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LUNA: Laboratory for Underground Nuclear Astrophysics

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Abstract. LUNA, Laboratory for Underground Nuclear Astrophysics at Gran Sasso, is studying thermonuclear reactions down to the energy of stellar nucleosynthesis. Significant results have been the measurements of the ^{3}He(^{3}He,2p)^{4}He cross section within the Gamow peak of the Sun, of ^{14}N(p,γ)^{15}O down to the energy of 70 keV and of ^{3}He(α, γ)^{7}Be down to 90 keV. The results and their implications will be discussed together with the status of the experiment and its perspectives.

1. Introduction

Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak. In this region, which is far below the Coulomb energy, the reaction cross-section σ(E) drops almost exponentially with decreasing energy E:

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

where $S(E)$ is the astrophysical factor and η is given by $2\,\pi\,\eta = 31.29\,Z_1\,Z_2(\mu/E)^{1/2}$. 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 centre of mass energy (in keV).

The extremely low value of the cross-section, ranging from pico to femto-barn and even below, has always prevented its measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small because of cosmic ray interactions. Instead, the observed energy dependence of the cross-section at high energies is extrapolated to low energy, leading to substantial uncertainties. In particular, there might be the contribution of narrow or sub-threshold resonances which cannot be accounted for by the extrapolation, but which could completely dominate the reaction rate at the Gamow peak.

In addition, another effect can be studied at low energies: the electron screening. The electron cloud surrounding the interacting nuclei acts as a screening potential, thus reducing the height of the Coulomb barrier and leading to a higher cross-section. The screening effect has to be measured and taken into account in order to derive the bare nuclei cross-section, which is the input data to the models of stellar nucleosynthesis.

In order to explore this new domain of nuclear astrophysics we have installed two electrostatic accelerators underground in the Gran Sasso laboratory: a 50 keV accelerator (Greife et al. 1994) and a 400 keV one (Formicola et al. 2003). The qualifying features of both the accelerators are a very small beam energy spread

Send offprint requests to: C. Broggini and a very high beam current even at low energy. The mountain provides a natural shielding equivalent to at least 3800 meters of water which reduces the muon and neutron fluxes by a factor 10^6 and 10^3, respectively. The γ ray flux due to natural radioactivity is similar to the surface one, but a detector can be more effectively shielded underground due to the suppression of the cosmic ray induced background.

2. The $^3He(^3He, 2p)^4He$ reaction

The initial activity of LUNA has been focused on the ^{3}He(^{3}He,2p)^{4}He cross section measurement within the solar Gamow peak (16-28 keV). Such reaction is a key one of the proton-proton chain. A resonance at the thermal energy of the Sun was suggested long time ago (Fowler 1972) to explain the observed ^{8}B solar neutrino flux: it would decrease the relative contribution of the alternative reaction ^{3}He(α,γ)^{7}Be, which generates the branch responsible for ^{7}Be and ^{8}B neutrino production in the Sun. A narrow resonance with a peak S-factor 10-100 times the value extrapolated from high energy measurements could not be ruled out with the pre-LUNA data (such an enhancement is required to reduce the ^{7}Be and ^{8}B solar neutrinos by a factor 2-3). As a matter of fact, ^{3}He(^{3}He,2p)^{4}He cross section measurements stopped at the center of mass energy of 24.5 keV (σ=7±2 pb), just at the upper edge of the thermal energy region of the Sun.

Briefly, the LUNA 50 keV accelerator facility consisted of a duoplasmatron ion source, an extraction/acceleration system, a double-focusing 90^o analyzing magnet, a windowless gas-target system and a beam calorimeter. The beam energy spread was very small (the source spread was less than 20 eV, acceleration voltage known with an accuracy of better than 10^{-4}), and the beam current was high even at low energy (about 300 μA). Eight thick (1 mm) silicon detectors of 5x5 cm^2 area were placed around the beam inside the target chamber, where there was a constant ^{3}He gas pressure of 0.5 mbar. The simultaneous detection of 2 protons has been the signature which unambiguously identified a ^{3}He(^{3}He,2p)^{4}He fusion reaction (detection efficiency: 5.3± 0.2%, Q-value of the reaction: 12.86 MeV).

