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Trojan Horse Method for n-induced reaction investigations at astrophysical energies

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The Trojan Horse Method (THM) is a valid indirect technique for measuring neutron-induced reaction cross sections of interest for astrophysics, also in the case of RIB's induced processes. Here we briefly report on the main results about the ^{7}Be(n,α)^{4}He THM investigation: the cross-section has been measured in a single experiment from ~2 MeV down to cosmological energies and compared with data available in literature. Moreover, the preliminary results concerning the more recent THM ^{14}N(n,p)^{14}C investigation are discussed.

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1. Introduction

Neutron-induced reactions play a significant role in the nucleosynthesis of the elements in the cosmos. Their interest ranges from the primordial nucleosynthesis up to the "stellar cauldrons" where neutron capture reactions could take place via the s- or the r-processes. In the last years, several efforts have been made to investigate neutron induced reactions via the indirect technique of the Trojan Horse Method (THM) [1, 2] by using the deuteron as a source of virtual neutrons [3] thus overcoming practical difficulties typical of direct measurements.
The main idea of the THM is to extract the cross section of the binary reaction of interest for astrophysics

$$A + x \to B + b \tag{1}$$

selecting the quasi-free (QF) contribution on a suitable reaction

$$A + a \to B + b + s \tag{2}$$

where a acts as Trojan Horse nucleus. To maximize the QF contribution to the reaction yield, a is selected among those systems showing a strong x⊕s cluster structure. In the hypothesis of QF break-up, s represents the "spectator" of the virtual reaction (1) of interest for astrophysics induced by the participant cluster x. Thus the cross section can be factorized in two terms, besides a kinematical factor KF, corresponding to the break-up and to the reaction pole respectively:

$$\frac{d^3\sigma}{dE_B\, d\Omega_B\, d\Omega_b} \propto (KF)\ |\phi(\mathbf{p}_s)|^2 \left(\frac{d\sigma}{d\Omega}\right)^{HOES} \tag{3}$$

where $|\phi(\mathbf{p}_s)|^2$ is the momentum distribution of cluster s inside a and $(\mathrm{d}\sigma/\mathrm{d}\Omega)^{HOES}$ is the half-off-energy-shell (HOES) cross section of the reaction (1). If the energy of the incoming particle is chosen high enough to overcome the height of the Coulomb barrier in the entrance channel of the reaction (2), the TH-nucleus break-up will occur in the nuclear field allowing to study the reaction (1) without the Coulomb and/or centrifugal suppression effects and electron screening.

2. Study of the ^{7}Be(n,α)^{4}He reaction via THM

The Standard Big Bang Nucleosynthesis model accurately predicts D, ^{3}He and ^{4}He primordial abundances in comparison with the observed ones while a large discrepancy concerning ^{7}Li is still present thus representing the still unsolved "lithium-problem" [4, 5].
From a pure nuclear physics perspective, the nuclear processes intervening in the ^{7}Li nucleosynthesis need to be carefully studied. Among these, the neutron-induced reactions on ^{7}Be affect the primordial ^{7}Li abundance through the ^{7}Be(n,p)^{7}Li and the ^{7}Be(n,α)^{4}He reactions. In order to complement the already available direct measurements, a devoted study of the ^{7}Be(n,α)^{4}He reaction has been recently performed in [7] while a further study on the ^{7}Be(n,p)^{7}Li was also made in [8].
In [7], the ^{7}Be-n reaction was investigated by means of the THM applied to the quasi-free ^{2}H(^{7}Be, $\alpha\alpha$)p reaction. The experiment was performed at the EXOTIC facility of Laboratori Nazionali di Legnaro, Italy, by using a 20.4 MeV ^{7}Be beam impinging on a 400 μg/cm^2 thick CD$_2$ target.

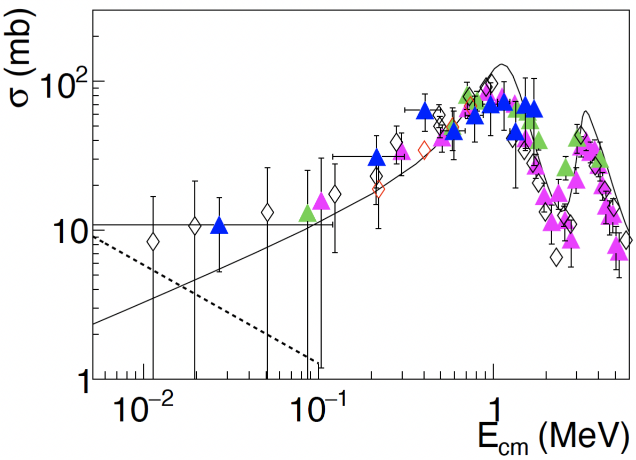

Figure 1: THM ^{7}Be(n,α)^{4}He cross-section measurement (blue triangles with the statistical error) compared with the direct measurements of [10] (red open diamonds) and [9] (black open diamonds). The purple and green triangles refer to the reverse measurement obtained in [11]. The solid line is the ENDF/B-VII.1 evaluation [13], while the dotted line gives the trend of the direct radiative capture (DRC) cross section given in [12].

