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NUCLEAR PROCESSES AT SOLAR ENERGY

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ABSTRACT

LUNA, Laboratory for Underground Nuclear Astrophysics at Gran Sasso, is measuring fusion cross sections down to the energy of the nucleosynthesis inside stars. Outstanding results obtained up to now are the cross-section measurements within the Gamow peak of the Sun of $^3He(^3He, 2p)^4He$ and the $D(p, \gamma)^3He$. The former plays a big role in the proton-proton chain, largely affecting the calculated solar neutrino luminosity, whereas the latter is the reaction that rules the proto-star life during the pre-main sequence phase. The implications of such measurements will be discussed. Preliminary results obtained last year on the study of $^{14}N(p, \gamma)^{15}O$, the slowest reaction of the CNO cycle, will also be shown.

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 in most cases below 100 keV, far below the Coulomb energy, the reaction cross-section σ(E) drops almost exponentially with decreasing energy E [1]:

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

where $S(E)$ is the astrophysical factor and η is the Sommerfeld parameter, 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 units of amu), and E is the center of mass energy (in units of keV).

The extremely low value of the cross-section, ranging from pico to femtobarn and even below, has always prevented its measurement in a laboratory on the Earth's surface, where the signal to background ratio would be too small because of cosmic ray interactions. Instead, the observed energy dependence of the cross-section at high energies is extrapolated to the low energy region, leading to substantial uncertainties. In particular, there might be a change of the reaction mechanism or of the centrifugal barrier, or there might be the contribution of narrow or subthreshold resonances, all of which cannot be accounted by the extrapolation, but 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 LNGS: a 50 kV accelerator [2] and a 400 kV one [3]. The qualifying features of both the accelerators are a very small beam energy spread and a very high beam current even at low energy. The accelerators are located in two dedicated small rooms of the Laboratori Nazionali del Gran Sasso (LNGS), separated from other experiments by about 60 m of rock. 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 is like 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 $^3He(^3He,2p)^4He$ cross section measurement within the solar Gamow peak (15-27 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 [4] [5] to explain the observed ^8B solar neutrino flux: it would decrease the relative contribution of the alternative reaction $^3He(\alpha,\gamma)^7Be$, which generates the branch responsible for ^7Be and ^8B 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 would be required to reduce the ^7Be and ^8B solar neutrinos by a factor 2-3). As a matter of fact, $^3He(^3He,2p)^4He$ cross section measurements stopped at the center of mass energy of 24.5 keV (σ=7±2 pb)[6], just at the upper edge of the thermal energy region of the Sun.

Briefly, the LUNA 50 kV 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 and the beam current was high even at low energy (about 300 μA measurable with a 3% accuracy). 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 ^3He gas pressure of 0.5 $mbar$ (measured to an accuracy of better than 1%).

The simultaneous detection of 2 protons has been the signature which unambiguously identified a $^3He(^3He,2p)^4He$ 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 ^4He beam on a ^4He target (0.5 $mbar$). Figure 1 shows our results together with two existing measurements [6][7] of the astrophysical factor $S(E)$. We point out that the 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±0.02 pb, which corresponds to a rate of about 1 event/month, rather low even for the "silent" experiments of underground physics.

The LUNA result [8] has shown that the $^3He(^3He,2p)^4He$ cross section increases at the thermal energy of the Sun due to the electron screening effect but does not have any narrow resonance. Consequently, the astrophysical solution of the ^8B and ^7Be solar neutrino problem based on its existence has been ruled out.

