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Review

Twenty years of LUNA

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ABSTRACT

One of the main ingredients of nuclear astrophysics is the knowledge of the thermonuclear reactions responsible for the stellar luminosity and for the synthesis of the chemical elements. Deep underground in the Gran Sasso Laboratory the cross sections of the key reactions of the proton–proton chain and of the Carbon–Nitrogen–Oxygen (CNO) cycle have been measured right down to the energies of astrophysical interest. The main results obtained by LUNA are reviewed, and their influence on the comprehension of the properties of the neutrino and of the Sun are discussed.

1. Introduction

Stars are not perfect and eternal bodies as believed by the ancient philosophers. On the contrary, gravity triggers the birth of a star which then works as a more or less turbulent nuclear fusion reactor to finally die out in a quiet or violent way, depending on its initial mass. As a matter of fact, only hydrogen, helium and lithium are synthesized in the first minutes after the big-bang. All the other elements of the periodic table are produced in the thermonuclear reactions taking place inside the 'cosmic cauldrons'. i.e. the stars [1].

Nuclear astrophysics studies all the reactions which provide the energy to the stars and realize the transmutation of the chemical elements. In particular, the knowledge of the reaction cross-section at the stellar energies is the heart of nuclear astrophysics. The reaction rate in the hot plasma of a star, with temperatures in the range of tens to hundreds of millions Kelvin, is obtained by weighting the reaction cross section $\sigma(E)$ with the energy distribution of the colliding nuclei: a Maxwell–Boltzmann $\phi(E)$ peaked at energies of 1–10 keV. The product between $\sigma(E)$ and $\phi(E)$ identifies the energy window where the reaction occurs in the star: the Gamow peak. At lower energies the cross section is too small whereas at higher energies the nuclei in the tail of the Maxwell–Boltzmann are too few. Inside the Gamow peak, which is far below the Coulomb energy arising from the repulsion between nuclei, the reaction can take place only due to the quantum mechanical tunnel effect:

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

where $S(E)$ is the astrophysical factor (which contains the nuclear physics information) 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, μ is the reduced mass (in units of amu), and E is the center of mass energy (in units of keV).

At these energies the cross sections are extremely small. Such smallness makes the star's lifetime of the length we observe, but it also makes direct measurement impossible in the laboratory. The rate of the reactions, characterized by a typical energy release of a few MeV, is too low, down to a few events per year, in order to stand out from the laboratory background. Instead, the observed energy dependence of the cross-section at high energies is extrapolated to the low energy

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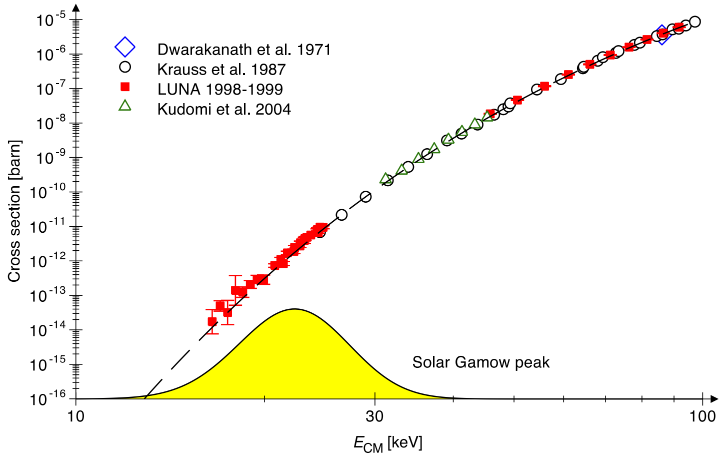

Fig. 1. The cross section of ^{3}He(^{3}He, 2p)^{4}He. Data from LUNA and other experiments.

region, leading to substantial uncertainties. For example, there might be narrow resonances at low energy or even resonances below the reaction threshold that influence the cross section at the Gamow peak. These effects cannot always be accounted for by an extrapolation.

LUNA, Laboratory for Underground Nuclear Astrophysics, started about twenty years ago to run nuclear physics experiments in an extremely low-background environment: the Gran Sasso Laboratory (LNGS) to reproduce in the laboratory what naturally occurs inside stars.

In order to explore this new domain of nuclear astrophysics we have installed two electrostatic accelerators underground in LNGS: a compact 50 kV "home-made" machine and a commercial 400 kV one [2,3]. Common features of the two accelerators are the high beam current, the long term stability and the precise beam energy determination. The first feature is required to maximize the reaction rate, the second is due to the long time typically needed for a cross section measurement, while the third is important because of the strong energy dependence of the cross section.

