Beam-energy dependence and updated test of the Trojan-horse nucleus invariance via a measurement of the $^2H(d,p)^3H$ reaction at low energies

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The $^2H(d,p)^3H$ bare nucleus astrophysical $S(E)$ factor has been measured indirectly at energies from about 500 keV down to several keV by means of the Trojan-horse method applied to the $^2H(^6Li,pt)^4He$ quasifree reaction induced at 11 MeV. The obtained results are compared with direct data as well as with previous indirect investigation of the same binary reactions. It shows that the precision of $S(E)$ data in the low-energy range extracted via the same Trojan-horse nucleus [$^6Li = (d \oplus \alpha)$] increases while the incident energy of the virtual binary process approaches the zero-quasi-free-energy point. The very good agreement between data extracted from different Trojan-horse nuclei [$^6Li = (d \oplus \alpha)$ vs $^3He = (d \oplus p)$] gives a strong updated test for the independence of the binary indirect cross section on the chosen Trojan-horse nucleus at low energies.

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I. INTRODUCTION

In recent decades, improvements in the field of astrophysics observation and models have triggered nuclear reaction measurements at astrophysical energies [1,2]. Because of their crucial role in understanding the first phases of the universe history and the subsequent stellar evolution, cross sections at the Gamow energy E_G should be known with increased accuracy. For example, the important $d + d$ nuclear reaction, in which we are interested in this work, takes place at an ultralow energy of about several keV to 300 keV in astrophysical environment: The region of interest ranges from 50 to 300 keV for the standard Big Bang nucleosynthesis, and it is only from a few to 20 keV for stellar evolution processes.

For charged-particle-induced reactions, the Coulomb barrier E_C, usually of the order of MeV, is much higher than E_G (typically smaller than few hundred keV), thus implying that as the energy is lowered the reactions take place via tunneling with an exponential decrease of the cross section. The direct measurement of nuclear reactions induced by charged particles at astrophysical energies has many experimental difficulties. The difficulties mainly come from the presence of the strong Coulomb suppression and of the electron screening effect which would lead to a screened cross section larger than the bare nucleus one at ultralow energies.

To overcome these difficulties, many efforts were devoted to the development and application of indirect methods in nuclear astrophysics. Among the most-used indirect methods, the Trojan-horse method (THM) [3–5] plays an important role and it has been applied to several reactions at the energies relevant for astrophysics in the past decade [5–24].

Many tests have been made to fully explore the potential of the method and extend as much as possible its applications: the target-projectile breakup invariance, the spectator invariance, and the possible use of virtual neutron beams. An important feature of the THM is that it can give good results if applied to radioactive ion beams [9,10]. Such studies are necessary, because the Trojan horse method has become one of the major tools for the investigation of reactions of astrophysical interest.

In recent works [12], the spectator invariance was extensively examined for the $^6Li(^6Li,\alpha\alpha)^4He$ and the $^6Li(^3He,\alpha\alpha)^1H$ case as well as for the $^7Li(d,\alpha\alpha)n$ and $^7Li(^3He,\alpha\alpha)^2H$ reactions, thus allowing comparison of results arising from $^6Li = (d \oplus \alpha)$ and $^3He = (d \oplus p)$ breakup to provide virtual d, and $d = (p \oplus n)$ and $^3He = (p \oplus d)$ breakup

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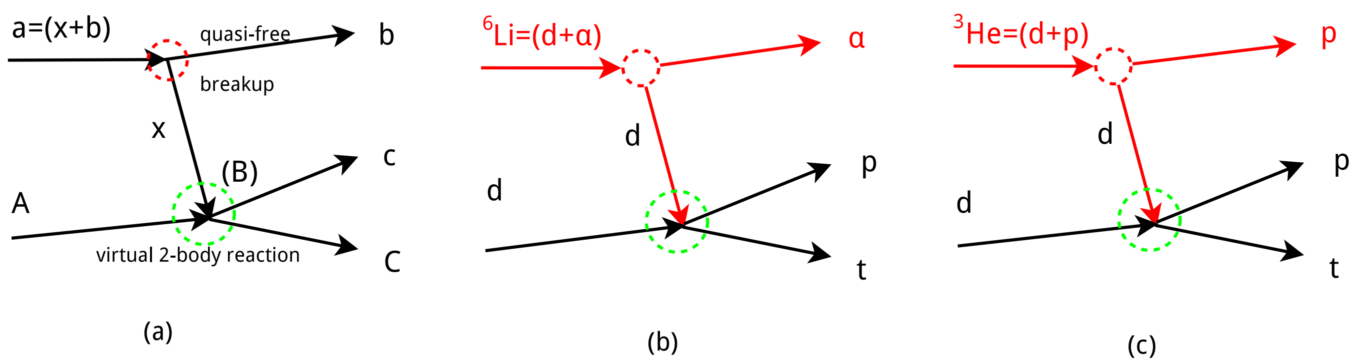

