Proc. 13th Int. Conf. on Nucleus-Nucleus Collisions
JPS Conf. Proc. **32**, 010062 (2020)
https://doi.org/10.7566/JPSCP.32.010062

Fluorine Destruction in Stellar Environments

R.G. Pizzone[1], G. D'Agata[1], I. Indelicato[1],M. La Cognata[1], P. Figuera[1], G.L. Guardo[1], S. Hayakawa[1,2], L. Lamia[1,3], M. Lattuada[1,3], M. Milin[4], G.G. Rapisarda[1], S.Romano[1,3], M.L. Sergi[1], N. Skukan[4], N. Soič[4], C. Spitaleri[1,3], A.Tumino[5]

[1]*INFN - Laboratori Nazionali del Sud, Catania, Italy*
[2] *RIKEN, CNS, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3] *Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Catania, Italy*
[4] *Rudjer Boskovic Institut, Bijenicka cesta, 54, 10000, Zagreb, HR*
[5] *Kore University, Viale delle Olimpiadi, 1, 94100 Enna EN, IT*

E-mail: rgpizzone@lns.infn.it

(Received July 8, 2019)

Abundance of ^{19}F exceeds by far the predicted one. This problem represents one of the unanswered questions of stellar modelling. A source of large uncertainties at relevant energies are the ^{19}F$(p, \alpha)^{16}$O and ^{19}F$(\alpha, p)^{22}$Ne reactions. Although the lowest energy point from direct experiments are at about $\sim$ 660 keV, the astrophysical relevant energy region is only known by R-Matrix calculations. In this work we apply the Trojan Horse Method (THM) to the appropriate quasi-free three-body reactions. The THM application allowed us to study the sub-Coulomb energy region and to get the corresponding S(E)-factor values, thus allowing for a detailed evaluation of its astrophysical impact.

KEYWORDS: stellar nucleosynthesis, indirect methods

1. Introduction

The key points of this work will be the study of the main destruction channel for ^{19}F, that turns out to be one of the less abundant elements in the universe with 12≤A≤56. For such nuclei, it is widely accepted that nucleosynthesis mainly takes place inside AGB-stars, in which the just-synthesized isotopes are brought to the surface by the *third dredge up* (TDU) [1]. Following the accepted models, at this evolutionary stage, AGB-stars are composed by a degenerate C-O core, surrounded by a He-shell and a H-shell. The latter two are separated by a thin layer called He-intershell ($10^{-2} \div 10^{-3}$ $M_\odot$). If temperature is high enough in the He-intershell, elements coming fron the CNO cycle, such as ^{14}N, can lead to the production of ^{19}F, by means of the chain ^{14} N$(\alpha, \gamma)^{18}$F$(\beta^+\nu)^{18}$O(p, $\alpha)^{15}$ N$(\alpha, \gamma)^{19}$F [2]. Low mass AGB-stars are the only production sites for ^{19}F observatively confirmed, but there are evidences that ^{19}F can be also formed in Supernovae and Wolf-Rayet objects, even if in reduced quantities.

If the pathways in which ^{19}F is produced are quite clear, it is now important to describe how it can be destroyed. In AGB stars it can happen with the ^{19} F(p, $\alpha)^{16}$ O or ^{19} F$(\alpha$, p)^{22} Ne reactions [1, 2]. Their relative importance critically depends on the environment: in He-rich environment, such as the convective envelope near the He-shell, the latter prevails. It is therefore important to know their reaction rate. This is not well known in the energy range of astrophysical interest, because direct measurements of the cross-section at the Gamow energy region for a stellar temperature of $T = 8 \cdot 10^8$ K should go at energies in the center of mass reference frame between 0.4 and 0.8 MeV, much lower than the energies for which direct measurements are available. Thus an experimental measurement is needed in the Gamow energy range to better understand fluorine burning in AGB environment.

