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1 Introduction

Stellar evolution and related nucleosynthesis play a fundamental role in the understanding of the origin of the chemical elements and in many related astrophysical problems such as the determination of the cosmic distance scale through primary and secondary distance indicators (like Cepheids, and thermonuclear type Ia supernovae), formation and evolution of galaxies and stellar clusters, the supernova engine mechanisms, and the Big Bang. In addition, stellar evolution is a powerful tool to investigate fundamental physics, such as the existence of particles beyond those included in the standard model, axions or some particles belonging to hidden sectors (e.g. hidden photons). The main goal of nuclear astrophysics is to provide a firm base for all these studies.

Thousands of nuclear interactions, either strong or weak processes, are of astrophysical interest. For most of them, the knowledge of their cross sections (or reaction rates) at relatively low energy is required to understand the synthesis of the elements. In a few cases, these interactions even have a direct influence on the physical parameters characterising stellar interiors, such as temperature and density, and, in turn, determine the stellar lifetimes.

Underground nuclear astrophysics was born twenty five years ago in the core of Gran Sasso, with the aim of measuring cross sections in the low energy range and derive reaction rates directly at stellar temperatures. LUNA (Laboratory for Underground Nuclear Astrophysics) started its activity as a pilot project with a 50 kV accelerator [1] and still remains the only laboratory in the world running an accelerator deep underground, currently a 400 kV accelerator with hydrogen and helium beams [2]. The extremely low laboratory background has allowed for the first time nuclear physics experiments with very small count rates, down to a couple of events per month. Only in this way, the important reactions responsible for the hydrogen burning in the Sun could be studied down to the relevant stellar energies [3][4]. Such decisive achievements have motivated the proposals for two similar facilities currently under construction in the Republic of China and in the United States.

Notable highlights at LUNA include the following: the exclusion of the 'ghost' resonance in the cross section of ${}^{3}\text{He}({}^{3}\text{He},2p){}^{4}\text{He}$ within the solar Gamow peak and the precise measurement of ${}^{3}\text{He}({}^{4}\text{He},\gamma){}^{7}\text{Be}$ have firmly established the correctness of the nuclear ingredients of the proton-proton chain in the standard solar model. Equally important, the direct measurement of the bottle-neck reaction of the CNO cycle, ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$, at very low energy provided a cross section lower by about a factor of two then existing extrapolations, decreasing by the same amount the flux of CNO neutrinos from the Sun and increasing by about one billion years the limit on the age of the Universe. Furthermore, the LUNA results have paved the way to the study of the metallicity of the core of the Sun through the forthcoming measurement of the CNO solar neutrinos.

Several years ago, at the end of the solar phase, a rich program started devoted to the study of Big Bang Nucleosynthesis and of the nucleosynthesis of the elements through the CNO, Ne-Na and Mg-Al cycles. The motivation here is to reproduce the abundance of the light elements and to identify the production site in stellar scenarios different from the Sun: hydrogen burning at the higher energies corresponding to the hydrogen shell of Asymptotic Giant Branch (AGB) stars or to the explosive phase of classical Novae.

The 400 kV current LUNA accelerator and the unique low-background conditions of the underground LNGS laboratory have been and still are the perfect blend for the study of most of the proton-capture reactions involved in the stellar H burning. On the other hand, a beam of higher energy is required to extend these studies to reactions be-

tween heavier isotopes, as those operating during more advanced phases of stellar evolution, namely the He and the C burnings. The LUNA MV project has been developed to overcome such a limit with the new 3.5 single-ended accelerator to be installed in Gran Sasso at the beginning of 2018. The accelerator will provide hydrogen, helium and carbon (also doubly ionized) high current beams and it 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 ¹²C(α,γ)¹⁶O and ¹²C+¹²C reactions represent the "Holy Grail" of nuclear astrophysics and they are the most ambitious goals of this project. The first of these two reactions 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 ¹²C+alpha is only 1/3 of that of the 3-alpha. Therefore, a change of the ¹²C+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.

 ${}^{12}C+{}^{12}C$ 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. This mass limit also controls the estimations of the expected numbers of these objects in a given stellar population, which are required to answer crucial questions such as: how many neutrons stars are there in the Milky Way? How many double neutron stars are there in closebinaries? And what is the expected merging rate?

Among the key processes for stellar nucleosynthesis, the sources of neutrons represent a longstanding and debated open problem [5][6]. 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. The identification of the astrophysical sites where these processes may operate requires the accurate knowledge of the efficiency of the possible neutron sources. Various reactions have been identified as promising neutron sources. Among them ${}^{13}C(\alpha,n){}^{16}O$ and ${}^{22}Ne(\alpha,n){}^{25}Mg$ represent the most favored candidates. This is because they operate from relatively low temperatures typical of He burning (100-300MK) and because ¹³C and ²²Ne are relatively abundant nuclei in stellar interiors. The ${}^{13}C(\alpha,n){}^{16}O$ reaction 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 in the Universe. The ${}^{22}Ne(\alpha,n){}^{25}Mg$ reaction operates in the He-burning shell of highmass (more than 4 solar masses) AGB stars and during the core-He burning and the shell-C burning of massive stars (more than 10 solar masses). Underground experiments with LUNA MV will allow us to gain a full understanding of these two reactions through the direct measurement of their cross sections in the energy range of astrophysical interest.

