PROCEEDINGS OF SCIENCE

Study of the $^{2}H(p,\gamma)^{3}He$ reaction in the Big Bang nucleosynthesis energy range at LUNA

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The first nucleus produced in the Universe is deuterium whose accumulation marks the beginning of the socalled Big Bang Nucleosynthesis (BBN). Its primordial abundance is strongly realted to the cosmological parameters, like for example the baryon density and the effective numbers of the neutrino families. Currently the main source of uncertainty in the primordial deuterium calculations comes from the $^{2}H(p,\gamma)^{3}He$ cross section at BBN energies [1].
The aim of the present work is to describe the experimental approach proposed by the LUNA collaboration, whose goal is to measure, with unprecedented precision, the total and the differential reaction cross section in the 10 keV$< E_{cm} <$300 keV energy range.

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1. Introduction

The Big Bang Nucleosynthesis (BBN) describes the production of light nuclides in the first minutes of cosmic time. It started with deuterium accumulation when the Universe was cold enough to allow ^{2}H nuclei to be survived to photo-disintegration.
A primordial deuterium abundance evaluation $D/H = (2.65 \pm 0.07) \cdot 10^{-5}$ [1] is obtained by merging BBN calculations and CMB analysis obtained by the Planck collaboration. This value is in tension with the astronomical observations on metal-poor damped Lyman alpha systems, according to which $D/H = (2.53 \pm 0.04) \cdot 10^{-5}$ [2]. The main source of uncertainty on standard BBN prediction of deuterium abundance is actually due to the radiative capture process $^2H(p,\gamma)^3He$ converting deuterium into helium, because of the poor knowledge of its S-factor at BBN energies. A measurement of this reaction cross section is thus desirable with a 3% accuracy in the energy range 10keV$< E_{cm} <$300keV [1]. Furthermore a precise measurement of the p+d reaction cross section is crucial for testing ab-initio calculations in theoretical nuclear physics.
Thanks to the low background of the underground Gran Sasso Laboratories (LNGS) and to the experience accumulated in more than twenty years of scientific activity, LUNA (Laboratory for Underground Nuclear Astrophysics) [3] [4] has planned to measure the $^2H(p,\gamma)^3He$ fusion cross section in the energy range of interest in 2016.
The experimental procedure for studying this reaction consists of two main phases characterized by two different setup. The former provides for a windowless gas target filled with deuterium at 0.3 mbar pressure together with a 4π BGO detector. This high efficiency detector will be used for investigating the energy range between 30 keV and 260 keV, trying to find a continuation of the previous results obtained by the LUNA collaboration in [5]. The latter phase, instead, will cover the medium-high energies (70keV$< E_{cm} <$260keV) using a High Purity Germanium detector (HPGe). The HPGe high resolution allows the differential cross section of the reaction to be evaluated by using the peak shape analysis.

2. Reasons for a new $^2H(p,\gamma)^3He$ measurement

The primordial abundance of the light nuclei produced during the early phases of the Universe can be calculated using cosmology, nuclear physics and particle physics inside the so-called Big Bang Nucleosynthesis (BBN) theory, through the reaction chain shown in figure 1. The reaction network begins with the production of deuterium by the $^2H(p,\gamma)^3He$ process. Nearly all the free neutrons end up bound in the most stable light element ^{4}He, while ^{2}H, ^{3}He,^{6}Li and ^{7}Li nuclei form in residual quantities.
The abundance of deuterium and of the other primordial nuclides can be inferred indirectly from merging a given cosmological model and the standard BBN dynamics. The simplest cosmological model that better describes the Universe evolution is the Lambda Cold Dark Matter (ΛCDM) model, based on three important experimental evidences: the cosmic expansion, the Cosmic Microwave Background (CMB) radiation and the Big Bang Nucleosynthesis. Thus, assuming this cosmological scenario together with high precision CMB measurement, like the one provided by the PLANK collaboration, the primordial abundance of deuterons with respect to protons is $D/H = (2.65 \pm 0.07) \cdot 10^{-5}$ [1].

