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Neutron-induced reactions investigated via the Trojan Horse Method

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Abstract. The Trojan Horse Method has been applied to many neutron-induced reactions using the deuteron as a virtual source of neutrons, to explore wide energy regions of interest for astrophysics and applied physics and to investigate the suppression of the centrifugal barrier, that is one of the key advantages of this Method. The neutron-induced experimental campaign has already concerned $^{17}\text{O}(n,\alpha)^{14}\text{C}$, $^6\text{Li}(n,\alpha)^3\text{H}$, $^7\text{Be}(n,p)^7\text{Li}$, $^7\text{Be}(n,\alpha)^4\text{He}$, $^{18}\text{F}(n,\alpha)^{15}\text{O}$ and $^{14}\text{N}(n,p)^{14}\text{C}$, and very recently $^{25}\text{Mg}(n,\alpha)^{22}\text{Ne}$ and $^{27}\text{Al}(n,p)^{27}\text{Mg}$, while others are planned to be measured soon, thus influencing different astrophysical scenarios. Particular attention is dedicated to a new measurement regarding the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction, aimed to disentangle the ^7Li ground state contribution from its first excited state to the cross section.

1. Introduction

Dealing with neutron induced reactions measurements is challenging and complex as much as they turn to be always more necessary. Areas of interest of their applications range from pure nuclear physics (nuclear structure and dynamics) to nuclear astrophysics, where n-induced reactions are fundamental basically in any astrophysical scenario. The same holds for applied physics, where these reactions are nowadays used to study and understand our cultural heritage (as an example the european Ancient Charm project [1]). Some of them, as $^{10}\text{B}(n,\alpha)^7\text{Li}$, are also used in nuclear energy power plants (to monitor the neutron fluxes in the plant), and in medicine, as it is discussed in section 3.2.

2. The need of indirect methods

Measuring neutron induced reactions is anyhow challenging. It is not possible to get a pure target of neutrons and the beam is not easy to have. Indeed, a primary neutron producer reaction, such as $^7\text{Li}(p,n)^7\text{Be}$, is necessary with low energy accelerators, but this will not produce monoenergetical neutrons. Moreover, it is not possible to accelerate neutrons in the usual ionization way. Despite many attempts are done in facilities spread around the world, it seems impossible to get an intense monoenergetical neutron beam.



Also the way to obtain the cross sections with the detailed balance principle applied to the inverse reactions is problematic, because of the low efficiency problems connected with neutron detection.

For all these reasons, the use of indirect methods is required to achieve results useful for pure and applied physics.

2.1. The Trojan Horse approach

The Trojan Horse Method (THM) [2] [3] results to be the best indirect technique for this case. It was born to determine bare nucleus S-factor at astrophysical energies, because it allows to obtain the cross section without the strong suppression at very low energies due to the Coulomb barrier.

This is made selecting the quasi free mechanism by the cross section of an appropriate 3-body reaction measured in the lab, where one of the two interacting particles is called the Trojan Horse nucleus, and has a very high probability of clusterization in two particles. In the peculiar circumstances of this mechanism, one of them will participate and the other will act as a spectator to the binary reaction, that is the goal of the experiment.

In recent years, THM has also been applied to neutron-involving reactions: for the case of neutron outgoing, it avoids the use of neutron detectors, reconstructing its kinematics by the other two outgoing particles of the reaction: this has been very helpful for the cases of ${}^2\text{H}(d,n){}^3\text{He}$ [4] and ${}^{13}\text{C}(\alpha,n){}^{16}\text{O}$ [5], where their cross section have been extracted detecting the charged outgoing particle and the spectator proton and deuteron, respectively. Instead, for the case when neutron is inducing the reaction, using the very well known p+n structure of deuteron, where their intercluster motion in $l = 0$ is well known and described by the Hultén function.

Using a CD_2 target (plastic and easy to get) has revealed to be a very cheap and simple way to have a perfect virtual neutrons source. Moreover, the use of this indirect method let us need only one beam energy to get a wide energy range for the excitation function.

3. Reactions measured

The first reaction used to test the Method in the neutron circumstances has been the ${}^6\text{Li}(n,\alpha){}^3\text{H}$, whose 2-body cross section has been extracted by the ${}^6\text{Li}(d,\alpha p){}^3\text{H}$ measured at Laboratori Nazionali del Sud (LNS) in Italy. This marked the first evidence that deuteron could be rightly used as neutron virtual source and was the first direct insight of the Trojan Horse cross section behaviour about the centrifugal barrier effects: it is evident from data that TH cross section is in agreement with direct results only if it is multiplied for the on-shell centrifugal effects [6] [7].

