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Trojan Horse Method for neutrons-induced reaction studies

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Summary. — Neutron-induced reactions play an important role in nuclear astrophysics in several scenario, such as primordial Big Bang Nucleosynthesis, Inhomogeneous Big Bang Nucleosynthesis, heavy-element production during the weak component of the s-process, explosive stellar nucleosynthesis. To overcome the experimental problems arising from the production of a neutron beam, the possibility to use the Trojan Horse Method to study neutron-induced reactions has been investigated. The application is of particular interest for reactions involving radioactive nuclei having short lifetime.

1. – Introduction

The direct measurement of nuclear reactions cross section at the low energies of interest for astrophysics is often a very difficult task. Indeed, at ultra-low energies the cross section is suppressed because of the presence of the centrifugal and Coulomb barriers arising, respectively, from the angular momenta and electrical charge of the interacting nuclei. To overcome the experimental difficulties, many indirect methods were developed. Among them, the Trojan Horse Method (THM) was successfully applied in the last decades to study charged-particles–induced reaction, and recently it was also exploited to study neutron-induced reactions. Even if the reactions involving neutrons do not suffer for the Coulomb suppression, direct neutron capture studies present several experimental difficulties, especially when short-lived nuclei are involved. Consequently, the application of indirect methods to get information about the cross section of neutron-induced reactions is of great interest.

Here, we report on the results of indirect measurements of (n,α) reactions, performed by applying the THM. Namely, the ^{6}Li$(n,\alpha)^{3}$He and the ^{17}O$(n,\alpha)^{14}$C have been successfully studied and the obtained cross section resulted in agreement with the directly

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measured ones. Moreover, these experiments have contributed to clarify some theoretical aspects in the application of THM, stressing the role of the centrifugal barrier lacking of any Coulomb effect. Finally, preliminary results on the study of the ^{18}F$(n,\alpha)^{15}$N reaction involving the use of the ^{18}F radioactive ion beam will be shown.

2. – Experimental results

The THM extracts the cross section of an astrophysically relevant two-body reaction $\mathrm{A}+x \rightarrow \mathrm{c}+\mathrm{C}$ at low energies from a suitable three-body reaction $\mathrm{a}+\mathrm{A} \rightarrow \mathrm{c}+\mathrm{C}+s$ [1-3]. The nucleus a (TH nucleus) is chosen with a strong x-s clusters structure and, in the Impulse Approximation description, only x interacts with A, whereas s is considered to be spectator to the reaction. The basic idea in using THM for neutron-induced reaction is to use the break-up of deuteron selecting the events where the neutron behaves as participant in the 2-body reaction of interest, while the proton acts as spectator. In the Plane Wave Impulse Approximation (PWIA) the cross section of the three-body reaction can be factorized as

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_c \mathrm{d}\Omega_C \mathrm{d}E_c} \propto KF\, |\Phi(p_{x\text{-}s})|^2 \frac{\mathrm{d}\sigma_{A-x}^{HOES}}{\mathrm{d}\Omega}, \tag{1}$$

where KF is a kinematic factor and $\Phi(p_{x\text{-}s})$ is the momentum distribution of the clusters inside the TH nucleus, described by the Hultèn function for the deuteron nucleus. So, measuring the three body cross section and the $\Phi(p_{x\text{-}s})$ function, it is possible to deduce the cross section of the process of interest, *i.e.* $\mathrm{A}+x$, in arbitrary units. The superscript *HOES* indicates that the two-body reaction cross section is Half Of Energy Shell, because the x-particle in the entrance channel is virtual, while the other particles involved in the two-body reaction of interest are real ones. For this reason, the THM allows to overcome the suppression of the cross section due to the presence of both Coulomb and centrifugal barrier between the interacting nuclei, as the x cluster is brought directly inside the nuclear field of the A-nucleus. The neutron-induced reactions allow to stress the role of the centrifugal barrier in the THM, thanks to the lack of any Coulomb effect.

The first n-induced reaction that has been studied with THM was ^{6}Li$(n,\alpha)^3$H [4]. The experiment was performed at LNS-INFN in Catania, Italy. A ^{6}Li beam was sent into a CD_2 target. The 2 ejectiles, α and ^{3}H, were detected by using two silicon position-sensitive detectors. The cross section for this reaction at low energy is dominated by the presence of an excited state in the ^{7}Li compound nucleus populated in $l = 1$. The experiment successfully reproduced the resonance in the angular range covered by the experimental set-up with the same resolution of the direct measurement. A comparison of the directly and indirectly measured data is shown in fig. 1.