The dolomite rock of Gran Sasso provides a natural shielding equivalent to at least 3800 m of water which reduces the muon and neutron fluxes by a factor 10^6 and 10^3, respectively, with the remaining neutrons due to the (α, n) reactions in the rock. The γ ray flux in the energy region of 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 within the shielding itself.

2. The resonance and the solar neutrino problem

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 (15–27 keV). Such a reaction is a key one of the hydrogen burning proton–proton chain, which is responsible for more than 99% of the solar luminosity. A resonance at the thermal energy of the Sun was suggested a long time ago to explain the observed ^{8}B solar neutrino flux. Such a resonance would decrease the relative contribution of the alternative reaction ^{3}He$(\alpha, \gamma)^7$Be, which generates the branch responsible for ^{7}Be and ^{8}B neutrino production in the Sun. As a matter of fact, nuclear physics, in particular the cross section of the different reactions of the proton–proton chain and of the CNO cycle, is the key ingredient to calculate the energy spectrum of the solar neutrinos: the different branches give rise to neutrinos of different energy.

The final setup was made of eight 1 mm thick silicon detectors of 5×5 cm^2 area placed around the beam inside the windowless target chamber filled with ^{3}He at a pressure of 0.5 mbar. The simultaneous detection of two protons has been the signature which unambiguously identified a ^{3}He(^{3}He, 2p)^{4}He fusion reaction (Q-value: 12.86 MeV). Fig. 1 shows the results from LUNA [4,5] together with higher energy measurements [6–8] which stop just at the upper edge of the thermal energy region of the Sun.

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 pbarn, which corresponds to a rate of about 2 events/month, rather low even for the "silent" experiments of underground physics. No narrow resonance has been found within the solar Gamow peak and, as a consequence, the astrophysical solution of the ^{8}B and ^{7}Be solar neutrino problem based on its existence has been definitely ruled out.

3. The ^{7}Be solar neutrino flux

^{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 since their flux depends almost linearly on its cross section. Unless a recoil separator is used, the cross section can be determined either

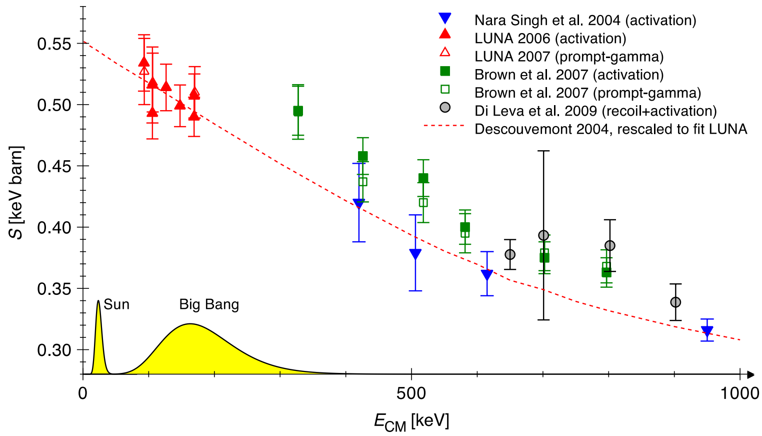

Fig. 2. Astrophysical S(E)-factor for $^3He(\alpha,\gamma)^7Be$. The results from the modern, high precision experiments are shown with their total error.

from the detection of the prompt γ rays or from the counting of the decaying ^7Be nuclei. The latter requires the detection of the 478 keV γ due to the excited ^7Li populated in the decay of ^7Be (half-life: 53.22 days).

Both methods have been used in the past to determine the cross section in the energy range $E_{c.m.} \geq 107$ keV but the $S_{3,4}$ extracted from the measurements of the induced ^7Be activity was 13% higher than that obtained from the detection of the prompt γ-rays [9].

The underground experiment has been performed with the $^4He^+$ beam from the 400 kV accelerator in conjunction with a windowless gas target filled with ^3He at 0.7 mbar. The beam enters the target chamber and is stopped on the calorimeter. The ^7Be nuclei produced by the reaction inside the ^3He gas target are implanted into the calorimeter cap which, after the irradiation, is removed and placed in front of a germanium detector for the measurement of the ^7Be activity.

In the first phase of the experiment, the $^3He(\alpha,\gamma)^7Be$ cross section has been obtained from the activation data [10,11] alone with a total uncertainty of about 4%. In the second phase, a new high accuracy measurement using simultaneously prompt and activation methods was performed down to the center of mass energy of 93 keV. The prompt capture γ-ray was detected by 135% germanium, heavily shielded and placed in close geometry with the target.

