Measurement of the ^{2}H(d,p)^{3}H reaction at astrophysical energies via the Trojan-horse method

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The study of the ^{2}H(d,p)^{3}H reaction is very important for the nucleosynthesis in both the standard Big Bang and stellar evolution, as well as for the future fusion reactor's planning of energy production. The ^{2}H(d,p)^{3}H bare nucleus astrophysical $S(E)$ factor has been measured indirectly at energies from about 400 keV down to several keV by means of the Trojan-horse method applied to the quasifree process ^{2}H(^{6}Li$,pt$)^{4}He induced at a lithium beam energy of 9.5 MeV, which is closer to the zero-quasifree-energy point. An accurate analysis leads to the determination of the $S_{\mathrm{bare}}(0) = 56.7 \pm 2.0$ keV b and of the corresponding electron screening potential $U_e = 13.2 \pm 4.3$ eV. In addition, this work gives an updated test for the Trojan-horse nucleus invariance by comparing with previous indirect investigations using the $^{3}\mathrm{He} = (d + p)$ breakup.

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I. INTRODUCTION

The $d + d$ nuclear reaction is important in both nuclear astrophysics [1–3] and fusion energy applications [4,5].

This reaction is among the thermonuclear processes occurring during the first minutes of the universe immediately after the Big Bang. In particular, knowledge and modeling of the primordial abundance of deuterium, which depends on precise cross-section data, give important information about the baryon density of the universe. Moreover, primordial deuterium is burned during the earliest evolution stage of stars: the pre-main-sequence phase. Thus, a better knowledge of the parameters characterizing these reactions can improve our understanding of the first phases of stellar evolution. As for the Standard Big Bang Nucleosynthesis, the region of interest ranges from 50 to 300 keV and is only from a few to 20 keV for stellar-evolution processes.

In addition to these important astrophysical topics, the interest of scientists around reactions involving deuterium has been also triggered by the promising possibility of exploiting them as a powerful and low-polluting source of energy in fusion reactors. These reactions belong to the network of processes inside fusion reactors. These reactors are expected to operate in the temperature range of $kT = 1$ to 30 keV.

Several experiments have been performed below 200 keV, but available data are not always in agreement within each other and some of them are affected by large systematic errors. Another weak point is that available data below 10 keV, the region of interest for fusion reactors as well as for burning deuteron in the pre-main-sequence phase of stellar evolution, are affected by the electron screening.

For these reasons, new indirect experimental studies were called for to provide new data in the full range of interest for pure and applied physics. The Trojan-horse method (THM) [6,7] has been applied to the indirect study of the $d + d$ reactions using $^{3}\mathrm{He} = (d + p)$ and $^{6}\mathrm{Li} = (d + \alpha)$ breakup [8,9], but the ^{6}Li breakup data give much fewer points and larger errors than the ^{3}He breakup.

In this paper, we report on a new investigation of the ^{2}H(d,p)^{3}H reaction by means of the THM applied to the ^{2}H(^{6}Li$,pt$)^{4}He quasifree process with a beam energy of 9.5 MeV, which is closer to the zero-quasifree-energy point.

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 [6,7] has been introduced as a powerful indirect tool in experimental nuclear astrophysics [8–21]. The THM provides a valid alternative approach to measure unscreened low-energy cross sections of charged particle

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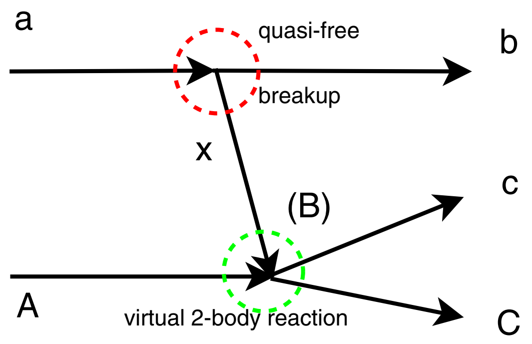

FIG. 1. (Color online) Schematic representation of the Trojan-horse method.

reactions. It can also be used to retrieve information on the electron screening potential when ultralow-energy direct measurements are available.

