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# Towards a high-precision measurement of the $^3$He$(\alpha,\gamma)^7$Be cross section at LUNA

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**Abstract.** The $^3$He$(^4$He$,\gamma)^7$Be reaction is the key process for the production of $^7$Be and $^8$B neutrinos in the Sun. We have designed a new experimental setup to study this reaction with high accuracy at low energies using two different experimental techniques. The first method consists in measuring the prompt capture gamma-ray transitions with an ultra-low background germanium detector heavily shielded and placed at close distance from a $^3$He windowless gas target. With another fully shielded large-volume germanium detector we will also measure the $\beta$-decay of the $^7$Be residual nuclei. The aim of the experiment is to reduce the error on the astrophysical factor $S_{3,4}$ to 4%.

**PACS.** 25.40.Lw Radiative capture – 26.20.+f Hydrostatic stellar nucleosynthesis

## 1 Introduction

The solar neutrino flux resulting from the $^7$Be$(p,\gamma)^8$B, depends on nuclear physics and astrophysics inputs [1]:

$$\Phi(B) = \Phi(B)(SSM) \cdot S_{3,3}^{-0.43} S_{3,4}^{0.84} S_{1,7}^{1} S_{e7}^{-1} S_{pp}^{-2.7} \cdot com^{1.4} opa^{2.6} dif^{0.34} lum^{7.2}. \quad (1)$$

The $^3$He$(\alpha,\gamma)^7$Be reaction is one of the major source of uncertainty in determining the B solar neutrino flux and dominates over the present observational accuracy of 7% [2]. The foreseeable accuracy of the new generation solar neutrino experiments is 3%. This could illuminate about solar physics if the uncertainty on $S_{3,4}$ is reduced to a corresponding level. Moreover, the $^3$He$(\alpha,\gamma)^7$Be reaction is important for understanding the primordial $^7$Li abundance [3].

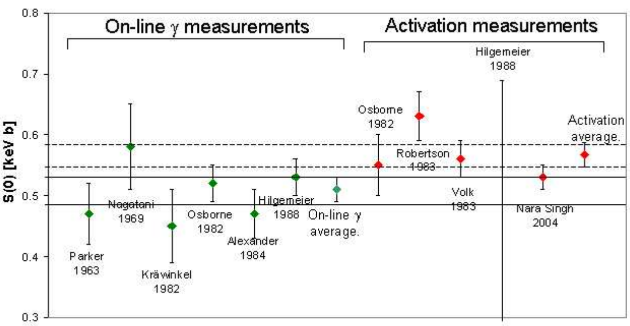


**Fig. 1.** Summary of past measurements performed with the on-line $\gamma$ detection technique and the activation method. With the new activation measurement by Nara Singh *et al.* [4] the discrepancy between the two methods is reduced from 15% to 11%.

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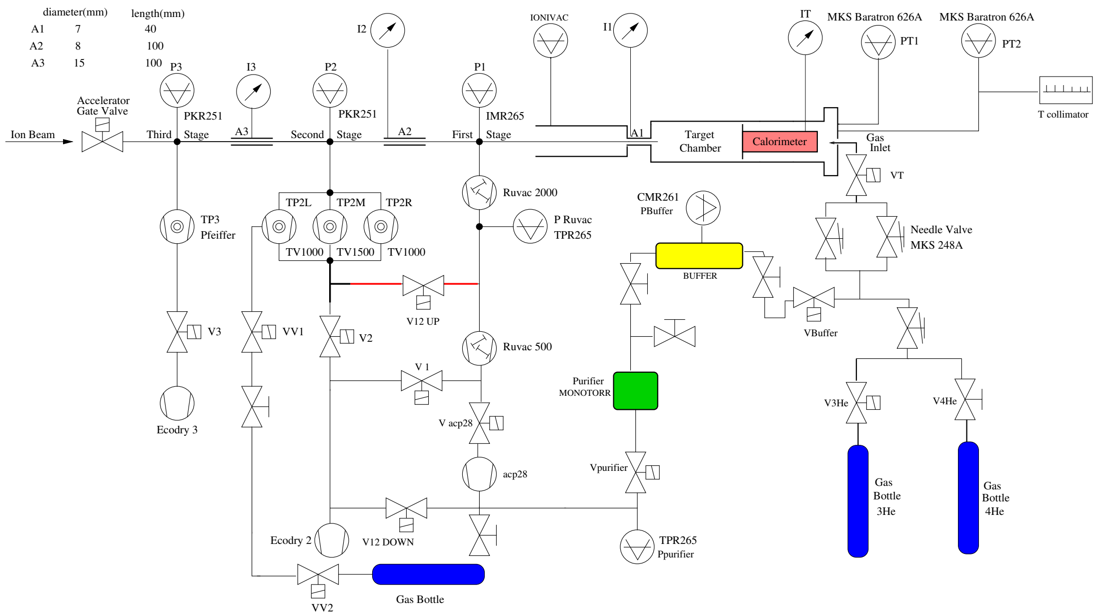


