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Low energy measurement of the $^{14}N(p,\gamma)^{15}O$ total cross section at the LUNA underground facility

LUNA Collaboration

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Abstract

Deep underground in Gran Sasso National Laboratory (Italy), at the LUNA facility, the cross section of the $^{14}N(p,\gamma)^{15}O$, the slowest process of the CNO cycle, has been measured at energies much lower than

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achieved before. Using a 400 kV accelerator, a windowless gas target and a 4π BGO summing detector, direct cross section data has been obtained down to 70 keV, reaching a value of 0.24 picobarn, corresponding to an S-factor of $1.74 \pm 0.14(\text{stat}) \pm 0.14(\text{syst})$ keV barn. The Gamow peak has been covered by direct experimental data for several scenarios of stable and explosive hydrogen burning. The $\omega\gamma$ strength of the 259 keV resonance has been re-measured obtaining $12.8 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$ meV. The stellar reaction rate has been calculated for temperatures $0.09 \times 10^9 - 0.3 \times 10^9$ K. A complete description of the experiment is here presented, including the impact of the present data on nucleosynthesis in AGB stars.

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Keywords: $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$; CNO cycle; Direct measurement; Underground accelerator

1. Introduction

Stars generate energy and synthesize chemical elements in thermonuclear reactions [1]. Non-resonant reactions induced by charged particles in a star take place in a narrow energy window called the Gamow peak, far below the Coulomb barrier.

At low energy, the cross section $\sigma(E)$ of a charged particle induced reaction drops steeply with decreasing energy due to the Coulomb barrier in the entrance channel [1]:

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

where $S(E)$ is the astrophysical S factor, and η is the Sommerfeld parameter with $2\pi\eta = 31.29\ Z_1 Z_2(\mu/E)^{1/2}$. Here Z_1 and Z_2 are the charge numbers of projectile and target nucleus, respectively, μ is the reduced mass (in amu units), and E is the center of mass energy[2] (in keV units).

Generally, $\sigma(E)$ has a very low value at the Gamow peak, this preventing a direct measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small because of cosmic ray interactions with detectors. Hence, cross sections are usually measured at high energies and expressed as the astrophysical S factor from Eq. (1). The S factor is then used to extrapolate the data to the Gamow peak region. Although $S(E)$ varies only slowly with energy for the direct process, resonances and resonance tails may hinder the extrapolation, resulting in large uncertainties [1]. Therefore, the primary goal of experimental nuclear astrophysics remains to measure the cross section at energies inside the Gamow peak, or at least to approach it as closely as possible.

The Laboratory for Underground Nuclear Astrophysics (LUNA) has been designed for this purpose and is located deep underground in the Laboratori Nazionali del Gran Sasso (LNGS)[3] in Italy. The Gran Sasso site is protected from cosmic rays by a rock cover (1400 m thick) equivalent to 3800 m water, suppressing the flux of cosmic ray induced muons by six orders of magnitude [2] and the neutron flux by three orders of magnitude [3]. Using this approach, in combination with high current accelerators [4,5] and high efficiency detection systems, two hydrogen burning reactions were studied for the first time directly in their respective solar Gamow peak: the $^{3}\mathrm{He}(^{3}\mathrm{He},2\mathrm{p})^{4}\mathrm{He}$ [6] and the $^{2}\mathrm{H}(\mathrm{p},\gamma)^{3}\mathrm{He}$ reaction [7].

[2] In the present work, E denotes the energy in the center of mass system, and E_{beam} is the projectile energy in the laboratory system.

[3] http://www.lngs.infn.it.