Low-energy studies for Nuclear Astrophysics (both above- and underground)

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Abstract. Experimental investigation of nuclear properties of interest in low-energy pose astrophysical scenarios such as quiescent burning stars and classical novae face interesting challenges. Cross-sections are often too low for measurement on the surface of the Earth, and short-lived radioactive elements play a key role in a number stellar scenarios. In this short review, I will mention two experimental approaches to this challenge, namely the possibility to carry out measurements underground at the LUNA accelerator (LNGS, Italy) and a novel approach that employs storage rings pioneered at GSI Laboratory (Germany).

1. Introduction
Stars are powered by thermonuclear reactions. In order to study the life cycle of stars as well as to understand the synthesis of new elements, an accurate and precise knowledge of a great number of nuclear properties is required. This short review will focus in particular on the nuclear properties of interest in low-energy stellar scenarios (T<1 GK), such as quiescent burning stars and classical novae. In these scenarios, nuclear reactions occur well below the Coulomb barrier, and cross-sections can be extremely small, of the order of 10^{-6}\sim12 bar, or even less. Measuring a nuclear reaction at these low energies in an Earth-based laboratory can be extremely challenging. Yields (counts/time) can be as low as few counts per year, and the signal from these events can easily be lost in the natural background on the surface of the Earth. Furthermore, in a number of stellar sites short-lived radioactive isotopes play a key role in the reaction network. Producing these isotopes in sufficient quantities and making them interact before they decay away can be extremely challenging.

There are several approaches to these experimental challenges. In this short review, I will focus in particular on measuring nuclear reaction underground at LUNA, and on the novel possibility to use storage rings for stable and radioactive beam measurements directly at energies of astrophysical interest at CRYRING.

2. Low-energy direct underground measurements at LUNA@LNGS
Laboratori Nazionali del Gran Sasso (Italy) is a unique deep underground laboratory located over 1400 meters below the Gran Sasso Massif. Here cosmic background is significantly reduced, allowing measurement of rare events in the cosmic silence. For over 20 years the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration has been measuring nuclear reactions exploiting this unique environment. At present, the collaboration utilises a 400 kV
Figure 1. (Top) The location of the LUNA-400kV machine underground at Laboratori Nazionali del Gran Sasso, as well as the former location of the old LUNA-50kV accelerator and the foreseen experimental hall for the new LUNA-MV accelerator. (Bottom) A photo of the LUNA-400 setup showing the LUNA-400KV accelerator as well as the two extant beamlines.

accelerator, the LUNA-400 (Fig. 1) to study nuclear reactions in the Big Bang and quiescent burning stages of stellar evolution [2]. The LUNA-400 machine [1] is capable of accelerating hydrogen and helium beams at typical beam currents of 100 \( \mu \text{A} \) with an energy resolution of 0.3 keV and excellent beam stability over time [1], a key requirement for the long (months, or even years) measurement campaigns.

Among recent highlights of scientific results obtained by LUNA is the successful completion of the experimental campaign aimed at measuring the \(^{17}\text{O}(p,\alpha)^{14}\text{N} \) reaction [3]. This reaction takes place during the Carbon-Nitrogen-Oxygen (CNO) cycle in quiescent burning in Asymptotic Giant Branch (AGB) stars, and is also active during nova explosion where it competes with the
The $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction, destroying $^{17}\text{O}$ and hindering the production of the gamma-ray emitter $^{18}\text{F}$ radioisotope [4]. This campaign at LUNA was the first ever underground spectroscopy study of low energy in-beam alpha particles, paving the way for future measurements using this technique [5]. Thanks to the background reduction afforded by the underground environment, a key resonance at $E_{cm}=65$ keV in the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction was found to be twice as strong as previously believed. Results [3] allowed for the first identification of solar dust (specifically, oxygen-rich Group II grains) coming from intermediate mass AGB stars, solving a long-standing puzzle [6], as well as having consequences in a host of other stellar sites [7].

A follow-up investigation of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction at LUNA using the same experimental setup was very recently completed as well [8]. The $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction also plays a role during the CNO cycle in AGB stars. Not only these results allowed us to place stronger constraints on the production site of oxygen-rich Group II grains, but we were also able to find a new potential production site for these grains that would reproduce observed isotopic abundances without the need to assume contamination of the grains by solar matter [6, 8].

Following up from the successful studies of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ (see above) and $^{17}\text{O}(p,\gamma)^{18}\text{F}$ [4] campaigns, the LUNA collaboration investigated the $^{18}\text{O}(p,\gamma)^{19}\text{F}$ reaction [9]. This reaction is at the branching point between two CNO sub-cycles during quiescent burning in AGB stars and controls, together with $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction, the production of a number of key isotopes including in particular $^{19}\text{F}$. This recent study excluded the possibility of a strong resonance at $E_{cm}=90$ keV in $^{18}\text{O}(p,\gamma)^{19}\text{F}$ which had previously been considered [10]. The improved precision of our new rate will contribute to pinpoint the stellar site in which the stable $^{19}\text{F}$ isotope is produced in our Galaxy [9].

Amongst other highlights at LUNA are the improvement of upper limits of the low-energy resonances of the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction in two complementary studies using a high-purity Germanium (HPGe) detector [11, 12, 13] and a Bismuth Germanate (BGO) scintillator array [14, 15]. These results had important consequences on the isotopes produced in AGB stars as well as excluding a potential solution of a standing puzzle in the isotopic abundances observed in Galactic globular clusters [16]. LUNA recently reported the first observation of a signal from the $E_{cm}=140$ keV resonance in $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ [17, 18] significantly improving our understanding of the production of Na and Mg isotopes in galaxies and stellar clusters, as well as the first measurement at BBN energies of the $^2\text{H}(\alpha,\gamma)^6\text{Li}$ reaction [19] that excluded one of the potential nuclear solutions to the controversial $^6\text{Li}$ puzzle.