With $^3He(^3He,2p)^4He$ LUNA has provided the first cross section mea-

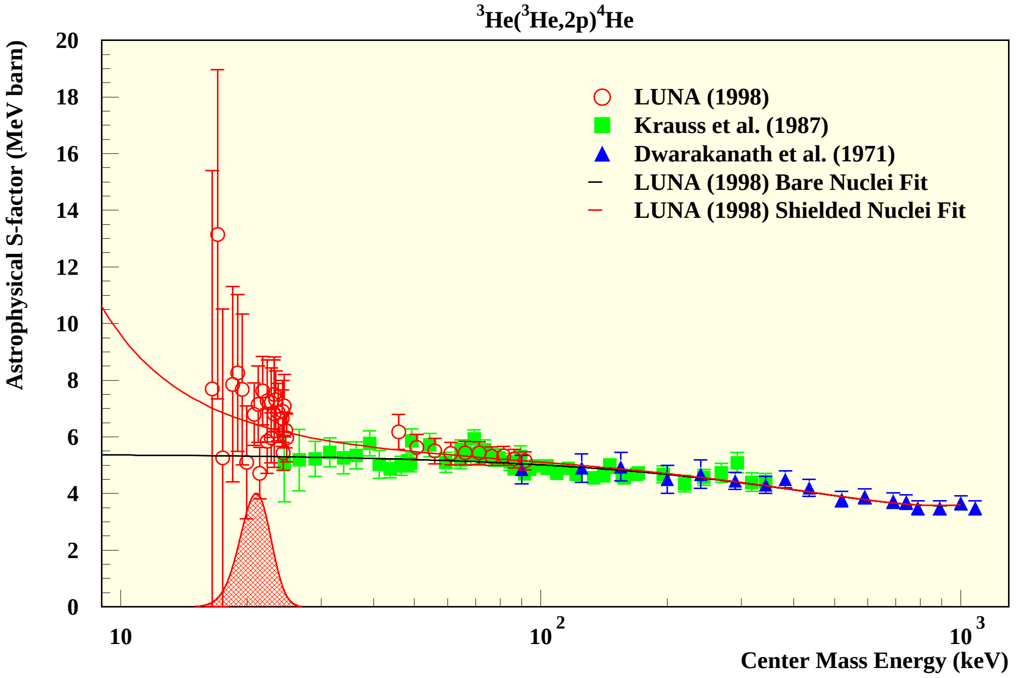

Figure 1: The $^3He(^3He,2p)^4He$ astrophysical factor $S(E)$. The position of the solar Gamow peak is also shown schematically.

surement of a key reaction of the proton-proton chain at the thermal energy of the Sun. In this way it has also shown 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 D(p,γ)^{3}He reaction

Inside the Sun, the D(p,γ)^{3}He reaction only effects the equilibrium abundance of deuterium. As a matter of fact, its cross section is much higher than the one of the deuterium producer reaction p(p,e$^+\nu$)d.

On the other hand, D(p,γ)^{3}He is the reaction which rules the life of the proto-stars before they enter the main sequence phase. Reliable proto-star models predict that a star forms by accretion of interstellar material onto a small contracting core. Until the temperature remains below 10^6 K, the main source of energy is the gravitational contraction. When the temperature approaches 10^6 K the first "nuclear fire" is switched on inside the star: the primordial deuterium is

