Trojan Horse particle invariance:the impact on nuclear astrophysics

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Abstract. In the current picture of nuclear astrophysics indirect methods and, in particular, the Trojan Horse Method cover a crucial role for the measurement of charged particle induced reactions cross sections of astrophysical interest, in the energy range required by the astrophysical scenarios. 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 key to the method is the quasi-free break-up and some of its properties will be investigated in the present work. In particular, the Trojan Horse nucleus invariance will be studied and previous studies will be extended to the cases of the binary d(d,p)t and ^{6}Li(d,α)^{4}He reactions, which were tested using different quasi-free break-up's, namely ^{6}Li and ^{3}He. The astrophysical S(E)-factor were then extracted with the Trojan Horse formalism applied to the two different break-up schemes and compared with direct data as well as with previous indirect investigations. The very good agreement confirms the independence of binary indirect cross section on the chosen spectator particle also for these reactions.

Keywords: nuclear astrophysics, cluster structure, indirect methods
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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. Among them an important role is played by the Trojan Horse Method (THM) which has been applied to several reactions in the past decade [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] 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 in the low-energy region of a two-body reaction with significant astrophysical impact:

$$a + x \rightarrow c + C \qquad (1)$$

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 [17].

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 [18], the spectator invariance [19, 20, 21] and the possible use of virtual neutron beams [22, 23]. In recent works [19, 20] 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 [20]. Agreement between the sets of data was found below and above the Coulomb barrier. The results already obtained are reported in table 1 with all the complete references.

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TABLE 1. Physical cases for which the Trojan Horse particle invariance was investigated. The relevant reference for each reaction is reported in the last column.

Quasi-free process	Binary reaction	Trojan Horse particle	ref.
^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He	^{6}Li(d,α)α	^{6}Li	[20]
^{6}Li(^{3}He,$\alpha\alpha$)H	^{6}Li(d,α)α	^{3}He	[20]
^{7}Li(d,$\alpha\alpha$)n	^{7}Li(p,α)α	d	[20, 22]
^{7}Li(^{3}He,$\alpha\alpha$)^{2}H	^{7}Li(p,α)α	^{3}He	[20, 22]
^{2}H(^{6}Li, pt)^{4}He	d(d,p)t	^{6}Li	[21]
^{2}H(^{3}He,pt)H	d(d,p)t	^{3}He	[21]

STUDY OF THE D(D,P)T REACTION

The idea of the present paper is to see whether the same can hold also for 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.

In Fig. 1, the different break-up schemes of interest are depicted. On the left side we report the QF break-up process which proceeds through ^{6}Li, while on the right it is portrayed the one which goes through ^{3}He. The two experiments

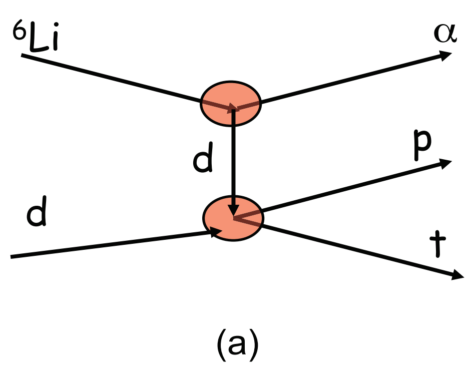

FIGURE 1. Sketch of the processes discussed in the text. Left (a): the quasi-free reaction involving the ^{6}Li break-up is shown. Right (b): the ^{3}He break-up is reported.

are discussed extensively elsewhere, in particular the ^{2}H(^{6}Li, pt)^{4}He reaction in [25, 21] and the ^{2}H(^{3}He,pt)H in [30]. In both cases the standard prescriptions of the THM, as discussed in [17, 24], to extract the energy trend of the S(E)-factor were applied. Therefore the binary cross section is extracted from the measured three-body one, in both experiments. The momentum distributions adopted for the data extractions were treated as prescribed in [27] and fitted with a Hänckel function for the ^{6}Li break-up (most suitable for the ^{6}Li case, as discussed in details in [26]) and with the Eckart function for the ^{3}He case.

