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# Updated evidences of the Trojan Horse particle invariance for ${}^2\text{H}(\text{d,p}){}^3\text{H}$ reaction

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The Trojan Horse nucleus invariance for the binary  $\text{d}(\text{d,p})\text{t}$  reaction was tested by means of new experiment using the quasi free  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  and  ${}^2\text{H}({}^3\text{He}, \text{pt})\text{H}$  reactions after  ${}^6\text{Li}$  and  ${}^3\text{He}$  break-up, respectively. The astrophysical  $S(E)$ -factor for the  $\text{d}(\text{d,p})\text{t}$  binary process was extracted from the present data in the framework of the Plane Wave Approximation applied to the two different break-up schemes. The obtained results are compared with direct data as well as with previous indirect investigations. The very good agreement confirms the applicability of the plane wave approximation and suggests the independence of binary indirect cross section on the chosen Trojan Horse nucleus also for the present case.

## I. INTRODUCTION

The study of nuclear reactions induced by charged particles at astrophysical energies has many experimental difficulties, mainly connected to 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 in nuclear astrophysics. Among the most used indirect methods, an important role is played by the Trojan Horse Method (THM) which has been applied to several reactions in the past decade [1–17] at the energies relevant for astrophysics (typically smaller than few hundred keV's), which usually are far below the Coulomb barrier, of the order of MeV's. 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] and the possible use of virtual neutron beams [21, 22]. Such studies are necessary, as the Trojan Horse method has become one of the major tools for the investigation of reactions of astrophysical interest (for recent reviews see [23, 24]). In recent works [19, 20] the spectator invariance was extensively examined for the  ${}^6\text{Li}({}^6\text{Li},\alpha\alpha){}^4\text{He}$  and the  ${}^6\text{Li}({}^3\text{He},\alpha\alpha)\text{H}$  case as well as the  ${}^7\text{Li}(\text{d},\alpha\alpha)\text{n}$  and  ${}^7\text{Li}({}^3\text{He},\alpha\alpha){}^2\text{H}$  reactions, thus comparing results arising from  ${}^6\text{Li}$  and  ${}^3\text{He}$  and deuteron and  ${}^3\text{He}$  break-up respectively [20]. Agreement between the sets of data was found below and above the Coulomb barrier. This suggests that  ${}^3\text{He}$  is a good “Trojan Horse nucleus”, in spite of its quite high  ${}^3\text{He}\rightarrow \text{d} + \text{p}$  break-up energy (5.49 MeV) and that the THM cross section does not depend on the chosen Trojan Horse nucleus, at least for the processes mentioned above.

In the present paper the TH nucleus invariance will be investigated for the  ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$  reaction using the most recent data and all available experimental THM data. The  $S(E)$ -factor measured for the  ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$  reaction through  ${}^3\text{He}$  break-up in the  ${}^2\text{H}({}^3\text{He},\text{pt})\text{H}$  interaction will be compared with the  $S(E)$ -factor for the same binary reaction obtained through  ${}^6\text{Li}$  break-up in the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  process. Our aim is to show that in both cases the Plane Wave Impulse Approximation (PWIA) is valid and that the use of a different spectator particle does not influence the THM reliability, in a new case that confirms what was already observed in [20] for other reactions of astrophysical interest.

## II. THE METHOD

The THM was successfully applied to study several two-body reactions relevant for astrophysical applications by using appropriate three-body break-up reactions. The method has proven to be particularly suited for acquiring information on charged as well as neutral particle induced reaction cross-sections at astrophysical energies, since it allows to overcome, in the case of charged-particle induced reactions, the Coulomb-barrier of the two-body entrance channel. 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. 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:



from a suitable three-body QF reaction



Referring to Fig. 1, the assumption is that of an interaction between the impinging nucleus and one of the clusters constituting the target (called participant  $x$ , deuteron in the present case), while the residual nucleus does not participate in the reaction (spectator  $s$ ,  ${}^4\text{He}$  or  $p$  in the two different cases). The latter is free from any effect due to the interaction between the incoming nucleus and the participants, reflecting in the exit channel the same momentum distribution, for the inter-cluster ( $x$ - $s$ ) motion inside  $b$ , it had before the occurrence of the QF break-up.