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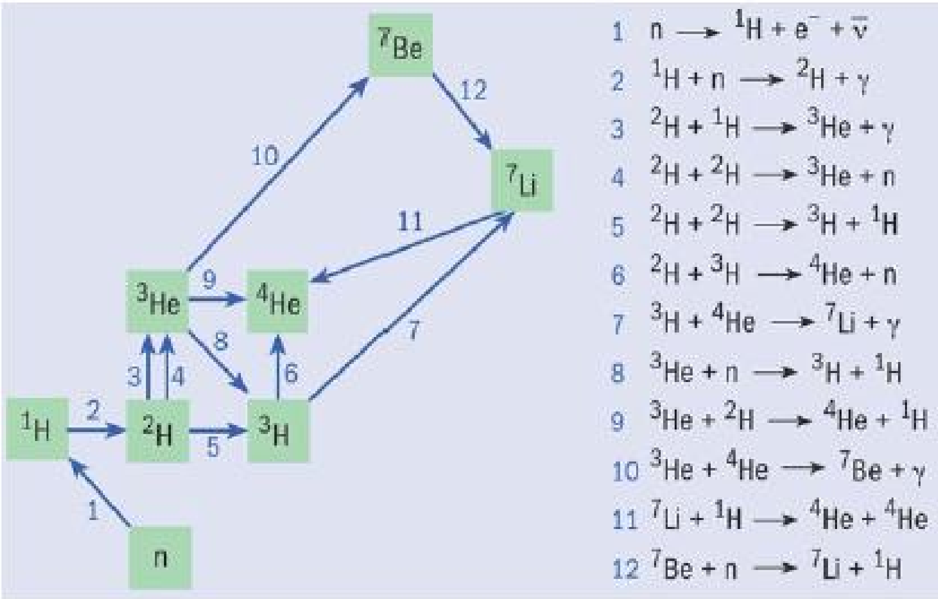

Figure 1: Leading processes of the Big Bang Nucleosynthesis.

The results of BBN theory have to be compared with the direct observations for light isotopes in the Universe. As a general method, the primordial abundances are obtained by the observation of emission or absorption lines in metal-poor systems, where the abundances are thought to be less contaminated by processes like stellar burning and cosmic-ray interactions. Recent observations in Damped Lyman-Alpha (DLA) systems at high redshift provide $D/H = (2.53 \pm 0.04) \cdot 10^{-5}$ [2], showing a small discrepancy with the previous value obtained by the BBN calculations.
These calculations depend mainly on the cross sections of a few nuclear processes, responsable for the deuterium creation and destruction. The four leading reactions controlling deuterium abundance are listed in table 2 with their corresponding error due to the uncertainty on each single cross section. The main source of uncertainty comes from the radiative capture process $^2H(p,\gamma)^3He$ converting deuterium into helium because of the lack of experimental data in the BBN energy region, about 30-300 keV, where the p+d cross section is known at the 6-10% level [1]. A new precise direct measurement of this reaction cross section in this energy range is thus desiderable.
Moreover, an accurate measurement of the $^2H(p,\gamma)^3He$ cross section can put strong constraints on the cosmological parameters being the deuterium abundance strongly dependent on the baryon density and extremely sensitive to the expansion rate of the Universe.
Finally the p+d reaction is of great interest also in the theoretical nuclear physics, because the "ab initio" calculations provide an accurate prediction for the total and differential cross section at low energies. However, the last calculation has provided a cross section about 10% larger than the currently adopted experimental value [8]. Using this theoretical cross section in the BBN calculations, an excellent agreement with astronomical data for deuterium abundance is reached. Again, a new precise direct measurement of the $^2H(p,\gamma)^3He$ cross section is desiderable to check theoretical predictions.
In this work a new study of the p+d reaction with the underground 400 kV LUNA accelerator is

Reaction	$\sigma_{D/H} \cdot 10^{-5}$
$p(n,\gamma)^2H$	±0.002
$d(p,\gamma)^3He$	±0.062
$d(d,n)^3He$	±0.020
$d(d,p)^3H$	±0.013

Table 1: List of the leading reactions controlling the deuterium abundance during the BBN, with the associated error coming from experimental (or theoretical) uncertainties in the cross section of each reaction, for a fixed baryon density $\Omega_b h^2 = 0.02207$ [1].

described. The aim is the direct measurement of the reaction cross section with a low (3-4%) overall uncertanty in the BBN energy range and the subsequent calculation of the primordial deuterium abundance with a similar uncertainty, comparable with the one obtained by observations.

