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Nuclear astrophysics and underground accelerators

Alessandra Guglielmetti, for the LUNA collaboration

Università degli Studi di Milano and INFN Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy

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ABSTRACT

Accurate knowledge of thermonuclear reaction rates is a key issue in nuclear astrophysics since it is important for understanding the energy generation, neutrino production and the synthesis of the elements in stars. Cross-section measurements are mainly hampered by the very low counting rate and cosmic background. An underground location is extremely advantageous for such studies, as demonstrated by the LUNA experiment in the Gran Sasso Laboratory (Italy). This paper reports on the results recently obtained by such an experiment and on the future perspectives in this field.

1. Introduction

Nuclear astrophysics is an extremely rich field, strongly correlated with many other research fields like observational astronomy, stellar modelling, neutrino physics, cosmology, nuclear physics etc. One of the most ambitious task of nuclear astrophysics is to explain the origin and relative abundances of the elements in the Universe, formed through different nuclear processes in different astrophysical scenarios. Therefore, nuclear fusion reactions are the core of nuclear astrophysics since they determine the formation of the elements in the earliest stages of the Universe (Big Bang nucleosynthesis, BBN) and in all the objects formed thereafter and control the energy generation, neutrino production and evolution of stars. An accurate and precise knowledge of the cross section of these reactions is thus very important at first for BBN with all its cosmological implications but is also a key ingredient for stellar models and in general is essential for describing the evolution of the Universe: many reactions still ask for high precision data. Moreover, the precise knowledge of reactions producing neutrinos is mandatory to use neutrinos as probes of the stellar interior and to derive informations on the particle's properties. From the nuclear physics point of view, the structure of the involved nuclei play a very important role in determining the reaction mechanism, which is obviously related with the reaction probability (cross section). Typical nuclear physics techniques can be used to measure such cross sections but should be better adopted in a very low background environment, as an underground laboratory, for reasons that will be explained in the following.

Thermonuclear fusion reactions in stars start from the most abundant and lightest element, hydrogen, and gradually synthesize heavier elements [1]. The first nuclear fusion process is the so-called Hydrogen burning which has the net result of transforming 4 protons into a ^{4}He nucleus with an energy release of about 27 MeV. Hydrogen burning coincides with the longest stage of a star's life (also known as its main sequence phase) and is responsible for the prodigious luminosity of the star itself. It mainly proceeds either through the p–p chain or through the more efficient CNO cycle. The latter and successive cycles such as the NeNa and MgAl become important for second-generation stars whose central temperatures and masses are higher than those of our Sun and whose evolution stage is such that the necessary seeds for these reactions are already present. Due to the higher Coulomb barriers, these cycles are relatively unimportant for energy generation but are essential for the nucleosynthesis of elements with mass number higher than 20.

All these fusion reactions occur in a very well defined energy range, the so-called Gamow peak [1], which arises from the convolution of the energy distribution of nuclei in the stellar plasma and the tunnelling probability through the Coulomb barrier between the interacting nuclei. In a non-degenerate, non-relativistic stellar plasma, the former is given by the Maxwell–Boltzmann distribution, with a maximum for $E = kT$ (where T is the star temperature and k the Maxwell–Boltzmann constant) and then decreases exponentially with increasing energy, while the latter decreases exponentially for decreasing energy. For example, for a central temperature of 1.5×10^7 K, as in our Sun, the maximum of the Maxwell–Boltzmann distribution occurs at about 1 keV, while the Coulomb barrier for most reactions in either the p–p chain or the CNO cycle is between 0.5 and 2 MeV. The Gamow peak for the same reactions is below 30 keV and, as a result, reaction cross sections can be extremely low, down to the femto-barn level, due to the

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E-mail address: alessandra.guglielmetti@mi.infn.it.