No event fulfilling our selection criteria was detected during a 23 day background run with a ^{4}He beam on a ^{4}He target (0.5 mbar). Figure 1 shows our results together with two existing measurements of the astrophysical factor $S(E)$. We point out that for the first time a nuclear reaction has been measured in the laboratory at the energy occurring in a star. Its cross section varies by more than two orders of magnitude in the measured energy range. At the lowest energy of 16.5 keV, it has the value of 0.02 pb, which corresponds to a rate of about 2 events/month, rather low even for the "silent" experiments of underground physics. The LUNA result (Bonetti et al. 1999) showed that the ^{3}He(^{3}He,2p)^{4}He cross section does not have any narrow resonance within the Gamow peak of the Sun. Consequently, the astrophysical solution of the ^{8}B and ^{7}Be solar neutrino problem based on its existence has been ruled out. As a matter of fact, a 1 keV width resonance centered at 17 keV should give an astrophysical factor of 172 MeV·b (459 MeV·b) to suppress the ^{8}B and ^{7}Be solar neutrinos by a factor 2 (3).

With ^{3}He(^{3}He,2p)^{4}He LUNA provided the first cross section measurement of a key reaction of the proton-proton chain at the thermal energy of the Sun. In this way it also showed that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

3. The $^{14}N(p, \gamma)^{15}O$ reaction

The CNO cycle was proposed by H. Bethe and C. von Weizsäcker as a process for hydrogen burning in stars. In our Sun this cycle accounts for just a few percent of the nuclear energy production, whereas the main part is supplied by the p-p chain. In stars that lie on the main sequence in the Hertzsprung-Russell diagram and that have a mass of at least 1.2 solar masses, however, core hydrogen burning is dominated by the CNO cycle. When the fuel (hydrogen) is exhausted in their core, stars

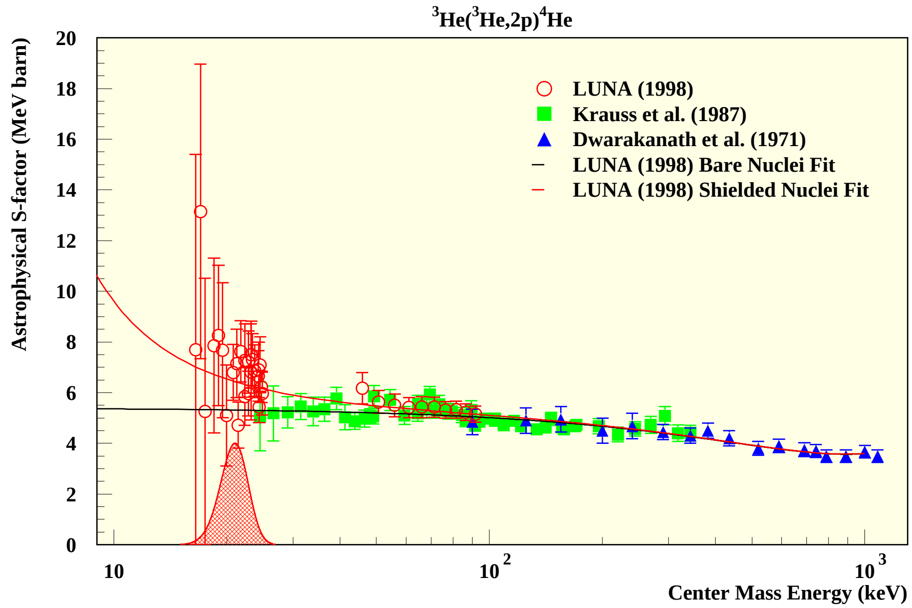

Fig. 1. Astrophysical S(E)-factor of ^{3}He(^{3}He,2p)^{4}He.

evolve off the main sequence and they become giants.

