Indirect measurement of $^{17}\text{O}(p,\alpha)^{14}\text{N}$ cross section at ultra-low energies

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Abstract. The indirect measurement of $^{17}\text{O}(p,\alpha)^{14}\text{N}$ cross section was performed by means of the Trojan Horse Method. This approach allowed to investigate the ultra-low energy range ($E_{c.m.} = 0-300$ keV) relevant for several astrophysics environments, where two resonant levels of $^{18}\text{F}$ at $E_{c.m.}^{R} = 65$ keV and $E_{c.m.}^{R} = 183$ keV play a significant role in the reaction rate determination.

1. Introduction

The $^{17}\text{O}+p$ reactions are of paramount importance for the nucleosynthesis in a number of stellar sites, including red giants (RG), asymptotic giant branch (AGB) stars, massive stars and classical novae [1, 2]. In particular the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ and $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction govern the destruction of $^{17}\text{O}$ and the formation of the short-live radio-isotope $^{18}\text{F}$ which is of special interest for gamma ray astronomy [1, 2].

The importance of the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction in stellar nucleosynthesis theory comes from its occurrence in the carbon-nitrogen-oxygen cycle (CNO cycle) in which it acts as a feedback into the main part of the cycle (see Fig.1). Knowledge of the ratio of the amount of $^{16}\text{O}$ to the amount of $^{17}\text{O}$ formed in CNO cycle then depends on a knowledge of the cross section for $^{16}\text{O}(p,\gamma)$, which forms the $^{17}\text{O}$, and for $^{17}\text{O}(p,\alpha)$ which destroys it. Actually, while the nuclear reaction rate $^{16}\text{O}(p,\gamma)^{17}\text{F}(\beta^{+})^{17}\text{O}$ is rather well known [3], the experimental status for its destruction dominant channel, $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction, is much less satisfactory [2, 3].

Stellar temperatures of primary importance for $^{17}\text{O}$ nucleosynthesis are typically in the ranges

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The lifetime of the $\beta^+$ unstable nuclei are displayed $T=0.01-0.1$ GK for RG, AGB, and massive stars, and $T=0.1-0.4$ GK for classical nova explosion [2]. Thus, the $^{17}$O(p,$\alpha$)$^{14}$N and $^{17}$O(p,$\gamma$)$^{18}$F reaction cross sections have to be precisely known in the energy range $E_{c.m.}=0.017-0.37$ MeV. In this energy range, the $^{17}$O(p,$\alpha$)$^{14}$N reaction cross section is dominated by two resonances: one at $E_{c.m.}^{R}=65$ keV above the $^{18}$F proton threshold, corresponding to the 5.673 MeV $^{18}$F level and the other one at $E_{c.m.}^{R}=183$ keV ($E_X=5.786$ MeV). While, in the last years, several measurements ([2] and references therein) of the $E_{c.m.}^{R}=183$ keV resonance for both (p,$\alpha$) and (p,$\gamma$) channels have drastically reduced the uncertainties on both $^{17}$O(p,$\alpha$)$^{14}$N and $^{17}$O(p,$\gamma$)$^{18}$F rates in the context of explosive H-burning, only one direct measurement for the $E_{c.m.}^{R}=65$ keV resonance was performed [4]. In fact, direct measurements of low-lying resonance strengths such that of the 65 keV resonant level, are very difficult because the Coulomb barrier and large uncertainties are still present on the available direct data. In addition, some sub-threshold levels could contribute to the total reaction rate and then a further study of this reaction in the energy region relevant for astrophysics is necessary. In the present work we report on the indirect measurement of $^{17}$O(p,$\alpha$)$^{14}$N reaction at energies below 300 keV by using the Trojan Horse Method [5, 6].

2. The experiment: measurement and data analysis

In order to reduce the uncertainties affecting the direct measurements, in the last twenty years many indirect methods have been developed. In particular the Trojan Horse Method (THM) [5, 6] is a powerful tool which selects, under appropriate kinematical conditions, the quasi-free (QF) contribution of a suitable three-body reaction performed at energies well above the Coulomb barrier to extract a charged particle two-body cross section at astrophysical energies, free of Coulomb suppression and electron screening effects.

