THE FLUORINE DESTRUCTION IN STARS: FIRST EXPERIMENTAL STUDY OF THE $^{19}$F($p, α$)16O REACTION AT ASTROPHYSICAL ENERGIES

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ABSTRACT

The $^{19}$F($p, α$)16O 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 ($E_{\text{cm}} \lesssim 300$ keV), because of the hindrance effect of the Coulomb barrier. The Trojan Horse (TH) method was thus used to access this energy region, by extracting the quasi-free contribution to the $^2\text{H}(^{19}\text{F}, α^{16}\text{O})n$ and the $^{19}\text{F}(^3\text{He}, α^{16}\text{O})d$ reactions. The TH measurement of the $α_0$ channel shows the presence of resonant structures not observed before, which cause an increase of the reaction rate at astrophysical temperatures up to a factor of 1.7, with potential consequences for stellar nucleosynthesis.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: AGB and post-AGB

Onlne-only material: color figures

1. ASTROPHYSICAL MOTIVATIONS

Fluorine is a key element for astrophysics. Its abundance is very sensitive to the physical conditions within stars and for such a reason it is used to probe hotly debated nucleosynthesis scenarios (Lucatello et al. 2011). The most likely environments where its production can take place in the Milky Way are: during the core collapse of Type II supernovae (Woosley & Haxton 1988) would represent the main fluorine destruction channel, possibly modifying F surface abundances, as proposed by Spyrou et al. (2000), the $^{19}$F($p, α$)16O reaction might bear a great importance as it would remove both protons and F nuclei from the nucleosynthesis scenario. Since the temperature at the base of the accreted material approaches $T_9 \sim 0.2$ (Pandey et al. 2008), the $^{19}$F($p, α$)16O cross section should be known at $E_{\text{cm}} \sim 50–300$ keV for accurate modeling.

2. AVAILABLE DIRECT DATA AND SPECTROSCOPIC INFORMATION

Proton-induced $^{19}$F destruction has been the subject of several experimental investigations, because of its astrophysical and spectroscopic relevance.

As pointed out in the Nuclear Astrophysics Compilation of Reaction Rates (NACRE; Angulo et al. 1999) and confirmed by Spyrou et al. (2000), the $^{19}$F($p, α_0$)16O channel is giving the largest contribution to the reaction rate of the $^{19}$F($p, α$)16O reaction for $0.01 < T_9 < 0.1$. In the NACRE compilation, the recommended $^{19}$F($p, α_0$)16O astrophysical S(E)-factor was obtained from several works (Breuer 1959; Warsh et al. 1963; Caracciolo et al. 1974; Cuzzocrea et al. 1980; Isoya et al. 1958; Morita et al. 1966), with the lowest-energy direct data reaching 461 keV center-of-mass (c.m.) energy (Breuer 1959). The Gamow window is only partially
covered by the unpublished data of Lorentz-Wirzba (1978), which have been used in Herndl et al. (1991) and Yamashita & Kudo (1993) to evaluate the astrophysical factor in the zero- and finite-range Distorted Wave Born Approximation (DWBA) approaches, respectively. These data support a strong suppression of compound $^{20}$Ne decay to the ground state of $^{16}$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 two (Angulo et al. 1999). The astrophysical factor was then extrapolated to low energies assuming a dominant contribution of the non-resonant part (Angulo et al. 1999). This conclusion disagrees with older measurements in Breuer (1959), 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 $^{20}$Ne as they are permitted by their quantum numbers (Tilley et al. 1998). This can be parameterized in terms of the boundary condition in the channel $x+A \rightarrow c+C$, causing a progressive increase of the uncertainties up to $\sim 50\%$ at the lowest temperatures (Angulo et al. 1999).

In conclusion, the available experimental data have allowed the computation of the rate for $B_B > 0.3$. 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 $\sim 50\%$ at the lowest temperatures (Angulo et al. 1999).

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 $^{19}$F($p, \alpha$)$^{16}$O astrophysical S(E)-factor by means of the Trojan Horse (TH) method.

