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The long-standing connection of BBN and Indirect measurements: the ^{3}He(n,p)^{3}H reaction at Big Bang energies

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Abstract. Nuclear reactions play a key role in the framework of the Big Bang Nucleosynthesis. A network of 12 principal reactions has been identified as the main path which drives the elemental nucleosynthesis in the first twenty minutes of the history of the Universe. Among them an important role is played by neutron-induced reactions, which, from an experimental point of view, are usually a hard task to be measured directly. Nevertheless big efforts in the last decades have led to a better understanding of their role in the primordial nucleosynthesis network. In this work we apply the Trojan Horse Method to extract the cross section at astrophysical energies for the ^{3}He(n,p)^{3}H reaction after a detailed study of the ^{2}H(^{3}He,pt)H three–body process. The experiment was performed using the ^{3}He beam, delivered at a total kinetic energy of 9 MeV by the Tandem at the Physics and Astronomy Department of the University of Notre Dame. Data extracted from the present measurement are compared with other published sets available in literature. Astrophysical applications will also be discussed in details.

1 Introduction

The ^{3}He(n,p)^{3}H process is one of the most relevant neutron induced reactions in Big Bang Nucleosynthesis (BBN) and has a strong impact on the primordial He and Li isotopes production. At the temperatures relevant for predicting Big Bang yields, the reaction rate is determined by the ^{3}He(n,p)^{3}H cross section in the energy range $0 \leq E_{cm} \leq 0.4$ MeV. The first studies of this reaction were performed by Coon et al. [1] in 1950 in the $0.1 \leq E_{cm} \leq 30$ MeV using a neutron beam. Errors turned out to be around 30%. Other measurements, more focused at lower energies, were conducted by Batchelor et al. [2] (direct one, $0.1 \leq E_{cm} \leq 1$MeV), Gibbons et al. [3] (inverse measurement) and Costello et al. [4] who measured directly in the range $0.3 \leq E_{cm} \leq 1.1$ MeV. Theoretical predictions are also available, the most recent one carried out by Drosg et al [5], which covered a wider energy range. Reaction rates were then calculated for astrophysical applications by Brune et al. [6], Adahchour et al. [7] and Smith et al. [8]. They all show a similar trend at temperatures of astrophysical interest while the reaction rate calculated by Caughlan & Fowler [9] is considerably higher. In the energy range of interest, the existing data are therefore sparse and mostly measured more than fifty years ago after facing tough experimental challenges, thus resulting several times in errors as high as 30% depending on the energy.

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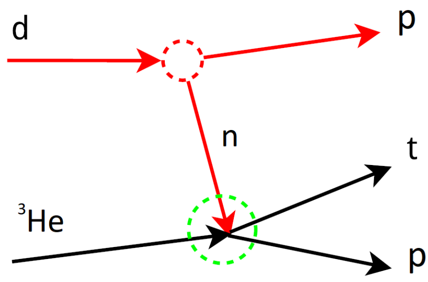

Figure 1. Diagrams describing the TH reaction ^{2}H(^{3}He,pt)H in the QF kinematics, proceeding through the direct ^{3}He(n,p)^{3}H sub-reaction.

Alternative and complementary ways to obtain the bare nucleus cross section, σ, have been provided by indirect methods such as the Coulomb dissociation method [10, 11] and the ANC (Asymptotic Normalization Coefficient) method [12]. Among those ones, the Trojan-Horse method (THM) [13, 18] is particularly suited to investigate, at astrophysical energies, binary reaction induced by neutrons or charged particles by using appropriate three-body reactions. It allows one to avoid both Coulomb and centrifugal barrier suppression and electron screening effects, thus very low energies can be reached and extrapolations are not needed. The latter has shown its great power for measuring reaction rates for the BBN in the whole energy range of interest. This is reviewed in [14] and has been extended to reactions induced by unstable nuclei of interest for BBN e.g .^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li [15–17]. The same methodology has been adopted here for the ^{3}He(n,p)^{3}H reaction. For the details on the method description please refer to [19, 20] and references therein. The THM has been successfully applied to the measurement of bare-nucleus cross sections of reactions between charged particles at sub-Coulomb energies. Many validity tests were also performed for it like the pole invariance test which was positively satisfied, for details see [21]. The method has been used in the last three decades to explore nucleosynthesis reactions other than the primordial ones in different sites, e.g., AGB stars [22–24], LiBeB depletion in stars [25, 26] as well as novae [27–29] .