3. The $^2H(p,\gamma)^3He$ reaction at BBN energies at LUNA

Thermonuclear fusion reactions between charged particles occur in a well defined energy range, called Gamow window [9], given by the convolution of the energy distribution of the available nuclei and the tunnelling probability through the Coulomb barrier. The former is provided by the Maxwell-Boltzmann distribution, showing a maximum for E=kT (with T temperature and k the Maxwell-Boltzmann constant) and then an exponential decreasing with increasing energy; while the latter decreases exponentially for decreasing energy. At BBN temperatures, the Gamow window varies between a few tens keV to hundreds keV resulting in a very low nuclear reaction cross section that can reach even the femto-barn order. It follows that a direct investigation of the reactions in the BBN energy range is often beyond technical capabilities as the signal-to-noise ratio is severely dominated by different sources of unwanted background, like the enviromental or the beam induced one. In an Earth's surface laboratory, the main contribution to the background comes from the interaction of cosmic rays with materials in the detection setup. The reaction cross sections are thus measured at higher energies and then extrapolated to the lower BBN energy range. However the extrapolation procedure can be uncertain because of the possible presence of unknown narrow resonances or tails of broad resonances and/or sub-threshold states. The only possibility to make direct measurement at BBN energies is to reduce the cosmic background. The natural shielding of about 1400 m of rock makes the Laboratori Nazionali del Gran Sasso (LNGS) an ideal candidate for this kind of measurements, providing a reduction of a factor 10^6 in muons, 10^3 in neutrons and 10^4-10^5 in gamma flux. Even if the expected $^2H(p,\gamma)^3He$ cross section is higher than other thermonuclear reactions at astrophysical energies, its experimental uncertainty will be dominated by systematic rather than statistical errors. Performing a measurement in an underground laboratory allows the background subtraction procedures with related systematic uncertanties to be avoided, reaching so higher accurancy levels.

The new $^2H(p,\gamma)^3He$ measurement planned at LUNA will exploit the 400 kV electrostatic accelerator [10] able to provide intense current of proton up to 500 μA and of alpha particles up to 300 μA, with a precise absolute energy ($\pm$ 0.3 keV), low spread (< 0.1keV) and long-term stability (5 ev/h).

The measurement foresees a windowless deuterium gas target, consisting of three-stage pumping

system able to increase the gas pressure from the accelerator high vacuum (1E-6 mbar) to the mbar level in the target chamber. Since no real window is present, the energy degradation of the proton beam is negligible and the final ion energy is precisely determinated.
The beam current is measured by a constant-gradient calorimeter characterized by two sides, a hot one heated to 70°C by thermoresistors and a cold one cooled to -5°C by a refrigerating system. The constant temperature gradient ensures that when the beam hits the calorimeter, less power is necessary to keep the temperature difference costant. Thus calculating the power difference between beam-on and beam-off conditions, the current can be evaluated.
Finally, the average gas pressure is controlled by an analog feedback system and logged permanently by a LabView application.
The gammma rays emitted by the $^2H(p,\gamma)^3He$ reaction will be detected in the energy range $50 < E_p(keV) < 400$ by a BGO detector having a 4π geometry. Additionally a HPGe detecor will be used to investigate the medium-high energy range and to obtain also the angular distribution of the emitted photons.