FIG. 1. The schematic representation of Trojan-horse method. (a) Normal, (b) TH: ^{6}Li, and (c) TH: ^{3}He.

to provide virtual p, respectively. Agreement between the sets of data was found below and above the Coulomb barrier. This suggests that ^{3}He is a good Trojan horse nucleus in spite of its quite high $^3\mathrm{He} \rightarrow d + p$ breakup 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.

The Trojan-horse method has also been applied to the indirect study of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction using $^6\mathrm{Li} = (d \oplus \alpha)$ [13,14] and $^3\mathrm{He} = (d \oplus p)$ breakup [15] to test the Trojan-horse nucleus invariance, but the ^{6}Li breakup data give fewer points and larger errors than that in the case of ^{3}He breakup. The Trojan-horse nucleus invariance cannot be well confirmed for this case with such big errors. In our previous paper [16], it gives a better result for the $S(E)$ factor using a lower beam energy.

In this paper, we report on a new investigation of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction by means of the THM applied to the $^2\mathrm{H}(^6\mathrm{Li},pt)^4\mathrm{He}$ quasifree process with the beam energy of 11 MeV. This makes the quasifree virtual binary process incident energy E_{dd}^{qf} go to the middle range of that in Ref. [14] with a larger beam energy of 14 MeV and that in Ref. [16] with a lower beam energy of 9.5 MeV. We will study the dependence of the $S(E)$ data precision on the incident beam energy for the same Trojan-horse nucleus compared with previous experiments. And at last, an updated test will be given to the Trojan-horse nucleus invariance for the case of $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction at low energies [Figs. 1(b) and 1(c)].

II. TROJAN-HORSE METHOD

The Coulomb barrier and electron screening cause difficulties in directly measuring nuclear reaction cross sections of charged particles at astrophysical energies. To overcome these difficulties, the THM has been introduced as a powerful indirect tool in experimental nuclear astrophysics. The THM provides a valid alternative approach to measure unscreened low-energy cross sections of charged particle reactions. It can also be used to retrieve information on the electron screening potential when ultra-low-energy direct measurements are available.

The basic assumptions of the THM theory have been discussed extensively in Refs. [4–8], and the detailed theoretical derivation of the formalism employed can be found in Ref. [4].

A schematic representation of the process underlying the THM is shown in Fig. 1. The method is based on the quasifree (QF) reaction mechanism, which allows one to derive indirectly the cross section of a two-body reaction,

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

from the measurement of a suitable three-body process under the quasifree kinematic conditions,

$$A + a \rightarrow C + c + b, \tag{2}$$

where the nucleus a is considered to be dominantly composed of clusters x and b [$a = (x \oplus b)$].

After the breakup of nucleus a due to the interaction with nucleus A, the two-body reaction [Eq. (1)] occurs between nucleus A and the transferred particle x whereas the other cluster b behaves as a spectator. The energy in the entrance channel E_{Aa} is chosen above the height of the Coulomb barrier $E_{Aa}^{C.B.}$, so as to avoid the reduction in cross section.

At the same time, the effective energy E_{Ax} of the reaction between A and x can be relatively small, mainly because the energy E_{Aa} is partially used to supply the binding energy ε_a of x inside a for the breakup to take place [Eq. (3)], and the Fermi motion of x inside a, E_{xb}, is used to span the region of interest around E_{Ax}^{qf}:

$$E_{Ax}^{qf} = E_{Aa}\left(1 - \frac{\mu_{Aa}}{\mu_{Bb}}\frac{\mu_{bx}^2}{m_x^2}\right) - \varepsilon_a. \tag{3}$$

Since the transferred particle x is hidden inside the nucleus a (so called Trojan-horse nucleus), it can be brought into the nuclear interaction region to induce the two-body reaction $A + x$, which is free of Coulomb suppression and, at the same time, not affected by electron screening effects.

