Astrophysical S-factor for the ^{2}H(p,γ)^{3}He reaction at big-bang nucleosynthesis energies

Isabela Tišma[1,*], *Matej* Lipoglavšek[1], *Miha* Mihovilovič[1,2,3], *Sabina* Markelj[1], *Matjaž* Vencelj[1], and *Jelena* Vesić[1,4]

[1]Jožef Stefan Institute, SI-1000 Ljubljana, Slovenia
[2]Faculty of Mathematics and Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia
[3]Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, DE-55128 Mainz, Germany
[4]GSI Helmholtzzentrum für Schwerionenforschung GmbH, DE-64291 Darmstadt, Germany

Abstract. We report on our latest experimental study of the ^{2}H(p,γ)^{3}He reaction in the energy range of interest for big-bang nucleosynthesis. The differential cross section at 135° and γ-ray angular distributions were measured and compared with the results deduced from the latest *ab-initio* calculation. The astrophysical S-factor for the ^{2}H(p,γ)^{3}He reaction was obtained in the center-of-mass energy range E = 97–210 keV, and it is found to be in reasonable agreement with that predicted by the *ab-initio* calculation.

1 Introduction

The ^{2}H(p,γ)^{3}He radiative capture reaction has a major role in big-bang nucleosynthesis (BBN). The uncertainty in this reaction rate has a strong impact on primordial abundances of ^{2}H, ^{3}He and ^{7}Li. In order to determine the reaction rate and its associated uncertainty, one requires the astrophysical S-factor, which is deduced either from the measured data or a nuclear reaction model. The latest BBN calculation of Coc *et al.* [1] predicts the primordial deuterium to hydrogen ratio of ^{2}H/H = $(2.45\pm0.10)\times10^{-5}$. This result is in good agreement with that of Cooke *et al.* [2], ^{2}H/H = $(2.527\pm0.030)\times10^{-5}$, deduced from astronomical observations. However, as now the observed deuterium abundance is known at about one percent level, the same precision is expected on the theoretically predicted result. Hence, there is a need for accurately measured nuclear cross section (S-factor) of the ^{2}H(p,γ)^{3}He reaction in the BBN energy range of interest. The total cross section for this reaction has already been measured by several research groups. The LUNA Collaboration [3] obtained a considerable amount of data for a very low energy region (up to E = 22 keV). However, there are only a few data points reported for the energy range of 30–300 keV [4–8], relevant for BBN, which seem to be in a disagreement with the latest *ab-initio* calculation of Marcucci *et al.* [9]. The most recent measurements, reported by Ma *et al.* [7], unveil a discrepancy in the S-factor of $\approx 20\%$ with respect to the values obtained by calculation of Ref. [9]. This disagreement brings on further difficulties, since one cannot reliably estimate the energy dependence of the S-factor, which is crucial to determine the reaction rate and primordial abundances.

*e-mail: isabela.tisma@ijs.si

2 Experiment

The experiment was performed using the 2 MV Tandetron accelerator at Jožef Stefan Institute in Ljubljana, Slovenia. The experimental setup was composed of two high-purity germanium (HPGe) detectors, placed at 90°±10.2° and at a backward angle of 135°±12.3° with respect to the beam axis. The detector efficiencies were 40% an 53%, relative to a 3"×3" NaI crystal at 1.33 MeV. In the first stage of the experiment, the absolute differential cross section was measured at 135°, using the proton beam of energies E_{p} = 260–321 keV. Subsequently, the γ-ray angular distributions were determined.

The two deuterated titanium targets used were prepared by implantation with Tectra IonEtch ion gun at 3.5 kV. The target depth profiles were obtained after the experiment with the proton beam by utilizing the ^{3}He beam and ^{2}H(^{3}He,p)^{4}He reaction [10]. For that purpose, we put a passivated implanted planar silicon (PIPS) detector with an active surface area of 300 mm^{2} at an angle of 135° with respect to the beam axis. For more details, see Ref. [11].

3 Results

Quantitative deuterium depth profiling [10] has shown that one of the targets had an effective thickness of 1.6 μm and was considered to be thick, while the other one had a thickness of 281 nm. The γ-ray spectra (from the ^{2}H(p,γ)^{3}He reaction) for the two targets are shown in Fig. 1. The γ-ray angular distributions (Fig. 2) were found from the relative full-energy peak (5.6 MeV) areas and efficiencies of the two HPGe detectors (at 90° an 135°). Eventually, the astrophysical S-factors were deduced from the measured differential cross sections and γ-ray angular distributions (procedure explained in Ref. [11]). Results are shown in Fig. 3, where they are plotted along with the polynomial best fit of Ref. [12], and theoretical prediction of Ref. [9].

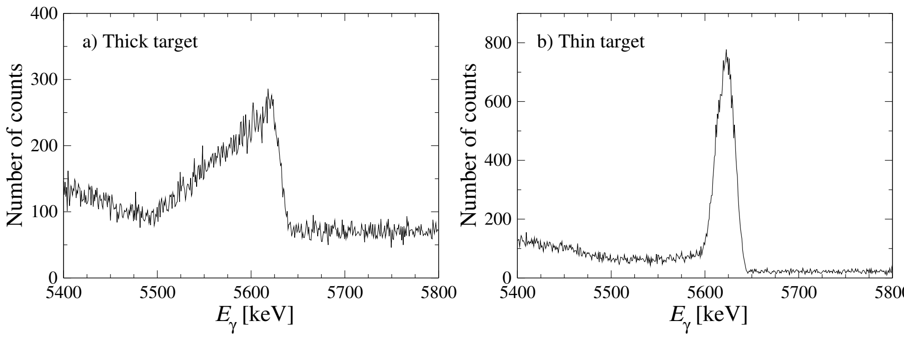

Figure 1. Full-energy peak in the γ-ray spectra from the ^{2}H(p,γ)^{3}He reaction, measured at θ = 135° with the proton beam of E_{p} = 260 keV.