QF processes are direct mechanisms in which the interaction between an impinging nucleus and the target can cause the target break-up (TBU) or of the projectile break-up (PBU). In particular, these processes have three particles in the exit channel, one of which can be thought as a spectator to the binary interaction of interest.

Under appropriate kinematical conditions, the three-body reaction  $a(b, cC)s$  is considered as the decay of the ‘‘Trojan Horse’’  $b$  into the clusters  $x$  and  $s$  followed by the interaction of  $a$  with  $x$ . If the bombarding energy  $E_a$  is chosen high enough to overcome the Coulomb barrier in the entrance channel of the reaction, the effect of the Coulomb barrier and electron screening effects are negligible.

The application of the THM significantly simplifies if the PWIA is valid. In this approach the triple differential cross section in the center-of-mass of the TH reaction can be written as

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \cdot |\Phi(p_{sx})|^2 \cdot \sum_{l_l} |L_{l_l}|^2 \left( \frac{d\sigma_{l_l}}{d\Omega_{cm}} \right)^{HOES} \quad (3)$$

where:

- $l_l$  is the orbital angular momentum of particles  $s$  and  $x$  in the entry channel of the binary subreaction and  $L_{l_l}$  is a function of relative momentum and kinetic energy in the entry channel of the binary subreaction as defined in [25];
- $[(d\sigma_l/d\Omega)_{cm}]^{HOES}$  is the half-off-energy-shell (HOES) differential cross section for the two body reaction at the center of mass energy  $E_{cm}$  given in post collision prescription by:

$$E_{cm} = E_{c-C} - Q_{2b} \quad (4)$$

where  $Q_{2b}$  is the two body Q-value of the binary process and  $E_{c-C}$  is the relative energy between the outgoing particles;

- 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  $\chi(r)$  for the x-s inter-cluster motion, usually described in terms of Hänkel, Eckart and Hultheñ functions depending on the x-s system properties.

The success of the THM relies on the QF kinematics (equivalent to  $p_{sx} \sim 0$  for nuclei like  ${}^3\text{He}$  or  ${}^2\text{H}$  where the dominant wave of the intercluster relative motion is  $l=0$ ), at which the TH conditions are best fulfilled. The occurrence of the QF mechanism at low energies has been pointed out in a number of papers [1, 26–28]. We will see how applying the conditions on the momentum distribution of the spectator, as discussed in Ref. [29], we can use the quite simple approach. This was already observed for the first time in Ref. [30]. It has also been verified that for spectator momenta around zero the PWIA gives results similar to those obtained by more complicate approaches, as reported in Ref. [31].

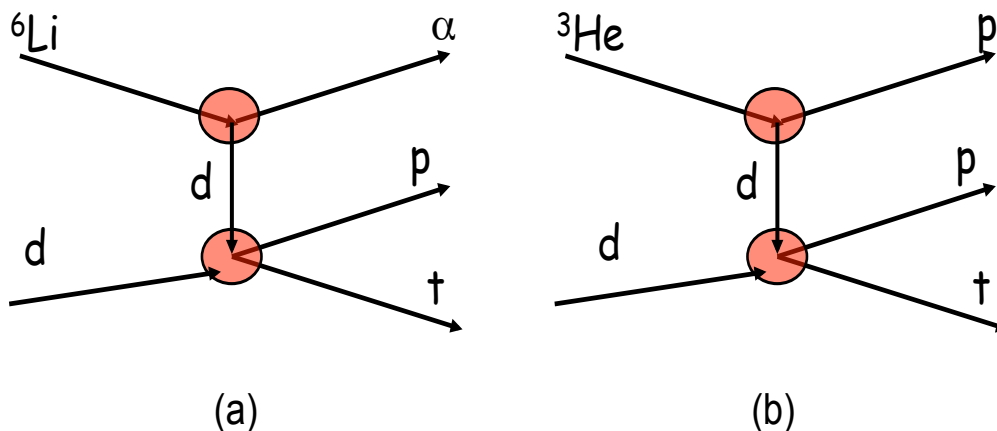


FIG. 1. (Color online) Sketch of the processes discussed in the text. Left (a): the quasi-free reaction involving the  ${}^6\text{Li}$  break-up is shown. Right (b): the  ${}^3\text{He}$  break-up is reported.

