EPJ Web of Conferences **163**, 00046 (2017)
FUSION17
DOI: 10.1051/epjconf/201716300046

Fusion reactions induced by radioactive beams: the ^{18}F(p,α)^{15}O case

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Abstract. Gamma ray astronomy has made big strides in the last decades paving the way to a better understanding of explosive nucleosynthesis. In particular, crucial information on novae nucleosynthesis is linked to the abundance of the ^{18}F isotope, which might be detected in explosive environments. Therefore, the reaction network producing and destroying this radioactive isotope has been extensively studied in the last years. Among those reactions, the ^{18}F(p,α)^{15}O cross section has been measured by means of several dedicated experiments, both using direct and indirect methods. The presence of resonances in the energy region of astrophysical interest has been reported by many authors. In the present work a report on a recent experiment performed via the Trojan Horse Method (THM) at the Texas A&M Cyclotron Institute is presented and the results are given and compared with the ones known in the literature, both direct and indirect. Data arising from THM measurements are then averaged and the reaction rate calculated in the novae energy range. Hints on future astrophysical applications will also be given.

1 Introduction

Gamma ray emission from novae detected in dedicated satellite-borne experiments has become a probe for understanding novae explosions as well as the structure of such exotic stellar objects. In particular, it was noted [1] that electron-positron annihilation should occur in nova envelopes, since short-lived β^+ unstable radioactive nuclei (i.e., positron emitters) are synthesized during the explosion, according to the present models. The 511 keV line might be one of the main observable features. Specifically, positrons emitted by ^{18}F may have the special feature to be emitted (and then quickly annihilated) at the moment (around 110 minutes, half-life of ^{18}F) when the novae envelope starts to be transparent to the γ-radiation [1–3].

^{18}F appears to be produced in the novae inner shells via the Hot-CNO cycle according to several authors [2]. In particular the production path goes through:

$$^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}(\mathrm{p},\gamma)^{18}\mathrm{Ne}(\beta^+)^{18}\mathrm{F}$$

or

$$^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}(\beta^+)^{17}\mathrm{O}(\mathrm{p},\gamma)^{18}\mathrm{F}$$

while its destruction is mainly connected with the following processes: $^{18}\mathrm{F}(\mathrm{p},\alpha)^{15}\mathrm{O}$ or $^{18}\mathrm{F}(\mathrm{p},\gamma)^{19}\mathrm{Ne}$, where the first is the main channel. Thus the cross sections and the related reaction rates for the ^{18}F(p,α)^{15}O reaction should be measured in the astrophysically relevant Gamow window [4], of the order of few hundreds keV (corresponding to $0.05 \leq T_9 \leq 0.5$).

In the last decade this reaction has been widely studied and, in particular, great efforts have been devoted to its study by means of direct measurements at the relevant astrophysical energies. Such a measurement appears to be very challenging not only for the involved energy range which leads to tiny cross sections but also because the ^{18}F is a radioactive isotope, so it requires dedicated techniques to be produced.

Several data sets are up-to-now available [5–13]. Nevertheless many uncertainties are still present on the low-energy resonance and its width, thus affecting the determination of the reaction rate at the temperatures relevant for astrophysics and, consequently, the novae nucleosynthesis. Therefore new experimental investigation, especially focused in the novae nucleosynthesis Gamow window, are mandatory.

2 Method

Alternative and challenging ways to obtain the bare nucleus cross section, σ_b, for charged-particles at sub-Coulomb energies have been provided by indirect methods. Among them, the Trojan Horse Method (THM) [14, 15] is particularly suited to investigate binary reactions induced at astrophysical energies by neutrons or

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charged particles by using appropriate three-body reactions. The THM allows one to avoid both Coulomb barrier suppression and electron screening effects, thus preventing the use of extrapolations. The method has proven very helpful in the last two decades for application to several aspects of nuclear astrophysics research like primordial nucleosynthesis [16–18], AGB nucleosynthesis [19, 20], the lithium problem [21–23], light elements depletion in stars [24, 25]. It has also been used with neutron induced reactions [26].

The basic assumptions of the Trojan Horse Method (THM) have already been reviewed recently in [27]. Most used Trojan Horse nuclides are deuteron and ^{6}Li but also ^{3}He has been successfully used several times showing the polar invariance of the quasi-free process [28, 29] which is at the very basis of the THM. The breakup process can then be thought as occurring within the nuclear region, so that Coulomb repulsion effects are greatly reduced. As a consequence, the method also becomes insensitive to problems connected with the electron screening effect, giving the possibility to measure the bare nucleus cross section. The first measurement with radioactive ion beams by means of THM was discussed in [30] where the ^{18}F(p,α)^{15}O reaction was studied for the first time by means of the THM. In this paper we will apply the method to a new experimental run for the ^{18}F(d,αn)^{15}O measurement in order to obtain relevant information on the ^{18}F(p,α)^{15}O cross section at energies relevant for astrophysics (see Fig. 1). This will help to confirm the indirect data already obtained in [30] and improve the statistics.