The basic assumptions of the THM theory have been discussed extensively in Refs. [7,10–13], and the detailed theoretical derivation of the formalism employed can be found in Ref. [7].

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

$$A + x \to C + c \tag{1}$$

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

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

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 only between nucleus A and the transferred particle x whereas the other cluster b behaves as a spectator to the virtual two-body reaction during the quasifree process. The energy in the entrance channel E_{Aa} is chosen above the height of the Coulomb barrier $E_{Aa}^{\mathrm{C.B.}}$, 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 overcome the binding energy ε_a of x inside a, even if particle x is almost at rest the extra energy is compensated for by the binding energy of a [Eq. (3)], and the Fermi motion of x inside a, E_{xb}, is used to span the region of interest around E_{Ax}^{qf}:

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

$$E_{Ax} = E_{Ax}^{\mathrm{qf}} \pm E_{xb}. \tag{4}$$

Since the transferred particle x is hidden inside the nucleus a (the 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 inverting the following relation:

$$\frac{d^3\sigma}{dE_{Cc}d\Omega_{Bb}d\Omega_{Cc}} = K_F|W|^2\frac{d\sigma}{d\Omega}^{\mathrm{TH}}, \tag{5}$$

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

$$\frac{d\sigma}{d\Omega}^{\mathrm{TH}} = \sum_l C_l P_l \frac{d\sigma_l}{d\Omega}(Ax \to Cc), \tag{6}$$

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 penetration function caused by the Coulomb wave function, and C_l is the scaling factor.

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 9.5 MeV provided by the HI-13 tandem accelerator was used to bombard a deuterated polyethylene target CD_2. The thickness of the target is about 160 μg/cm^2. In order to reduce the angle uncertainty coming from the large beam spot(whose size was normally ranging from 2 to 10 mm) on the target, a strip target of 1 mm width was used. In this way, the reaction zone can be limited to the width of the strip target, and better angular resolution can be obtained.

A position-sensitive detector PSD_1 was placed at 40° with respect to the beam line direction covering angles from 35° to 45° to detect the outgoing particle triton (t), and another detector PSD_2 was used at 78° on the other side with respect to the beam line covering angles from 73° to 83° to detect the outgoing particle proton (p). The arrangement of the experimental setup was modelled in a Monte Carlo simulation in order to cover a region of quasifree angle pairs. A monitor

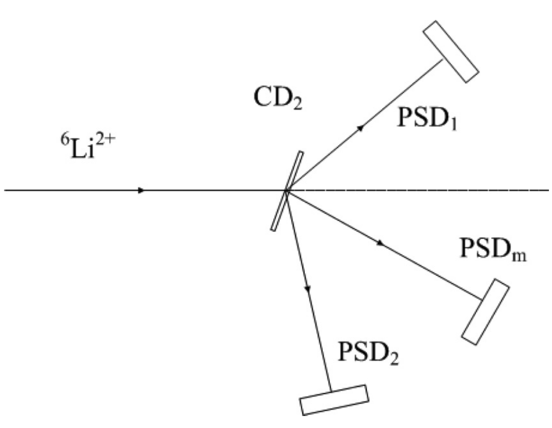

FIG. 2. Experiment setup for the ^{2}H(^{6}Li, pt)^{4}He reaction.

PSD_m was placed at 32° opposite PSD_1 covering angles from 27° to 37° for runtime monitoring of the beam energy and the target thickness variation. The energy resolution of the PSDs is about 0.6%–0.8% for a 5.48 MeV α source.

No particle identification was performed in the experiment. This was beneficial to improve the energy and angular resolution without ΔE detectors that would lead to additional straggling effects for the detected particles, while it was easy to select events for this reaction from the kinematics in the off-line analysis with the help of the simulation.

The trigger for the event acquisition was given by coincidence of signals and schematically indicated as 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. 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.