**Fig. 2.** Schematic diagram of the windowless gas target system.

In the last twenty years the $^3$He$(\alpha,\gamma)^7$Be reaction have been measured using two techniques. In the first method direct $\alpha$-capture $\gamma$ rays were detected, while in the second the delayed $^7$Be $\beta$ decay $\gamma$ rays were counted.

The average $S(0)$ S-factors, obtained with the two techniques, show a discrepancy of the order of 11% (see fig. 1).

Possible explanations for this discrepancy can be found in the systematic errors of the two methods: for example in the on-line $\gamma$ measurement the low-energy angular distribution knowledge and the beam heating effect; in the activation measurement the beam-induced reactions on beam-stopper impurities leading to the production of $^7$Be. Recently, Nara Singh *et al.* [4] studied the $^3$He$(\alpha,\gamma)^7$Be reaction with high precision but with the activation technique only (see fig. 1). Therefore a new high-precision measurement of the $^3$He$(\alpha,\gamma)^7$Be reaction, using both techniques at the same time, is highly desirable.

Here we report on a new measurement undergoing deep underground at the INFN (Istituto Nazionale di Fisica Nucleare) Laboratori Nazionali del Gran Sasso (LNGS)[1], 1500 m below the Gran Sasso Mountain (L'Aquila, Italy), where cosmic ray background is highly reduced by the natural shielding of the rock.

The measurement will be performed using both the direct $\gamma$ detection and the activation techniques with the same experimental setup at the LUNA II 400 kV facility. The aim of the present work is to reduce the S-factor uncertainty down to 4%.

## 2 Experimental setup

The experiment will be performed using the LUNAII 400 kV accelerator. Details on the machine can be found in ref. [5]. Briefly, it consists of a radio frequency (RF) ion source, a singletron electrostatic extraction-accelerator system (embedded in a tank, which is filled with a gas mixture of $N_2$-$CO_2$ at 20 bar), a 45° magnet (30 cm radius) and a vertical steerer. The accelerator provides ion beam of approximately 500 $\mu$A protons and 250 $\mu$A He. The absolute beam energy is known with an accuracy of 0.3 keV and the energy spread and long-term energy stability were observed to be 100 eV and 5 eV/h.

We use an $\alpha$ beam in conjunction with a recirculating $^3$He windowless gas target (a schematic diagram is shown in fig. 2). According to refs. [6,7,8,9] the deuterium and proton beam contamination have been found less in a $^4$He beam than in an $^3$He beam.

The beam enters the target chamber through three apertures of high gas flow impedance and is stopped on a beam calorimeter placed at the downstream part of the chamber. During the experiment the $^3$He gas coming from the target is continuously recirculated. The gas is recovered from the first two pumping stages, cleaned through a heated getter gas purifier (Monotorr from SAES GETTER) and fed back into the target chamber. The purity of the gas inside the target is checked using a silicon detector that measures the scattered $\alpha$-particles on the target atoms.

The beam current is measured through a calorimeter with constant temperature gradient. The power delivered by the beam is calculated as the difference between heating power without and with ion beam with an accuracy of 1%.

The target pressure is measured by a Baratron capacitance manometer (MKS model 127) in two different positions inside the gas target with an uncertainty of 0.25%. Typical gas pressure inside the target chamber is 1 mbar.