The TH triple differential cross section can be written in a factorized form, as in eq. 3 in terms of the 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. 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 [19, 20] for the two examined cases. Here the same methodology is applied to the  ${}^3\text{He}$  break-up in the  ${}^2\text{H}({}^3\text{He},\text{pt})\text{H}$  interaction that will be compared with the same binary reaction obtained through  ${}^6\text{Li}$  break-up in the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  process. In figure 1 the two studied processes are sketched: in the (a) panel the  ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$  reaction studied through the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  process is shown while in the (b) panel the same reaction is studied through the  ${}^2\text{H}({}^3\text{He},\text{pt})\text{H}$  interaction.

### III. THE EXPERIMENT

The study of the quasi-free reaction  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  for the THM application was performed in the Tandem-Dynamitron Laboratorium of the Ruhr Universität Bochum for a preliminary run. The results are presented in [32]. A second experimental run, on which the

TABLE I. Experimental details of the set-up described in the text.

Detector	angular range (deg)
PSD <sub>1</sub>	42-54
PSD <sub>2</sub>	18-28
PSD <sub>3</sub>	42-54
PSD <sub>4</sub>	105-115

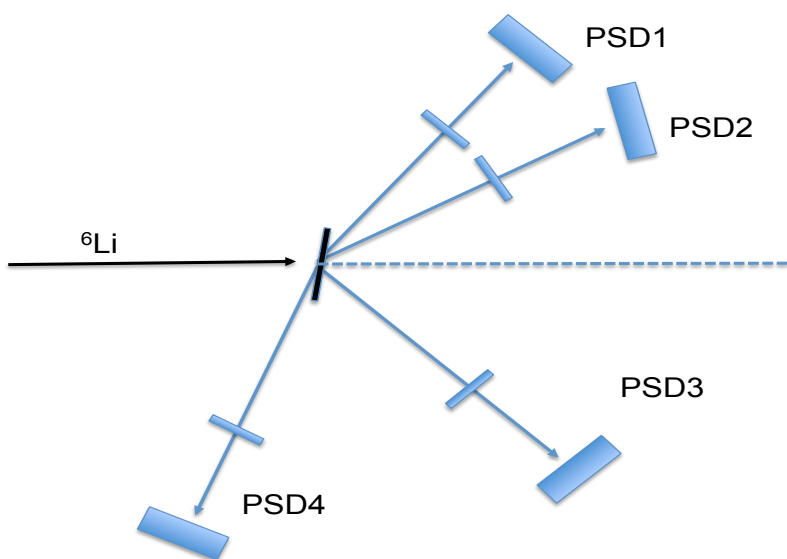


FIG. 2. (Color online) Sketch of the experimental set-up discussed in the text.

present paper is focused, was then performed at the INFN - LNS - Catania. In particular, in this second run, the number of detectors was increased to improve the statistics and also the larger dimensions of the “CAMERA 2000” scattering chamber (2 m diameter) allowed for an improved angular resolution. The experimental set-up is described in figure 2: four PSD’s were placed at angles corresponding to the quasi-free regions (see table I for the details). The  ${}^6\text{Li}$  beam (intensity  $2\div 5$  pA and energy  $E_{Li}=14$  MeV) provided by the INFN - LNS - Catania Tandem impinged on a deuterated polyethylene foil ( $\approx 170 \mu\text{g}/\text{cm}^2$  thick). The beam-spot on target was around 1 mm while the target was tilted 12 degrees with respect to the beam axis. In front of each PSD a silicon detector ( $15 \mu\text{m}$  thick) was placed to allow  $\Delta E/E$  particle identification.