IV. DATA ANALYSIS AND RESULTS

The position and energy calibration of the detectors was performed by using elastic scattering from different targets (^{197}Au, ^{12}C, and CD_2) induced by a proton beam at energies of 6, 7, 8 MeV. A standard α source of 5.48 MeV was also used.

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 $^6\mathrm{Li} + d \to t + p + \alpha$, 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).

A. Selection of the three-body-reaction events

The basic step of data analysis is to select the three-body-reaction events of ^{2}H(^{6}Li$,pt)^4$He from all exit channels. Figure 3 shows the experimental spectrum of the $E_1 - E_2$ kinematic locus. Comparing with the Monte Carlo simulation [21], we can select the range by means of a graphical cut (red line polygon in the figure) where the three-body reaction ^{2}H(^{6}Li$,pt)^4$He events are located. It was used as a basic selection cut in the further data analysis.

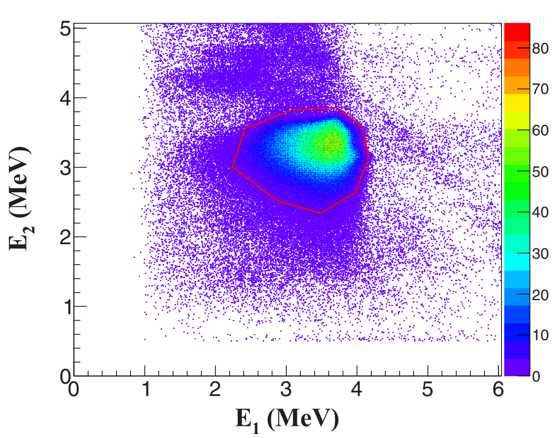

FIG. 3. (Color online) Selection of the three-body-reaction events of ^{2}H(^{6}Li$,pt)^4$He from the $E_1 - E_2$ kinematic locus.

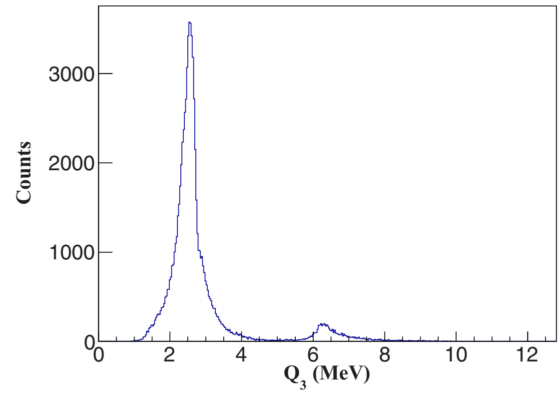

FIG. 4. (Color online) Experimental Q_3-value spectrum from the selection of Fig. 3 for the kinematic locus of ^{2}H(^{6}Li$,pt)^4$He. The relevant peak is the one at about 2.5 MeV.

B. Q_3-value spectrum

Once selected the events of the ^{2}H(^{6}Li$,pt)^4$He reaction, the experimental Q_3 value was extracted, as reported in Fig. 4.

There is a peak whose centroid is at about 2.5 MeV (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.

The events outside of the 2.5 MeV peak belong to background and to some other reactions not in agreement with the assumption that the first particle is a triton and the second one is a proton, so that the calculated Q_3 value deviated from the expected value. They show up as peaks or spots that can be easily separated from the prominent peak of interest.

Only events inside the 2.5 MeV Q-value peak (2.0 MeV $< Q_3 <$ 3.0 MeV) were considered for the further analysis.

C. Momentum distribution of α inside ^{6}Li

As in all standard THM analysis, the next step is to identify and separate the quasifree mechanism from all the other processes. 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 within the Trojan-horse nucleus. Thus, the momentum distribution of the third and undetected particle was examined in the framework of the plane wave impulse approximation (PWIA) [see Eq. (5)]. This gives a major constraint for the presence of the quasifree mechanism and the possible application of the THM.