The scientific program we are presenting in this proposal is related only to the first 5 years of activity with the new accelerator, i.e. 2018-2022. In such amount of time it will not be possible to study all the processes we have highlighted above, in addition to other ones worth being studied underground such as (α, γ) reactions on ²H, ¹⁴N, ¹⁵N, ¹⁷O and

¹⁸O. In particular, we decided to start by measuring over a much wider energy region the cross section of a reaction we already studied with the 400 kV accelerator: ${}^{14}N(p,\gamma){}^{15}O$. This way we will perform the tuning of LUNA MV and we will more precisely extrapolate the reaction cross section within the Gamow peak of the Sun, i.e. the burning energy region.

Then, we will focus the activity of one of the two beam lines on the study of ${}^{12}C+{}^{12}C$: the understanding of its cross section at low energy will be the main goal of the first 5 years of LUNA MV. Alternating in time with ${}^{12}C+{}^{12}C$, the study of ${}^{13}C(\alpha,n){}^{16}O$ will be performed on the other beam line (the accelerator can feed only one line at a time). Finally, ${}^{22}Ne(\alpha,n){}^{25}Mg$ will be the last reaction covered by this scientific plan. On the other hand, ${}^{12}C(\alpha,\gamma){}^{16}O$ will be the main goal of the second scientific plan at LUNA MV, starting in the year 2023.

In the following, we describe the LUNA MV underground facility in the north side of Hall B of LNGS, the qualifying features of the new 3.5 MV accelerator and the first scientific plan.

2 The underground laboratory and the 3.5 MV accelerator

The LUNA-MV facility will be installed at the north side of Hall B and will consist of an accelerator room with concrete walls and a multistorly steel building hosting the control room and technical facilities including the cooling system, the electric power center, etc (Figure 1). The concrete walls and ceiling (thickness of 80 cm) of the accelerator room serve as neutron shielding. The dimensions have been identified by GEANT4 simulations and subsequently validated with independent calculations at the INFN central radioprotection service (LNF-ISMEL) using an MCNP code. Considering the worst case scenario for the operation of the LUNA-MV facility of maximum neutron production rate of $R_n = 2 \times 10^3 \text{ s}^{-1}$ with an energy $E_n = 5.6$ MeV, the MCNP simulations determine $f_{mean} = 1.38 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ as the neutron flux averaged over the entire external surface of the shielding. According to the same simulations $f_{max} = 5.70 \times 10^{-7} \text{ cm}^{-2} \text{s}^{-1}$, the maximum neutron flux outside the shielding, is reached at the point close to the target stations. This point is located at the north side of the accelerator room, far away from other experimental installations present in Hall B. These $f_{max}(f_{mean})$ are a factor 5 (20) lower than $f_{LNGS} = 3 \times 10^{-6} cm^{-2} s^{-1}$, the reference neutron background at LNGS. In addition, the energy distribution of the neutrons produced by LUNA MV just outside the shielding is very similar to that of the natural background at LNGS: about 20% have energy higher than 1 keV.



Figure 1: Location of the LUNA-MV installation with the 3.5 MV accelerator and the two beam lines.

The LUNA-MV accelerator 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⁺, ¹²C⁺ and ¹²C⁺⁺ in the energy range from 0.350 to 7 MeV into two different beam lines via a $\pm 35^{\circ}$ switching analyzing magnet having a mass energy product of 0.48 AMU×MeV

5 mm) located at the target position.				
1 u +	TV: 0.3 - 0.5 MV	$500 \mathrm{e}\mu\mathrm{A}$		
11	TV: 0.5 - 3.5 MV	$1000 \mathrm{e}\mu\mathrm{A}$		
4 U _+	TV: 0.3 - 0.5 MV	300 eµA		
IIC	TV: 0.5 - 3.5 MV	$500 \mathrm{e}\mu\mathrm{A}$		
$^{12}C^{+}$	TV: 0.3 - 0.5 MV	$100 \mathrm{e}\mu\mathrm{A}$		
C	TV: 0.5 - 3.5 MV	$150 \mathrm{e}\mu\mathrm{A}$		
$^{12}C^{2+}$	TV: 0.5 - 3.5 MV	$100 \mathrm{e}\mu\mathrm{A}$		
	Other ion beam parameters			
Beam current stability	over 1 h	5%		
Deam current stability	over 1 min	2%		
Beam energy stability ov	$1\times 10^{-5} \times$ TV or 20 V			
Beam energy reproducib	$1\times 10^{-4} \times$ TV or 50 V			
Operational details				
Ion species change-over duration< 30 min				
Intervention free operation >24 h				
Interruption time after maximum intervention free operation < 45 mi				
Servicing interval 700				
Annual operation capability 7400				

Expected ion beam currents transported through an aperture (length 40 mm, diameter 5 mm) located at the target position.