^{14}N(p,γ)^{15}O is the slowest reaction of the CNO cycle and it rules its energy production rate. In particular, it is the key reaction to know the CNO solar neutrino flux, as well as to determine the age of the globular clusters, the oldest components of the Milky Way. As a matter of fact, the CNO solar neutrino flux depends almost linearly on this cross section (Bahcall 1989). In addition, the departure of a star from the main sequence is powered by the CNO cycle (Imbriani et al. 2004,and references therein). As a consequence, the luminosity of the turn off point in the Hertzsprung-Russell diagram of a globular cluster (i.e. the bluest point on the main sequence), which gives the age of the cluster, is determined also by the value of the ^{14}N(p,γ)^{15}O cross section. The higher the cross section is, the younger is the age, for a given turn off luminosity.

The energy region studied so far in nuclear physics laboratories is well above the region of interest for the CNO burning in astrophysical conditions (in particular, the solar Gamow peak is between 20 and 33 keV). According to Schröder (Schröder et al. 1987), who measured down to 0.2 MeV, the main contribution to the total S-factor at zero energy, S(0), comes from the radiative capture into the ground state of ^{15}O and into its excited state at E=6.79 MeV. In particular, they give S(0) = 3.20 ± 0.54 keV·b. On the other hand, (Angulo & Descouvement 2001) re-analyzed Schröder's experimental data using a R-matrix model and they obtained S(0) = 1.77 ± 0.20 keV·b. The difference mainly comes from the different contribution of the capture to the ^{15}O ground state: Angulo and Descouvement have a value lower by a factor 19 than the one of Schröder et al.. Results from indirect measurements also indicated a lower cross section.

Clearly, new studies of $^{14}N(p,\gamma)^{15}O$ at low energies were strongly demanded to clarify the situation. The peculiarities of the 400 kV LUNA facility are particularly well suited for this study, where γ-rays with energy up to $\simeq$7.5 MeV have to be detected at very low count-rate (Q-value of the reaction: 7.3 MeV).

In the first phase of the LUNA study, data have been obtained with solid targets of TiN (typical thickness of 80 keV) reactively sputtered on a 0.2 mm thick Ta backing. A 126 % HpGe, placed at 55^o from the beam direction and at distances between 1.5 and 20.5 cm from the target, detected the γ rays. As a matter of fact, a detector with excellent energy resolution and small summing probability is necessary in order to unambiguously separate the different contribution to the cross section.

Details of the R-matrix fit can be found in (Angulo & Descouvement 2001), whereas details on the analysis of our data, which starts at E=130 keV, are given in (Formicola et al. 2004). In short, the fit, which has to be done for each transition, was performed in two steps.

First, the transition to the 6.79 MeV state was fitted including the data set given by (Schröder et al. 1987). The R-matrix fit for the transition to the 6.79 MeV state gives $S_{6.79}(0) = 1.35 \pm 0.05$ (statistical) ± 0.08 (systematic) keV·b. This value is about 20 % lower than the R-matrix fit (Angulo & Descouvement 2001) of the data from (Schröder et al. 1987) alone.

As the next step, we analyzed the LUNA data together with the data from (Schröder et al. 1987) (corrected to take into account the summing effect) for the ground state transition. When extrapolated to zero energy the R-matrix fit gives $S_{gs}(0) = 0.25 \pm 0.06$ keV·b This value is about a factor 3 higher than the R-matrix fit (Angulo & Descouvement 2001) of the data from (Schröder et al. 1987) alone.