A new 3.5 MV machine, the LUNA-MV [20], will be installed underground in Laboratori Nazionali del Gran Sasso in the near future. This new machine is capable of providing intense hydrogen, helium and carbon beams. Its initial scientific program includes key nuclear astrophysics reaction such as the $^{13}\text{C}(\alpha,\gamma)^{16}\text{O}$ and $^{12}\text{C}+^{12}\text{C}$ reactions.

### 3. Direct and indirect measurements at CRYRING@FAIR

Direct approaches like the one described in the previous section are not always suitable for the investigation of reactions involving short-lived nuclei ($t_{1/2} \ll \text{hours}$). Measurements in inverse kinematics using e.g. in-flight beam production techniques offer a way to study some reactions of nuclear astrophysics interest. However, the beam purity using in-flight production techniques is generally poor, and the beam intensity can be too low to measure. A novel approach developed at GSI Laboratory (Germany) offers an interesting alternative to this techniques. Injecting the radioactive beam in a storage ring [21] allows to purify the beam composition as well as to enhance the luminosity by recirculating the unreacted beam inside the ring. This technique opens up the possibility to use high-purity in-flight beams to carry out high-luminosity studies that cannot be performed in other facilities, provided beam lifetimes allow transport and storage ($t_{1/2} > \sim 1\text{ s}$). This technique was used for the first time at the Experimental Storage Ring (ESR) in GSI to measure the $^{124}\text{Xe}(p,\gamma)^{125}\text{Cs}$ reaction in the high-energy tail of the Gamow window [22].
A newly commissioned storage ring at GSI, CRYRING (part of FAIR Phase-0), offers new possibilities for nuclear astrophysics studies [23]. CRYRING uniquely allows storage of beams at energies from 100 keV/A to 10 MeV/A, which are typical energies of interest for low-energy (T<1 GK) nuclear astrophysics scenarios. The momentum spread of the recirculating beam is controlled by an electron cooler, allowing values of $\Delta p/p \sim 1$ part in $10^4$. In order to exploit this unique possibility, a chamber system called CARME (CRYRING Array for Reaction MEasurements) is being constructed and commissioned (Fig. 2). CARME will be installed at CRYRING for combined nuclear and atomic physics measurements. In order to store the ionised beam at such low energies, Extreme High Vacuum ($10^{-12}$ XHV) must be achieved inside the ring. This is a major technological challenge and requires careful selection of all materials placed under vacuum, including those of the detectors and mounting frames. CARME will be made up by two symmetrical chambers (Fig. 2 - grey and blue) linked together by an interaction chamber (Fig. 2 - green). An in-ring cryogenic microdroplet target will be mounted at the interaction chamber. Reactions products generated by the stored beam interacting with the in-ring target will be detected by an array of up to eight Double-sided Silicon Strip Detectors (DSSD) mounted either upstream, or downstream, or both of the jet target depending on the physics requirements of the reaction. These highly-segmented DSSD will have 128 x 128 strips.
and will allow us to achieve precise measurements of angular distributions. Furthermore, X-ray detectors will be placed in front of thin Beryllium windows located around the interaction chamber so as to detect atomic interactions between the stored beam and the target. Atomic physics cross-section often have significantly lower uncertainties compared with nuclear physics processes, and offer a novel and potentially very reliable way to normalise the cross-section. CARME is foreseen to be used for high-resolution direct and indirect measurements. The first approved study is one such high-resolution $^{30}$P(d,p)$^{31}$P indirect transfer study of the $^{31}$P compound nucleus produced during the $^{30}$P(p,γ)$^{31}$S reaction, using the same technique as e.g. ref. [26]. The $^{30}$P(p,γ)$^{31}$S reaction is one of the most important sources of uncertainty in nova explosions [24] and contributes very significantly to the present uncertainty on the isotopic abundances in nova ejecta [25]. A better knowledge of the expected isotopic abundances would improve present constraints on nova model simulations. $^{30}$P beams are quite challenging to obtain using traditional techniques, but can be obtained with good intensities ($\sim 10^6$ pps) using the in-flight technique, and later purified inside a storage ring. Furthermore, recycling the un-reacted beam will result in a factor $\sim 10^5$ increase in luminosity, allowing for unprecedented luminosity and an essentially background-free measurement.

CRYRING also has a local source that can inject stable beams inside the ring bypassing the main GSI accelerators. This source could be exploited for stable beam studies requiring high-precision measurements for which the intrinsically pure beams and in-ring target would be a good match. As an example, a proposal for a study the $^2$H(p,γ)$^3$He reaction at CRYRING in inverse kinematics is currently being prepared. This reaction is of key interest in Big Bang Nucleosynthesis [27], and high-precision studies are now needed. Other reactions, both with stable and radioactive beams are being considered for study as well.

4. Conclusions

Studies of nuclear properties of interest in low-energy nuclear astrophysics scenarios are of critical importance to improve our understanding of the life cycle of stars and of the synthesis of the elements. New facilities and techniques are being developed around the world in order to push forward the current boundaries of our knowledge. Interesting opportunities will open up in the near future with the installation of a new machine, the LUNA-MV, underground at LNGS (Italy) as well as with the start Phase 0 of the FAIR project (GSI, Germany), including the CRYRING storage ring.

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