Investigation of the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction in the THM framework

M. La Cognata$^{1}$, A.M. Mukhamedzhanov$^{2}$, I. Indelicato$^{1,3}$, S. Cherubini$^{1,3}$, A. Coc$^{6}$, M. Gulino$^{1,3}$, V. Kroha$^{5}$, L. Lamia$^{1,3}$, J. Mrázek$^{5}$, R.G. Pizzzone$^{1}$, G.G. Rapisarda$^{1,3}$, S. Romano$^{1,3}$, M.L. Sergi$^{1,3}$, C. Spitaleri$^{1,3}$

$^{1}$INFN - Laboratori Nazionali del Sud, Catania, Italy
$^{2}$Cyclotron Institute - Texas A&M University, College Station, TX, USA
$^{3}$Dipartimento di Fisica e Astronomia - Università di Catania, Catania, Italy
$^{4}$School of Physics and Astronomy, University of Edinburgh, Edinburgh, and SUPA - Scottish Universities Physics Alliance, United Kingdom
$^{5}$Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic
$^{6}$CSNSM CNRS/IN2P3, Université Paris Sud, Orsay, France
$^{7}$Università degli Studi di Enna “Kore”, Enna, Italy

E-mail: lacognata@lns.infn.it

Abstract. The $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction is an important fluorine destruction channel in the proton-rich outer layers of asymptotic giant branch (AGB) stars and it might also play a role in hydrogen-deficient post-AGB star nucleosynthesis. So far, available direct measurements do not reach the energy region of astrophysical interest ($E_{cm} \sim 300$ keV), because of the hindrance effect of the Coulomb barrier. Therefore, below $E_{cm} = 460$ keV, where data do not exist, a non-resonant contribution is calculated for s-capture and the cross section has been extrapolated assuming this contribution as the dominant one. The Trojan Horse (TH) method was thus used to access this energy region, by extracting the quasi-free contribution of the $^2\text{H}(^{19}\text{F},\alpha)^{16}\text{O})n$ and the $^{19}\text{F}(^2\text{He},\alpha^{16}\text{O})d$ reactions. A novel approach, the so-called Modified R-matrix, has been developed to analyze the data, aiming to account for the half-off-energy-shell nature of the TH cross section and for the experimental energy resolution. The TH measurement has been devoted to the study of the $\alpha_0$ channel, which is the dominant one at such energies. It has shown the presence of resonant structures not observed in direct measurements that cause an increase of the reaction rate at astrophysical temperatures (about $10^8$ K) up to a factor of 1.7, with potential important consequences for stellar nucleosynthesis.

1. Introduction

Fluorine is a key isotope for astrophysics as its abundance is used to probe hotly-debated nucleosynthesis scenarios, as it is very sensitive to the physical conditions within stars [1]. Three are the most likely environments where its production could have taken place in the Milky Way, namely $\nu$-process just above the collapsing core of a Type II supernova [2], Wolf-Rayet stars [3] and in the convective zone generated by a thermal pulse in AGB stars [4]. Recently, fluorine overabundances have been observed in R-Coronae-Borealis stars by factors of 800 to 8000 [5]. Such overabundances are evidence for the synthesis of fluorine in these hydrogen-deficient supergiants. In spite of its key importance, a thorough view of fluorine abundance and nucleosynthesis is not
at hand yet.

Regarding AGB stars, which are considered the major contributors to the Galactic fluorine supply [6], the largest observed fluorine overabundances could not be explained with standard AGB models and required additional mixing [7]. A possible lack of proper account of C-bearing molecule (i.e., CH, CN, CO, and C2) contribution might provide an explanation in the case of Population II stars [8], providing a renormalization of the observed abundances, though the understanding of F production in the case of metal-poor AGB stars is far from satisfactory [1]. An alternative explanation could be given by a reassessment of the nuclear reaction rates intervening in fluorine production and destruction. Deep mixing phenomena in AGB stars can alter the stellar outer-layer isotopic composition due to proton capture nucleosynthesis at relatively low temperatures (T_9 < 0.04), affecting the transported material [9, 10, 11]. In this environment, the ^19F(p,α)^16O reaction at E_{cm} ∼ 27 – 94 keV (corresponding to the Gamow window [12]) would represent the main fluorine destruction channel, possibly modifying F surface abundance.

