Subnuclear Physics: Past, Present and Future
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ORIGIN AND STATUS OF LUNA AT GRAN SASSO

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Abstract

The ultimate goal of nuclear astrophysics, the union of nuclear physics and astronomy, is to provide a comprehensive picture of the nuclear reactions which power the stars and, in doing so, synthesize the chemical elements. Deep underground in the Gran Sasso Laboratory the key reactions of the proton-proton chain and of the carbon-nitrogen-oxygen cycle have been studied down to the energies of astrophysical interest. The main results obtained in the past 20 years are reviewed and their influence on our understanding of the properties of the neutrino, the Sun, and the Universe itself is discussed. Finally, future developments of underground nuclear astrophysics beyond the study of hydrogen burning are outlined.

Introduction

Only hydrogen, helium and lithium are synthesized in the first minutes after the big-bang. The other elements of the periodic table are produced in the thermonuclear reactions taking place inside the stars. Nuclear astrophysics studies these reactions which provide also the power that allows the stars to shine over their lifetimes. 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 degrees, 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 $\Phi(E)$ and $\sigma(E)$ 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 and, as a consequence, the reaction cross section $\sigma(E)$ drops nearly exponentially with decreasing energy:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta(E)}$$

where S(E) is the astrophysical factor (which contains the nuclear physics information) and $\eta(E)$ is the Sommerfeld parameter, given by $2\pi\eta = 31.29 \cdot Z_1 \cdot Z_2 \cdot (\mu/E)^{0.5}$. Z_1 and Z_2 are the charges of the interacting nuclei, μ is the reduced mass (in units of amu), and E is the center of mass energy (in units of keV). At low energies the cross sections are extremely small, because of the small probability to go through the Coulomb barrier. Such smallness makes the star life-time of the length we observe, but it also makes impossible the direct measurement 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 region, leading to substantial uncertainties. LUNA, Laboratory for Underground Nuclear Astrophysics, started 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 Nature makes inside the stars. As a matter of fact, the dolomite rock of Gran Sasso 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.

LUNA at Gran Sasso

Two electrostatic accelerators able to deliver hydrogen or helium beam have been installed underground: first a compact 50 kV "home made" machine [1] and then a commercial 400 kV one [2]. Common features of the two accelerators are the high beam current, the long term stability and the precise beam energy determination. The first feature maximizes the reaction rate, the second is demanded by the long time typically needed for a cross section measurement, and the third is important because of the exponential energy dependency of the cross section.

In particular, the 400 kV accelerator is embedded in a tank, a cylinder of 0.9 m diameter and 2.8 m long, filled with an insulating mixture of N_2/CO_2 gas at 20 bar. The high voltage is generated by an inline Cockcroft-Walton power supply located inside the tank. The radio frequency ion source directly mounted on the accelerator tube can provide beams of 1 mA hydrogen and 500 μA He^+ over a continuous operating time of 40 days. The ions can be sent into one of two different, parallel beam lines (Fig.1), allowing the installation of two different target setups. In the energy range between 150 and 400 keV, the accelerator can provide up to 500 μA of hydrogen and 250 μA of helium at the target stations, with 0.3 keV accuracy on the beam energy, 100 eV energy spread, and 5 eV h^{-1} long-term stability.