Thus, the two-body cross section of interest can be extracted from the measured quasifree three-body reaction by inverting the following relation:

$$\frac{d^3\sigma}{dE_{Cc}d\Omega_{Bb}d\Omega_{Cc}} = K_F|W|^2\frac{d\sigma}{d\Omega}^{TH}, \tag{4}$$

where K_F is the kinematical factor, $|\mathrm{W}|^2$ is the momentum distribution of the spectator b inside the Trojan-horse nucleus a, and $d\sigma/d\Omega^{TH}$ is the half-off-energy-shell (HOES) cross section of the two-body reaction $A + x \to C + c$:

$$\frac{d\sigma}{d\Omega}^{TH} = \sum_l C_l P_l \frac{d\sigma_l}{d\Omega}(Ax \to Cc), \quad (5)$$

where $\frac{d\sigma_l}{d\Omega}(Ax \to Cc)$ is the real on-energy-shell cross section of the two-body reaction $A + x \to C + c$ for the l partial wave, P_l is the Coulomb penetration factor, and C_l is a scaling factor.

The relevant two-body reaction cross section can be extracted from the measured three-body cross section after selecting quasifree events. Then, the $S(E)$ factor can be determined from the definition below, where the Sommerfeld parameter is $\eta = Z_1 Z_2 e^2/(4\pi\epsilon_0 \hbar v)$:

$$S(E) = \sigma(E) E \exp(2\pi\eta). \quad (6)$$

The lack of screening effects in the THM $S_{\text{bare}}(E)$ factors gives the possibility to return the screening potential U_e from comparison with direct data using the following screening function with U_e as free parameter.

$$f_{\text{lab}}(E) = \sigma_s(E)/\sigma_b(E) \simeq \exp(\pi\eta U_e/E). \quad (7)$$

III. EXPERIMENT

The measurement of the ^{2}H(^{6}Li$\,,pt$)^{4}He reaction was performed at the Beijing National Tandem Accelerator Laboratory at the China Institute of Atomic Energy. The experimental setup was installed in the nuclear reaction chamber at the R60 beam line terminal as shown in Fig. 2. The ^{6}Li^{2+} beam at 11 MeV provided by the HI-13 tandem accelerator was used to bombard a deuterated polyethylene target CD_2, where "D" denotes "^{2}H." The thickness of the target was about 160 μg/cm^2. In order to reduce the angle uncertainty coming from the large beam spot, a strip target with 1 mm width was used.

A position-sensitive detector PSD_1 was placed at $40^\circ \pm 5^\circ$ with respect to the beam line and about 238 mm from the target to detect the outgoing triton (t), and another detector PSD_2 was used at $78^\circ \pm 5^\circ$ at opposite side with respect to the beam line at 245 mm from the target to detect the outgoing proton (p). The arrangement of the experimental setup was modeled with a Monte Carlo simulation in order to maximize the quasifree contribution to the total reaction yield. A PSD_m was placed at $32^\circ \pm 5^\circ$ opposite to PSD_1 as a monitor. It was important to achieve good angular and energy resolution. This was crucial for quasifree mechanism identification and selection. The energy resolution of the PSDs was about 0.6–0.8% for 5.48-MeV α source. The position resolution of PSDs was about 0.5 mm.

