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Reaction rate of the $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ reaction at astrophysical temperatures

M. La Cognata[1,2,3], C. Spitaleri[1,2], A. Mukhamedzhanov[4], R.E. Tribble[4], T. Al-Abdullah[4], A. Banu[4], S. Cherubini[1,2], A. Coc[5], V. Crucillà[1,2], V. Goldberg[4], M. Gulino[1,2], B. Irgaziev[6], G.G. Kiss[7], L. Lamia[1,2], J. Mrazek[8], R.G. Pizzone[1,2], S.M.R. Puglia[1,2], G.G. Rapisarda[1,2], S. Romano[1,2], M.L. Sergi[1,2,3], G. Tabacaru[4], L. Trache[4], W. Trzaska[9], S. Tudisco[1,2], and A. Tumino[1,10]

[1] INFN Laboratori Nazionali del Sud, Catania, Italy
e-mail: `LaCognata@lns.infn.it`
[2] Dipartimento di Metodologie Chimiche e Fisiche per l'Ingegneria, Università di Catania, Italy
[3] CSFNSM Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy
[4] Cyclotron Institute, Texas A&M University, College Station, TX, USA
[5] CSNSM, CNRS/IN2P3, Universitè Paris Sud, Orsay, France
[6] GIK Institute of Engineering Sciences and Technology, Topi, District Swabi, N. W. F. P., Pakistan
[7] ATOMKI, Debrecen, Hungary
[8] Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic
[9] Physics Department, University of Jyvaskyla, Finland
[10] Università Kore, Enna, Italy

Abstract. The $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ reaction rate has been deduced by means of the Trojan horse method. For the first time the contribution of the 20 keV resonance has been directly evaluated, giving a value about 35% larger than the one in the literature. Moreover, the present approach has allowed to improve the accuracy by a factor 8.5, as it is based on the measured strength instead of spectroscopic measurements. The contribution of the 90 keV resonance has been also determined, which turned out to be of negligible importance to astrophysics.

Key words. Stars: AGB and post-AGB – Nuclear reactions, nucleosynthesis, abundances – Stars: abundances

1. Introduction

Fluorine is one of the few elements whose nucleosynthesis is still debated as three possible astrophysical sites for fluorine production have been identified, namely Type II Supernovae (SNe II), Wolf-Rayet (WR) stars, and asymptotic giant branch (AGB) stars (Renda et al. 2004). In particular, in AGB stars fluorine

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Send offprint requests to: M. La Cognata abundance is enhanced with respect to the solar one by up to a factor 30 (Jorissen et al. 1992). In such stars, ^{19}F nucleosynthesis takes place at the same evolutionary stage and in the same region as the s-process nucleosynthesis. For these reasons, AGB stars play an extremely important role in astrophysics and the understanding of fluorine production, allowing to constrain the existing models (Lugaro et al. 2004), would make predictions on AGB star nucleosynthesis and s-process element yields more accurate. This is because ^{19}F abundance is very sensitive to the temperatures and the mixing processes taking place inside AGB stars. Anyway, if standard theoretical abundances are compared to the observed ones (Jorissen et al. 1992), a remarkable discrepancy shows up because the largest ^{19}F abundances cannot be matched for the typical ^{12}C/^{16}O ratios (Lugaro et al. 2004). It has been shown that extra-mixing phenomena, such as the cool bottom process (Nollett et al. 2003), could help to pin down the origin of this discrepancy (Lugaro et al. 2004). A complementary way to explain ^{19}F abundance can be provided by nuclear physics, in particular by an improved measurement of the ^{18}O$(p,\alpha)^{15}$N reaction rate. In fact, this reaction represents the main ^{15}N production channel, which is burnt to ^{19}F via the ^{15}N$(\alpha,\gamma)^{19}$F reaction during thermal pulses, at temperatures of the order of 10^8 K. Thus a larger ^{18}O$(p,\alpha)^{15}$N reaction rate would lead to an increase of the ^{19}F supply, while the ^{12}C/^{16}O ratio would not change. Such an alternative account would also imply an enrichment of ^{15}N in the stellar surface, as a result of the cool bottom processing of material from AGB outer layers at the bottom of the convective envelope (Nollett et al. 2003), at temperatures of about 10^7 K. Therefore a new investigation of the ^{18}O$(p,\alpha)^{15}$N reaction at low energies, in the 0-1 MeV energy range, would also play a key role to explain the long-standing problem of the ^{14}N/^{15}N ratio in meteorite grains (Nollett et al. (2003) and references therein). Indeed, this ratio turns out to be much smaller than the predicted one for mainstream and A+B grains and any proposed astrophysical explanation, including extra-mixing scenarios, could not help the make the model predictions more accurate (Nollett et al. 2003). In the following, the first measurement of the low-laying resonances in the ^{18}O$(p,\alpha)^{15}$N reaction is discussed and how the reaction rate is influenced is extensively illustrated.

