

Nuclear Astrophysics At LUNA: Status And Perspectives

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Abstract. The talk will be mainly devoted to the measurement of the cross section of the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reaction which belongs to the p-p chain. Actually, solar neutrino fluxes depend both on astrophysical and on nuclear physics inputs, namely on the cross sections of the reactions responsible for neutrino production inside the Solar core. While the flux of solar ${}^8\text{B}$ neutrinos has been recently measured at Superkamiokande with a 3.5% uncertainty and a precise measurement of ${}^7\text{Be}$ neutrino flux is foreseen in the next future, the predicted fluxes are still affected by larger errors. The largest nuclear physics uncertainty to determine the fluxes of ${}^8\text{B}$ and ${}^7\text{Be}$ neutrinos comes from the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reaction. The uncertainty on its S-factor is due to an average discrepancy in results obtained using two different experimental approaches: the detection of the delayed γ rays from ${}^7\text{Be}$ decay and the measurement of the prompt γ emission. The LUNA Collaboration has performed a new high precision experiment with both techniques at the same time. Thanks to the low background conditions of the Gran Sasso LUNA accelerator facility, the cross section has been measured down to 93 keV, the lowest interaction energy ever reached. The S-factors from the two methods do not show any discrepancy within the experimental errors. An extrapolated $S(0) = 0.560 \pm 0.017$ keV barn is obtained. Moreover, branching ratios between the two prompt γ -transitions have been measured with 3-8% accuracy. Recently, the LUNA Collaboration has presented to the Scientific Board of Gran Sasso Laboratory its experimental program for the next five years based on the existing 400 kV accelerator facility. A Letter of Intent addressing the possibility to install a 3 MV machine at Gran Sasso has also been submitted to the Board. The LUNA scientific programs with both the 400 kV and 3 MV accelerator facilities will be illustrated in the final part of the talk.

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INTRODUCTION

Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak. The extremely low value of the cross-section inside the Gamow peak has always prevented its measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small because of cosmic ray interactions. In order to explore this new domain of nuclear astrophysics LUNA (Laboratory for Underground Nuclear Astrophysics) started in 1991 its activity by installing a 50 kV electrostatic accelerator underground at Gran Sasso, followed in the year 2000 by a second 400 kV one. The qualifying features of both accelerators are a very small beam energy spread and a very high beam current even at low energy.

Outstanding results have been obtained on the cross-sections of ${}^3\text{He}({}^3\text{He},2p){}^4\text{He}$ [1] and ${}^2\text{H}(p,\gamma){}^3\text{He}$ [2], both measured within the Gamow peak of the Sun, and of ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$, measured down to 70 keV [3,4,5]. With these experiments LUNA has shown that, performing the measurements underground with the typical techniques of low background physics, nuclear cross-sections can be measured down to the energy of the nucleosynthesis inside stars.

In particular, our result on ${}^3\text{He}({}^3\text{He},2p){}^4\text{He}$ down to 16 keV (20 fbarn cross-section with a count rate of 2 events per month) has ruled out the astrophysical solution of the solar neutrino problem based on the existence of a narrow resonance within the Gamow peak of the Sun. The ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$ reaction has been studied by LUNA with two different techniques: a germanium detector with solid target at 'high' energy and a BGO summing crystal with a windowless gas target down to 70 keV. Our measured cross-section is about a factor 2 smaller than the previous extrapolation on the NACRE compilation [6]. The astrophysical consequences of such a reduction are significant: the CNO neutrino yield in the Sun is decreased by about a factor two [7,8], the age of the oldest Globular Clusters is increased by 0.7-1 Gyr [9] and the dredge-up of carbon to the surface of Asymptotic Giant Branch (AGB) stars is much more efficient [10].

We have recently completed the analysis of the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ data [11]. The uncertainty on this cross-section is the main nuclear limitation to the extraction of physics from the ${}^8\text{B}$ and ${}^7\text{Be}$ solar neutrino flux measurements. We have performed a high accuracy study by detecting the emitted prompt γ -rays and counting the produced ${}^7\text{Be}$ atoms. We obtain an extrapolated S-factor with a 3% error, thus reducing the uncertainty on the predicted ${}^7\text{Be}$ solar neutrino flux from 9.4% to 5.5% (from 12% to 10% for the ${}^8\text{B}$ flux). Nuclear physics does not give anymore a dominant contribution to the total uncertainty of the solar neutrino fluxes [11,12,13]. This result, together with the previous determination of the ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$ cross section had a clear impact on the BOREXINO experiment at Gran Sasso as quoted in the very recent article [14] describing the first results of BOREXINO.