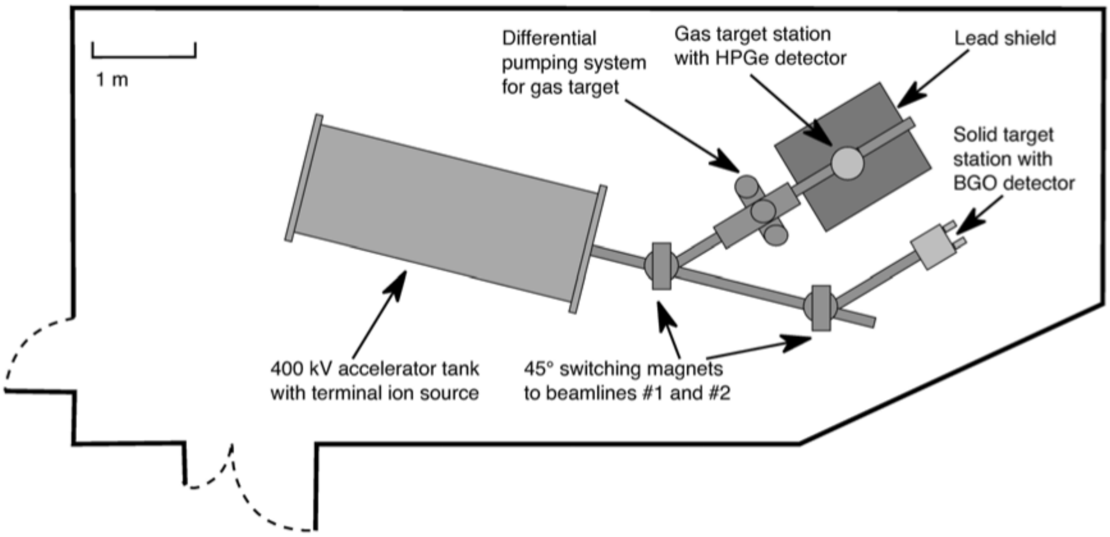

Figure 1: The LUNA set-up with the 400 kV accelerator.

Hydrogen Burning in the Sun

As the Sun mass contracted from an initially large gas cloud, half of the gravitational energy released was radiated into the space and half was converted into the kinetic energy of hydrogen and helium nuclei, thereby increasing the temperature of the system. At the central temperature of approximately 10 million degrees the kinetic energy of the hydrogen nuclei was high enough to penetrate the Coulomb barrier with significant probability and to switch on the hydrogen burning: $4^1\text{H} \rightarrow {}^4\text{He}+2e^+ +2\nu_e$.

Since the mass of the helium nucleus is lower than four times the proton mass, approximately 0.7% of the hydrogen rest mass is converted into energy in each of the transmutations. Hydrogen fusion supplies the necessary energy to halt the contraction, it provides all the energy required for the long life of the Sun, and it produces neutrinos detectable on Earth.

The Sun is a middle-aged main-sequence star which began to burn hydrogen approximately 4.5 billion years ago. In another 5 billion years it will begin burning helium and will eventually turn into a celestial body consisting mainly of carbon and oxygen. In the central region of the Sun, at the temperature of 15 million degrees and at the density of 150 g cm^{-3}, hydrogen burning does not take place in one step but rather