4. The experimental procedure

Two measurement campaigns are planned at LUNA for measuring the $^2H(p,\gamma)^3He$ cross section, characterized by the use of the two different detectors.
The first phase foresees a deuterium gas target 10 cm long at 0.3 mbar of pressure and a cylindric BGO detector having a length of 28 cm with a radial thikness of 7 cm. The crystal is optically divided into six sectors, each covering an azimuthal angle of 60 degrees. The chamber and the calorimeter are hosted inside the BGO hole as shown in figure 2. Thanks to the high detection

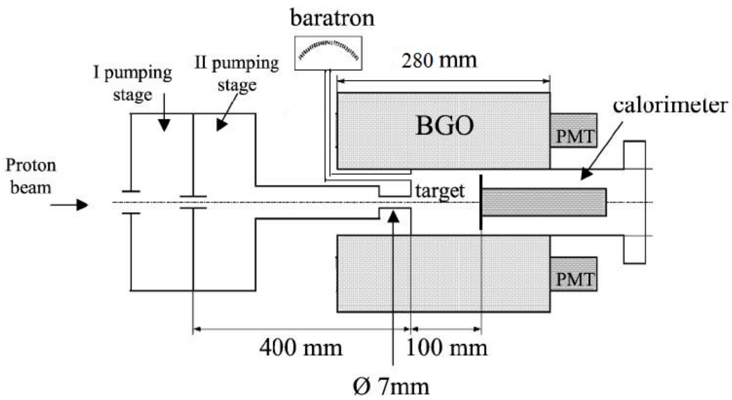

Figure 2: Gas target setup and BGO detector.

efficiency (about 60%) in the range of interest for the $^2H(p,\gamma)^3He$ reaction (5.5 MeV), this setup will provide a cross section measurement down to very low energies.
The efficiency calibration can be obtained at a few per cent level using Monte Carlo simulations of the setup, tuned with radioactive sources (^{137}Cs, ^{60}Co and ^{88}Y) at low energies and with the well-known resonant reaction $^{14}N(p,\gamma)^{15}O$ emitting γ rays in the p+d energy range. In order to reduce systematic errors, the spatial position of the resonance will be obtained coupling the BGO detector

with a well collimated NaI detector to be moved along the gas target with millimeter precision.

In a second phase, the use of a longer chamber together with an High Purity Germanium (HPGe) detector, having a nominal efficiency of 137%, is planned. The detector will be placed in close geometry at 90°C with respect to the proton beam direction (z-axis). The HPGe crystal, faced to an extended target, detects photons in the $20^\circ < \theta_{lab} < 160^\circ$ angular range, with integrated efficiency of about 0.35%. The good energy resolution of the HPGe detector (about 5 keV FWHM at $E_\gamma = 6MeV$) allows the photon energy to be precisely measured. It depends on the proton beam energy E_{beam} and on the angle of emitted photons with respect to the beam axis θ_{lab}:

$$E_\gamma = \frac{{m_p}^2 + {m_d}^2 - {m_{He}}^2 + 2(E_{beam} + m_p)m_d}{2(E_{beam} + m_p + m_d - p_p cos\theta_{lab})}$$

where E_γ is the photon energy, m_p, m_d and m_{He} are the masses of nuclides involved in the reaction, p_p is the proton momentum. For a given beam energy, the photon energy is uniquely determinated by $cos\theta_{lab}$ due to the Doppler effect and the angular distribution of the emitted photons can be established from the shape of the full energy peak. To apply this method, the HPGe efficiency along the beam axis has to be calculated. In order to do this measurement, the HPGe detector will be moved along the z-axis with 0.1 mm precision, as shown in figure 3. Also in this case,

