Nuclear Astrophysics at the Low-Energy Frontiers: Updates from underground laboratories

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Abstract. Nuclear fusion reactions are the heart of nuclear astrophysics: they sensitively influence the nucleosynthesis of the elements in the earliest stages of the Universe and in all the objects formed thereafter; control the associated energy generation and neutrino luminosity; influence the evolution of stars. Unfortunately, measuring reaction cross sections at astrophysically relevant energies is exceptionally challenging due to Coulomb repulsion between nuclei, resulting in cross section values as low as fbar. Laboratorial measurements of these cross sections are often unfeasible due to overwhelming cosmic-ray-induced backgrounds. One effective solution to this problem is to conduct experiments in underground laboratories. The Laboratory for Underground Nuclear Astrophysics (LUNA) is an experimental approach based on an underground accelerator focusing on studying nuclear fusion reactions. Its primary objective is to accomplish direct measurement of cross sections for nuclear reactions that have significance in stellar and primordial nucleosynthesis. This article will present the latest findings and future objectives.

1 Introduction

Nuclear astrophysics is a multifarious field, interrelated with astronomy, cosmology, neutrino physics, and nuclear physics. Nuclear fusion reactions serve as the centerpiece of this discipline. The lifespan of stars can be depicted as a series of phases in which successively heavier elements incinerate at the core. With primordial hydrogen and helium as a starting point, various material is produced, and theoretical models endeavor to align anticipated elemental ratios with cosmic observations. Since interacting nuclei have positive charges, they repel each other, proportional to their nuclear charge, meaning that a temperature of approximately 10^7 K is necessary for hydrogen burning so that the projectiles can break through the Coulomb barrier. Fusion is only possible if the Coulomb barrier is surpassed. Classically, the interaction energy must be higher than the effective height of the Coulomb barrier, while in quantum mechanics, particles with an energy E < E_C possess a slim probability to penetrate the Coulomb barrier (Tunnel effect). This outcome coincides with the Gamow peak [1]. At these energies nuclear cross sections can significantly decrease (pbar or fbar), thereby resulting in a count rate being much lesser than the environmental background of a detector.

One possible solution to reduce natural and cosmic background is to establish an accelerator facility deep underground, such as the LUNA experiment under the Gran Sasso Mountain with a thickness of 1400 m of rock — equivalent to 3800 m of water — to suppress muon and neutron fluxes by six and three orders of magnitude, respectively. The experimental apparatus (see figure 1) includes a 400 kV electrostatic accelerator which provides a high-intensity proton or alpha beam. The beam energy at the exit of the accelerator has a spread of less than 100 eV, and the energy drift is less than 5 eV/h. The beam energy uncertainty is kept to 0.3 keV, and the calibration is frequently rechecked and found consistent with new measurements [2]. The beam can be delivered to either a solid or gas target [3]. In the case of a solid target, the proton beam can be guided and focused to the target station using a gas target separated from the accelerator by a solid wall; the proton beam can be guided and focused to the target station using a gas target separated from the accelerator by a solid wall, while in quantum mechanics, particles with an energy E < E_C possess a slim probability to penetrate the Coulomb barrier (Tunnel effect). This outcome coincides with the Gamow peak [1]. At these energies nuclear cross sections can significantly decrease (pbar or fbar), thereby resulting in a count rate being much lesser than the environmental background of a detector.

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maintain a pressure of $10^{-7}$ mbar inside the accelerating tube. The beam is transmitted through several apertures of decreasing diameter to collimate the beam into the target chamber [4, 5]. Thanks to the described experimental apparatus, crucial hydrogen [6] and helium-burning [7, 8] and Big Bang Nucleosynthesis [9] reaction cross sections have been measured in the past down to astrophysical energy levels. Few selected scientific cases will be discussed in the following.

