

THE FLUORINE DESTRUCTION IN STARS: FIRST EXPERIMENTAL STUDY OF THE $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ REACTION AT ASTROPHYSICAL ENERGIES

M. La Cognata*

INFN-Laboratori Nazionali del Sud, Catania, Italy

E-mail: lacognata@lns.infn.it

A. M. Mukhamedzhanov

Cyclotron Institute - Texas A&M University, College Station, TX, USA

I. Indelicato

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

M. Aliotta

School of Physics and Astronomy, University of Edinburgh, Edinburgh, and SUPA - Scottish Universities Physics Alliance, United Kingdom

V. Burjan

Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

S. Cherubini

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

A. Coc

CSNSM CNRS/IN2P3, Université Paris Sud, Orsay, France

M. Gulino

Università degli Studi di Enna "Kore", Enna, & INFN - Laboratori Nazionali del Sud, Catania, Italy

Z. Hons

Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

G.G. Kiss

ATOMKI, Debrecen, Hungary

V. Kroha

Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

L. Lamia

Dipartimento di Fisica e Astronomia - Università di Catania, Catania, Italy

J. Mrázek

Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

Š. Piskoř

Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

R.G. Pizzone

INFN-Laboratori Nazionali del Sud, Catania, Italy

S.M.R. Puglia

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

G.G. Rapisarda

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

S. Romano

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

M.L. Sergi

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

A. Tumino

Università degli Studi di Enna "Kore", Enna, & INFN - Laboratori Nazionali del Sud, Catania, Italy

C. Spitaleri

Dipartimento di Fisica e Astronomia - Università di Catania & INFN-Laboratori Nazionali del Sud, Catania, Italy

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 of the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction 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 $^{19}\text{F}(^3\text{He}, \alpha)^{16}\text{O}d$ 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 α_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.

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1. Introduction

Fluorine is a key isotope for astrophysics as its abundance is used to probe hotly-debated nucleosynthesis scenarios, being 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: v-process just above the collapsing core of a Type II supernova [2], Wolf-Rayet stars [3] and 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 – 8000 [5]. Such overabundances are evidence for the synthesis of fluorine in these hydrogen-deficient supergiants. In spite of its key importance, a definite view of fluorine abundance and nucleosynthesis is not presently available.

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 have provided an explanation in the case of Population II stars [8], due to the consequent renormalization of the observed abundances. However, the understanding of F production in the case of metal-poor AGB stars is far from satisfactory [1]. A reassessment of the nuclear reaction rates intervening in fluorine production and destruction might afford an alternative explanation for the known inconsistencies between model predictions and observations. Indeed, 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 $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction at $E_{cm} \sim 27 - 94$ keV (corresponding to the Gamow window [12]) would represent the main fluorine destruction channel, possibly modifying F surface abundance.

2. The Trojan Horse Method

At astrophysical energies the measurement of the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ cross section is very difficult. This has to be ascribed to 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 degrades 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 $\sigma_b(E)$ at ultra-low energies. In the case of resonance reaction, the problem of electron screening is even more delicate as only few studies are available [10].

To avoid extrapolation, alternative experimental methods for determining $\sigma_b(E)$ 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 $A(a, cC)s$ 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:

$$\frac{d^2\sigma}{dE_{xA}d\Omega_s} = NF \sum_i (2J_i + 1) \times \left| \sqrt{\frac{k_f(E_{xA})}{\mu_{cC}}} \frac{\sqrt{2P_i(k_{cC}R_{cC})} M_i(p_{xA}R_{xA}) \gamma_{cC}^i \gamma_{xA}^i}{D_i(E_{xA})} \right|^2 \quad (2.1)$$

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

$$M_i(p_{xA}R_{xA}) = \left[(B_{xAi} - 1) j_{l_i}(\rho) - \rho \frac{\partial j_{l_i}(\rho)}{\partial \rho} \right]_{\rho=p_{xA}R_{xA}} \quad (2.2)$$

where $j_{l_i}(\rho)$ is the spherical Bessel function, $p_{xA} = \sqrt{2\mu_{xA}(E_{xA} + B_{xs})}/\hbar$ (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], Eq. 1.13 pag. 322). In Eq.2.1, 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}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 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 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}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, α_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 $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ reaction has been investigated by applying the Trojan Horse Method to the $^2\text{H}(^{19}\text{F}, \alpha_0)^{16}\text{O}n$ reaction [17], thus allowing to estimate the low-energy resonance contribution to the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ S(E)-factor at astrophysical energies. Therefore, the γ_p and γ_{α_0} reduced widths were extracted from the $^2\text{H}(^{19}\text{F}, \alpha_0)^{16}\text{O}n$ TH data by means of the modified R-matrix approach, as discussed in [17], by means of Eq.2.1. These parameters were then used to evaluate the resonance contribution to the on-energy-shell (OES) $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ astrophysical S(E)-factor, parametrized by standard R-matrix formulas. The OES S(E)-factor calculated with the reduced widths γ_p and γ_{α_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). As shown in [28], systematic errors, due to nuclear reaction theory, are negligibly smaller than statistical and normalization errors, being $\sim 4\%$

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 ~ 0.4 MeV, thus their role is marginal at astrophysical energies (below 0.3 MeV).

