First measurement of the $^{18}$O($p,\alpha$)$^{15}$N cross section at astrophysical energies

To cite this article: M La Cognata et al 2010 J. Phys.: Conf. Ser. 202 012019

View the article online for updates and enhancements.
First measurement of the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ cross section at astrophysical energies

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$^{1}$, W Trzaska$^{9}$, S Tudisco$^{1,2}$ and A Tumino$^{1,10}$

$^{1}$INFN Laboratori Nazionali del Sud, Catania, Italy
$^{2}$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, Université 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

E-mail: LaCognata@lns.infn.it

Abstract. The $^{18}\text{O}(p, \alpha)^{15}\text{N}$ 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.

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 [1]. In particular, in AGB stars fluorine abundance is enhanced with respect to the solar one by up to a factor 30 [2]. In such stars, $^{19}\text{F}$ 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 [3], would make predictions on AGB star nucleosynthesis and s-process element yields more accurate. This is because $^{19}\text{F}$ 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 [2], a remarkable discrepancy shows up because the largest
19F abundances cannot be matched for the typical 12C/16O ratios [3]. It has been shown that extra-mixing phenomena, such as the cool bottom process [4], could help to pin down the origin of this discrepancy [3]. A complementary way to explain 19F abundance can be provided by nuclear physics, in particular by an improved measurement of the 18O(α,N)15N reaction rate. In fact, this reaction represents the main 15N production channel, which is burnt to 19F via the 15N(α,γ)19F reaction during thermal pulses, at temperatures of the order of 10^8 K. Thus a larger 18O(α,N)15N reaction rate would lead to an increase of the 19F supply, while the 12C/16O ratio would not change.

2. The measurement

In order to reduce the nuclear uncertainties affecting its reaction rate we have performed an experimental study of the 18O(α,N)15N 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 ([5, 6, 7] and references therein). The cross section of the 18O(α,N)15N reaction is deduced from the 2H(18O,α15N)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 18O nuclear field. Therefore, the cross section of the 18O(α,N)15N 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 interaction is performed at high energies (several tens of MeV). The THM cross section for the 2H(18O,α15N)n reaction proceeding through a resonance in the subsystem 19F = 18O+p = 15N+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 2H(18O,α15N)n three-body reaction is [5, 8]:

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

(1)

Here, \(M_i(E)\) is the direct transfer reaction amplitude for the binary reaction 18O+d → 19F+n leading to the population of the \(i-th\) resonant state of 19F with resonance energy \(E_{R_i}\), \(E\) is the 18O-p relative kinetic energy related to \(E_{15N}\) by the energy conservation law, \(\Gamma_{(15N)_i}(E)\) is the partial resonance width for the decay 19F → α+15N and \(\Gamma_i\) 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 \(\Gamma_{(15N)_i}(E)\) is the main difference between the THM cross section and the cross section for the resonant binary sub-reaction 18O(α,N)15N [5, 8, 7]. 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 \(M_i(E)\). The experiment was performed at Laboratori Nazionali del Sud, Catania (Italy). The SMP Tandem Van de Graaff accelerator provided the 54 MeV 18O beam which was accurately collimated to achieve the best angular resolution. The intensity was 5 enA on the average and the relative beam energy spread was about 10^-4. Thin self-supported deuterated polyethylene (CD2) targets, about 100 µg/cm^2 thick, were adopted in order to minimize angular straggling. The detection setup consisted of a telescope (A), to single out Z=7 particles, made up of an ionization chamber and a silicon position sensitive detector (PSD A). Negligible angular straggling was introduced on the 15N detection by the ionization chamber. Three additional silicon PSD’s (B, C and D) were placed on the opposite side, with the aim of detecting alpha particles from the 2H(18O,α15N)n QF three-body process. No ΔE detectors were put in front of PSD’s B, C and D to decrease detection thresholds and to achieve the best energy and angular resolution.
Figure 1. Cross section of the $^2$H($^{18}$O, $^\alpha$N)$^n$. The arrows mark the corresponding $^{19}$F excited states.

