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The ^{14}N(p, γ)^{15}O measurement at low energy

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Summary. — The ^{14}N(p, γ)^{15}O reaction has been investigated by the LUNA experiment at the National Laboratory of Gran Sasso (LNGS). This study has been performed with two different technical set-ups. The first one, suitable for the detection of γ-rays coming from the single transitions, has been realized with a HPGe detector and a solid target. The second has been made of a BGO summing crystal as a detector and a windowless gas target. The high-detection efficiency and the target purity of the gas target set-up allowed to measure the total S-factor down to $E_{\mathrm{c.m.}} = 71$ keV.

PACS `24.30.-v` – Resonance reactions.
PACS `24.50.+g` – Direct reactions.
PACS `26.20.+f` – Hydrostatic stellar nucleosynthesis.

1. – Introduction

The ^{14}N(p, γ)^{15}O is the slowest CNO cycle reaction, thus its cross-section determines the energy production rate and the neutrinos flux from the sun due to the CNO cycle.

This reaction plays an important role in the globular clusters dating, which are stars born all together in the primordial universe. The most reliable and widely adopted globular clusters dating technique is based on the estimation of the turn off point luminosity, where the stars escape from the main sequence. The H-burning of the stars departed from the main sequence is predominantly through the CNO cycle. Thus the turn off point luminosity is strictly dependent on the cross-section of the $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ reaction. On the other side it is possible to associate the turn off point luminosity to the age of the globular cluster, some astrophysical models do that [1]. As a consequence, an increase of the $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ reaction rate implies a fainter turnoff point for a given age, or a younger age for a given turnoff luminosity.

1˙1. *The* $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ *in the literature*. – The $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ is a direct capture reaction ($Q = 7297$ keV) and the composed $^{15}\mathrm{O}$ decay directly to the ground state or to the excited states at 6.79, 6.18 and 5.18 MeV. The lowest energy explored in direct on-line γ measurements is about 240 keV [2], which is well above the range of interest for stellar CNO burning (20–80 keV). At stellar energies the cross-section of $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ is influenced by a subthreshold resonance at -504 keV. At higher energies mainly the $J^\pi = 1/2^+$ resonant state at $E_\mathrm{R} = 259$ keV contributes to the cross-section.

According to Schröder *et al.* [2], who used the Breit-Wigner formalism, the main contribution to the total S-factor at zero energy ($S(0)$) comes from the transitions to the ground state and to the excited state at 6.79 MeV. They gave $S(0) = 3.20 \pm 0.54$ keV-b.

Angulo and Descouvement [3], reanalyzing Schröder experimental data by the R-matrix method, reported a significant lower $S(0)$, namely 1.77 ± 0.20 keV-b. The main discrepancy concerns the contribution of the ground-state transition, which has been found to be nearly 20 times smaller than the value quoted by Schröder.

1˙2. *Laboratory for Underground Nuclear Astrophysics*. – The LUNA experiment has been able to study the $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ reaction in an energy region nearer to the one of astrophysical interest thanks to the unique background suppression provided by the LNGS Underground Laboratory and the characteristics of the 400 kV "LUNA2" accelerator [4]. This machine was built up mainly for this kind of measurements, where an intense and very stable beam is requested even at low energies (50–400 kV).

2. – The solid-target experiment

The first part of the measurement performed with solid targets and a HPGe detector was suited to study the single γ-transition.

The targets consisted of a TiN layer (with a typical thickness of 80 keV), reactively sputtered on a 0.2 mm thick Ta backing. The target quality was frequently checked at the 259 keV resonance: no significant deterioration was observed after a bombarding time of several days.

The 126% HPGe detector was used to detect the γ-rays from the reaction: it was placed at 55° to the beam direction in close geometry to the target, at about 1.5 cm distance from it.

The cross-section angular distribution has been checked with other Ge detectors positioned at 0 and 90 degrees. All transitions show isotropy at the 259 keV resonance and no forward-backward asymmetry outside the resonance. Consequently, an angle-integrated γ-ray yield may be derived directly from the yield collected by the Ge detector at 55°.