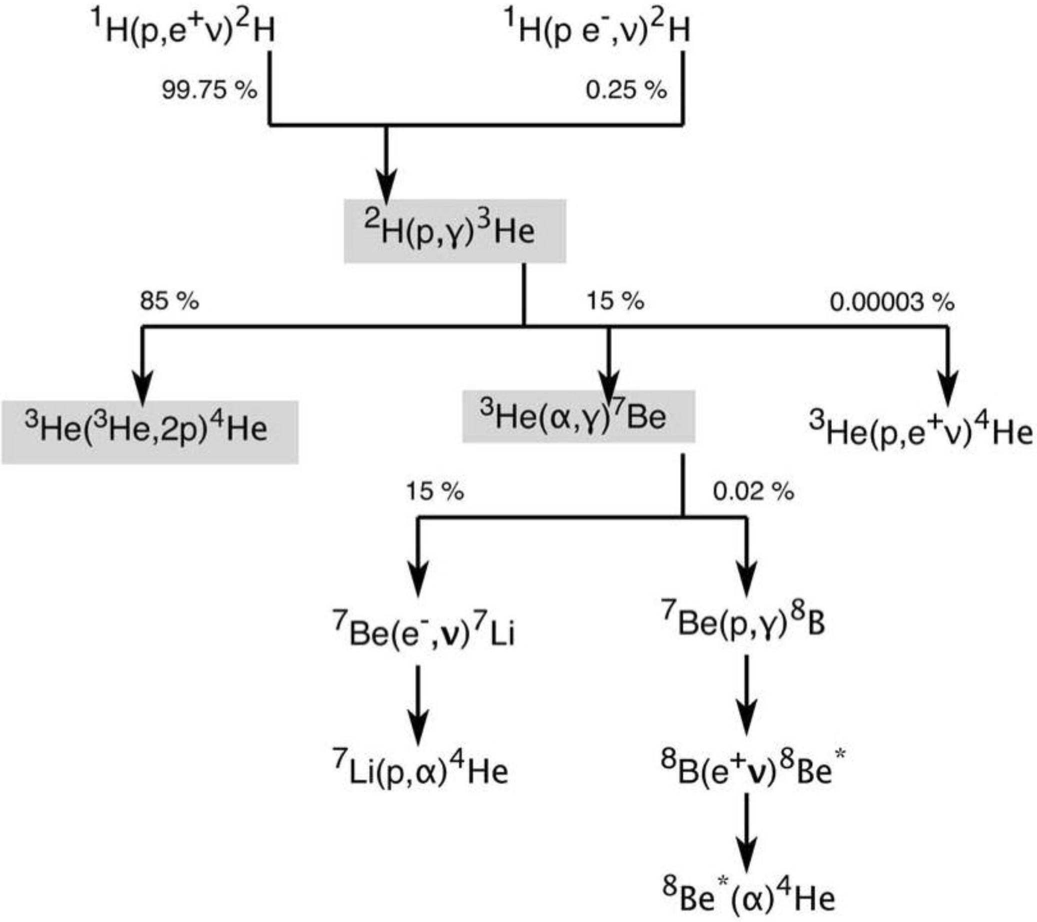

Figure 2: The proton-proton chain (pp) with the different branching ratios. The reactions studied by LUNA are highlighted.

proceeds through a sequence of two-body reactions: the proton-proton chain (Fig.2) and the CNO cycle. The relative importance of the different reactions is determined by the abundance of the nuclear species fusing together and by their fusion cross section at the Gamow peak energy. In particular, the pp chain is responsible for more than 99% of the luminosity of the Sun, whereas the CNO cycle accounts for less than 1% of nuclear energy production.

In 1964 both J.N. Bahcall and R. Davis proposed the detection of solar neutrinos in order to directly verify the hypothesis of nuclear-energy generation in stars and to study the inner region of the Sun.

The Solar Neutrino Problem and the Narrow Resonance

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 has a Q-value of 12.86 MeV and it is a key one of the pp chain. As a matter of fact, it is the most probable fate of ^{3}He in the Sun (85% of the fusions).

The hypothesis of a narrow (~ keV) resonance in the cross section of ^{3}He(^{3}He,2p)^{4}He at low energy was advanced at the beginning of the seventies as a solution to the solar neutrino problem. Such a resonance would have explained the observed ^{8}B solar neutrino flux, about a factor 3 lower than the predicted one. Fewer than 1 neutrino in 10000 comes from the ^{8}B decay. However, their relatively high end-point energy (about 15 MeV) makes their detection much less difficult; unsurprisingly, ^{8}B neutrinos are the best studied neutrinos from the Sun. The resonance would have further enhanced the relative contribution of ^{3}He(^{3}He,2p)^{4}He, and the flux of the ^{8}B neutrinos, generated in the branch starting with ^{3}He(α,γ)^{7}Be, would have been suppressed.

The final set-up was made of eight 1 mm thick silicon detectors of 5x5 cm^2 area placed around the beam inside the windowless target chamber filled with ^{3}He at the 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.