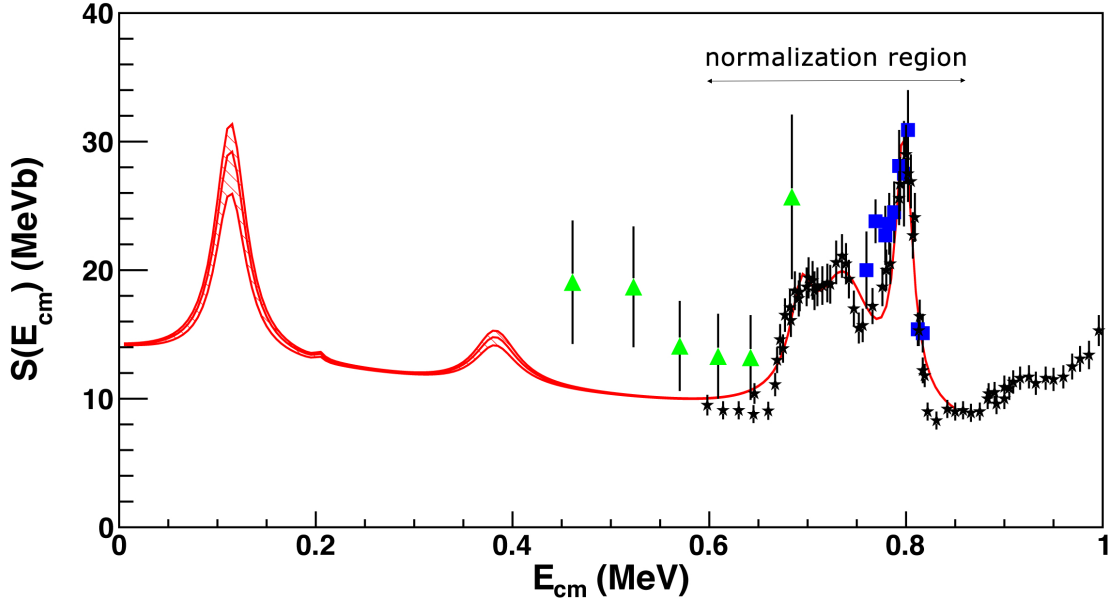


Figure 1: R-matrix parameterization of the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ astrophysical factor. Above 0.6 MeV, the reduced partial widths are obtained through a R-matrix fit of the available direct data (black stars [13], blue squares [14], green triangles [15]). Below 0.6 MeV, the resonance parameters are obtained from the modified R-matrix fit of the $d^2\sigma/dE_{cm}d\Omega_n$ TH cross section, normalized to the direct data in the 0.6 – 0.9 MeV range. The non-resonant contribution is taken from [16]. The best fit is demonstrated by the middle line, the red band highlighting the region allowed by the uncertainties (statistical + normalization) on the fitting parameters (compare [17]).

The reaction rate R for the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ 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 (cool bottom process [9]), 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 ~ 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. Answer to the question asked during the conference

During the conference, one of the conveners asked a very interesting question about the $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ reaction: “How do the resonance observed in $^{19}\text{F}(p, \alpha)^{16}\text{O}$ agree with the ones observed in $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ in the work by Caroline et al.?”

Indeed, while no measurement exists at energies below than ~ 400 keV for the (p, α_0) channel, in a recent work [27] (no work by Caroline et al. is present in the literature, our guess is that [27] is the paper meant in the question) the cross section of the (p, γ) channel is reported down to about 200 keV. Therefore, a comparison is possible between the ^{20}Ne states that are populated through the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ and the $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ reactions, at least inside the overlap region as THM data extends down to zero energy. As shown in Tab.I of Ref.[27], in the $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ reaction resonances at 213 keV ($J^\pi = 2^-$), 323 keV ($J^\pi = 1^+$), 460 keV ($J^\pi = 1^+$), 564 keV ($J^\pi = 2^-$) and 634 keV ($J^\pi = 1^+$) were observed, clearly demonstrating the possibility to populate ^{20}Ne levels in the energy region of astrophysical interest, below 600 keV, and making the straight line extrapolation in [16] maybe unrealistic. However, none of these levels has natural parity, therefore they cannot decay to the $\alpha + ^{16}\text{O}_{\text{g.s.}}$ channel, having spin 0. This fact supports the absence of resonances in the $\sim 200 - 600$ keV region (only an upper limit is given in this work, compare Ref.[17]), though no comparison can be performed below 200 keV, where a 2^+ resonance has been definitely identified in this work. More measurements, both direct and indirect, are necessary to further validate the present data. Moreover, direct data in this range would also allow us to investigate the electron screening effect in the case of resonance reactions.

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