New measurement of the d(d,p)t reaction at astrophysical energies via the Trojan-horse method

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Abstract

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 reactors 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 2H(6Li, pt)4He induced at a lithium beam energy of 9.5 MeV, which is closer to the zero quasi-free energy point. An accurate analysis leads to the determination of the Sbare(0) = 56.7$\pm 2.0keV \cdot bandofthecorrespondingelectronscreeningpotentialUe = 13.2\pm$ 4.3eV. In addition, this work gives an updated test for the Trojan horse nucleus invariance comparing with previous indirect investigations using 3He = (d + p) breakup.

Full Text

Preamble

New Measurement of the d(d,p)t Reaction at Astrophysical Energies via the Trojan-Horse Method

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The study of the d(d,p)t reaction is of great importance for nucleosynthesis in both standard Big Bang and stellar evolution scenarios, as well as for the planning of future fusion reactors for energy production. The bare-nucleus astrophysical S(E) factor for the d(d,p)t reaction has been measured indirectly at energies from approximately 400 keV down to several keV using the Trojan-horse method applied to the quasi-free process 2H(6Li, pt)4He induced at a lithium beam energy of 9.5 MeV, which is closer to the zero quasi-free energy point. Through careful analysis, we have determined Sbare(0) = 56.7 ± 2.0 keV · b and the corresponding electron screening potential Ue = 13.2 ± 4.3 eV. Additionally, this work provides an updated test of Trojan-horse nucleus invariance compared with previous indirect investigations using 3He = (d + p) breakup.

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INTRODUCTION

The d+d nuclear reactions are important in both nuclear astrophysics [1–3] 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 modeling of the primordial abundance of deuterium, which depends on precise cross-section data, provide important information about the baryon density of the universe. Moreover, primordial deuterium is burned during the earliest evolutionary stage of stars: the pre-main sequence phase. Thus, a better understanding of the parameters characterizing these reactions can improve our knowledge of the first phases of stellar evolution. For Standard Big Bang Nucleosynthesis, the region of interest ranges from 50 to 300 keV, while for stellar evolution processes it is only several to 20 keV.

In addition to these important astrophysical topics, scientific interest in reactions involving deuterium has also been 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, which are expected to operate in the temperature range of kT = 1–30 keV. Several experiments have been performed below 200 keV, but the available data are not always in agreement with each other and some are affected by large systematic errors. Another weakness is that data below 10 keV—the region of interest for fusion reactors as well as for deuteron burning in the Pre-Main Sequence phase of stellar evolution—are affected by electron screening. For these reasons, new indirect experimental studies were needed to provide data across the full range of interest for both pure and applied physics. The Trojan Horse Method (THM) [6, 7] has been applied to the indirect study of d+d reactions using 3He = (d + p) and 6Li = (d + α) breakup [15, 16], but the 6Li breakup data provide far fewer points and larger errors than in the case of 3He breakup.

In this paper, we report on a new investigation of the d(d,p)t reaction using the THM applied to the 2H(6Li, pt)4He quasi-free process with a beam energy of 9.5 MeV, which is closer to the zero quasi-free energy point.

[Figure 1: see original paper]

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 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 THM theory have been discussed extensively in [7–11], and the detailed theoretical derivation of the formalism employed can be found in [7]. A schematic representation of the process underlying the THM is shown in Figure 1. The method is based on the quasi-free (QF) reaction mechanism, which allows one to indirectly derive the cross section of a two-body reaction (Eq. 1) from the measurement of a suitable three-body process under quasi-free kinematic conditions:

$$A + a \to B + b$$

where the nucleus a is considered to be dominantly composed of clusters x and b (a = x   b). After the breakup of nucleus a due to its interaction with nucleus A, the two-body reaction 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 EAa is chosen above the height of the Coulomb barrier EC.B. to avoid reduction in the cross section. At the same time, the effective energy EAx of the reaction between A and x can be relatively small, mainly because the energy EAa is partially used to overcome the binding energy 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, Exb, is used to span the region of interest around:

$$E_{Ax}^{qf} = E_{Aa} \cdot \frac{x}{a}$$

$$E_{Ax} = E_{Ax}^{qf} \pm E_{xb}$$

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 quasi-free three-body reaction by inverting the following relation:

$$\frac{d^3\sigma}{dE_C d\Omega_B b d\Omega_C c} = K_F \cdot |W|^2 \cdot \frac{d\sigma}{d\Omega_{TH}}$$

where KF is the kinematical factor, |W|2 is the momentum distribution of the spectator b inside the Trojan-horse nucleus a, and dσ/dΩTH is the half-off-energy-shell (HOES) cross section of the two-body reaction A + x → C + c:

$$\frac{d\sigma}{d\Omega_{TH}} = \sum_l C_l \cdot P_l \cdot \frac{d\sigma_l}{d\Omega}(Ax \to Cc)$$

where dσl/dΩ(Ax → Cc) is the real on-energy-shell cross section of the two-body reaction A + x → C + c for the l partial wave, Pl is the penetration function caused by the Coulomb wave function, and Cl is the scaling factor.

III. EXPERIMENT

The measurement of the 2H(6Li, pt)4He 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 Figure 2. A 6Li2+ beam at 9.5 MeV from the HI-13 tandem accelerator was used to bombard a deuterated polyethylene target (CD2) with a thickness of about 160 µg/cm2. To reduce angular uncertainty arising from the large beam spot, a linear target with 1 mm width was used.

A position-sensitive detector PSD1 was placed at 40° ± 5° relative to the beam line direction and approximately 238 mm from the target to detect the outgoing triton (t), while another detector PSD2 was positioned at 78° ± 5° on the opposite side of the beam line at 245 mm from the target to detect the outgoing proton (p). The arrangement of the experimental setup was modeled in Monte Carlo simulation to cover a region of quasi-free angle pairs. A monitor detector PSDm was placed at 32° ± 5° opposite to PSD1. The energy resolution of the PSDs is about 0.6%–0.8% for a 5.48 MeV α source.

It should be mentioned that no ΔE detector was mounted before the PSDs; that is, no particle identification was performed in the experiment. This was beneficial for improving the energy and angular resolution, as ΔE detectors would cause additional energy and angular straggling when particles pass through them. However, it was straightforward to select events for this reaction without particle identification using kinematics in the data analysis with the help of simulation.

The trigger for event acquisition was given by the coincidence logic Gate = PSD1 × (PSD2 + PSDm). Energy and position signals for the detected particles were processed by standard electronics and sent to the MIDAS acquisition system for online monitoring and data storage for offline analysis. 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 using elastic scattering on different targets (197Au, 12C, and CD2) induced by a proton beam at energies of 6, 7, and 8 MeV. A standard α source of 5.48 MeV was also used. After calibrating the detectors, the energy and momentum of the third undetected particle (α) were reconstructed from the complete kinematics of the three-body reaction 6Li + d → t + p + α, under the assumption that the first particle is a triton (detected by PSD1) and the second is a proton (detected by PSD2).

A. Selection of the Three-Body Reaction Events

The first step in data analysis is to select the three-body reaction events of 2H(6Li, pt)4He from all exit channels. Figure 3 shows the experimental spectrum of the E1–E2 kinematic locus. By comparing with Monte Carlo simulation [21], we can select the region using a graphical cut (red polygon) where the three-body reaction 2H(6Li, pt)4He events are located. This will be used as a basic selection cut in the subsequent data analysis.

B. Q-Value Spectrum

Once the three-body reaction events of 2H(6Li, pt)4He are selected, the experimental Q3 value can be extracted, as shown in Figure 4 [Figure 4: see original paper]. There is a peak whose centroid is at about 2.5 MeV, in good agreement with the theoretical prediction Q = 2.558 MeV. This provides clear evidence of good detector calibration as well as correct identification of the reaction channel. Events outside the 2.5 MeV peak originate from background and some reactions located in the energy range of Figure 3 but not consistent with the assumption that the first particle is a triton and the second is a proton, causing the calculated Q3 value to deviate from the expected value. Only events within the 2.5 MeV Q-value peak were considered for further analysis.