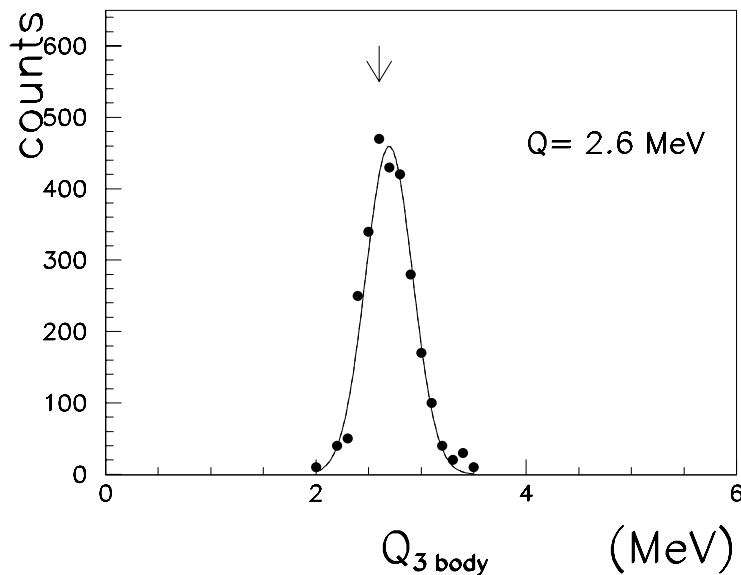


FIG. 3. Q-value for the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  reaction after kinematical reconstruction. The peak around 2.6 MeV is a clear signature of the good calibration of detectors as well as of the correct identification of the reaction channel. The solid line represents the gaussian fit to the data.

#### IV. DATA ANALYSIS AND RESULTS

The position and energy calibration of the detectors involved were performed by using data from different scatterings and reactions on different targets, induced at a beam energy of 4 MeV, 7 MeV and 14 MeV. A standard alpha-source of 5.48 MeV was also used. Since position and energy of the two ejectiles were measured, the complete kinematics of the reaction was determined allowing to extract information on the energy, momentum and angle of the third undetected particle.

After detectors calibration, protons and tritons were identified by means of the  $\Delta E/E$  technique. Once selecting  $p$  and  $t$  on the two detectors, the Q-value of the three body reactions was extracted, as reported in figure 3. Events below the peak, whose centroid is at about 2.6 MeV (in good agreement with theoretical prediction,  $Q=2.56$  MeV) are produced by the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  reaction and have been selected for further analysis. As in all standard THM analysis the next step is to identify and separate the quasi-free mechanism from all the other processes occurring in the target and we refer for further details to [33]. This is usually done by recalling the definition of a QF reaction, i.e. a reaction where the third particle



(spectator) retains the same momentum it had in the entrance channel, i.e. within the Trojan Horse nucleus ( $^3\text{He}$  in our case). In fact, among all the available observables, the most sensitive to the involved reaction mechanisms is the shape of the momentum distribution  $|\varphi(p_{sx})|^2$ . According to the prescriptions in [34–36], the momentum distribution of the third and undetected particle will be examined. This gives a major constraint for the presence of the quasi-free mechanism and the possible application of the THM. In order to extract the experimental momentum distribution of the spectator,  $\varphi(p_{sx})_{exp}^2 = \varphi(p_s)_{exp}^2$  in the system where the Trojan Horse particle  $b$  is at rest, the energy sharing method can be applied to each pair of coincidence detectors, selecting narrow energy and angular windows,  $\Delta E_{cm}$  and  $\Delta\theta_{cm}$ . The center-of-mass angle,  $\theta_{cm}$ , is defined according to [37]. Keeping in mind the factorization of Eq. 3, since  $[(d\sigma/d\Omega)_{cm}]^{HOES}$  is nearly constant in a narrow energy and  $\theta_{cm}$  window, one can obtain the shape of the momentum distribution of the undetected proton directly from the coincidence yield divided by the kinematical factor.