The ‘non solar’ phase of LUNA has already started with the running experiment on $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$. Two are the reasons making this reaction so relevant: the 1.8 MeV map taken by the satellites which look at the γ -sky and the anomalous meteoritic abundance of ^{26}Mg . This experiment is scheduled to finish by the end of 2007. The latter experiment will conclude the experimental program so far approved by the Gran Sasso Scientific Committee. A new phase is going to start as described in the following.

LUNA GOALS FOR THE FUTURE

With a study which lasted about one year we have identified a sample of nuclear reactions of great astrophysical importance which can strongly profit from an underground measurement (Table1).

TABLE 1. Candidate reactions for an underground measurement. For each reaction we give the Q-value, the Gamow energy, i.e. the effective mean energy for the fusion reaction in the star, the lowest measured energy and the lowest energy achievable in LUNA. Reaction in italic can be studied at the 400 kV accelerator presently installed in Gran Sasso but they would benefit of a higher energy machine. Reaction written in bold-italic definitely require a beam energy of a few MeV.

Reaction	Q-value (MeV)	Gamow energy (keV)	Lowest meas. Energy (keV)	LUNA limit estimate (keV)
<i>$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$</i>	7.16	300	950	500
<i>$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$</i>	-0.47	470-700	850	630
<i>$^{13}\text{C}(\alpha,n)^{16}\text{O}$</i>	2.21	170-250	270	200
<i>$^2\text{H}(\alpha,\gamma)^6\text{Li}$</i>	1.47	50-300	700 (direct) 50 (indirect)	50
<i>$^{15}\text{N}(p,\gamma)^{16}\text{O}$</i>	12.13	10-300	130	50
<i>$^{17}\text{O}(p,\gamma)^{18}\text{F}$</i>	5.6	35-260	300	65
<i>$^{18}\text{O}(p,\gamma)^{19}\text{F}$</i>	8.0	50-200	143	143
<i>$^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$</i>	11.7	100-200	240	138
<i>$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$</i>	8.8	50-300	250	68
<i>$^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$</i>	4.01	364	536	364

Part of the LUNA scientific program can be performed with the 400 kV accelerator already running underground in the so called LUNA2 laboratory. To study $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$, the ‘Holy Grail’ of nuclear astrophysics, $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$, the neutron sources inside stars, and other (α,γ) reactions a new accelerator of a few MV voltage installed in a dedicated space underground is required. Such project, which could produce an extremely important step forward in nuclear astrophysics, is the subject of a Letter of Intent recently submitted to the Gran Sasso Scientific Committee.

The first reaction we propose to study is ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$, one of the most important Big-Bang nucleosynthesis processes. Existing experimental data reach $E_{\text{cm}} = 400$ keV while indirect measurements, strongly discrepant with extrapolations based on the above data, have been recently performed down to about 50 keV. This reaction can well be studied with the present 400 kV machine down to about 50 keV c.m. (150 keV laboratory beam energy).

We now come to thermonuclear reactions inside the stars. The temperature in the stellar interior is determined by the mass of the star. Low-mass stars like our Sun operate mainly on the proton-proton (pp) chain, while more massive stars produce energy through the operation of the Carbon-Nitrogen-Oxygen (CNO) cycles. However, in second generation stars, whose central temperatures are higher than those for the quiescent CNO cycle, additional cycles in the hydrogen burning stage can occur. Because of the higher Coulomb barriers involved in the processes, these higher burning cycles are relatively unimportant as a source of energy, but they are essential for the nucleosynthesis of elements in the mass $A \geq 20$ region. LUNA has already studied in the past the key processes of the pp chain and of the first CNO cycle. We plan now to explore the other cycles by measuring the (p,γ) reactions on ${}^{15}\text{N}$, ${}^{17}\text{O}$, ${}^{18}\text{N}$, ${}^{22}\text{Ne}$ and ${}^{23}\text{Na}$.

Details of the first reaction we plan to measure with the 400 kV accelerator starting from spring 2008 (namely ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$) and on the more outstanding cases which would benefit of a higher energy machine are given in the following sections.

${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$

Recently, the ${}^6\text{Li}$ isotope has been detected in a number of metal-poor stars [15 and references therein]. These observations are significant because they suggest a ${}^6\text{Li}$ plateau similar to the well-known Spite plateau for ${}^7\text{Li}$ [16]. The observed ${}^7\text{Li}$ abundance [15,17] is a factor of 3 below the value predicted by standard big-bang nucleosynthesis based on the baryon-to-photon ratio from cosmic microwave background observations [18]. The ${}^6\text{Li}$ data, however, are higher by as much as two to three orders of magnitude than the predicted big-bang production. This gives rise to a ${}^6\text{Li}$ problem in big-bang nucleosynthesis, in addition to the well-known ${}^7\text{Li}$ problem.