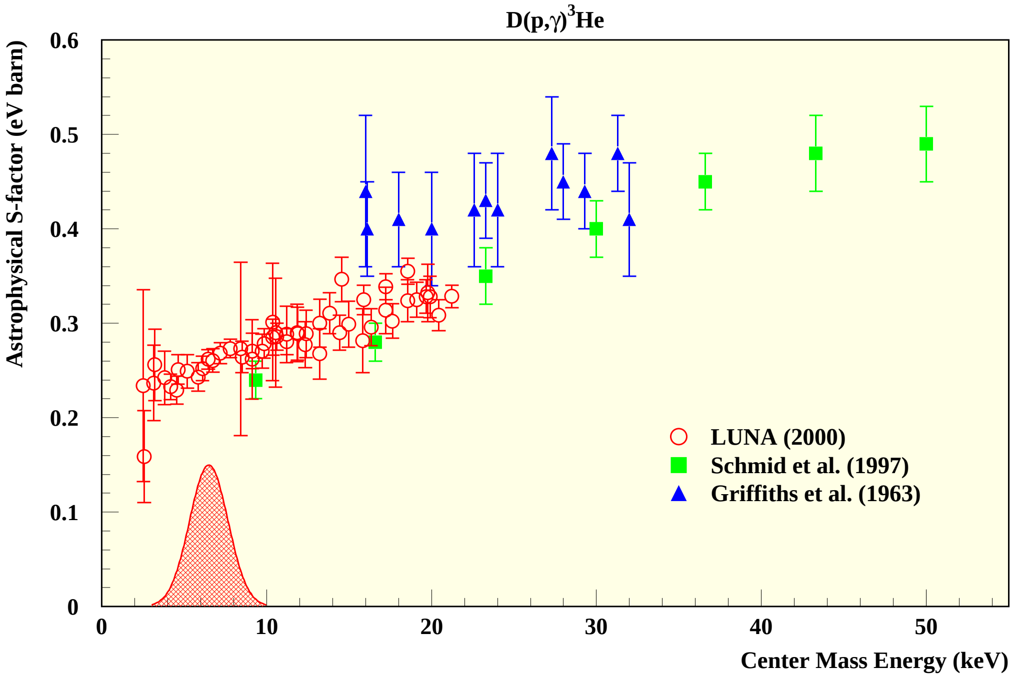

Figure 2: The D(p,γ)^{3}He astrophysical factor $S(E)$. The position of the solar Gamow peak is also shown schematically.

converted into ^3He via d(p,γ)^{3}He, thus providing 5.5 MeV for each reaction. The total amount of nuclear energy generated by this d-burning is comparable with the whole gravitational binding energy of the star. The on-set of d-burning slows down the contraction, increases the lifetime of the star and freezes its observational properties until the original deuterium is fully consumed. A reliable knowledge of the rate of d(p,γ)^{3}He down to a few keV (the Gamow peak in a proto-star) is a fundamental prerequisite for the proto-stellar models.

Finally, d(p,γ)^{3}He is also a cornerstone in the big-bang nucleosynthesis. Because of the deuterium "bottleneck" [9], i.e. the photo-disintegration of deuterium, the formation of ^3He is delayed until the temperature drops to about $8{\cdot}10^8K$. As a consequence, the knowledge of the d(p,γ)^{3}He cross section at low energies is necessary for the big-bang nucleosynthesis models.

The D(p,γ)^{3}He cross section measurement was made in LUNA by using the 50 kV accelerator connected to a differentially pumped gas-target system designed to fit the characteristics of a large BGO gamma ray detector [10]. The BGO, a 28 *cm* long cylinder placed around the deuterium target, was detecting the 5.5 *MeV* gamma with a 70% efficiency.

Figure 2 shows the LUNA results together with the only two existing measurements [11][12] of the astrophysical factor $S(E)$ at low energy. The cross section varies by more than three orders of magnitude in the measured energy range. At the lowest energy of 2.5 *keV* it has the value of 9.2±4 *pb*, which corresponds to a rate of 50 events/day.

In figure 2 we see one of the problems of nuclear astrophysics: not only there are no measurements in the interesting energy region, but also the extrapolations of the existing ones can have a significant disagreement.

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

$^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO cycle, the key one 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 [13]. The position of the Turn Off point in the Hertzsprung-Russel diagram of a globular cluster is also determined by the value of the $^{14}N(p,\gamma)^{15}O$ cross section and it gives the age of the cluster. As a matter of fact, a star at the Turn-Off point is burning hydrogen in the shell through the CNO cycle, it expands and, as a consequence, it has a decrease of the surface temperature.

The energy region studied so far in nuclear physics laboratories is well above the region of interest for the CNO burning in astrophysical conditions (20-80 *keV*). At solar energies the cross section of $^{14}N(p,\gamma)^{15}O$ is dominated by a sub-threshold resonance at -504 *keV*, whereas at energies higher than 100 *keV* it is dominated by the 278 *keV* resonance, with transitions to the ground-state of ^{15}O or to the excited states at energies of 5.18 *MeV*, 6.18 *MeV* and 6.79 *MeV*. According to Schröder et al. [14], who measured down to 0.2 *MeV*, the main contribution to the total S-factor at zero energy, S(0),comes from the transitions to the ground state of ^{15}O and to its excited state at E_x = 6.79 MeV. In particular, they give S(0) $= 3.20 \pm 0.54\ keV \cdot b$. On the other hand, Angulo et al. [15] reanalyzed Schröder's experimental data using a R-matrix model and they obtained S(0) $= 1.77 \pm 0.20\ keV \cdot b$, which is a factor 1.7 lower than the values used in the recent compilations. The difference mainly comes from the different contribution of the direct capture to the ^{15}O ground state: Angulo et al. have a value lower by a factor 19 than the one of Schröder et al.. We underline that at the lowest energies

Schröder et al. give only upper limits to the cross section, due to the presence of a strong cosmic ray background in the spectrum.

