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Low-energy d+d fusion via the Trojan Horse Method

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Abstract. The ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions have been recently investigated from E$_{dd}$=1.5 MeV down to 2 keV, by means of the Trojan Horse Method (THM) applied to the Quasi Free ^{3}He+d interaction at 18 MeV [1]. The knowledge of their fusion cross section at low energies is of interest for pure and applied physics. Both reactions belong to the network of processes to fuel the first inertial confinement fusion reactors in the range of kT= 1 to 30 keV. These energies overlap with the burning temperatures of deuterium in the Pre-main sequence of stellar evolution. They are key processes in the Standard Big Bang Nucleosynthesis (SBBN), in an energy region from 50 to 300 keV and experimental data at least up to 1 MeV are required for an accurate calculation of the reaction rate. Providing experimental data for both channels from a single experiment and over the entire energy range of interest is crucial for an accurate calculation of the reaction rates. This is what has been obtained from the present Trojan Horse (TH) investigation with new reaction rates which deviate by more than 20% from available direct data. This represents also the first pioneering experiment in quasi free regime where the charged spectator is detected.

1. Introduction

Low energy ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions belong to the Standard Big Bang Nucleosynthesis (SBBN) network, synthesizing D, ^{3}He, ^{4}He and ^{7}Li in the early universe.They are the most important and still critical points at the SBBN relevant energies ($d-d$ relative energies E$_{dd}$ from 50 to 350 keV). All published measurements for both channels have been mainly focused either on the E$_{dd}$ region below 200 keV [2, 3, 4, 5] or at E$_{dd}$ above 1 MeV [6], while an accurate calculation of the reaction rate needs the cross section to be known from E$_{dd}$=30 keV to at least 1 MeV. All the reaction rates quoted so far rely either on polynomial [7, 8] or in the best case on R-Matrix fits [9], whose different slopes bring inside the calculations deviations of more than 15%. In a recent work [10] the total cross section for both ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions was measured at E$_{dd}$ from 55 to 325 keV in

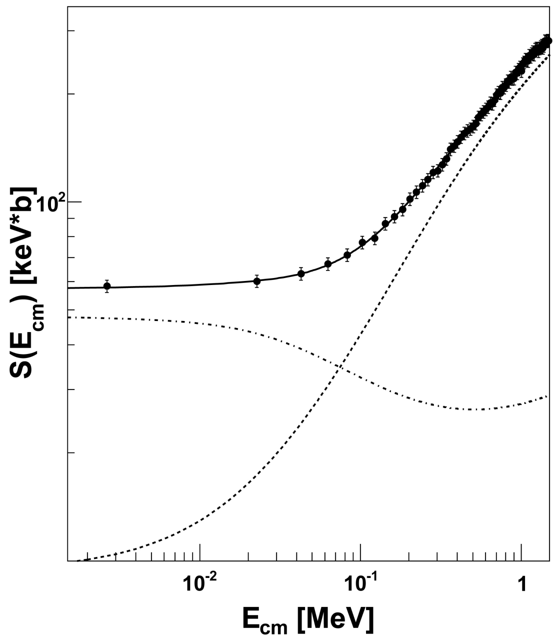

Figure 1. $S(E)$ factor for the ^{2}H(d,p)^{3}H reaction: black dots=THM results; The black solid lines represents the new TH parameterization as sum of the dashed-dotted (l=0) and dashed (l=1) lines. See text for details.

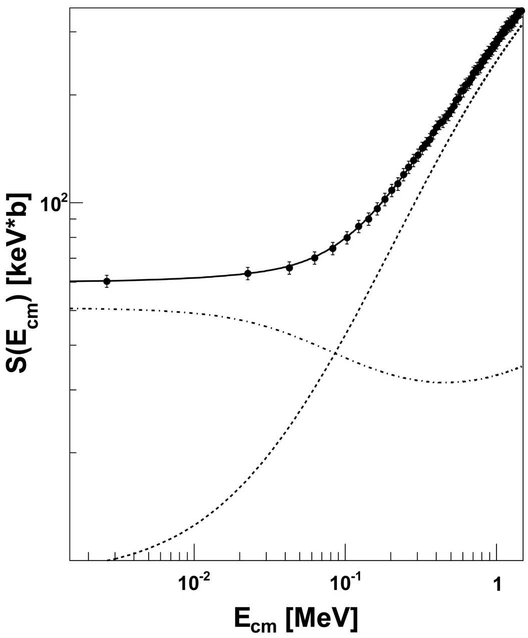

Figure 2. $S(E)$ factors of the ^{2}H(d,n)^{3}He reaction: black dots=THM data; Lines have the same meaning as in Fig.1.

