LUNA: Nuclear Astrophysics
Deep Underground

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Key Words
underground measurements, solar hydrogen burning, big bang nucleosynthesis

Abstract
Nuclear astrophysics strives for a comprehensive picture of the nuclear reactions responsible for synthesizing chemical elements and for powering the stellar evolution engine. Deep underground in the Gran Sasso National Laboratory, the cross sections of the key reactions of the proton-proton chain and of the carbon-nitrogen-oxygen cycle have been measured right down to the energies of astrophysical interest. The salient features of underground nuclear astrophysics are summarized here. We review the main results obtained by LUNA during the past 20 years and discuss their influence on our understanding of the properties of the neutrino, the Sun, and the universe itself. Future directions of underground nuclear astrophysics toward the study both of helium and carbon burning and of stellar neutron sources in stars are outlined.
1. INTRODUCTION

The stars that fascinate us are not perfect and everlasting bodies, as believed by ancient philosophers. Gravity triggers the birth of a star, which then functions as a more or less turbulent chemical factory (1) and finally dies out in a quiet or violent way, depending on its initial mass (2). Only hydrogen, helium, and lithium are synthesized in the first few minutes after the big bang. All the other elements of the periodic table are produced in the thermonuclear reactions that take place within stars, in which the nuclear roots of life are embedded (3, 4). The aim of nuclear astrophysics is to obtain a comprehensive picture of all these reactions, which allow the transmutation of the chemical elements and provide the energy to run the engine of stellar evolution (5).

Knowledge of the reaction cross section at stellar energies lies at the heart of nuclear astrophysics. At these energies, the cross sections are extremely small. Such smallness makes the star lifetime 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 megaelectronvolts—down to a few events per year—is not high enough to stand out from the background. The Laboratory for Underground Nuclear Astrophysics (LUNA), located in the Gran Sasso National Laboratory, began 20 years ago to run nuclear physics experiments in an extremely low-background environment. Just as the timbre of a note played on a piano cannot be distinguished in a crowded room, whereas it can in a music hall, the LUNA physicists are tuning their accelerators and detectors in the “music hall” located deep inside the mountain. This enables...
them to distinguish the tiny signal from nucleosynthesis reactions, thereby reproducing in the laboratory what occurs naturally inside the stars.

In this review, we describe the main features of thermonuclear reactions at very low energy, the characteristics of the background attainable at Gran Sasso, and the experimental equipment employed by LUNA. We then give an overview of hydrogen burning in stars and discuss the main results from LUNA, emphasizing their impact on models of the Sun and properties of the neutrino. Finally, we outline the next steps of underground nuclear astrophysics, particularly the study of helium and carbon burning and stellar neutron sources.

2. THERMONUCLEAR REACTIONS

Thermonuclear reactions between nuclei occur inside a star in a relatively narrow energy window, typically at an energy much lower than the height of the barrier arising from the Coulomb repulsion between nuclei. Consequently, reactions take place because of quantum mechanical tunneling, which leads to a very small (but not vanishing) probability that the incoming nucleus will penetrate the Coulomb barrier and reach its reaction partner.

Because of the tunneling, at these energies the reaction cross section $\sigma(E)$ drops almost exponentially with decreasing energy $E$,

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

where $S(E)$ is the so-called astrophysical S-factor and $2\pi\eta = 31.29Z_1Z_2(\mu/E)^{1/2}$. $Z_1$ and $Z_2$ are the electric charges of the nuclei, $\mu$ is the reduced mass (in atomic mass units), and $E$ is the energy (in kiloelectronvolts) in the center-of-mass system (2, 3). For most thermonuclear reactions, the astrophysical S-factor varies slowly with energy and contains all the nuclear physics information.

The reaction rate in the hot plasma of a star, with temperatures in the range of tens to hundreds of millions of degrees 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 to 10 keV. The product of $\sigma(E)$ and $\phi(E)$ identifies the energy window in which reactions occur 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. The energy release from the reaction, that is, the $Q$-value, corresponds to the mass difference between the entrance and exit channels.

To obtain the precise nuclear physics data required by modern astrophysics, one should measure the reaction cross section directly at the relevant stellar energy. For solar reactions, the cross-section values at the Gamow peak range from picobarns to femtobarns and even below ($1b = 10^{-24}$ cm$^2$). Although their ultralow count rates try the patience of physicists, these extremely small cross sections are a blessing to mankind because they account for the longevity of hydrogen burning in stars like our Sun.

However, the low count rates pose another experimental problem: In direct laboratory measurements at the Earth’s surface, the signal-to-background ratio is too small. Much of this background is also associated with the cosmic rays that bombard Earth. So, instead of a direct measurement at astrophysical energies, data must be obtained at higher energies, where the signal-to-background ratio is more favorable, then extrapolated to the energies of interest. However, any extrapolation is fraught with uncertainty. For example, narrow resonances at low energy or even resonances below the reaction threshold may influence the cross section at the Gamow peak. Those effects cannot always be accounted for by an extrapolation.
Another effect can be studied at low energies: electron screening (6–9). In the laboratory, the electron cloud surrounding the target nucleus partially screens the nucleus’s positive electric charge. This screening reduces the height of the Coulomb barrier, thus increasing the tunneling probability and eventually the reaction cross section. The screening effect has to be taken into account in order to derive the cross section for bare nuclei, which is the input data to nucleosynthesis network codes. These codes, in turn, must take into account the screening by electrons in the stellar plasma (6). Despite the impressive-sounding temperatures of many millions of degrees Kelvin in stellar interiors, the study of stars requires nuclear physics experiments performed at very low energy, measuring exceedingly small cross sections.