2. The Trojan Horse Method

Such low energies make the measurement of the ^19F(p,α)^16O cross section very difficult. In general, two effects prevent to achieve a satisfactory knowledge of the relevant nuclear processes for application to astrophysics, namely the Coulomb barrier exponentially suppressing the cross section and the presence of atomic electrons. As regards the Coulomb suppression, in the cited range the cross section drops well below the picobarn scale and the scarce reaction yield spoils the signal-to-noise ratio and eventually makes the statistical accuracy of the measurement inadequate. Atomic electrons, on the other hand, screen the nuclear charges thus determining an enhancement of the cross section at the lowest energies (electron screening). Therefore, the bare-nucleus cross section, which is the relevant nuclear physics input, has to be extrapolated from higher energies where the cross section can be more easily measured to explore the energies relevant to astrophysics. A weak point in the laboratory approach is the need for an assumption about the energy dependence of the bare nucleus cross section σ_b(E) at ultra-low energies. To avoid extrapolation, alternative experimental methods for determining σ_b(E) have been introduced. In particular, the Trojan Horse Method (THM) has proved effective in the extraction of the bare-nucleus cross section for reactions having charged particles in the exit channel. The THM allows one to study a reaction of astrophysical interest free of Coulomb suppression and electron screening at astrophysical energies with no need of extrapolation (see [26], for instance). In the THM approach, the low-energy cross section of a A(x,c)C reaction is obtained by extracting the quasi-free (QF) contribution to a suitable A(a,cc) reaction. In QF kinematics, particle a, characterized by a prominent x + s cluster structure, is used to transfer the participant cluster x and feed the excited states of the B = c + C system, while the other constituent cluster s is emitted without interacting with the system B, thus behaving as a spectator to the A(x,c)C sub-process. Because of the clear signature of the QF process, this reaction mechanism can be unambiguously singled out from the A(a,cc)s reaction yield. Moreover, the use of a three-body reaction allows for a number of kinematic test to separate the A(a,cc)s channel from background reactions [17]. Particle x is virtual so the A(x,c)C THM cross section is half-off-energy-shell (HOES) and cannot be right juxtaposed to the direct (on-energy-shell, OES) cross section. In the case of resonance reactions, the so-called modified R-matrix approach [17] has been introduced to extract the physical information of interest from the QF reaction yield, given by the reduced widths. In the modified R-matrix framework, assuming that the rearrangement reaction A(x,c)C proceeds via isolated non interfering resonances so that a two-level, one-channel R-matrix formula applies, the cross section of the THM reaction
can be written as:

\[
\frac{d^2\sigma}{dE_{xA}d\Omega_s} = \text{NF} \sum_i (2J_i + 1) \times \sqrt{\frac{k_i(E_{xA})}{\mu_{cC}}} \sqrt{2p_i(k_{cC}R_{cC})M_i(p_{xA}R_{xA})\gamma_i^k \gamma_i^A}^{2} D_i(E_{xA})
\]

in the plane wave impulse approximation (PWIA), where NF is a normalization factor, \(J_i\) the spin of the \(i\)-th resonance, \(k_f(E_{xA}) = \sqrt{2\mu_{cC}(E_{xA} + Q)/h}\) (\(Q\) is the reaction Q-value, \(E_{xA}\) the \(x-A\)-relative energy), \(p_i\) the penetration factor in \(i\)-wave, \(R_{xA}\) and \(R_{cC}\) the channel radii.

\[
M_i(p_{xA}R_{xA}) = \left[(B_{xAi} - 1) j_i(\rho) - \rho \frac{\partial j_i(\rho)}{\partial \rho}\right]_{\rho=p_{xA}R_{xA}}
\]

where \(j_i(\rho)\) is the spherical Bessel function, \(p_{xA} = \sqrt{2\mu_{xA}(E_{xA} + B_{xs})/h}\) (\(B_{xs}\) the binding energy of the \(a = (xs)\) system), and \(B_{xAi}\) an arbitrary boundary condition chosen as in [17] to yield the observable resonance parameters. Finally, \(D_i(E_{xA})\) is the standard R-matrix denominator in the case of two-level, one-channel R-matrix formulas [21]. In Eq.1, the same reduced widths appear as in the S(E)-factor, the only difference being the absence of any Coulomb or centrifugal penetration factor in the entrance channel. From the fitting of the experimental THM cross section they can be obtained and used to deduce the \(^{19}\text{F}(p,\alpha)^{16}\text{O}\) astrophysical factor, which is not affected by the electron screening neither by experimental energy resolution. Normalization is achieved by extending the indirect measurement to an energy region where directly measured resonances are available and scaling the deduced widths to match the values in the literature.