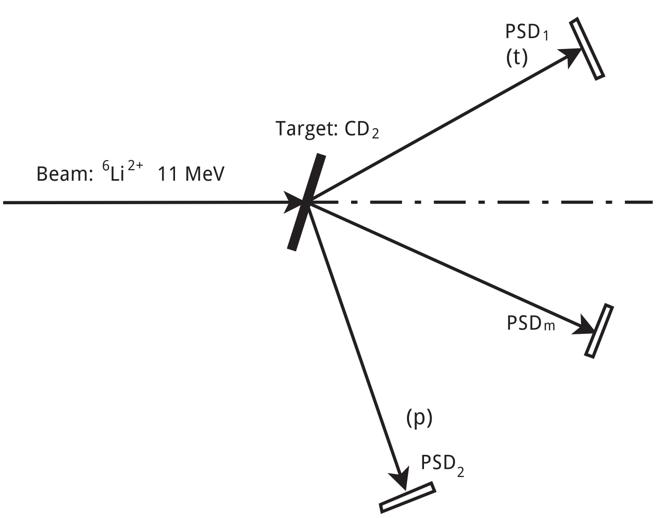

FIG. 2. Experiment setup of the ^{2}H(^{6}Li$\,,pt$)^{4}He reaction measurement.

In order to avoid a large energy loss in the target and angular straggling of the outgoing particle detected in PSD_2 with a big angle of about 78°, the target was put not perpendicular to the incident beam but at an angle about 20° tilted to the PSD_2 side. Thus, the path lengths of two outgoing particles passing through the target are similar for the two detectors PSD_1 and PSD_2.

No ΔE detector was mounted since no particle identification was needed in the experiment. It was beneficial to improve the energy and angular resolution without additional straggling of energies and angles when particles passing through these detectors. Events for the reaction of interest were selected from the kinematical locus in data analysis with the help of simulation.

The trigger for the event acquisition can be represented as $\text{Gate} = PSD_1 \times (PSD_2 + PSD_m)$. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system MIDAS for on-line monitoring and data storage for off-line analysis.

The position and energy calibrations of the detectors were performed using elastic scatterings on different targets (^{197}Au of 90 μg/cm^2, ^{12}C of 27 μg/cm^2, and CD_2) induced by a proton beam at energies of 6, 7, and 8 MeV. A standard α source of 5.48 MeV was also used. In order to perform position calibration, a grid with a number of equally spaced slits was placed in front of each PSD for calibration runs.

The total time of the ^{2}H(^{6}Li$\,,pt$)^{4}He reaction cross-sectional measurement was about 18 h (shorter than the 9.5-MeV runs, which were about 30 h). The average beam current was about 8 pnA. The average raw event rate was about 18.7 event/s PSD_1, 6.8 event/s PSD_2, 14.5 event/s PSD_m, and 37.6 event/s trigger. The dead time of detectors and electronics was about 3 μs. The live time was almost equal to the raw total time. The random events could be neglected.

IV. DATA ANALYSIS AND RESULTS

After the calibration of the detectors, the energy and momentum of the third undetected particle (α) were reconstructed from the complete kinematics of the three-body reaction $^6\text{Li} + d \to t + p + \alpha$, under the assumption that the first particle is a triton (detected by PSD_1) and the second one is a proton (detected by PSD_2). The detailed data analysis for the 9.5-MeV runs is reported in Ref. [16], and the method is similar for the 11-MeV runs.

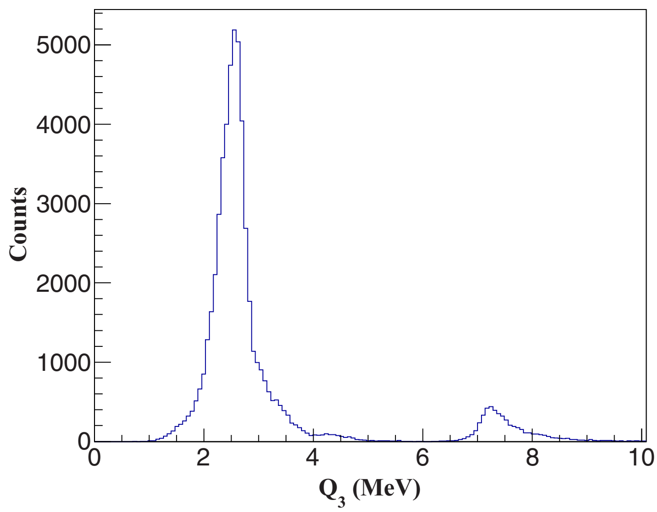

FIG. 3. Experimental Q_3 value spectrum for the 11-MeV runs with events from the kinematic locus cuts. The peak around 2.5 MeV is in good agreement with the theoretical value of $^2H(^6Li,pt)^4He$ ($Q = 2.558$ MeV).