The present study of the $^{17}$O(p,$\alpha$)$^{14}$N reaction in the energy window relevant for astrophysics was performed by selecting the QF-contribution of the $^2$H($^{17}$O,$^{14}$N$\alpha$)n reaction [7]. The deuteron was used as ‘trojan horse nucleus’ because of its p-n cluster structure: the proton is brought in the nuclear field of $^{17}$O while the neutron acts as a spectator to the reaction [7]. The experiment was performed at the Laboratori Nazionali del Sud in Catania. The SMP Tandem Van de Graaf accelerator provided a 41 MeV $^{17}$O beam with a spot size on target of about 1.5 mm ad intensities up to 2-3 nA. Deuterated polyethylene targets (CD2) of about 150 $\mu$g/cm$^2$ were placed at 90°.
with respect to the beam axis. The detection setup consisted of six Position Sensitive Detector (PDS) and two ionization chambers filled with 60 mbar of isobuthane gas as $\Delta E$ detector. The angular ranges were chosen in order to cover momentum values $p_s$ of the undetected neutron ranging from -100 MeV/c to 100 MeV/c. This allows us to select the kinematical region where a strong contribution of the Quasi Free (QF) mechanism is expected.

The first step in a THM analysis is the selection of the three-body reaction channel. After the energy and position calibration of the detectors, nitrogen particles were selected with the standard $\Delta E$-$E$ technique and for these selected events the experimental Q-value spectrum was reconstructed and compared with the theoretical value (Fig. 2). A sharp peak centered at about -1 MeV shows up, which corresponds to our three-body reaction, according to the expected theoretical value ($Q_{\text{theor}} = -1.033$ MeV). The agreement between the two values is a test of the goodness of the adopted calibration.

The selection of the QF-condition is related to the behavior of the spectator momentum values. In fact, the QF-processes are characterized by the presence in the exit channel of a particle that acts as a spectator; this means that in the exit channel the spectator particle, the neutron in this case, must have the same momentum distribution that it had before the interaction of oxygen beam with the deuteron target. By following the Plain Wave Impulse Approximation (PWIA) [8] the experimental momentum distribution was deduced as reported in [9] and the result is shown in Fig. 3. The full line superimposed onto the data represents the shape of the theoretical Hulthén function which is normalized to the experimental maximum. A quite good agreement shows up, making us confident that in the experimentally selected kinematical region the QF mechanism gives the main contribution to the $^2\text{H}^1\text{H}^17\text{O}$ reaction. The further analysis was performed by considering coincidence events corresponding to neutron momentum values ranging between -30 and 30 MeV/c.

3. Results and Conclusion
In the framework of the PWIA, the three-body cross section can be factorized into different terms [10]:

$$\frac{d^3\sigma}{dE_{cm} d\Omega_{14N} d\Omega_{\alpha}} \propto KF \cdot |\Phi(p_s)|^2 \cdot \frac{d\sigma^N}{d\Omega}$$

(1)
where $K_F$ is a kinematical factor containing the final state phase-space factor, $\Phi(\vec{p}_s)$ is the Fourier transform of the radial wave function $\chi(\vec{r})$ for the p-n intercluster relative motion. By applying the previous formula, the behavior of the nuclear cross section for the reaction studied here is obtained and the result is shown Fig.4 where a clear evidence of both levels at $E_{c.m.}=65$ and 183 keV is given. For this reason this figure represents the first experimental measurement of the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ two-body reaction at very low energy, well below the Coulomb barrier ($\sim 2.1$ MeV) where several excited states of $^{18}\text{F}$ have been populated. In particular, all populated states have a great importance on reaction rate calculation being in the energetic region of Gamow peak. Moreover, the presence of two sub-threshold states at energy $E_X=5.605$ MeV and $E_X=5.603$ MeV should be taken into account because their contribution and because their high energy tails could be interference with the resonant level at 65 keV. The error bars represent the statistical uncertainties. The ‘nuclear’ two-body cross section is expressed in arbitrary units since the current TH investigation doesn’t allow to extract the results in absolute units.

However, besides the encouraging results obtained through the indirect investigation of such reaction, our results are affected by a statistical error of $\sim 25\%$. In order to increase the statistics and to improve the resolution, a further experiment was performed at Nuclear Structure Lab of the University of Notre Dame (Indiana, USA) in November 2008. The data analysis is still in progress.

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