3. Direct measurements
Proton-induced \(^{19}\text{F}\) destruction has been the subject of several experimental investigations, because of its astrophysical and spectroscopic relevance. In the NACRE compilation [16], containing the most recent cross-section measurements, the recommended \(^{19}\text{F}(p,\alpha_0)^{16}\text{O}\) astrophysical S(E)-factor, which is the dominant channel at astrophysical energies, was obtained from several works [15, 22, 14, 23, 13, 24], with the lowest-energy direct data reaching 461 keV center-of-mass energy [15]. The Gamow window is only partially covered by the unpublished data of [18], which have been used in [19, 20] to evaluate the astrophysical factor in the zero- and finite-range DWBA approaches, respectively. These data supported a strong suppression of compound \(^{20}\text{Ne}\) decay to the ground state of \(^{16}\text{O}\) at \(E_{cm} \sim 0.14 - 0.6\) MeV. However, these results were not included in the NACRE compilation as possible systematic errors affecting the absolute normalization might lead to an underestimate of S(E) by a factor of 2 [16]. The astrophysical factor was then extrapolated to low energies assuming a dominant contribution of the non-resonant part [16]. This conclusion disagrees with older measurements in [15], where the existence of two resonances with \(J^\pi = 1^-\) and \(0^+\) had been reported at \(E_{cm} \sim 0.4\) MeV. It is worth noting that additional resonances might be populated in \(^{20}\text{Ne}\) as they are permitted by their quantum numbers [25].

In conclusion, the available experimental data have allowed the computation of the rate for \(T_9 > 0.3\). Below this temperature, the rate is determined mainly from the non-resonant \((p,\alpha_0)\) channel, causing a progressive increase of the uncertainties up to about 50% at the lowest temperatures [16].

To ascertain the actual contribution of resonances at astrophysical energies and evaluate their impact on astrophysics, an experimental program has been set forth to measure the \(^{19}\text{F}(p,\alpha_0)^{16}\text{O}\) astrophysical S(E)-factor by means of the Trojan Horse (TH) method.
4. The THM astrophysical factor and reaction rate

The $^{19}$F($p,\alpha_0$)$^{16}$O reaction has been investigated by applying the Trojan Horse Method to the $^2$H($^{19}$F,$\alpha_0$)$^n$ reaction [17], thus allowing to estimate the low-energy resonance contribution to the $^{19}$F($p,\alpha_0$)$^{16}$O S(E)-factor at astrophysical energies. Therefore, the $\gamma_p$ and $\gamma_{\alpha_0}$ reduced widths were extracted from the $^2$H($^{19}$F,$\alpha_0$)$^n$ TH data by means of the modified R-matrix approach, as discussed in [17], by means of Eq.1. These parameters were then used to evaluate the resonance contribution to the on-energy-shell (OES) $^{19}$F($p,\alpha_0$)$^{16}$O astrophysical S(E)-factor, parametrized by standard R-matrix formulas. The OES S(E)-factor calculated with the reduced widths $\gamma_p$ and $\gamma_{\alpha_0}$ given in [17] is shown in Fig.1. Since the TH cross section provided the resonance contribution only, the non-resonant part of the S(E)-factor has been taken from [16]. The curve evaluated from the best fit parameters is demonstrated by the middle red line. The red band accounts for the errors introduced in the present calculations (statistical + normalization).

The main result of the present work is the estimate of the contribution of the 12.957 MeV $^{20}$Ne level to the total astrophysical factor, as it is responsible of the resonance at 113 keV, well inside the energy range of astrophysical interest. Moreover, a lower limit has been established for the contribution of the 13.222, 13.224 and 13.226 MeV $^{20}$Ne states, to satisfy the condition set by [18, 19, 20], namely the dominance of direct reaction mechanism in the 0.14–0.6 MeV energy range. These levels yield resonances at $\sim$ 0.4 MeV, thus their role is marginal at astrophysical energies (below 0.3 MeV).

