Bare nucleus S(E) factor of the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions via the Trojan Horse Method

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Abstract. The Trojan Horse Method was applied for the first time to the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions by measuring the ^{2}H(^{3}He,p^{3}H)^{1}H and ^{2}H(^{3}He,n^{3}He)^{1}H processes in quasi free kinematics. The ^{3}He+d experiment was performed at 18 MeV, corresponding the a d-d energy range from 1.5 MeV down to 2 keV. This range overlaps with the relevant region for Standard Big Bang Nucleosynthesis as well as with the thermal energies of future fusion reactors and deuterium burning in the Pre Main Sequence phase of stellar evolution. This is the first pioneering experiment in quasi free regime where the charged spectator is detected. Both the energy dependence and the absolute value of the bare nucleus S(E) factors have been extracted for the first time. They deviate by more than 15% from available direct data with new S(0) values of 57.4±1.8 MeVb for ^{3}H+p and 60.1±1.9 MeVb for ^{3}He+n. None of the existing fitting curves is able to provide the correct slope of the new data in the full range, thus calling for a revision of the theoretical description. This has consequences in the calculation of the reaction rates with more than a 25% increase at the temperatures of future fusion reactors.

1. Introduction

The ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions at low energies are important in pure and applied physics. These reactions are part of the Standard Big Bang Nucleosynthesis (SBBN) network, synthesizing D, ^{3}He, ^{4}He and ^{7}Li in the early universe. Before the WMAP accurate results, SBBN was the only way to evaluate the baryonic density in the Universe (η), by comparing observed and calculated light-element abundances. Since measuring primordial abundances has improved, the interest in the reaction rates as input parameters for accurate consistency tests of the SBBN model has increased again. This applies in particular to the deuterium, the best baryometer, as its primordial abundance decreases rapidly with η and its later chemical evolution is simple, being essentially destroyed in stars [2]. The uncertainty of η inferred from deuterium is contributed equally by the observational error in the deuterium abundance and by the uncertainties in the cross sections of reactions belonging to the deuterium SBBN network [1]. Among them, the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He processes 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 lower E_{dd} region [3, 4, 5, 6] or at E_{dd} above 1 MeV [7]. 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 [8, 9] or in the best case on R-Matrix fits [10], whose different slopes bring inside the calculations deviations of more than 15%. In a recent work [11] 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 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 in order to provide new data in the SBBN energy range of interest. Moreover, the importance of 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 [5], has shown a clear enhancement attributed to electron screening. The deduced electron screening potential of U_e= 25$\pm$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 [12], 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 [13] 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 wich vary by 10-15%. A valid alternative approach is represented by the Trojan Horse Method (THM) ([14, 15, 16, 17] 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 problems of direct measurements [17, 18]. The THM has already been applied several times to reactions connected with fundamental astrophysical problems ([14, 15, 16] 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 [19] 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 QF events from target break-up to be detected. A detailed account of the measurement and related data analysis is given in [19]. Here, we briefly report on the main analysis details and final results.

2. Data analysis and results

After the channel selection, accomplished as reported in [19], the occurrence and the dominance of the QF mechanism in both cases was indicated by the consistency within 3% of the shape of the experimental momentum distribution deduced in PWIA (see [14, 15, 16] for details) with the theoretical one [19]. According to previous R-matrix calculations [10], it is 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 in the determination of the $S(E)$ factor throughout the investigated E_{cm} region. With this information, data analysis follows the standard procedure as reported in [14, 15, 16] 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} ≥15 keV). However, available data sets below 200 keV for both ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions present different accuracies and large scatters, probably due to large systematic errors in some of those measurements [8]. Thus, a weighted normalization was carried out to direct data of [3, 4, 5, 6, 7, 11], from E_{cm}= 1.5 MeV down to 15 keV, each with their quoted total errors (both statistical and systematic combined in quadrature). The weighted normalization procedure [21] clearly favours the most accurate direct data, some of which have total uncertainties better than 1% [5, 7]. 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 $S(E)$ factors of the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions are shown in the upper part of Figs. 1 and 2, respectively. TH data are shown as black full dots, with uncertainties accounting for statistical and normalization errors. Direct data from [3, 4, 5, 6, 7] are shown as colored symbols (the legend in both figures associates a symbol and a color to each ref.). 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 [8], blue [9] and yellow [10] 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. We provide a new parameterization of the THM S(E) factor 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. This gives the total S(E) factor shown as a black solid line in each figure. For a better assessment and comparison, the bottom panels of Figs. 1 and 2 show the residual scattering in the direct data about this curve divided by the weighted dispersion σ (1.82 keVb for the ^{3}H+p and 4.24 keVb for the ^{3}He+n channel), as reported in [9] for a one parameter fit or renormalization where systematics dominate. The dashed horizontal lines represent the 1-sigma error bars. These plots help to visualize the trends of the deviation from the normalized theoretical S(E) factor for each of the direct data sets. 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. 1 and 2 help to compare these values with previous ones usually taken as reference [8, 9, 10]. 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 [5] were first normalized to the THM S_{bare}(E) (black solid line) and then fitted with the screening function [23] 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. Further improvements in the precision of direct low-energy data would help to pin point the electron screening potential.