3. UNDERGROUND NUCLEAR ASTROPHYSICS

For stable stellar hydrogen burning, relevant temperatures range from 20 to $100 \times 10^6$ K, which correspond to Gamow peak energies of 10 to 50 keV, depending on the precise reaction of interest. The challenge of taking measurements at the Gamow peak involves suppressing the laboratory- and beam-induced background as well as enhancing the signal by boosting the beam intensity, target density, and detection efficiency.

3.1. Laboratory Background

The laboratory γ-ray background has two main sources: natural and cosmic ray–induced radioactivity. The decay of radioisotopes from natural decay chains produces a high density of γ-ray lines in the region below 2.6 MeV, where the highest-energy γ rays due to natural radioactivity are found. Figure 1 illustrates the different steps in background reduction that are necessary for nuclear astrophysics experiments.

There is a sizable difference in background between, for instance, a naked detector and a commercially available graded shield (10) that includes 10 cm lead. This difference is due to the suppression of the soft component of cosmic rays and γ rays from nearby radioisotopes. It is possible to further reduce background by using a shallow underground laboratory at 100 mwe (meters water equivalent) and applying a more sophisticated shield (11). At that point, the remaining background would be dominated by muon-induced events.

Such muon-induced events stem from (a) the decay of the radioactive nuclei due to muon spallation and the capture of stopping negative muons, (b) the inelastic scattering and capture of the muon-induced neutrons, and (c) the energy loss of muons passing through the detector. Although the prompt muon effects can be reduced by surrounding the detector with a veto counter, the muon-induced radioactivity may have a relatively long lifetime (1–10 s), so rejection of such events by vetoing is not practical. Instead, the remaining background can be overcome by performing the experiments in a deep underground laboratory (12, 13), where the muon flux is greatly reduced [e.g., by six orders of magnitude (14) at the 3,800-mwe-deep Gran Sasso National Laboratory].

At higher γ-ray energies, specifically $E_\gamma > 2.6$ MeV, these considerations become more transparent. In this energy region, no significant improvement in background can be reached by applying an additional lead shield. Use of a shallow underground laboratory helps somewhat, and a muon veto reduces the background. Deep underground, the muon flux becomes negligible, and the veto does not further reduce the background counting rate. A further reduction below the very low γ-ray background observed at LUNA (15) can in principle be achieved by shielding the setup against neutrons. The neutron flux at Gran Sasso, which is three orders of magnitude lower than at the Earth’s surface originates primarily from (α, n) reactions in the surrounding rock (16).
Figure 1
Laboratory γ-ray background measured with (a) a 100%–relative efficiency germanium detector at $E_γ < 2.7$ MeV and (b) a bismuth germanate (BGO) detector (scaled for equal volume with the germanium) for $5.2$ MeV $< E_γ < 14$ MeV. Green, the Earth’s surface with no shield; brown, the Earth’s surface with lead shield; blue, 110-mwe (meters water equivalent) underground Felsenkeller laboratory (Dresden) with lead shield (11); blue dashed line, actively vetoed spectrum in the 110-mwe underground Felsenkeller lab; red, 3,800-mwe LUNA lab with lead shield for the germanium (12) and no lead shield for the BGO (15).

Note that nuclear astrophysics is only one of the fields explored deep underground. The salient features of underground physics have been reviewed (17). Major underground activities are the detection of neutrinos generated by hydrogen burning in the Sun (18, 19), radioactivity in the Earth (20), and cosmic rays in the Earth’s atmosphere (21) and the search for rare processes such as neutrinoless double-β decay (22), proton decay (23), and dark matter interactions (24). Recently, a compendium of major facilities was published (25).

3.2. Beam-Induced Background

In any experiment that uses an ion beam, the beam interacts with nuclei other than the target to be studied. Such nuclei may be found in the beam-transport system (especially in beam-limiting apertures, but also in drift tubes, magnets, and residual gas), or they may be part of the target itself. Such interactions can give rise to γ-ray background.

Such ion beam–induced background is independent of the underground depth and must be dealt with by (a) reducing the inventory of materials hit by the ion beam and (b) taking appropriate precautions to eliminate worrisome components. For low-energy nuclear astrophysics experiments, these tasks are greatly facilitated by two factors. First, contaminants with an atomic number greater than the target to be studied generally have a lower interaction probability than the target itself because of their higher Coulomb barrier. Many experiments study light nuclei of $Z \leq 8$, so common materials such as aluminum or steel generally do not give background. Second, the otherwise common activation of beam-line components is not an issue with
low-energy protons or α beams. In cases where the background still interferes, it must be carefully identified, localized (e.g., 15), and whenever possible eliminated.

3.3. LUNA at Gran Sasso

There are several techniques to measure cross sections at the Gamow peak. So far, all of them have been pursued in only one laboratory: LUNA.

For nuclear reactions in which charged particles are emitted, it is usually possible to make an in-beam measurement at the surface of the Earth, except when coincident background due to cosmic rays is a problem. If so, only an underground measurement is feasible, as has been demonstrated for the \(^3\text{He}(\text{He},2\text{p})\) \(^4\text{He}\) reaction (26, 27).