For the total S-factor a contribution from the transition to the 6.18 MeV state of $S_{6.17}(0) = 0.06$ keV·b from (Angulo & Descouvement 2001) has been added to obtain $S_{tot}(0) = 1.7 \pm 0.1$ (statistical) ± 0.2(systematic) keV·b. It is smaller by about a factor 2 than the value given by the most recent compilations: $3.5^{+0.4}_{-1.6}$ keV·b (Adelberger et al. 1998) and 3.2 ± 0.8 keV·b (Angulo et al. 1999). As a consequence, the CNO neutrino yield in the Sun is decreased by about a factor two, and the age of the oldest Globular Clusters is increased by 0.7-1 Gyr.

The final analysis of the LUNA solid target data (Imbriani et al. 2005) includes all the transitions which contribute to the $^{14}N(p,\gamma)^{15}O$ cross section at low energy: ground state, 6.79, 6.17, 5.24 and 5.18 MeV. In addition, the astrophysical factor of the radiative capture into the 6.79 MeV state has been remeasured at 'high' energy (from 0.6 to 1.3 MeV proton energy) with the Bochum tandem accelerator. The resulting R-matrix fit, extrapolated to zero energy, gives a total astrophysical factor $S_{tot}(0) = 1.61 \pm 0.08$ keV·b. Recently, an independent study reported cross section data, taken at proton energy E_p from 155 to 524 keV (Runkle et al. 2005), in very good agreement with ours.

3.1. The gas target experiment

In order to measure the $^{14}N(p,\gamma)^{15}O$ total cross section at very low energies, it is essential to have both γ ray detectors with very high efficiency to compensate for the rapidly decreasing cross section as well as a very pure and thin ^{14}N target, to suppress the ion beam induced background and to minimize the straggling on the energy loss. In addition, the target must be stable for the long time required by the low energy measurements. All this has been achieved in the second phase of the LUNA study with a large 4π BGO summing detector (about 70% efficiency and 8% resolution in the energy region between 6 and 8 MeV) and with a windowless gas target.

Briefly, the ion beam enters the target chamber through three apertures of high impedance and it is stopped in a beam calorimeter placed at the downstream part of the chamber. The chamber is designed to fit inside the central hole (diameter $\phi = 6$ cm) of the BGO.

Because of the high absolute detection efficiency and of the near 4π geometry of the BGO detector, γ rays emitted in a cascade are with high probability summed into a peak at $E_\gamma = Q + E$, where Q is the Q-value of the