If the existence of the ${}^6\text{Li}$ plateau is confirmed, a pre-galactic source of ${}^6\text{Li}$ has to be introduced as an explanation. This could either be an extremely enhanced production in big-bang nucleosynthesis, mainly through the ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ reaction, or non-standard physics like the decay of relic gravitinos [19]. It has been shown that ${}^6\text{Li}$ production through the pre-galactic interaction of energetic particles with the interstellar medium cannot explain the level of detected ${}^6\text{Li}$ [20]. Most scenarios of pre-galactic ${}^6\text{Li}$ production, except for an enhanced ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ cross-section, produce not only ${}^6\text{Li}$ but also ${}^7\text{Li}$, therefore worsening the ${}^7\text{Li}$ problem. A sensitivity study of nuclear reaction rates for big-bang nucleosynthesis has shown that the nuclear uncertainty in the predicted ${}^6\text{Li}$ abundance is dominated by the uncertainty in the ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ cross-section [21]. The reaction is dominated by d-wave capture to the first excited state in ${}^6\text{Li}$ and produces single γ -rays from ~ 1.6 to 2.2 MeV. The Gamow peak ranges from

50 to 300 keV in the centre of mass. Because of its electric quadrupole nature the cross-section is predicted to be extremely small, few pbarn to few tens of pbarn in the energy range 50-100 keV. The cross-section of the ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ reaction has been previously measured, in the energy range of big-bang nucleosynthesis, in a Coulomb dissociation study at Karlsruhe [22]. Preliminary results from GSI [23] indicate, with large uncertainties, a lower cross-section at similar energies (Figure 1). Theoretical calculations [e.g. 24] yield values that are systematically lower than the data [22,23]. The NACRE compilation consequently cites an uncertainty of a factor 3 in the rate at big-bang nucleosynthesis temperatures.

The Q-values of ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ and ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reactions are similar: 1.474 and 1.586 MeV, respectively. At big-bang energies, only capture to the ground state in ${}^6\text{Li}$ is energetically possible. Consequently, the observed γ -ray spectra from the LUNA ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ study have been used to evaluate the feasibility of a ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ measurement.

The measurement could be performed with the presently available 400 keV accelerator in the lab energy range 150-400 keV corresponding to c.m. values of 50-130 keV (the corresponding rate of emitted photons at the lowest energy is 4 h^{-1} with 100 μA alpha beam and 10^{18} atoms/cm² target thickness). However, a higher energy (3-3.5 MV) accelerator could allow reaching the 0.711 keV resonance and overlap the existing data.

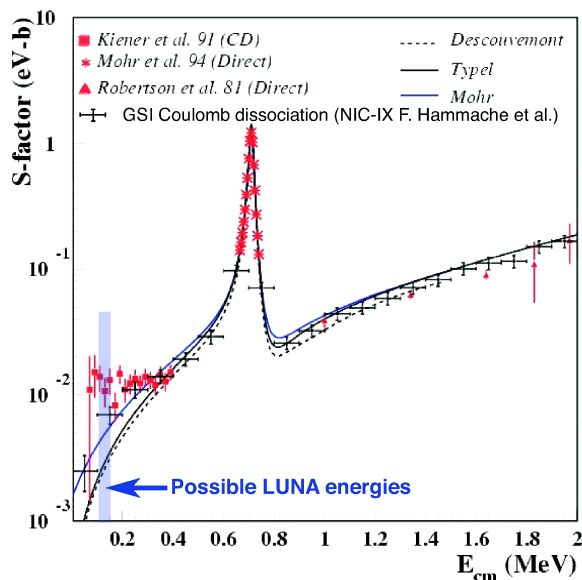


FIGURE 1. Existing results on the astrophysical factor of ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$

In conclusion, this reaction could profit of the same set-up used for the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reaction [11] and, more important, is a clear example of the advantages offered by an underground location such at Gran Sasso.

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

The measurement of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction ($Q=7161.91$ keV) should be done in a nearly 4π geometry with an angle-segmented crystal ball detector. The measurement of angular distributions is necessary to separate the E1 and E2 components of both ground-state and cascade transitions. The efficiency of such a detector has been preliminarily studied with Monte-Carlo techniques. For the expected reaction rate calculation, a conservative value of 50 % for the summing peak efficiency has been adopted, although preliminary calculations show that its value would be as high as 90 %, assuming a BGO crystal ball segmented like a truncated icosahedron polyhedron. With this geometry the detector has 11 effective angles with an average detection efficiency per angle of about 5 %. However, we consider a conservative value of 2.5 %.