The same method was also applied to the study of the ^{17}O$(n,\alpha)^{14}$C process [5]. This reaction is interesting for nuclear astrophysics. Indeed, it takes place in the nucleosynthesis of heavy elements in various astrophysical scenarios [6, 7], and it could also help to explain anomalies in ^{18}O/^{16}O and ^{17}O/^{16}O ratios found in asymptotic giant branch stars and in circumstellar Al_2O_3 meteorite grains [8].

For incident neutron energies from thermal up to a few hundred keV, the cross section of this reaction is characterized by the presence of several narrow resonant states in the ^{18}O compound nucleus. Three resonances have energy above the ^{17}O+n threshold (8044 keV), and one sub-threshold level is present. Direct measurements ([9] and references therein) have shown the population of the two excited states at energies 8213 keV

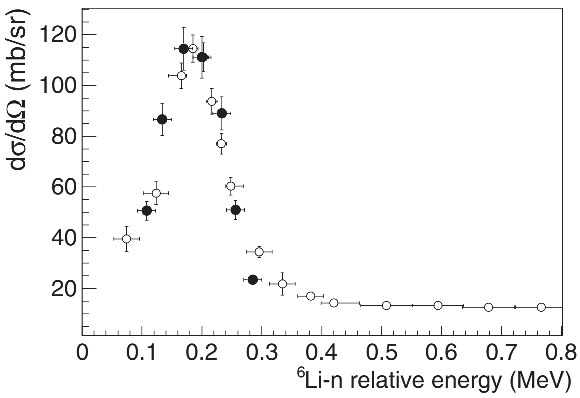

Fig. 1. – Nuclear cross section for the ^{6}Li$(n,\alpha)^{3}$H. The solid and open symbols represent the THM and the directly measured data, respectively.

and 8282 keV and the influence of the sub-threshold level at 8038 keV, while the population of the state at 8125 keV is suppressed because of the high angular momentum involved.

Two experimental runs were performed to study this reaction by THM: the first one at LNS-INFN in Catania, Italy, and the second one at NSL of the University of Notre Dame, USA. In both experiments a ^{17}O beam impinged onto a CD_2 target. The ejectiles were detected by using a ΔE-E telescope at forward angles for the heavier particle and a position-sensitive silicon detector for the α-particles.

The THM cross section of the ^{17}O$(n,\alpha)^{14}$C reaction shows the population of all the 4 expected resonances of ^{18}O. As the Coulomb effects are not present in neutron-induced reaction, the population of all the four resonances demonstrate the capability of the THM to overcome even the angular-momentum barrier in the entrance channel, thanks to the virtual nature of the involved neutron. In particular, in figs. 2(a) and 2(b) the presence of the level at $E^* = 8125 \pm 2$ keV, $J^\pi = 5^-$ must be noted. It has been clearly observed in both of the experiments, but was missing in the direct measurements because of the suppression due to the centrifugal barrier. A good agreement of direct and THM cross section was obtained when the THM data were corrected for the penetrability probability given by $P_l(kr) = 1/[kr(j_l(kr)^2 + n_l(kr)^2)]$, where kr is the wave number, and $j_{l_1}(kr)$ and $n_{l_1}(kr)$ are the spherical Bessel and Neumann functions, respectively. This comparison is shown in fig. 2(c).

Recently, some calculations of the rate of the ^{17}O$(n,\alpha)^{14}$C have been performed by using a modified R-matrix approach, and the contribution due to the sub-threshold level has been evaluated. The results have been submitted for publication by our research group.

The most interesting application of the THM for n-induced reaction studies regards the reactions involving radioactive isotopes having short lifetime. Indeed, in this case direct measurements are extremely difficult, if not impossible. By using the THM, one can use a RIB as the projectile and a deuteron placed in the target as the source of (virtual) neutrons in a 3-body reaction suitably chosen in order to study the 2-body process of interest.

The first attempt to apply the THM with a radioactive ion beam has been performed by using the CRIB facility of the University of Tokyo, installed at the Riken laboratory,