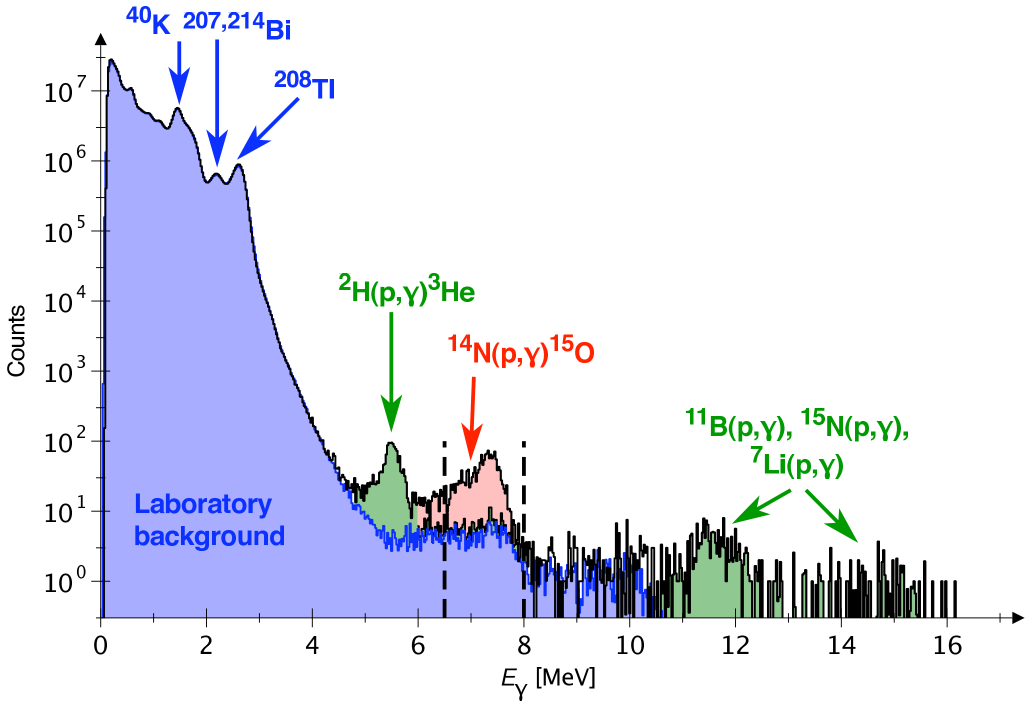

Fig. 2. BGO spectrum at the center of mass energy E=90 keV.

reaction (7.3 MeV) and E is the energy in the center of mass system. This is the reason why, with this set-up, we can give the value of the total cross section but not the one of each of the captures into the different ^{15}O states, as we did with the germanium detector.

Figure 2 shows the spectrum taken at E=90 keV, with typical current of 300 μA and 1 mbar gas target pressure. The counts from the reaction are shaded in light gray, whereas the laboratory background, normalized to equal lifetime (11.4 days), is shaded in dark gray. The most important components of the background induced by the proton beam are also indicated. Figure 3 shows our results (Lemut et al. 2006), corrected for the electron screening effect (Assenbaum et al. 1987) (10% and 3% effect at 70 and 150 keV, respectively). Typical errors are 3(stat) and and 4.5% (syst). Only at the lowest energy, 70 keV, they increase to 10% (stat) and 7% (syst), with the latter one mainly due to beam energy calibration and detection efficiency. At this energy, with 53 days of running time, there are 11 counts/day from the reaction (corresponding to a cross section of 0.24 pb), 22 counts/day from the laboratory background and 1 count/day from beam induced background in the region of interest (ROI) between 6.5 and 8 MeV. The same BGO detector would have a factor 1600 higher laboratory background in the ROI if measuring at the surface. The underground laboratory background, at these energies, is most likely due to γs from (n,γ) reactions in the detector and surrounding material. In Figure 3 we see that our data starts at a much lower energy than the previous direct experiments, while overlapping over a wide energy range. The statistical uncertainties are lower, and the systematic uncertainties are comparable or lower. Finally, we remark the excellent agreement of the present data with the R-matrix fit from the LUNA study of ^{14}N(p,γ)^{15}O with the germanium detector set-up (Imbriani et al. 2005).

