Experimental challenges in low-energy nuclear astrophysics

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Abstract. Nuclear astrophysics is an interdisciplinary field at the border between nuclear physics and astrophysics. It aims at answering fundamental questions such as how and where are elements synthesised, how energy is generated in stars and how stars evolve and eventually die. Nuclear astrophysics experiments use Earth-bound facilities to investigate nuclear reactions and nuclear properties of interest in stellar scenarios. This review will focus in particular on thermonuclear reactions occurring in relatively low temperature scenarios \(T < 1 \text{ GK}\) such as quiescent burning stars and classical novae. Because of the hindering effect of the Coulomb repulsion between nuclei, nuclear cross sections in these scenarios can be extremely small \((10^{-12} \text{ barn and even lower})\) and the signals produced can be challenging to disentangle from the natural background on the Earth’s surface. Moving underground to reduce the background induced by cosmic rays is one possible solution to this problem. For more than 20 years, the LUNA experiment has studied nuclear reactions employing accelerators based deep underground in the Gran Sasso Laboratory in Italy. In this review, recent results obtained at LUNA, as well as future prospects at the new LUNA-MV accelerator, soon to be installed underground will be reviewed. Another possible approach is to employ indirect methods to probe nuclear properties of astrophysical interest. This review work will mention in particular the novel possibility of carrying out nuclear astrophysics experiments at the newly commissioned CRYRING storage ring in GSI, Germany.

1. Introduction
Thermonuclear reactions are responsible both for producing the energy required to keep stars shining and for the synthesis of elements needed for life. Understanding the birth, evolution and death of a star requires precise and accurate knowledge of a great variety of properties of the nuclear species involved in the complex nuclear reaction networks. This review will focus in particular on the nuclear reactions cross sections. Because of the hindering effect of the Coulomb repulsion between charged nuclei, cross sections at the temperatures of interest for low energy nuclear astrophysics \((T < 1 \text{ GK})\) can be extremely small, of the order of \(10^{-12} \text{ barn or even lower}\) as shown in Fig. 1.

Because the cross section \(\sigma(E)\) varies very rapidly in the energy region of interest, it is conventional to express instead the interaction probability using the S-factor \(S(E)\), which is implicitly defined from the cross section as

\[
\sigma(E) = \frac{1}{E}S(E)\exp^{-2\pi\eta}
\]
where $E$ is the energy (in keV) in the centre-of-mass, and $2\pi\eta = 31.27Z_1Z_2\sqrt{\mu/E}$ is the Sommerfeld parameter, $Z_{1,2}$ are the nuclear charges of the two nuclei involved in the reaction, $\mu$ is the reduced mass and $E$ is the centre-of-mass energy in MeV. The S-factor is useful to study the cross section dependency on nuclear effects, and on nuclear resonances in particular (see Fig. 1).

Figure 1. Differential cross section (top panel) and differential S-factor (bottom panel) for the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction. Note the differential cross section is as low as $10^{-5}$ $\mu$barn/sr at the lowest energy point measured. Adapted from reference [1]

Carrying out a direct measurement of a nuclear reaction cross section at energies of astrophysical interest in an Earth-based laboratory can be extremely challenging. As an example, let us consider a proton-induced charge-particle reaction with a cross section of $10^{-12}$ barn. Performing an experiment with a typical beam intensity of 1 $\mu$A and a target thickness of $10^{17}$ atoms/cm$^2$ would result in a yield $Y$ (counts/year)

$$Y = I_{\text{beam}} \times N_{\text{targets}} \times \sigma = 10^{13} \text{pps} \times 10^{17}\text{cm}^{-2} \times 10^{-36}\text{cm}^{-2} \simeq 20 \text{ counts/year} \quad (2)$$

if we consider a detection efficiency of nearly 100%, which could be typical for a charge-particle reaction. If one were to perform a gamma detection experiment instead, typical efficiencies could be around 1% resulting in as little as 0.3 counts/year. Such weak signals require lengthy experimental campaigns and are exceedingly difficult to disentangle from the natural radioactive background. One possible approach to this issue is to carry out the measurement in an underground laboratory, in order to suppress the cosmic component of the natural background. This is the approach taken by the LUNA (Laboratory for Underground Nuclear Astrophysics)
collaboration at the underground Laboratori Nazionali del Gran Sasso (LNGS), located in central Italy under the Gran Sasso massif. Another possibility is to employ indirect methods to study the nuclear properties of interest, and this review will focus in particular on the novel possibility of carrying out indirect measurements using the \((d, p)\) technique at the CRYRING storage ring, at GSI Laboratory, Germany.