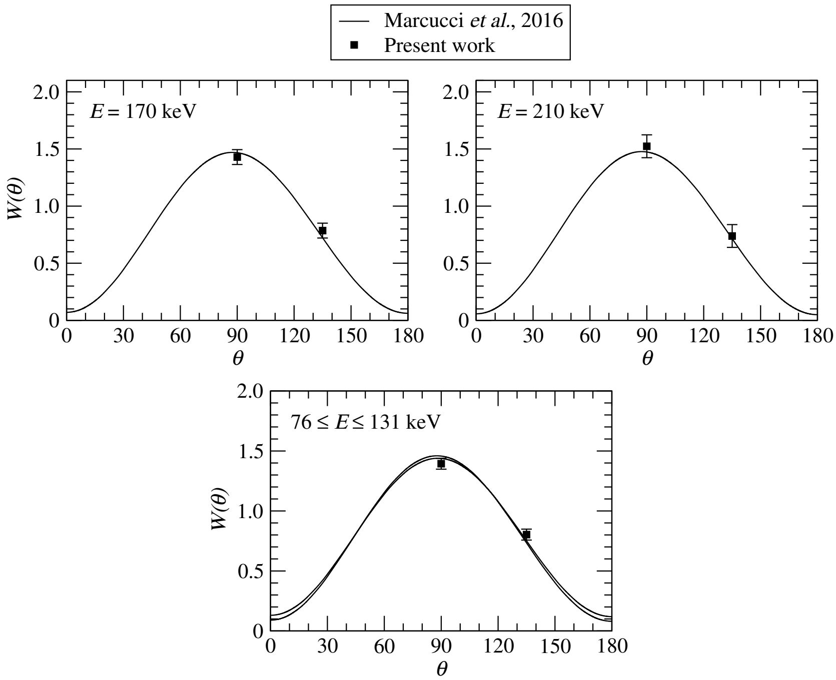

Figure 2. Angular distribution of the ^{2}H(p,γ)^{3}He reaction. The experimental data were obtained at θ = 90° and 135°.

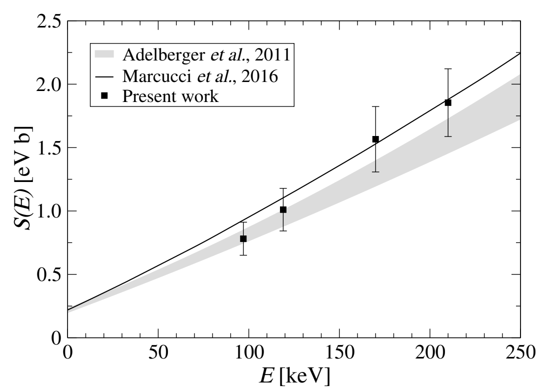

Figure 3. Astrophysical S-factor for the ^{2}H(p,γ)^{3}He reaction in the energy range of interest for BBN. Error bars show statistical uncertainty only.

4 Conclusions

The results obtained for the angular distribution of the ^{2}H(p,γ)^{3}He reaction indicate a strong angular dependence of the differential cross section, as initially assumed, and are very well described by the calculation of Marcucci *et al.* [9]. In addition, the theoretically predicted S-factors are in a reasonable agreement with our experimental findings. However, more data are needed in order to resolve the discrepancy between the previous experiments and the latest prediction of Ref. [9]. Unfortunately, the further measurements at our facility are not possible at the moment, due to the following limitations: 1. The proton beam energies lower than 260 keV are hardly accessible by our accelerator. Thus, in order to reach the lower energies it is necessary to use the thick targets; 2. Currently, we have only two germanium detectors at our disposal – we opted for the detection angles of 90° and 135°, since at these angles we could put the detector closest to the target, which ensured the maximum detection efficiency.

References

[1] A. Coc *et al.*, Phys. Rev. D **92**, 123526 (2015).
[2] R. J. Cooke *et al.*, Astrophys. J. **855**, 102 (2018).
[3] C. Casella *et al.* (LUNA Collaboration), Nucl. Phys. A **706**, 203 (2002).
[4] G. M. Griffiths *et al.*, Can. J. Phys. **40**, 402 (1962).
[5] G. M. Griffiths *et al.*, Can. J. Phys. **41**, 724 (1963).
[6] G. M. Bailey *et al.*, Can. J. Phys. **48**, 3059 (1970).
[7] L. Ma *et al.*, Phys. Rev. C **55**, 588 (1997).
[8] G. J. Schmid *et al.*, Phys. Rev. C **56**, 2565 (1997).
[9] L. E. Marcucci *et al.*, Phys. Rev. Lett. **116**, 102501 (2016).
[10] M. Mayer *et al.*, Nucl. Instr. Meth. B **267**, 506 (2009).
[11] I. Tišma *et al.*, Eur. Phys. J. A **55**, 137 (2019).
[12] E. G. Adelberger *et al.*, Rev. Mod. Phys. **83**, 195 (2011).