The LUNA results obtained with the BGO set-up account for more than 90% (50%) of

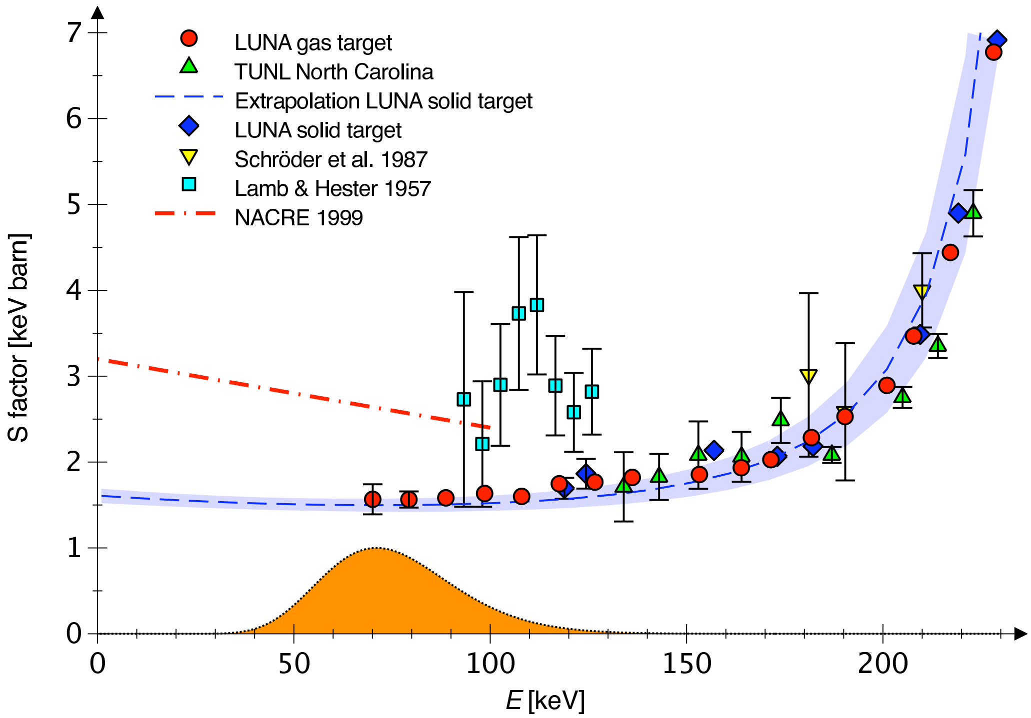

Fig. 3. Astrophysical S(E)-factor of $^{14}N(p,\gamma)^{15}O$ as function of the center of mass energy E. The errors are statistical only. The Gamow peak for T_6=60 is also shown.

the area under the Gamow peak for T_6 >90 (60), where T_6 is the stellar temperature in 10^6 K units (the energy region covered by previous experiments corresponds to T_6 >170). This way, the $^{14}N(p,\gamma)^{15}O$ has been measured at energies where non explosive CNO burning takes place in important astrophysical scenarios as AGB stars (asymptotic giant branch, i.e. stars which burn hydrogen and helium, respectively, in two shells surrounding a degenerate carbon-oxygen core).

4. The $^{3}He(\alpha,\gamma)^{7}Be$ experiment

$^{3}He(\alpha,\gamma)^{7}Be$ (Q-value=1.586 MeV) is the key reaction for the production of ^{7}Be and ^{8}B neutrinos in the Sun. The error on $S_{3,4}$, 9.4% (Adelberger et al. 1998) is the main nuclear limitation to the extraction of physics from the ^{8}B and, very soon, ^{7}Be neutrino flux measurements from the Sun. The $^{3}He(\alpha,\gamma)^{7}Be$ reaction is also responsible for the production of ^{7}Li in big-bang nucleosynthesis. Its uncertainty strongly effects the prediction of the primordial ^{7}Li abundance.

The capture reaction is dominated, at low energies, by the non-resonant direct capture mechanism to the ground state and the 429 keV first excited state of ^{7}Be. One expects to observe two primary γ-ray transitions, DC $\rightarrow$ 0 and DC $\rightarrow$ 429 keV with the latter followed by a 429 keV secondary transition. An independent determination of the number of ^{7}Be nuclei produced in the reaction requires the detection of the 478 keV γ-ray activity of the first excited state in the daughter nucleus ^{7}Li populated in the EC decay of the ^{7}Be nucleus (branching ratio of 10.44 ± 0.04 %, $T_{1/2}$ = 53.22 ± 0.06 day). Both methods have been used in the past to determine the absolute cross section σ(E) in the energy range $E_{c.m.} \geq 107$ keV (see (Hilgemeier et al. 1988), (Singh et al. 2004) and References therein) but the dispersion of the evaluated $S_{3,4}$ astrophysical factors produce a significant uncertainty on the adopted $S_{3,4}$ value. Moreover, the $S_{3,4}$ extracted from the measurements of the induced ^{7}Be activity are 13% higher (Adelberger et al. 1998) than the values obtained from the measurements of the prompt capture γ-rays transitions.