A. Selection of the quasifree three-body reaction events

The first step of data analysis is to select the three-body reaction events of $^2H(^6Li,pt)^4He$. This can be easily done comparing the Monte Carlo simulation of the $^2H(^6Li,pt)^4He$ three-body reaction with the experimental spectrum of the $E_1 - E_2$ kinematic locus [16]. Events thus identified were selected by means of a graphical cut. It will be used as a basic selection cut in the following data analysis.

Once selected the three-body reaction events of $^2H(^6Li,pt)^4He$, the experimental Q_3 value was extracted and shown in Fig. 3. A peak centered at about 2.5 MeV shows up (in good agreement with the theoretical prediction, $Q = 2.558$ MeV). It is a clear signature of the good calibration of detectors as well as of the correct identification of the reaction channel. Only events inside the 2.5-MeV Q-value peak were considered for the further analysis.

As a cross-check, the mass of the undetected particle m_3 can be extracted following the method described in Ref. [25]. A m_3 spectrum can be obtained (shown in Fig. 4) when the theoretical value $Q_3 = 2.558$ MeV is assumed with the cuts selected as above for the three-body reaction events of $^2H(^6Li,pt)^4He$. It is clear that $m_3 \simeq 4$ agrees with α. Once given the Q_3 and m_3 value, the mass of the two detected particles can be calculated by the kinematic relations with the cuts selected as above. The calculated mass spectrum was added to Fig. 4. The mass number of the first particle $m_1 \simeq 3$ agrees with triton (t), and the second one $m_2 \simeq 1$ agrees with proton (p), according to the assumption. This is a good test of particle identification with kinematics.

The obtained momentum distribution, which is similar to the one reported in Ref. [16] gives a main test for the presence of the quasifree mechanism and the possible application of the THM. For the further analysis, the condition of $|p_s| < 20\,\mathrm{MeV/c}$ was added to the above cuts to select the quasifree events of the three-body reaction.

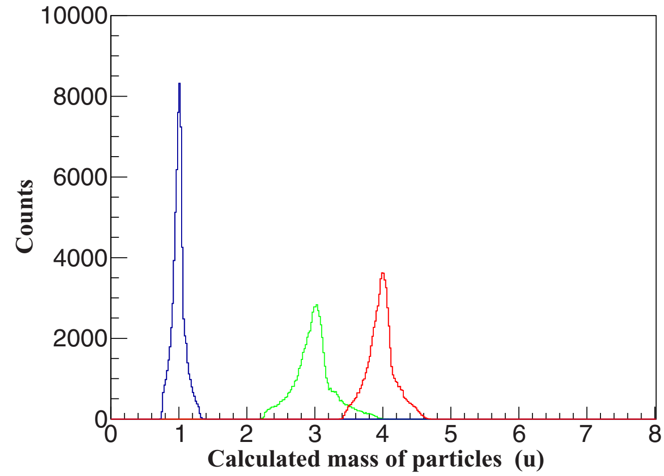

FIG. 4. Calculated mass spectrum of the three outgoing particles. Green: $m_1 \simeq 3$ (t), blue: $m_2 \simeq 1$ (p), and red: $m_3 \simeq 4$ (α).

B. Results and discussion: $S(E)$ factor

After selecting the quasifree three-body reaction events, the energy trend of the $S(E)$ factor for the two-body reaction $^2H(d,p)^3H$ was extracted by means of the standard procedure of the THM [16] and normalized to direct data. It should be pointed out that direct data suffer from the electron screening effect which does not affect the THM results. Thus, the $S(E)$ factor extracted via THM is called $S_{\mathrm{bare}}(E)$. In addition, U_e can be extracted as in Ref. [16] by comparing THM data with direct ones. The normalization was performed in the energy range where the electron screening effect is still negligible.

The final incident energies of the two-body reaction in the center-of-mass system $E_{\mathrm{c.m.}}$ was calculated from the two detected outgoing particles proton and triton with the relation $E_{\mathrm{c.m.}} = E_{dd} = E_{pt} - Q_2$, where E_{pt} is the energy of proton and triton in the center-of-mass system and Q_2 is the Q value of the two-body reaction $^2H(d,p)^3H$.