For nuclear reactions in which only γ rays are emitted, there are in principle two approaches. In-beam γ-ray spectrometry deep underground has been used to study \(^2\text{H}(\text{p},\gamma)^3\text{He}\) (28), \(^1\text{H}(\text{p},\gamma)^1\text{H}\) (29–33), \(^3\text{He}(\text{He},\gamma)^7\text{Be}\) (34, 35), and \(^1\text{H}(\text{p},\gamma)^1\text{H}\) (36) reactions. The in-beam approach requires experimenters to account for several uncertainties, such as the angular distribution of the emitted γ rays. This weakness can be overcome in selected cases where the created nucleus is radioactive, thus allowing an independent cross-check. An activation study with deep underground activity counting has been performed in the study of \(^3\text{He}(\text{He},\gamma)^7\text{Be}\) (37, 38). All these approaches benefit from the reduced background deep underground.

4. EXPERIMENTAL APPARATUS AT LUNA

The measurement of the cross section and the determination of the astrophysical S-factor for thermonuclear reactions require an experimental apparatus composed of an accelerator, a target, and a detection system.

4.1. Accelerators

Two different accelerators have been used at LUNA: a compact 50-kV “homemade” machine (39) and a commercial 400-kV one (40). Common features of the two accelerators are their high beam current, long-term stability, and precise beam-energy determination. The first feature maximizes the reaction rate, the second provides 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.

The 50-kV machine was designed and built at Ruhr Universitàt in Bochum, Germany, and then moved to Gran Sasso. It consists of a duoplasmatron ion source, an ion-beam extraction and acceleration system, and a double-focusing 90° analyzing magnet. Its compact shape optimizes the beam transmission. This machine can deliver beams of protons, \(^3\text{He}^+,\) and \(^4\text{He}^+\) of 300 to 500 μA at energies between 10 and 50 keV, with an energy spread of less than 20 eV and a long-term stability (39). This capability allowed investigators to study (a) two fundamental reactions of the proton-proton (\(\text{pp}\)) chain, \(^1\text{H}(\text{He},2\text{p})^3\text{He}\) and \(^2\text{H}(\text{p},\gamma)^4\text{He}\), at solar Gamow peak energies and (b) the screening effect in the \(^2\text{H}(\text{He},\gamma)^4\text{He}\) reaction.

Even though it produced outstanding results (27, 28, 41), this accelerator should be considered as a pilot project toward a higher-energy facility, namely the 400-kV accelerator (Figure 2) (40). This electrostatic accelerator is embedded in a tank 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 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
The LUNA setup. The two beam lines are in the foreground, and the accelerator is in the background. The beam line on the left is dedicated to the measurements with solid targets, whereas the one on the right hosts the windowless gas target. The setup for the study of $^3$He($^4$He,$\gamma$)$^7$Be is shown during installation; the shield is only partially mounted.

can be sent into one of two different, parallel beam lines, thereby allowing the installation of two different target setups. In the energy range between 150 and 400 kV, the accelerator can provide up to 500 $\mu$A of protons and 250 $\mu$A of $^4$He at the target stations, yielding 0.3-keV accuracy on the beam energy, 100-eV energy spread, and 5-eV h$^{-1}$ long-term stability. Finally, the accelerator is controlled by programmable logic controller–based computers, which allow for safe operation over long periods without an operator present.

4.2. Targets and Ancillary Measurements

LUNA measurements have been performed with both solid and gas targets. Compared with gas targets, solid targets may contain a larger number of atoms per square centimeter: Typical areal densities range from $2 \times 10^{17}$ to $2 \times 10^{18}$. They allow for the measurement of the cross-section angular dependency because the beam-hit position on the target can be precisely determined. Gas targets are more stable to beam bombardment and may reach extreme purity, which is essential to minimize the beam-induced background. The areal densities used in LUNA are between $5 \times 10^{16}$ and $1 \times 10^{18}$. For solid targets, LUNA uses well-known production techniques such as implantation, evaporation, and sputtering (30). For gas targets a specific setup, consisting of a windowless gas target (i.e., a differentially pumped target) and a recirculation system (38, 42), was designed and installed at Gran Sasso and is depicted in Figure 3.
A typical disadvantage of a gas target is the so-called beam-heating effect. This effect is due to the power deposition, which heats and thins the gas along the beam path. Different techniques are necessary to obtain the real number of atoms per square centimeter in the beam region. A technique based on Rutherford scattering has been employed to limit systematic uncertainties due to gas density to less than 2% (43). Alternatively, the target thickness along the beam can be obtained through the energy shift of a known resonance (32, 44).

Solid targets, in turn, may rapidly deteriorate under intense beams. Such deterioration may change the density profile, which must be known in determining the reaction rate. To monitor the target thickness and its stability under the beam, one may use the resonance scan technique. This approach consists of selecting a resonance of the reaction to be studied or of a parasitic reaction and measuring the yield profile as a function of the beam energy. The selected resonance should have an energy width smaller than or equal to the target thickness. The target thickness as well as the maximum yield can be continually monitored during the entire duration of the measurement.

For the cross-section measurement, it is essential to know the beam current on target. Whereas for a solid target the current is measured through a conventional Faraday cup, for a gas target this is not possible due to the ion charge–state changes (45). Therefore, LUNA has developed a beam calorimeter (42) with a constant temperature gradient between the hot side and the cold side. The power to the hot side is provided by the beam and by resistors embedded in the end cap of the calorimeter. The number of projectiles is then obtained by the difference in heating powers dissipated by the resistors with and without the beam, divided by the kinetic energy of the projectiles themselves at the calorimeter surface. If properly calibrated, the calorimeter can give a systematic uncertainty of the order of 1% on the beam current (42). Calorimeter calibration is an example of the measurements done in laboratories at the Earth’s surface; it is an important step for the completion and integration of the results obtained underground.