The averaged results for the d(d,p)t reaction after ^{6}Li break-up (red dots, see [21] for details) are then compared with the ones extracted from ^{3}He break-up (see [30], blue triangles). Data, expressed in the form of the astrophysical S(E)-factor for the binary d(d,p)t reaction, were extracted from the measured three-body cross section according to the standard THM prescriptions [17] and in the framework of the Plane Wave Impulse Approximation. We can point out that the errors in the ^{6}Li break-up case are much larger than in the case of ^{3}He breakup. This is mainly due to the presence of the sequential mechanism in ^{7}Li, already discussed in [25] that decreases the number of the QF events. Also the normalization errors and errors connected to the penetrability factor are fully included in the error bar shown in the pictures. Polynomial fits were then performed on the data giving S_0= 75 $\pm$21 keV·b in the case of the ^{6}Li break-up, while for ^{3}He one obtains S_0= 58 $\pm$2 keV·b. The results are in agreement, within the experimental errors, also with previous direct measurements [28, 29]. Coherent results from both the considered break-up schemes (as in

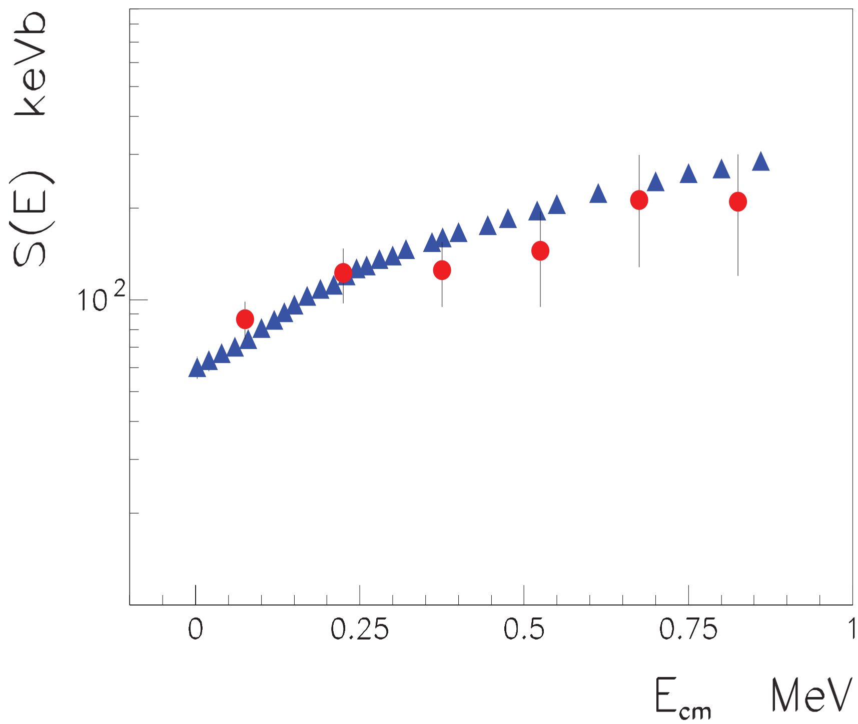

FIGURE 2. Averaged astrophysical S(E)-factor for the d(d,p)t reaction measured via THM after ^{6}Li break-up (dots) and after ^{3}He break-up(blue triangles), extracted from [30] clearly showing the Trojan Horse particle invariance. The polynomial fit to data from [30] is reported for comparison as a solid line.

figure 1) are achieved, not only in terms of the S(E)-factors but also for the electron screening effect.

STUDY OF ^{6}LI(D,α)^{4}HE

The present experiment was aimed to study the ^{6}Li(d,α)^{4}He reaction by means of the THM applied to the ^{6}Li(^{3}He,$\alpha\alpha$)H three-body reaction. The measured cross section, extracted by the THM, is compared in the $E_{cm} = 0.4 - 5$ MeV energy range with several data sets present extracted from ^{6}Li break-up (Figure 4). The agreement is very good throughout the whole energy range after a separate normalization of the indirect to direct data. Moreover the resonance at about 3 MeV (corresponding to the 25.2 MeV, 2^{+}, energy level in ^{8}Be) is clearly reproduced in the data set arising from ^{3}He break-up.

The investigation of this energy range is not relevant for astrophysical implications for the ^{6}Li depletion [5] but it provides a strong validity test for THM. In fact, as in the excitation function extracted in an indirect way does indeed reproduce the direct data both below and above the Coulomb barrier. Another interesting aspect of this analysis is the possibility to study the pole invariance of the quasi-free mechanism [19]. It is assumed, in fact, that changing the spectator particle in the quasi-free process (on which is founded the THM) does not give any change to the binary reaction of interest. This effect has been already explored in the case of the ^{7}Li(p,α)^{4}He reaction [19]. In the case of the ^{6}Li(d,α)^{4}He reaction we can see that in the energy range $0.4 - 1$ MeV we can compare data for the ^{6}Li(d,α)^{4}He arising from the ^{6}Li(^{3}He,$\alpha\alpha$)H reaction (present work) with the ones extracted from ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He [2, 18] (see Fig. 4). The agreement is very good within the experimental errors. This strengthen a lot the present knowledge of the Trojan Horse Method and makes the application of the method more straightforward even with a simplified approach.

