Nuclear reactions in AGB nucleosynthesis: the ^{19}F(α, p)^{22}Ne at energies of astrophysical relevance

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Abstract. The abundance of ^{19}F in the universe is strictly related to standard and extra-mixing processes taking place inside AGB-stars, that are considered to be the most important sites for its production. Nevertheless the way in which it is destroyed is far from being well understood. For this reason we studied the ^{19}F(α,p)^{22}Ne reaction, that is supposed to be the main destruction channel in the Helium-rich part of the star. In this experiment, the reaction has been studied in the energy range of relevance for astrophysics (0÷1 MeV) via the Trojan Horse Method (THM), using the three-body reaction ^{6}Li(^{19}F,p^{22}Ne)d.

1 Introduction

The only Fluorine stable isotope - ^{19}F - has been clearly observed in AGB stars [1], where it can be produced in the He-intershell region through the chain of reactions ^{18}O(p,α)^{15}Na(α,γ)^{19}F. Due to the high abundance of alpha particles in the He-intershell, the ^{19}F(α,p)^{22}Ne reaction is expected to dominate over the competitive reaction channels in this region. Fluorine can in fact be destroyed by the ^{19}F(n,γ)^{20}F, reaction triggered by the neutrons produced in ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg reactions, and via the ^{19}F(p,α)^{16}O reaction (already studied using THM by [2] and [3]). It is now clear how Fluorine abundance is really sensitive to the physical condition of the stars, and can be used as a probe to clarify if stellar interior nucleosynthesis is well understood or not [4, 5]: in this case Fluorine abundance can not be reproduced by the up-to-date models. A possible reason of this fact is the large uncertaities at Helium burning temperatures ($0.2 \leq T_9 \leq 0.8$), due to the lack of experimental data about the cross-section in the energy region of astrophysical interest. In particular, before this measurement (results partially published in [6, 7]), there were no experimental data below

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0.660 MeV in the center-of-mass reference frame, being the Gamow window between 0.200 and 1.200 MeV. This is caused by the presence of the Coulomb barrier. In cases like this one, the use indirect methods, such as the Trojan Horse Method (THM) [8] can be rather useful to overcome the technical difficulties related to the height of the Coulomb barrier.

2 The Experiment

To study the ^{19}F(α,p)^{22}Ne reaction, the THM was applied by using a ^{6}Li beam (6 MeV energy, 5 enA intensity) and that can be considered as a cluster $\alpha \oplus d$, impinging on a ^{7}LiF target (150 μm thick), with the aim to induce the ^{6}Li(^{19}F,p^{22}Ne)d three-body reaction to study the ^{19}F(α,p)^{22}Ne two-body one: in this reaction, the α particle is considered as the participant to the two-body reaction, while the deuteron continues its course undisturbed, and is therefore considered the spectator for the process of interest. Following the THM prescriptions, the beam energy was chosen to measure the ^{19}F(α,p)^{22}Ne cross-section in the energy region of interest for astrophysics.

The experiment was performed at Ruđer Bošković Institute (Zagreb, Croatia) and the set-up was composed by two ΔE-E telescopes (placed at 12.3°±7° and 32.3°±7°) made up using thin silicon detectors (82 mm^2 active surface, 15μm and 9μm thickness respectively) as ΔE stage and thick (500μm each) Position Sensitive Detectors (PSDs) as E stage, both meant for deuteron particles detection. On the opposite side of the beam, another 3 PSDs with the same specifics are placed at 37.7°±12°, 81°±9° and 119.9°±11° and are devoted to proton detection (Fig. 1). The necessity to have detectors sensible to the position is given by the fact that one of the three particles in the exit channel of the ^{6}Li(^{19}F,p^{22}Ne)d, in this case ^{22}Ne, is not experimentally detected, but its characteristics are reconstructed form the energies and positions of the two measured ones.