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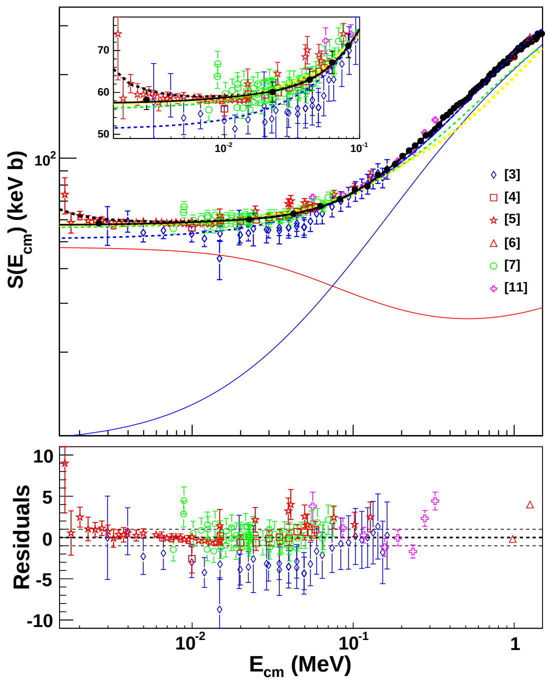

Figure 1. (Color online) $S(E)$ factor for the ^{2}H(d,p)^{3}H reaction: black dots=THM results; colored symbols=direct data. See text for the description of the lines. Bottom panel: residuals of direct data to the black solid line, with dashed lines indicating the 1-sigma error bars.

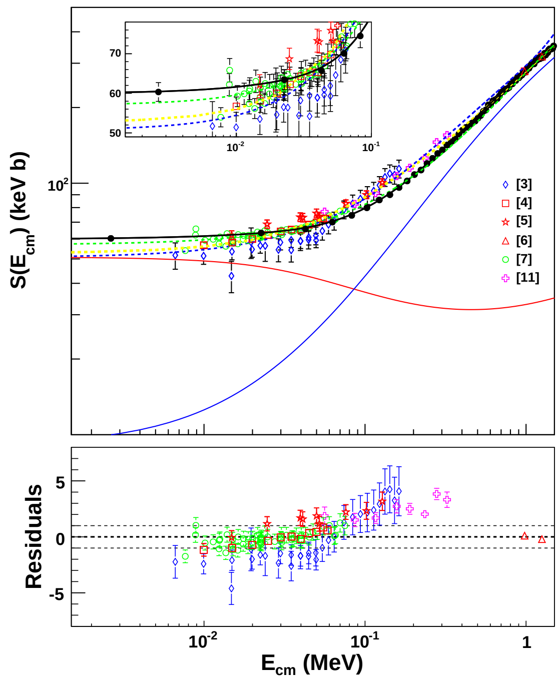

Figure 2. (Color online) $S(E)$ factors of the ^{2}H(d,n)^{3}He reaction: black dots=THM data; colored symbols=direct data. Lines have the same meaning as in Fig.1. Same meaning also for the bottom panel.

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