In recent years, neutron induced reactions [30] have been addressed as well, using deuterons as TH nuclei to transfer neutrons, while protons act as spectators. As is sketched in Fig. 1, this work will present the investigation of the ^{2}H(^{3}He,pp)^{3}H quasi-free reaction, thus applying the THM in order to retrieve the cross section for the ^{3}He(n,p)^{3}H reaction at astrophysical energies.

2 Experiment and results

The ^{3}He beam, delivered at a total kinetic energy of 9 MeV by the FN Tandem accelerator at the Nuclear Physics Laboratory of the University of Notre Dame, was impinged on a 100 μg/cm^{2} isotopically enriched (up to 98%) deuterated polyethylene target, which was manufactured at the INFN-LNS target laboratory. Detectors were placed as sketched in angular positions reported in [31]. Three silicon position sensitive detectors (PSD 1-3), 1000 μm thick were used; PSD1 was coupled with a 35 μm thin, 10×50 mm^{2} silicon detector for particle identification, while no particle identification was required for the other two detectors,

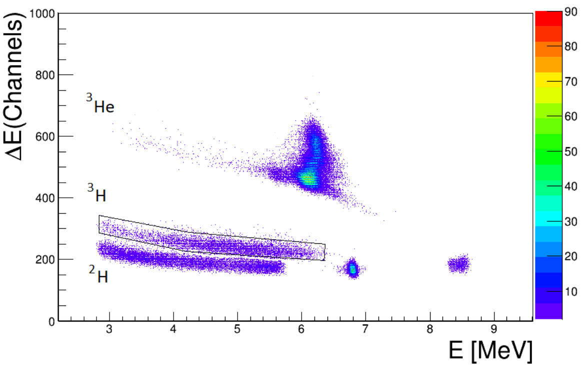

Figure 2. ΔE/E plot for PSD1 for a typical run of the ^{2}H(^{3}He,pt)H reaction. The black selection represents events identified as tritons.

thus optimizing the energy resolution of the apparatus. Two symmetrical monitor detectors were placed on both sides of the beam at 60^o to check the beam symmetry. Another point-like silicon detector (PL1) was placed at 45° for on-line monitoring of the target thickness and its deuterium content during the experiment. A metal grid, with equally spaced slits, was placed in front of each PSD in order to perform an accurate angular calibration. As a first stage of the measurements, devoted calibration runs were performed for energy and angular calibration. Thanks to the spatial resolution of PSD and to the accurate positioning of the detectors which were measured by optical means, an angular resolution of about 0.15 deg. was calculated. This is required by THM for an improved spectator momentum resolution which is crucial for QF mechanism selection.

The first phase of the analysis is the identification of the three-body process of interest among those occurring in the target. For this purpose, a particle identification is performed for PSD1 via the ΔE/E technique as reported in fig. 2. Many loci are populated and in particular those related to deuterons and tritons are present, the latter being selected by means of the graphical cut. For further analysis only events corresponding to the tritium locus in ΔE/E matrices are used. The identification is then completed as reported extensively in [31] taking advantage of Q-value spectra investigations as well as kinematic loci. After it, the momentum distribution of the experimentally obtained spectator momentum distribution is taken as the main evidence of the occurrence of quasi-free process as prescribed in reference [32]. It is then verified that the proton acts as a spectator and therefore a cut on its momentum distribution is performed, using for the further analysis only events which has $p_s \leq 30$ MeV/c.

By applying the standard THM prescriptions as it is extensively reported in [31] experimental data are compared with direct data present in literature after normalization (at energies between 350 and 400 keV). The final results are then reported in the table 1. The obtained results show a good agreement with direct and indirect measurements already present in the literature, and gives, again, a strong confirmation of THM approach to neutron induced reactions.

Table 1. Cross section for the process of interest normalized to direct data as discussed in the text.

Energy (MeV)	Cross section (barn)	error on σ(E)
0.005	10.4	1.0
0.035	3.8	0.3
0.065	2.4	0.2
0.095	2.0	0.2
0.125	1.8	0.2
0.155	1.5	0.1
0.185	1.2	0.1
0.215	1.2	0.1
0.245	1.0	0.1
0.275	1.0	0.1
0.305	1.0	0.1
0.335	0.8	0.1
0.365	0.8	0.1

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