2. Direct underground measurements at LUNA
For more than 20 years, the LUNA collaboration has carried out precise and accurate direct measurements of nuclear reactions underground at LNGS. LUNA started its activity in 1991 using a 50 kV electrostatic accelerator (LUNA-1) [2] which was subsequently replaced in 2002 by a 400 kV machine (LUNA-400kV) [3]. This latter machine is capable of accelerating hydrogen and helium nuclei with typical beam currents of at least 100 \(\mu A\), with an beam energy resolution of 0.3 keV and excellent beam stability over time [3]. Fig. 2 shows the location of the LUNA-400kV accelerator, still in use, as well as the former experimental site of the 50 kV machine, and the site for the new LUNA-MV machine (see later).

![Figure 2. A sketch of the underground Laboratori Nazionali del Gran Sasso showing the locations of the LUNA accelerators. See text for details.](image)

Systematic studies were carried out in order to quantitatively assess the background reduction afforded by 1400 meters of rock above the underground laboratory. In particular, Fig. 3 shows the natural background rate measured underground by a HPGe detector surrounded by a lead shield [4] superimposed on the background measured by the same detector above ground. The background suppression achieved is of several orders of magnitude at all gamma energies, greatly enhancing the potential sensitivity of underground gamma spectroscopy experiments.

More recently, similar background comparison tests were performed for silicon detectors used in an alpha spectroscopy experimental campaign [5]. Fig. 4 shows the natural background measured by an array of silicon detectors [6] underground in LNGS and overground in Edinburgh (UK). In both cases, the measurements were carried out with and without a partial lead shield surrounding the setup. Even though the silicon detectors employed in the experimental campaign were too thin (300-700 \(\mu m\)) for natural background gamma rays to deposit all of their energy, recoil Compton events were shown [6] to contribute significantly to the low-energy background in silicon detectors. At energies lower than 2 MeV, the background reduction afforded by the underground environment is especially significant (over one order of magnitude) and using a lead shield around the setup reduces the background even more. At higher energies, and around 5 MeV in particular, the intrinsic background from radioactive elements in the bulk of the
detector plays a significant role and the advantage of moving underground becomes less obvious. See ref. [6] for more details.

Several studies were carried out at LUNA exploiting the reduction in background afforded
by the underground environment. See ref. [7] for a review. In particular, the original LUNA-1 accelerator was used to carry out a study [8] of the \(^{3}\text{He}(^{3}\text{He},2p)^{4}\text{He}\) reaction which was pivotal to understand the (at the time unknown) neutrino oscillations behind the neutrino puzzle. LUNA was able to measure cross sections as low as \(20 \times 10^{-15}\) barn and exclude a nuclear solution to the problem [8]. Another highlight of the experimental results obtained at LUNA is the direct measurement of the \(^{14}\text{N}(p,\gamma)^{15}\text{O}\), the bottleneck reaction of the CNO cycle, at the LUNA-400kV machine [9]. Its revised rate had several significant consequences, in particular in the determination of the age of globular clusters [9].

More recently, the LUNA collaboration has undertaken a systematic campaign aimed at measuring the reactions of the CNO and NeNa cycle. See ref. [10] for a review of the ongoing campaigns and recent results. In particular, a direct measurement \(^{22}\text{Ne}(p,\gamma)^{23}\text{Na}\) reaction [11, 12] revealed several previously unobserved resonances and significantly reduced previous upper limits on unobserved ones, with important implications in a number of stellar sites [13]. Furthermore a recent direct re-measurement of the \(^{17}\text{O}(p,\alpha)^{14}\text{N}\) reaction revealed an enhancement of a factor of two for the strength of a resonance at \(E_{\text{CM}} = 65\, \text{keV}\), that dominates the reaction rates at temperatures of astrophysical interest [5]. This measurement had significant implications in a number of astrophysical scenarios [14], and on the identification of stellar grains in particular [15].

A third phase of the LUNA experiment has been approved by the Italian Istituto Nazionale di Fisica Nucleare (INFN) and has already begun construction. A new 3.5MV single-ended accelerator will be installed underground the hall B of LNGS (see Fig. 2). The design goals are high beam intensity and beam stability for proton and helium beams. Among the first reactions to be considered for investigation are the neutron sources \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) and \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\).