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already mentioned exponential drop of the tunnelling probability with decreasing energy. It follows that a direct investigation of thermonuclear reactions at or near their Gamow energy is often beyond technical capabilities as the signal-to-noise ratio is severely dominated by any source of unwanted background. In a laboratory at the Earth's surface, the greatest contribution to the background typically arises from the interaction of cosmic rays with the material in the detection setup. Reaction cross-sections are therefore extrapolated from data taken at higher energies, albeit with significant uncertainties remaining at the lowest energies of astrophysical interest. The extrapolation procedure is typically carried out on the so-called astrophysical S-factor defined by:

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

where η is the Sommerfeld parameter given by:

$$\eta = (31.29/2\pi)Z_1Z_2(\mu/E)^{1/2}$$

with Z_1 and Z_2 integral charges of the interacting nuclei; μ the reduced mass; and E the centre-of-mass interaction energy in keV. The astrophysical S-factor has a much reduced energy dependence compared to the cross section. However, the existence of narrow resonances in or near the Gamow energy region, the tails of broad resonances and/or sub-threshold states, as well as a change in the reaction mechanism at ultra-low energies, can all translate in non-negligible contributions to the reaction cross section (or equivalently the astrophysical factor) thus rendering the extrapolation procedure extremely uncertain.

An alternative solution to the extrapolation procedure requires a drastic reduction of any unwanted background to optimize the signal-to-noise ratio. This can often be achieved by carrying out the measurement in deep underground laboratories.

2. The LUNA project in the underground Gran Sasso Laboratory

The LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration has exploited the low-background environment of the underground laboratory under the Gran Sasso Mountain in Italy (LNGS) to perform direct measurements at the relevant astrophysical energies. The rock overburden of about 1400 m (3800 m water equivalent) reduces the muon component of the cosmic background by a factor of 10^6; the neutron component by a factor of 10^3; and the gamma component by a factor of 10 with respect to a laboratory on the Earth's surface. As a result, the gamma background above 3 MeV in an HPGe detector placed underground at LNGS is reduced by a factor of $\sim$2500 with respect to the same detector placed over-ground. In addition, going underground enhances the effect of passive shielding particularly for lower energy gammas where the background is dominated by environmental radioactivity. Indeed, a passive shield can be built around the detector also in a laboratory at the Earth's surface. However, passive shielding are of limited utility since additional background from interactions of the cosmic rays with the shielding material overwhelms the positive effect of attenuation in the shielding itself. An exception is the extremely large thickness which can be achieved in an underground laboratory, where the cosmic background is much reduced.

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 beam currents achievable, the long-term stability, and the precise energy determination. The first two features are essential to maximize the reaction rate, while the third one is important in view of the exponential energy dependence of the cross section. With the first machine, operating between 1992 and 2001, two key reactions of the p–p chain were studied at the solar Gamow peak energies: the ^{3}He(^{3}He, 2p)^{4}He [4] and d(p, γ)^{3}He [5]. In addition, the screening effect, i.e. lowering of the Coulomb barrier for a nucleus surrounded by electrons with respect to a bare one, was investigated through the d(^{3}He, p)^{4}He reaction [6]. The 400 kV machine started operations in the year 2000 and is still operating. The most important results obtained include the study of the ^{14}N(p, γ)^{15}O reaction [7–10] with its consequences on the CNO neutrino production and on the age of the globular clusters, the ^{3}He(^{4}He, γ)^{7}Be reaction [11–13] impacting ^{7}Li production in BBN and ^{7}Be and ^{8}B neutrino fluxes. Other key reactions belonging to the CNO cycle (^{15}N(p, γ)^{16}O [14]) or MgAl cycle (^{25}Mg(p, γ)^{26}Al [15–17]) of Hydrogen burning have also been measured with the 400 kV machine. Here, one of the most recently obtained results will be reported, as an example of measurement that took advantage being performed underground, and its astrophysical consequences discussed. The most important LUNA results are included in two quite recent reviews [18,19].