An R-matrix fit has been applied to the LUNA experimental data (for details, see [3, 5]) for both the 6.79 MeV and the ground-state transitions. The extrapolated values obtained are: $S_{6.79}(0) = 1.35 \pm 0.05$ (statistical)± 0.08 (systematic) keV-b and $S_{\mathrm{g.s.}}(0) = 0.25 \pm 0.06$ keV-b. For the total S-factor a contribution from the transition to the

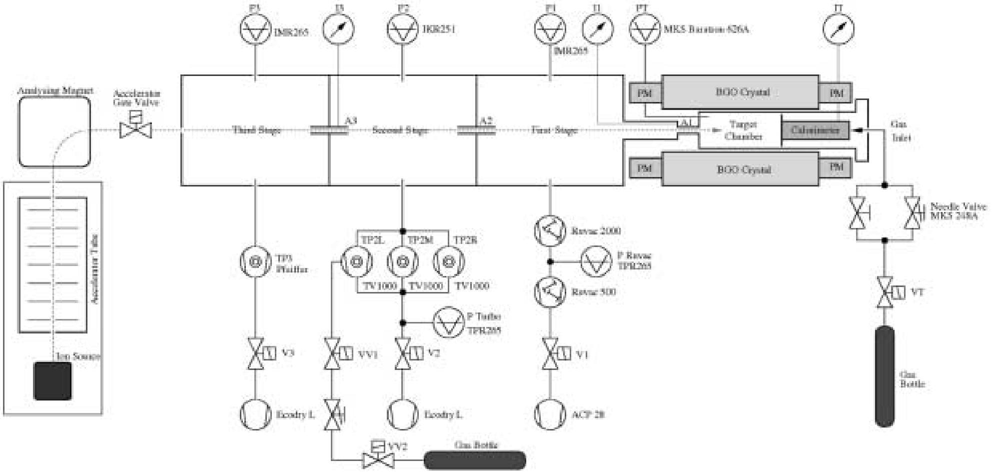

Fig. 1. – The set-up scheme of the gas target experiment.

6.18 MeV state of $S_{6.18}(0) = 0.06$ keV-b from [2] has been added to obtain $S_{\mathrm{tot}}(0) = 1.7 \pm 0.1$ (statistical) ± 0.2 (systematic) keV-b. Our value can be compared with 1.77 ± 0.20 keV-b from the theoretical paper [3] and 1.70 ± 0.22 keV-b [6]. It is smaller than the value given by most recent compilations (3.2 ± 0.8 keV-b [7]).

The main astrophysical consequences are the reduction of the CNO neutrinos flux expected from the Sun of about a factor two and the increase of the globular cluster's age by 0.7–1 Gy with respect to the current estimate.

The lowest energy reached in this first part of the experiment has been 140 keV of nominal beam energy.

3. – The gas target experiment

During the second phase of the ^{14}N(p, γ)^{15}O experiment, the measurements have been performed using a windowless gas target where the interaction chamber is completely surrounded by a high-efficiency BGO detector. The goal of this second part is to measure directly the total S-factor down to the lowest energy reachable with a good precision.

The experimental set-up (fig. 1) is composed by a series of pumping stages that go from the accelerator (working pressure 10^{-6} mbar) to the interaction chamber (typical pressure used 0.5–2 mbar) each one separated from others by collimators. This windowless set-up is necessary to have a low-energy spread of the beam in the path before the interaction chamber, because at low energy the cross-section of the direct capture reactions drops exponentially.

The BGO detector has a cylindrical geometry that covers almost the 4π solid angle. It is composed by six optically independent crystals, each one coupled with two photomultipliers to reduce the electronic background. This detector has for the ^{14}N(p, γ)^{15}O region of interest (5–8 MeV) a total efficiency of about 65% and an energy resolution of about 8%.

The beam stopper is a power calorimeter to collect the beam charge. The head of it has been inserted in the interaction chamber and it has been maintained at 70 °C.