C. Momentum Distribution of α inside 6Li

As in all standard THM analyses, the next step is to identify and separate the quasi-free mechanism from all other processes. This is typically done by recalling the definition of a QF reaction: 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 undetected particle provides a major constraint for the presence of the quasi-free mechanism and the possible application of THM.

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 must be selected. Since $(d\sigma/d\Omega)$TH is nearly constant in a narrow energy and 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 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 standard geometrical parameters.

An evident distortion of the momentum distribution appears, 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 qt from the projectile a to the center of mass of the final system B = C + c. In the present case, the value of qt is about 133 MeV/c, and the width of the momentum distribution is about 23 MeV/c, which agrees with the trend of the curve that represents the best fit to the function reported in Ref. [12], FWHM(qt) = f0[1 $-$ exp($-$qt/q0)]. For the further analysis, the condition |ps| $<$ 20 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 Ue

The final step is to extract the energy dependence of the S(E) factor using the standard THM procedure after selecting the quasi-free three-body reaction events. Therefore, Eq. (5) and Eq. (6) are applied. The relevant two-body reaction cross section can be extracted from the measured three-body cross section with a cut selecting the quasi-free events from the three-body reaction. Then, the S(E) factor can be determined from the definition S(E) = σ(E)E exp(2π), where the Sommerfeld parameter is = Z1Z2e2/(v). In the present work, only the s-wave (l = 0) was considered for the energy range Ecm = 0–400 keV.

The results for the d(d,p)t reaction in terms of the bare-nucleus astrophysical Sbare(E) factor are presented in Figure 6 [Figure 6: see original paper] (blue points) after normalization with direct data (red points) [16, 22]. The normalization was performed in the energy range Ecm = 40–400 keV, where the electron screening effect is still negligible. It should be pointed out that direct data suffer from electron screening effects, which do not affect the THM results. Thus, the S(E) extracted via THM is called Sbare(E). A polynomial fit to the data yields Sbare(0) = 56.7 ± 2.0 keV • b.

The data from the present experiment (blue points) are compared with those from PRC-2013 [15] for 6Li = (d + α) breakup in a previous THM experimental run (pink points) and those from APJ-2014 [16] for 3He = (d + p) breakup (green points). Overall agreement is found among both direct and indirect data sets within experimental errors. It should be noted that the errors in the present case are much smaller than in the case of PRC-2013 [15], which used the same Trojan horse at higher beam energy and employed ΔE detectors for particle identification.

The lack of screening effects in the THM Sbare(E) factors makes it possible to extract the screening potential Ue from comparison with direct data using the following screening function with Ue as a free parameter:

$$f_{lab}(E) = \frac{\sigma_s(E)}{\sigma_b(E)} \simeq \exp\left(\frac{\pi\eta U_e}{E}\right)$$

The result is shown in Figure 7 [Figure 7: see original paper]. The red points are the direct data by Greife et al. (1995) [22]. The blue dashed line is the fitting curve for direct data (screened), and the green line is the fit to the THM data (unscreened) from the present work. We obtain a value of Ue = 13.2 ± 4.3 eV, which is also in agreement with that of Ref. [16], Ue = 13.4 ± 0.6 eV.

Overall agreement within experimental errors is found among both direct and indirect data sets using different Trojan-horse nuclei. The errors in the present case are much smaller than in the case of PRC-2013 [15], which used the same Trojan horse 6Li. In addition, the data extracted via THM applied to 6Li and 3He breakup are comparable among themselves. That is, the use of a different spectator particle does not influence the THM results. Thus, this work provides an updated test of Trojan-horse nucleus invariance.

V. SUMMARY

A new investigation of the 2H(6Li, pt)4He reaction measurement to extract information on the astrophysical Sbare(E) factor and screening potential Ue for the d(d,p)t reaction via THM is presented in this paper, with results summarized in Table I.

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Note: Figure translations are in progress. See original paper for figures.