Institute of Physics Publishing Journal of Physics: Conference Series **39** (2006) 263–265
doi:10.1088/1742-6596/39/1/063 TAUP 2005: Proc. Ninth Int. Conf. on Topics in Astroparticle and Underground Physics

Underground measurement of $^{14}N(p,\gamma)^{15}O$ astrophysical factor at low energy

F Confortola[1], D Bemmerer[2], R Bonetti[3], C Broggini[2], M L Casanova[1], P Corvisiero[1], H Costantini[1], J Cruz[4], A Formicola[5], Z Fülop[6], G Gervino[7], A Guglielmetti[3], C Gustavino[5], G Gyürky[6], G Imbriani[8,11], A P Jesus[4], M Junker[5], A Lemut[1], M Marta[3], R Menegazzo[2,9], P Prati[1], V Roca[8], C Rolfs[10], C Rossi-Alvarez[2,9], F Schümann[10], E Somorjai[6], O Straniero[11], F Strieder[10], F Terrasi[8] and H P Trautvetter[10]

[1] Università degli Studi di Genova, Dipartimento di Fisica e INFN, Genova, Italy
[2] INFN, Padova, Italy
[3] Università degli Studi di Milano, Istituto di Fisica e INFN, Milano, Italy
[4] Centro de Fisica Nuclear da Universidade de Lisboa, Portugal
[5] INFN, Laboratori Nazionali del Gran Sasso, Italy
[6] ATOMKI, Debrecen, Hungary
[7] Università di Torino, Dipartimento di Fisica Sperimentale and INFN, Torino, Italy
[8] INFN, Napoli, Italy
[9] INFN, Laboratori Nazionali di Legnaro, Italy
[10] Institut für Experimentalphysik III, Ruhr-Universitt Bochum, Germany
[11] Osservatorio Astronomico di Collurania, Teramo, Italy

E-mail: Federica.Confortola@ge.infn.it

Abstract. In stars, four hydrogen nuclei are converted into a helium nucleus by two competing nuclear fusion processes: the proton - proton chain (p-p) and the carbon - nitrogen - oxygen (CNO) cycle. At temperatures higher than $2 \cdot 10^7$ K, the CNO cycle dominates the energy production. In particular, its rate is determined by the slowest reaction: $^{14}N(p,\gamma)^{15}O$. Direct measurement in a laboratory at the surface of the Earth is hampered by the background due to the cosmic rays. Here we report on an experiment performed with the LUNA (Laboratory for Underground Nuclear Astrophysics) accelerator placed deep underground in the Gran Sasso laboratory (Italy). Thanks to the cosmic ray suppression provided by the mountain shield, we could measure the $^{14}N(p,\gamma)^{15}O$ cross section for the first time directly at energies corresponding to stellar temperatures and with unprecedented accuracy. The results are strictly related to carbon stars formation, an independent lower limit on the age of the universe and solar neutrinos flux. The ^{13}N and ^{15}O neutrinos coming from the CNO cycle are strictly correlated to the $^{14}N(p,\gamma)^{15}O$ S-factor and their flux will play an important role in some future solar neutrino experiment, such as Borexino.

1. Introduction

The $^{14}N(p,\gamma)^{15}O$ capture reaction ($Q = 7297$ keV) determines the energy production and the solar neutrinos flux due to the CNO being the slowest reaction of this cycle. CNO neutrinos produced are predominantly from ^{13}N and ^{15}O decay, their continuous energetic spectrum covers the region of ^7Be neutrino lines and its contribution is around 20% in that region. Furthermore this reaction sets the globular cluster age, the oldest resolved stellar populations. The most reliable and widely adopted dating technique is based on the luminosity measurement at turnoff, the main sequence bluest point. At the turnoff the star burn hydrogen mainly through the CNO cycle. Thus stars' departure velocity from the main sequence is determined by the $^{14}N(p,\gamma)^{15}O$ cross section. As a consequence, an increase of the $^{14}N(p,\gamma)^{15}O$ reaction rate implies a fainter turnoff point for a given age, or a younger age for a given turnoff luminosity.

At stellar energies, far below the Coulomb barrier, the cross section of $^{14}N(p,\gamma)^{15}O$ is dominated by radiative capture into the ^{15}O ground state and into its excited states at 5.181, 6.172 and 6.791 MeV. Both the direct and the resonant process (with resonances above the reaction threshold and a single sub-threshold resonance) contribute to the capture into each of the states [1].