The EXOTIC facility is devoted to the in-flight production of light weakly bound RIB's and it has allowed for the production of the unstable ^{7}Be beam in the past [6].
The detection of the alpha particles in the angular range covering the QF angular region was accomplished by four ΔE-E telescopes, with ionization chambers (ICs) for the ΔE stage and Double Sided Silicon Strips Detectors (DSSSD) as E stage for position-energy reconstruction. The IC's were filled with 100 mbar isobutane gas, while 1.5 μm thick mylar foils were used as entrance and exit windows. After selecting the reaction channel and the reaction mechanism (see [7] for details), the HOES differential cross section was then extracted by means of Eq.3 and converted to the on-energy-shell (OES) cross section by correcting for the angular distribution and the centrifugal barrier penetrability. The ^{7}Be(n,α)^{4}He cross section as derived by the THM data analysis of [7] is shown in Figure 1 as blue triangles with the corresponding uncertainties, by using the data of [9] (black open diamonds) for normalization. The present data nicely agree with those of [10] (red open diamonds) and our previous investigation discussed in [11] (purple and green triangles). In the same figure, the dashed line refers to the evaluation of the total s-wave component for the present reaction as derived in [12], while the solid line represents the ENDF/B-VII.1 evaluation by [13].

3. Study of the ^{14}N(n,p)^{14}C reaction via THM: preliminary results

The ^{14}N(n,p)^{14}C reaction plays an important role in the s-process of nucleosynthesis: ^{14}N is very abundant since it is a dominant product of hydrogen-burning in the CNO cycle, taking place during earlier stellar evolutionary stages. Because of its relatively high cross section, this reaction can act as a strong neutron poison subtracting neutrons from the reaction chain to heavier elements. Also, ^{14}N is of crucial importance in the origin of fluorine, whose only stable isotope is ^{19}F. The He-burning shell in asymptotic giant branch stars is thought to be the most likely site for the

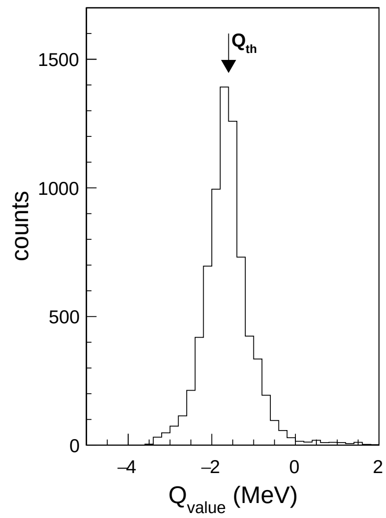

Figure 2: The experimental Q-value for the selected ^{2}H(^{14}N,p ^{14}C)p events. The black arrow correspond to the theoretical Q value, Q$_{th}$=-1.599 MeV.

synthesis of fluorine, mainly through the nuclear chain ^{14}N(α,γ)^{18}F(β^+) ^{18}O(p,α)^{15}N(α,γ)^{19}F. In this sense, the ^{14}N(n,p)^{14}C reaction plays a key role because of its double effect of removing neutrons and producing protons. In addition, the protons can trigger the ^{18}O(p,α)^{15}N or the ^{13}C(p,γ)^{14}N reactions, being the last one in competition with the ^{13}C(α,n)^{16}O reaction [14–21].
To measure the ^{14}N(n,p)^{14}C reaction cross section, the THM was applied by selecting the QF contribution of the ^{2}H(^{14}N,p ^{14}C)p reaction. The experiment was performed at Laboratori Nazionali del Sud of Catania, Italy, by using a 40 MeV ^{14}N beam, accelerated by the SMP Tandem accelerator, impinging on a 150 μg/cm^2 thick CD_2 target with a spot size on target of about 1.5 mm ad intensities up to 2-3 pnA. The experimental setup consisted of one 500 μm DSSSD (double sided silicon strips detectors) with an active area of 50 x 50 mm^2 with 16 strips per side orthogonally oriented and one 1000 μm position sensitive detector (PSD) devoted to proton detection. They were placed at distance d=28.4 cm and d= 25.5 cm from the target, respectively. The carbon nuclei were identified by means of a ΔE-E telescope (T) made of a 20 μm strip detector as ΔE and a 500 μm DSSSD as E-detector, placed at a distance d = 80 cm from the target on the opposite side with respect to the beam direction. The detectors covered the laboratory angles between 19.4° and 30.6° (DSSSD), between 35.0° and 45.0° (PSD) and between -3.2° and -6.8° (ΔE-E telescope).
The first step in a THM analysis is the selection of the three-body reaction channel. After the energy and position calibration of the detectors, carbon particles were selected with the standard ΔE-E technique and for these selected events the experimental Q-value spectrum was reconstructed and compared with the theoretical value (Figure 2). The experimental Q-value spectrum is centered at -1.61 MeV showing a FWHM of about 130 keV, reflecting the energy loss of the incoming beam in the target. The experimental value nicely agrees with the theoretical one of -1.599 MeV, thus showing the correct selection of the reaction channel. Further studies are ongoing.

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