A BGO set-up for the direct measurement of the D(p,γ)³He fusion cross section at LUNA

Viviana Mossa on behalf of the LUNA collaboration
INFN, Sezione di Bari, Via Amendola 173, 70126 Bari, Italy
E-mail: viviana.mossa@ba.infn.it
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Abstract. The Big Bang Nucleosynthesis (BBN) describes the production of light nuclides occurred during the first minutes of cosmic time. It started with the accumulation of deuterium, whose primordial abundance is sensitive to the universal baryon density and to the amount of relativistic particles. Currently the main source of uncertainty to an accurate theoretical deuterium abundance evaluation is due to the poor knowledge of the D(p,γ)³He cross section at BBN energies. The present work wants to describe one of the two experimental approaches proposed by the LUNA collaboration, whose goal is to measure with unprecedented precision, the reaction cross section in the energy range 30 < E_{cm}[keV] < 300.

1. Introduction

Primordial deuterium abundance depends on the universal expansion rate and on the reaction rate of the relevant processes involved in its creation and destruction. Recent observations in Damped Lyman-Alpha (DLA) systems at high redshifts provide \( (D/H)_{\text{obs}} = (2.527 \pm 0.030) \times 10^{-5} \), where \( (D/H)_{\text{obs}} \) is the abundance of deuterons with respect to protons [1]. The primordial abundance of deuterium can be inferred also indirectly merging a given cosmological model and the standard Big Bang Nucleosynthesis (BBN) dynamics. Assuming the ΛCDM cosmological scenario together with high precision CMB measurement, the deuterium primordial abundance is \( (D/H)_{\text{BBN}} = (2.587 \pm 0.065) \times 10^{-5} \) [2]. These two deuterium abundance determinations, while broadly consistent, are off by more than one standard deviation. This tension might be the result of experimental systematics due to the poor knowledge of the reactions cross section. In particular the main source of uncertainty on standard BBN prediction of deuterium abundance is actually due to the capture process D(p,γ)³He converting deuterium into helium, because of the poor knowledge of its S-factor at BBN energies. A measurement of this reaction is thus desirable with a 3% accuracy in the energy range 30 < E_{cm}[keV] < 300 [3]. In addition a precise measurement of this cross section is crucial for testing ab-initio calculations in theoretical nuclear physics.
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2. The BGO setup

The LUNA experiment exploits the low background environment of the underground INFN laboratory under the Gran Sasso Mountain (LNGS) to perform direct cross section measurements at relevant astrophysical energies [4]. A considerable effort was devoted in the past to the study of the Big Bang Nucleosynthesis [5].

The measurement described here is based on the use of a 400 kV electrostatic accelerator able to provide intense proton beam with 50-400 keV of energy and with current up to 300 $\mu$A, characterized by a precise absolute energy ($\pm$0.3 keV), low spread (<0.1 keV) and long-term stability (5 ev/h) [6].

A windowless deuterium gas target 10 cm long at 0.3 mbar of pressure has been used. The lack of a real window prevents the beam energy loss before entering the interaction chamber and limits the beam energy straggling. To confine the gas inside the interaction chamber, a strong pressure gradient between the target and the beam line is maintained by three pumping stages separated by three water cooled apertures of decreasing diameter.

The beam current is measured by a calorimeter with a constant temperature gradient between a hot and a cold side [7]. A chiller keeps the cold side at the constant temperature $T_{\text{cold}} = -20^\circ\text{C}$, while eight heating resistors provide a power $W_0$ to keep the hot side at the constant temperature $T_{\text{hot}} = 70^\circ\text{C}$, so that, in stationary conditions, a constant power is delivered by the resistors to maintain the temperature gradient. When the ion beam hits the hot side, it contributes to its heating and reduces correspondingly the electric power needed to keep the temperature gradient constant. Thus calculating the power difference between beam-off and beam-on conditions, the current can be evaluated.

The $\gamma$-rays emitted by the $\text{D}(p, \gamma)^{3}\text{He}$ reaction have been detected by a cylindric BGO detector having a length of 28 cm with a radial thickness of 7 cm. The crystal is optically divided into six sectors, each covering an azimuthal angle of 60 degrees granting a almost $4\pi$ geometry configuration. The interaction chamber and the calorimeter are hosted inside the BGO hole as shown in figure 1.

![Figure 1. Drawing of the target inside the BGO detector.](image)

With this set-up, the counting rate (full detection $\gamma$-peak) obtained is of the order of $10^4$ - $10^5$ events/hour in the considered energy range, making the measurement with the
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BGO detector relatively fast for reaching 10000 events under the photopeak to ensure a low systematic uncertainty ( < 1%). On the other hand the large angular coverage of BGO makes the counting yield almost independent of the angular distribution of the emitted photons.

A second phase was performed at LUNA using a High Purity Germanium detector (HPGe) facing the gas target in a close geometry. Thanks to its high energy resolution (about 5 keV at $E_\gamma = 6$ MeV) the study of the angular distribution of the emitted γ-rays was also possible [8].