3. The ^{17}O(p, γ)^{18}F reaction

The ^{17}O + p thermonuclear reaction rates are relevant to Hydrogen burning in a variety of astrophysical sites, including red giants stars, massive stars, Asymptotic Giant Branch (AGB) stars and classical novae. These last are explained as thermonuclear explosions on the surface of white dwarfs stars accreting hydrogen-rich material from less evolved companions in binary star systems. They have been proposed as key source of a few rare isotopes in the Universe, among which ^{17}O and ^{18}F. The latter is a β^+ emitter ($T_{1/2}$ = 110 min) and the 511 keV gamma-rays following the positron–electron annihilation could potentially be detected by satellites giving a signature of novae outbursts and constraining current nova models, provided the cross sections of the reactions involved in the formation of ^{18}F are sufficiently well known. These reactions are essentially the ^{17}O(p, γ)^{18}F and its competitor ^{17}O(p, α)^{14}N, both belonging to the CNO cycle. At energies relevant for classical novae, the ^{17}O(p, γ)^{18}F reaction is dominated by a combination of direct capture contribution and low energy tails of broad resonances and by a resonance at a centre-of-mass energy E_{cm} = 183 keV. Several groups have previously investigated the reaction, but the outcome was not satisfactory. At LUNA, this reaction was studied by impinging the high intensity proton beam provided by the 400 kV accelerator on Ta_2O_5 solid targets, enriched in ^{17}O. Details on the target preparation and characterization are reported in [20]. Two different experimental techniques have been employed: the detection of the prompt gamma emitted with a large volume (115% relative efficiency) HPGe detector in closed geometry and the collection of the ^{18}F target nuclei for an off-line measurement of their decay (activation measurement). The activation spectra were recorded using the low background facility STELLA [21] installed at LNGS. The ^{17}O(p, γ)^{18}F reaction proceeds by populating several states in ^{18}F leading to a complex decay scheme. The advantage of an underground measurement is evident in the quality of the gamma spectra obtained: an example of an on-resonance (E_{cm} = 183 keV) prompt-γ spectrum is shown in Fig. 1: all transitions are clearly visible and well above the room background (in grey). Indeed several of these transitions were not known before.

The reaction has been measured in the energy range E_{cm} = 160–370 keV and the resonance strength of the 183 keV resonance determined with unprecedented precision to be $\omega\gamma = (1.67 \pm 0.12)$ μeV [22,23]. The total S factor has been obtained through a combined fit of prompt γ-ray and activation results and lead to $S(0) = 5.0 \pm 0.3$ eV barn. An overall global fit including other existing data sets was also carried out and a recommended astrophysical reaction rate determined. The reaction rate uncertainty attained is now below the required precision for nova models. We verified, following a full set of hydrodynamic nova models, that

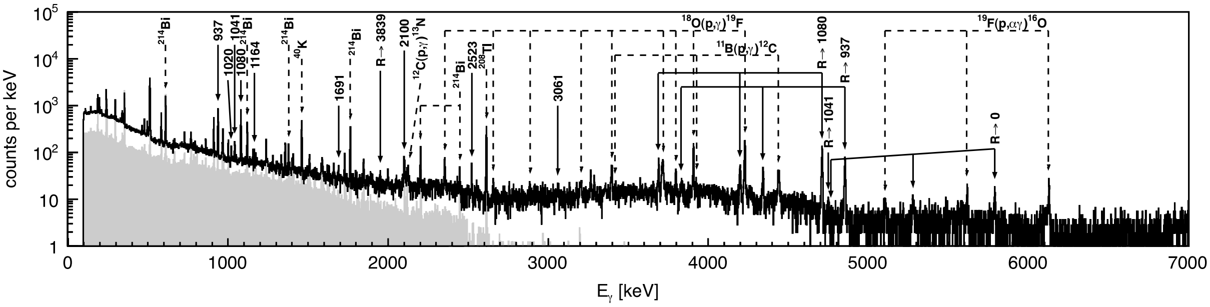

Fig. 1. $^{17}O(p, \gamma)^{18}F$ gamma spectrum: Sample spectrum of an on-resonance measurement. See text for details.

the abundances of oxygen and fluorine isotopes obtained with the present reaction rate are determined with 10% precision and put firmer constraints on observational signatures of novae events [23].