Figure 3 shows the results from LUNA [3] together with the ones from a recent higher energy measurements. 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. In particular, 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 the astrophysical solution to the solar neutrino problem based on its existence has been definitely ruled out. We now know that the solution to the problem lies in the nature of the neutrino itself: it oscillates. Produced inside the Sun as an electron neutrino it may become a muon or tau neutrino by the time it reaches the Earth.

^{3}He(α,γ)^{7}Be (Q-value: 1.586 MeV), the competing reaction for ^{3}He burning, has been also studied in LUNA. The cross section of this reaction can be obtained by using two different experimental approaches: the measurement of the prompt γ rays and the detection of the delayed γ rays from ^{7}Be decay. Both techniques have been simultaneously employed underground, obtaining results in excellent agreement with each other. Thanks to the LUNA measurement the uncertainty on the ^{7}Be solar neutrino

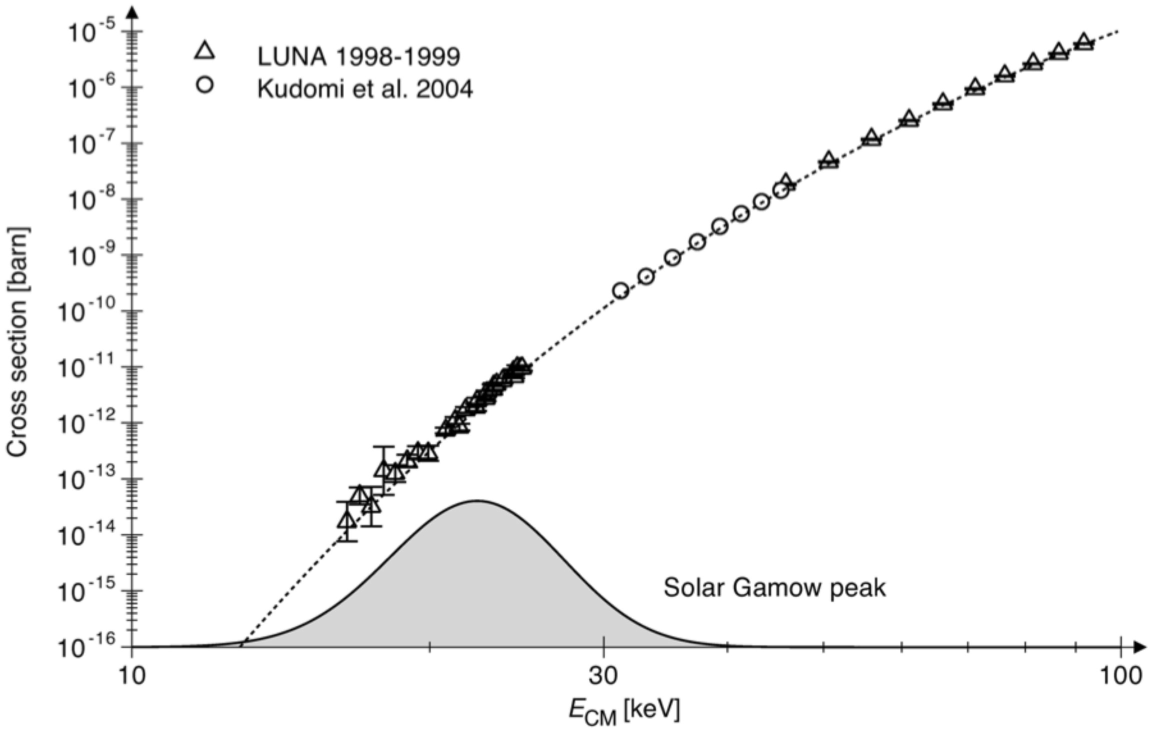

Figure 3: The cross section of $^{3}He(^{3}He,2p)^{4}He$ as function of the centre of mass energy.

flux went from 9.4% down to 5.5% [4,5]. The 0.86 MeV ^{7}Be neutrinos are the second largest component of the spectrum, amounting to 7% of the total and they have been very recently measured by Borexino with 5% error. The dominant component of the total neutrino flux (92%) are the neutrinos coming from $^{1}H(p,e^{+}\nu)^{2}H$. However, their continuous spectrum has an end-point energy of 0.42 MeV, which makes their detection extremely difficult and only possible, till now, in the radiochemical experiments with Gallium (Gallex/GNO and Sage).

