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Trojan Horse Method with neutrons induced reactions: the ^{17}O(n,α)^{14}C reaction

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Abstract. The experimental study of the ^{17}O(n,α)^{14}C reaction has been performed in the energy range 0-350 keV. This reaction could play an important role in explaining heavy elements (s-process) nucleosynthesis in various astrophysical scenario. To overcome the practical problems arising from the neutrons production, a new application of the Trojan Horse Method has been recently suggested. In more details, the ^{17}O(n,α)^{14}C reaction has been studied using the quasi-free ^{2}H(^{17}O,α^{14}C)^{1}H reaction, induced at an energy of 43.5 MeV. The measurement allows one to investigate the ℓ=3, 75 keV resonance (E*=8.125 *MeV*, J$^{\pi}$=5^{-}), absent in the available direct measurements because of centrifugal suppression effects. Moreover, the results show that the contribution of the 166 keV and 236 keV resonances is in energy agreement with the available direct data. A clear contribution of the -7 keV subthreshold level is also present.

INTRODUCTION

The importance of the ^{17}O(n,α)^{14}C reaction is twofold, first in nuclear reactors and second in many astrophysical scenario. However, only few direct measurements are reported in literature, showing discordances at neutron thermal energy range [1, 2, 3, 4].

The knowledge of the ^{17}O(n,α)^{14}C is important for nuclear reactors where the neutron induced reaction on ^{14}N or ^{17}O are the dominant sources of the radioactive isotope ^{14}C ($T_{1/2}$=5730yr) [5]. In nuclear astrophysics, the reaction plays a role in the inhomogeneous Big-Bang model, in which the ^{14}C may act as a bottleneck in the production of elements heavier than A=17 [6], or in stellar nucleosynthesis, where this channel can be considered as a "neutron-poison" for standard *s*-nucleosynthesis since it has the net effect of reducing the total neutron flux [7].

Direct measurements have shown the population of the two excited states at energies 8213 keV and 8282 keV and the influence of the sub-threshold level at 8038 keV, while no evidence for the 8125 keV level is present. Indeed, as this resonance is populated in *f*-wave, its contribution is suppressed by the centrifugal barrier penetrability [8].

For all these reasons, a detailed measurement of the cross section in the energy range from 0 up to a few hundred keV is needed. However, the measurement of the cross section in the reactions involving the neutrons present two principal problems: the production of the neutron beam or alternatively, using the inverse reactions, the detection of the neutrons.

The aim of this work is to show how the application of the indirect method of the Trojan Horse Method (THM) allows to use the deuteron quasi-free (QF) break-up as a source of virtual neutrons [9, 10, 11].

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THE EXPERIMENT

The THM has been developed in the early 1990s as an extension of the well studied quasi-free break-up processes to low energies. It aims to study low energy nuclear reactions hindered by the Coulomb barrier and, since then, it has been successfully applied to several reactions of astrophysical interest [12, 13, 14]. Recently, this approach has been extended to the radioactive ion beams [15, 16] and to the neutron induced reactions [17]. Here, the ^{17}O(n,α)^{14}C reaction has been studied via the THM experiment ^{2}H(^{17}O,α^{14}C)p, where deuteron has been chosen as TH-nucleus thanks to its obvious $p-n$ structure and its well-known radial wave function for the intercluster *s*-wave $p-n$ motion given by the Hulthén wave function [18]. In such framework and referring to the QF-process of Fig.1, the emerging proton represents the *spectator* while the neutron is the *participant* for the binary reaction in the lower pole, eventually proceeding through the ^{18}O* excited levels [19].

The analysis of the QF reactions is usually performed in the framework of the Plane Wave Impulse Approximation (PWIA). This approach allows then to factorize the three-body cross section as

$$\frac{d^3\sigma}{dE_{^{14}C}dE_\alpha d\Omega_{^{14}C}} \propto KF|\Phi(p_S)|^2 \left(\frac{d\sigma}{d\Omega}\right)^{HOES} \tag{1}$$

where KF is a kinematical factor containing the final-state phase-space factor and it is a function of masses, momenta and angles of the outgoing particles, $\Phi(p_s)$ is the Fourier transform of the radial wave function for the x-s intercluster motion inside A and $(d\sigma/d\Omega)^{HOES}$ is the half-off energy shell cross section [20].