Due to the high beam current the local target density along the beam path can be lower than the density

[1] Web resource: `http://www.lngs.infn.it`

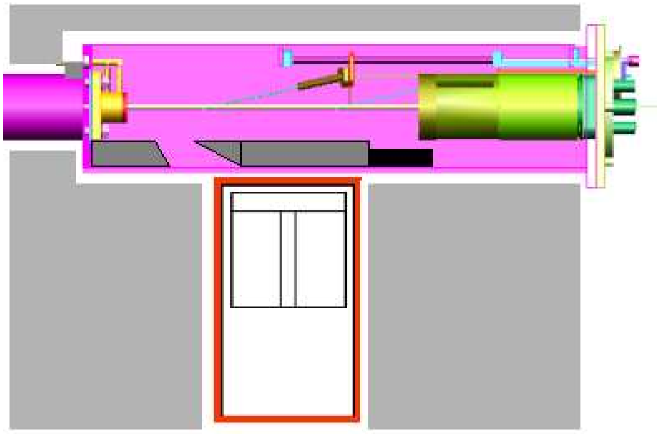

**Fig. 3.** Schematic view of the inner part of the target chamber. The internal lead collimator, the beam power calorimeter, the movable setup for the silicon detector and the long collimator before the carbon foil (at 20° with respect to the beam direction) are shown. The HpGe detector is positioned below the target chamber.

measured at the side of the through-the-pressure gauge. This effect, known as beam heating effect, depends on the power for unit length delivered by the beam on the gas target [10].

To avoid systematic uncertainties the target density, together with the beam current, is measured through $\alpha$-Rutherford scattering cross section with a silicon detector positioned inside the target chamber (see fig. 3) with an uncertainty of 0.1%.

To optimize the detector time of life and the target chamber geometry we have decided to use a double scattering setup. The $\alpha$-particles are first scattered by the gas atoms in the target chamber and subsequently by a carbon foil of 15 $\mu$g/cm$^2$, put at 20° in respect to the beam direction (see fig. 3).

The effective density profile as a function of the position along the beam direction, the beam current and target pressure will be obtained with a series of dedicated measurements with silicon detector with an estimated accuracy better than 1%.

## 3 The on-line $\gamma$ detection technique

The $^3$He$(\alpha,\gamma)^7$Be reaction is an $\alpha$-capture reaction that can occur through electromagnetic decay to the $^7$Be ground state (DC→0) or to the first excited state (DC → 429 keV) with the emission of $\gamma$'s of energy $E_\gamma = 1586\,\text{keV} + E_{cm}$ or $E_\gamma = 1157\,\text{keV} + E_{cm}$, respectively (in the latter with the subsequent emission of the 429 keV $\gamma$).

To measure the cross section we will detect the two primary transitions (1.2 and 1.6 MeV) using a 135% ultra low background Canberra HpGe detector positioned under the target chamber in very close geometry. Since the energy of the primary $\gamma$-transitions is in the energy region of the natural radioactive isotopes we will build a copper and lead shielding around the detector of 0.3 m$^3$. Passive shielding is particularly effective underground since the muons flux, coming from cosmic rays that, at surface, produces secondary $\gamma$-rays in the lead shielding, is reduced by six orders of magnitude thanks to the natural shielding of the Gran Sasso mountain. The expected attenuation factor for the $^{40}$K 1.46 MeV $\gamma$ is $10^{-5}$–$10^{-6}$, according to a GEANT4 simulation [11] where the complete geometry of the target and of the shielding has been considered. In order to reduce the background on the detector, low activity materials have been used in the construction of the target chamber, silicon detector support and calorimeter. In particular the target chamber is made by OFC copper and no welding materials have been used in the chamber assembly.

According to the DC model calculations [12] the DC→0 and DC→429 keV angular distributions are dominated by $E1$ transitions that can occur through s- or d-waves. Most recent angular distributions measurements [13] showed a small anisotropy of these transitions, manifesting interference effects of both partial wave contributions also at the lowest measured energy ($E_{cm}$ = 148 keV). It should be noted, however, that the DC model predictions depend sensitively on the s- and d-wave phase shifts in the $^3$He + $^4$He elastic scattering channel, which are known experimentally only at $E_{cm} \geq 1.4$ MeV. A detector placed at 55° with respect to the beam direction, would become almost independent of angular distribution anisotropy.