The Metallicity of the Sun and the Age of the Universe

In the CNO cycle the conversion of hydrogen into helium is achieved with the aid of carbon and nitrogen previously synthesized in older stars (Fig.4). Carbon and nitrogen work as catalysts and they are not destroyed. $^{14}N(p,\gamma)^{15}O$ (Q-value: 7.297 MeV) is the bottleneck reaction of the 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. The CNO neutrinos have end-point energies of 1.20 MeV (^{13}N) and 1.73 MeV (^{15}O) and they are a fraction of the total neutrino flux equal to the relative contribution of the CNO cycle to the luminosity of the Sun (less than 1%).
In the first phase of the LUNA study, data have been obtained down to 119 keV energy with solid targets of TiN and a germanium detector. This way, the five different radiative capture transitions which contribute to the cross section of $^{14}N(p,\gamma)^{15}O$ 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.

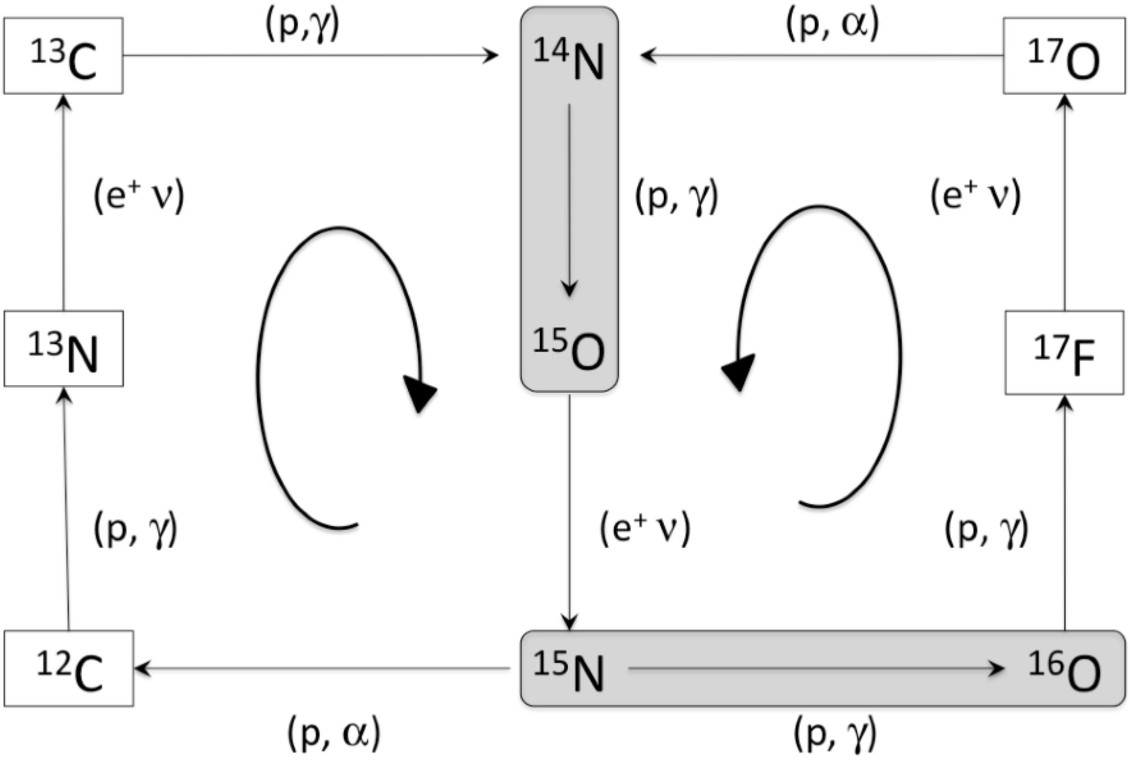

Figure 4: The first and second CNO cycles. Only the first cycle is important for the Sun because $^{15}N(p,\gamma)^{16}O$ has a cross section which is a factor 2000 lower than $^{15}N(p,\alpha)^{12}C$. The reactions studied by LUNA are highlighted.