The obtained momentum distribution is reported in figure 4 where it is compared with the theoretical prediction of the spectator momentum distribution, obtained using the Woods-Saxon potential with the standard geometrical parameters reported in [36]. An evident distortion of the momentum distribution shows up and its measured full width at half maximum turns out to be around 47 MeV/c which is much smaller than the expected prediction of 72 MeV/c. This evidence was already observed for  $^6\text{Li}$  as well as for other isotopes in [35, 36] where the width of the momentum distribution for the spectator inside the Trojan Horse nucleus was studied as a function of the transferred momentum from the projectile  $a$  to the center-of-mass of the final system  $B = C + c$ . This can be written as the Galilean invariant quantity following the approach of [35, 36]. In the present case the value of  $q_t$  is about 150 MeV; the present result is then compared with the data from [35, 36] in figure 5. A clear agreement is present both with the other experimental data as well as with the curve which represents the best fit to the function reported in [35].

The next step is to apply the standard procedure of the THM, as discussed in [24], to extract the energy trend of the S(E)-factor. Therefore equation 3 is applied allowing the extraction of the binary cross section from the measured three-body one. The sequential mechanisms and their contributions were treated as in [32] and the Coulomb penetration factor was calculated following [32].

The results for the d(d,p)t reaction, in terms of the bare nucleus astrophysical S(E)-factor

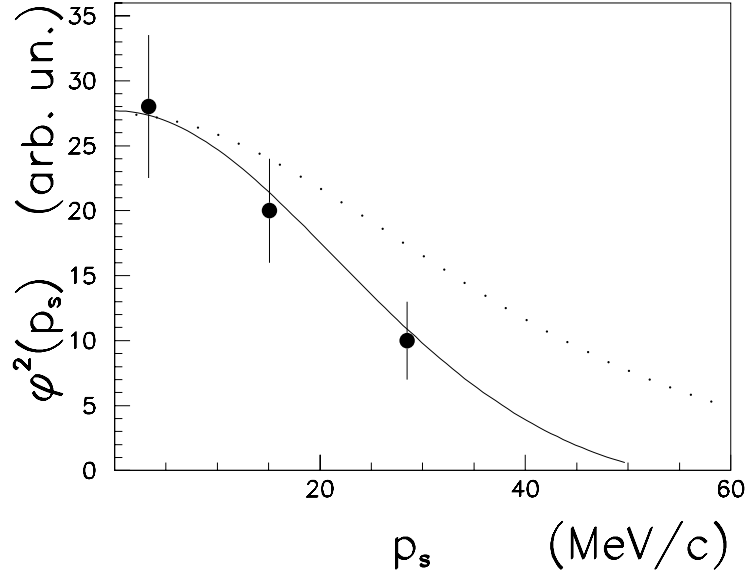


FIG. 4. Momentum distribution for the intercluster motion of deuteron inside  ${}^6\text{Li}$  for the  ${}^2\text{H}({}^6\text{Li}, \text{pt}){}^4\text{He}$  case. The fit to the experimental data is reported for comparison. The dotted line represents the theoretical calculation discussed in the text.

