Nuclear astrophysics at Gran Sasso Laboratory: the LUNA experiment

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Abstract

Nuclear processes are responsible for energy generation that makes stars shine, and for the synthesis of the elements in stars and also play a decisive role in explaining the chemical composition of the interstellar medium. Thermonuclear fusion reactions convert protons into heavier elements from He to Fe. Deep underground in the Gran Sasso Laboratory the key reactions of the proton-proton chain, the carbon-nitrogen-oxygen cycle and the neon sodium cycle have been studied down to the energies of astrophysical interest. The latest results are reviewed, together with future developments of underground nuclear astrophysics.

1 Introduction

Thermonuclear reactions most likely proceed at energies below the Coulomb barrier height. Therefore the cross-sections are extremely small and very difficult to be measured. In the laboratory, the rate of the reactions, characterized by a typical energy release of a few MeV, is very low and one should adopt all the possible techniques to achieve the point.

A possible solution to reach the low energies of interest for astrophysics is to install an accelerator facility in a laboratory deep underground reducing the natural and cosmic background. The Laboratory for Underground Nuclear Astrophysics (LUNA) is located at Gran Sasso National Laboratories, Italy, where the 1400 meters of rocks dominating the laboratory guarantee a reduction of six orders of magnitude in the cosmic muon flux and a reduction of three orders of magnitude in the neutron flux.

Several experimental campaigns have been accomplished in the past; in particular reactions of hydrogen burning [1] e.g. ^{22}Ne(p,γ)^{23}Na [2–5], ^{17}O(p,α)^{14}N [6] and ^{23}Na(p,γ)^{24}Mg [7] were deeply studied and outstanding results were achieved. Also few reactions of Big Bang Nucleosynthesis were measured as the ^{2}H(α,γ)^{6}Li [8] and ^{2}H(p,γ)^{3}He reactions. This paper focuses on ^{17}O(p,α)^{14}N and ^{2}H(p,γ)^{3}He cross section measurements and on the future program.

2 LUNA experimental setup

The first accelerator installed underground was a compact 50 kV machine (now dismissed) and, in a second phase, a commercial 400 kV accelerator. Both machines had/have high beam current, long term stability and precise control of the beam energy. The first feature maximizes the reaction rate, the second is demanded by the long time typically needed for a cross-section measurement, and the third is important because of the exponential energy dependence of the cross-section.

The 400 kV accelerator (LUNA400), presently in operation, is an electrostatic accelerator produced by High Voltage Engineering Europe. It is embedded in a 2 m^3 steel tank filled with a gas mixture of N_2 (75%) and CO_2 (25%) at a total pressure of 20 bar. The High Voltage is provided by an Inline-Cockcroft-Walton power supply; it is stabilized by a RC-filter at the HV power supply output and by an active feedback loop based on a chain of resistors. This is a key feature, as the cross sections to be measured depend exponentially on the beam energy. Using a proton beam, it has been shown that the long-term energy stability remains within 2 eV [9].

The beam is provided by a radio frequency ion source from the excitation of a gas that forms an ion plasma with charge e$+$ confined by an axial magnetic field. The source is mounted directly on the

