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NUCLEAR ASTROPHYSICS DEEP UNDERGROUND: THE LUNA EXPERIMENT*

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At astrophysically relevant temperatures, nuclear cross-sections are extremely small and experimental measurements in a laboratory at the Earths surface are hampered by the cosmic background. The LUNA Collaboration has exploited the unique features of the rock cover offered by the LNGS underground laboratory in terms of background reduction, to study very important hydrogen (H)-burning reactions at astrophysically relevant energies. After a general introduction on the LUNA experiment, this paper reports briefly on the recently obtained results.

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1. Introduction

It is well known [1] that stars generate energy and produce elements by means of thermonuclear fusion reactions, which start from the most abundant and lightest element, hydrogen, and gradually synthesize heavier elements. The hydrogen burning can proceed either through the p–p chain or through the more efficient CNO cycle or even through the NeNa and MgAl cycles in stars more evoluted and hotter than our Sun. The net result is the transformation of 4 protons into a ^{4}He nucleus with an energy release of about 27 MeV. The fusion of hydrogen into helium occurs during the longer part of the stars life (main sequence) and is responsible for the prodigious luminosity of the star itself. All these fusion reactions occur in a very well defined energy range, the so-called Gamow peak, which is

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the result of the overlapping between the energetic distribution of nuclei in stars at a given temperature and the energetic dependence of the reaction cross-section. The first, given by the Maxwell–Boltzmann distribution, has a maximum for $E = kT$ (where T is the star temperature and k the Maxwell–Boltzmann constant) and then decreases exponentially for increasing energy while the second, given by the tunnelling probability through a Coulomb barrier, decreases exponentially for decreasing energy. In particular, the reaction cross-section for charged particles can be written as

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)\,, \tag{1}$$

where $S(E)$ is the astrophysical S factor which contains the pure nuclear behaviour of the cross-section and η is the Sommerfeld parameter given by

$$\eta = \frac{31.29}{2\pi} Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2}\,. \tag{2}$$

The LUNA (Laboratory for Underground Nuclear Astrophysics) Collaboration has exploited the silent environment of the underground laboratory under the Gran Sasso Mountain in Italy (LNGS) to perform direct measurements at the relevant energies. The rock cover of about 1400 m (3400 m water equivalent) reduces the muon component of the cosmic background of a factor 10^6, the neutron component of a factor 10^3 and the gamma component of a factor 10 with respect to the Earths surface. As a result, the gamma background above 3 MeV in an HPGe detector placed underground at LNGS is reduced by a factor ~ 2500 with respect to the same detector placed over-ground. Moreover, for lower energy gammas where the background is dominated by environmental radioactivity, the effect of passive shielding is enhanced by going underground. Indeed, in a laboratory on the Earths surface, a passive shielding can be built around the detector but the shield efficiency cannot be increased by making it thicker with the addition of further material since cosmic muons interact with it creating background signals in the detector itself. This problem is, of course, dramatically reduced in an underground laboratory.

2. The LUNA facility

LUNA started its activity in 1991 by installing a 50 kV electrostatic accelerator underground at LNGS [2] (now decommissioned), followed in the year 2000 by a 400 kV machine [3]. The qualifying features of both accelerators are a very small beam energy spread and a very high beam current even at low energies. The LUNA-400 kV facility consists of a Cockroft–Walton accelerator with two beam lines. Intense beams of protons or alpha particles are accelerated up to 400 keV with intensities up to 500 and 200 μA, respectively. The beam lines are equipped with different experimental setups. Both solid-state or (windowless) gas targets can be used, according to the reaction of interest. For γ-ray detection a high-efficiency low-resolution BGO and a high-resolution low-efficiency HPGe detector are available.

The first thermonuclear reactions investigated at LUNA-50 kV were hydrogen-burning reactions belonging to the *pp*-chain, namely the $d(p,\gamma)^3$He [4], the ^{3}He(^{3}He,2p)^{4}He [5] and the d(^{3}He,2p)^{4}He [6]. With the LUNA-400 kV facility it became possible to investigate also reactions like ^{3}He(^{4}He,γ)^{7}Be [7]. In this latter phase, also hydrogen-burning reactions belonging to the CNO and MgAl cycles, as well as reactions for Big Bang nucleosynthesis could be investigated.

3. Recent measurements: the ^{15}N$(p,\gamma)^{16}$O reaction

The ^{15}N$(p,\gamma)^{16}$O reaction is an important reaction of the CNO cycles. It links the first CNO cycle to the second one allowing for the production of the oxygen and fluorine isotopes and giving the access also to the third and fourth cycles that are responsible of the production of elements until neon [8].

The ^{15}N can interact with protons via (p,γ) and (p,α) reactions. The branching ratio, or the ratio of probabilities for the occurrence of the (p,α) (strong nuclear interaction) and (p,γ) (weaker electromagnetic interaction) reaction, is given by the ratio of the corresponding reaction rates. In the case of ^{15}N$(p,\gamma)^{16}$O, this ratio determines after how many cycles of CNO I the carbon will be lost as catalyst and the CNO II will proceed. Varying the S-factor of ^{15}N$(p,\gamma)^{16}$O by a factor two could change the amount of ^{16}O production by 30% [9].

This reaction has been extensively studied using a BGO detector with both the isotopically enriched solid-state [10] and the windowless gas target approach [11].

In the low-resolution, high efficiency measurement with the BGO detector, solid targets (titanium nitride targets enriched in ^{15}N (nominal value about 98%) produced using the reactive sputtering technique) were used. Since the target properties (stoichiometry and isotopic ratio) are directly related to the measured yield, two ancillary measurements were performed to determine these characteristics:

- high Z Elastic Recoil Detection (ERD) performed in Munich,
- resonance scan profiles performed at the FZD in Dresden.

For each bombarded target, the stoichiometry was determined by the ERD measurements and the ^{14}N content by the height of the plateau of the resonance scans performed on the $E_{\rm R} = 278$ keV resonance of the $^{14}{\rm N}(p,\gamma)^{15}{\rm O}$ reaction. The data analysis was performed with two different techniques yielding consistent results. A publication is in preparation [10].

In an effort to study the same reaction over a wider energy range, another measurement was performed at LUNA with an HPGe detector and solid-state isotopically enriched targets in collaboration with the University of Notre Dame, USA. The same set-up was used at three different accelerators (LUNA, covering the lower energy range, and two machines at the University of Notre Dame, covering the higher energies) to span over a wide energy interval (100–2000 keV) in the same experimental conditions [12].

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