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Study of reaction ^{17}O(p,α)^{14}N via the Trojan Horse Method for application to ^{17}O nucleosynthesis

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Abstract. The ^{17}O(p,α)^{14}N is one of the most important reaction to be studied in order to get more information about the fate of ^{17}O in different astrophysical scenarios.
We report on the indirect measurement of ^{17}O(p,α)^{14}N reaction at energies below 300 keV by using the Trojan Horse Method. The experimental approach and the preliminary data of such investigation will be discussed.

Key words. Stars: classical Novae – Stars: nucleosynthesis – Nuclear Physics: cross section measurements – Nuclear Physics: Indirect methods

1. Introduction

The knowledge of the ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F reaction rates is necessary for evaluating the abundances of elements in several hydrogen-burning stellar sites as Red Giants (RG), asymptotic giant branch (AGB) stars, massive stars and classical novae (Coc et al. (2000); Chafa et al. (2007)). These two reactions take place in the carbon-nitrogen-oxygen (CNO) cycle and they are

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specifically important for the nucleosynthesis of the rarest oxygen isotope, ^{17}O. In particular they govern the destruction of ^{17}O and the formation of the short-live radio-isotope ^{18}F which is of special interest for gamma ray astronomy (Coc et al. (2000); Chafa et al. (2007)). Actually, while the nuclear reaction rate ^{16}O(p,γ)^{17}F(β^{+})^{17}O governing the production of ^{17}O is rather well known (Angulo et al. (1999)), the experimental status for its destruction dominant channel, ^{17}O(p,α)^{14}N reaction, is much less satisfactory (Chafa et al. (2007); Angulo et al. (1999)). Stellar temperatures of primary importance for ^{17}O nucleosynthesis are typically in the ranges T=0.01-0.1 GK for RG, AGB, and massive stars, and T=0.1-0.4 GK for classical nova explosion (Chafa et al. (2007)). Thus, the ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F reaction cross sections have to be precisely known in the center-of-mass energy range $E_{c.m.}$=0.017-0.37 MeV. In this energy range, the ^{17}O(p,α)^{14}N reaction cross section is dominated by two resonances: one at $E^{R}_{c.m.}$=65 keV above the ^{18}F proton threshold, corresponding to the 5.673 MeV ^{18}F level and the other one at $E^{R}_{c.m.}$=183 keV (E_X=5.786 MeV). While, in the last years, several measurements (Chafa et al. (2007) and references therein) of the $E^{R}_{c.m.}$=183 keV resonance for both (p,α) and (p,γ) channels have drastically reduced the uncertainties on both ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F rates in the context of explosive H-burning, only one direct measurement for the $E^{R}_{c.m.}$=65 keV resonance was performed (Blackmon et al. (1995)). In fact, direct measurements of low-lying resonance strengths such that of the 65 keV resonant level, are very difficult because the large Coulomb barrier and large uncertainties are still present on the available direct data. In addition, some subthreshold 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.

2. The experiment

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) (Spitaleri et al. (1999, 2004)) 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,α)^{14}N reaction in the energy window relevant for astrophysics was performed by selecting the QF-contribution of the ^{2}H(^{17}O,^{14}Nα)n reaction. 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 (Zadro et al. (1989)). 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 pnA. Deuterated polyethylene targets (CD2) of about 150 μg/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 ΔE 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.

3. Data analysis

After detector calibration, the first step of the analysis is the identification of the events corresponding to the ^{2}H(^{17}O,^{14}N)n TH reaction. In order to identify the channel of interest and to choose the kinematical conditions where the quasi-free process is dominant, ^{14}N particles were selected using the standard ΔE-E technique. After that, the experimental Q-value spectrum was reconstructed with those events (Fig. 1). A sharp peak centered at about -1 MeV shows up, which corresponds to our

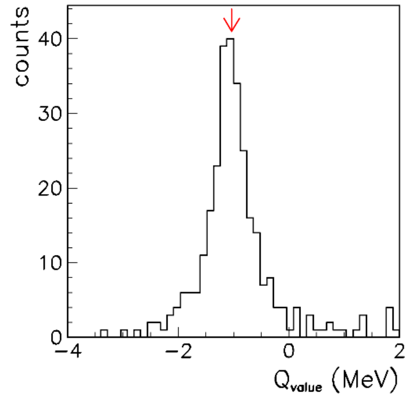

Fig. 1. Experimental Q-value for the three body reaction $^{2}H(^{17}O,^{14}N)n$. The peak at about -1.0 MeV must be compared with the -1.033 MeV theoretical Q-value (red arrow). The agreement between the two values is a test of the goodness of the adopted calibration.

three-body reaction, according to the expected theoretical value (Q_{theor} = -1.033 MeV).