In order to extract the experimental momentum distribution of the spectator in the system where the Trojan-horse particle b is at rest, narrow energy and angular windows should be selected. Since $(d\sigma/d\Omega)^{\mathrm{TH}}$ is nearly constant in a narrow energy and $\theta_{\mathrm{c.m.}}$ window, one can obtain the shape of the momentum distribution $|W|^2$ of the undetected particle directly from the three-body-reaction yield divided by the kinematical factor K_F, according to Eq. (5).

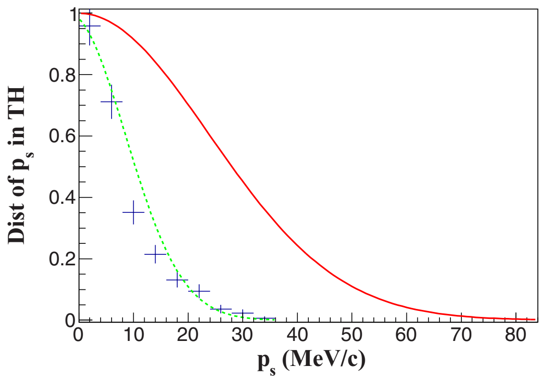

FIG. 5. (Color online) Experimental spectrum of momentum distribution for intercluster motion of α inside ^{6}Li (the blue points and the dotted green line for the fitting curve) compared with the theoretical calculation (the red line).

The obtained momentum distribution is reported in Fig. 5, where it is compared with the theoretical prediction of the spectator momentum distribution, obtained using the Woods–Saxon potential with the standard geometrical parameters [14].

An evident distortion of the momentum distribution shows up and its measured full width at half maximum (FWHM) turns out to be around 23 MeV/c, which is much smaller than the expected prediction of 72 MeV/c. This evidence was already observed in Ref. [14], where the width of the momentum distribution for the spectator inside the Trojan-horse nucleus was studied as a function of the transferred momentum q_t from the projectile a to the center of mass of the final system $B = C + c$. In the present case, the value of q_t is about 133 MeV/c, and the width of the momentum distribution is about 23 MeV/c. It is in agreement with the trend of the curve that represents the best fit to the function reported in Ref. [14], $W_{\rm FWHM}(q_t) = f_0[1 - \exp(-q_t/q_0)]$, using the same parameter value.

For further analysis, the condition of $|p_s| < 20$ MeV/c was added to the basic cut to select the quasifree events of the three-body reaction.

D. $S(E)$ factor and U_e

The last step was to extract the energy trend of the $S(E)$ factor by means of the standard procedure of the THM after selecting the quasifree three-body-reaction events.

Therefore, Eqs. (5) and (6) were applied after selecting the quasifree events from the three-body reaction. Then, the $S(E)$ factor can be determined from the definition of $S(E) = \sigma(E)E\exp(2\pi\eta)$, where $\eta = Z_1Z_2e^2/(\hbar v)$ is the Sommerfeld parameter. In the present work, only the s-wave ($l = 0$) was considered for the energy range of $E_{\rm c.m.} = 0$ to 400 keV.

The results for the $^2{\rm H}(d,p)^3{\rm H}$ reaction in terms of the bare nucleus astrophysical $S_{\rm bare}(E)$ factor are presented in Fig. 6 (blue points) after normalization with direct data (red points) [9,22]. The normalization was performed in the energy range of $E_{\rm c.m.} = 40$ to 400 keV, in which the electron-screening effect is still negligible. It should be pointed out that direct data suffer from the electron-screening effect which does not affect

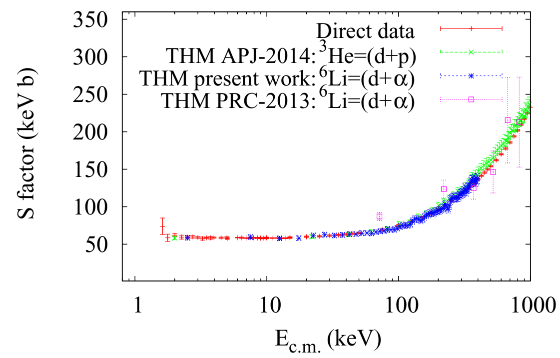

FIG. 6. (Color online) The $S(E)$ factor obtained from THM measurement compared with direct data.

the THM results. This is why the $S(E)$ extracted via THM is called $S_{\rm bare}(E)$. A polynomial fit was then performed on the data, giving $S_{\rm bare}(0) = 56.7 \pm 2.0$ keV b.