4.3. Detectors

Apart from the $^3\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction, in which protons were detected through the use of commercial silicon detectors as single-stage or $\Delta E-E$ telescopes, all other LUNA measurements
require the detection of γ rays. Here the choice of the most suitable detector depends on the desired physical information. The 4π bismuth germanate (BGO) summing crystal used at LUNA (42), a 28-cm-long cylinder with a 20-cm diameter and a 6-cm bore hole, can reach an efficiency as high as 70% for a 7-MeV γ ray, thus allowing the measurement of extremely low reaction yields. However, the BGO crystal’s energy resolution is very poor and does not allow measurements of cascades and branching ratios to different levels because most of the γ-ray transitions are summed in a single peak. With a germanium detector, the efficiency dramatically decreases to the level of a few parts per mill, but the energy resolution is much better, allowing complex γ-ray cascades to be disentangled. Moreover, angular distribution measurements can be made by placing the detector at different angles with respect to the ion beam.

Nevertheless, summing effects can disturb the data evaluation for close geometry configurations. This can be addressed through the use of a composite detector such as a clover (46), wherein four small germanium detectors are enclosed inside the same cryostat, thereby reducing summing-in corrections.

5. HYDROGEN BURNING IN THE SUN

As the Sun’s 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 (2). If gravitational energy had been the only energy source during this contraction and heating phase, then the Sun would have “died” at only 30 million years of age, as estimated by Lord Kelvin in the nineteenth century (47). Instead, 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: $^4\text{H} \Rightarrow ^3\text{He} + 2e^+ + 2\nu_e$. This reaction releases useful energy and produces neutrinos detectable on Earth. Specifically, as the mass of the helium nucleus is lower than four times the proton mass, approximately 0.7% of the hydrogen rest mass was converted into energy in each of the transmutations.

Hydrogen fusion supplies the necessary energy to halt the contraction, and it provides all the energy required for the long life of the star. The Sun is a middle-aged main-sequence star whose shining arises from the burning of hydrogen fuel. The Sun 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 that consists primarily of carbon and oxygen. In the central region of the Sun, which has a temperature of 15 million degrees and a density of $\sim 150$ g cm$^{-3}$, hydrogen burning does not take place in one step but rather proceeds through a sequence of two-body reactions: the pp chain and the CNO cycle. The relative importance of the different reactions is determined by (a) the abundance of the nuclear species fusing together and (b) their fusion cross section at the Gamow peak energy.

5.1. Proton-Proton Chain

The first step and so-called bottleneck in the chain is the production of deuterium (48), which takes place through two different weak processes (Figure 4): (a) $^1\text{H}(p,e^+\nu)^2\text{H}$, which gives rise to the so-called pp neutrinos, and (b) $^1\text{H}(pe^-\nu)^2\text{H}$, a source of pep neutrinos. The latter, a three-body process, is strongly suppressed (by a factor of approximately 400) compared with the former. Once produced, the deuterium quickly burns with hydrogen to synthesize $^3\text{He}$. At this point, several possible scenarios emerge. The $^3\text{He}(p,e^+\nu)^4\text{He}$ reaction has a negligible rate because it is a weak process that is further suppressed, compared with $^1\text{H}(p,e^+\nu)^2\text{H}$, due to the atomic number
of helium. The most probable fate of $^3$He is to fuse with another $^3$He nucleus to produce $^4$He in the strong reaction $^3$He($^3$He, 2$p$)$^4$He. Approximately 14% of the time, the fusion takes place with the much more abundant $^4$He through the electromagnetic process $^3$He($^4$He, $\gamma$)$^7$Be. At this level, the chain branches again due to the competition between the electron-capture decay of $^7$Be, $^7$Be($e^-, \nu$)$^7$Li, and the fusion of $^7$Be with hydrogen, $^7$Be($p, \gamma$)$^8$B. The former is a weak process and is approximately 1,000-fold more probable than the latter scenario because it has no Coulomb barrier suppression. Once produced, $^7$Li quickly fuses with hydrogen to produce $^8$Be, which is extremely unstable and soon splits into two helium nuclei. $^7$Be($p, \gamma$)$^8$B seldom occurs, but this process is of crucial importance because it leads to the emission of high-energy neutrinos in the $^8$B decay to $^7$Be.

5.2. Carbon-Nitrogen-Oxygen Cycle

In the CNO cycle, the conversion of hydrogen into helium is achieved with the aid of carbon previously synthesized in older stars (3). Carbon works as a catalyst: It is not destroyed by the cycle, and it strongly affects the rate of the CNO cycle with its abundance. Because $^{15}$N($p, \alpha$)$^{12}$C has a cross section that is a factor of $\sim$2,000 lower than $^{14}$N($p, \alpha$)$^{11}$C, the second CNO cycle is strongly suppressed compared with the first one. In the Sun, the CNO cycle accounts for only a small fraction of nuclear-energy production (less than 1%), and it is controlled by $^{14}$N($p, \gamma$)$^{15}$O, the bottleneck reaction. Only at temperatures somewhat hotter than found at the Sun’s center, 20 million degrees, would the production of energy through the CNO cycle equal that of the pp chain. Above this temperature, the CNO cycle dominates energy production, as the effects of the Coulomb barriers no longer strongly suppress the energy-production rate.