Two experiments were performed: the first one at Laboratori Nazionali del Sud (LNS) in Catania, Italy and the second one at the Institute for Structure and Nuclear Astrophysics (ISNAP) of the University of Notre Dame, USA. A ^{17}O beam of 41(43.5)MeV was delivered onto a CD$_2$ target in the LNS (ISNAP) experiment.

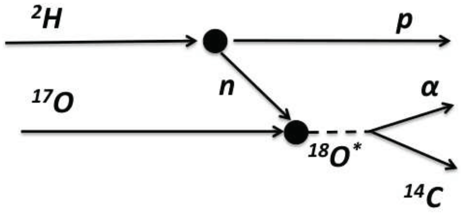

FIGURE 1. The QF ^{2}H(^{17}O, α^{14}C)n reaction used for the THM investigation of the binary ^{17}O(n,α)^{14}C reaction. Deuteron has been used as TH-nucleus and the outgoing proton is the *spectator* while the neutron acts as *participant* in the ^{17}O-n interaction. The other two fragments, α and ^{14}C, have been detected.

A schematical view of the used detection setup is shown in Figure 2. It was chosen to cover the phase-space region where a strong contribution of the QF reaction mechanism is expected. Four 500 μm thick Position Sensitive Detectors (PSD) referred to as A2, A3, B2 and B3 and two telescopes, made up of a ionization chamber (IC) as ΔE and a 1000 μm PSD (A1 and B1) as E detector, were employed. A2 and B2 were placed at a distance d2=476 mm and d5=494 mm from the target, covering the angular ranges 17.5°±2.5° while A3 and B3 were placed at d3=381 mm and d6=405 mm from the target covering the angular range 27.3°±3.5°. Finally, the two telescopes were placed at a distance d1=464 mm and d4=495 mm from the target, and they covered the angular range 7.5°±2.5°. The ICs, filled with about 50 mbar isobutane gas, had an energy resolution of ∼10%, which was enough to discriminate particles by their charge but not their mass. Two thin mylar foils respectively of 0.9μm and 1.5μm were used as entrance and exit windows of each IC. Their thickness was chosen to minimize the angular straggling. The telescopes were optimized for ^{14}C detection while the other PSDs for alpha particles.

The reaction of interest was identified by selecting the events, in which a carbon was detected in the telescope in coincidence with a signal on a detector placed on the opposite side with respect to the beam axis. The reconstructed Q-value for the three-body reaction (Q=-0.5±0.3MeV) results in agreement with the expected one (Q=-0.407MeV), as shown in Figure 3. Following the procedure described elsewhere [21, 22], many tests were performed to probe the presence of QF reaction process and to extract the half-off-energy-shell (HOES) cross section of the ^{17}O(n,α)^{14}C reaction.

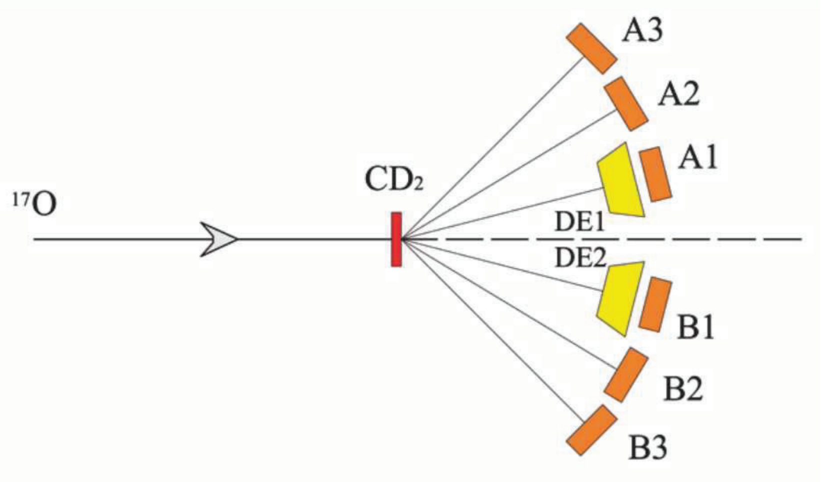

FIGURE 2. Schematic view of the experimental setup. The ^{17}O beam impinging on a CD_2 target. The emitted particles were detected by four PSDs (A2, A3, B2 and B3) and by two ΔE-E telescopes (DE1-A1 and DE2-B1).