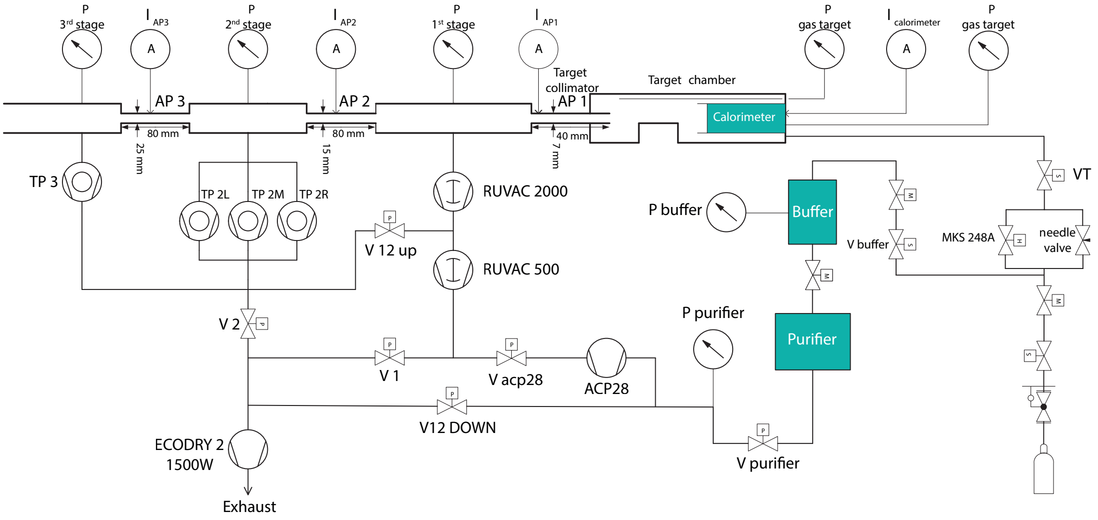

Fig. 1: Schematic lay-out of the LUNA windowless gas target setup.

accelerator tube and the ions are extracted by a voltage applied to an electrode inside the tube itself. The source is able to produce ion beams up to 1 mA intensity for hydrogen at 75% purity and up to 0.5 mA for helium. The machine has been calibrated in energy, through the non-resonant radiative capture reaction ^{12}C(p,γ)^{13}N [9]. The calibration has been checked several times by the well known resonances of (p,γ) captures on ^{23}Na, ^{25}Mg and ^{26}Mg. The uncertainty on the beam energy is equal to 100 eV statistical and 300 eV systematic. The energy spread of the accelerator is smaller than 0.1 keV, and the long term energy stability is better than 5 eV/h.

The ions can be sent into one of two beam lines, thereby allowing the installation of two different target setups, i.e. solid and gas target. In the first case, the proton beam is guided and focused to the target station using an highly stable analysing magnet and a copper pipe extending to 2 mm from the target. The pipe is cooled to liquid nitrogen temperature and serves as a cold trap to prevent carbon buildup.

Instead, in case of the windowless gas target the setup is more complex and includes, besides the several magnets, vacuum pumps, necessary to maintain a pressure of 10^{-7} mbar inside the accelerating tube (Fig. 1). Before reaching the gas target, the beam passes through: a Faraday cup, used to monitor the proton beam current, a safety gate valve which automatically closes when the pressure, on the gas target side, exceeds 10^{-4} mbar and three water-cooled apertures (Fig. 1) with decreasing diameter and hence increasing impedance which collimate the beam into the target chamber. Typical pressures in the second and third pumping stages are in the 10^{-6} - 10^{-7} mbar range, with the gas pressure maintained at 1 mbar in the target chamber. When isotopically enriched or rare gases are used, the exhaust from the Roots pumps cannot be discarded but must instead be recycled. The gas coming out from the first and the second stages can be compressed by a dry forepump, sent to a purifier which removes oxygen and nitrogen contaminations and finally stocked in a buffer.

3 The ^{17}O(p,α)^{14}N reaction

The $^{17}\mathrm{O}(p,\alpha)^{14}$N reaction ($Q_{val}$=1.2 MeV) plays a key role in several astrophysical scenarios, in particular in AGB stars [10–12]. Models predict that massive AGB stars should produce significant amounts of cosmic dust, and yet no pre-solar grain appears to match the HBB signature expected from these stars [13]. The most obvious candidates, Group II grains, have ^{17}O/^{16}O ratios that are a factor of two lower than expected. For this reason is crucial the measurement of the $^{17}\mathrm{O}(p,\alpha)^{14}$N cross section.

At energies of astrophysical interest its reaction rate is dominated [15] by a narrow and isolated resonance at E_p=70 keV. This resonance has been studied several times in the past, using both direct and indirect methods, as summarised in ref. [16]. However, the picture painted in the literature is still not completely satisfying. The uncertainty in the resonance strength is not negligible (≈20%). Furthermore, published strength values obtained with direct measurements have all been retracted or reanalysed [16]. An experimental campaign aimed at measuring the E_p=70 keV resonance in $^{17}O(p,\alpha)^{14}N$ was recently completed at the underground LUNA accelerator by a thick-target setup. Solid Ta_2 O_5 targets, 95% enriched in ^{17}O and roughly 5 keV thick for 200 keV protons, were used [17]. Protons were accelerated at a typical beam intensity of 100 μA and alpha particles produced by the reaction at E_{alpha}= 1 MeV were detected with an array of eight silicon detectors mounted in an hemi-spherical configuration. A small lead shielding was mounted around the setup to further suppress the natural background. Aluminised mylar foils, nominally 2.4 μm thick, were mounted in front of each detector to shield the intense flux of elastically scattered protons [18]. As a result, the energy of the alpha particle at the silicon detector was around 250 keV, making the measurement extremely challenging. Nevertheless, the signal at the E_p=70 keV resonance was detected at a five sigma confidence level and tuned out to be about 3 times higher than the previous literature value [19]. This achievement has strong consequences in a number of astrophysical scenarios [14] and gives ligth to the long-standing issue in the identification of the over mentioned pre-solar grains [13] produced in massive AGB stars.