2 The $\text{D}(p,\gamma)^3\text{He}$ cross section measurement

Big Bang Nucleosynthesis (BBN) occurs during the first minutes of cosmological time in a rapidly expanding hot and dense Universe, where a fraction of protons and nearly all free neutrons end up bound in $^4\text{He}$, while $^2\text{H}, ~^3\text{He}, ~^6\text{Li}, ~^7\text{Li}$ and $^7\text{Be}$ nuclei form in trace quantities. The $\text{D}(p,\gamma)^3\text{He}$ is responsible for deuterium burning during BBN and it is of primary importance in cosmology because it affects the primordial deuterium abundance, that in turn is very sensitive to fundamental cosmological parameters such as the baryon density and the amount of relativistic species permeating the early Universe [10]. This reaction is also of a particular interest in theoretical nuclear physics because it offers a unique opportunity to test $ab ~initio$ calculations. Up to few years ago, the $\text{D}(p,\gamma)^3\text{He}$ reaction was the most uncertain among the deuterium destruction channels. In the low-energy range ($E_{cm} \approx 2 - 20$ keV), mostly relevant to hydrogen burning in the Sun and in protostars, cross sections were obtained with a systematic error of at most 5.3% with the 50 kV LUNA accelerator [11]. In the BBN energy range and beyond ($E_{cm} \approx 30 - 700$ keV), several data sets were available, however not with the required accuracy, with systematic errors of 9% or higher [12–15]. The situation was further compounded by the fact that a recent $ab ~initio$ calculation [16] disagrees at the 8% level with the best fit of experimental data reported in Iliadis et al. [17]. These large uncertainties had a significant impact on the comparison between predicted and observed primordial abundance of deuterium. As a consequence of the poor experimental data for the $\text{D}(p,\gamma)^3\text{He}$ reaction, firm conclusions on the cosmological model could not be drawn. For all these reasons, a new experimental campaign started at LUNA in 2016.

The experiment was performed using the gas target filled with molecular deuterium; $\gamma$-rays were detected with a 137% HPGe detector in close geometry with the interaction chamber. The cross-section was measured with an unprecedented high precision in 30-50 keV steps inside the energy range of interest for BBN ($30 \text{ keV} < E_{cm}$).
< 300 kV) [9, 18]; the corresponding S-factor is shown in figure 2. Beam-induced background contribution and possible deuterium implantation were evaluated with measurements with inhe54He gas in the target chamber.

3 The $^{17}$O$(p,\gamma)^{18}$F cross section measurement

The $^{17}$O$(p,\gamma)^{18}$F reaction plays a crucial role in the hydrogen burning phases of different stellar scenarios, as Asymptotic Giant Branch Stars (AGB) [19]. At temperature of $20 \text{MK} < T < 80 \text{MK}$ the main contribution to the astrophysical reaction rate comes from the poorly constrained 65 keV resonance [20], whose strength is presently determined only through indirect measurements. Considering the typical experimental values in a laboratory for beam current, isotopic enrichment and detection efficiency, this strength yields to an expected count rate of less than one count per Coulomb, making the direct measurement of this resonance extremely challenging. A new high sensitivity setup has been installed at LUNA; the residual background underground was further reduced by a devoted shielding of lead and borated (5%) polyethylene. Gamma-rays were detected using a 4π BGO [21, 22] detector whose efficiency was optimized installing aluminum target chamber and holder. With about 400 C accumulated charge on Ta$_2$O$_5$ targets, with nominal $^{17}$O enrichment of 90%, the LUNA collaboration has performed the first direct measurement of the 65 keV resonance strength.

4 The LUNA-MV project

The activity of the LUNA experiment will continue in the next 20 years with the LUNA-MV project which aims at studying the phases of stellar evolution successive to the quiescent Hydrogen burning, in particular the helium and carbon burning phases. To face the challenge, a new 3.5 MV single-ended accelerator has been installed in hall B of Gran Sasso Laboratories and is now part of a facility called: Bellotti Ion Beam Facility. The new accelerator of Gran Sasso Laboratories and is now part of a facility called: Bellotti Ion Beam Facility. The new accelerator is the main goal of the first part of the project. The neutron flux just outside the accelerator is the astrophysical reaction rate comes from the poorly constrained 65 keV resonance [20], whose strength is presently determined only through indirect measurements. Considering the typical experimental values in a laboratory for beam current, isotopic enrichment and detection efficiency, this strength yields to an expected count rate of less than one count per Coulomb, making the direct measurement of this resonance extremely challenging. A new high sensitivity setup has been installed at LUNA; the residual background underground was further reduced by a devoted shielding of lead and borated (5%) polyethylene. Gamma-rays were detected using a 4π BGO [21, 22] detector whose efficiency was optimized installing aluminum target chamber and holder. With about 400 C accumulated charge on Ta$_2$O$_5$ targets, with nominal $^{17}$O enrichment of 90%, the LUNA collaboration has performed the first direct measurement of the 65 keV resonance strength.

References


Figure 2. S-factor of the D(p,γ)³He reaction; LUNA results are represented with filled red circles. Other experimental data are also shown. The best fit (red solid line) include all the reported experimental data. Band represents the 68% confidence level.