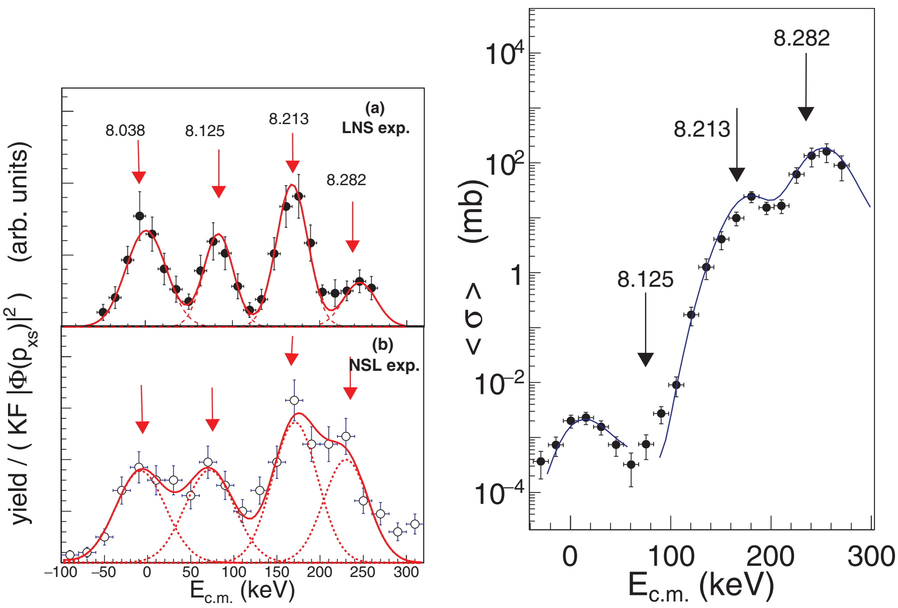

Fig. 2. – Yield of the ^{17}O$(n,\alpha)^{14}$C reaction measured at NSL (a) and LNS (b). (c) Comparison of the THM data (points) with the directly measured data (solid line) smeared out at the THM experimental resolution. The arrows show the resonances of the ^{18}O and the energies are reported in MeV.

Japan. The reaction ^{18}F+d has been studied with the aim to infer information about the ^{18}F$(p,\alpha)^{15}$O reaction, that has a great astrophysical interest in the framework of Nova explosion [10]. To overcome the experimental problems arising from the radioactive nature of the used beam, the adopted experimental set-up was able to define event-by-event the direction of the incoming beam and the beam impact point onto the target, and to detect the ejectiles going into a large solid angle. In particular a couple of double-side silicon strip detectors was used at forward angles to detect the heavier particle, and 8 positions-sensitive detectors $45 \times 45\,\text{mm}^2$ were placed around the beam line and devoted to the lighter particle detection.

Even if the experiment was optimized for the ^{18}F$(p,\alpha)^{15}$O reaction study, it allowed to get also some preliminary information about the ^{18}F$(n,\alpha)^{15}$N reaction. This reaction plays an important role in astrophysics, in particular in the explosive production of ^{15}N. Indeed, some calculations have indicated as main pathway for ^{15}N production the reaction sequence ^{14}N$(\alpha,\gamma)^{18}$F$(n,\alpha)^{15}$N [11].

The preliminary excitation function for the ^{18}F$(n,\alpha)^{15}$N reaction, lacking of any suppression due to angular-momentum barrier effect in the entrance channel, is shown in fig. 3. The statistic of the experiment is very poor, so a second experimental run has been performed in order to increase the statistic and to get more information about the spin and parity values of the populated resonances. The data analysis of the new experiment is in progress.

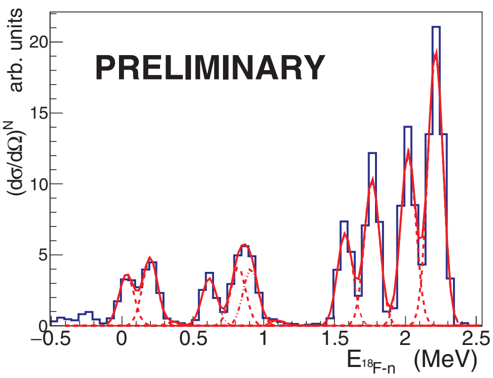

Fig. 3. – Bare nuclear cross section for the $^{18}F(n,\alpha)^{15}N$. The solid line represents a multi-Gaussian fit of the data. The dotted lines show the contribution of each Gaussian.

3. – Conclusions and outlook

The THM has been extensively exploited to study nuclear reaction induced by charged particles in the low energy region of interest for astrophysics. Recently it has been applied also in the study of neutron-induced reaction, demonstrating the capability to infer information about this kind of reactions. The use of the method for studying reactions involving radioactive nuclei of short lifetime is of particular interest. Recently, a THM experiment using the ^{18}F radioactive ion beam has been performed, and the bare nuclear cross section of the $^{18}F(n,\alpha)^{15}N$ reaction has been measured.

The encouraging results have triggered the proposal of new experiments. In particular both the reactions $^{7}Be(n,\alpha)^{4}He$ and $^{7}Be(n,p)^{7}Li$ will be soon studied by applying the THM (see S. Hayakawa contribution in these proceedings).

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