Finally, the good agreement between the two THM measurements, within the experimental uncertainties, allow us to avarage the two data sets, weighting over the respective errors, in order to improve the statistics and data quality.

RESULTS AND CONCLUSIONS

Following the procedure described in [23, 24], the experimental data were normalized to the available direct measurements, integrated to the angular distribution and fitted following the modified R-matrix approach in order to calculate the reduced γ-widths of the excited levels, as reported in Table 1. Finally, after the extrapolation of the total cross section and its normalization to direct data it was possible to calculate the reaction rate. The calculation result is shown in Figure 4 with a red line, while the red band highlights the region allowed by uncertainties (statistical and normalization). This result may change significantly the abundance ratios of the element involved in the nucleosynthesis network of both the Inhomogeneous Big Bang and the weak component of the *s*-process.

TABLE 1. Summary of the ^{18}O resonances in the energy range explored in the experiment with the resonance parameters calculate via the modified R-matrix approach.

^{18}O* (MeV)	$E_{c.m.}$ (keV)	J^π	Γ_n^{THM} (eV)	Γ_α^{THM} (eV)	Γ_{tot}^{THM} (eV)
8.039	-7	1^-	0.01±0.001	2362±307	2362±307
8.125	75	5^-	0.05±0.006	36±5	36±5
8.213	166	2^+	86±11	2171±282	2257±293
8.282	236	3^-	1714±446	13021±3386	14735±3832

In conclusions, the ^{17}O(n,α)^{14}C reaction was studied by means of the THM applied to the ^{2}H(^{17}O,α^{14}C)^{1}H process. This is an extension of the THM to the neutron induced reactions. From such measurement, it was possible to excite the subthreshold level centered at -7 keV in the center-of-mass system corresponding to the 8.039 MeV level of ^{18}O, which is important to determine the ^{17}O(n,α)^{14}C reaction rate. Moreover, the use of deuteron as a source of virtual neutrons allows us to populate the level centered at 75 keV in the ^{17}O-n center-of-mass system, corresponding to the 8.121 MeV level of ^{18}O. Due to its J^π assignment ($J^\pi=5^-$), the population of such level is suppressed in direct measurements because of its $\ell=3$ angular momentum. The application of the modified R-matrix approach allows to measure the neutron and alpha partial widths that are in agreement with the ones available in literature while are extracted for the first time in the case of the 8.125 MeV level. Therefore, extensive calculations are undergoing to

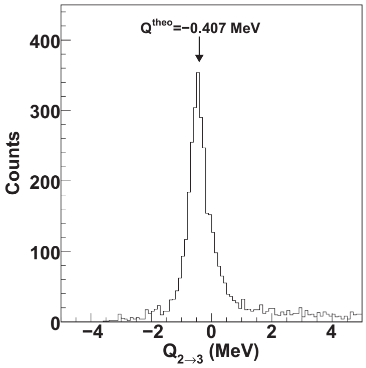

FIGURE 3. Experimental Q-value in agreement with the theoretical prediction of -0.407 MeV for the ^{2}H(^{17}O,α^{14}C)^{1}H reaction. No addictional process takes place as a single peak shows up in the spectrum.

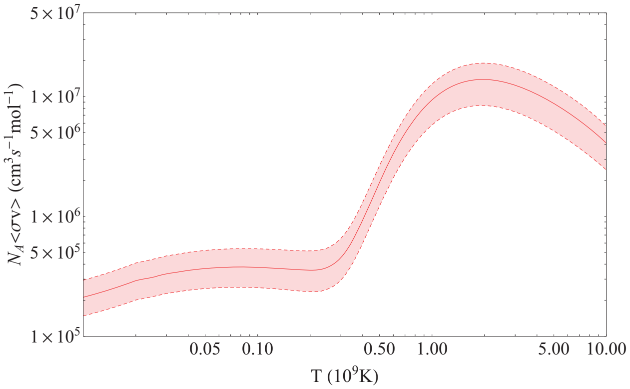

FIGURE 4. The THM reaction rate (red line) with the statistical and normalization errors (red band).

understand the consequences of the present results on astrophysics.

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