Another neutron induced reaction studied with THM is ${}^{17}\text{O}(n,\alpha){}^{14}\text{C}$, that turns out to be of great interest for the astrophysical scenario of s-process nucleosynthesis, which is all about neutron captures [8]. In that context, reactions as ${}^{17}\text{O}(n,\alpha){}^{14}\text{C}$ are called neutron-poisons, because the total amount of neutron available for s-process depends on their reaction rate. With THM a new measurement has been performed in the energy range of astrophysical interest, resulting in a reaction rate quite different from the ones found in literature, and astrophysical consequences have still to be evaluated [9].

Partial results of a preliminary test to get the cross section of ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ have been already published [10], while the final ones are going to be submitted for publication. However, because of the particular importance of this reaction for applications, a new and very precise measurement has been performed and is still under analysis, as reported in section 3.2.

3.1. Results under analysis and applications to exotic beams

Great efforts have been put on the measurement of ${}^7\text{Be}(n,\alpha){}^4\text{He}$ and ${}^7\text{Be}(n,p){}^7\text{Li}$, made in two runs (the first in LNL, Italy and the second at CRIB, Japan) to get these two cross sections

very relevant for the Big Bang Nucleosynthesis scenario. Good results coming out from these experiments [11] [12] are a proof that TH perfectly suits the needs of measurements involving exotic beams, such as ${}^7\text{Be}$.

Also ${}^{14}\text{N}(n,p){}^{14}\text{C}$ has been measured at LNS, because it is the first n-poison of s-process, mentioned above. Results are still under analysis [13].

Moreover, in the very recent past other two neutron induced reactions have been measured, both at LNS. The first was the ${}^{25}\text{Mg}(n,\alpha){}^{22}\text{Ne}$ to get the ${}^{22}\text{Ne}(\alpha,n){}^{25}\text{Mg}$ cross section using the detailed balance principle. The latter is, indeed, one of the most influencing reaction for the star nucleosynthesis scenario, which hardly impacts the s-process and all the rest of the life of a star.

The second one is ${}^{27}\text{Al}(n,p){}^{27}\text{Mg}$, that has been the first step of a long term campaign of measurement involving Al isotopes, which will very soon involve also exotic beams. This has been thought to give constraints to reaction rates involving the abundance of ${}^{26}\text{Al}$, very important to trace the active nucleosynthesis in the Galaxy.

3.2. The case of ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$

This peculiar neutron induced reaction is of interest for the nuclear energy production in power plants, to have control on reactions induced on the percentage of ${}^{10}\text{B}$ in the natural boron, considering that ${}^{11}\text{B}(p,\alpha\alpha){}^4\text{He}$ is the only good candidate for a clean (aneutronic) energy obtained by fusion. Moreover, it is very important for medicine, considering that the cure protocol of eye melanomas and glioblastoma multiforme [14] and the synovial ablation for rheumatoid arthritis [15] consist in inducing this reaction inside the patient. For purposes of medicine, an energy range from 0 to 100 keV is of interest in the excitation function, while in the energy production case from 0 to 15 MeV. However, cross section measurement available in literature are still not exhaustive for these applications.

This reaction has already been measured using Trojan Horse Method [10], but a new run has been performed in order to separate the two main contributions to this cross section, coming from the ground state and from the first excited state of the ${}^7\text{Li}$, separated by 0.477 MeV.

The experimental run has been performed in 2014 in Laboratori Nazionali del Sud (LNS, Catania), using a 28 MeV ${}^{10}\text{B}$ beam impinging on a CD_2 target, measuring ${}^{10}\text{B}(d,\alpha){}^7\text{Li}H$ cross section, as it is sketched in fig. 2. Results obtained cover the sensitive energy range from 0 to 1.5 MeV.

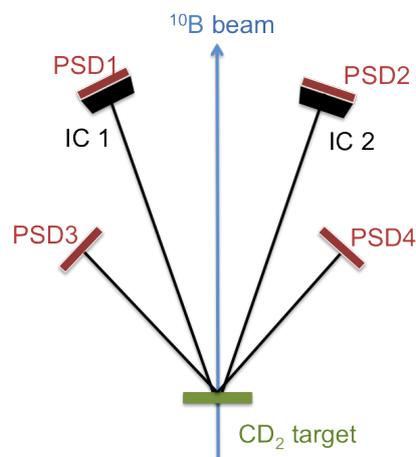


Figure 1. Scheme of the experimental setup used in the scattering chamber

${}^7\text{Li}$ and α were the outgoing particles detected with the use of four Position Sensitive Detectors (PSD), symmetrically placed inside the scattering chamber, setted as in fig. 1.