3. Setup characterization

The gas target density has been calculated by measuring directly the temperature and the pressure profiles along the beam axis. As shown in figure 2 (left), the pressure inside the target chamber is constant within ±0.3%, while inside the collimator there is a monotonous decrease, as expected for a high-impedance tube. Finally in the tube connecting the chamber to the first pumping stage, the trend continues to decrease with a lower slope. Figure 2 (right) shows the trend of the temperature profile: inside the target chamber, the temperature drops monotonously between the beam stop, heated to 343 K, and the collimator; while inside the connecting tube, it shows a constant trend within 0.2% at about 294 K. The gas density also depends on the heat transfer

Figure 2. Left panel: Measured pressure profiles in deuterium at 0.3 mbar. Lines are a guide to the eye. Right panel: Measured temperature profiles.

from the ion beam to the gas target (beam heating effect). This effect has been studied experimentally for the deuterium gas target at 0.3 mbar of pressure performing measurements at constant beam energy and different currents. In figure 3, the results obtained with a proton beam of 300 keV and different beam currents are shown: a current of 200 μA leads a target density reduction of about 1%.

Before the beam intensity can be obtained, the calorimetric power $W_{\text{cal}}$ must be electrically calibrated by associating it to the electrical power $W_{\text{el}}$, measured using the chamber and calorimeter as a Faraday cup. Four calibration campaigns have been
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Figure 3. Counts/Coulomb vs beam current in a deuterium gas target at $p=0.3$ mbar and $E_{\text{beam}} = 300$ keV.

performed in different periods of the year and the results obtained, summarized in figure 4, show the trend of $W_{\text{el}}$ as a function of $W_{\text{cal}}$. All data lie on the same line, proving that the calibration remains constant in time and the residual plot shows that, for almost all data points, the deviation from the fitting line is less than 1%. The detection efficiency of the setup, about 60% in the range of interest for the reaction (5.5 MeV), has been obtained at a few per cent level using a Monte Carlo code [9]. The simulation has been tuned to match the experimental data: at low energies the efficiency is measured with radioactive calibrated sources ($^{137}\text{Cs}$, $^{60}\text{Co}$ and $^{88}\text{Y}$); while at higher energies, where the signals are expected during the $\text{D}(p, \gamma)^3\text{He}$ study, using the photons emitted from the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction having a resonance at $E_{p}^{\text{res}} = 278$ keV.

Figure 4. Top panel: electrical calibration of the calorimeter. Statistical error bars are smaller than the size of the data points. Bottom panel: residual plot [7].
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4. BGO-phase data analysis

The reaction cross section has been measured filling the interaction chamber with deuterium gas at 0.3 mbar of pressure and varying the proton energy from 50 to 300 keV. For each investigated energy a further run with no gas inside the chamber has been performed in order to evaluate the beam induced background or the eventual deuterium implantation, since the cosmic background contribution is largely suppressed by the Gran Sasso mountain. The most common source of beam induced background are reactions due to the interactions of proton beam with surrounding materials, such as \(^{14}\text{N}(p, \gamma)^{15}\text{O}\) and \(^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}\). As shown in figure 5 (left panel) this contribution has been found to be negligible for energies up to 250 keV.

A further beam induced background contribution can be due to the interaction of beam protons with deuterium implanted in the collimator and in the calorimeter. The ionized deuterium, having a very small physical size, diffuses inside the metal, making this extra target variable in time. When the deuterium gas is exhausted from the chamber, the rate of parasitic reactions decreases exponentially because the absorbed deuterium migrates away (diffusion and de-adsorption) from the effective extra target in a relatively short time. This background source has been studied in detail with the BGO setup. With this geometry the reaction chamber, the collimator and the hot side of calorimeter are fully contained within the hole of the BGO detector. In such a way photons from D(p, γ)³He reactions produced by beam protons with implanted deuterium are efficiently detected. Figure 5 (right panel) shows the counting rate in an energy region around 5.7 MeV as a function of time. This measurement was done without gas in the chamber after a long run at \(E_{\text{beam}} = 300\) keV with a pressure of 0.3 mbar of deuterium. The existence of a beam induced background decreasing exponentially with time, due to D(p, γ)³He reaction occurring in the shallow metal, is apparent. It has been found that the average contribution of the D(p, γ)³He parasitic reactions is of the order of 5%.

![Figure 5. Left panel: Comparison between the spectra at 250 keV of energy in deuterium (blue) and with no gas in the chamber (red). Right panel: Reaction counting rate vs time.](image)
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5. Conclusion

The low background and the high quality of the LUNA facility at LNGS has allowed the $D(p, \gamma)^3\text{He}$ cross section to be measured, filling the lack of experimental data in the BBN energy range with a higher precision with respect to the existing one and verifying theoretical nuclear models. This study is of primary importance also to derive the baryon density of Universe with high accuracy, comparable to the one obtained with CMB experiments. In addition it allows to constrain the existence of the so called ”dark radiation”, composed by undiscovered relativistic species permeating the universe, such as sterile neutrinos.

The data analysis is still ongoing and the results will be published soon.

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