The key features of our study of ^{3}He$(\alpha,\gamma)^7$Be are the the detection in the same experiment of both the prompt capture γ-ray and of the 478 keV γ-ray from the ^{7}Be decay, the extremely low laboratory background and the high accuracy (relative error ≤ 5 %) down to very low energy ($E_{c.m.} \simeq$ 90 keV). The experiment is performed with the ^{4}He$^+$ beam from the 400 kV accelerator in conjunction with a windowless gas target made of oxygen free high conductivity (OFHC) copper, chosen because of its radioactive clearness, and filled with ^{3}He at 0.7 mbar pressure.

The beam enters the target chamber through a 7 mm diameter collimator and it is stopped on a power calorimeter placed 35 cm downstream. The prompt capture γ-ray is detected by a 150 % relative efficiency ultra low background HpGe detector placed in close geometry with the target. The germanium detector is surrounded by a 4 cm copper + 25 cm lead shielding and everything is closed inside an anti-radon box. At energies higher than 0.5 MeV we measured a background rate of 4.1 counts/h/kg, a factor 7 only worse than the best ultra-low background germanium set-up running in Gran Sasso (in spite of the presence of the beam-pipe entering our shielding and of the calorimeter inside the target chamber).

The ^{7}Be nucleus produced by the ^{3}He$(\alpha,\gamma)^7$Be reaction inside the ^{3}He gas target are implanted into the calorimeter cap (thanks to the forward kinematics and low lateral straggling). After the irradiation, this cap (7 cm diameter) is removed and transported to the counting facility. Two detectors are used to measure the collected ^{7}Be activity. Both are placed in the low level laboratory of LNGS. The first detector is a 120 % relative efficiency HPGe detector with lead + copper shielding. The laboratory background in this detector at 478 keV is roughly 6 counts/keV/day. The second HPGe detector has similar efficiency but it is an ultra low background detector equipped with lead shielding and radon box. The relevant laboratory background here is 0.2 counts/keV/day (more than 3 orders of magnitude lower than what can be achieved in an external laboratory).

Data taking started in autumn 2005 and it has been completed by September 2006. We have already obtained the ^{3}He$(\alpha,\gamma)^7$Be cross section at the beam energy of 400, 350 and 300 keV from the activation data (Bemmerer et al. 2006), i.e. by counting the ^{7}Be nuclei collected on the calorimeter cap. The dominant error is the systematic one, mainly due to the uncertainties on ^{7}Be counting efficiency (1.8%), beam intensity (1.5%) and effective target thickness (1.3%). This data (Fig. 4) are the first activation results at energies directly relevant to big-bang ^{7}Li production. Their uncertainty of 4 % (systematic and statistical combined in quadrature) is comparable to or lower than previous activation studies at high energy and lower than prompt-γ studies at comparable energy. To give an estimate for the low-energy implications, rescaling the most recent R-matrix fit (Descouvement et al. 2004) to the present data results in $S(0)$ = 0.547±0.017 keV barn, consistent with, but more precise than, (Singh et al. 2004). We are now analyzing our prompt-γ data in order to obtain a cross section measurement with precision comparable to the 4 % reached in the activation work.

5. Status and perspectives

The 'non solar' phase of LUNA has already started with the now running experiment on ^{25}Mg$(p,\gamma)^{26}$Al (Q-value 6.3 MeV). This is the slowest reaction of the Mg-Al cycle. The β^+ decay of ^{26}Al$_{gs}$ [1] to the excited state of ^{26}Mg gives rise to a 1.8 MeV γ-ray, one of the most important line for γ astronomy. Two reasons make the low energy measurement of this cross section so relevant: the 1.8 MeV full sky map taken by the satellites which look at the γ sky

[1] About 80% of the released ^{26}Al is in the ground state ($t_{1/2} = 7 \cdot 10^5$ year), the remaining 20% goes into the 228 keV isomeric state ($t_{1/2}$ = 6s).