In summary, new measurements of the $^{14}N(p,\gamma)^{15}O$ cross section at energies E $\leq$ 200 keV are strongly demanded. In particular it is necessary to well measure the contribution of the direct capture to the ground state of ^{15}O. The peculiarities of the 400 kV LUNA facility [3] 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). As a matter of fact, in such a measurement the cosmic ray background has to be strongly suppressed and ultra-low background detectors have to be employed. In addition, high beam intensities and detectors with excellent energy resolution have to be coupled to targets of high stability and purity, in order to minimize the beam-induced background.

Due to the strong energy dependence of the cross section, we carefully determined the uncertainties of our accelerator: $\pm$300 eV on the absolute energy from E_p = 130 to 400 keV, proton energy spread of better than 100 eV and long term energy stability of 5 eV per hour [3].

The preliminary results shown in figure 3 have been obtained with the beam

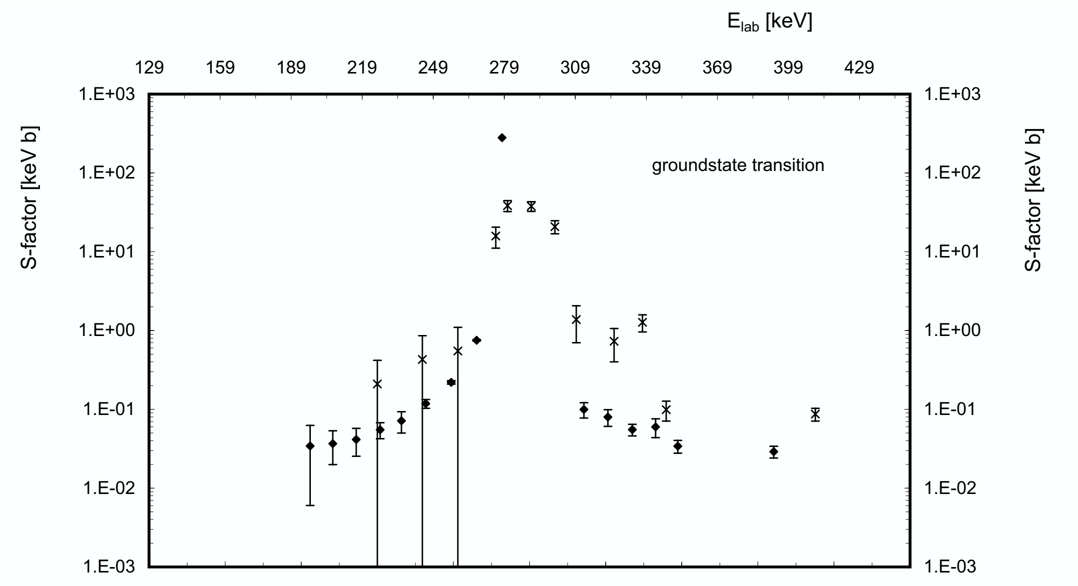

Figure 3: Preliminary LUNA results for the ground-state transition of $^{14}N(p,\gamma)^{15}O$ (filled rhombus) and Schröder results (crosses).

passing through a Ta collimator and focused to a spot of about 1.5 cm diameter on a TiN target on Ta backing. A 126% HpGe detected the γ rays from the reaction: it was placed at 55^o from the beam direction at about 1.5 cm distance from the target. A detector with excellent energy resolution is necessary in order to unambiguously separate the different contribution to the cross section.

Figure 3 is given just to show the data quality improvement achieved thanks to the cosmic ray suppression. With only a small fraction of the data we already have an acceptable error in a region where the previous experiment could give only upper limits. We are now completing the analysis of all the data we collected in 2002 to cover the energy region down to about 100 keV. With them it will be possible to separately know the contribution to the cross section of both the direct capture to the ground state of ^{15}O and to its excited state at 6.79 MeV.