In the ^{18}F(d,αn)^{15}O process, the QF break-up is identified and selected, with deuteron splitting into its constituents p and n, whereby n is regarded as the spectator to the ^{18}F(p,α)^{15}O virtual reaction. Moreover, appropriate kinematics conditions can be selected so that the ^{18}F(p,α)^{15}O binary reaction can then take place at low interaction energies, in principle even negligible, according to the post collision prescription:

$$\mathrm{E_{cm}} = \mathrm{E}_{\alpha-^{15}\mathrm{O}} - \mathrm{Q_{2b}} \qquad (1)$$

where $E_{\alpha-^{15}O}$ is the relative energy between the detected α and ^{15}O while Q_{2b}(= 2.88 MeV) is the Q-value for the ^{18}F(p,α)^{15}O process.

According to the Plane Wave Impulse Approximation (PWIA), the three-body differential cross section measured in an α-^{15}O coincidence experiment can be expressed in terms of the two-body one as:

$$\frac{d^3\sigma}{dE_{\alpha_1} d\Omega_\alpha d\Omega_O} \propto (KF)\,|\Phi_(p_s)|^2 \left(\frac{d\sigma}{d\Omega}\right)^{HOES} \qquad (2)$$

where KF is a kinematical factor. The experimental spectator momentum distribution $|\Phi(\tilde{p}_s)|^2$ is related to the p-n relative motion in the ^{2}H nucleus [31] with $(d\sigma/d\Omega)^{HOES}$ the half off-energy-shell binary cross section of astrophysical interest.

Experimental evidence for a QF contribution in the ^{18}F(d,αn)^{15}O process process has been obtained in a different experimental run in a wide energy range [30].

For the target break-up, one expects a maximum in the QF contribution at the kinematical conditions where the spectator energy is zero, thus reflecting the neutron momentum distribution in ^{2}H, which shows a maximum at p_s=0, since the relative p-n motion is mainly l=0 [31]. This gives rise to the choice of the detection angles for the outgoing α and ^{15}O particles. They are calculated using three-body kinematics under the condition that the spectator energy, E_n, is null and are referred to as the *quasi-free angles* in the standard prescriptions of the THM.

Since the Coulomb barrier is assumed to be overcome in the entrance channel, the obtained half-off-energy-shell cross section, $(d\sigma/d\Omega)^{HOES}$, should be the nuclear part only of the cross section for bare-nuclei, without the Coulomb barrier and also without electron screening effects. Moreover, the nuclear cross section is obtained within an arbitrary normalization constant to be matched to direct measurements, so that direct data have to be available at energies suitable for the normalization procedure. The agreement between the two cross sections at higher energies and the subsequent normalization represents indeed a necessary requirement for the application of the THM to a reaction of astrophysical interest and constitutes a natural step also for reactions induced by radioactive ion beams.

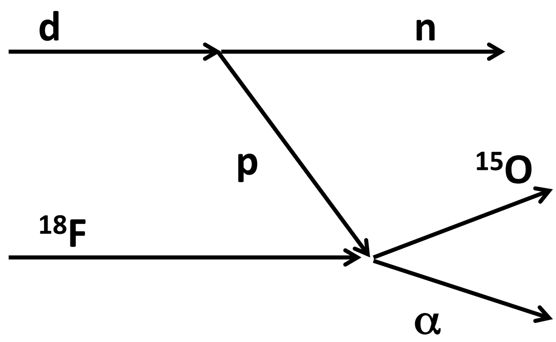

Figure 1. Schematic representation of the quasi-free mechanism of interest in the three-body reaction used in the Trojan horse method. The upper vertex marks the deuteron break-up while the lower vertex marks the half-off energy-shell process ^{18}F(p,α)^{15}O.

3 Results

The experiment, was performed at Cyclotron Institute of the Texas A&M University and it is described in [32]. The THM prescriptions and analysis were applied and the three body reaction of interest was selected. Taking into account the properties of quasi-free processes data were gated as reported ex tensively in [32]. Applying the formalism described above, the two body cross section is derived by dividing the experimental three-body one by the product of the kinematic factor modulated by the momentum distribution of the spectator inside the Trojan Horse nucleus [15].

The extracted $[d\sigma/d\Omega]^{\mathrm{HOES}}$ as a function of E_{cm}, was then compared to a previous THM run performed in CNS

Table 1. Energy levels of ^{19}Ne in the energy range explored by the present experiment. Progressive numbers in first column correspond to energy levels. The ^{19}Ne* energy values are taken from [30]

Number	E_{cm} (MeV)	Energy ^{19}Ne* (keV)	$J^{(\pi)}$	Reference
1	-0.34	6070	$3/2^+$,$5/2^-$	[9]
3	-0.16	6255	$11/2^-$	[9]
4	0.05	6460	$3/2^+$,$5/2^-$	[9, 35]
5	0.13	6537	$5/2^+$,$9/2^+$	[35]
6	0.33	6755	$3/2^-$	[9, 11, 35]
7	0.56	6967	$5/2^+$	[35]

at the CRIB facility whose details are reported extensively in [30]. A good agreement shows up, within the experimental uncertainties. The observed levels, correspond to levels in ^{19}Ne which are reported in Table 1, taken from [35] or [9]. Although the energy resolution is poorer than in the previous run (mainly due to the poorer angular resolution of the present experimental apparatus), the agreement between the two data sets confirms once again the applicability of the THM to the present reaction.

