Progress of LUNA

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Progress of LUNA

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Abstract. At H-burning temperatures in the Sun, nuclear cross sections are extremely small and experimental measurements in a laboratory at the Earth’s surface are hampered by the cosmic background. The LUNA collaboration has exploited the unique features of LNGS underground laboratory in terms of background reduction, to study very important H-burning reactions at astrophysically relevant energies. This paper will focus on the results recently obtained for the \( ^3\)He\( ^4\)He,\( \gamma \)\( ^7\)Be reaction using two different experimental techniques and with a close eye on the minimization of the systematical uncertainties. On going and future measurements will also be presented.

1. Introduction

It is well known [1] that stars generate energy and produce elements by means of thermonuclear fusion reactions, which start from the most abundant and lightest element, hydrogen, and gradually synthesize heavier elements. The hydrogen burning can proceed either through the p-p chain or through the more efficient CNO cycle or even through the NeNa and MgAl cycles in stars more evolved and hotter than our Sun. The net result is the transformation of 4 protons into a \( ^4\)He nucleus with an energy release of about 27 MeV. The fusion of hydrogen into helium occurs during the longer part of the star’s life (main sequence) and is responsible for the prodigious luminosity of the star itself.

All these fusion reactions occur in a very well defined energy range, the so-called Gamow peak, which is the result of the overlapping between the energetic distribution of nuclei in stars at a given temperature and the energetic dependence of the reaction cross-section. The first, given by the Maxwell-Boltzmann distribution, has a maximum for \( E=kT \) (where \( T \) is the star temperature and \( k \) the Maxwell-Boltzmann constant) and then decreases exponentially for increasing energy while the second, given by the tunneling probability through a Coulomb barrier, decreases exponentially for decreasing energy. In particular the reaction cross-section for charged particles can be written as:

\[
\sigma(E) = \frac{S(E)}{E} \exp\left(-\frac{2\pi\eta}{E}\right)
\]

where \( S(E) \) is the astrophysical S factor which contains the pure nuclear behavior of the cross section and \( \eta \) is the Sommerfeld parameter given by:

\[
\eta = \left(\frac{31.29}{2\pi}\right) \frac{Z_1 Z_2}{\mu} \left(\frac{\mu}{E}\right)^{1/3}
\]

being \( Z_1 \) and \( Z_2 \) the charges of the interacting nuclei, \( \mu \) the reduced mass and \( E \) the interaction energy in the center of mass system in keV. As an example, in our Sun, whose temperature is \( 1.5 \times 10^7 \) °K, the maximum of the Maxwell-Boltzmann distribution occurs at about 1 keV, the Coulomb barrier for most of the reactions of the p-p cycle is between 0.5 and 2 MeV and the Gamow peak for the same reactions is below 30 keV. At such low energy, the cross section is extremely low, down to the femtobarn level in “the worst” cases, due to the already mentioned exponential decrease of the cross section with
decreasing energy. Therefore, direct measurements are mostly hampered by the cosmic background in a laboratory at the earth’s surface where the signal to background ratio would be too small. The usual approach is to extrapolate the observed energy dependence of the cross section at high energies down to the low and significant energy region leading to substantial uncertainties. In particular a possible narrow resonance in the unmeasured region, the tail of a broad or sub-threshold resonance or even a change in the reaction mechanism can completely change the reaction rate.

2. Why underground: the LUNA project
The LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration has exploited the silent environment of the underground laboratory under the Gran Sasso Mountain in Italy (LNGS) to overcome this difficulty by performing direct measurements at the relevant energies. The rock cover of about 1500 m (3400 m water equivalent) reduces the muon component of the cosmic background of a factor $10^6$, the neutron component of a factor $10^3$ and the gamma component of a factor 10 with respect to the earth’s surface. As a result, the gamma background above 3 MeV in an HPGe detector placed underground at LNGS is reduced of a factor ~2500 with respect to the same detector placed over-ground. Moreover, for lower energy gammas where the background is dominated by environmental radioactivity, the effect of passive shielding is enhanced by going underground. Indeed, in a laboratory on the Earth’s surface, a passive shielding can be built around the detector but the shield efficiency cannot be increased by making it thicker with the addition of further material since cosmic muons interact with it creating background signals in the detector itself. This problem is of course dramatically reduced in an underground laboratory.

The LUNA collaboration has installed two accelerators underground: a compact 50 kV “home-made” machine [2] and a commercial 400 kV one [3]. Common features of the two are the intense current production, the long term stability and the precise energy determination. The first two features are essential to maximize the reaction rate, while the third is important in view of the exponential energy dependence of the cross section. With the first machine, operating between 1992 and 2001, two fundamental reactions of the p-p chain were studied at solar Gamow peak energies: the $^3\text{He}(^3\text{He},2\gamma)^7\text{He}$ [4] and d(p,$\gamma^7$He [5] and the screening effect, consisting in a lowering of the Coulomb barrier for a nucleus surrounded by electrons with respect to a bare one, was investigated through the d($^3\text{He},p)^7\text{He}$ reaction [6]. The 400 keV machine, started operations in the year 2000 and is still operating. The main results obtained are the cross sections of the $^5\text{N}(p,\gamma)^7\text{O}$ reaction [7], which represents the bottle-neck of the CNO cycle, and of the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ one. In this paper I will concentrate on the latter result and on the ongoing and future measurements at LUNA.