The results of the bare nucleus astrophysical $S_{\mathrm{bare}}(E)$ factor for the $^2H(d,p)^3H$ reaction are presented in Fig. 5 (upper panel) after normalization in the energy range from 100 to 400 keV with direct data [15,26], and they are compared with data from our previous experiments ([16] and PRC-2013 [14]) using the same Trojan horse nucleus $^6Li = (d \oplus \alpha)$ breakup.

In order to show the variation of the disagreement of the $S(E)$ data extracted via THM to the direct data in the low energy range, the plot of $S_{\mathrm{THM}}/S_{\mathrm{Direct}}$ vs $E_{\mathrm{c.m.}}$ is reported in Fig. 5 (lower panel) as well.

To quantify the improvement in the precision of the extracted $S(E)$ values with different beam energy, we defined an average disagreement value of S_{THM} to S_{Direct} as follows after fitting the direct data:

$$\xi_{\mathrm{THM}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sqrt{[S_{\mathrm{THM}}(E_i) - S_{\mathrm{DirFit}}(E_i)]^2}}{S_{\mathrm{DirFit}}(E_i)} \times 100\%.$$

The energy information and disagreement of the extracted $S(E)$ to direct one together with $S_0(E)$ and U_e data are given in Table I.

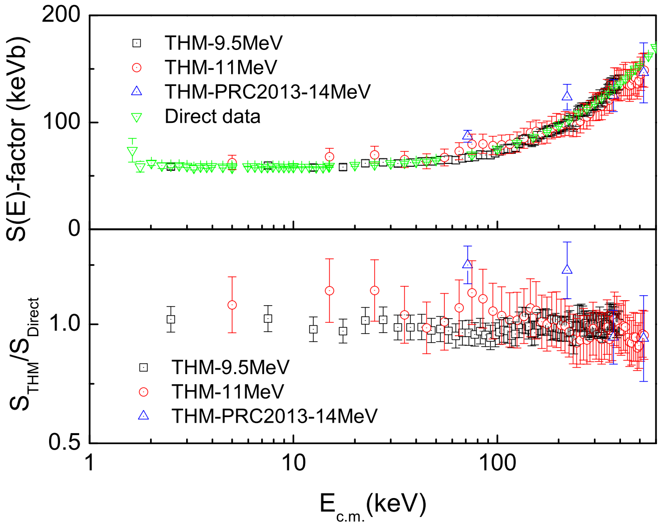

FIG. 5. The $S(E)$ factor obtained from THM measurements with same TH [^{6}Li = $(d \oplus \alpha)$] and different energy compared with direct data. The $S_{\mathrm{THM}}/S_{\mathrm{Direct}}$ value with $E_{\mathrm{c.m.}}$ is shown below as well.

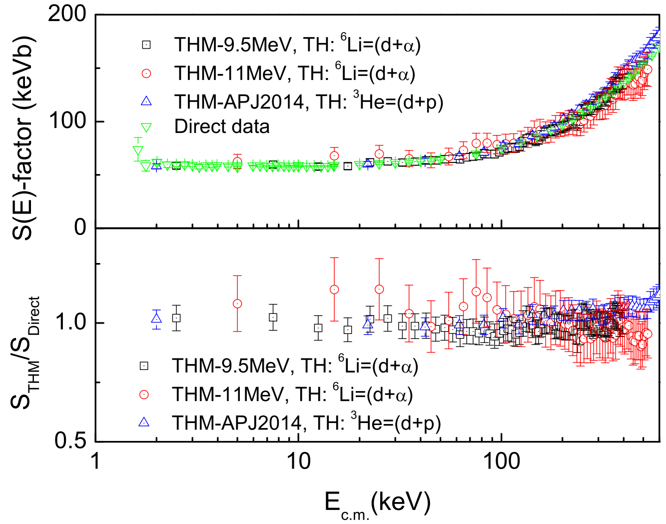

FIG. 6. The $S(E)$ factor obtained from different THM measurements with different TH (^{6}Li = $(d \oplus \alpha)$ vs ^{3}He = $(d \oplus p)$) compared with direct data to test the Trojan horse nucleus invariance. The $S_{\mathrm{THM}}/S_{\mathrm{Direct}}$ value with $E_{\mathrm{c.m.}}$ is shown below as well.