The data from the present experiment (blue points) are compared with those from PRC-2013 [8] of $^6{\rm Li} = (d + \alpha)$ breakup in a previous THM experimental run (pink points) and those from APJ-2014 [9] of $^3{\rm He} = (d + p)$ breakup experiment (green points). An overall agreement is present among both direct and indirect data sets, within the experimental errors.

It should be pointed out that the errors in the present case are much smaller than in the case of PRC-2013 [8] using the same Trojan horse with higher beam energy and with ΔE detectors for particle identification.

It is also in agreement, within the experimental errors, with the result using a different Trojan horse ^{3}He [9]. That is, data extracted via the THM applied to ^{6}Li and ^{3}He breakup are comparable between themselves. The Trojan-horse-particle invariance is confirmed in an additional and independent case that adds up to the one already observed in Ref. [23].

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

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

The result is shown in Fig. 7. The red points are the direct data by Greife *et al.* (1995) [22]. The blue dashed line is the

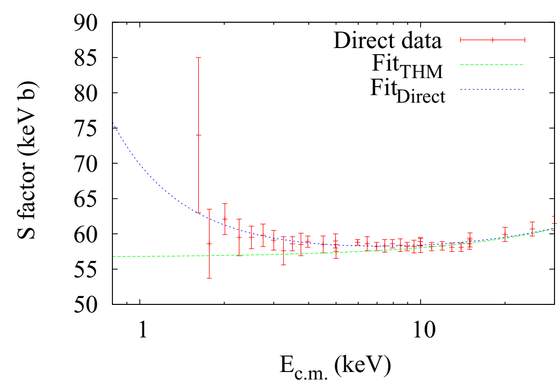

FIG. 7. (Color online) Fitting of $S(E)$ to obtain U_e.

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

Work	TH	E_0 (MeV)	E^{qf}_{Ax} (MeV)	$S_0(E)$ (keV b)	U_e (eV)
Present	^{6}Li $= (d+\alpha)$	9.5	0.089	56.7 ± 2.0	13.2 ± 4.3
Ref. [8]	^{6}Li $= (d+\alpha)$	14	0.866	75 ± 21	
Ref. [9]	^{3}He $= (d+p)$	17	0.178	57.7 ± 1.8	13.4 ± 0.6

fitting curve of direct data (screened), and the green line is the fitting of THM data (unscreened) of the present work. Thus, we obtain a value of $U_e = 13.2 \pm 4.3$ eV, which is also in agreement with the one of Ref. [9] $U_e = 13.4 \pm 0.6$ eV. The relevant parameters referring to the THM measurements of the ^{2}H$(d,p)^{3}$H reaction are reported in Table I for better comparison.

V. SUMMARY

A new measurement of the ^{2}H$(^{6}$Li$,pt)^{4}$He reaction to extract information on the astrophysical $S_{\rm bare}(E)$ factor and screening potential U_e for the ^{2}H$(d,p)^{3}$H reaction via the THM has been performed at a ^{6}Li beam energy of 9.5 MeV. The $S(E)$ factor for the ^{2}H$(d,p)^{3}$H reaction has been derived from about 400 keV down to several keV. The errors in the present case are much smaller than in the case of PRC-2013 [8], which uses the same Trojan horse ^{6}Li. The present results do not change the prediction reported in Ref. [3] for the primordial nucleosynthesis scenario.

An overall agreement within the experimental errors is present among both direct and indirect data sets using different Trojan-horse nuclei. That is, the use of a different spectator particle does not influence the THM results. Thus, this work gives an updated test for the Trojan-horse nucleus invariance.

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