Such measurements at low energies are difficult: astrophysically relevant reaction usually take place at energies from some keV or lower to some MeV, because of the Coulomb barrier is at some MeV. In such conditions, the cross-section is strongly reduced (order of magnitude of some picobarn or lower). For this reasons extrapolations are often used and cross-section is calculated starting from values at higher energies. The trend of cross section is then extended to an energy range where, if there are no resonances, its behaviour is strongly decreasing. To make thing easier, it is very useful to use the so called "astrophysical factor" $S(E) = \sigma(E)Ee^{2\pi\eta}$, in which the decreasing behaviour of the cross-section is compensated by $e^{2\pi\eta}$, where η is the Sommerfeld paramenter. In this way extrapolations are made easier. Such a procedure can be unreliable, because it doesn not take into account the presence of resonances at low-energy (or below the threshold). In this energy region *electron screening* is also important [3]. This phenomenon lowers the effects of the Coulomb barrier between the interacting nuclei, and it is due to electrons. The probability of interaction between projectile and target is therefore enhanced. Theoretical models do not reproduce well all this facts, and so the bare nucleus cross-section, is not reachable from the measured one.
For all those reasons, several indirect methods were proposed. Their aim was to study the reaction of interest starting from processes that have some kind of link with it, and that are easier to study. Among them, the *Trojan Horse Method* (THM) [4,5] allows us to measure the cross-section between charged particles at low energies, without taking into account Coulomb barrier and electron screening effects. This method avoids extrapolations, thus making stellar models more accurate and reliable. It was verified in the last years by means of several validity tests, e.g. the pole-invariance test [6, 7] The THM has significantly contributed to a number of astrophysical problems such as the Big Bang Nucleosynthesis [8], stellar nucleosynthesis [9] light elements depletion [10–12] and AGB nucleosynthesis [13]. THM has proved very useful in the case of measuring cross sections at astrophysical energies for reactions involving radioactive nuclei, e.g. ^{18} F(p,α)^{15}O [14–16] and neutrons [17].

2. THM measurements for F depleting reactions

We refer to [18, 19] for details on data analysis of the ^{19} F(p,α_0)^{16}O as it was studied by means of the THM applied to the quasi-free ^{19} F(d,α_0 ^{16}O)n reaction. It is necessary to state that for the first time the astrophysical S(E)-factor was measured at the lower energies required from astrophysics.Using those novel results the reaction rate for this reaction is then calculated according to the formula

$$R_{ij} = \frac{N_i N_j}{1+\delta_{ij}}\langle\sigma v\rangle =$$
$$= \frac{N_i N_j}{1+\delta_{ij}}\left(\frac{8}{\pi A}\right)^{\frac{1}{2}}\left(\frac{1}{k_B T}\right)^{\frac{3}{2}} \cdot \int_0^\infty S(E_{c.m.})\exp\left[-\left(\frac{E_{c.m.}}{k_B T}+2\pi\eta(E_{c.m.})\right)\right]dE_{c.m.} \tag{1}$$

where $S(E_{c.m.})$ is the measured fusion astrophysical factor, v is the relative velocity of the ij-pair and N_i is the number of nuclei of species i.

In table I the obtained reaction rate is compared as a function of temperature, T_9, to the NACRE compilation [20].

It is evident that for temperatures $T_9 \sim 0.1$ ($T_9 = T/10^9$ K), temperature at which the ^{19}F destruction by extra-mixing process becomes more efficient, the present reaction rate is up to a factor of 2 higher than the rate calculated by Angulo et al. (1999). The enhancement is caused by the 113 keV peak in the ^{19} F(p,α_0)^{16}O astrophysical factor. This enhancement of the reaction rate can help solving the puzzle of fluorine nucleosynthesis in AGB stars since larger ^{19}F destruction is expected by additional mixing processes.

As regards the ^{19}F(α, p)^{22}Ne we refer to [21, 22] for details on measurements and data analysis. Again the astrophysical factor was extracted by means of the THM and used to calculate the reaction

Table I. Reaction rate obtained for $^{19}F(p,\alpha_0)^{16}O$ compared as a function of temperature to the NACRE compilation [20].