The reaction rate R for the $^{19}$F($p,\alpha_0$)$^{16}$O reaction was calculated using the astrophysical factor in Fig.1 by means of standard equations [12]. For T$_9$ $\sim$ 0.1 the reaction rate R largely
departs from the non-resonant one, the difference being clearly due to the presence of the 113 keV resonance. The largest difference, about 70%, occurs at temperatures relevant for post-AGB stars, exceeding the upper limit set by the uncertainties in [16]. For $T_9 < 0.04$, i.e. at temperatures relevant to extra-mixing in AGB stars, the increase in the reaction rate is smaller than about 20%. The 13.226 MeV state in $^{20}$Ne gives instead a small contribution to the total reaction rate, following the conclusions drawn in [19, 20].

The energy resolution was not enough to achieve a good separation between resonances, especially at $\sim 400$ keV, thus preventing from an accurate estimate of their total widths. Thus, the interesting results already achieved call for improved investigations in the full energy region with a better energy resolution to perform more accurate spectroscopy of the involved resonances. A new experiment has been performed to verify and improve the measured TH astrophysical factor. Data analysis is ongoing. However, no consequences are expected for astrophysics as these are essentially linked to the 113 keV peak clearly observed here.

5. Acknowledgments

The work was supported in part by the US Department of Energy under Grant No. DE-FG02-93ER40773 and DEFG52-06NA26207, NSF under Grant No. PHY-0852653 and by the Italian Ministry of University and Research under Grant No. RBFR082838 (FIRB2008).

References
[1] S. Lucatello et al., *Astrophys. J.* 729, 40 (2011).
[2] S.E. Woosley and W.C. Haxton, *Nature* 334, 45 (1988).
[3] G. Meynet and M. Arnould, *Astron. Astrophys.* 355, 176 (2000).
[4] S. Cristallo et al., *Astrophys. J.* 696, 797 (2009).
[5] G. Pandey, D.L. Lambert and N. Kameswara Rao, *Astrophys. J.* 674, 1068 (2008).
[6] A. Jorissen, V.V. Smith and D.L. Lambert, *Astron. Astrophys.* 261, 164 (1992).
[7] M. Lugaro et al., *Astrophys. J.* 615, 934 (2004).
[8] C. Abia et al., *Astrophys. J.* 715, L94 (2010).
[9] K.M. Nollett, M. Busso and G.J. Wasserburg, *Astrophys. J.* 582, 1036 (2003).
[10] M.L. Sergi et al., *Phys. Rev. C* 82, 032801 (2010).
[11] M. Busso et al., *Astrophys. J.* 717, L47 (2010).
[12] C. Rolfs and W.S. Rodney, *Cauldrons in the Cosmos*, Univ. of Chicago Press, Chicago, 1988.
[13] A. Isoya, H. Ohmura and T. Momota, *Nucl. Phys.* 7, 116 (1959).
[14] R. Caracciolo et al., *Lett. Nuovo Cimento* 11, 33 (1974).
[15] G. Breuer, *Z. Phys.* 154, 339 (1959).
[16] C. Angulo et al., *Nucl. Phys. A* 656, 3 (1999).
[17] M. La Cognata et al., *Astrophys. J.* 739, L54 (2011).
[18] H. Lorentz-Wirzba, Ph.D. Thesis, Universität Münster, 1978.
[19] H. Herndl et al., *Phys. Rev. C* 44, R952 (1991).
[20] Y. Yamashita and Y. Kudo, *Prog. Theor. Phys.* 90, 1303 (1993).
[21] A.M. Lane and R.G. Thomas, *Rev. Mod. Phys.* 30, 257 (1958).
[22] K.L. Warsh, G.M. Temmer & H.R. Blieden, *Phys. Rev.* 13, 1690 (1963).
[23] P. Cuzzocrea, et al., *Lett. Nuov. Cimento* 28, 515 (1980).
[24] S. Morita et al., *J. Phys. Soc. Japan* 21, 2435 (1966).
[25] D.R. Tilley et al., *Nucl. Phys.* A 636, 247 (1998).
[26] C. Spitaleri et al., *Physics of Atomic Nuclei* 74, 1725 (2011).