4 The $^2H(p,\gamma)^3He$ reaction

Nuclear physics plays a role in the very early life of the Universe: between 3 and 20 minutes after the Big Bang, a few light isotopes of H, He, Li and Be are formed through a net of reactions. This is known as Big Bang Nucleosynthesis and its importance is not just limited to the formation of the primordial material giving origin, about 10^9 y later, to the first pro-stars. Actually, the rate of the BBN reactions and the final abundances of the involved isotopes are strictly related to fundamental quantities like the barion density of the Universe. The barion to photon density is the sole free parameter to describe, according the Lambda Cold Dark Matter model (ΛCDM [21]), the Universe evolution. From the Cosmic Microwave background measured by the PLANK satellite [20] and the cross section of the BBN reactions, the abundances of the primordial isotopes can be calculated and compared with astronomical observations. This open the possibility to infer, from the accurate determination of the nuclear cross section, information widely beyond the limit of nuclear astrophysics. Among the relevant process for BBN nucleosynthesis there's the $^2H(p,\gamma)^3He$ currently under study at LUNA.

The primordial abundance of deuterium, $(D:H)_{obs}$, is presently known with good accuracy, $(D:H)_{obs}$= (2.527 ± 0.030) 10^{-5} [22], while the corresponding $(D:H)_{BBN}$ obtained from the BBN calculations, $(D:H)_{BBN}$ = (2.58 ± 0.04) 10^{-5} [23], is affected by the insufficient knowledge of S_{12} in the relevant energy interval. Only a single dataset of S_{12} is available in the relevant energy range [24] and, according to the Authors, it is affected by a systematic error of 9%. The situation is even worst when considering a 20% discrepancy of that data with the theoretical previsions [25]. For all these reasons an experimental effort to measure the cross section with 3-5% accuracy is needed.

The $^2H(p,\gamma)^3He$ experiment at LUNA consists of two main phases characterized by different setups. The former is a windowless gas target filled with deuterium surrounded by a 4π BGO detector [26]. The data taking as well as the analysis of this phase have been concluded and the results will be published as soon as also the second phase will be over. The set up of this latter phase consists of a 137% HPGe detector in close geometry with the interaction chamber. With this setup the angular distribution can be inferred by exploiting the high energy resolution of the detector and the Doppler effect responsible for the broad energy distribution of the detected gamma rays coming from different directions inside the extended gas target. The $^2H(p,\gamma)^3He$ photons have an energy of about 5.5 MeV, far away from the energy of the commonly used radioactive sources. Thus, for determining the setup efficiency a different technique based on the well-known resonant reactions $^{14}N(p,\gamma)^{15}O$ and on ^{60}Co radioactive decay has been used. In order to reduce the systematic error due to the summing correction, the set-up efficiency