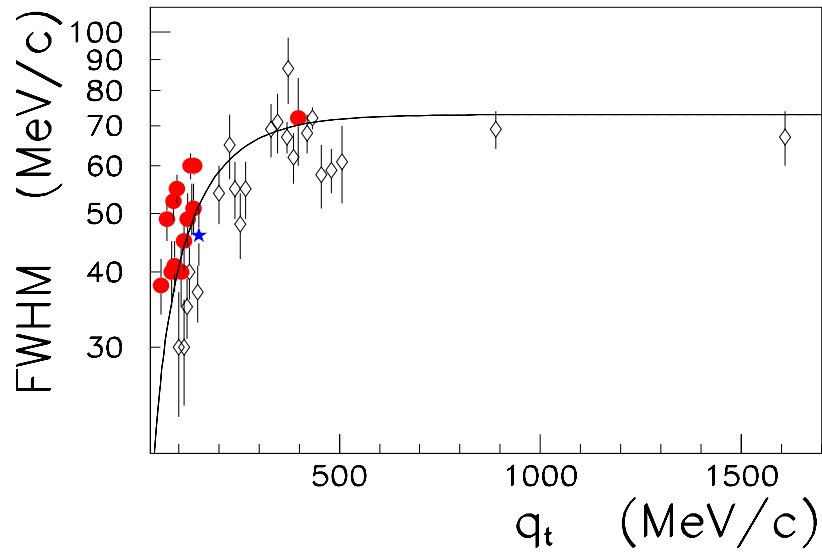


FIG. 5. (color online) Momentum distribution width for the deuteron inside  ${}^6\text{Li}$  as a function of the transferred momentum as reported in [35]. The present result is marked as a blue star, red dots mark results from [35], diamonds results from [34] and the line represents the best fit reported in [35].

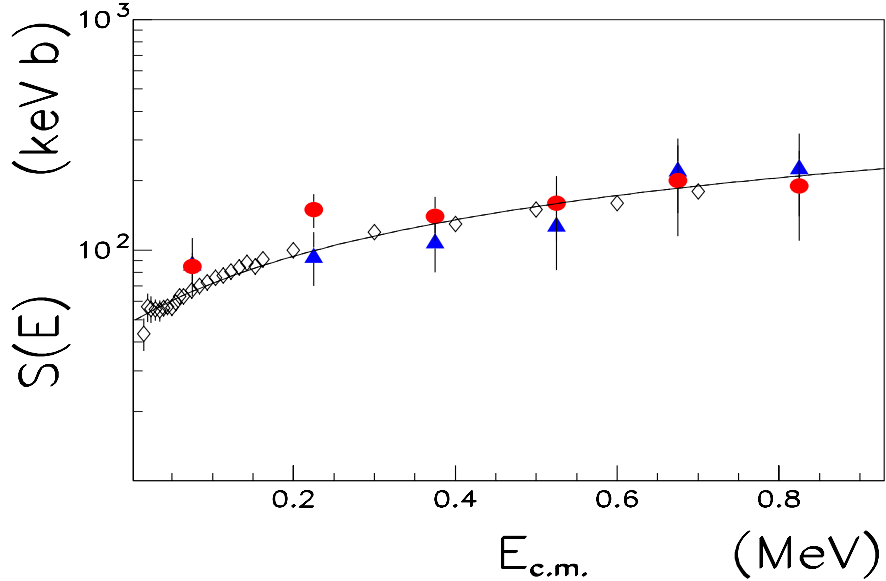


FIG. 6. (color online) Astrophysical  $S(E)$ -factor for the  $d(d,p)t$  reaction measured via THM after  ${}^6\text{Li}$  break-up. The blue points represent the data extracted in the present work, while the red ones refer those reported in [32]. Both data sets are normalized to the direct data from [38, 39] (diamonds). The polynomial fit to the direct data is given as a dashed line.

are presented in figure 6 (blue points) after normalization with direct data (red points, [38, 39]). We point out that direct data suffer from the electron screening effect which does not affect the THM results. The data from the present experiment (blue points) are compared with those arising from  ${}^6\text{Li}$  breakup in a previous experimental run (black points), and already published in [32]. An overall agreement is present among both indirect and direct data sets, within the experimental errors.