5.3. Neutrinos

Neutrinos are particles that interact weakly with matter. They travel at approximately the speed of light, and they reach the Earth 8 min after they are produced in the center of the Sun. Because
we know that hydrogen fusion, $^4\text{H} \Rightarrow ^4\text{He} + 2\text{e}^+ + 2\nu$, produces 26.7 MeV of energy, and if we assume that the present luminosity of the Sun corresponds to the present energy-production rate (49) (it takes more than 10^4 years for electromagnetic energy to reach the surface of the Sun), then calculating neutrino flux is straightforward. We simply divide the solar luminosity, $3.85 \times 10^{26}$ W, by the energy required to produce one neutrino, $13.35\text{ MeV} = 2.14 \times 10^{-12}$ J, to obtain a rate of $1.80 \times 10^{38}$ neutrinos s^{-1}. This corresponds to a flux of approximately 60 billion neutrinos cm^{-2} s^{-1} on the Earth. To calculate the energy spectrum of the solar neutrinos, we must know the cross section of the different reactions of the pp chain and the CNO cycle: They give rise to neutrinos of different energies.

In particular, pp neutrinos have a flux of $6.04 \times 10^{10}$ cm^{-2} s^{-1} (50), corresponding to 92% of the total neutrino flux. Their continuous spectrum has an end-point energy of 0.42 MeV, which makes the detection of these neutrinos extremely difficult. 7Be neutrinos are produced with two different energies: 0.86 MeV (89.7% branching ratio) and 0.38 MeV. The 0.86-MeV 7Be neutrinos are the second largest component of the spectrum, amounting to 7% of the total with a flux of $4.55 \times 10^9$ cm^{-2} s^{-1}. 8B neutrinos have a much lower flux, $4.72 \times 10^6$ cm^{-2} s^{-1}; fewer than 1 neutrino in 10,000 comes from the 8B decay. However, their relatively high end-point energy (∼15 MeV) makes their detection much less difficult; unsurprisingly, 8B neutrinos have been the best-studied neutrinos from the Sun. The CNO cycle produces neutrinos with end-point energies of 1.20 MeV (13N) and 1.73 MeV (15O). The latest results of the Standard Solar Model (50) predict that CNO neutrinos make a 0.5% contribution to the total flux.

In 1964 both Bahcall and Davis (51) proposed the detection of solar neutrinos in order to study the inner region of the Sun and thereby directly verify the hypothesis of nuclear-energy generation in stars. Nearly 40 years of experimental and theoretical work have shown that the source of the energy radiated by the Sun is hydrogen fusion in the solar interior. Also, the study of solar neutrinos has revealed something important about the nature of the neutrino itself: It oscillates. An electron neutrino produced inside the Sun may become a muon or tau neutrino by the time it reaches the Earth.

6. HYDROGEN BURNING STUDIED AT LUNA

LUNA started as a pilot project in 1991. In the following sections, we discuss LUNA’s contributions over the past 20 years to our current understanding of the Sun and neutrinos.

6.1. ^2H(p,γ)^3He: The Energy Source of the Protostar

Inside the Sun, the $^2\text{H}(p,\gamma)^3\text{He}$ reaction controls the equilibrium abundance of deuterium. The $^2\text{H}(p,\gamma)^3\text{He}$ reaction controls the life of protostars before they enter the main-sequence phase. Protostar models predict that a star forms by accretion of interstellar material onto a small, contracting core. Until the temperature is below 10^6 K, the main source of energy is the gravitational contraction. When the temperature approaches 10^6 K, the first nuclear “fire” is ignited inside the star: The primordial deuterium is converted into $^3\text{He}$ via $^2\text{H}(p,\gamma)^3\text{He}$, providing 5.5 MeV for each reaction. The total amount of nuclear energy generated by this deuterium burning is comparable to the entire gravitational-binding energy of the star. The onset of deuterium burning slows down the contraction, increases the lifetime of the star, and freezes its observational properties until the original deuterium is fully consumed. Reliable knowledge of the rate of $^2\text{H}(p,\gamma)^3\text{He}$ down to a few kilo-electronvolts (the Gamow peak in a protostar) is a fundamental prerequisite for the protostellar models.
The $^2$H($p,\gamma$)$^3$He astrophysical factor $S(E)$ with the total error.

$^2$H($p,\gamma$)$^3$He is also a cornerstone in the big bang nucleosynthesis (BBN). Because of the deuterium bottleneck (52), that is, the photodisintegration of deuterium, the formation of $^3$He is delayed until the temperature drops to approximately $8 \times 10^8$ K. Again, knowledge of the cross section at low energies is required.

The $^2$H($p,\gamma$)$^3$He cross-section measurement was performed at LUNA with the 50-kV accelerator connected to a differentially pumped gas-target system designed to fit the large BGO $\gamma$-ray detector (42). The BGO, placed around the deuterium target, detected the 5.5-MeV $\gamma$ ray with 70% efficiency. The LUNA results (28), together with two previous measurements (53, 54) of the astrophysical factor $S(E)$ at low energy, are given in Figure 5. Their agreement with the theoretical calculations is excellent (55).

6.2. $^3$He($^4$He,$^2p$)$^4$He: In Search of the Resonance

LUNA’s initial activity was focused on the $^3$He($^4$He,$^2p$)$^4$He cross-section measurement within the solar Gamow peak (15–27 keV). This is a key reaction of the $pp$ chain. A resonance at the thermal energy of the Sun was suggested long ago (56, 57) to explain the observed $^8$B solar neutrino flux. Such a resonance would decrease the relative contribution of the alternative reaction $^3$He($^4$He,$\gamma$)$^7$Be, which generates the branch responsible for $^7$Be and $^8$B neutrino production in the Sun.

