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First evidences for ^{19}F(α, p)^{22}Ne at astrophysical energies

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Abstract. ^{19}F experimental abundances is overestimated in respect to the theoretical one: it is therefore clear that further investigations are needed. We focused on the ^{19}F(α, p)^{22}Ne reaction, representing the main destruction channel in He-rich environments. The lowest energy at which this reaction has been studied with direct methods is $E_{C.M.} \approx 0.91$ MeV, while the Gamow region is between $0.39 \div 0.8$ MeV, far below the Coulomb barrier (3.8 MeV). For this reason, an experiment at Rudjer Boskovic Institut (Zagreb) was performed, applying the Trojan Horse Method. Following this method we selected the quasi-free contribution coming from ^{6}Li(^{19}F,p ^{22}Ne)^{2}H at E_{beam}=6 MeV at kinematically favourable angles, and the cross section at energies $0 < E_{C.M.} < 1.4$ MeV was extracted in arbitrary units, covering the astrophysical region of interest.

1. Astrophysical background

Fuson reaction inside stars are the main responsible for element production if $A < 60$. Heavier elements are not produced in this way, because of the Coulomb barrier between the interacting nuclei. If $A > 60$, other processes are activated, such as the neutron capture (s-process and r-process), that do not contribute to the stellar energy production, but are important for heavy elements nucleosynthesis. Their producton takes place inside Asimptotic Giant Branch (AGB) stars [1], in which the synthetized isotopes are brought on the surfice by the so-called *third dredge up*: in this phase the star is caracterized by a degenerete carbon-oxygen core, surrounded by a helium and hydrogen shells, separeted by a "thin" layer ($10^{-2} - 10^{-3} R_{\odot}$), called helium-intershell. At high enough temperatures ($T \approx 10^8$ K), the ^{14}N produced in the CNO cycle could bring to the formation of ^{19}F, using the production chain $^{14}N(\alpha,\, \gamma)^{18}F(\beta^{+}\nu)^{18}N(p,\, \gamma)^{19}F$. It is important to underline that AGB stars are the only confirmed sites of ^{19}F production so far. The abundance of ^{19}F is not well reproduced by the various astrophysical models, being lower than what is observed. It is therefore important to study how ^{19}F is destroyed, given that the production pattern is quite clear. In AGB stars it can be destroyed by $^{19}F(p,\,\alpha)^{16}O$ [2] and $^{19}F(\alpha,\,p)^{22}Ne$, with the latter having greater importance in He-rich environments. This is the key argument of the present work. At typical temperatures ($T = 8 \cdot 10^8$ K) for low-mass ($2 \div 4\,M_\odot$) AGB stars, the Gamow window of astrophysical interest is located between 390 and 800 keV, while direct measurements have reached the lowest energies are at $E_{C.M.} = 0.91$ MeV [3][4], making extrapolation at lower energies necessary, where the cross-section is exponentially small. If Coulomb barrier is considered, another problem arises: the Coulomb barrier is at $E_c \simeq 3.8$ MeV, far above the Gamow window. Keeping this in mind is easy to understand how using indirect methods could be useful. Among them, the Trojan Horse Method (THM) [5] [6] [7] [8] are needed for this kind of reaction. In this work in particular, the three-body reaction $^{19}F(^6Li,\,\alpha\,^{22}Ne)^2H$ is used to study the $^{19}F(\alpha,\,p)^{22}Ne$ two-body reaction.

2. Experimental set-up

When approaching to the THM is important to verify some conditions regarding the *Trojan Horse* nucleus (whether projectile or target) and the particles in the exit channel. For the first of the two, we have to be sure that:

- The TH nucleus must show a cluster-like structure
- The Binding energy of the constituting cluster must be small in comparison to the beam energy
- The momentum distribution of the cluster inside the TH nucleus must be known

Keeping this in mind, it is possible to fix the experimental set-up in a way that maximizes the THM contribution to the reaction. We therefore studied the reaction $^{19}F(\alpha,\,p)^{22}Ne$ starting from the three-body reaction $^{19}F(^6Li,\,\alpha\,^{22}Ne)^2H$ using the Trojan Horse Method, which allows to have indirect measurements of the two-body cross section, avoiding inconveniences brought by Coulomb barrier, if the condition above are satisfied. In this experiment the ^6Li projectile was used as THM nucleus, given that it can be described as composed by an α particle (participant) and a deuteron (spectator) with large probability.