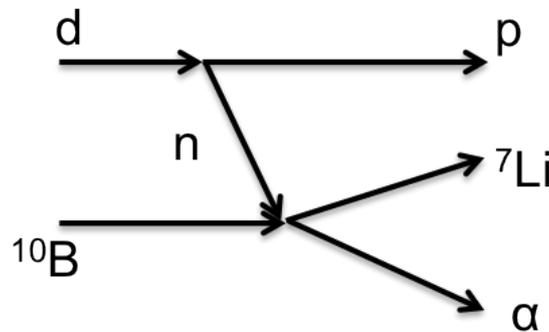


Figure 2. Sketch of the transfer reaction measured at LNS. The deuteron inside the CD_2 target has been the neutron virtual source, while the ${}^{10}\text{B}$ was the beam. ${}^7\text{Li}$ and α particles have been detected, while the spectator proton kinematics has been reconstructed.

The goal of separating the two contributions was achieved using a very thin target ($56 \mu\text{g}/\text{cm}^2$), minimizing the energy straggling and loss of the beam and the outgoing particles.

Once α and ${}^7\text{Li}$ produced have been discerned via their energy loss in isobutane gas inside ionization chambers placed in front of two of the four PSD in the scattering chamber, the Q-value spectrum, reported in [16], clearly shows two separated peaks related to the channels desired. Some details are reported in [16] and [17].

Angular distributions have been extracted thanks to the avoidance of the centrifugal barrier for each level foreseen by literature in the measured E_{cm} range. They result to be well in agreement with what reported in literature, as shown in fig. 3 where the case of 11.600 MeV level is plotted (α_0 data set). In this figure blue and red dots mark different kinematical conditions of the experimental run, while the black line is the theoretical distribution, calculated as [19] for the J_π foreseen by literature, namely $5/2+$ [18].

4. Conclusions

The THM extension to neutron induced reactions has proved to be a very powerful instrument to overcome centrifugal barrier effects, helping in the study of levels which are suppressed in direct measurements, allowing the possibility to measure angular distributions and nuclear properties and obtaining the strength of each level, thanks to the new Modified R-matrix approach [20].

Moreover, it perfectly suits complex situations of measurements (including RI beams case), because the use of deuteron as a virtual neutron source permits the use of simple setups, easy targets and the need of only one beam energy to get a wide energy range in the excitation function, finally making simple and less expensive the research.

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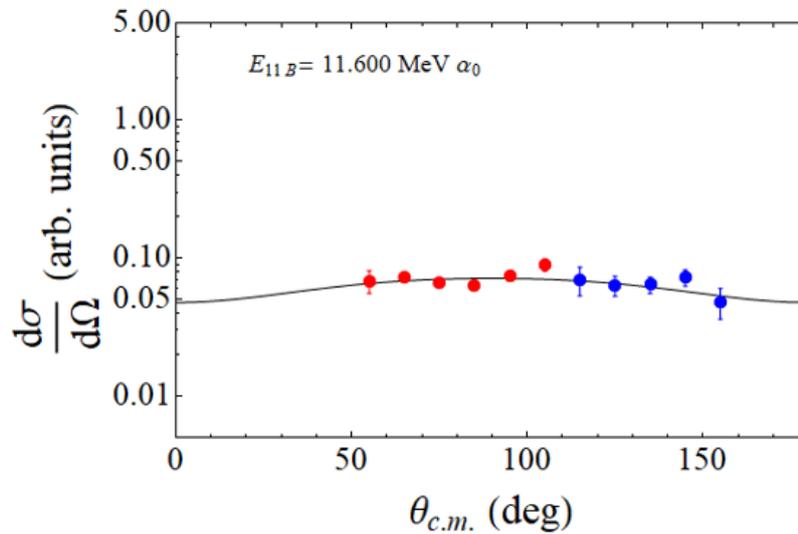


Figure 3. Angular distribution of the ^{11}B level at 11.600 MeV for the α_0 data obtained. Red and blue dots correspond to different kinematical conditions of the experiment, compared to the theoretical angular distribution (black line) calculated as in [19].

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