New measurement of $S_{\text{bare}}(E)$ factor of the d(d,p)t reaction at astrophysical energies via the Trojan-horse method

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The study of d(d,p)t reaction is very important for the nucleosynthesis in both standard Big Bang and stellar evolution, as well as for the future fusion reactor planning of energy production. The d(d,p)t 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 quasi-free process $^2\text{H}(^6\text{Li}, p)^4\text{He}$ induced at the lithium beam energy of 9.5 MeV, which is closer to the zero quasi-free energy point, in CIAE HI-13 tandem accelerator laboratory. An accurate analysis leads to the determination of the d(d,p)t S(E) factor $S_{\text{bare}}(0) = 56.7 \pm 2.0$ keV·b and of the corresponding electron screening potential $U_e = 13.2 \pm 4.3$ eV. In addition, this work also gives an updated test for the Trojan horse nucleus invariance comparing with previous indirect investigations using $^3\text{He} = (d + p)$ breakup.

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I. INTRODUCTION

The d+d nuclear reactions are important in both nuclear astrophysics [1, 2] and fusion energy applications [4, 5].

These reactions are among the thermonuclear processes occurring during the first minutes of the universe immediately after the Big Bang. In particular, knowledge and modelling 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 it is only several 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 exploit them as a powerful and low-polluting source of energy in fusion reactors. These reactions belong to the network of processes inside the fusion reactors. These reactors are expected to operate in the temperature range of kT = 1-30 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, region of interest for fusion reactors as well as for burning deuterion in the Pre-Main Sequence phase of stellar evolution, are affected by the electron screening.

For these reasons, new indirect experimental study was 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 $^3\text{He} = (d + p)$ and $^6\text{Li} = (d + \alpha)$ breakup [13, 14], but the $^6\text{Li}$ breakup data give much less points and larger errors than that in the case of $^3\text{He}$ breakup.

In this paper, we report on a new investigation of the d(d,p)t reaction by means of the THM applied to the quasi free process $^2\text{H}(^6\text{Li}, p)^4\text{He}$ with a beam energy of 9.5 MeV, which is closer to the zero quasi-free 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 Trojan-horse method \[6, 7\] has been introduced as a powerful indirect tool in experimental nuclear astrophysics \[8–11\]. 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.

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

\[
A + x \rightarrow C + c
\]

from the measurement of a suitable three-body process Eq. (2) under the quasi-free kinematic conditions.

\[
A + a \rightarrow C + c + b
\]

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 quasi-free process. The energy in the entrance channel \(E_{Ax}\) is chosen above the height of the Coulomb barrier \(E^{C,B}_{Aa}\), 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 \(E_{Ax}\) is partially used to overcome the binding energy \(\varepsilon_a\) of \(x\) inside \(a\), even if particle \(x\) is almost at rest the extra-energy is compensated by the binding energy of \(a\) (Eq. (3)), and the Fermi motion of \(x\) inside \(a\) compensates at least partially for the \(A + a\) relative motion (Eq. (4)).

\[
E^{qf}_{Ax} = E_{Ax} \left(1 - \frac{\mu_{AA} \mu_{Ax}^2}{\mu_{Ax}^2 \mu_{Ab}^2}\right) - \varepsilon_a
\]

\[
E_{Ax} = E^{qf}_{Ax} \pm E_{xb}
\]

Since the transferred particle \(x\) is hidden inside the nucleus \(a\) (so called Trojan-horse nucleus), the particle \(x\) 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 interesting two-body reaction cross section can be extracted from the measured three-body reaction using the relation formulation Eq. (5) after selecting the quasi-free events:

\[
\frac{d^3 \sigma}{dE_{Cd}d\Omega_{Bb}d\Omega_{Cc}} = KF \cdot |W|^2 \cdot \frac{d\sigma}{d\Omega}^{HOES}
\]

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

\[
\frac{d\sigma}{d\Omega}^{HOES} = \sum_{l} (P_l \cdot \frac{d\sigma}{d\Omega} (Ax \rightarrow Cc))
\]

where \(P_1\) is the penetration function caused by the Coulomb wave function.