It is clear from Fig. 5 and Table I that the errors of both the 11-MeV runs and the 9.5-MeV runs are much smaller than that in PRC-2013 [14] using the same Trojan horse at a higher beam energy (14 MeV) with ΔE detectors for particle identification in the experimental setup. The data precision of the 9.5-MeV runs are better than those of the 11-MeV runs in the low energy range, although data of the 11-MeV runs can extend to higher energies (up to 500 keV). Part of the reason for the larger errors in the 11-MeV runs is due to the shorter measurement time (the raw events is about 60% of that in the 9.5-MeV runs, which lead to the contribution of the statistical errors increasing about 29%), but mainly due to the beam energy change.

When the beam energy of the reaction is reduced from 14 to 11 MeV and then to 9.5 MeV, we see an average improvement of disagreement with direct measurements in the energy range of 0 to 500 keV from 14.8% to 4.9% and then to 2.0%.

The increased accuracy is mainly due to the three updates we performed: First, the strip target with 1-mm width was used to reduce the angle uncertainty coming from the large beam spot. Second, no ΔE detector was mounted before PSDs. It was beneficial to improve the energy and angular resolution, avoiding the additional straggling of energies and angles when particles pass through ΔE detectors if they were mounted. Finally, the beam energy was reduced from 14 MeV to 11 and 9.5 MeV, leading to a quasifree binary incident energy E_{dd}^{qf} closer to the lower Gamow energy range near the zero-energy point than that in PRC-2013 [14], as shown in Table I. This result will help us to obtain more quasifree events in the low-energy range and get better result. It is one of the main reasons why the previous PRC-2013 [14] experiment cannot get a good comparison with APJ-2014 [15] data.

In summary, it can be seen from Table I and Fig. 5 that the precision of $S(E)$ data in the low-energy range extracted via the same Trojan-horse nucleus improves when the incident energy decreases approaching the zero-quasifree-energy point.

However, it can happen that in order to have some overlap with direct data, E_{Ax}^{qf} is chosen a bit shifted to higher energies with respect to E_G, and E_G is reached by taking advantage of the Fermi motion between x and s inside the Trojan horse nucleus. This is done by increasing the beam energy, which assures also a larger astrophysical energy region. The result of this paper warns that the beam energy has to be chosen more carefully so as not to worsen the quality of data. The optimal energy is the best compromise between being as close as possible to E_G and spanning an energy region large enough to have good overlap with direct data.

The data from the present experiment and our previous one [16] are also compared with those from APJ-2014 [15] using ^{3}He = $(d \oplus p)$ as Trojan-horse nucleus. The comparison is shown in Fig. 6. An overall agreement is present among both direct and indirect data sets with different Trojan-horse nuclei, within the experimental errors, especially for the 9.5-MeV

TABLE I. Comparison of ^{2}H$(d,p)^3$H indirect studies via THM.

Work	TH	E_0 (MeV)	E_{dd}^{qf} (keV)	S_0 (keV b)	U_e (eV)	ξ_{THM}
Previous work [16]	^{6}Li = $(d \oplus \alpha)$	9.5	89	56.7 ± 2.0	13.2 ± 4.3	2.0%
Present work	^{6}Li = $(d \oplus \alpha)$	11	342	61.1 ± 6.8	19.6 ± 9.2	4.9%
PRC-2013 [14]	^{6}Li = $(d \oplus \alpha)$	14	866	75 ± 21		14.8%
APJ-2014 [15]	^{3}He = $(d \oplus \mathrm{p})$	17	178	57.7 ± 1.8	13.4 ± 0.6	4.2%

data in the low-energy range. That is, the use of a different spectator particle does not influence the THM results. Thus, the Trojan-horse particle invariance, which was already observed in Ref. [12], is well confirmed in an additional case in the Gamow energy range. This work gives a much stronger updated test for the independence of the binary indirect cross section on the chosen Trojan-horse nucleus at low energies than the previous one in PRC-2013 [14].

V. SUMMARY

A new investigation of the ^{2}H(^{6}Li$\,,pt$)^{4}He reaction measurement was performed to extract information on the astrophysical $S_{\mathrm{bare}}(E)$ factor for the ^{2}H$(d,p)^3$H reaction via the THM at a low incident energies. The obtained results were compared with direct data as well as with the previous indirect investigations of the same binary reactions [14–16].