LUNA’s final setup comprises eight 1-mm-thick silicon detectors with an area of $5 \times 5 \text{ cm}^2$ placed around the beam inside the windowless target chamber, which is filled with $^3$He at a pressure of 0.5 mbar. The simultaneous detection of two protons unambiguously identified a $^3$He($^4$He,$^2p$)$^4$He fusion reaction ($Q$-value: 12.86 MeV). Figure 6 shows the results from LUNA (26, 27), together with higher-energy measurements (58–60) of the astrophysical factor $S(E)$.

For the first time, a nuclear reaction has been measured in the laboratory at the energy occurring in a star (27). 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 pb, which corresponds to a rate of approximately two events per month—rather low even for the so-called silent experiments of underground physics. No narrow resonance has been found within the solar Gamow peak; as a consequence, the astrophysical solution of the $^8$B and $^7$Be solar neutrino problem based on its existence has been ruled out.
6.3. $^3$He($^4$He,$\gamma$)$^7$Be: Solar Neutrino Oscillations

$^1$He($^4$He,$\gamma$)$^7$Be ($Q$-value: 1.586 MeV) is the key reaction for the production of $^7$Be and $^8$B neutrinos in the Sun because these neutrinos’ flux depends almost linearly on its cross section. Unless a recoil separator is used (61), the cross section can be determined either from the detection of the prompt $\gamma$ rays (62–68) or from the counting of the produced $^7$Be nuclei (61, 66, 69–71). The latter approach requires detection of the 478-keV $\gamma$ due to the excited $^1$Li populated in the decay of $^7$Be (half-life: 53.22 days). Both methods have been used to determine the cross section in the energy range $E_{CM} \geq 10^7$ keV, but the $S_{3,4}$ extracted from the measurements of the induced $^7$Be activity was 13% higher than that obtained from the detection of the prompt $\gamma$ rays (72).

An underground experiment was performed with the $^4$He beam from the 400-kV accelerator in conjunction with a windowless gas target filled with $^3$He at 0.7 mbar. The beam entered the target chamber and was stopped on the calorimeter (Figure 3). The $^7$Be nuclei produced by the reaction inside the $^3$He gas target were implanted into the calorimeter cap, which was removed after the irradiation and placed in front of a germanium detector for the measurement of the $^7$Be activity.

In the first phase of this experiment, the $^3$He($^4$He,$\gamma$)$^7$Be cross section was obtained from the activation data alone (37, 38), with a total uncertainty of $\sim$4%. In the second phase, a new high-accuracy measurement that simultaneously used prompt and activation methods was performed down to the center-of-mass energy of 93 keV. The prompt-capture $\gamma$ ray was detected by a 135% germanium, placed in close geometry with the target, and heavily shielded. The spectrum, taken at a beam energy of 250 keV, is shown in Figure 7. The astrophysical factors obtained with the two methods (34) are the same within the quoted experimental error (Figure 8). Similar conclusions have been reached in a new simultaneous activation and prompt experiment (73), which covered the $E_{CM}$ energy range from 330 to 1,230 keV.

The energy dependency of the cross section seems to be theoretically well determined at low energy. If the normalization is the only free parameter, we can rescale the fit from Reference 74 to our data, yielding $S_{3,4}(0) = 0.560 \pm 0.017$ keV b. Thanks to our small error, the total uncertainty on the $^8$B solar neutrino flux decreases from 12% to 10%, whereas the one on the $^7$Be flux decreases from 9.4% to 5.5% (34). The $^7$Be flux is now theoretically predicted with an error as small as the
Counts (keV h)⁻¹

Laboratory γ-ray background

Figure 7

$^3$He$(^4$He,γ)$^7$Be spectrum at a beam energy of 250 keV (red) and the laboratory background (blue).

The energy window covered by LUNA is above the Gamow peak of the Sun but well within the Gamow peak of the BBN. Our precise results clearly rule out the $^3$He$(^4$He,γ)$^7$Be cross section as a possible source of the discrepancy between the predicted primordial $^7$Li abundance (76) and the much lower observed value (77, 78).

6.4. $^{14}$N(p,γ)$^{15}$O: The Composition of the Sun and the Age of the Universe

$^{14}$N(p,γ)$^{15}$O (Q-value: 7.297 MeV) is the slowest reaction of the CNO cycle; it controls the cycle’s energy-production rate. Moreover, this reaction provides the $^{13}$Na n d$^{15}$O solar neutrino flux, which depends almost linearly on it, and it determines the age of globular clusters, which consist of $10^4$ to $10^6$ gravitationally bound stars that are the oldest stars in their galaxies. The luminosity of the turnoff point in the Hertzsprung-Russell diagram of a globular cluster, namely the point at which the main sequence turns toward cooler and brighter stars, is used to determine

Figure 8

Astrophysical $S(E)$-factor for $^3$He$(^4$He,γ)$^7$Be. The results from the modern, high-precision experiments are shown with their total error.
Bismuth germanate spectrum taken with a 100-keV proton beam on nitrogen of natural isotopic abundance. Red, peaks from $^{14}\text{N}(p,\gamma)^{15}\text{O}$ and $^{15}\text{N}(p,\gamma)^{16}\text{O}$; dark yellow, beam-induced background; blue, laboratory background. In spite of the small isotopic abundance of $^{15}\text{N}$ (0.366% only), the peak arising from $^{15}\text{N}(p,\gamma)^{16}\text{O}$ can be easily seen thanks to the much-reduced background.