3. The $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction
The $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction is the onset of the $^7\text{Be}$ and $^8\text{B}$ branches of the p-p chain from which the $^7\text{Be}$ and $^8\text{B}$ neutrinos are generated. Solar neutrino fluxes depend on both astrophysical and nuclear physics inputs: in the case of $^7\text{Be}$ and $^8\text{B}$ neutrinos, one of the most important parameters is the cross section of the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction. After the successful measurements of the $^8\text{B}$ neutrino flux with a 3.5% uncertainty performed by SNO [8] and SuperKamiokande [9] and in view of a similar result on the $^7\text{Be}$ neutrino flux from the Borexino experiment [10], a comparable uncertainty on the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ cross section is demanded. Only under these circumstances, the neutrinos will give reliable information on the interior of the Sun and on its physical and chemical properties.

Moreover, the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction is fundamental for the Big-Bang nucleosynthesis (BBN) being the main source for $^7\text{Li}$ production. The predicted abundance of such isotope is a factor 2-3 higher than the observed one. Even if it is unlikely that the explanation of this discrepancy could come from the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ cross section, a better knowledge of its value represents the necessary basis for the search of alternative solutions to the $^7\text{Li}$ problem.
In the last forty years, the \(^3\)He\(^4\)He,\(^7\)Be reaction has been measured using two different approaches: either the detection of direct \(\alpha\)-capture \(\gamma\)-rays (prompt \(\gamma\) method) or the detection of the \(^7\)Be radioactivity through the electron capture of \(^7\)Be into \(^7\)Li and its subsequent de-excitation from the first excited to the ground state (activation method). Results obtained with the two techniques show, on average, a discrepancy of about 15\% which is the origin of the large uncertainty on the \(^3\)He\(^4\)He,\(^7\)Be cross section [11].

To solve this problem, the LUNA collaboration planned and performed an experiment with both techniques at the same time and with a careful eye on reducing the systematical uncertainties. A recirculating \(^3\)He extended windowless gas target was coupled to a 137\% HPGe detector in close view of the interaction chamber. The \(^4\)He intense beam of the LUNA 400 kV machine was focused on a removable copper beam-stop which served both as the end cap of a calorimeter (to measure the beam current) and as a catcher for the \(^7\)Be nuclei allowing for a delayed off-line measurement of their activity. Being the Q-value of the reaction about 1.5 MeV, the prompt \(\gamma\)-rays are in the region of natural background: a massive shielding (0.3 m\(^3\)) was therefore built around the target chamber and the HPGe detector. This consisted in several layers of lead bricks and an inner layer of Oxygen Free High Conductivity (OFHC) copper bricks. Moreover, the target chamber and the calorimeter were constructed using OFHC copper and no welding materials were used. All this system was enclosed in an anti-radon envelope consisting in a Plexiglas box flushed with \(\text{N}_2\) gas to avoid \(^222\)Rn accumulation.

As already underlined, the efficiency of the shielding was increased by the underground location and a background suppression of five orders of magnitude was obtained for \(\gamma\)-rays below 2 MeV with respect to a background spectrum measured underground with no shielding [12]. The typical \(\alpha\)-beam current was high (about 250 \(\mu\)A), thus causing a reduction of the target density due to the so-called beam-heating effect. This was measured through the detection of the beam particles elastically scattered on the target atoms [13]. Moreover, in order to reduce the systematic error coming from the uncertainty on the angular distribution, a lead collimator was positioned inside the target chamber to collect mostly \(\gamma\)-rays emitted at 55\°, where the contribution of the second Legendre polynomial vanishes. After each run, the calorimeter cap was dismounted and its activity counted off-line with a 125\% HPGe detector, shielded by 15 cm of lead and 10 cm of copper on each side and placed in the low activity laboratory of LNGS [14].

The experiment was divided into two phases: in the former the cross section was measured at \(E=127\) and \(E=148\) keV (CM reference frame) with the activation technique only [15], in the latter both techniques were used to measure the cross section at \(E=93, 106\) and 170 keV [16]. A comparison of the results obtained with the two techniques was therefore possible and reduced significantly the systematic uncertainties. Moreover, the cross sections measured with the two methods were consistent at the level of 4\% [16], as can be seen by looking at the inset of figure 1.