Therefore we have put an internal lead collimator, inside the target chamber (see fig. 3), designed in such a way that the detector collects mostly the $\gamma$'s emitted at 55°. At the same time, this design reduces the effective target length seen by the detector to approximately 15 cm corresponding to a beam energy loss $\Delta E$ of 8 keV for 1 mbar of $^3$He gas. The internal lead collimator has been also designed to shield the detector from beam-induced $\gamma$'s coming from reactions occurring on the entrance collimator and on the calorimeter cap (beam stopper).

Taking into account the angular distribution measured, and considering the extreme cases of isotropy and full anisotropy, we have estimated that with our setup the angular distribution systematic effect is reduced to less than 4%.

With direct method we will explore, in the first phase of the experiment, the energy region $\Delta E_{cm}$ = 100–170 keV. With the detection efficiency of the apparatus previously described and a typical $\alpha$-beam current of 200 $\mu$A the expected counting rate for the 1.6 MeV $\gamma$ will be about 100 counts/day at $E_{cm}$ = 100 keV and 2000 counts/day at $E_{cm}$ = 170 keV.

## 4 The activation technique

An alternative way to measure directly the $\gamma$ rays produced by the $^3$He$(\alpha,\gamma)^7$Be reaction is to detect the $\gamma$'s from the $^7$Be electron-capture decay to the 478 keV state in $^7$Li. Since the $^7$Be residual nuclei are produced inside the gas target are moving in the beam direction, they are implanted into a removable copper calorimeter cap

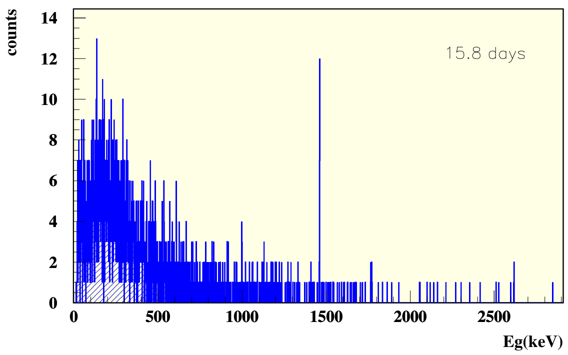


**Fig. 4.** Background $\gamma$-ray spectrum obtained with the ultra-low background 125% HpGe detector at the low activity laboratory at LNGS. The measuring life-time is 15.8 days.

**Table 1.** Expected counting rate for the 480 keV $^7$Be $\gamma$ after an irradiation time of one day, 200 $\mu$A $\alpha$-current and 1 mbar of gas target pressure.

| $E_{lab}$ | $E_{cm}$ | $\sigma$(nb) | no. ev/week |
|---|---|---|---|
| 280 | 120 | 3.1 | 60 |
| 327 | 140 | 7.2 | 150 |
| 373 | 160 | 16.8 | 320 |

(diameter = 6 cm, see fig. 3). To prevent $^7$Be nuclei eventually escaping from the cap, a covering foil will be inside the chamber wall. The same setup described in sect. 3 will be used for the activation method.

After $\alpha$-beam irradiation, the cap and the foil $^7$Be activity will be measured with 125% HpGe detector. This detector is installed at the Low Activity Laboratory of the LNGS and is completely shielded by 15 cm of lead and 10 cm of copper. The background in the region of interest for the $^7$Be decay $\gamma$ is about 2 counts/day (see fig. 4). Preliminary measurements aimed to investigate the calorimeter copper purity to search for possible parasitic reactions, as $^6$Li(p,$\gamma$)$^7$Be, $^6$Li(d,n)$^7$Be and $^{10}$B(p,$\alpha$)$^7$Be, have been done at Atomki (Debrecen, Hungary). A sample of a calorimeter cap has been irradiated with $p$ and $d$ beams. No $^7$Be nuclei have been detected at the detection limit of the test setup (0.3 ppm). Further measurements to investigate the beam purity, will be performed directly at the LUNAII accelerator bombarding the cap with $\alpha$-beam at different energies with $^4$He gas in the target chamber and looking for possible $^7$Be nuclei produced in the cap.

In table 1 the expected counting rate of the 480 keV decay $^7$Be $\gamma$, assuming an irradiation time of 1 day with an $\alpha$-beam current of 200 $\mu$A and a gas target pressure of 1 mbar, is reported. We will measure the $^3$He($\alpha,\gamma$)$^7$Be cross section with both the activation and on-line gamma detection techniques at selected energies, ranging from $E_{cm}$ = 100–170 keV, comparing directly the two methods.

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