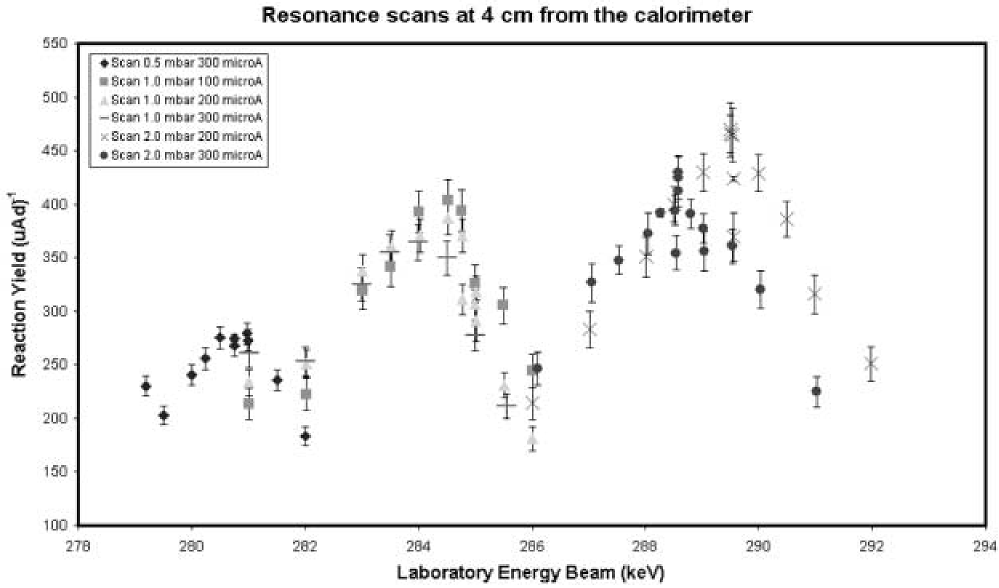

Fig. 2. – The resonance scans in a particular position in the target chamber at 3 nominal pressure and different currents.

3˙1. *Target density characterization.* – A gas target gives good properties in terms of purity, stability and variable thickness, but it needs an evaluation of the real density of the target on the beam axis inside the interaction chamber. Some preliminary measurements have been performed to correctly estimate the gas density starting from the pressure monitored during the measurements by a capacitance gauge with a 0.25% accuracy.

In a first step, to estimate the target density with the beam off, the gas pressure and temperature have been measured using a test chamber with transversal holes along the beam axis direction. We have found an exponential trend of the temperature along the beam axis with higher values near the calorimeter head. The trend changes with the nominal pressure value inside the target, the temperature increases with the pressure for a better gas convection. So there is a density reduction in the last part of the target chamber.

In a second step we have evaluated the effect produced by the beam on the gas target. In fact for the high beam current ($I_{\mathrm{beam}} = 200$–$400\ \mu$A) there is a local heating of the gas due to the dissipated power with a consequent additional density variation [8].

A dedicated set-up, consisting in a small NaI detector, movable along the beam axis, has been used to measure the beam heating effect with different current-pressure conditions. With this set-up it is possible to see at which energy the 259 keV resonance is positioned exactly in front of the detector (fig. 2), placed orthogonally to the beam axis and shielded by lead. In this way the energy loss has been measured for different point inside the target chamber, and the gas density was deduced from it. In the standard measurement condition the beam heating effect is not negligible and it has to be included in the data analysis.

3˙2. *Background study.* – Thanks to the strong muon suppression provided by the underground laboratory, the beam induced background becomes dominant in the region above 4 MeV for beam energies higher than 110 keV. The beam, hitting the collimator at the target entrance and the calorimeter at the end of the target, produces γ-rays from proton-induced reactions on impurities, for example ^{11}B(p, γ)^{12}C and ^{13}C(p, γ)^{14}N. The contribution of background reaction in the γ-spectra has been estimated performing measurements with the beam on an inert gas (^{4}He).

Only for the lowest measured energies (under 110 keV of proton beam) in the region of interest of the ^{14}N(p, γ)^{15}O γ-summing peak (6.5–8 MeV), the beam induced background is almost suppressed and the main background source comes from natural background (about 20 events/day in the ROI).

3˙3. *Results.* – We measured with the gas target set-up the ^{14}N(p, γ)^{15}O cross-section down to 71 keV in the centre of mass. This last energy was measured for a long period to reach a good statistical precision (better than 10%), because the rate of the reaction was half of the natural background rate (about 10 event/day in the ROI).

Data analysis is still in progress.

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