

LUNA: FROM SUN TO NOVAE AND BEYOND

Carlo Broggini (the LUNA Collaboration)
INFN, via Marzolo 8, I-35131 Padova

Abstract

One of the main ingredients of nuclear astrophysics is the knowledge of the thermonuclear reactions which power the stars and, in doing so, synthesize the chemical elements. Deep underground in the Gran Sasso Laboratory the cross section 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 of LUNA are reviewed and their influence on our understanding of the properties of the neutrino and of the Sun is discussed. We then describe the current LUNA program mainly devoted to the nucleosynthesis of the light elements through the cross section measurement of the most important reactions in the CNO, Ne-Na and Mg-Al cycles. Finally, the future of LUNA towards the study of helium burning is outlined.

1 Introduction

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. Thermonuclear reactions occur in the hot plasma of a star inside an energy window, the Gamow peak, which is far below the Coulomb energy arising from the repulsion between nuclei. In this region the cross section is given by:

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

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

Cross sections are extremely small within the Gamow peak. 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 ^{1, 2)}.

2 LUNA at Gran Sasso

Two electrostatic accelerators able to deliver hydrogen or helium beam have been installed in LUNA: first a compact 50 kV "home made" machine ³⁾ and then a commercial 400 kV one ⁴⁾. Common features of the two accelerators are the high beam current, the long term stability and the precise beam energy determination. 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 N₂/CO₂ 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

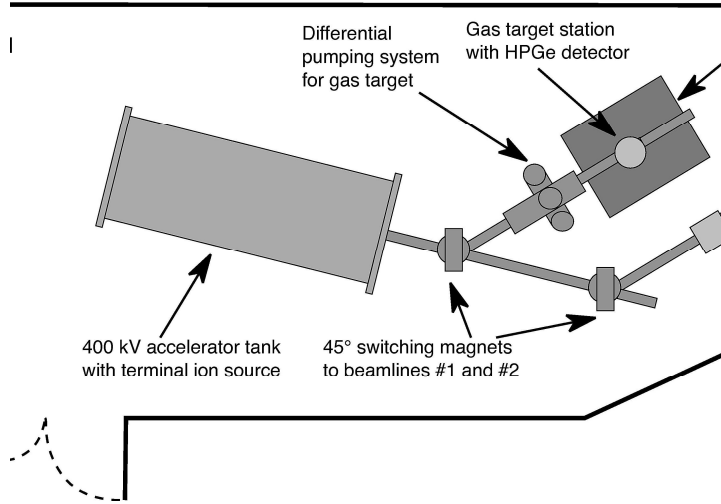


Figure 1: *The LUNA set-up with the 400 kV accelerator*

directly mounted on the accelerator tube can provide beams of hydrogen and 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 0.5 mA of hydrogen and 0.25 mA of helium at the target stations, with 0.3 keV accuracy on the beam energy, 100 eV energy spread, and 5 eV per hour long-term stability. 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.

3 ^3He burning and solar neutrinos

The initial activity of LUNA has been focused on the $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ 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 in its cross section at the thermal energy of the Sun was suggested long time ago to explain the observed ^8B solar neutrino flux. As a matter of fact, such a resonance would decrease the

relative contribution of the alternative reaction ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$, which generates the branch responsible for ${}^7\text{Be}$ and ${}^8\text{B}$ neutrino production in the Sun.

The experimental set-up was made of eight 1 mm thick silicon detectors of $5\times 5\text{ cm}^2$ area placed around the beam inside the windowless target chamber filled with ${}^3\text{He}$ at the pressure of 0.5 mbar. The simultaneous detec-

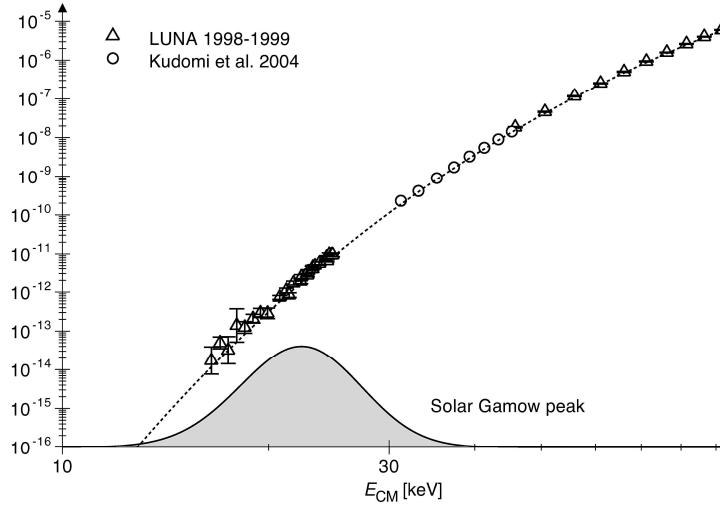


Figure 2: *Astrophysical $S(E)$ -factor of ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$.*

tion of two protons has been the signature which unambiguously identified a ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$ fusion reaction. Fig.2 shows the results from LUNA ⁵⁾ together with higher energy measurements ^{6, 7, 8)}. For the first time a nuclear reaction has been measured in the laboratory at the energy occurring in a star. In particular, at the lowest energy of 16.5 keV the cross section is 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 and, as a consequence, the astrophysical solution of the ${}^8\text{B}$ and ${}^7\text{Be}$ solar neutrino problem based on its existence has been definitely ruled out.