Typical solid ^{12}C -enriched targets are those implanted in high purity gold. Preliminary estimates of the expected counting rate were carried on assuming conservative values for the target areal density ($2.0 \cdot 10^{18}$ atoms/cm²), summing peak detection efficiency (50 %), single angle detection efficiency (2.5 %) and beam intensity (500 μA). For the cross-section values, recent R-matrix fits were assumed. The summing peak, located at $Q+E_{\text{cm}}$, is above the natural laboratory background, taking full advantage of the high suppression factor for the cosmic ray background in detectors at Gran Sasso. The laboratory background counting rate is expected to be about 20 counts/day in the 4π detector summing peak and about 1 count/day in a single-angle detector, without shielding. The reaction rate is estimated to be 20 counts/day for the summing peak at $E_{\text{cm}}=533.6$ keV and 1 count/day for the single angle detector at the same energy. The high cosmic ray suppression of Gran Sasso reduces the γ ray background of 4 orders of magnitude. This gives a high improvement in the measurement of this reaction at low energy. Under these conditions a new study of the reaction at Gran Sasso could reach about 500 and 600 keV for the total S-factor and the E1/E2 components, respectively.

Neutron detectors

The measurement of $^{13}\text{C}(\alpha,n)^{16}\text{O}$ ($Q=2215.6$ keV) and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ ($Q=-478$ keV) should be done with a nearly 4π geometry neutron detector. One possibility is to use an existing neutron detector available to the collaboration [25,26], in the following named "Stuttgart detector". This detector is approximately a 1m·1m cylindrical polyethylene moderator containing 12 ^3He proportional counter chambers. The chambers are arranged into two rings at radii optimized for the neutron energy of interest. Several layers of passive shielding materials (paraffin wax, polyethylene, boron and cadmium) could be arranged around the detector. Typical values for efficiency of the Stuttgart detector range from 10 % to 32 %. For the expected reaction rates calculation, the conservative value of 10 % for the efficiency has been adopted.

Another possibility is to develop a new detection setup based on the traditional approach above described and liquid scintillators chambers which have already been tested at Gran Sasso [27]. Each scintillator chamber is a cylindrical cell containing one litre of scintillator [27]. Each cell is composed of a white Teflon tube 500 mm long, 50 mm internal diameter, 1.5 mm thick, which acts as a diffusing coating. It is inserted into a light-tight stainless-steel tube of 59 mm internal diameter, 1.5 mm thick filled with the scintillator (BC501A, produced by Bicron Corp.): this is ideal for γ -neutron discrimination because of its different pulse shape response. The exact efficiency of the detection setup will be studied during the project development with Monte-Carlo techniques.

$^{13}\text{C}(\alpha, n)^{16}\text{O}$

For a reinvestigation of $^{13}\text{C}(\alpha, n)^{16}\text{O}$, targets enriched in ^{13}C are required. The ideal solution is given by solid targets, with typical ^{13}C areal density ranging from $1 \cdot 10^{18}$ to $10 \cdot 10^{18}$ atoms/cm².

Preliminary estimates of the expected counting rate were done assuming conservative values for the target areal density ($1.0 \cdot 10^{18}$ atoms/cm², corresponding to about 38 keV energy loss), detection efficiency (10 %) and beam intensity (100 μA). The laboratory background counting rate in the detector is expected to be about 20 counts/day without shielding against laboratory neutrons and about 1 count/day with shielding. The reaction rate is expected to be ~ 20 counts/day at $E_{\text{cm}}=235.8$ keV and 1 count/day at $E_{\text{cm}}=205.2$ keV. The neutron background suppression of Gran Sasso is 3 orders of magnitude. This gives a high improvement in the measurement of this reaction at low energy which could reach, at LUNA, the upper edge of the Gamow peak (about 200 keV c.m.).

$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

In this case the target would be a windowless gas target with recirculation system, since enriched ^{22}Ne gas is rather expensive. A typical ^{22}Ne gas pressure is 5 mbar corresponding to a gas density of $1.25 \cdot 10^{17}$ atoms/cm³ (at 293 K). Assuming a gas target length of 10 cm (extended gas target), the resulting Ne areal density is $1.25 \cdot 10^{18}$ atoms/cm².

Also in this case, preliminary estimates of the expected counting rate were done considering conservative values for the target areal density ($1.25 \cdot 10^{18}$ atoms/cm², corresponding to about 56 keV energy loss), detection efficiency (10 %) and beam intensity (100 μA). The reaction rate is expected to be 20 counts/day at $E_{\text{cm}}=618.3$ keV and 1 count/day at $E_{\text{cm}}=553.1$ keV. The reaction rate when including the 552 keV resonance is expected to be about 20 counts/day assuming the upper-limit value of 60 neV for the resonance strength [25]. Also in this case we would have a large improvement in an underground measurement at low energy possibly reaching with good statistics the interaction energy of about 600 keV.

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