The first validity check that standard THM prescriptions do recommend is to reproduce the direct excitation function. This is done by comparing the distributions measured with direct methods to the one measured by means of THM. The latter should be normalized to the direct data. The THM cross section extracted above is corrected for the penetrability factor (below the Coulomb barrier) which also makes the comparison of half-off-energy-shell and on-energy-shell data [15] possible. The penetrability factor is, as usual, described in terms of the regular and irregular Coulomb functions.

THM data are also not affected by suppression effects coming from the centrifugal barrier. Assuming the J^π values of the populated ^{19}Ne excited states as in Table 1, the data of each resonance have been integrated over the full angular range by means the corresponding Legendre polynomial. Finally, the data have been corrected also for the penetrability of the centrifugal barriers.

It is then possible to normalize to the direct data (after comparison with the data from [30]) at the higher possible energies (0.5-0.65 MeV) in the present case. The comparison is reported in [32]. Energy states reported in Table 1 were investigated in the present work; in particular the explored energy range makes relevant the contribution from the 6255 (sub threshold state), 6460, 6537, 6755, 6967 keV states of ^{19}Ne . The respective J^π were assigned accordingly as reported in the Table 1. A specific discussion should be done for the resonance at E_{cm}=0.05 MeV (corresponding to the 6460 keV state in ^{19}Ne) where two possible values of J^π were taken into account. This is clear in Fig. 2. In the upper panel the black circles correspond to the choice of $J^\pi = 3/2^+$ for the 6460 keV state in ^{19}Ne following [35]. Direct data from [5, 6] are reported for comparison and normalization purposes. In the lower panel the full dots represents the results for a $J^\pi=5/2^-$ assumption for the same level as discussed in [9]. This uncertainty leads therefore to an uncertainty between the S(E) lower limit (corresponding to $J^\pi=5/2^-$ for the 6460 keV state in

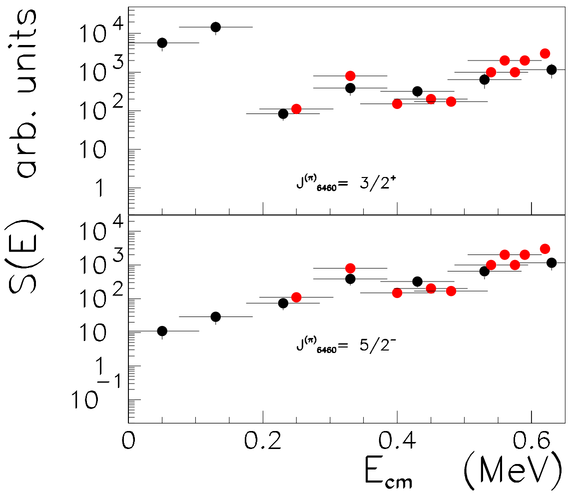

Figure 2. Average of the present data (black dots) and those from [5, 6] in red. Lower panel: S(E)-factor extracted with the choice of $J^{(\pi)}$=5/2$^-$ for the 6460 keV state in ^{19}Ne. Upper panel: S(E)-factor for $J^{(\pi)}$= 3/2$^+$.

^{19}Ne) and an upper limit assuming $J^\pi = 3/2^+$. Further studies (both with direct and indirect methods) and in particular the angular distribution will be necessary to improve the data quality in the low energy range.

It was possible, with the present experimental run, to confirm the possibility of application of the THM to the ^{18}F(d,αn)^{15}O reaction for studying the ^{18}F(p,α)^{15}O (as reported in [30]) within the experimental errors. This was also possible in the present case where the experimental set-up and the beam production line is much simpler than the ones used in [30] (e.g. simpler detection system and no beam-tracking available in the present case). This also strengthens the role of the THM for nuclear astrophysics in the further years since it may play a leading task in the field of radioactive beams, even in cases where the experimental setup is quite simple, like the present one. In fact, it was possible to extract the astrophysical S(E)-factor by means of the THM for a reaction induced by an unstable beam, thus confirming results from [30] in all the energy range relevant for astrophysics. Future astrophysical applications of the present results will be investigated via the means of R-Matrix theory in a forthcoming paper, with special attention to the role of the involved resonances. Moreover, on the experimental side efforts are necessary to improve the energy and angular resolution of the detection system and therefore reduce the statistical error on the S(E)-factor. The extraction of the angular distribution will also be crucial to assign the J^π of the involved levels and will be the aim of a future, dedicated experiment, to be performed in the future with the optimized version of the detection system adopted in [30] which turned out to be the best performing for the THM application.

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