Figure 9

Bismuth germanate spectrum taken with a 100-keV proton beam on nitrogen of natural isotopic abundance. Red, peaks from $^{14}\text{N}(p,\gamma)^{15}\text{O}$ and $^{15}\text{N}(p,\gamma)^{16}\text{O}$; dark yellow, beam-induced background; blue, laboratory background. In spite of the small isotopic abundance of $^{15}\text{N}$ (0.366% only), the peak arising from $^{15}\text{N}(p,\gamma)^{16}\text{O}$ can be easily seen thanks to the much-reduced background.

the age of the cluster and to derive a lower limit on the age of the universe (79). A star at the turnoff point burns hydrogen in the shell through the CNO cycle; this is why the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ cross section plays an important role in age determination.

In the first phase of the LUNA study, data were obtained down to 119 keV through the use of solid targets of TiN and a 126% germanium detector. The five different radiative-capture transitions that contribute to the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ 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 via the $4\pi$ BGO summing detector placed around a windowless gas target filled with nitrogen at a pressure of 1 mbar. The BGO spectrum at a beam energy of 100 keV is shown in Figure 9. At the lowest center-of-mass energy, 70 keV, a cross section of 0.24 pb was measured, yielding an event rate of 11 counts per day from the reaction.

The results obtained first with the germanium detector (29, 30) and then with the BGO setup (31) were approximately twofold lower than the existing extrapolation (72, 80, 81) from previous data (82, 83) at very low energy (Figure 10) and are in agreement with results from indirect methods (84–89). As a consequence, the CNO neutrino yield in the Sun is decreased approximately twofold, and the age of the globular clusters is increased by 0.7 to 1 billion years (89a) up to 14 billion years. The lower cross section also affects stars that are much more evolved than the Sun; in particular, the dredging up of carbon to the surface of asymptotic giant branch stars (90) is more efficient (91).

The main conclusion from the LUNA data has been confirmed by an independent study at higher energy (92). However, there is a 15% difference between the total S-factors extrapolated by the two experiments at the Gamow peak of the Sun. This difference arises from the extrapolation of the capture to the ground state in $^{15}\text{O}$, a transition strongly affected by interference effects between several resonances and the direct-capture mechanism.

To provide precise data for the ground-state capture, a third phase of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ study was 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 (93). The total error on the \( S \)-factor was reduced to 8%: \( S_{14}(0) = 1.57 \pm 0.13 \text{ keV b} \) (33). This is significant because, having finally solved the solar neutrino problem, we are now facing the problem of solar composition: There is a conflict between helioseismology and the new metal abundances that emerged from improved modeling of the photosphere (50, 94). Thanks to the relatively small error, it will soon be possible to measure the metallicity of the core of the Sun (i.e., the elements other than hydrogen and helium) by comparing the detected CNO neutrino flux with the predicted flux. The CNO neutrino flux in the low-metallicity scenario is \( \sim 35\% \) lower than in the high-metallicity scenario. Use of these scenarios will allow us to test whether the early Sun was chemically homogeneous (95), which is a key assumption of the Standard Solar Model.

### 6.5. Ongoing Measurements

The solar phase of LUNA has almost reached its end. A new and rich program of nuclear astrophysics, mainly devoted to the MgAl and NeNa cycles, began at the 400-kV facility about two years ago with the measurement of \( ^{25}\text{Mg}(p,\gamma)^{26}\text{Al} \) (96). The MgAl and NeNa cycles are important for second-generation stars with central temperatures and masses that are higher than those of our Sun (3, 5). Due to their higher Coulomb barriers, these cycles are relatively unimportant for energy generation, although they are essential for the nucleosynthesis of elements with mass number higher than 20. Low-energy resonances (or the low-energy part of the direct capture) that are inaccessible in a laboratory at the Earth’s surface could be measurable underground. Some reactions have already been measured aboveground, but an underground reinvestigation could substantially improve our knowledge of the related reaction rate in the different astrophysical scenarios responsible, for example, for the texture of the isotopes that are filling the universe.

LUNA is now measuring \( ^{15}\text{N}(p,\gamma)^{16}\text{O} \) with enriched \( ^{15}\text{N} \) targets. \( ^{15}\text{N}(p,\gamma)^{16}\text{O} \) is the leak reaction from the first to the second CNO cycle. The results already obtained with nitrogen of natural isotopic composition (0.366% \( ^{15}\text{N} \)) (36) extend to energies that are lower than ever.
measured before and provide a cross section at nova energies that is approximately twofold lower than previously believed.

The measurement in preparation, \(^2\text{H}(\text{He},\gamma)^6\text{Li}\), is not connected to the hydrogen-burning cycles but rather is a key reaction of the BBN. This reaction determines the amount of primordial \(^6\text{Li}\) in the universe. Recently, the \(^6\text{Li}\) isotope was detected in a number of metal-poor stars (97, 98), and its quantity is two to three orders of magnitude higher than what was expected from the BBN (76).

7. OUTLOOK

Measurements of cross sections directly at the energy of astrophysical interest have been successfully used to elucidate the reactions governing stellar hydrogen burning. To keep pace with the rapid progress of observational astronomy and astrophysical modeling, investigators should also explore the nuclear reactions that (a) govern helium and carbon burning and (b) produce the neutrons that give rise to the so-called astrophysical s-process. Owing to the different nature of these reactions, new techniques and new equipment are necessary for this task.

The \(^{12}\text{C}(\alpha,\gamma)^16\text{O}\) reaction is often referred to as the Holy Grail of nuclear astrophysics (99–104). It plays a fundamental role in the evolution of stars during the helium-burning phase and determines the abundance ratio between carbon and oxygen, the two most important elements in the development of life. This abundance ratio influences the nucleosynthesis of elements up to the iron peak for massive stars, the cooling timescale of white dwarfs, and the properties of thermonuclear as well as core-collapse supernovae.

