whole data set. Further details can be found in Refs. [23,24].

Examples of angular distributions obtained at E_p = 0.387 and 0.327 MeV are reported as red dots in Figure 2. They have been compared with the (very few) data available in the literature at similar energies. Stars represent the data reported by Mc Lean, Ellett and Jacobs [5], while triangles are the data reported by Herndl et al [27]. Both the data sets have been normalized to match our absolute cross section scale. A very good agreement between the various data sets can be observed. The shape of angular distributions in this energy domain is quite peculiar, showing a strong forward-peaked anisotropy. This finding can be attributed both to the presence of direct processes at sub-Coulomb energies (possibly triggered by the $t+^{16}O$ or the $\alpha+^{15}N$ cluster structure in ^{19}F) [27,29,30] or to the interference between close-lying states with opposite parities [7,8,10]. In Ref. [25] we analysed the energy evolution of the shapes of angular distributions and we find that both the effects can be simultaneously present in the energy region here explored.

Starting from the experimental angular distributions, we can estimate the integrated cross section and the *S*-factor. The results are shown in Figure 3 as green stars with bars (statistical errors) and grey band (non-statistical error), together with the results of the previous experiment discussed in Section 2. The two measurements matches quite well in their overlap region. To obtain information about the spectroscopy of ^{20}Ne states involved in this energy region, we performed an *R*-matrix fit of the whole data set, shown as solid blue line in Figure 3. A non-resonant background of the same functional form as reported by NACRE has been included in the fit. We can observe important contributions given by the E_x = 13.642, 13.586, 13.544 MeV states, as pointed out in the previous section, together with the contributions of the lower excited states at E_x = 13.226, 13.095 MeV. At very low energy, we included also the E_x = 12.957 MeV state, as pointed out by recent analyses performed with the Trojan Horse Method [21,22]. The fit reproduces reasonably well the data in the whole domain; the only free parameters of the fit were the scaling factor of the direct contribution and the strength of the 250 keV resonance. The other resonance parameters have been fixed to the values reported in Refs. [21,22]. A strong contribution, due to the broad (Γ=162 keV, $J^\pi=2^+$) 13.095 MeV state can be observed. This state interferes with the 12.957 MeV 2^+ state at low energy, resulting in a typical interference pattern that enhance the cross section of the high energy tail of the 13.095 MeV resonance, in agreement with the experimental data.

Starting from the *R*-matrix fit here discussed, we calculated the reaction rate and we compared it to the extrapolations reported by NACRE. We observed an important enhancement of the reaction rate in the 0.4 and 0.08 GK regions, respectively due to the contributions of the 13.095 and 12.957 MeV states. In these temperature regions, the resulting reaction rate is a factor 1.5-2 larger than the NACRE extrapolation. This finding can indicate a more efficient destruction way of fluorine in hydrogen rich stellar environment, in the same direction of some recent stellar observation of abundance of fluorine in metal poor AGB stars.

4 Conclusions

In this paper we briefly report results obtained in two different experiments aimed at exploring the behavior of the $^{19}F(p,\alpha_0)^{16}O$ reaction in the 0.2-1.0 MeV energy domain, a region where very few data are present in the literature. The first experiment was performed in Naples and explored the 0.6-1.0 MeV bombarding energy region. We obtained improved spectroscopic information for excited states in ^{20}Ne in the 13.55-13.65 MeV excitation energy domain, pointing out the possible evidence of a new 1^- state at E_x=13.628 MeV. The second experiment was performed at Laboratori Nazionali di Legnaro and covered the 0.2-0.6 MeV range. In this case we observed contributions due to states at 13.095 and 13.226 MeV, together with a hint on the contribution given by the low energy 12.957 MeV state, seen also with the Trojan Horse Method. A *R*-matrix fit of the whole data set allowed us to determine the *S*-factor in a broad energy domain; starting from this fit it was possible to obtain an improved estimate of the reaction rate at temperatures typical of AGB stars, with a result 1.5-2 times larger than the NACRE predictions.

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