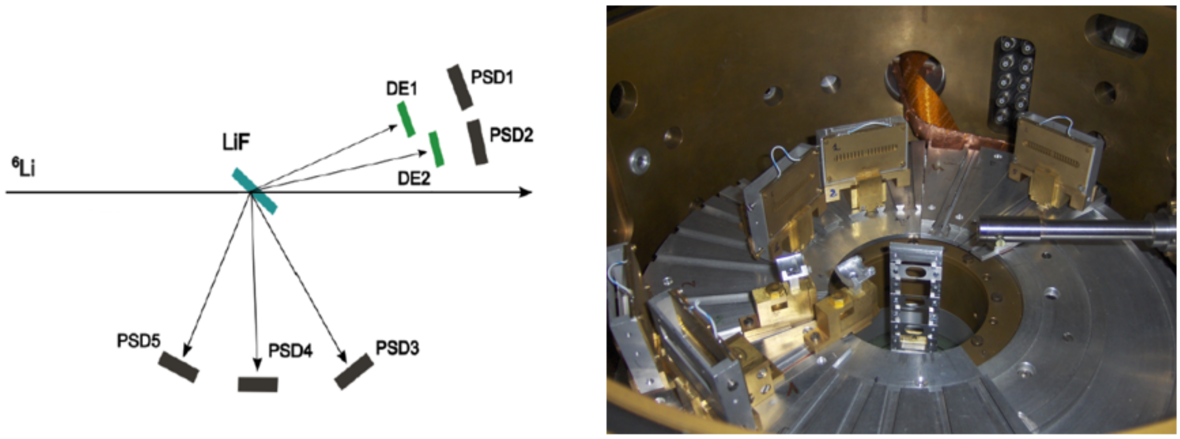

Figure 1: Experimental Set-up

The experimental set-up is shown in Fig.1. The aim was to detect deuterium (spectator particle) and protons, coming from the three-body reaction. A beam of ^6Li hit a ^7LiF target, oriented at 45^o with respect to the beam axis to reduce, on the average, the straggling of the particles emerging from the target. Following the THM prescriptions, beam energy was chosen to be 6 MeV. The detection apparatus was composed by two ΔE-E telescopes, made by a thick silicon detector (500 μm) and a thin one (9 : μm), placed at 12.3° and 32.3° meant for deuterium detection, and three other thick silicon detectors meant for proton detection (−37.3°, −81° and −119.9°). The events were registered by the acquisition system only if coincidence occurs between one of the detectors placed at one side of the beam and one on the other side. All the used detectors are position sensitive (PSD), because good angular resolution is crucial for such measurements. In this work we focused on coincidences between PSD2 and PSD3 (with respect to the Fig.1), given that this coincidence were proven to be the most favourable one.

3. Channel selection

By means of the standard ΔE-E technique we were able to identify incoming particles. Using them we were able to select deuterons, but we did not know which were effectively coming from the reaction of interest. In order to ascertain that, we needed to compare the expected theoretical Q-value with the experimental one. In Fig.2 is shown that the Q-value spectrum had a single peak centred at the theoretical value ($Q = 0.199$ MeV).Experimental data were also consistent with the simulated kinematic locus for the three-body reaction.

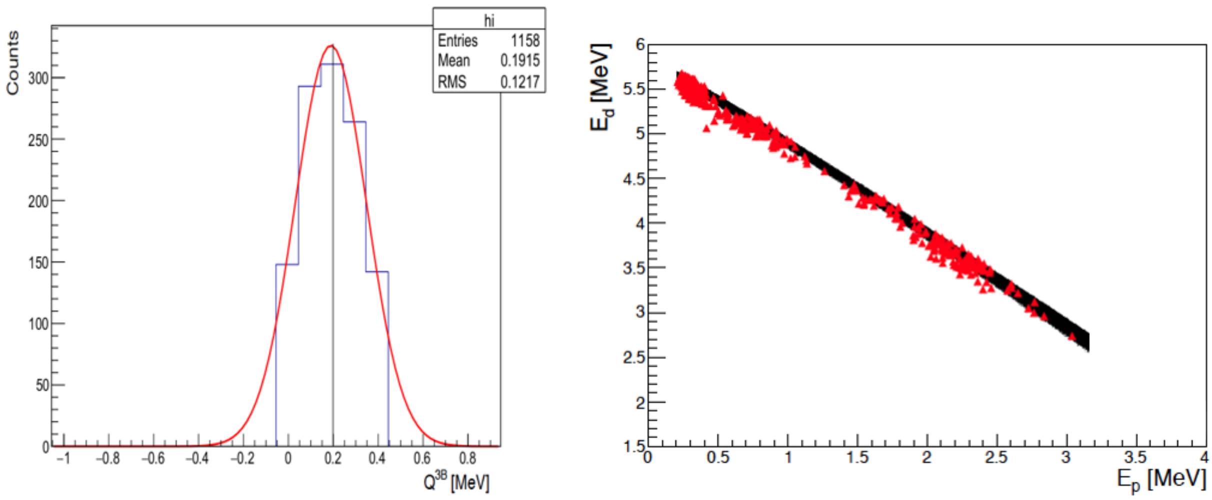

Figure 2: Left panel: experimental Q-value for the three body reaction (the blue line represent the theoretical value)
Right panel: comparison between $E_p vs. E_d$ experimental scatter plot and Monte Carlo simulation kinematic locus

The next step of the data analysis was to check if the reaction mechanism was predominantly a quasi-free reaction. For this purpose the experimental momentum distribution of the deuterium inside ^6Li, fitted with an Hankel function whose width is given by $W(q) = f_0(1 - e^{-\frac{q_t}{q_0}})$, with $q_t = p_{beam} - \dfrac{p_p + p_{^{22}Ne}}{2}$ transferred momentum, f_0 asymptotical width of the function and $q_0 = 122 \pm 3.5$ MeV fit parameter, was compared with literature [9] (Fig3).