The two data sets obtained via THM applied to the  ${}^2\text{H}({}^6\text{Li}, p){}^4\text{He}$  reaction were then averaged, after weighting over the errors and the result is shown in figure 7 as a function of the energy (black points). The averaged results are then compared with the THM results for the  $d(d,p)t$  reaction from  ${}^3\text{He}$  break-up as reported in [40] (red triangles). We can point out that the errors in the present case are much larger than in the case of  ${}^3\text{He}$  breakup. This is mainly due to the presence of the sequential mechanism in  ${}^7\text{Li}$ , already discussed in [32] 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. A polynomial fit was then performed on the averaged data giving  $S_0 = 75 \pm 21$

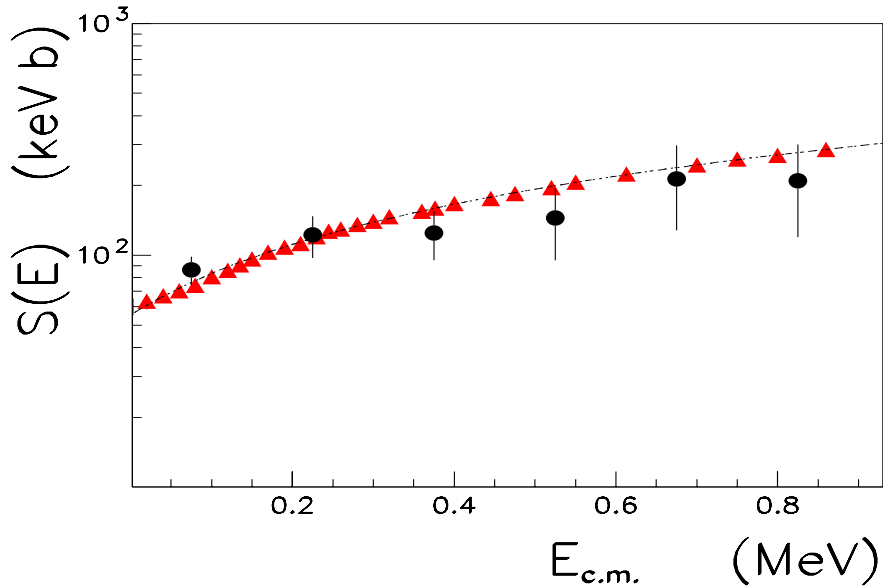


FIG. 7. (color online) Averaged astrophysical  $S(E)$ -factor for the  $d(d,p)t$  reaction measured via THM after  ${}^6\text{Li}$  break-up (black dots) and after  ${}^3\text{He}$  break-up (red points), extracted from [40] clearly showing the Trojan Horse particle invariance. The polynomial fit to data from [40] is reported for comparison as a solid line.

keV·b in agreement, within the experimental errors, with previous THM results. The full polynomial parameterization of the  $S(E)$  factor in function of the energy (in units of MeV) gives:

$$S(E) = 75 + 148.4 \cdot E + 14.6 \cdot E^2 \quad (5)$$

expressed in keV·b.

Thus we find that, also in the present case, data extracted via the THM applied to the  ${}^6\text{Li}$  and  ${}^3\text{He}$  break-up are comparable among themselves and that the THM shows Trojan Horse particle invariance also in the case of the  $d(d,p)t$  reactions. This confirms in an additional and independent case what was already observed in [20] for the  ${}^6\text{Li}(d,\alpha){}^4\text{He}$  and the  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  reactions.

## V. CONCLUSIONS

A full investigation of the  ${}^2\text{H}({}^6\text{Li}, p){}^4\text{He}$  reaction is presented in the present paper. The QF contribution is extracted and the THM applied to retrieve information on the

astrophysical  $S(E)$ -factor for the  $d(d,p)t$  reaction. A good agreement with the direct data is achieved in the whole energy range. The present result is then compared with data from  ${}^3\text{He}(d, pt)\text{H}$  reaction to confirm also for the  $d(d,p)t$  case the evidence of the TH nucleus invariance at energies above and below the Coulomb barrier. As for the  ${}^6\text{Li}(d,\alpha){}^4\text{He}$  and the  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  reactions [20] we conclude that the PWIA is valid in all these cases and that the use of a different spectator particle does not influence the THM results also in this further case.

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