The ^{19}F(α, p)^{22}Ne and ^{23}Na(p,α)^{20}Ne reaction in AGB nucleosynthesis via THM

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Abstract. In AGB environment, fluorine and sodium abundances are still matter of debate. About ^{19}F (only stable isotope of fluorine), its abundance 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. On the other hand, ^{23}Na presence in Globular Clusters, along with is well-known anticorrelation with oxygen has made clear that this element must be produced in previous generations stars, and intermediate-mass AGB stars are one of the possible candidates for its production. For this reason we studied the ^{19}F(α,p)^{22}Ne and ^{23}Na(p,α)^{20}Ne reactions in the energy range of relevance for astrophysics via the Trojan Horse Method (THM), using the three-body reactions ^{6}Li(^{19}F,p^{22}Ne)d and ^{23}Na(d,pn)^{20}Ne.

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 (already studied using THM by [2] and [3]) and ^{19}F(α,p)^{22}Ne. 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 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.

Another reaction of great interest in AGB nucleosynthesis is the ^{23}Na(p, α)^{20}Ne, that is cosidered to have great importance in intermediate-mass AGB stars ($M = 4 \div 8\ M_\odot$), and could be strongly related to the wide known Na/O anticorrelation in globular clusters [10]. This reaction is also of great importance because it represents the turning point between the NeNa and MgAl cycles. Both have the result to fuse hydrogen into helium, and for a mass number $20 \leq A \leq 40$, both (p, α) and (p, γ) channels are open, so those kind of reaction will compete. One of the two cycles can be active if the reaction rate branching ratio $B_{p\alpha/p\gamma} = N_A\langle\sigma v\rangle_{p\alpha}/N_A\langle\sigma v\rangle_{p\gamma}$ is large enough. H−burning in the mass range $A \geq 20$ is important to understand Ne, Na, Mg and Al abundances observed in stars: the relative isotopic abundance depends on the temperature and density conditions inside the H−burning region of a certain star. About NeNa−cycle, at temperature $T \sim 6 \cdot 10^6$ K, ^{22}Ne is entirely transformed in ^{23}Na. An extra production of this element is predicted at temperatures higher than $35 \cdot 10^6$ K, reaching 60% at $T \sim 60 \cdot 10^6$ K. This extra production is provided by ^{20}Ne reaction. In the end ^{23}Na starts burning at $T \geq 60 \cdot 10^6$ K [11].

^{23}Na(p, α)^{20}Ne has not been studied at astrophysical energies with direct methods in the energy range of astrophysical interest. Here the Gamow window lies bwetween 50 keV and 200 keV, while the Coulomb barrier is at 2.57 MeV. Several states of ^{24}Mg were however studied [12], via the ^{23}Na(^{3}He, d)^{24}Mg transfer reaction at 20 MeV. Two resonant states at 37 keV and 138 keV were found: the former had a too low cross section to be studied (but uncertainties were reduced by a factor of 515), and the latter is still the bigger source of uncertainties (circa a factor of 12) in the temperature region near $T \sim 70 \cdot 10^6$ K.

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) impinging on a ^{7}LiF target (150 μm thick). The ^{6}Li particle can be considered as a cluster $\alpha \oplus d$. The aim of this experiment was 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: here the α particle is considered as the participant to the two-body one, 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 (Fig. 1) 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. The necessity to have detectors sensible to the

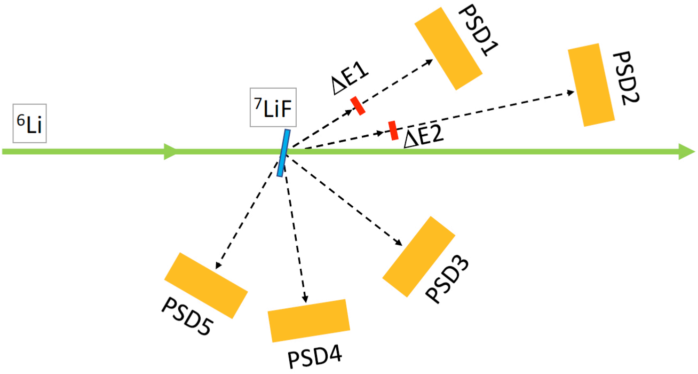

Figure 1. Sketch of the adopted experimental set-up. The two ΔE-E telescopes are situated on one side of the beam axis. Three PSDs were placed on the other side with respect to the beam direction.