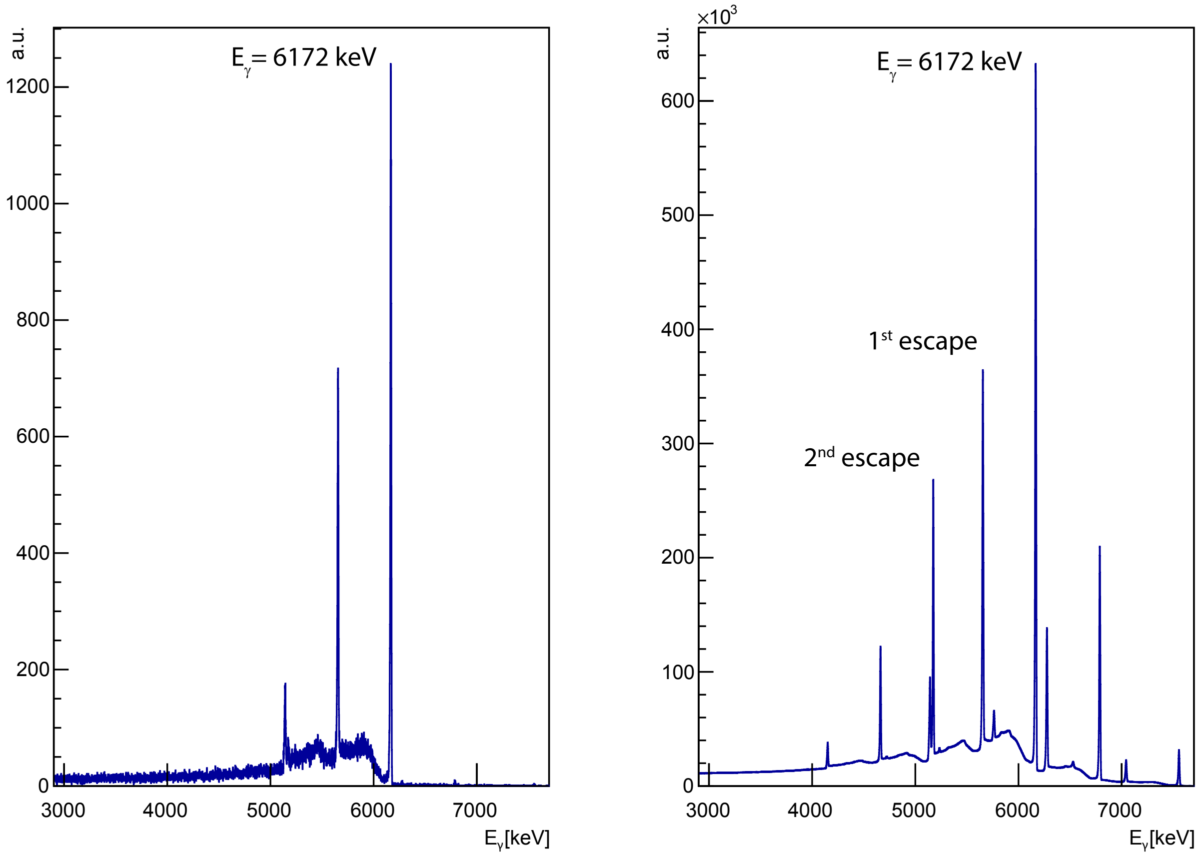

Fig. 2: $^{14}N(p,\gamma)^{15}O$ resonance spectra: left the one acquired in coincidence configuration, right the one acquired in inclusive configuration.

has been measured exploiting the coincidence between two γ-rays emitted in cascade (from source as well as from reaction) and detected by two different germanium detectors, the main detector (Ge1) and a second one used as the acquisition trigger (Ge2). Whenever Ge2 detects an event 1, it enables Ge1 that can thus detect photon 2 emitted in cascade: the ratio of the observed photons with respect to the number of triggers provides the Ge1 efficiency. In case of ^{60}Co, for each radioactive decay process, two photons, 1 = 1.17 MeV and 2 = 1.33 MeV, are produced. In the case of the resonant capture, several decay branches are able to provide two photons in cascade of energies up to 6.7 MeV, even higher than the $^2H(p,\gamma)^3He$ reaction. This method allows fixing precisely the detector energy response (fig. 2).
To measure the cross section an energy scan in the energy range of interest (30 keV $<$ E_{cm} $<$ 300keV) with 30-50 keV steps was done; two runs were performed for each energy: one with deuterium gas inside the scattering chamber, the other with ^4He in order to evaluate the beam induced background contribution and the eventual deuterium implantation. The data taking has been completed, the analysis is ongoing.

5 The future of LUNA: LUNA MV

While the most relevant nuclear processes involved in the H-burning phase are now known with a quite satisfactory level of accuracy (missing tiles and/or refinements in the above discussed mosaic will be likely fixed at the existing facilities in the next fore coming years), the picture for the successive evolutionary phases is still far to be completed. When the hydrogen in the star core has been spent, the gravitational contraction starts again and the temperature in the core reaches values high enough to allow fusion reactions between the hydrogen ashes, i.e. the He nuclei. In such conditions, the 3-alpha process is the mechanism to fill the mass gap between Helium and Carbon. This way the stellar core gets populated in He and ^{12}C which, in the following phases, are involved in key reactions as the ^{12}C(α,γ)^{16}O and the ^{12}C+^{12}C. The first process competes with the 3-alpha during the He-burning step while the fusion of two ^{12}C nuclei is possible only in stars with a mass great enough to produce core temperatures greater than hundreds of million Kelvin (typically more than 7 Solar masses). The astrophysical energies for such processes range, according to the peculiar stellar environment, from hundreds to a few thousands of keV and their study at an accelerator facility needs intense ion beams in the MeV range.