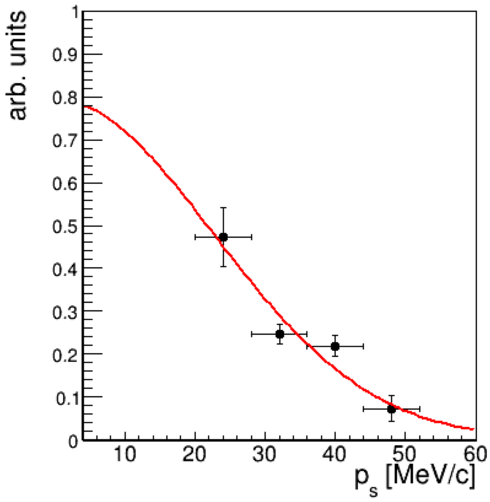

Figure 3: Deuterium momentum distribution inside ^6Li fitted with an Hankel function

4. Results

An estimation of the cross section was possible. Using the standard formulation for the differential cross-section in the THM, $\frac{d^3\sigma}{d\Omega_p d\Omega_{22_{Ne}} dE_{Ecc}} \propto \left[KF|\Phi(p_s)|^2\right] \times \left(\frac{d\sigma}{d\Omega}\right)^{HOES}$ [7], we obtained what is shown in Fig.4. A first estimation of the cross section (even if still in arbitrary units) for the reaction $^{19}F(\alpha,\, p)^{22}Ne$ at astrophysical energies was performed.

In Fig.4 the experimental results were fitted with a sum of several gaussian functions, whose centroids are consistent with the literature [10] (reported in Tab.1).

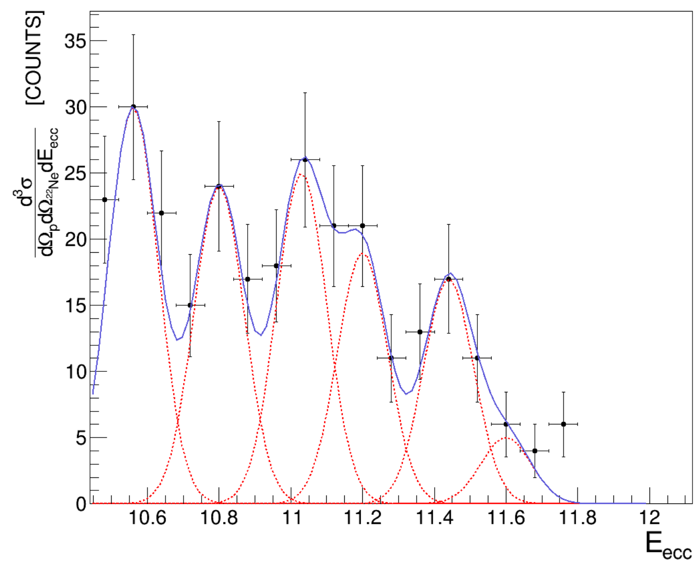

Figure 4: Triple differential cross section for the reaction of intrest, fitted using several gaussian functions)

E*($^{23}Na)^{th}$ [MeV]	J^{π}	E*($^{23}Na)^{exp}$ [MeV]	$E^{th}_{C.M.}$ [MeV]	$E^{exp}_{C.M.}$ [MeV]
10.575	$3/2^-$	10.6	0.107	0.1
10.823	$3/2^+$	10.8	0.356	0.3
11.038	$1/2^+$	11.0	0.571	0.6
11.238	$3/2^-$	11.2	0.771	0.8
11.355	$1/2^+$	11.4	0.887	0.9
11.554	$1/2^+$	11.6	1.086	1.1

Table 1: Experimentally desumed energy levels(as in Fig. 4)compared with the theorical ones [10]

This measurement, although still preliminary and mainly used as a test of validity for the usage of THM in (α, p) reactions, is the first one of the cross-section for the reaction $^{19}F(\alpha,\, p)^{22}Ne$ in the astrophysical energetic region of interest. The same methodology has been used in other recently studied reactions [11] [12] [13] [14] [15].
in the near future, R-Matrix calculations will be used to extract the resonance strength useful for the reaction rate calculations. Such result will be accomplished thanks to the recently developed modified R-Matrix formulation. This is essential to study astrophysical implications of this measurement.

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