### 3. Direct and indirect measurements at CRYRING

Direct measurements in direct kinematics, as described in the previous section, are often unsuitable for the investigation of the rates of reactions occurring between short-lived nuclei \((t_{1/2} \ll \text{hours})\), often of great interest for nuclear astrophysics. Measurements in inverse kinematics using in-flight methods of beam production can offer an alternative, but the beam quality is poor and the energies are typically not optimal. A novel approach of using heavy ion beams, decelerated and cooled in-flight in storage rings, was recently pioneered at GSI, Germany [16]. This approach opens up the potential use of high quality beams of previously inaccessible elements/radioactive isotopes [17]. Isotopically pure beams can be used to bombard thin, pure targets (avoiding reactions on contaminants such as carbon [18]), a particularly important feature in studying astrophysical reactions, while maintaining good luminosity due to the re-circulating beam. The pioneering measurement in ref. [16] was carried out at the ESR storage ring in GSI, which is unsuitable for ions circulating at energies significantly lower than 10 MeV/u, typically of interest for nuclear astrophysics. However, the newly installed CRYRING storage ring, currently being commissioned at GSI, would allow ions to circulate even at energies of the order of a few hundred keV/u opening up the possibility of carrying out direct measurements in inverse kinematics using heavy-ion beams in a storage ring.

This section will describe a modular reaction chamber system consisting of two symmetrical interaction chambers for use in nuclear and atomic physics experiments. The two chambers can be mounted either upstream, or downstream, or both upstream and downstream, of a cryogenic jet target. Fig. 5 shows a single chamber mounted upstream. An array of highly segmented Double-sided Silicon Strip Detectors (DSSDs) will be housed in two interaction sub-chambers (Fig. 6) to maximise the angular coverage at very forward (or very backward) angles in the laboratory. The chamber mounted downstream can be used for direct measurements (\(e.g.\) p,\(\alpha\)) where reaction products are emitted at forward laboratory angles. The upstream chamber will be used instead for transfer reaction measurements, such as (d,p). In this case, reaction products
Figure 5. A drawing of the nuclear reaction chamber system that will be installed at the CRYRING. Only one chamber is shown, the other chamber could be mounted on the other side of the gas jet target. Note the interaction chambers housing the Double-Sided Silicon Strip Detectors, and the HPGe X-ray detectors mounted around the cryogenic jet target.

Figure 6. A drawing of the detector chamber furthest from the jet target. Detectors are placed at approximately ±5 mm from the beam axis to detect recoils or ejecta emitted at very forward/backwards laboratory angles. The beam passes in the central hole between the detectors, which can be moved outwards to increase the beam clearance.

are emitted at forward angles in the centre-of-mass frame, corresponding to backward angles in the laboratory frame. The (d,p) transfer technique is particularly useful in measuring the
energies, the spectroscopic factors $C^2S$ [18], and the spin-parities of low angular momentum transfer states (i.e. $l=0,1$) which usually play a key role in astrophysical scenarios. In particular, a first proposal to measure the $^{30}$P(d,p)$^{31}$P reaction using this chamber was submitted, and accepted, at the 2017 GSI G-PAC. This indirect study aims at investigating $^{31}$P, the mirror partner of the compound nucleus produced by $^{30}$P(p,γ)$^{31}$S reaction. The $^{30}$P(p,γ)$^{31}$S reaction plays a key role in the synthesis of all elements heavier than Ca in classical novae (ref. [19] and Fig. 7) and is critical to understand $^{30}$Si/$^{28}$Si isotopic ratios observed in pre-solar grains thought to originate from ONe novae [20]. Pre-solar grains are tiny fragments of material, ejected from novae pre-dating the formation of the Solar system, and brought to Earth by meteorites. An improved knowledge of the rate of the $^{30}$P(p,γ)$^{31}$S reaction could allow us to unambiguously identify the type of nova from which a given grain originates from, greatly enhancing the current experimental constraints on nova models.

![Figure 7](image.jpg)

**Figure 7.** Uncertainties in a nova model prediction of the isotopic abundance composition of novae ejecta arising from uncertainties in the $^{30}$P(p,γ)$^{31}$S reaction rate. Adapted from ref. [19].

4. Conclusions

Low-energy nuclear astrophysics aims at measuring the cross section of nuclear reactions taking place in a variety of low-temperatures scenarios, such as quiescent burning and classical novae. These cross sections measurements are extremely challenging measurements because of the hindering effect of the Coulomb barrier. One possible approach is to carry out the measurements underground, in order to suppress the natural background and enhance the signal to noise ratio. The LUNA collaboration has followed this approach to produce high-precision measurements for the last 20 years. The LUNA-MV machine, soon to be installed underground at the Laboratori Nazionali del Gran Sasso, will open up new and exciting prospects for underground nuclear physics. Another possible approach is to carry out the measurements inside a storage ring, employing radioactive beams produced via in-flight techniques. These beams can be used for both direct and indirect measurements. This novel technique will be employed for a variety of nuclear astrophysical studies at the CRYRING storage ring in GSI, Germany.
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