${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$, the competing reaction for ${}^3\text{He}$ burning, has been also measured by LUNA both by detecting the prompt γ rays and by counting of the decaying ${}^7\text{Be}$ nuclei with a total uncertainty of 4% ⁹⁾.

4 The carbon and nitrogen content of the Sun core

$^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ is the slowest reaction of the CNO cycle and it rules its energy production rate. In particular, it is the key reaction to predict 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 $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ 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 a 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 ^{10, 11)} and then with the BGO set-up ¹²⁾ were about a factor two lower than the existing extrapolation ^{13, 14)} from previous data ^{15, 16)} at very low energy (fig.3). On the other hand, they were in good agreement with the reanalysis ¹⁷⁾ of ¹⁶⁾ and with the results obtained with indirect methods ¹⁸⁾. Because of this reduction the CNO neutrino yield in the Sun is decreased by about a factor of 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 $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ 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 ¹⁹⁾. 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. 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, a key assumption of the standard Solar Model ²⁰⁾.

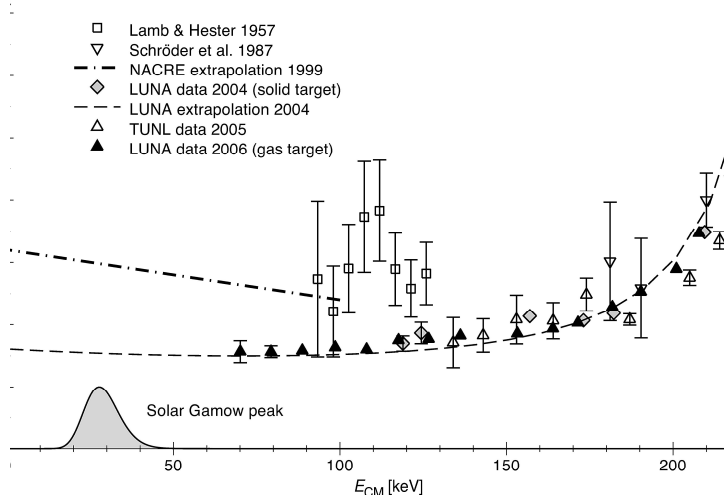


Figure 3: *Astrophysical $S(E)$ -factor of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction from direct measurements. The errors are statistical only (the systematic ones are similar).*

The lower cross section is affecting also stars which are more evolved than our Sun. In particular, the lower limit on the age of the Universe inferred from the age of the oldest stellar populations, the globular clusters, is increased by 0.7-1 billion years ²¹⁾ up to 14 billion years and the dredge-up of carbon to the surface of asymptotic giant branch stars is more efficient ²²⁾.

5 Hydrogen burning and beyond

A new and rich program of nuclear astrophysics mainly devoted to CNO, Ne-Na and Mg-Al cycles started a few years ago after the solar phase of LUNA. Of particular interest are those bridge reactions which are connecting one cycle to the next, as $^{15}\text{N}(p,\gamma)^{16}\text{O}$ ²³⁾ and $^{17}\text{O}(p,\gamma)^{18}\text{F}$ ²⁴⁾, or which are key ingredients of gamma astronomy, as $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ ²⁵⁾, or big-bang nucleosynthesis, as $^2\text{H}(\alpha,\gamma)^6\text{Li}$ ²⁶⁾ (LUNA measurements related to big-bang nucleosynthesis are the subject of a dedicated paper in these proceedings). Due to the higher Coulomb barrier of the reactions involved, the cycles become important at temperatures higher than the one of our Sun: hydrogen burning in the shell of

massive stars and Novae explosions (about 30-100, and 100-400 million degrees, respectively). Relatively unimportant for energy generation, these cycles are essential for the 'cooking' of the nuclei up to ^{27}Al . In particular, LUNA is now measuring $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$, the reaction of the Ne-Na cycle with the highest uncertainty (up to a factor of 2000 in the region of interest), and $^{17}\text{O}(p,\alpha)^{14}\text{N}$, the reaction closing the second CNO cycle.

After hydrogen burning the natural evolution of LUNA is the study of the next step in the fusion chain towards ^{56}Fe : the helium burning. In particular, $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$, the "Holy Grail" of nuclear astrophysics, which determines the abundance ratio between carbon and oxygen, the two key elements to the development of life, and which shapes the nucleosynthesis in massive stars and the properties of supernovae. Equally important are $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$, the stellar sources of the neutrons which synthesize half of the trans-iron elements through the S-process: neutron captures followed by β decays. This program requires a new 3.5 MV accelerator which has already been financed and which is going to be installed underground in about three years from now in hall C of Gran Sasso.

6 Conclusions

More than twenty years ago LUNA started underground nuclear astrophysics in the core of Gran Sasso and it still remains the unique 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. As a consequence, the important reactions which are responsible for the hydrogen burning in the Sun have been studied for the first time down to the relevant stellar energies. Since a few years LUNA is not focused anymore on the Sun and is studying those hydrogen burning reactions which are responsible for the abundance of the light elements in the Galaxy. The future of LUNA, which is going to start with the installation of a 3.5 MV accelerator underground in Gran Sasso, will be the study of the next step in the fusion chain beyond hydrogen burning: helium burning.

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