The astrophysical factor obtained with the two methods [12] is the same within the quoted experimental error. Similar conclusions have then been reached in a new simultaneous activation and prompt experiment [13] which covers the $E_{c.m.}$ energy range from 330 to 1230 keV. In Fig. 2 the results from the modern experiments are shown [10–15].

The energy dependence of the cross section seems to be theoretically well determined at low energy. If we leave the normalization as the only free parameter, we can rescale the fit of [16] to our data and we obtain $S_{3,4}(0) = 0.560 \pm 0.017$ keV barn. We note that a theoretical uncertainty of ± 0.02 keV barn is estimated on $S_{3,4}(0)$ [17]. Thanks to our small error, the total uncertainty on the ^8B solar neutrino flux goes from 12% to 10%, whereas the one on the ^7Be flux goes from 9.4% to 5.5% [12].

The ^7Be flux is now predicted with an error similar to the experimental one which will soon be achieved by Borexino. Thanks to such small errors, it will be possible to have a precise study of the signature typical of neutrino oscillations in matter, i.e. the energy dependence of the oscillation probability.

The energy window covered by LUNA is above the solar Gamow peak but well within the Gamow peak of big-bang nucleosynthesis. Our precise results clearly rule out the $^3He(\alpha,\gamma)^7Be$ cross section as a possible source of the discrepancy between the predicted primordial ^7Li abundance and the lower observed value.

4. The composition of the Sun core

$^{14}N(p,\gamma)^{15}O$ (Q-value: 7.297 MeV) 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 ^{13}N and ^{15}O solar neutrino flux, which depends almost linearly on its cross section.

In the first phase of the LUNA study, data have been obtained down to 119 keV energy with solid targets of TiN and a 126% germanium detector. This way, the five different radiative capture transitions which contribute to the $^{14}N(p,\gamma)^{15}O$ cross section at low energy were measured. The total cross section was then studied down to very low energy in the second phase of the experiment by using the 4π BGO summing detector placed around a windowless gas target filled with nitrogen at 1 mbar pressure. At the lowest center of mass energy of 70 keV a cross section of 0.24 pbarn was measured, with an event rate of 11 counts/day from the reaction.

The results obtained first with the germanium detector [18,19] and then with the BGO setup [20] were about a factor two lower than the existing extrapolation [9,21] from previous data [22,23] at very low energy (Fig. 3), while in agreement with results from indirect methods.

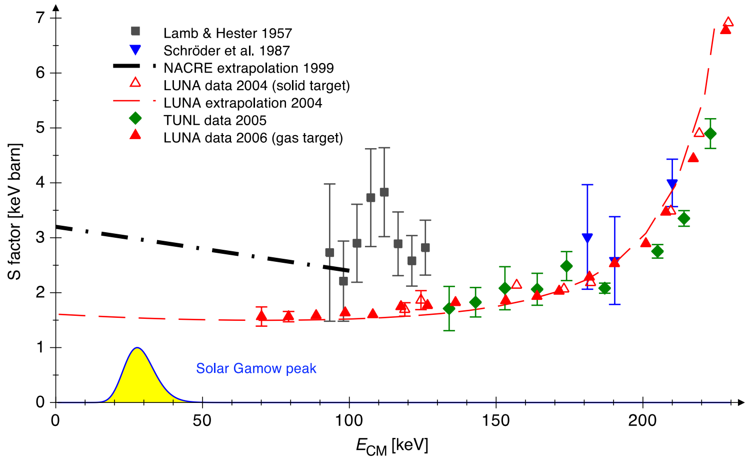

Fig. 3. Astrophysical S(E)-factor of the $^{14}N(p,\gamma)^{15}O$ reaction. The errors are statistical only (the systematic ones are similar).

As a consequence, the CNO neutrino yield in the Sun is decreased by about a factor two. The lower cross section also affects stars which are more evolved than our Sun: in particular, the age of the globular clusters is increased by 0.7–1 billion years [24] up to 14 billion years and the dredge-up of carbon to the surface of asymptotic giant branch stars is more efficient [25].

The main conclusion from the LUNA data has been confirmed by an independent study at higher energy [26]. However, there is a 15% difference between the total S-factor extrapolated by the two experiments at the Gamow peak of the Sun. In particular, this difference arises from the extrapolation of the capture to the ground state in ^{15}O, a transition strongly affected by interference effects between several resonances and the direct capture mechanism.