3. THE TH THEORY: THE MODIFIED R-MATRIX APPROACH

The TH method has been developed in the early 1990s with the aim of measuring low-energy nuclear reactions unhindered by the Coulomb barrier (Baur 1986; Cherubini et al. 1996; Spitaleri et al. 1999; La Cognata et al. 2008). Since then it has been successfully applied to several reactions of astrophysical interest. Recently, a generalized R-matrix approach has been developed (Mukhamedzhanov et al. 2007; La Cognata et al. 2007, 2010a, 2010b; Mukhamedzhanov et al. 2008) to analyze multi-resonance TH reactions. This differs from standard R-matrix (Lane & Thomas 1958) as it considers the half-off-energy-shell character of the TH cross section. Let us consider the TH reaction

$$a + A \rightarrow s + c + C,$$

(1)

where $a = (s,x)$. This TH reaction is used to obtain the astrophysical factor for the resonant subreaction

$$x + A \rightarrow c + C.$$

(2)

If the cluster $s$ escapes without interacting with the $x+A$ system (quasi-free (QF) condition), the TH reaction amplitude is given by an expression similar to the binary resonant reaction amplitude (see Equation (10) in La Cognata et al. 2010a). In details, it contains the overlap function $T_{A} = \langle \Phi_{\Delta} | \Phi_{A} \rangle$ of the internal wave function of the system $F = x + A = c + C$ excited to the level $\tau$ and the bound-state wave function of $A$. This can be parameterized in terms of the boundary condition in the channel $x+A$ and of the reduced width amplitude $\gamma_{\Delta A \tau}$, as the R-matrix amplitude for the binary resonant reaction $x + A \rightarrow c + C$ proceeding through the resonance state $F_{\tau}$ (A. Mukhamedzhanov 2011, in preparation). Assuming non-interfering resonances, the TH cross section is obtained in the plane-wave (PW) approximation:

$$\frac{d^2\sigma}{dE_{cm}d\Omega_{cm}} = NF \sum_{\tau} (2J_{\tau} + 1) \times \left( \frac{k_{f}(E_{A}) \sqrt{2P_{r}(k_{c}R_{c})}M_{r}(p_{A}R_{A})\gamma_{c_{\tau}}} {\mu_{c}D_{r}(E_{A})} \right)^{2}. \quad (3)$$

Here, $NF$ is a normalization factor, $J_{\tau}$ the spin of the $\tau$th resonance, $k_{f}(E_{A}) = \sqrt{2\mu_{c}E_{A}(E_{A} + Q)/\hbar}$ ($Q$ is the Q-value of reaction 2, $E_{A}$ the $x-A$-relative energy), $P_{r}$ is the penetration factor in $l_{r}$-wave, $R_{A}$ and $R_{c}$ are the channel radii.

$$M_{r}(p_{A}R_{A}) = \left[ B_{A\tau} - 1 \right] j_{\Delta r}(\rho) - \frac{\partial j_{\Delta r}(\rho)}{\partial \rho} \bigg|_{\rho = p_{A}R_{A}}. \quad (4)$$

where $j_{\Delta r}(\rho)$ is the spherical Bessel function, $p_{A} = \sqrt{2\mu_{c}(E_{A} + B_{A\tau})/\hbar}$ ($B_{A\tau}$ is the binding energy of the $a = (x,s)$ system), and $B_{A\tau}$ an arbitrary boundary condition chosen as in La Cognata et al. (2010a) to yield the observable resonance parameters. Finally, $D_{r}(E_{A})$ is the standard R-matrix denominator in the case of two-level, one-channel R-matrix formulæ (Lane & Thomas 1958), containing shift and penetration functions besides the boundary conditions set as above.

4. MEASUREMENT AND RESULTS

Two experimental runs were performed, using two different TH nuclei to transfer the participant proton. In the first run, the QF $^2$H($^{19}$F, $^{16}$O)n reaction at 50 MeV beam energy was measured, in the second the $^2$F($^{19}$F, $^{16}$O)d reaction at $E_{beam} = 18.2$ MeV (to check for pole invariance; Pizzzone et al. 2011). In what follows we will focus on the measurement of the $^{19}$F($p, \alpha_0$)$^{16}$O astrophysical factor and we will describe the first run only (where the spectator $s$ is the neutron); the experimental setups were similar in the two experiments. A 1 mm collimated $^{19}$F beam impinged onto deuterated polyethylene (CD2) targets ($\sim 100\mu$ cm$^{-2}$ thick). The experimental setup comprised a $\Delta E - E$ telescope, consisting of an ionization chamber and a silicon position sensitive detector (PXD1) on one side of the scattering chamber and four additional silicon PSDs (PXD2-5) on the opposite side of the beam axis. The $\Delta E - E$ telescope was optimized for the detection of $^{16}$O recoils, while the PSDs for coincident detection of the $a$-particles. Angular conditions were selected to optimize the QF contribution. Channel selection was accomplished by gating on the $\Delta E - E$ spectra to select the $Z = 8$ locus and on the Q-value of the $^2$H($^{19}$F, $\alpha_0^{16}$O)n reaction.