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 both with the germanium detector [6] and with the BGO set-up [7] were about a factor two lower than the existing extrapolation [8] from previous data at very low energy (Fig.4). As a consequence, the CNO neutrino yield in the Sun is decreased by about a factor two.

In order to provide more precise data for the ground state capture, the most difficult one to be measured because of the summing problem, we performed a third phase of the $^{14}N(p,\gamma)^{15}O$ study with a composite germanium detector. This way the total error on the S-factor has been reduced to 8%: $S_{1,14}(0)=1.57\pm0.13$ keV barn [9]. This is significant because, finally solved the solar neutrino problem, we 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 [10].

Thanks to the relatively small error on $S_{1,14}$, 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, which almost linearly depends on the carbon and nitrogen content of the solar core where fusion reactions take place, is decreased by about 30% in going from the high to the new low metallicity scenario. This way it will be possible to test whether the early Sun was chemically homogeneous [11], a key assumption of the standard solar model.

$^{14}N(p,\gamma)^{15}O$ plays also a key role in determining the age of the globular clusters, which are the oldest stellar populations of a galaxy. The age is obtained from the luminosity of the turn off point in the Hertzsprung-Russell diagram of the cluster, which in turn depends on the $^{14}N(p,\gamma)^{15}O$ cross section (a star at the turn off is burning hydrogen through the CNO cycle). The age of the clusters give then a lower limit to the age of the Universe. In particular, this limit is increased by 0.7-1 billion years [12] up to 14 billion year as a consequence of the factor 2 reduction measured by LUNA on the $^{14}N(p,\gamma)^{15}O$ cross section.

The lower cross section also affects stars that are much more evolved than the Sun. In particular, the dredge up of carbon to the surface of asymptotic giant branch stars is much more efficient [13].

$^{14}N(p,\gamma)^{15}O$ is an excellent example to explain why physicists have been studying for years these reactions which have such extremely small cross sections. From the nuclear point of view they are often of modest interest. It is the application to astrophysics, and to so many different astrophysical scenarios, which makes them so fascinating.

Hydrogen Burning at High Temperature

The solar phase of LUNA has reached the end. A new and rich program of nuclear astrophysics mainly devoted to CNO, Mg-Al and Ne-Na cycles has already started with the measurement of $^{15}N(p,\gamma)^{16}O$ [14] and $^{25}Mg(p,\gamma)^{26}Al$ [15]. Due to the higher Coulomb barrier of the reactions involved, these cycles become important at temperature higher than the one of our Sun: hydrogen burning in the shell of massive stars and Novae explosions. Relatively unimportant for energy generation, these cycles are essential for