5 Present status and future directions

In order to study the $^{14}N(p,\gamma)^{15}O$ reaction down to the lowest energies it is essential to have both a γ ray detector with very high efficiency, to compensate for the rapidly decreasing cross section, and a very thin and pure ^{14}N target, to minimize the straggling on the energy loss and the beam induced background. This can be achieved with the same 4π BGO summing detector used in the measurement of $D(p,\gamma)^3He$ and with a new windowless gas target (a gas target is generally much more pure than a solid one). Such a set-up has been constructed in 2001, connected to the 400 kV accelerator and fully tested before summer this year. We have now started collecting the data.

There are two reactions already scheduled to be measured in the future: $^3He(\alpha,\gamma)^7Be$ and $^{25}Mg(p,\gamma)^{26}Al$. $^3He(\alpha,\gamma)^7Be$ (Q-value: 1.6 MeV) is the key reaction for the production of ^7Be and ^8B neutrinos in the Sun. The joint effort of all experiments on solar neutrinos and solar physics has finally cast light on the long-standing solar neutrino puzzle. As a consequence, we can now go back to the original motivation of solar neutrino detection: the study of the Sun. The error on $S_{3,4}$, about 16%, is, at the moment, the main limitation to the extraction of physics from the ^8B neutrino flux measurement. For instance, a 3-5% determination of $S_{3,4}$ would allow a study of the central region of the Sun with an accuracy better than the one given by helioseismology.

$^{25}Mg(p,\gamma)^{26}Al$ (Q-value: 6.3 MeV) is a reaction of the $MgAl$ cycle. Its low energy measurement would be important for two reasons: the study of the nucleosynthesis of the elements with mass number between 24 and 27 and the γ

ray astronomy. As a matter of fact, ^{26}Al is a radioactive nucleus, with $7.4{\cdot}10^5$ year half-life. Its decay gives rise to a 1.8 MeV gamma ray: one of the key line of γ astronomy. There is now a full sky map at 1.8 MeV, provided by the NASA Compton Gamma-Ray Observatory. The ESA INTEGRAL Observatory is going to improve the picture of the 1.8 MeV sky in the near future. The study of the reaction producing ^{26}Al is essential to understand such a sky.

6 Conclusions

LUNA started its activity almost 10 years ago in order to explore the new domain of nuclear astrophysics at 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 have provided the only existing measurements of important fusion reactions within the Gamow peak of the Sun: $^3He(^3He,2p)^4He$ and $D(p,\gamma)^3He$. The results on $^3He(^3He,2p)^4He$ have shown that nuclear physics was not the origin of the solar neutrino puzzle.

We are now measuring $^{14}N(p,\gamma)^{15}O$, the key reaction of the CNO cycle. After this we will study $^3He(\alpha,\gamma)^7Be$ and $^{25}Mg(p,\gamma)^{26}Al$. The former is the key reaction for the production of ^7Be and ^8B neutrinos in the Sun, whereas the latter is essential to understand the γ sky at 1.8 MeV.

References

1. C. Rolfs and W.S. Rodney, Cauldrons in the Cosmos, The University of Chicago Press (1988).
2. U. Greife et al., Nucl.Instr.Meth. **A350**, 327 (1994).
3. A. Formicola et al., Nucl.Instr.Meth. **A507**, 609 (2003).
4. W.A. Fowler, Nature **238**, 24 (1972).
5. V.N. Fetysov and Y.S. Kopysov, Phys. Lett. **B40**, 602(1972).
6. A. Krauss et al., Nucl.Phys. **A467**, 273 (1987).
7. M.R Dwarakanath and H. Winkler, Phys.Rev. **C4**, 1532 (1971).
8. R. Bonetti et al., Phys. Rev. Lett. **82**, 5205(1999).

9. S. Weinberg, Gravitation and Cosmology, John Wiley and Sons (1972).

10. C Casella et al., Nucl.Instr.Meth. **A489**, 160 (2002).

11. G.M. Griffits et al., J. Phys. Lett. **41**, 724 (1963).

12. G.J. Schmid et al., Phys. Rev. Lett. **76**, 17 (1996).

13. J.N. Bahcall, Neutrino Astrophysics, Cambridge University Press (1989).

14. U. Schroeder et al., *Nucl. Phys* A**467**, 240 (1987).

15. C. Angulo and P. Descouvemont, Nucl. Phys. **A690**, 755 (2001).