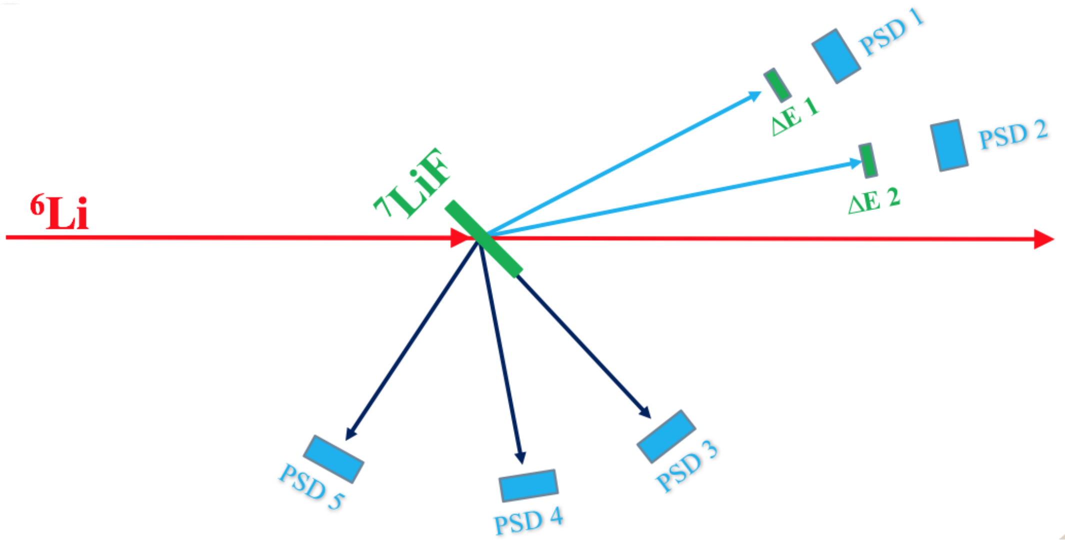

Figure 1. Sketch of the experimental set-up

About the THM application in this case, in this case the Trojan Horse (TH) nucleus is in the beam and we chose to reveal the spectator (deuterons) along with the light outgoin particle (protons). This last fact is due to the characteristics of the ^{22}Ne particles coming from the ^{19}F(α,p)^{22}Ne reaction, that

are emitted at very forward angles ($\vartheta_{\mathrm{Ne}} \leq 6°$) - where the elastic scattering ^{6}Li + ^{19}F (circa 4kHz) would eventually break down the detectors - and at energies (3.5 MeV) that are not high enough to emerge from the target.
In order to maximize the statistics on PSD1 and PSD2, it was also decided to tilt the target at 45° with respect to the beam direction in order to maximize deuteron detection. This is crucial because of the low reaction rate for the reaction and the low energy ($E_d \leq 5$MeV, determined by means of a proper Monte Carlo simulation) of the deuteron particles.

3 Results and Conclusions

Once deuterons are identified by means of the ΔE-E technique, the Q-value for the three-body process can be isolated and the quasi-free contribution can be separated from the sequential decay (procedure explained in [7]). The half-of-energy-shell binary cross-section of interest can be expressed, in quasi-free conditions, as a function of the measured three-body differential cross-section (in the simplest approach) as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)^{HOES} \propto \left(KF\,|\Phi(p_s)|^2\right)^{-1} \cdot \frac{d^3\sigma}{dE_{CM}d\Omega_d\Omega_p} \tag{1}$$

where KF is a kinematic factor and $|\Phi(p_s)|^2$ is tied to the relative motion of the TH nucleus, with p_s momentum of the spectator particle (deuteron) inside the TH nucleus (^{6}Li). Dividing the measured three-body triple differential cross-section for KF and $|\Phi(p_s)|^2$ it is therefore possible to obtain the two-body one of interest in arbitrary units. Those data were then fitted by means of the *Modified R-Matrix* procedure [2] and a first evaluation of the widths of the involved resonances has been performed [6, 7]. The measured cross-section was then normalized to direct data [9] in the overlap region (0.6÷0.9 MeV in the center-of-mass reference frame), obtaining in the end the absolute units cross-section for the ^{19}F(α,p)^{22}Ne reaction. A comparison between the existing reaction rate [9] and the new one was also attempted, and it resulted in an enhancement - in the temperature window of astrophysical interest - up to a factor of four for the destruction rate of ^{19}F via the (α,p) reaction (Tab. 1).

Temperature [10^9K]	Rate $\left[\frac{cm^3}{mol \times sec}\right]$	$\frac{R_{THM}}{R}$
0.10	2.59×10^{-22}	1.08
0.20	6.00×10^{-14}	1.81
0.30	4.67×10^{-10}	3.71
0.40	1.11×10^{-7}	3.29
0.50	5.09×10^{-6}	1.66
0.60	1.14×10^{-4}	1.12

Table 1. Reaction rate and ratio between experimental THM results (R_{THM}) and the one parametrized from the results of [9] (R), $\frac{R_{THM}}{R}$, for several temperatures in units of 10^9 K

In conclusion, with this experiment it was possible, for the first time, to measure the ^{19}F(α,p)^{22}Ne cross-section inside the energy range of astrophysical relevance, and its impact on the reaction rate has been evaluated. An investigation on the effect of this new rate on fluorine nucleosynthesis is still in progress [7].

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