\(^{12}\text{C}+^{12}\text{C}\) fusion reactions catalyze carbon burning. Their rate determines the evolution of massive stars, up to either a modest end as a white dwarf or a fiery death as a core-collapse supernova (113, 114). The fusion reactions also affect the ignition conditions and timescales of thermonuclear supernovae. The \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) and \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reactions provide the neutrons for the buildup of the s-process isotopes (100, 111, 115–117). Most elements that are heavier than iron are produced through this process, which involves a series of subsequent neutron captures and \(\beta\) decays.

To study these and other exciting reactions, as listed in Table 1, a new, few-megavolt accelerator should be installed in a deep underground laboratory (118). It should also be able to accelerate not only protons and \(\alpha\) particles, but also ions up to carbon or even oxygen so that carbon burning can be studied. As for the beam current, for all these ions an intensity of \(\sim 1\) mA would be required for the necessary sensitivity.

Table 1  Nuclear reactions of astrophysical interest recommended for study at future underground accelerator facilities

<table>
<thead>
<tr>
<th>Type</th>
<th>Reaction</th>
<th>(Q)-value (MeV)</th>
<th>(E_{\text{Gamow}}) (keV)</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\alpha,\gamma))</td>
<td>(^2\text{H}(\alpha,\gamma)^6\text{Li})</td>
<td>1.5</td>
<td>100–500</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>(^{12}\text{C}(\alpha,\gamma)^16\text{O})</td>
<td>7.2</td>
<td>300</td>
<td>104–106</td>
</tr>
<tr>
<td></td>
<td>(^{14}\text{N}(\alpha,\gamma)^18\text{F})</td>
<td>4.4</td>
<td>200–700</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>(^{13}\text{N}(\alpha,\gamma)^19\text{F})</td>
<td>4.0</td>
<td>500</td>
<td>108</td>
</tr>
<tr>
<td>(^{12}\text{C})-induced</td>
<td>(^{12}\text{C}(^{12}\text{C},n)^{20}\text{Ne})</td>
<td>4.6</td>
<td>1,500</td>
<td>12, 109</td>
</tr>
<tr>
<td></td>
<td>(^{12}\text{C}(^{12}\text{C},p)^{13}\text{Na})</td>
<td>2.2</td>
<td>1,500</td>
<td>12, 109</td>
</tr>
<tr>
<td></td>
<td>(^{13}\text{C}(\alpha,n)^{16}\text{O})</td>
<td>2.2</td>
<td>200</td>
<td>110, 111</td>
</tr>
<tr>
<td></td>
<td>(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg})</td>
<td>0.5</td>
<td>500</td>
<td>112</td>
</tr>
</tbody>
</table>
Such a project is presently being planned at several different sites in Europe and North America. It would be desirable to install a new underground accelerator at the site of the present LUNA machine, Gran Sasso National Laboratory, because of the facility's excellent infrastructure and proven low background. However, due to the limited underground laboratory space at Gran Sasso, other sites must be considered.

One such site is the Canfranc Laboratory in Spain (119), which is less well shielded (2,400 mwe) than Gran Sasso and therefore has a higher remaining muon flux. However, at the LUNA site the background is dominated by neutrons, not muons (15), and the neutron flux at the two sites is comparable. Access to this site is by horizontal road tunnel, which would facilitate the installation of complex, maintenance-intensive equipment such as an accelerator.

In the United States, plans to construct an underground facility at the site of the previous Homestake experiment include two accelerators with connected beam lines (120). One machine should have similar functions as LUNA's 400-kV accelerator, but with greatly increased beam intensity, whereas the second accelerator should be in the megavolt range and should study most of the reactions listed in Table 1.

Two projects in Boulby (United Kingdom, 2,800 mwe) and Praid (Romania, 900 mwe) (121, 122) are also in the planning stages. In these facilities, the laboratory should be placed in a salt matrix deep underground, where the levels of uranium and thorium and therefore neutron flux are generally much lower.

Regardless of the outcome of the ongoing siting discussion, both astrophysics and nuclear physics will greatly benefit from the new precision that will be enabled by a future, higher-voltage accelerator underground. A better understanding of nuclear burning in stars, obtained via direct new data, will allow us to model stellar scenarios that are now understood only in general terms. Also, improved experimental data for nuclear fusion reactions near or below the Coulomb barrier will present a fresh challenge for theoretical modeling of these reactions.

8. CONCLUSIONS

Twenty years ago, LUNA started underground nuclear astrophysics experiments in the core of Gran Sasso mountain, below 1,400 m of dolomite rock. The extremely low background has allowed physicists to perform experiments with count rates as low as a few events per year. For the first time, the important reactions that are responsible for 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 were made, nuclear physics is no longer an important error source for the solar model, and solar neutrinos can now be exploited to probe the deep interior of the Sun. When applied to astrophysical scenarios different from the Sun, LUNA results increase the limit on the age of the universe up to 14 billion years.

Thanks to its underground environment, LUNA has spurred great improvement in our comprehension of hydrogen burning. In the next two decades, underground nuclear astrophysics will try to reach similar results in the study of the helium and carbon burning and of the neutron sources in the stars.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.
ACKNOWLEDGMENTS

It is a pleasure to thank our colleagues at LUNA, without whom the results reviewed in this paper could have not been obtained.

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