4. The future and the LUNA-MV project

Taking advantage of the presence of two beam lines at the LUNA facility, in parallel to the measurement above presented, the $^2H(\alpha, \gamma)^6Li$ reaction was measured by impinging an intense alpha beam on a deuterium windowless gas target. This reaction is fundamental for ^6Li production in BBN and direct data in the energy range relevant for BBN were not available. At LUNA it was possible to obtain two data points in this energy range [24] and the expected primordial ^6Li production was calculated. In these months two other reactions are being studied: the $^{17}O(p, \alpha)^{14}N$, competitor of the $^{17}O(p, \gamma)^{18}F$ above presented, and the $^{22}Ne(p, \gamma)^{23}Na$ belonging to the NeNa cycle. After the completion of these measurements, the LUNA 400 kV machine will be used to study a few more (p, γ) and (p, α) reactions on Oxygen and Sodium isotopes. Moreover, a new experimental program has very recently been developed and is presently under evaluation by the Scientific Committee of Gran Sasso Laboratory. If approved, it will allow to perform interesting measurements up to the end of 2018. All of these can be studied with the 400 kV accelerator since the relevant energy range, or at least part of it, is accessible to such a machine. After that, reactions that take place at higher temperatures (i.e. higher energies) than those occurring during the hydrogen-burning processes studied so far are planned to be measured using a higher voltage machine, in the MV range. For this reason, already in 2007, the LUNA collaboration submitted a Letter of Intent (LoI) [25] to the LNGS Scientific Committee which contained an experimental program mainly devoted to Helium burning reactions, the so-called LUNA-MV project. In particular the $^{12}C(\alpha, \gamma)^{16}O$ and the (α, n) reactions on ^{13}C and ^{22}Ne were foreseen.

The cross section of the $^{12}C(\alpha, \gamma)^{16}O$ reaction at the relevant Gamow energy (∼300 keV) determines the helium burning time scale and, together with the convection mechanism, the abundances of carbon and oxygen at the end of helium burning. The carbon abundance at the end of helium burning has important consequences for the subsequent evolution of the star and for the nucleosynthesis path. In particular, the amount of intermediate-light elements Ne, Na, Mg, and Al ejected during a type II Supernova explosion scales directly with this parameter, while the amount of the elements produced in the advanced explosive burning phases beyond carbon burning scale inversely [26]. The situation is similar for type I Supernovae. Thus, stellar models show an exceptional sensitivity on the cross section of $^{12}C(\alpha, \gamma)^{16}O$ and an experimental determination with a precision of the order of 10% or better is required to provide adequate constraints on stellar evolution. A measurement at the astrophysical energy is unfeasible due to the extremely low cross section and the astrophysical reaction rate relies on an extrapolation of existing data. This extrapolation of high-energy data is complicated by a complex reaction scheme. The lack of low-energy data with high precision implies that significant progress on the determination of the $^{12}C(\alpha, \gamma)^{16}O$ cross section can only be made by an extensive, dedicated project in a low background environment with the primary focus on measurements of the ground state transition through angular distribution. The experiment will strongly benefit from the low background environment at higher γ-ray energies in the LNGS.

The $^{13}C(\alpha, n)^{16}O$ and the $^{22}Ne(\alpha, n)^{25}Mg$ are the so-called n-source reactions as they are responsible of the n-flux for the creation of the heavy elements. Indeed, more than 50 years ago Burbidge, Burbidge, Fowler & Hoyle [27] proposed neutron-captures as the path to build up most elements heavier than iron. Since then, much effort was spent to understand the neutron-capture nucleosynthesis in stars of different mass and composition. Major neutron-capture processes are the s-process and r-process. While little is known about astrophysical sites where the r-process takes place, the basic properties of the s-process have been identified. Two different components of the s-process can be distinguished: (i) the weak component, responsible for all isotopes with masses $60 < A < 90$, is supposed to take place during the hydrostatic evolution of massive stars; (ii) the main component, responsible for heavier isotopes (from Kr to Bi), occurs in Asymptotic Giant Branch stars. The major sources for the required neutron flux are the $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$ reactions that operate under different conditions: the former has a positive Q-value (2.216 MeV) while the latter has a negative one of −0.478 MeV and it can only be associated with higher temperature conditions. In low-mass AGB stars the $^{13}C(\alpha, n)^{16}O$ reaction is the major neutron source. The precise experimental study of its reaction rate with related uncertainty is fundamental for the distribution of the s-process elements in the stellar surface material. Therefore, a direct measurement in the relevant temperature range is mandatory and will increase our knowledge on the heavy element production. The study of the $^{13}C(\alpha, n)^{16}O$ reaction at astrophysical energies requires the detection of neutrons in the energy range between $E_n \approx$ 1 and 3 MeV with high efficiency. Most of the direct experiments performed so far in laboratories at Earth's surface using different detection techniques were limited by neutron background arising from cosmic-ray induced reactions, by radio-impurities in the detection setup and by cosmic-ray induced high energy γ-ray background. Recently, the reaction was also indirectly measured with the Trojan Horse Method [28]. For direct measurements, significant progress can only be achieved if the background is successfully reduced, as can be done in a deep underground laboratory as LNGS.