steps of about 50 keV. Although uncertainties of better than 4% are quoted, there are some concerns about the procedure followed to calculate the reaction rates. For this reason, a new experimental campaign was recommended by the astrophysical community, to provide new data in the SBBN energy range of interest. Moreover, the importance of the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions in the ultra-low energy region below 30 keV is twofold: it overlaps with the burning temperatures (0-10 keV) of deuterium in Pre Main Sequence (PMS) stars and corresponds to the thermal energy range of future fusion power plants. However, the measured cross section below 10 keV, available only for the ^{2}H(d,p)^{3}H channel with a gas target [4], has shown a clear enhancement attributed to electron screening. The deduced electron screening potential of U_e= 25±5 eV is significantly larger than the adiabatic limit (14 eV) provided by atomic physics. Unfortunately, nuclear reactions in the laboratory are affected by a different mechanism of electron screening than in a plasma [11], either astrophysical or laboratory fusion with inertial confinement. Hence, the laboratory screening effects of the bound electrons should be removed from the data to assess the reaction rate correctly. This makes the knowledge of the bare nucleus cross section essential for several purposes, from basic to applied research. Usually, a simple extrapolation of available unscreened higher energy data [12] is taken as an approximation of the bare nucleus cross section, and compared to measured low-energy data to extract the electron screening potential. However, this approach can lead to large uncertainties. One can consider that available theoretical extrapolations of the bare nucleus ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He cross sections provide quite different S(0) values which vary by 10-15%. A valid alternative approach is represented by the Trojan Horse Method (THM) ([13, 14, 15] and references therein), that provides at present the only way to measure the energy dependence of the bare nucleus cross section down to the relevant ultra-low energies, overcoming the main

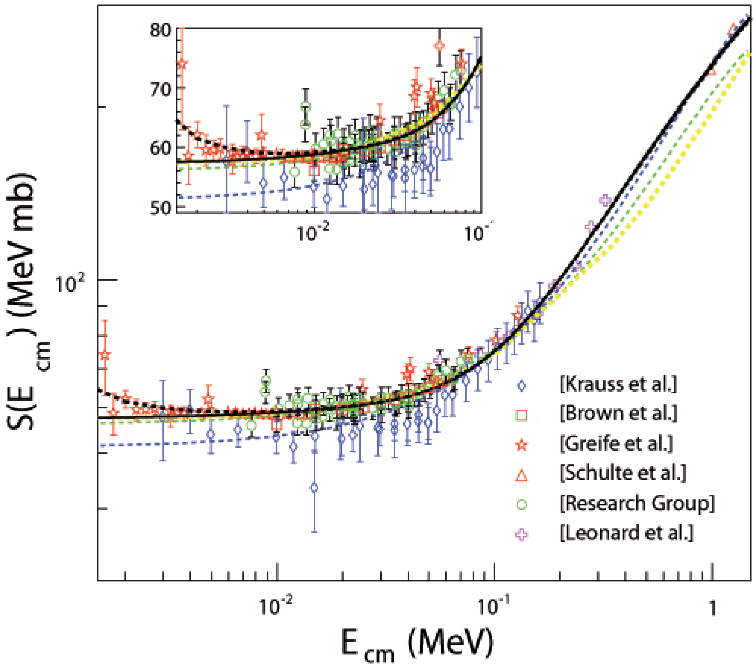

Figure 3. (Color online) $S(E)$ factor for the ^{2}H(d,p)^{3}H reaction: black solid line=THM result; colored symbols=direct data. See text for the description of the other lines.

problems of direct measurements [16, 17, 18]. The THM has already been applied several times to reactions connected with fundamental astrophysical problems [19-35] and references therein). In the present paper we report on a novel investigation of the deuterium depletion reactions ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He [1, 36] throughout the energy range relevant for pure and applied physics by means of the THM. The method was applied by choosing the ^{2}H(^{3}He,p^{3}H)^{1}H and ^{2}H(^{3}He,n^{3}He)^{1}H reactions in QF kinematics with ^{3}He as the Trojan horse. For the first time in the application of the THM, we have detected the particle that acts as a spectator to both ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H binary processes, namely the proton. This technique was mandatory for the ^{3}He+n fusion channel to avoid the limitation of standard neutron detectors. However, it was well suited also for the ^{3}H+p channel, preventing unwanted quasi free (QF) events from target break-up to be detected. A detailed account of the measurement and related data analysis is given in [1, 36]. Here, we briefly report on the main steps of analysis and on the final results.