The LUNA MV project has conceived to approach these particular sub-frames of the stellar evolution mosaic: it is based on a new 3.5 MV single-ended accelerator to be installed under the Gran Sasso mountain. The accelerator will be devoted to the study of those key reactions of helium and carbon burning that determine and shape both the evolution of massive stars towards their final fate and the nucleosynthesis of most of the elements in the Universe. In particular, the ^{12}C(α,γ)^{16}O and ^{12}C+^{12}C reactions are the most ambitious goals of the project [27,28]. The first reaction competes with the triple-alpha during the He burning. Both release a comparable amount of energy (about 7 MeV), but the He consumption of the ^{12}C+alpha is only 1/3 of that of the 3-alpha. Therefore, a change of the ^{12}C+alpha reaction directly affects the He burning lifetime. Furthermore, it determines the C:O ratio left at the end of the He burning. This is a fundamental quantity affecting, for instance, white dwarf cooling timescale and the outcomes of both type Ia and core-collapse supernovae. The ^{12}C+^{12}C reaction is the trigger of C burning. The temperature at which C burning takes place depends on its rate: the larger the rate, the lower the C-burning temperature. Since the temperature controls the nucleosynthesis processes, reliable estimations of all the yields produced by C burning, for example the weak component of the s process which produce the elements between Fe and Sr, require the precise knowledge of the ^{12}C+^{12}C rate. The ^{12}C+^{12}C rate also determines the lower stellar mass limit for C ignition. This limit separates the progenitors of white dwarfs, nova and type Ia supernovae, from those of core-collapse supernovae, neutron stars, and stellar mass black holes.

In an underground environment, there is a clear advantage for experiments looking at neutron emission too. For instance, the neutron flux at LNGS is about 3 orders of magnitude lower than at a surface laboratory, just because of the reduced flux of neutrons from cosmic-ray muons. Background neutrons in LNGS and in other underground laboratories are therefore originated from (α,n) reactions on light elements (A $\pm$ 12–28). The alpha particles are emitted by radioactive decays in the rock, mainly those belonging to the ^{238}U family. As a consequence, the list of the outstanding reactions which can be addressed with MV accelerator includes the “neutron sources” as pointed out for the first time in the famous BBFH article in 1957 [29]. Neutron-captures (slow or rapid, i.e., the s or r process, respectively) were early recognized as the most important mechanism to produce the elements heavier than iron. Several reactions can produce neutrons, among them ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg represent the most favored candidates [27,28]. This is because they operate from relatively low temperatures typical of He burning (100 - 300 MK) and because ^{13}C and ^{22}Ne are relatively abundant nuclei in stellar interiors. The ^{13}C(α,n)^{16}O reaction, with a Q-value of about 2.22 MeV, operates in the He-burning shell of low-mass (less than 4 solar masses) AGB stars and it is the neutron source reaction that allows the creation of the bulk of the s-process elements such as Sr, Zr and the light rare earth elements. The Gamow peak in AGB stars lies around 190 keV while low energy data with a suitable accuracy are available in literature down to about 300 keV [30]. In view of new experimental studies, the presence of a broad resonance at E_{cm} $\approx$ 800 keV definitively makes necessary an α beam up to 1 MeV to reconstruct a full excitation curve. However, an exploratory experiment with a nominal sensitivity of a few event per day, which should be enough to touch the upper edge of the Gamow window, is planned at the LUNA400 facility and the data taking should be completed within the year 2018. The ^{22}Ne(α,n)^{25}Mg reaction, with a negative Q-value and a reaction threshold at E_α = 560 keV, operates in the He-burning shell of high-mass (more than 4

