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

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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...
$^{19}\text{F}$ abundances cannot be matched for the typical $^{12}\text{C}/^{16}\text{O}$ 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 $^{19}\text{F}$ abundance can be provided by nuclear physics, in particular by an improved measurement of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction rate. In fact, this reaction represents the main $^{15}\text{N}$ production channel, which is burnt to $^{19}\text{F}$ via the $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ reaction during thermal pulses, at temperatures of the order of $10^8$ K. Thus a larger $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction rate would lead to an increase of the $^{19}\text{F}$ supply, while the $^{12}\text{C}/^{16}\text{O}$ 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 $^{18}\text{O}(p,\alpha)^{15}\text{N}$ 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 ([5, 6, 7] and references therein). The cross section of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction is deduced from the $^{2}\text{H}(^{18}\text{O},\alpha^{15}\text{N})n$ 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 $^{18}\text{O}$ nuclear field. Therefore, the cross section of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ 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 $^{2}\text{H}(^{18}\text{O},\alpha^{15}\text{N})n$ reaction proceeding through a resonance in the subsystem $^{19}\text{F} = ^{18}\text{O} + p = ^{15}\text{N} + \alpha$ 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 $^{2}\text{H}(^{18}\text{O},\alpha^{15}\text{N})n$ three-body reaction is [5, 8]:

$$\frac{d^2\sigma}{dE_{\alpha;i} d\Omega_n} \propto \frac{\Gamma_{(\alpha^{15}\text{N})i}(E) |M_i(E)|^2}{(E - E_{Ri})^2 + \Gamma_i^2(E)/4}$$  \hspace{1cm} (1)

Here, $M_i(E)$ is the direct transfer reaction amplitude for the binary reaction $^{18}\text{O} + d \rightarrow ^{19}\text{F} + n$ leading to the population of the $i-th$ resonant state of $^{19}\text{F}$ with resonance energy $E_{Ri}$, $E$ is the $^{18}\text{O}-p$ relative kinetic energy related to $E_{\alpha;i}^{15}\text{N}$ by the energy conservation law, $\Gamma_{(\alpha^{15}\text{N})i}(E)$ is the partial resonance width for the decay $^{19}\text{F} \rightarrow \alpha + ^{15}\text{N}$ 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 $\Gamma_{(p,^{18}\text{O}i)}(E)$ is the main difference between the THM cross section and the cross section for the resonant binary sub-reaction $^{18}\text{O}(p,\alpha)^{15}\text{N}$ [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 $^{18}\text{O}$ 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 $\mu\text{g}/\text{cm}^2$ 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 $^{15}\text{N}$ 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 $^{2}\text{H}(^{18}\text{O},\alpha^{15}\text{N})n$ QF three-body process. No $\Delta E$ 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,$\alpha$)$^{15}$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,$\alpha$)$^{15}$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 [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:

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

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 $\omega \gamma_3 = 8.3^{+3.5}_{-2.6} 10^{-19}$ eV, which is well within the confidence range established by NACRE, $6^{+17}_{-5} 10^{-19}$ 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 $\omega = 1.76 \pm 0.33 \times 10^{-7}$ 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
duced 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 $^{18}\text{O}(p, \alpha)^{15}\text{N}$ 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 $^{19}\text{F}$ (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 $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction can play a role.
These studies will be the subject of forthcoming works.

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