While the LUNA data partly covered the energy window interesting for BBN (80-400 keV), an extrapolation is still needed for reaching the solar Gamow peak at 22 keV. The most recent results [17, 18] were taken into account together with the LUNA data [16]: two different theoretical approaches were followed [19, 20] to fit each of the three experiments and the weighted average of the extrapolated \(S(0)\) values was considered as the “best” value. This resulted in:

\[
S(0) = 0.567 \pm 0.018 \pm 0.004 \text{ keV} \cdot \text{b}
\]

where the last error accounts for the uncertainty on the adopted theoretical model. The most recent results [17, 18] and the LUNA data [16] for the astrophysical \(S\)-factor as a function of the center of mass energy are shown in figure 1, together with the theoretical extrapolations [19, 20] of the \(S(0)\) value.

The goal of the 3\% uncertainty was therefore reached but a unique set of data exploring the entire interesting energy range is highly desirable to precisely determine the \(S\) factor energy dependence.

3. Ongoing and future measurements

After the completion of the \(^3\)He\(^4\)He,\(^7\)Be experiment, LUNA started to measure the \(^{25}\)Mg\((p,\gamma)^{26}\)Al reaction; the slowest of the Mg-Al cycle which operates in massive stars like AGB’s. The \(\beta^+\) decay of
the ground state of $^{26}$Al ($T_{1/2} = 7 \times 10^5$ yr) to the first excited state of $^{26}$Mg gives rise to a 1.8 MeV $\gamma$-ray which is very important for $\gamma$-astronomy [21]. Indeed, the presence of $^{26}$Al in the interstellar medium has been determined from observation of this $\gamma$-line from satellites like COMPTEL [22] and INTEGRAL [23] and from the observation of $^{26}$Mg isotopic enrichment in carbonaceous meteorites (extinct $^{26}$Al) [24]. Satellite observations provide evidence that $^{26}$Al nucleosynthesis is still active on a large scale while meteorites enrichment in $^{26}$Mg demonstrates that $^{26}$Al must have been produced not later than 4.6 billion years ago (time of the condensation of the solar-system material). Any astrophysical scenario for $^{26}$Al nucleosynthesis must be concordant with both observations. The $^{25}$Mg(p,$\gamma$)$^{26}$Al reaction is the most important source of $^{26}$Al production. The reaction is dominated by narrow resonances which have been measured down to 190 keV. However, from the known level scheme of $^{26}$Al, one expects low-lying resonances at $E = 93, 109$ and 130 keV, among which the lowest energy one appears to be the most important. The LUNA collaboration used enriched $^{25}$Mg solid targets and two different detection set-ups: a high efficiency but low resolution BGO detector to measure the strength of the lower energy resonances ($93, 109, 130$ and $190$ keV) and a high resolution but low efficiency HPGe to determine cascades and branching ratios for the higher energy ones ($190$ and $317$ keV). Moreover, an AMS independent measurement of the same higher energy ($190$ and $317$ keV) resonances was used for comparison. The data analysis of this experiment is still ongoing.

At the beginning of year 2007, the LUNA collaboration prepared a detailed proposal, resulting from a two-year study effort, containing a list of reactions of astrophysical relevance which could be studied with the 400 kV machine and which could profit from the underground location. Among these, reactions of the CNO cycle, NeNa cycle and BBN are present. This proposal was approved by LNGS and funded by INFN and the experimental program started last year. One of these reactions, namely the $^{15}$N(p,$\gamma$)$^{16}$O, has been indeed orally presented during this conference [25] being at the ultimate stage of data taking.

The next reaction to be studied will be the $^2$H(α,γ)$^6$Li, the main $^6$Li production source during BBN. $^6$Li abundance in metal poor stars is three orders of magnitude higher than BBN predictions. Existing direct data reach $E=650$ keV while indirect measurements at lower energies are in strong disagreement. The region of interest for BBN is between 50 and 300 keV and could be reached with the 400 kV machine. Presently, the beam induced-background due to the d(d,n)$^3$He and d(d,p)$^3$H has been deeply investigated both experimentally and with simulations leading to encouraging results. A set-up similar to the one used for the $^3$He(He,γ)$^7$Be experiment (the Q-values of the two reactions are almost identical), but with an eye on the beam-induced background minimization, will be designed and built and data taking will start soon.

In addition to the already cited proposal, the LUNA collaboration prepared a Letter of Intent (LOI) with the ambitious program of installing a 3 MV machine at LNGS. This could allow the study of He burning reactions among which the $^{12}$C(α,γ)$^{16}$O “holy grail” of nuclear astrophysics and of several (α,γ) and (p,γ) processes having deep consequences in nucleosynthesis, stellar evolution, supernova mechanism, etc. The proposed LOI received very positive response but the decision of LNGS is still pending, major problems being space requirements and possible interferences with other low-background experiments.
Figure 1. Astrophysical S factor for the $^7$He($^4$He,$\gamma$)$^7$Be reaction obtained from recent experiments. The filled squares are from reference [17], the open squares from reference [18] while the filled circles are the LUNA data [16]. The solid and dotted curves are the theoretical predictions by [19] and [20] respectively, obtained considering the weighted average of S(0) of the different experiments (see text). The inset shows a detailed comparison of the prompt (filled circles) and activation (open circles) LUNA results.

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