3. Extraction of the cross section

A description of the data analysis is reported in [8], 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, $^\alpha$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 [9]) 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:

$$ (\omega\gamma)_i = \frac{2J_{i\gamma_F} + 1}{(2J_{i\gamma_O} + 1)(2J_{i\gamma_p} + 1)} \frac{\Gamma(p^{18}O)_i \Gamma(\alpha^{15}N)_i}{\Gamma_i}. \quad (2) $$

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 [9], 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 [8]. The electron screening gives a negligible contribution around 144 keV (4% maximum [10]), thus no systematic uncertainty is introduced by normalizing to the highest energy resonance. If $\omega\gamma_3$ is taken from [11], one gets $\omega\gamma_3 = 8.3^{+3.8}_{-2.6} \times 10^{-19}$ eV, which is well within the confidence range established by NACRE, $6^{+17}_{-5} \times 10^{-19}$ eV [9]. The largest contribution

Figure 2. Comparison of the THM reaction rate (black lines) of the $^{18}$O($p, \alpha$)$^{15}$N reaction with the NACRE one [9] (red lines). The full lines are the ratio of the recommended rate to the NACRE one. The dot-dashed and dotted black lines represent the upper and lower limits respectively, allowed by the experimental uncertainties. $T_9$ is the temperature in billion kelvin.
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 $\omega_{\gamma 2} = 1.76 \pm 0.33 \times 10^{-7}$ eV for the 90 keV resonance, in good agreement with the result in NACRE [9]. The significant improvement of the accuracy of the deduced resonance strength is mainly due to the fact that NACRE recommended value is based on spectroscopic data while the present result is obtained from experimental ones. We underscore that the improvement comes from a reduced systematic uncertainty strictly connected with the spectroscopic approach. In fact, the resonance strength deduced by means of spectroscopic measurements is affected by large and not-well-defined uncertainties, because they are strongly model dependent. They rely on the optical model potentials adopted in the data analysis, and different set of potentials or of parameters, though giving a reasonable account of the experimental data, lead to the extraction of spectroscopic factors that can differ even by one order of magnitude.

4. Reaction rate

The reaction rate for the $^{18}$O$(p,\alpha)^{15}$N reaction has been deduced by using the narrow resonance approximation [9], which is fulfilled for the resonances under investigation. The resulting rate is given in Fig. 2 as a function of the temperature. In order to compare with the one reported in NACRE [9], 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 black 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 $T=3 \times 10^7$ 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 [4] and, in turn, on the surface abundances and isotopic ratios in AGB stars. The 8.084 MeV excited state of $^{19}$F (corresponding to the 90 keV resonance) provides a negligible contribution to the reaction rate in agreement with the previous estimate by [12]. 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.

As a next step, the astrophysical consequences of the present work are to be evaluated, both onto the scenarios sketched in the introduction and on alternative environments. In addition, at higher temperatures, higher energy resonances in the $^{18}$O$(p,\alpha)^{15}$N reaction can play a role. These studies will be the subject of forthcoming works.

References

[1] Renda A, et al. 2004 MNRAS 354 575
[2] Jorissen A, et al. 1992 ApJ 261 164
[3] Lagard M, et al. 2004 ApJ 615 934
[4] Nollett K M, et al. 2003 ApJ 582 1036
[5] La Cognata M, et al. 2007 Phys. Rev. C 76 065804
[6] Spitaleri C, et al. 1999 Phys. Rev. C 90 055802
[7] Mukhamedzhanov A, et al. 2008 J. Phys. G: Nucl. Part. Phys. 35 014016
[8] La Cognata M, et al. 2008 Phys. Rev. Lett. 101 152501
[9] Angulo C, et al. 1999 Nucl. Phys. A 656 3
[10] Assenbaum H J, et al. 1987 Z. Phys. A 327 461
[11] Becker H W, et al. 1995 Z. Phys. A 351 453
[12] Champagne A E, et al. 1986 Nucl. Phys. A 457 367