In this work, the THM has been applied to study the \(d(d,pt)\) reaction via the quasi free process \(^2\text{H}(^6\text{Li},pt)^4\text{He}\), where \(^6\text{Li} = (d + \alpha)\) is used as the Trojan horse nucleus, the \(d\) acts as the participant while the \(\alpha\) acts as the spectator to the virtual two-body reaction. The beam energy of lithium is selected to be about 9.5 MeV, which is closer to the zero quasi-free energy point according to the Equation 3.

III. EXPERIMENT

The measurement of the reaction \(^2\text{H}(^6\text{Li},pt)^4\text{He}\) was performed in Beijing National Tandem Accelerator Laboratory at China Institute of Atomic Energy. The experimental setup was installed in the nuclear reaction chamber at the R60 beam line terminal as shown in Figure 2. The \(^6\text{Li}^{2+}\) beam at 9.5 MeV provided by the HI-13 tandem accelerator was used to bombard a deuterated polyethylene target CD2. The thickness of the target is about 160\(\mu\text{g/cm}^2\). In order to reduce the angle uncertainty coming from the large beam spot, a linear target with 1 mm width was used.

A position sensitive detector PSD1 was placed at 40° ± 5° to the beam line direction and about 238 mm
from the target to detect outgoing particle $t$, and another detector PSD$_2$ was used at $78^\circ \pm 5^\circ$ in the other side of the beam line and 245 mm distance from the target to detect the outgoing particle $p$. The arrangement of the experimental setup was modelled in Monte Carlo simulation in order to cover a region of quasi-free angle pairs. A PSD$_n$ was placed at $32^\circ \pm 5^\circ$ opposite to PSD$_1$ as a monitor. The trigger for the event acquisition was given by coincidence of signals by 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 were performed by the scatterings on different targets ($^{197}$Au, $^{12}$C, and CD$_2$) induced by the proton beam at energy of 6, 7, 8 MeV. A standard $\alpha$ source of 5.48 MeV was also used.

After the calibration of the detectors, the energy and momentum of the third undetected particle ($\alpha$) are calculated from the complete kinematics of the three-body reaction $^6$Li + d $\rightarrow$ t + p + $\alpha$, on the assumption that the first particle is $t$ (detected by PSD$_1$) and the second one is $p$ (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 focus. Comparing with the Monte Carlo simulation [19], we can select the range by a GCut (red line polygon) where the three body reaction $^2$H($^6$Li, pt)$^4$He events are focused. It will be used as a basic cut in the following data analysis.

FIG. 3: Selection of the three body reaction events of $^2$H($^6$Li, pt)$^4$He from the $E_1 - E_2$ kinematic focus

B. $Q_3$ value spectrum

Once selecting the three-body reaction events of $^2$H($^6$Li, pt)$^4$He, the experimental Q value of the three-body reaction can be extracted, as reported in Figure 4.

There is a peak whose centroid is at about 2.538 MeV (in good agreement with the theoretical prediction, $Q = 2.5588$ 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 Q-value peak are considered for the further analysis.
C. Momentum distribution of $\alpha$ inside $^6\text{Li}$

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 will be examined. 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 cutted in the center-of-mass system. Since $[(\sigma/d\Omega)_{c.m.}^{\text{HOFES}}]$ is nearly constant in a narrow energy and $\theta_{c.m.}$ 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 $KF$, according to the relation formulation Eq.\(5\).

The obtained momentum distribution is reported in Figure\(5\) where it is compared with the theoretical prediction of the spectator momentum distribution, obtained using the Woods-Saxon potential with the standard geometrical parameters.

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.\(12\), 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 $\alpha$ 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, and the width of the momentum distribution is about 23 MeV/c. It shows the agreement with the trend of the curve that represents the best fit to the function reported in Ref.\(12\), $W_{\text{FWHM}}(q_t) = f_0[1 - \exp(-q_t/q_0)]$.

For the further analysis, the cut of $|p_{x,\text{cm}}| < 20\text{MeV/c}$ will be added to the above cuts to select the quasi-free events of the three-body reaction.