2. Discussion and results

In previous R-matrix calculations [9], it was necessary to include the $l = 0$ and $l = 1$ components for both ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions for the determination of the $S(E)$ factor throughout the investigated E_{cm} region. Provided this information, data analysis follows the standard procedure as reported in [21, 22, 31] and references therein. With the deduced scaling ratio of the s- and p-wave contributions, the $S(E)$ factors for both reactions were then extracted as a function of E_{cm} in steps of 20 keV, with a statistical error of 4%. The normalization of the S(E) factors to direct data has to be carried out in a region where electron screening effects are negligible ($E_{cm} \geq$15 keV). To account for the different accuracies and large scatters of direct data [2, 3, 4, 5, 6, 10], a weighted normalization was carried out to all of them from E_{cm}= 1.5 MeV down to 15 keV, each with their quoted total errors (both statistical and

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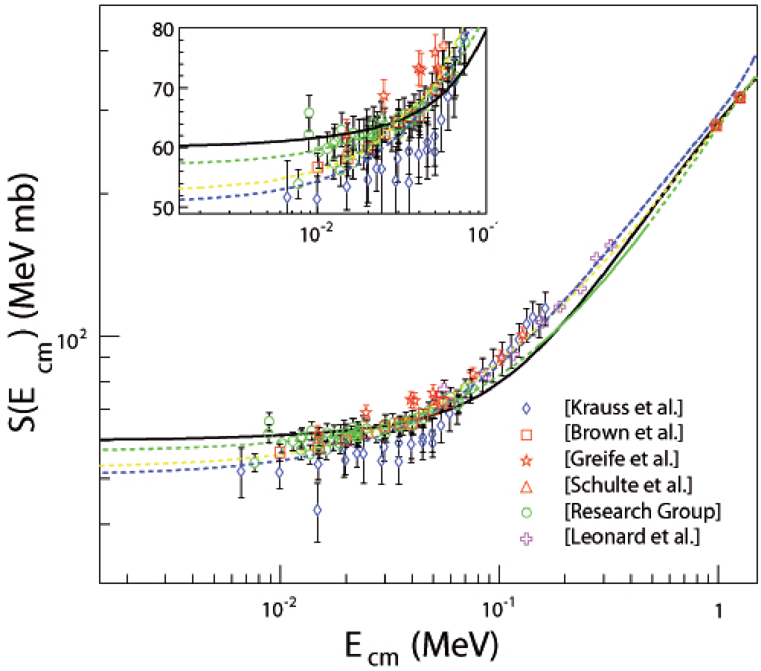

Figure 4. (Color online) $S(E)$ factors of the ^{2}H(d,n)^{3}He reaction: black solid line=THM result; colored symbols=direct data. See text for the description of the other lines.

systematic combined in quadrature). The weighted normalization procedure clearly favors the most accurate direct data, some of which have total uncertainties better than 1% [4, 6]. A total of 43 THM data points were used in the energy regions where direct data are available. The procedure leads to an overall normalization error of about 1%, obtained from the standard error combination in quadrature. The TH $S(E)$ factors of the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions are shown as black full dots in Figs. 1 and 2, respectively, with uncertainties accounting for statistical and normalization errors. We provide a new parameterization of the THM S(E) factor (black solid line in both figures) as a sum of the theoretical $l = 0$ and $l = 1$ contributions (red and blue solid lines, respectively), with relative weight fixed from the fit to the measured three-body coincidence yield. Direct data from [2, 3, 4, 5, 6] are shown as colored symbols in Figs. 3 and 4 (the legend in both figures associates a symbol and a color to each ref.), with the black TH solid line superimposed on them. The very regular trend of TH data contrasts with that of direct data taken as a whole, both in energy dependence and absolute values, with deviations of more than 15%. The polynomial/R-matrix fits to direct data, usually taken as reference, are shown as green [7], blue [8] and yellow [9] dashed lines. They barely overlap with most of the direct low-energy data, in particular in the case of the ^{3}He+n channel, probably due to their larger scatter. Conversely, the green line seems to agree with low-energy TH data, while for E_{cm} >200 keV they seem to be better reproduced by the blue line. However, none of them correctly reproduces the slope of the THM S(E)-factor in the entire energy region investigated, thus calling for a revision of the previous theoretical descriptions based on these new high quality data.

The THM parameterizations of the S(E) factors lead to new values of S(0) = 57.4±1.8 keVb for ^{3}H+p and 60.1±1.9 keVb for ^{3}He+n, with uncertainties including the 1% normalization error and 3% coming from the theory, combined in quadrature. The insets in the upper panel of both Figs. 3 and 4 help to compare these values with previous ones usually taken as reference [7, 8, 9].

The deviations are of 15%-20%. A comparison between the THM S(0) factors to the ^{2}H(d,p)^{3}H direct data below 15 keV provides further insight into the electron screening effect. Low-energy direct data at 14.95 keV from [4] were first normalized to the THM S_{bare}(E) (black solid line) and then fitted with the screening function [1] leaving U_e as free parameter. This provides a value of $U_e = 13.2 \pm 1.8$ eV, not exceeding the adiabatic limit (14 eV) for a molecular deuteron target (gas target), but covering it with its uncertainty. Additional low energy direct data for both channels would help to fix the electron screening potential.
Preliminary estimates of reaction rates based on the new THM data show that they experience relevant changes. For the ^{3}H+p (^{3}He+n) channel, the rate increases (decreases) by up to 15% at the SBBN temperatures with respect to previous calculations [7, 8, 9], while a stronger increase of more than 25% for both channels is found at the temperatures relevant for PMS and future fusion power plants.

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