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The Trojan Horse Method as a tool to investigate low-energy resonances: the $^{18}O(p,\alpha)^{15}N$ and $^{17}O(p,\alpha)^{14}N$ cases

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The $^{18}O(p,\alpha)^{15}N$ and $^{17}O(p,\alpha)^{14}N$ reactions are of primary importance in several astrophysical scenarios, including nucleosynthesis inside Asymptotic Giant Branch stars and oxygen and nitrogen isotopic ratios in meteorite grains. They are also key reactions to understand exotic systems such as R-Coronae Borealis stars and novae. Thus, the measurement of their cross sections in the low energy region can be crucial to reduce the nuclear uncertainty on theoretical predictions, because the resonance parameters are poorly determined. The Trojan Horse Method, in its newly developed form particularly suited to investigate low-energy resonances, has been applied to the $^{2}H(^{18}O,\alpha^{15}N)n$ and $^{2}H(^{17}O,\alpha^{14}N)n$ reactions to deduce the $^{18}O(p,\alpha)^{15}N$ and $^{17}O(p,\alpha)^{14}N$ cross sections at low energies. Resonances in the $^{18}O(p,\alpha)^{15}N$ and $^{17}O(p,\alpha)^{14}N$ excitation functions have been studied and the resonance parameters deduced.

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1. Introduction

Asymptotic giant branch (AGB) stars play a major role in nuclear astrophysics as they are the site for synthesis of s-elements. A way to constrain AGB models is to observe isotopes whose abundances are sensitive to the nucleosynthesis processes taking place in AGB internal layers. For instance, since ^{19}F is produced in the He intershell and then dredged up to the surface together with s-process elements, its abundance can be used to constrain the efficiency of the dredge-up and to the physical conditions in the deep layers of AGB stars [1]. Other observables that turn out to be very sensitive to the mixing processes are the ratios of the abundances of some CNO isotopes, such as ^{18}O, ^{17}O, ^{15}N, and ^{13}C to the most abundant ones, namely ^{16}O, ^{14}N, and ^{12}C [2]. These isotopic ratios are determined with high accuracy from the analysis of pre-solar grains, formed in the outer layers of AGB stars. Therefore, they are also sensitive to extramixing processes, such as the cool bottom process [2], which play a key role to reconcile such observations and the models. In fact, when comparing, for instance, observed fluorine abundances or ^{14}N/^{15}N ratios in meteorite grains with predictions unacceptable discrepancies show up that can be only partly alleviated with upgraded astrophysical models [2, 1] or improved observational data [3]. A possible solution may be provided by revised ^{18}O$(p,\alpha)^{15}$N and ^{17}O$(p,\alpha)^{14}$N reaction rates, which can significantly modify the expected ^{19}F, ^{18}O, ^{17}O and ^{15}N yields due to AGB nucleosynthesis [4, 5, 6, 7].

The ^{18}O$(p,\alpha)^{15}$N and ^{17}O$(p,\alpha)^{14}$N reactions may also play an important role to understand more exotic system, such as R-Coronae Borealis and novae, respectively. Indeed, R-Coronae Borealis stars show ^{16}O/^{18}O ratios hundreds of times smaller than the standard Galactic values. According to the double degenerate (DD) model, they are formed by accreting material from a He white dwarf onto a CO white dwarf in a close binary system [8]. This scenario provide a qualitative account of the ^{18}O abundance enhancement, provided that H-rich material from the white-dwarf thin envelope is admixed. A revised ^{18}O$(p,\alpha)^{15}$N reaction rate can provide a clue to better understand these exotic systems. Regarding ^{17}O abundance, this isotope is important for the formation of the short-lived ^{18}F radioisotope, which is responsible of $e^+ - e^-$ annihilation γ-ray emission in novae during the early epochs after explosion [9]. Therefore, such γ-rays deliver precious information on the nova explosion mechanism, allowing for the observation of the nova before its visual discovery. The ^{18}F abundance is fixed by the competing (p,γ) and (p,α) channels, the latter removing ^{17}O nuclei from the ^{18}F production path. Again, an improved ^{17}O$(p,\alpha)^{14}$N reaction rate can shed light on the novae phenomenon.

2. Results

The Trojan Horse Method (THM) cross section for a $A+a \to c+C+s$ (where $A = x+s$) reaction proceeding through a resonance F_i in the subsystem $F_i = c+C$ can be obtained if the process is described as a transfer to the continuum, where the emitted spectator s keeps the same momentum as the one it has inside A (quasi-free (QF) condition). If such a hypothesis is satisfied, the cross section for the $A+a \to c+C+s$ $2 \to 3$ reaction can be written as [6]:

$$\frac{d^2\sigma}{dE_{cC}\,d\Omega_s} \propto \frac{\Gamma_{(cC)_i}(E)\,|M_i(E)|^2}{(E-E_{R_i})^2+\Gamma_i^2(E)/4}. \tag{2.1}$$