The $^{22}Ne(\alpha, n)^{25}Mg$ is the dominant neutron source responsible for the weak component of the s-process in the massive stars, both during core helium burning and in shell carbon burning. Moreover, the $^{22}Ne(\alpha, n)^{25}Mg$ also affects the abundance of ^{60}Fe ejected during type II supernova explosion and the peak luminosity of type Ia supernovae [29]. For more than thirty years, direct measurements of the ^{22}Ne(α, n)^{25}Mg reaction have been performed close to the energy region of interest to the s-process: $E_{cm} = 600 \pm 300$ keV but the resonance strengths from the different measurements disagree by up to a factor of 5 [29], a value much larger than the quoted uncertainties. The lowest energy resonance measured is located at $E_\alpha = 831$ keV, just at the upper edge of the energy region of interest. Studies of the relative resonance contributions to the reaction rate show that, at the relevant temperatures to the s-process, the resonance at $E_\alpha = 831$ keV and those at lower energies are the most important.

Also in this case, previous direct measurements of the ^{22}Ne(α, n)^{25}Mg reaction were mainly hampered by extremely low count rates and by natural background due to cosmic rays. The direct underground measurement, taking advantage of the background reduction and of improved set-up for neutron detection, possibly including also the measurement of neutrons' energy, will significantly improve the knowledge of this reaction. In particular, a precise measurement of the known resonance down to the one at $E_\alpha = 831$ keV will be performed at first, followed then by a detailed search for unknown resonances down to $E_\alpha \sim$ 600 keV.

After the submission of the LoI, an intense interaction took place between the LUNA collaboration on one side and the LNGS Scientific Committee and the LNGS management on the other side. Two more documents (LoI addendum [30] and LoI update [31]) were submitted by the LUNA collaboration to the LNGS Scientific Committee. A dedicated committee of scientists covering different expertise in the field of nuclear astrophysics was established. This produced a very positive report on the LUNA MV project, strongly recommending its realization at LNGS. The so-called "B node" at LNGS was identified at first as the best possible place to install the accelerator underground, due to its size and distance from the other LNGS experiments. More recently, it turned out that such a location would have delayed the project too much due to the legal implications related to the presence on site of water uptake positions of the local aqueduct. The new location selected for the project is the South part of the Hall C of the Gran Sasso Laboratory where presently the OPERA experiment is installed. There, a worldwide unique underground facility centred on a 3.5 MV single-ended accelerator providing hydrogen and helium beams will be realized. Two different beam lines are foreseen devoted to solid and gas target experiments, respectively. This will allow us to study the key reactions of Helium burning described above and to re-investigate the ^{3}He(^{4}He, γ)^{7}Be reaction over a wide energy range in order to further diminish its experimental uncertainty. The LUNA-MV project was selected as a special project ("Progetto premiale") by the Italian Research Ministry and financed in 2012 and 2013 with a total amount of about 5.3 millions of euros. A key issue is the realization of a neutron shielding to the rest of the laboratory to preserve the "low background" characteristic of LNGS. In order to evaluate the neutron fluxes potentially produced by the reactions above described (note that also the ^{12}C(α, γ)^{16}O reaction is producing a neutron background due to the parasitic ^{13}C(α, n)^{16}O component given by ^{13}C impurities in the ^{12}C solid target), a series of GEANT4 simulations are being developed, assuming a worst-case scenario of 2000 n/s of 5.6 MeV energy (the maximum possible energy foreseen). Different materials are being tested with the goal of reaching a neutron flux of the order of 1% of the LNGS natural one just outside the shielding itself. Presently, the project is foreseen to start taking data in spring 2018.

5. Conclusions

The LUNA experiment has demonstrated the clear advantages offered by an underground location to a facility dedicated to measure cross sections of nuclear reactions relevant to astrophysics. The future of such a project is well outlined and will allow to obtain relevant data for the next 15 years. Similar projects are under development in the US [32] and in China.

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