In the last decade of twenty century there were many experimental studies of the $^{14}N(p,\gamma)^{15}O$ reaction, and the lowest energy explored in the direct online γ ray measurements was about 250 keV [2] well above the range of interest for CNO stellar burning (20 − 80 keV). According to Schröder *et al.* [2], who used the Breit Wigner formalism to analyze their data, the main contribution to the total S factor extrapolated at zero energy (S_0) comes from the transitions to the ground state of ^{15}O and to the excited state at 6.79 MeV; they reported $S_0 = 3.20 \pm 0.54$ keV b.

In 2001, Angulo and Descouvemont [3] reanalyzed Schröder *et al.* data by means of an R-matrix model and reported a significantly lower S_0, namely 1.77 ± 0.20 keV b. The main discrepancy had come from the contribution of the direct transition to ground state, which was found to be nearly 20 times smaller than the value reported by Schröder *et al.* This revision has been confirmed indirectly by Doppler shift attenuation [4] and Coulomb excitation measurements [5].

Due to the Coulomb barrier (height E_c) in the charged particle's non-resonant induced reactions, the cross section $\sigma(E)$ drops strongly with decreasing energy E. Thus it becomes increasingly difficult to measure $\sigma(E)$ and to deduce the astrophysical $S(E)$ factor defined by the equation [6]:

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

with the Sommerfeld parameter given by $2\pi\eta(E) = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$, where Z_1 and Z_2 are the nuclear charges of the interacting particles in the entrance channel, μ is the reduced mass (in amu), and E is the center mass energy (in keV). Since the astrophysical S factor usually varies only slowly with energy, high energy measurements of $S(E)$ are used to extrapolate the data to astrophysical energies.

Since 1993 the LUNA Collaboration faces this experimental problem coupling the extremely low cosmic rays and neutron background of the National Laboratory under the Gran Sasso mountain (Italy) with high luminosity setups based on custom high current accelerators [7, 8] and high efficiency detectors [9]. In the past the $^3He(^3He,2p)^4He$ and the $^2H(p,\gamma)^3He$ reaction have been measured by the LUNA group directly inside their Gamow peaks [10, 11].

2. Experimental features

Due to the characteristics of the cross section trend, strong dependence on the interaction energy and the very small values, we need both high energy beam resolution and high detection efficiency combined with low background.

The experimental setup consist in a small linear accelerator that delivers a proton beam to a windowless gas target and a 4π BGO summing crystal detector for the γ rays. The main features of the setup are described in [9].

The LUNAII 400 kV accelerator [8] is able to provide beams of high intensity (up to 500 μA for protons) with an energy resolution of 0.1 keV.

The beam passes through different pumping stages separated by apertures used as flow impedances. The target chamber has a cylindrical shape of 120 mm length and 60 mm diameter with two ports for gas inlet and for pressure check (target reference pressure) with a MKS Baratron capacitance mano-meter with an accuracy of 0.25 %.

The BGO detector is shaped as a 28 cm long cylinder with a coaxial hole of 6 cm diameter. The crystal is divided into 6 optically independent sectors (radial thickness 7 cm), each covering an azimuthal angle of 60 degrees. Two Hamamatsu R1847-07 photomultipliers are coupled to the opposite faces of each sector. The target chamber is positioned in the detector center, in this way the acceptance solid angle of the detector is near the full solid angle. The simulated efficiency with the LUNA Monte Carlo code [12] in the Region of Interest (ROI from 6.5 to 8 MeV) is around 70% with an energy resolution of 8%.

The laboratory background rate in the ROI, without any passive shielding, was 21.1±0.8 counts/day and the lowest counting rate reached in this experiment was 11.0±0.8 counts/day at $E = 70$ keV. We measured the beam induced background coming from parasitic reaction lines in the ROI with helium gas runs [13].

More details on this measurement are in [14].

3. Conclusion

The total cross section of the $^{14}N(p,\gamma)^{15}O$ reaction has been directly measured down to $E =$ 70 keV, within the energy window where stellar CNO hydrogen burning takes place. The data taking is concluded and the analysis is still in progress. In future it will be possible to calculate the reaction rate for several scenarios of hydrogen burning from the present cross section data directly.

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