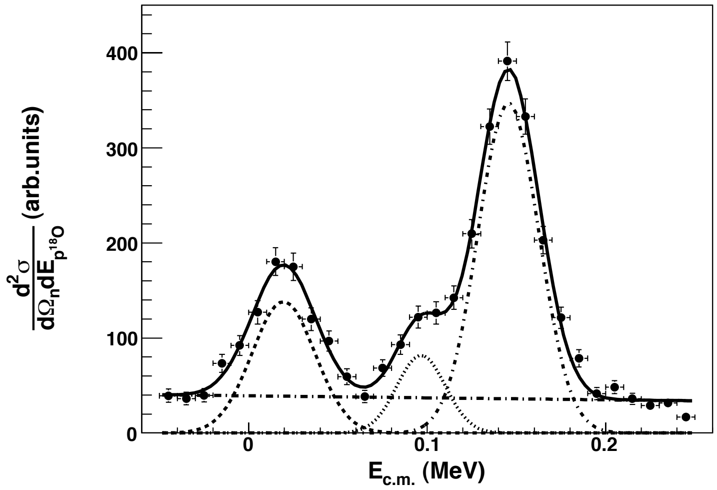

Figure 1: Cross section of the ^{2}H(^{18}O$,\alpha^{15}$N)n THM reaction

Here, $M_i(E)$ is the direct transfer reaction amplitude for the binary reaction $A(a,F_i)s$ leading to the population of the i-th resonant state of F_i with the resonance energy E_{R_i}, E is the E_{ax} relative kinetic energy, $\Gamma_{(cC)_i}(E)$ is the partial resonance width for the decay F$_i \rightarrow c+C$ and Γ_i is the total resonance width of F_i. Therefore, the cross section of the THM process can be easily connected to the one for the two-body reaction of interest by evaluating the transfer amplitude $M_i(E)$. In particular, the resonance parameters can be extracted, allowing for the evaluation of the resonance strength of the i-th resonance, which is the relevant parameter for astrophysical application in the case of narrow resonances, being directly connected with the reaction rate [10].

Following this approach the resonance strengths of the 20 keV and 90 keV resonances in the ^{18}O$(p,\alpha)^{15}$N reaction [4, 5, 6] and the resonance strength of the 65 keV resonance in the ^{17}O$(p,\alpha)^{14}$N reaction [7] have been extracted from the cross sections of the 2 $\rightarrow$ 3 QF reactions ^{2}H(^{18}O$,\alpha^{15}$N)n and ^{2}H(^{17}O$,\alpha^{14}$N)n. The THM only allows to deduce such strengths in arbitrary units, thus normalization have been accomplished by scaling the THM resonance strengths to the measured ones, namely of the 144 keV and of the 183 keV resonances in the ^{18}O$(p,\alpha)^{15}$N and ^{17}O$(p,\alpha)^{14}$N reaction cross sections, respectively.

The cross section of the THM ^{2}H(^{18}O$,\alpha^{15}$N)n is shown in Fig.1. As extensively discussed in [4, 5, 6], $(\omega\gamma)_{20\mathrm{keV}} = 8.3^{+3.8}_{-2.6} \times 10^{-19}$ eV and $(\omega\gamma)_{90\mathrm{keV}} = (1.76 \pm 0.33) \times 10^{-7}$ eV, in good agreement with the strength given by NACRE [10]. If the reaction rate is calculated according to the prescription for narrow resonances [4, 5, 6], one finds that in the low temperature region (below T$_9 = 0.03$) the reaction rate can be about 35% larger than the one given by NACRE, while the indetermination is greatly reduced with respect to the NACRE one, by a factor ≈ 8.5, because of the revised strength of the 20 keV resonance, while the 90 keV resonance in the ^{18}O$(p,\alpha)^{15}$N reaction yield a negligible contribution.

The cross section of the THM ^{2}H(^{17}O$,\alpha^{14}$N)n is shown in Fig.2 [7]. Horizontal error bars represent the integration energy bin, while the solid line represents the fit of the two-body cross section using three Gaussian functions to describe the resonant behavior and a straight line to account for the nonresonant contribution to the cross section. No interference effect is taken into

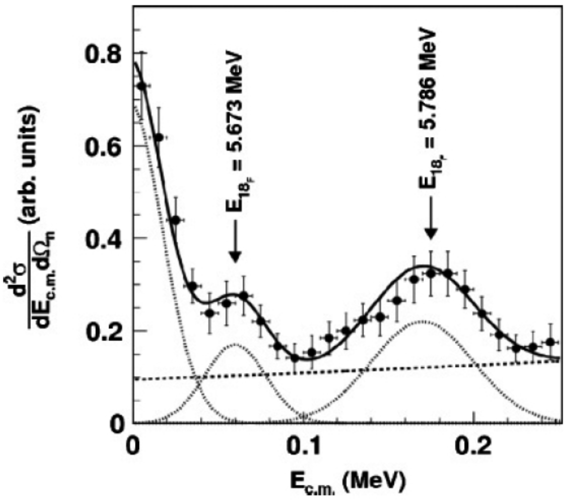

Figure 2: Cross section of the $^{2}H(^{17}O,\alpha^{14}N)n$ THM reaction

account. Using an approach similar to the one discussed for the $^{18}O(p,\alpha)^{15}N$ reaction, By taking $(\omega\gamma)_2 = (1.66 \pm 0.10) \times 10^{-3}$ eV, namely the weighted average of the three values for the 183 keV resonance (referred to as resonance 2, while the 65 keV is called resonance 1) strength given in the literature [10], one gets $(\omega\gamma)_1 = 3.66^{+0.76}_{-0.64} \times 10^{-9}$ eV. Regarding the model uncertainty, this is less than about 10% because of the absence of any spectroscopic factor and the use of a double ratio compensating for the errors due to, for instance, the choice of the interaction radius. Considering the upper and lower limits, the resulting $(\omega\gamma)_1^{THM}$ value is in agreement with the value of $(\omega\gamma)_N = (5.5^{+1.8}_{-1.5}) \times 10^{-9}$ eV adopted in NACRE.

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