Compelling evidence for the occurrence of the QF mechanism is provided by the observed agreement between the experimental $p-\alpha$ momentum distribution inside the deuteron and the theoretical one given by the square of the Hulthén wave function in momentum space (in the PW approximation; Spitaleri et al. 1999; Pizzzone et al. 2009). Since this is a necessary condition for the QF mechanism being present and dominant, only events satisfying the condition $Q < p_{\alpha} < 40$ MeV c$^{-1}$ for the neutron momentum range, where the agreement is observed ($\chi^2 = 1.4$), are considered in the extraction of the QF cross section $d^3\sigma/dE_{cm}d\Omega_{cm}d\Omega_{n}$ of the $^2$H($^{19}$F, $\alpha_0^{16}$O)n reaction. A minor background contribution was identified as being
due to the $^2\text{H} + ^{19}\text{F} \rightarrow \alpha + ^{17}\text{O} \rightarrow \alpha + ^{16}\text{O} + n$ sequential decay. Such contribution represents $\sim 7\%$ of the gated coincidence yield in the $p - ^{19}\text{F}$ relative-energy range $E_{\text{cm}} = 0 - 1$ MeV and was subtracted by fitting the $E_n - ^{16}\text{O}$ relative-energy spectrum. A similar discussion applies to the $^{19}\text{F} + ^{3}\text{He} \rightarrow ^{16}\text{O} + \alpha$ reaction. Anyway, too low statistics prevented us to extract angular distributions as well as the TH cross section from this data set. The normalized coincidence yield is given in Figure 1. It was obtained by dividing the selected coincidence yield by the product of the phase-space factor and of the $p - n$ momentum distribution (see La Cognata et al. 2010a, 2010b, and references therein). The experimental data clearly show the presence of three resonance groups corresponding to $^{20}\text{Ne}$ states at $12.957$ and $13.048$ MeV, $13.222$, $13.224$, and $13.226$ MeV; and $13.529$, $13.586$, and $13.642$ MeV levels. The normalized yield was fitted simultaneously with four Gaussian curves to separate the resonance contributions. In Figure 1 the multi-Gaussian fitting curve is shown by a black line, the red and green lines outline the contribution of the $12.957$ and $13.048$ MeV $^{20}\text{Ne}$ levels, respectively, the blue line describes the combined yield of the $13.222$, $13.224$, and $13.226$ MeV states while the purple line one of the $13.529$, $13.586$, and $13.642$ MeV levels, as marked by the arrows. (A color version of this figure is available in the online journal.)

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Table 1
Reduced and Observable Partial Widths from R-matrix Fits

<table>
<thead>
<tr>
<th>$E_R$ (MeV)</th>
<th>$J^\pi$</th>
<th>$\gamma_p$ (MeV$^{-1/2}$)</th>
<th>$\gamma_{\alpha}$ (MeV$^{-1/2}$)</th>
<th>$\Gamma_p$ (MeV)</th>
<th>$\Gamma_{\alpha}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.957</td>
<td>2$^+$</td>
<td>0.110$^{+0.007}_{-0.012}$</td>
<td>0.068</td>
<td>9.6$^{+1.2}_{-1.0}$ x 10$^{-12}$</td>
<td>0.038</td>
</tr>
<tr>
<td>13.048</td>
<td>4$^+$</td>
<td>0.690$^{+0.069}_{-0.049}$</td>
<td>0.0446</td>
<td>(1.22$^{+0.14}_{-0.17}$) x 10$^{-11}$</td>
<td>0.010</td>
</tr>
<tr>
<td>13.222$^a$</td>
<td>0$^+$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>13.224$^a$</td>
<td>1$^-$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>13.226</td>
<td>3$^-$</td>
<td>0.305$^{+0.020}_{-0.026}$</td>
<td>0.086</td>
<td>(8.1$^{+1.9}_{-1.4}$) x 10$^{-8}$</td>
<td>0.053</td>
</tr>
</tbody>
</table>

From modified R-matrix (Equation (3))

| 13.529      | 2$^+$   | 0.0410                      | 0.0561                       |                  |                  |
| 13.586      | 2$^+$   | 0.0825                      | 0.0904                       |                  |                  |
| 13.642      | 2$^+$   | 0.0581                      | 0.0467                       |                  |                  |

From standard R-matrix (Lane & Thomas 1958)

Notes. Resonance energies, spin parities, and $\omega_0$ partial widths are fixed to the values in the literature (Tilley et al. 1998) in the modified R-matrix fitting.