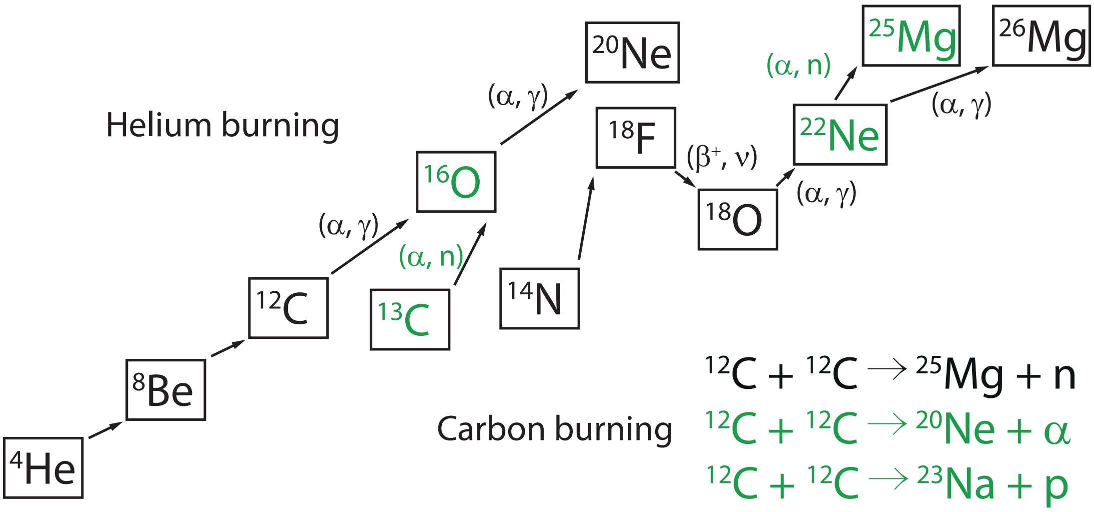

Fig. 3: The network of reactions of the helium and carbon burning phases. In green the processes which are part of the LUNA scientific program.

solar masses) AGB stars and during the core-He burning and the shell-C burning of massive stars (more than 10 solar masses). Last experimental studies date back to the year 2001 [31] and produced cross section values down to a minimum energy of 825 keV and upper limits at the lower energies. The last evaluation of the reaction rate is due to Longland and coworkers [32] who re-analyzed all the available data adopting however several assumptions and new, accurate experiments pushing the limit of direct measurements at the lowest energies, are definitively necessary.

The LUNA-MV facility will be installed at the beginning of the year 2019 in the north side of Hall B, one of the three big experimental areas of the underground Gran Sasso laboratory and will consist of an accelerator room with concrete walls and a further building hosting the control room and technical facilities including the cooling system, the electric power center, the monitors to guarantee the respect of the radiation levels. The concrete walls and ceiling (thickness of 80 cm) of the accelerator room will serve as neutron shielding. Considering the worst case scenario for the operation of the LUNA-MV facility of a maximum neutron production rate of $R_n = 2\ 10^3\ s^{-1}$ with an energy $E_n = 5.6$ MeV, the simulations determined a mean value for the neutron flux outside the accelerator room, Φ_n, of about $\Phi_n^{max} \sim 1.4\ 10^{-7}\ cm^{-2}\ s^{-1}$. The Φ_n^{max} values is about a factor 5 lower than $\Phi_{n-LNGS} = 3\ 10^{-6}\ cm^{-2}\ s^{-1}$, the reference neutron background at LNGS [33] (sum of the thermal, epi-thermal and fast components).

The LUNA-MV accelerator [28] is an Inline Cockcroft Walton accelerator currently under construction at High Voltage Engineering Europe (HVEE). The machine will cover a Terminal Voltage (TV) range from 0.2 to 3.5 MV and will deliver ion beams of H^+, $^4He^+$, $^{12}C^+$ and $^{12}C^{++}$ in the energy range from 0.35 to 7 MeV. A key feature to perform experiments on reactions important in astrophysics scenarios is the intensity of the beam delivered to the target. Such intensity will be particularly high with LUNA-MV. Following the deployment at LNGS, a six months installation and commissioning phase will start and first data taking for physics experiments are envisaged to start at LUNA-MV during the year 2020. A summary of the reactions which will be measured in the first five years of data taking is reported in fig. 3.

Since the year 2017, LUNA is no more the sole underground facility for nuclear astrophysics studies. New underground facilities are now in operation in USA-SD (CASPAR: Compact Accelerator System for Performing Astrophysical Research, at Homestake mine; accelerated species p and He; maximum beam energy = 1 MeV) and in China (JUNA: Jinping Underground Nuclear Astrophysics laboratory; accelerated species p and He; maximum beam energy = 0.4 MeV, beam intensity around

10 mA). The possibility to install a MV accelerator in presently considered at the Canfranc underground laboratory too. As for the past LUNA activity, the underground deployment of the next experiments will be not enough to guarantee significant steps forward. The development of new solid and/or gas target set-ups which have to be resilient to alpha and carbon beams with delivered power of a few kW, and of high-efficiency detectors with large angular coverage and high granularity, will be fundamental as well.

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