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R. G. Pizzone · C. Spitaleri · M. L. Sergi · L. Lamia · A. Tumino
C. A. Bertulani · L. Blokhintsev · V. Burjan · V. Kroha
M. La Cognata · J. Mrazek · A. M. Mukhamedzhanov · R. Spartá

Trojan Horse Particle Invariance: An Extensive Study

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Abstract In the last decades, the Trojan Horse method (THM) has played a crucial role for the measurement of several particle (both neutron and charged one) induced cross sections for reactions of astrophysical interest. To better understand its cornerstones and its applications to physical cases, many tests were performed to verify all its properties and the possible future perspectives. The Trojan Horse nucleus invariance proves the relatively simple approach allowed by the pole approximation and sheds light in the involved reaction mechanisms. Here we shortly review the complete work for the binary ^{2}H(d,p)^{3}H, ^{6}Li(d,α)^{4}He, ^{6}Li(p,α)^{3}He, ^{7}Li(p,α)^{4}He reactions, by using the quasi free reactions after break-ups of different nuclides. Results are compared assuming the ^{6}Li and ^{3}He break-up in the case of the d(d,p)t, ^{6}Li(d,α)^{4}He reactions and considering the ^{2}H and ^{3}He break-up for ^{6}Li(p,α)^{3}He, ^{7}Li(p,α)^{4}He reactions. These results, regardless of the Trojan Horse particle or the break-up scheme, confirms the applicability of the standard description of the THM and suggests the independence of binary indirect cross section on the chosen Trojan Horse nuclei for a whole spectra of different cases. This gives a strong basis for the understanding of the quasi-free mechanism which is the foundation on which the THM lies.

1 Introduction

Nuclear reactions induced by charged particles at astrophysical energies are extremely difficult to study, mainly for the presence of the Coulomb barrier and the electron screening effect. In the last decades strong efforts were devoted to the development and application of indirect methods to be applied in nuclear astrophysics.

R. G. Pizzone (✉) · C. Spitaleri · M. L. Sergi · L. Lamia · M. La Cognata · R. Spartá
INFN LNS and Universitá di Catania, Catania, Italy
E-mail: rgpizzone@lns.infn.it

A. Tumino
Universitá Degli studi di Enna Kore, Enna, Italy

C. A. Bertulani
Physics Department, Texas A&M University, Commerce, TX, USA

L. Blokhintsev
Moscow State University, Moscow, Russia

V. Burjan · V. Kroha · J. Mrazek
Academy of Science, Rez near Praha, Prague, Czech Republic

A. M. Mukhamedzhanov
Cyclotron Institute, Texas A&M University, College Station, TX, USA

Among them an important role is played by the Trojan Horse Method (THM) which has been applied to several reactions in the past decade [2,4–8,11–14,17,18,20,27,28] at the energies relevant for astrophysics (typically smaller than few hundred keV's). THM allows one to extract the low energy behavior of a binary reaction by applying the well known theoretical formalism of the Quasi-Free (QF) process, in the simplest cases. The basic idea of the THM is to extract the cross section of a two-body reaction (see Eq. 1) with significant astrophysical impact, in the low-energy region:

$$a + x \rightarrow c + C, \tag{1}$$

from a suitable QF break-up of the so called Trojan Horse nucleus, e.g. A=$x \oplus s$ where usually x is referred to as the *participant* and s as the *spectator* particle. We refer to previous papers and references therein for an extensive discussion on THM and its theoretical formalism [3,9,21–23,26].

The TH triple differential cross section can be written in a factorized form, as in Eq. (2), in terms of the half-off-energy-shell (HOES) differential cross section whose energy trend is the relevant information for the THM. Its absolute value can be extracted through normalization to the direct data available at higher energies.

In particular it can be written via the following expression:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \cdot |\Phi(p_{sx})|^2 \cdot \frac{d\sigma^{HOES}}{d\Omega_{cm}} \tag{2}$$

where:

- $[(d\sigma/d\Omega)_{cm}]^{HOES}$ is the HOES differential cross section for the two body reaction at the center of mass energy E_{cm} given in post collision prescription [20];
- KF is a kinematical factor containing the final state phase-space factor and it is a function of the masses, momenta and angles of the outgoing particles;
- $\Phi(p_{sx})$ is the Fourier transform of the radial wave function for the $x - s$ motion.

Thus, if the PWIA is valid, the HOES differential cross section for the binary sub-reaction determined from the TH reaction should not depend on the type of the TH nucleus as it was outlined in [15,25] for the two examined cases.

Many tests have been made to fully explore the potentiality of the method and extend as much as possible its applications: the target/projectile break-up invariance [10], the spectator invariance [25] and the possible use of virtual neutron beams [1,24]. In recent works [15] the spectator invariance was extensively examined for the ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He and the ^{6}Li(^{3}He,$\alpha\alpha$)H case as well as the ^{7}Li(d,$\alpha\alpha$)n and ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H reactions, thus comparing results arising from ^{6}Li and ^{3}He and deuteron and ^{3}He break-up respectively [15]. The same was recently [16] extended to the important physical case of the d(d,p)t binary reaction, studied via the quasi free ^{2}H(^{6}Li, pt)^{4}He and ^{2}H(^{3}He,pt)H reactions after ^{6}Li and ^{3}He break-up, respectively. Agreement between the different sets of data was found below and above the Coulomb barrier and we refer to the references cited above for further details.