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. The experimental momentum distribution was reconstructed in PWIA (Jain et al. (1970)) by applying the energy sharing method (Arena et al. (1978)) and the result reported in Fig.2. 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 $^{2}H+^{17}O$ reaction.

4. Results and conlusions

Following the PWIA prescription, the nuclear two-body cross-section ($d^{N}\sigma/d\Omega$) was derived by dividing the selected three-body coincidence yield using the simple formula:

$$\frac{d^3\sigma}{dE_{c.m.}d\Omega_{^{14}N}d\Omega_{\alpha}} \propto (KF)\,|\Phi(\boldsymbol{p}_s)|^2 \left(\frac{d\sigma}{d\Omega_{c.m.}}\right) \quad (1)$$

where KF is a kinematical factor containing the final state phase-space factor, $\Phi(\boldsymbol{p}_s)$ is the Fourier transform of the radial wave function $\chi(\boldsymbol{r})$ for the p-n intercluster relative motion. In Fig. 3 the obtained two-body cross section ($d^{N}\sigma/d\Omega$) is shown and 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 $^{17}O(p,\alpha)^{14}N$ two-body reaction at very low energy, well below the Coulomb barrier (~2.1 MeV), where several excited states of ^{18}F are seen to be populated. In particular, all these states have a large importance on reaction rate calculation being in the energy region of Gamow peak. Indeed, because of the experimental energy resolution (±20 keV), the resonance at 65 keV was not well separated from the high-energy tail of the sub-threshold states and in particular it was not possible to distinguish and evaluated the contribution of each sub-threshold state (E_X=5.603 and 5.605 MeV in ^{18}F). However, since the widths of the resonances (~eV) are much lower of their energy separation (~keV) no interference effect was taken into account.

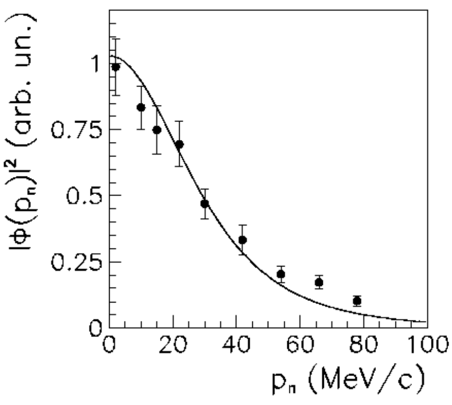

Fig. 2. Experimental neutron momentum distribution. The full line represents the shape of the theoretical Hulthén function in momentum space.

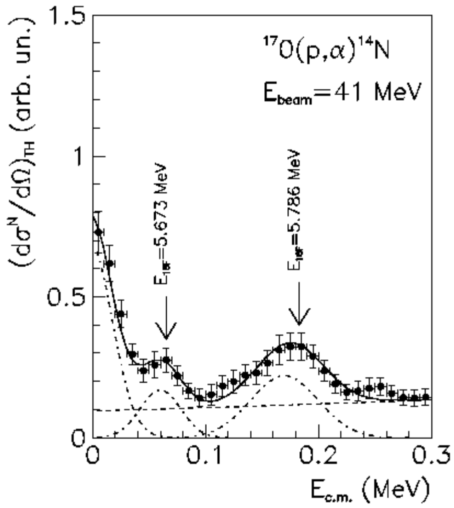

Fig. 3. Nuclear excitation function ($d^N\sigma/d\Omega$) of the $^{17}O(p,\alpha)^{14}N$ reaction by means of the THM in the PWIA approach. The arrows are placed at the resonance peaks in the excitation function. The values of the corresponding energy are also reported (Sergi et al. (2008)).

The error bars represent the statistical uncertainty. 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.

In order to separate the different contributions on the ($d^N\sigma/d\Omega$), a fit of the nuclear cross section has been performed, in the low energy region $E_{c.m.}$ <300 keV. The adopted fitting curve is made up of a sum of three Breit-Wigner functions to fit the resonant behaviour and a straight line to account for the nonresonant contribution to the cross section. In the fit, the resonance energies were kept fixed at their known values (Tilley et al. (1995)). The FWHM of each resonance was 40 keV, since the energy resolution for the actual experimental condition was about 20 keV, much larger than the intrinsic width of each resonance (less than 1 keV (Tilley et al. (1995)). The resulting fit are displayed in Fig. 3 where the black line superimposed onto the TH data is the best fit curve.

However, besides the encouraging results obtained through the indirect investigation of such reaction, our results are affected by a statistical error of ~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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