An overview of the $^{19}$F($p,\alpha_0$)$^{16}$O reaction with direct methods

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Abstract. The study of the $^{19}$F($p,\alpha$)$^{16}$O reaction at low energy is important both for Nuclear Structure and Astrophysics. Despite of its importance, the $S$-factor of this reaction is poorly known, especially at astrophysical energies. We present an overview of the $^{19}$F($p,\alpha_0$)$^{16}$O reaction cross section, as obtained from recent direct measurements and from published works in the literature. We include in the systematic also data from an unpublished work, where several excitation functions and angular distributions for $\alpha_0$ and $\alpha_\pi$ channels are reported.

1. Introduction
The $^{19}$F($p,\alpha$)$^{16}$O reaction can provide important information both for the study of Nuclear Structure of $^{20}$Ne [1] and the nucleosynthesis of Fluorine and heavier elements in massive stars [2]. In the first case it allows to investigate the spectroscopy of natural parity states in the compound $^{20}$Ne nucleus [3] above the proton separation threshold ($S_p = 12.844$ MeV [4]), where the possible existence of $^{20}$Ne quartet excitations has been predicted in various theoretical works [5, 6].

Furthermore, the direct investigation of the $^{19}$F($p,\alpha$)$^{16}$O reaction at energies well lower then the Coulomb barrier is very useful for solving astrophysical problems related to the understanding of CNO-F cycles in hydrogen burning stages of stellar evolution [2] and the nucleosynthesis of fluorine [7]. In fact, this reaction represents the branching point between the CNO cycles and the NeNa one [2] and the amount of catalytic material that is lost from the CNO cycles to activate the NeNa one is regulated by the competition between the $^{19}$F($p,\alpha$) and $^{19}$F($p,\gamma$) reactions [2, 8, 9]. Another interesting problem is connected to the galactic fluorine abundance. It is strongly dependent on the condition within the astrophysical sites and therefore it is used to probe different nucleosynthesis scenarios [7]. Moreover, asymptotic giant branch (AGB) stars are regarded as the major contributors to the fluorine abundance in the Milky Way [10], but the observed upper limit of fluorine abundance is well lower then the one predicted with the most recent AGB models [11]. This may be caused by possible deep mixing phenomena that could expose the catalytic material at temperature high enough to activate the fluorine destruction via the $^{19}$F($p,\alpha$) reaction.

Despite its importance, very few direct investigations of the $^{19}$F($p,\alpha$)$^{16}$O reaction at low energies have been reported in literature. These data would be useful both to directly determine the presence of low energy resonances and to give good reference points for the absolute normalization of data obtained with indirect methods, like the Trojan Horse (THM) one [12, 13].
Figure 1. $^{19}$F($p,\alpha_0$) S-factor data sets in the 0.2MeV ≤ $E_{cm}$ ≤ 3.3MeV energy range. Red circles represent the unpublished data from Ref. [22], while the data sets from Refs.[3, 21, 23] (respectively blue circles, red rhombuses and blue triangles) are not included in the NACRE compilation.

In this proceeding we report an overview of the $^{19}$F($p,\alpha_0$)$^{16}$O direct experimental data in a quite large energy range (0.2MeV ≤ $E_{cm}$ ≤ 3.3MeV), to try to clarify some ambiguities still present in the S-factor.

2. Astrophysical S-factor: an overview

The integrated cross section and S-factor of the $^{19}$F($p,\alpha_0$)$^{16}$O reaction have been the subject of direct experiments performed in past times. In particular, the Nuclear Astrophysics Compilation of Reaction Rates (NACRE [14]) reports the following direct data sets in the $E_{cm} = 0.4−3.2$MeV energy domain: Morita et al. [15], Clarke and Paul [16], Cuzzocrea et al. [17], Isoya et al. [18], Caracciolo et al. [19] and Breuer [20].

The higher energy points, red stars in Fig. 1, come from the old paper of Morita et al. [15], where the energy domain 2.64MeV ≤ $E_p$ ≤ 3.35MeV was covered. The corresponding integrated cross section was obtained in relative units and has been normalized by NACRE to 28mb at $E_{cm}$ ≈ 2.5MeV for comparison with the other data sets. These data overlap nicely with the absolute data from Breuer and Jahnke [21] (blue triangles), not included in the NACRE compilation. In the 1.5MeV ≤ $E_{cm}$ ≤ 2.5MeV we observe the presence of differences between the relative data of Clarke and Paul [16] (yellow points) and the absolute data by Cuzzocrea et al. [17] (green triangles). In particular, the Clarke and Paul data, normalized by NACRE to $\sigma = 42$mb at the $E_p$ ≈ 1.3MeV resonance, seem to overrate the S-factor in their high energy part.

The data from Isoya et al, carried out by means of a proportional counter and a proton beam covering an energy range from 0.630MeV to 1.460MeV, have also been normalized by NACRE at the $E_p$ ≈ 1.3MeV resonance. These experimental points are in good agreement with ones from Caracciolo et al. [19] (green triangles), in the region of the $E_{cm} = 0.842$MeV $^{20}$Ne resonance, but disagree at lower energies with Breuer [20] (light blue open circles), leading to strong uncertainties, of the order of 50% [14], in the S-factor extrapolation down to the Gamow peak.

The behaviour of the S-factor at lower energies could be better understood by considering the results of two recent experiments carried out in Naples (Lombardo et al. [3, 24, 25], $E_p$ ~
0.6–1MeV) and at Laboratori Nazionali di Legnaro (Lombardo et al. [23], $E_p \simeq 0.2–0.6$MeV), indicated with blue circles in Fig. 1. These two experiments confirm the $S$-factor rise at low energies seen in Ref. [20], and point out the presence of broad resonances at low energies, in agreement with indirect observations made with the Trojan Horse Method [7, 26].

Finally, we included in the systematic of data also unpublished results, discussed in an INFN Activity Report, by Cuzzocrea et al. [22]. In this work, very fine step ($\approx 10$keV) excitation functions are reported in the $0.9$MeV $\leq E_p \leq 1.0$ MeV domain for 8 different detection angles. By extracting the data and integrating the corresponding angular distributions we obtained the $S$-factor showed with the red circles in Fig. 1. This data set is consistent with the high energy part of the data from Lombardo et al. [3] and it is in quite nice agreement with the two relative data sets from Refs. [16, 18], confirming the consistency of the NACRE normalization at the $E_p \approx 1.3$ MeV resonance.

3. Conclusions and Perspectives
We discuss an overview of direct data sets of the $^{19}$F(p,α)$^{16}$O reaction cross section in the energy range $E_{cm} \leq 3.3$MeV. We considered the data reported in the NACRE compilation and the data from Refs. [3, 21, 23], not indicated by NACRE. By including the unpublished results from Ref. [22] we are able to give absolute values of the $S$-factor in the $E_p \approx 1.3$MeV resonance region, where only relative data sets were reported in the literature. For the future, we plan to perform a $R$-matrix fit of this data set, together with other reaction and scattering channels populating $^{20}$Ne excited states, to improve the spectroscopy of this self-conjugated nucleus.

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