D. $S(E)$ factor and U$_c$

The last step is to extract the energy trend of the $S(E)$ factor by means of the standard procedure of the THM after selecting the quasi-free three-body reaction events. Therefore, Eq.\(5\) and Eq.\(6\) are applied. The interested two-body reaction cross section can be extracted from the measured three-body reaction divided by $KF$ and experimental momentum distribution $|W|^2$, with cuts of selecting the quasi-free 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 the Sommerfeld parameter is $\eta = Z_1Z_2e^2/(\hbar v)$.

The results for the $d(d, p)$ reaction in terms of the bare nucleus astrophysical $S_{\text{bare}}(E)$ factor are presented in Figure\(6\) (blue points) after normalization with direct data (red points)\(14,20\). It should be pointed out that direct data suffer from the electron screening effect which does not affect the THM results. A polynomial fit was then performed on the data giving $S_{\text{bare}}(0) = 56.7 \pm 2.0\text{keV b}$.

The data from the present experiment (blue points) are compared with those from PRC-2013\(13\) of $^6\text{Li} = (d + \alpha)$ breakup in a previous THM experimental run (pink points) and those from APJ-2014\(14\) of $^3\text{He} = (d + p)$ breakup experiment (green points). An overall agreement is present among both direct and indirect data sets, within the experimental errors.

We point out that the errors in the present case are much smaller than in the case of PRC-2013\(13\), which using the same Trojan horse $^6\text{Li}$. It is also in agreement, within the experimental errors, with the result using a different Trojan horse $^3\text{He}$\(14\). That is, data extracted via the THM applied to $^6\text{Li}$ and $^3\text{He}$ breakup are comparable among themselves. The Trojan horse particle invariance is confirmed in an additional and independent case which was already observed in Ref.\(21\).

The lack of screening effects in the THM $S_{\text{bare}}(E)$ factors gives the possibility to return the screening potential U$_c$ from comparison with direct data using the following screening function Equation\(1\), with U$_c$ as free parameter.

$$f_{\text{-tab}}(E) = \sigma_s(E)/\sigma_0(E) \simeq \exp(\pi\eta U_c/E)$$

(7)

The result is shown in Figure\(7\). The red points are the direct data by Greife et al. (1995)\(20\). The blue dashed line is the fitting curve of direct data (screened), and
the green line is the fitting of THM data (unscreened) of the present work. Thus, we obtained a value of $U_e = 13.2 \pm 1.3$ eV, which is also in agreement with the one of Ref. [14] $U_e = 13.4 \pm 0.6$ eV.

V. SUMMARY

A new investigation of the $^2$H($^6$Li,pt)$^4$He reaction measurement to extract information on the astrophysical $S_{bare}(E)$ factor and screening potential $U_e$ for the d(d,p)t reaction via the THM is presented in the present paper, shown in Table I.

An overall agreement is present among both direct and indirect data sets using different Trojan horse nucleus, within the experimental errors.

The errors in the present case are much smaller than in the case of PRC-2013 [13], which using the same Trojan horse $^6$Li.

In addition, the data extracted via the THM applied to $^6$Li and $^3$He breakup are comparable among themselves. 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.

TABLE I: Comparison of d(d,p)t indirect study via THM.

| Work       | TH | $E_0$ (MeV) | $E^{df}_{As}$ (MeV) | $S_0(E)$ (keV·b) | $U_e$ (eV) |
|------------|----|-------------|---------------------|-----------------|------------|
| Present    | $^6$Li = (d + a) | 9.5 | 0.089 | 56.7 ± 2.0 | 13.2 ± 4.3 |
| PRC-2013 [13] | $^6$Li = (d + a) | 14 | 0.866 | 75 ± 21 | - |
| APJ-2014 [14] | $^3$He = (d + p) | 17 | 0.178 | 57.7 ± 1.8 | 13.4 ± 0.6 |

not influence the THM results. Thus, this work gives an updated test for the Trojan horse nucleus invariance.

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