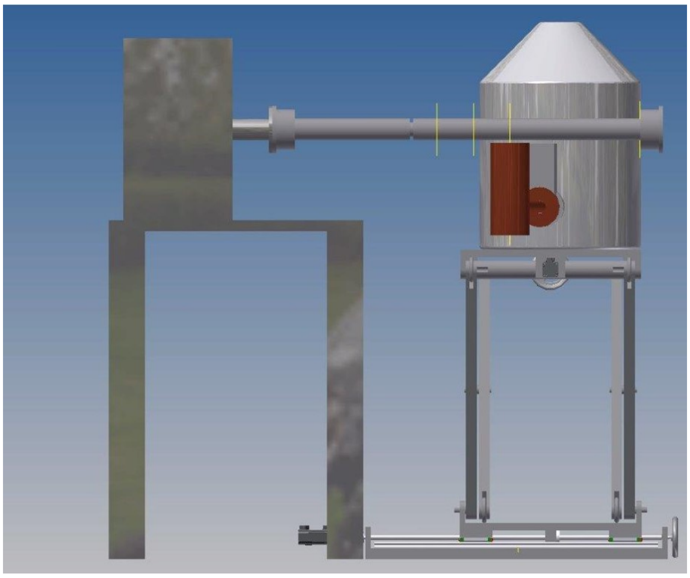

Figure 3: Gas target setup and HPGe detector moved along beam axis.

having an energy of about 5.5 MeV, the reaction emitted gamma are far away from the energy range of the commonly used radioactive sources. Thus, for the efficiency evaluation, different techniques has been developed: one is based on the well-known resonant reactions $^{14}N(p,\gamma)^{15}O$ and $^{19}F(p,\alpha\gamma)^{16}O$ [11], the other on the standard coincidence between two gamma-rays emitted in cascade [12]. For the $^{14}N(p,\gamma)^{15}O$ reaction, in order to reduce the systematic error due to the summing correction, the detector will be placed in far geometry from the chamber where the summing is completely negligible. The HPGe support, in fact, can be also moved along the vertical axis with a 0.1 mm precision (figure 4). Also in this phase the main detector will be coupled with a collimated NaI moved along the beam axis, in order to identify the correct position of the resonance inside the target chamber.

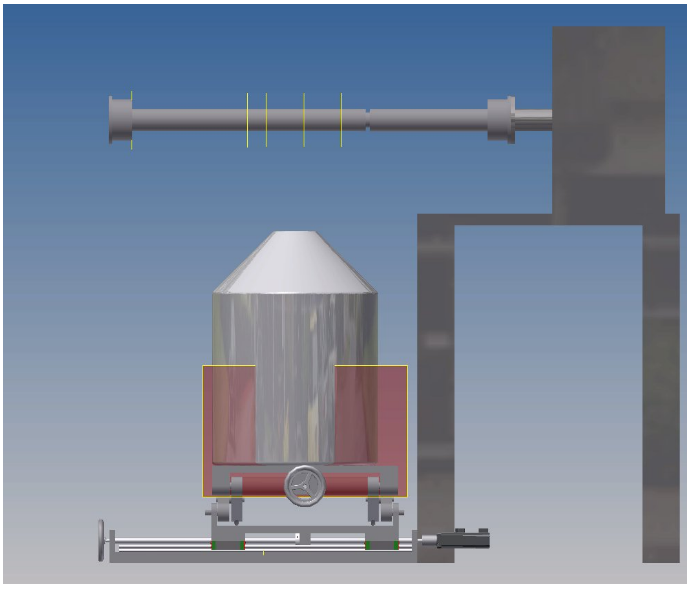

Figure 4: HPGe vertical movement.

5. Conclusion

The improvement on direct observations of deuterium abundance [2] and the accurancy of the CMB data [13][14] make the lack of $^2H(p,\gamma)^3He$ reaction data in BBN energy range the higher barrier to improve the constraints on the main cosmological parameters. As ligth nuclei are involved in this process, the p+d reaction is of high interest also for the theoretical nuclear physics. It follows that a new study of the $^2H(p,\gamma)^3He$ reaction inside the BBN energy region, trying to reach a few per cent level precision, is extremely important.
The low background at LNGS will make it possible. These new data together with those previously acquired at LUNA in [5], where the $^2H(p,\gamma)^3He$ cross section was studied in the Solar Gamow peak (2.5keV< E_{cm} <22keV), will provide a complete cross section scan in the wide 0 - 267 keV central mass energy range.

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