The results already obtained are reported in Table 1 with all the complete references.

2 Future Perspectives

In order to better understand these empirical results it was decided to continue these studies with the investigation of the ^{6}Li(p,α)^{3}He binary reaction. The latter was already studied via the deuteron break-up in [25]. Using the same methodology adopted for the reactions presented in Table 1 the same process was examined through

Table 1 Physical cases for which the Trojan Horse particle invariance was investigated

Quasi-free process	Binary reaction	Trojan Horse particle	ref.
^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He	^{6}Li(d,α)α	^{6}Li	[15]
^{6}Li(^{3}He,$\alpha\alpha$)H	^{6}Li(d,α)α	^3He	[15]
^{7}Li(d,$\alpha\alpha$)n	^{7}Li(p,α)α	d	[15,24]
^{7}Li(^{3}He,$\alpha\alpha$)^{2}H	^{7}Li(p,α)α	^3He	[15,24]
^{2}H(^{6}Li, pt)^{4}He	d(d,p)t	^{6}Li	[16]
^{2}H(^{3}He,pt)H	d(d,p)t	^3He	[16]

The relevant reference for each reaction is reported in the last column

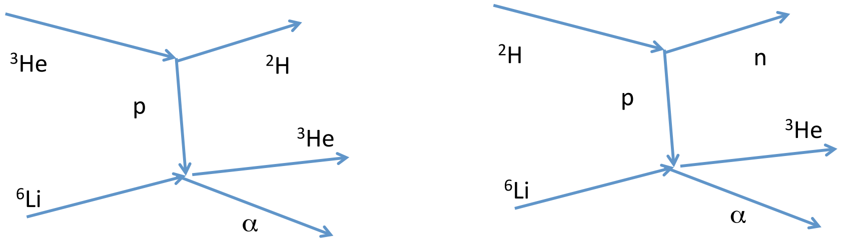

Fig. 1 Quasi-free break-up schemes as discussed in the text. In the *left panel* the ^{3}He break-up is sketched for the ^{6}Li(^{3}He,α^3He)^{2}H three-body process while in the *right panel* the d break-up in the ^{6}Li(d,α^3He)n is reported

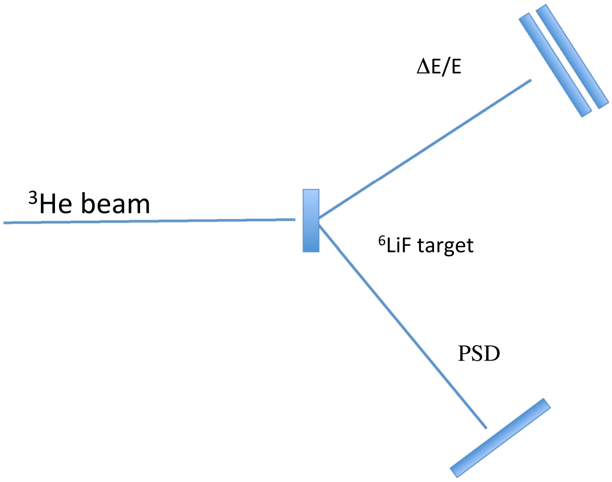

Fig. 2 Experimental set-up for the ^{6}Li(^{3}He,α^3He)^{2}H discussed in the text

^{3}He break-up after the ^{6}Li(^{3}He,α^3He)^{2}H QF reaction. The two different break-up processes are reported in Fig. 1.

The experimental study of the ^{6}Li(^{3}He,α ^{3}He)^{2}H reaction was performed at the Nuclear Physics Institute of ASCR in Rez, near Prague. A 25 MeV ^{3}He cyclotron beam was delivered onto an isotopically enriched lithium fluoride target (^{6}Li   95%). The experimental setup (see Fig. 2) consisted of a silicon ΔE-E telescope for ^{3}He identification, made up of 11.5 μm ΔE and 500 μm position-sensitive E-detector, placed at a distance d=20 cm from the target and of one silicon position sensitive detector (PSD) to discriminate α nuclei places at the same distance of the ΔE-E telescope from the target. They were placed on opposite sides with respect to the beam direction covering the laboratory angles 57.5°–70.9° and 59.3°–71.6°, respectively. The angular ranges were chosen in order to cover momentum values p_s of the undetected deuteron ranging from 0 MeV/c to about 100 MeV/c. This assures that the bulk of the QF contributions for the break-up process of interest falls inside the investigated regions, allowing also to cross check the method outside the relevant phase-space regions. The trigger for the event acquisition was given by the coincidences between the two telescopes. Energy and positions signals for the detected particles were processed by standard electronics together with the coincidence relative time. The data analysis is still being performed under the standard prescriptions of the THM [19].

A clear picture arise from this whole set of measurements. In all those cases the Trojan Horse Particle invariance has been verified thus testing, for an increasing number of cases the relatively simple theoretical approach used in the THM.

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