It shows that the precision of $S(E)$ data in the low-energy range extracted via the same Trojan-horse nucleus becomes better when the incident energy decreases from high value down to the zero-quasifree-energy point. It is one of the main reasons of why the previous PRC-2013 [14] experiment cannot get a good comparison with APJ-2014 [15] data.

The very good agreement between data extracted from different Trojan-horse nuclei (^{6}Li $= (d \oplus \alpha)$ vs ^{3}He $= (d \oplus p)$ [15]) gives a much stronger updated test than the previous one [14] for the Trojan-horse nucleus invariance at very low energies.

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[1] G. Wallerstein, I. Iben, P. Parker *et al.*, Rev. Mod. Phys. **69**, 995 (1997).
[2] R. G. Pizzone, R. Spartá, C. Bertulani *et al.*, Astrophys. J. **786**, 112 (2014).
[3] G. Baur, Phys. Lett. B **178**, 135 (1986).
[4] S. Typel and G. Baur, Ann. Phys. **305**, 228 (2003).
[5] R. E. Tribble, C. A. Bertulani, M. La Cognata *et al.*, Rep. Prog. Phys. **77**, 106901 (2014).
[6] C. Spitaleri, M. La Cognata, L. Lamia *et al.*, Eur. Phys. J. A **52**, 77 (2016).
[7] E. G. Adelberger, A. Garcia, R. G. H, Robertson, Rev. Mod. Phys. **83**, 195 (2011).
[8] A. Tumino, C. Spitaleri, S. Cherubini *et al.*, Few-Body Syst **54**, 745 (2013).
[9] S. Cherubini, M. Gulino, C. Spitaleri *et al.*, Phys. Rev. C **92**, 015805 (2015).
[10] R. G. Pizzone, B. Roeder, M. Mckluskey *et al.*, Eur. Phys. J. A **52**, 24 (2016).
[11] R. G. Pizzone, C. Spitaleri, A. M. Mukhamedzhanov *et al.*, Phys. Rev. C **80**, 025807 (2009).
[12] R. G. Pizzone, C. Spitaleri, L. Lamia *et al.*, Phys. Rev. C **83**, 045801 (2011).
[13] A. Rinollo, S. Romano, C. Spitaleri *et al.*, Nucl. Phys. A **758**, 146 (2005).
[14] R. G. Pizzone, C. Spitaleri, C. A. Bertulani *et al.*, Phys. Rev. C **87**, 025805 (2013).
[15] A. Tumino, R. Sparta, C. Spitaleri *et al.*, Astrophys. J. **785**, 96 (2014).
[16] C. Li, Q. Wen, Y. Fu *et al.*, Phys. Rev. C **92**, 025805 (2015).
[17] A. Tumino, C. Spitaleri, A. M. Mukhamedzhanov *et al.*, Phys. Lett. B **700**, 111 (2011).
[18] A. Tumino, C. Spitaleri, A. M. Mukhamedzhanov *et al.*, Phys. Lett. B **705**, 546 (2011).
[19] Li Chengbo, R. G. Pizzone, C. Spitaleri *et al.*, Nucl. Phys. Rev. **22**, 248 (2005).
[20] S. Romano, L. Lamia, C. Spitaleri *et al.*, Eur. Phys. J. A **27**, 221 (2006).
[21] Q.-G. Wen, C.-B. Li, S.-H. Zhou *et al.*, Phys. Rev. C **78**, 035805 (2008).
[22] Q.-G. Wen, C.-B. Li, S.-H. Zhou *et al.*, J. Phys. G: Nucl. Part. Phys **38**, 085103 (2011).
[23] C.-B. Li, Q.-G. Wen, S. Zhou *et al.*, Chin. Phys. C **39**, 054001 (2015).
[24] Q.-G. Wen, C.-B. Li, S.-H. Zhou *et al.* Phys. Rev. C **93**, 035803 (2016).
[25] E. Costanzo, M. Lattuada, S. Romano *et al.*, NIM A **295**, 373 (1990).
[26] U. Greife, F. Gorris, M. Junker *et al.*, Z. Phy. A **351**, 107 (1995).