2. The measurement

In order to reduce the nuclear uncertainties affecting its reaction rate we have performed an experimental study of the ^{18}O$(p,\alpha)^{15}$N reaction by means of the Trojan horse method (THM), which is an indirect technique to measure the relative energy-dependence of a charged-particle reaction cross section at energies well below the Coulomb barrier (La Cognata et al. (2007); Spitaleri et al. (1999); Mukhamedzhanov et al. (2008) and references therein). The cross section of the ^{18}O$(p,\alpha)^{15}$N reaction is deduced from the ^{2}H$(^{18}$O$,\alpha^{15}$N$)n$ three-body process, performed in quasi-free (QF) kinematics. The beam energy is chosen larger than the Coulomb barrier for the interacting nuclei, so the break-up of the deuteron (acting as the Trojan-horse nucleus) takes place inside the ^{18}O nuclear field. Therefore, the cross section of the ^{18}O$(p,\alpha)^{15}$N reaction is not suppressed by the Coulomb interaction of the target-projectile system, while no electron screening enhancement is spoiling the nuclear information because the reaction is performed at high energies (several tens of MeV). The THM cross section for the ^{2}H$(^{18}$O$,\alpha^{15}$N$)n$ reaction proceeding through a resonance in the subsystem ^{19}F = ^{18}O+p = ^{15}N+α can be obtained if the process is described as a transfer to the continuum, where the emitted neutron keeps the same momentum as the one it has inside deuteron (QF condition). If such a hypothesis is satisfied, the cross section for the QF ^{2}H$(^{18}$O$,\alpha^{15}$N$)n$ three-body reaction is (La Cognata et al. 2007, 2008):

$$\frac{d^2\sigma}{dE_{\alpha^{15}\mathrm{N}}\,d\Omega_n} \propto \frac{\Gamma_{(\alpha^{15}\mathrm{N})_i}(E)\,|M_i(E)|^2}{(E-E_{R_i})^2+\Gamma_i^2(E)/4} \qquad (1)$$

Here, $M_i(E)$ is the direct transfer reaction amplitude for the binary reaction ^{18}O + d $\rightarrow$

^{19}F + n leading to the population of the $i-th$ resonant state of ^{19}F with resonance energy E_{R_i}, E is the ^{18}O-p relative kinetic energy related to $E_{\alpha^{15}\mathrm{N}}$ by the energy conservation law, $\Gamma_{(\alpha^{15}\mathrm{N})_i}(E)$ is the partial resonance width for the decay $^{19}\mathrm{F} \rightarrow \alpha + {}^{15}\mathrm{N}$ and Γ_i is the total resonance width of the $i-th$ resonance. The appearance of the transfer reaction amplitude $M_i(E)$ instead of the entry channel partial resonance width $\Gamma_{(p^{18}\mathrm{O})_i}(E)$ is the main difference between the THM cross section and the cross section for the resonant binary sub-reaction ^{18}O$(p,\alpha)^{15}$N (La Cognata et al. 2007, 2008; Mukhamedzhanov et al. 2008). Therefore the cross section of the three-body process can be easily connected to the one for the two-body reaction of interest by evaluating the transfer amplitude $M_i(E)$.

3. Extraction of the cross section

The experiment was performed at Laboratori Nazionali del Sud, Catania (Italy). A description of the data analysis is reported in (La Cognata et al. 2008), here we show the main results. The extracted three-body cross section has been integrated in the whole angular range. The resulting ^{2}H$(^{18}$O$,\alpha^{15}$N$)n$ reaction cross section is shown in Fig. 1 (full circles). The experimental energy resolution turned out to be about 40 keV (FWHM). Horizontal error bars represent the integration bin while the vertical ones arise from statistical uncertainty and angular distribution integration. The solid line in the figure is the sum of three Gaussian functions to fit the resonant behaviour and a straight line to account for the non-resonant contribution. The resonance energies were then deduced: $E_{R1} = 19.5 \pm 1.1$ keV, $E_{R2} = 96.6 \pm 2.2$ keV and $E_{R3} = 145.5 \pm 0.6$ keV (in fair agreement with the ones reported in the literature, see Angulo et al. (1999)) as well as the peak values of each resonance in arbitrary units: $N_1 = 138 \pm 8$, $N_2 = 82 \pm 9$ and $N_3 = 347 \pm 8$. The peak values were used to derive the resonance strengths:

$$(\omega\gamma)_i = \frac{2J_{^{19}\mathrm{F}_i}+1}{(2J_{^{18}\mathrm{O}}+1)(2J_p+1)}\frac{\Gamma_{(p^{18}\mathrm{O})_i}\Gamma_{(\alpha^{15}\mathrm{N})_i}}{\Gamma_i}\,. \quad (2)$$