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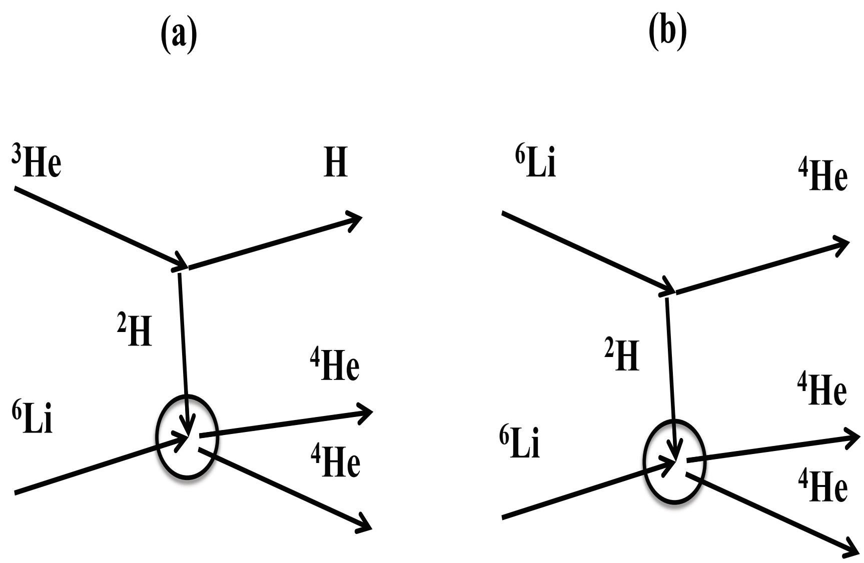

FIGURE 3. Sketch of the ^{6}Li(d,α)^{4}He processes discussed in the text. Left (a): the quasi-free reaction involving the ^{6}Li break-up is shown. Right (b): the ^{3}He break-up is reported.

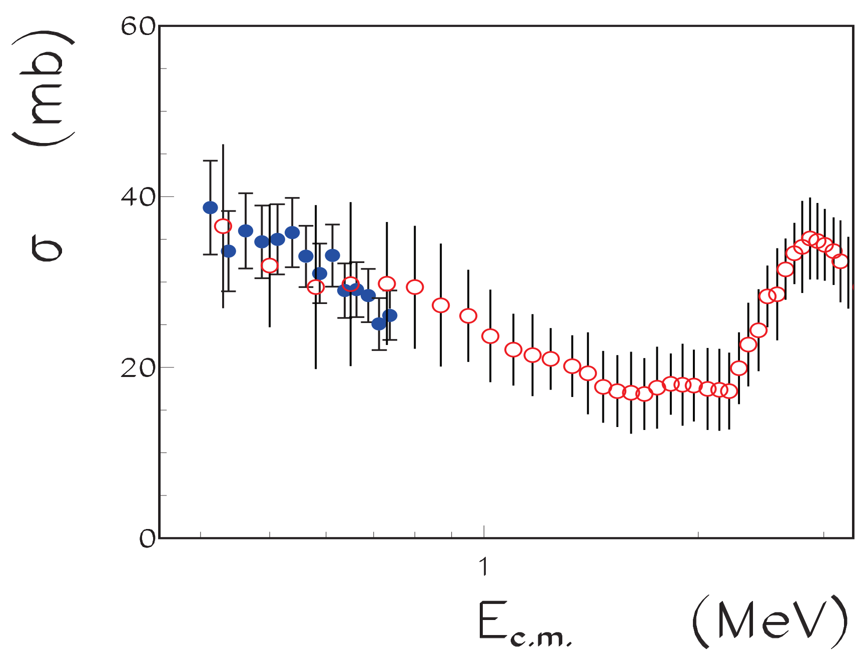

FIGURE 4. Excitation function for the ^{6}Li(d,α)^{4}He reaction extracted by means of THM. The indirect data (blue symbols) arising from ^{6}Li break-up are compared with those extracted from ^{3}He (red markers). The agreement is clearly within the experimental errors.

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