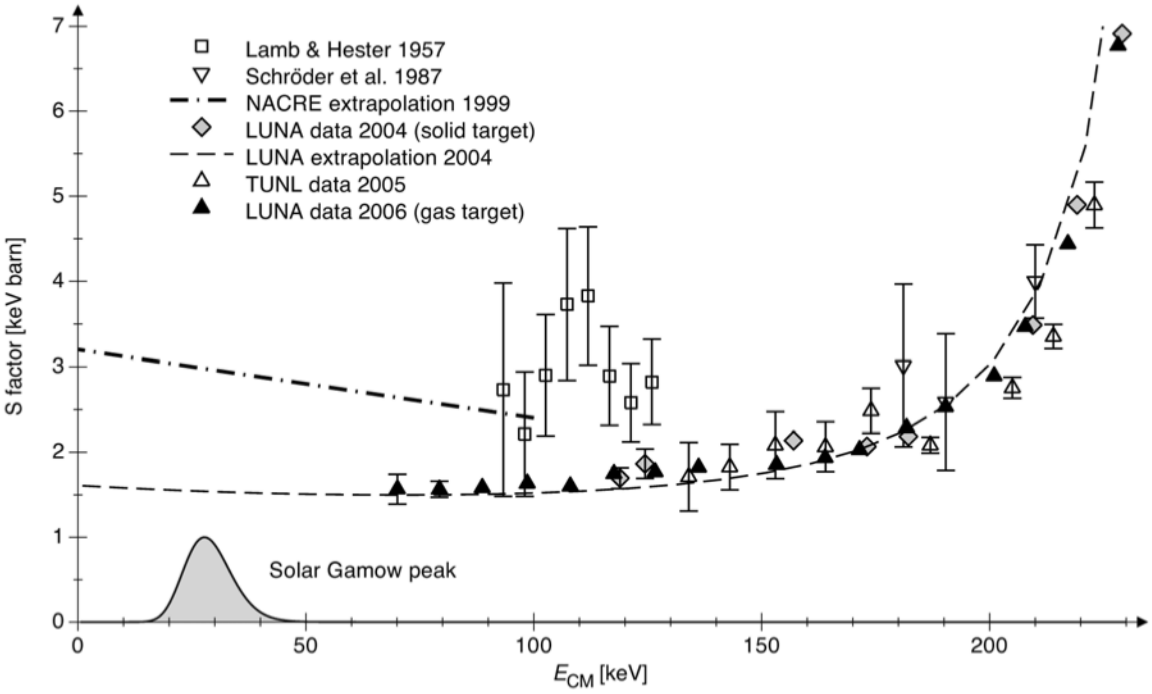

Figure 5: The astrophysical S factor of $^{14}N(p,\gamma)^{15}O$.

the synthesis of the different isotopes. In particular, LUNA is now measuring $^{17}O(p,)^{18}F$, the bridge reaction connecting the second to the third CNO cycle, and $^{2}H(\alpha,\gamma)^{6}$ Li, the key reaction of big-bang nucleosynthesis which determines the amount of primordial ^{6}Li in the Universe.

The Future: Helium Burning

LUNA has shown the advantages of the low background environment on the study of the hydrogen burning processes at the stellar energies. Natural evolution is the exploitation of the underground environment to study the next step in the fusion chain towards ^{56}Fe (the element with the highest binding energy per nucleon): the helium burning. In particular, $^{12}C((\alpha,\gamma)^{16}O$ is the most important reaction of nuclear astrophysics and it 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 are also $^{13}C(\alpha,n)^{16}O$ 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. This exciting and ambitious program requires a dedicated space of about 150 m^2 where to install a 3.5 MV accelerator in an underground laboratory. A possible place to host the accelerator has been already identified in Gran Sasso. In the next two decades underground nuclear astrophysics will significantly improve the picture of stellar nucleosynthesis by studying the key processes of the helium burning.

Conclusions

Twenty years ago, LUNA started underground nuclear astrophysics in the core of Gran Sasso and it still remains the only facility of this kind in the world. The extremely low background has allowed experiments with count rates as low as a few events per year. For the first time, the important reactions which are responsible for the hydrogen burning in the Sun have been studied down to the relevant stellar energies. As a consequence, 50 years after the first pioneering cross section measurements, nuclear physics is no longer the dominant error source of the solar model. In particular, solar neutrinos can now be exploited to probe the deep interior of the Sun. When applied to the study of globular clusters, our results also increase the limit on the age of the Universe up to 14 billion years. Since a few years LUNA is not focused anymore on the Sun and it is studying those reactions which are responsible for the abundance of the chemical elements into the Cosmos. I'm sure that the key topic of underground nuclear astrophysics for the future will be the study of helium burning in the stars.

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