In order to provide precise data for the ground state capture, a third phase of the $^{14}N(p,\gamma)^{15}O$ study has been performed with a composite germanium detector in the beam energy region immediately above the 259 keV resonance, where precise data effectively constrain a fit for the ground state transition in the R-matrix framework. This way the total error on the S-factor has been reduced to 8%: $S_{1,14}(0) = 1.57 \pm 0.13$ keV barn [27]. This is significant because we have finally solved the solar neutrino problem and are now facing the solar composition problem: the conflict between helioseismology and the new metal abundances (i.e. the amount of elements different from hydrogen and helium) that emerged from improved modeling of the photosphere [28]. Thanks to the relatively small error, it will be possible in the near future to measure the carbon and nitrogen content of the Sun core by comparing the predicted CNO neutrino flux with the measured one. As a matter of fact, the CNO neutrino flux is decreased by about 30% in going from the high to the low metallicity scenario. This way it will be possible to test whether the early Sun was chemically homogeneous [29], a key assumption of the standard Solar Model.

5. Current measurements

The solar phase of LUNA has almost reached the end. A new and rich program of nuclear astrophysics mainly devoted to the CNO, Mg–Al and Ne–Na cycles has already started at the 400 kV facility with the measurement of $^{15}N(p,\gamma)^{16}O$ [30] and $^{25}Mg(p,\gamma)^{26}Al$ [31]. These cycles become important for second generation stars with central temperatures and masses higher than those of our Sun. Due to the higher Coulomb barriers, they are relatively unimportant for energy generation while being essential for the nucleosynthesis of elements with mass number higher than 20. LUNA is now measuring $^{2}H(\alpha,\gamma)^{6}$ Li, the key reaction of big-bang nucleosynthesis which determines the amount of primordial ^{6}Li in the Universe and $^{17}O(p,\gamma)^{18}F$, the bridge reaction connecting the second to the third CNO cycle.

6. The future

LUNA has shown the advantages of the low background environment on the study of the hydrogen burning processes at the stellar energies. The next step will be the exploitation of the underground environment to study the key processes of helium and carbon burning. In particular, $^{12}C(\alpha,\gamma)^{16}O$, the "Holy Grail" of nuclear astrophysics, which determines the abundance ratio between carbon and oxygen, the two key elements to the development of life. This abundance ratio shapes the nucleosynthesis in massive stars up to the iron peak and the properties of supernovae. Of great significance is also $^{12}C + ^{12}C$, which initiates the carbon burning. Its rate determines the critical mass separating the evolution of a massive star towards a carbon–oxygen white dwarf or a supernova. Equally important are $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, the stellar sources of the neutrons which synthesize most of the trans-iron elements through the S-process: neutron captures followed by β decays.

The study of these exciting cases asks for a MV accelerator in a deep underground laboratory. Such a project is presently under discussion at several different sites in Europe and North America. First of all at the site of the present LUNA accelerator, the LNGS laboratory, with its excellent infrastructure and proven low background. However, other places are also studied. For example the Canfranc laboratory in Spain, Boulby in the United Kingdom and Praid in Romania. In the United States, two accelerators with connected beam lines are included in the DUSEL underground science facility planned at the site of the previous Homestake experiment. One machine should have similar tasks as the present LUNA 400 kV accelerator, but with greatly increased beam intensity, whereas the second accelerator should be in the MV range.

7. Conclusions

LUNA started underground nuclear astrophysics about twenty years ago in the core of Gran Sasso, below 1400 m of dolomite rock. The extremely low background has allowed nuclear physics experiments with a very small count rate, down to a few events per year. The important reactions responsible for hydrogen burning in the Sun have been studied for the first time down to the relevant stellar energies. In particular, the measurement of $^{3}He(^{3}He, 2p)^{4}He$ has shown that nuclear physics was not the origin of the solar neutrino puzzle. The cross section of $^{3}He(\alpha, \gamma)^{7}Be$ has been measured with two different experimental approaches and with a 4% total error. Thanks to this small error, the total uncertainty on the ^{7}Be solar neutrino flux has been reduced to 5.5%. Finally, the study of $^{14}N(p, \gamma)^{15}O$ has shown that the expected CNO solar neutrino flux has to be decreased by about a factor two, with an error small enough to pave the way to the measurement of the central metallicity of the Sun.

Over the years LUNA has made important progress in the comprehension of hydrogen burning thanks to its underground environment. In the next two decades underground nuclear astrophysics will try to improve the picture of stellar nucleosynthesis by studying the key processes of helium and carbon burning and of the neutron sources in stars.

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