$^a$ The contribution of these resonances is assumed to be negligible in the fitting.

$^b$ The spin-parity assignment to this resonance is ambiguous, also $J^\pi = 0^+$ is reported (Tilley et al. 1998).

The normaIzation error accounts for reduced widths of these states different from the ones in Table 1, but still leading to an S(E)-factor in agreement with the direct one within the quoted uncertainties. The experimental energy resolution was accounted for by smearing the calculated TH cross section to match the shape of the peak at about 0.75 MeV. Such a procedure, described in La Cognata et al. (2009), yielded an energy resolution of 60 keV. The normalized $\gamma_p$ and $\gamma_{\alpha}$ are listed in Table 1. In the calculation, the $\Gamma_{\alpha}$ partial widths, being essentially the total widths, were kept fixed at the values in the literature (Tilley et al. 1998), as well as the energy and spin parity of each resonance. The $d^2\sigma/dE_{cm}dQ_{\alpha}$ best-fit cross section obtained from Equation (3) is shown together with the TH data in Figure 2 (middle red line, $\chi^2 = 2.1$). The top and bottom lines mark the upper and lower limits set by the statistical and normalization errors. A good fit is obtained without including non-resonant contributions.

Values of $\gamma_p$ and $\gamma_{\alpha}$ from the fitting were then used to evaluate the resonance contribution to the on-energy-shell (OES) $^{19}$F($p, \alpha$)$^{16}$O astrophysical factor, according to standard R-matrix formulae. This is possible as in the modified R-matrix approach the same reduced widths appear as in the OES S(E)-factor, the only difference being the absence of any Coulomb or centrifugal penetration factor in the entrance channel (see Equation (3)). The OES S(E)-factor calculated with $\gamma_p$ and $\gamma_{\alpha}$ in Table 1 is shown in Figure 3. Since the TH cross section provided the resonance contribution only, the non-resonant part of the cross section was taken from Angulo et al. (1999). The middle red curve represents the S(E)-factor obtained using the parameters from the best fit, while the red band arises from the uncertainties in the resonance parameters of the 12.957, 13.048, 13.222, 13.224, and 13.226 MeV $^{20}$Ne states, namely 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 a 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 Lorentz-Wirzba (1978); Herndl et al. (1991); Yamashita & Kudo (1993), namely the dominance of direct reaction mechanism in the 0.14–0.6 MeV energy range. These levels yield resonances at ~0.4 MeV, thus their role is marginal below 0.3 MeV, except if the strengths of the 13.222 and 13.224 MeV resonances were very large, which seems to be excluded within the errors of the direct data (Lorentz-Wirzba 1978; Herndl et al. 1991; Yamashita & Kudo 1993).

5. REACTION RATE AND CONCLUSIONS

The reaction rate $R$ for the $^{19}$F($p, \alpha$)$^{16}$O reaction was calculated using the astrophysical factor in Figure 3 by means of standard equations (Rolfs & Rodney 1988; Iliadis 2007). The best-fit curve (middle line in Figure 3) was used and the upper and lower limits provided the uncertainty range. The results are displayed in Figure 4: in panel (a) the reaction...
rate in cm\(^3\) mol\(^{-1}\) s\(^{-1}\) while in panel (b) its ratio to the one calculated following the NACRE prescription is shown. This was deduced assuming a non-resonant behavior of the S(E)-factor from 0.6 MeV downward, thus it will be referred to as the non-resonant reaction rate \(R_{\text{NR}}\). \(R/R_{\text{NR}}\) represents essentially the deviation of the \(^{19}\text{F}(p,\alpha)^{16}\text{O}\) reaction rate obtained here from the one in the literature. 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 Angulo et al. (1999). The 13.226 MeV state in \(^{20}\text{Ne}\) gives a factor of the same order (Lucatello et al. 2011), this updated reaction rate can help to solve the fluorine puzzle in these stars in the framework of extra-mixing. In the \(M = 2\,\odot\) and \(Z = 10^{-4}\) AGB stellar model\(^9\) used for preliminary calculations, the mixed material experiences temperatures up to \(T_9 \sim 0.05\), where the reaction rate is 27% higher than in NACRE. An even larger destruction is expected in those environments where the reaction rate enhancement approaches a factor of 1.7 (\(T_9 \sim 0.1\)). Therefore, extensive calculations are undergoing to understand the consequences of the present results on astrophysics.

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\(^9\) Stellar parameters are taken from Cristallo et al. (2009).