T_9	R_{THM}/R_{NACRE}
0.011	1.305
0.015	1.321
0.02	1.341
0.05	1.561
0.09	1.855
0.14	1.578
0.2	1.515
0.25	1.577
0.3	1.630
0.4	1.625
0.5	1.574
0.6	1.512
0.7	1.454
0.8	1.401
0.9	1.353

rate. We report here in table II the values of the reaction rate obtained in that case by means of the THM measurement.

Table II. Reaction rate obtained for $^{19}F(\alpha, p)^{22}Ne$ compared as a function of temperature to Ugalde et al. [23].

T_9	R_{THM}/R_{UGALDE}
0.1	1.08
0.2	1.81
0.3	3.71
0.4	3.29
0.05	1.66
0.60	1.12

An increase in the contribution of the present channel higher up to a factor of 4 (if upper limits are considered) shows up in the region of astrophysical interest between 0.2×10^9 K and 0.6×10^9 K with respect to the literature [23]. Such an enhancement can be seen in Table II, along with temperature and rate values. Since the cross-section of the ^{19} F(α, p)^{22}Ne reaction measured through the THM is up to a factor of 4 larger than that reported in the literature, we believe that these experimental results could crucially affect our knowledge of ^{19}F nucleosythesis in the most relevant energy region for He-shell burning. Such an analysis will be the subject of a forthcoming paper.

References

[1] Lugaro, M., Ugalde, C., Karakas, A. I., et al. 2004, The Astrophysical Journal, 615, 934
[2] Cristallo S., Di Leva A., Imbriani G. et al., 2014, A&A 570 46
[3] Assenbaum, H, Langanke, K., and Rolfs, C. 1987, Z. Phys.A **327**, 461
[4] Spitaleri C. 1991, in *Problems of Fundamental Modern Physics, II* : Proceedings, Ed. by R. Cherubini,P. Dalpiaz, and B. Minetti (World Sci., 1991), p. 21
[5] Spitaleri, C., La Cognata, M., Lamia, L., et al. 2016, Eur. Phys. J. A**52**, 77
[6] Pizzone R.G., Lamia, L., Spitaleri, C., et al. 2011, Phys. Rev. C, 83, 045801

[7] Pizzone, R.G., Spitaleri, C., Bertulani, C., et al. 2013, Phys. Rev. C 87, 025805
[8] Pizzone, R.G., Spartá, R., Bertulani C., et al. 2014, The Astrophysical Journal, **786**, 112
[9] Tumino, A., et al. 2018, Nature, **785**, 96
[10] Lamia, L., Spitaleri, C., Tognelli, E., et al. 2015, The Astrophysical Journal, **811**, 99
[11] Lamia, L., Spitaleri, C., La Cognata, M., et al. 2012, A. & A. **541**, 158
[12] Spitaleri, C., Lamia, L., Puglia, S.M.R., et al. 2014, Phys. Rev. C **90**, 035801
[13] Palmerini, S., Sergi, S., La Cognata, M., et al. 2013, The Astrophysical Journal 764, 128
[14] Cherubini, S., Gulino, M., Spitaleri, C.,et al. 2015, Phys. Rev. C 92, 015805
[15] Pizzone, R.G. , Roeder, B, Mckluskey M., et al. 2016, Eur. Phys. J. A52, 24
[16] La Cognata, M., Pizzone, R. G., José, J., et al. 2017, The Astrophysical Journal, 846, 65
[17] Guardo, G. L., Spitaleri, C., Lamia, L., et al. 2017, Phys. Rev. C, 95, 025807
[18] La Cognata M., Mukhamezhanov A., Spitaleri C., et al., 2011, The Astrophysical Journal Letters, **739**, L 54
[19] Indelicato, I., La Cognata, M., Spitaleri, C., et al. 2017, The Astrophysical Journal, 845, 19
[20] Angulo et al., 1999, Nucl. Phys. A 656 3-183
[21] Pizzone, R.G. , D'Agata G., La Cognata M., Indelicato I., et al. 2017, The Astrophysical Journal 836, 57
[22] D'Agata G. et al., 2018, The Astrophysical Journal, 860, 61
[23] Ugalde, C., et al. 2008, Phys. Rev. C77 035801