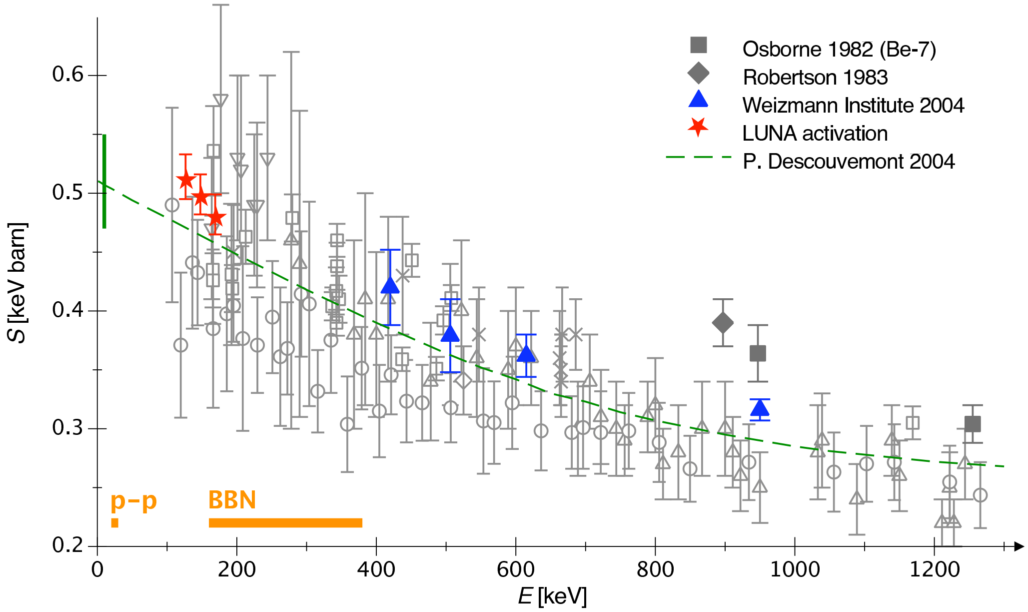

Fig. 4. Astrophysical S-factor for $^3He(\alpha,\gamma)^7Be$. Activation data: filled squares, filled diamonds, filled triangles, stars (present work) and prompt-γ data. Dashed line: previously adopted R-matrix fit (Descouvement et al. 2004). Horizontal bars: energies relevant for p–p chain and for BBN.

and the anomalous meteoritic abundance of ^{26}Mg.

We have measured underground the resonances at the centre of mass energy of 304 and 189 keV with a Ge detector in order to improve the accuracy of the strength determination and to assess the structure of the γ-ray cascade. The study of the 189 keV is of particular interest since a very recent measurement (Arazi et al. 2006) of this resonance strength via accelerator mass spectroscopy has given a factor 5 lower value than the one recommended by NACRE. The analysis of our data is now in progress.

The study of the resonances at 130 and 92 keV (for which no direct measurement exists) will be performed in LUNA this year with the high efficiency BGO detector used in the $^{14}N(p,\gamma)^{15}O$ experiment.

We already have a program rich of experiments which can be done next years with the 400 kV accelerator. In particular, we are planning to study down to very low energy $D(\alpha,\gamma)^6Li$, the (p,γ) reactions on ^{15}N, ^{17}O, ^{18}O, ^{23}Na, ^{22}Ne and $^{13}C(\alpha,n)^{16}O$. We are also discussing the possibility to measure $^{12}C(\alpha,\gamma)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ with a new 'high' voltage accelerator (3-4 MV).

6. Conclusions

LUNA started its activity almost 15 years ago with the goal of exploring the fascinating domain of nuclear astrophysics at very low energy. During these years it has proved that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars. In particular, we measured $^3He(^3He,2p)^4He$ within the Gamow peak of the Sun, $^{14}N(p,\gamma)^{15}O$ down to 70 keV energy, entering this way the Gamow peak of AGB stars, and $^3He(\alpha,\gamma)^7Be$ with high accuracy down to 90 keV.

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