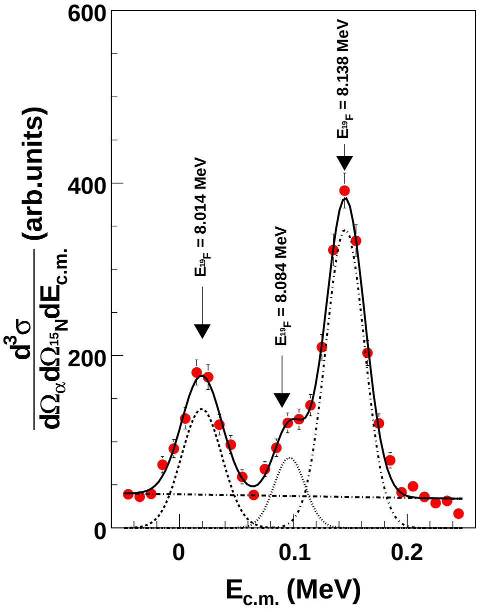

Fig. 1. Cross section of the ^{2}H$(^{18}$O$,\alpha^{15}$N$)n$. The arrows mark the corresponding ^{19}F excited states.

In this work we did not extract the absolute value of the cross section. Anyway, the proton and alpha partial widths for the third resonance are well known (Angulo et al. 1999), thus we can determine the strength for the 20 keV and 90 keV resonances from the ratio of the peak values of the THM cross sections, as discussed by (La Cognata et al. 2008). The electron screening gives a negligible contribution around 144 keV (4% maximum Assenbaum et al. (1987)), thus no systematic uncertainty is introduced by normalizing to the highest energy resonance. If $\omega\gamma_3$ is taken from (Becker et al. 1995), one gets $\omega\gamma_1 = 8.3^{+3.8}_{-2.6}\,10^{-19}$ eV, which is well within the confidence range established by NACRE, $6^{+17}_{-5}\,10^{-19}$ eV (Angulo et al. 1999). The largest contribution to the error is due to the uncertainty on the resonance energy, while statistical and normalization errors sum up to about 9.5%. With the same procedure, we got $\omega\gamma_2 = 1.76 \pm 0.33\,10^{-7}$ eV for the 90 keV resonance, in good agreement with the result in NACRE (Angulo et al. 1999).

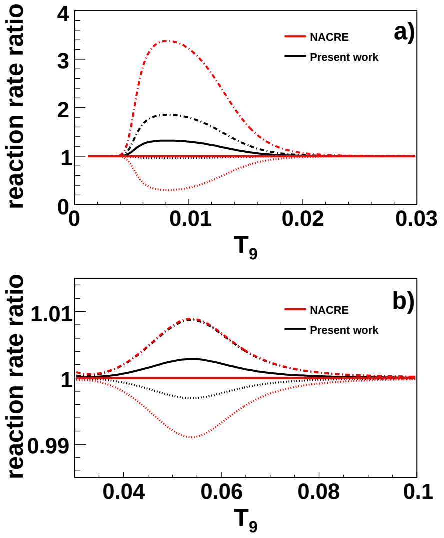

Fig. 2. Comparison of the THM reaction rate (black lines) of the $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ reaction with the NACRE one (Angulo et al. 1999) (red lines). The full lines are the ratio of the recommended rate to the NACRE one. The dot-dashed and dotted lines represent the upper and lower limits respectively, allowed by the experimental uncertainties. T_9 is the temperature in billion kelvin.

4. Reaction rate

The reaction rate for the $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ reaction has been deduced by using the narrow resonance approximation (Angulo et al. 1999), which is fulfilled for the resonances under investigation. According to this approximation, the contribution to the rate of the $i-th$ resonance is given by:

$$R^{i}_{^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}} = N_A \left\langle \sigma v \right\rangle_{R_i} =$$

$$N_A \left(\frac{2\pi}{\mu k_B} \right)^{3/2} \hbar^2 (\omega\gamma)_i T^{-3/2} \exp\left(-E_{R_i}/k_B T\right) \quad (3)$$

where μ is the reduced mass for the projectile-target system and T is the temperature of the astrophysical site. The resulting rate is given in Fig. 2 as a function of the temperature. In order to compare with the one reported in NACRE (Angulo et al. 1999), the ratio of the THM reaction rate to the NACRE one is deduced and shown as a full black line in Fig. 2. In this representation, the NACRE rate is given by a full red line, that is by 1 in the whole examined range. The dot-dashed and dotted lines represent the upper and lower limits respectively, allowed by the experimental uncertainties. As before, black and red lines mark THM and NACRE data. In the low temperature region (below T= $3\,10^7$ K, Fig. 2a) 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 of 8.5, in the case the error on the NACRE rate is supposed to come entirely from the uncertainty on the 20 keV resonance strength, to make the comparison homogeneous. Those temperatures are typical of the bottom of the convective envelope, thus an increase of this reaction rate might have important consequences on the cool bottom process (Nollett et al. 2003) and, in turn, on the surface abundances and isotopic ratios in AGB stars. The 8.084 MeV excited state of $^{19}\mathrm{F}$ (corresponding to the 90 keV resonance) provides a negligible contribution to the reaction rate in agreement with the previous estimate by Champagne et al. (1986). This is clearly displayed by Fig. 2b), where an increase of less than 1% is obtained due to the THM measurement of the 90 keV level resonance strength.

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