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, ^{22}Ne, is not experimentally detected, but its characteristics are reconstructed form the energies and positions of the two measured ones.

About the THM application 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 choice was made considering the characteristics of the ^{22}Ne particles coming from the ^{19}F(α,p)^{22}Ne reaction, that are emitted at very forward angles ($\vartheta_{Ne} \leq 6°$) - 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 10° 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 ($E_d \leq$ 5MeV, determined by means of a proper Monte Carlo simulation) of the deuteron particles.

About the ^{23}Na(p,α)^{20}Ne reaction, the THM was applied using a brand new ^{23}Na beam (58 MeV energy, 0.8 enA intensity) delivered at Laboratori Nazionali del Sud. This beam impinged on a CD_2 target, inducing the ^{23}Na(d,pn)^{20}Ne three-body reaction: here the Trojan Horse nucleus is in the terget. Deuteron in fact can be thought as a cluster composed by a proton and a neutron: the first particle participates to the reaction, inducing the ^{23}Na(p,α)^{20}Ne, while the second acts as a spectator. The experimental set-up consisted in two symmetrical ΔE-E telescopes - composed by a ionization chamber filled with isobuthane (50 mb internal pressure) and two PSDs (500 μm thick) - centered at 6° and two thick PSDs (1000 μm) at higher angles (centered at 25 °). The telescopes were used to identify and measure ^{22}Ne energy and angle of emission, while the thick PSDs were meant for alpha particles.

3 Results and Conclusions

3.1 The ^{19}F(α,p)^{22}Ne reaction

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 than be written, in quasi-free conditions and in the simplest approach, as a function of the measured three-body differential cross-section as follows:

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

Here KF is a kinematic factor, and $|\Phi(p_s)|^2$ is tied to the relative motion of the TH nucleus: p_s in fact represents the 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), thus obtaining 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, for the first time the ^{19}F(α,p)^{22}Ne cross-section inside the energy range of astrophysical relevance was measured, 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].

3.2 The ^{23}Na(p,α)^{20}Ne reaction

After the selection of the heavy fragment (^{20}Ne), again the Q-value for the three-body process can be isolated and the quasi-free contribution can be separated from the sequential decay for both coincidences between a ΔE-E telescopes and the 1000 μm thick PSD placed on the opposite side of the beam (Fig.2). Once the channel is selected, an evaluation of the momentum distribution of the participant particle inside the Trojan Horse nucleus has been made. Its experimental behaviour follows a Hultén function (FWHM≃52 MeV/c), in agreement with literature [13]. The procedure reported in section 3.1 can therefore be used. In the future, the half-of-energy-shell binary cross-section of interest will be extracted and the impact of this new measurement on the reaction rate will be evaluated.

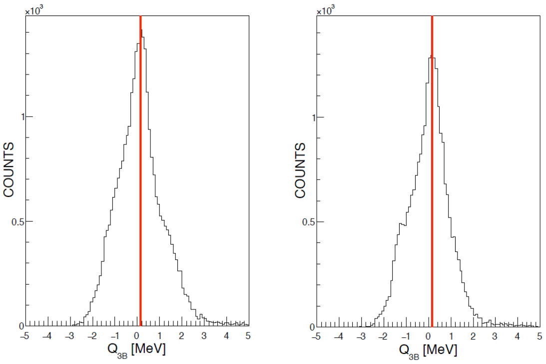

Figure 2. Q_{value} of the three body reaction for both coincidences: the red line indicates the theoretic value for the three body reaction (Q_{value}=0.152 MeV)

This publication was supported by OP RDE, MEYS Czech Republic under the project EF16_013/0001679

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