Table 1: Design specifications of the LUNA-MV accelerator.

(see Figure 1). The two independent targets will be located at 2 m distance from the analyzing magnet. Details of the characteristics of the machine can be found in Table 1.

The delivery of accelerator to LNGS is scheduled for the first months of 2018. In the previous period the machine will be setup and fully tested at the seller's site. The six months installation and commissioning phase at LNGS will start directly after installation and is under the responsibility of HVEE. Data taking for physics experiments is envisaged to start at the beginning 2019.

3 ${}^{14}N(p,\gamma){}^{15}O$

3.1 Abstract

During the last decades several experiments have been performed to pin down the reaction rate of ${}^{14}N(p,\gamma){}^{15}O$ at solar temperatures. Still, this reaction has an uncertainty of about 8% when extrapolated to the solar Gamow peak [7]. While the expected low rate at solar temperatures prohibits a direct experiment, a measurement over a wide energy region at LUNA MV can provide valuable data to reduce the error in the low energy extrapolation of the cross section of ${}^{14}N(p,\gamma){}^{15}O$. Also, this experiment can be the tool to verify the LUNA MV and surrounding solid target setup performance under realistic conditions.

3.2 Astrophysical motivations

The ¹⁴N(p, γ)¹⁵O controls the speed of the whole CNO cycle since it proceeds with the slowest rate. This reaction acts like a bottleneck that congests all other CNO isotopes in their flow through the cycle so that ¹⁴N eventually becomes the most abundant catalyst involved in the cycle. Importantly, the rate of energy generation of the CNO cycle is determined by the ¹⁴N(p, γ)¹⁵O reaction. It takes place during the hydrogen burning phases of stars: in the central core on the main sequence for stars with initial masses $M_i > 1.2 - 1.5 M_{\odot}$, at the termination of the main sequence in stars of lower masses, and later in shell during the red (super)giants stages.

A key aspect of the astrophysical relevance of this nuclear reaction was remarkably put by [8] when, following the LUNA measurements of the cross section, the rate was reduced by a factor $\simeq 0.6$ compared to the NACRE version at the relevant stellar energies (Nuclear Astrophysics Compilation of Reaction Rates). The effect on the age of globular clusters (GCs), hence on the lower limit to the age of the Universe, was significant: with the revised LUNA rate stellar evolutionaty models predicted a typical increase of 0.7-1.0 Gyr (with an uncertainity of $\simeq \pm 0.5$ Gyr) for the ages of GCs.

As discussed by Herwig and Austin [9], the ${}^{14}N(p,\gamma){}^{15}O$ rate affects also the strength of thermal pulses during the asymptotic giant branch evolution of low- and intermediatemass stars, hence influencing the efficiency of the third dredge-up. This latter process is believed to be a primary channel for the carbon enrichment in the cosmic matter cycle.

Further improving the accuracy in the cross section of the ${}^{14}N(p,\gamma){}^{15}O$ reaction with the upcoming LUNA MV experiment may also produce an important impact on the building assumptions of so-called standard solar model, in particular to constrain the CNO content in the Sun's core [10]. This is especially relevant in view of comparing the photospheric chemical composition of the Sun with the abundances in the interior: quantifying the differences is essential to investigate physical processes such as element diffusion – with consequent sink of the heavier elements towards the centre – [11], as well as the accretion of metals onto the surface [e.g., 12].

Though the CNO cycle is expected to provide a minor contribution (~ 1%) to the nuclear energy generation in the Sun (with the proton-proton chain being the dominant source), a substantial flux of neutrinos is released by the ${}^{13}N(\beta^+\nu){}^{13}C$ and ${}^{15}O(\beta^+\nu){}^{15}N$ decays in the most central regions where the CN cycle operates in nuclear equilibrium regime. For illustrative purposes, figure 2 shows a few structural properties of the solar model computed with the PARSEC stellar evolution code [11]. This latter may be employed to explore the theoretical impact of the LUNA MV data for the ${}^{14}N(p,\gamma){}^{15}O$ reaction.



Figure 2: Chemical profiles (left panel) and neutrino fluxes received at Earth (right panel) according to the predictions of the PARSEC solar model [11].

As a matter of fact, recent works have shown that, since the CN-cycle keeps an almost linear dependence on the C+N abundance in the core, the neutrino fluxes can be used as accurate tools to probe the total CN abundance. At present the error budget in the C+N estimation is totally dominated by the uncertainties ($\simeq 11\%$) in the cross section of the reactions $^7\text{Be}(p,\gamma)^8\text{B}$ and $^{14}\text{N}(p,\gamma)^{15}\text{O}$. [13]. Clearly, reducing the uncertainty of the latter reaction with LUNA MV will importantly contribute to set more stringent constraints on the central chemical composition of the Sun, provided a precise measure of the CNO neutrino flux is available.

3.3 State of the art

We recall here that, because of the tunnel effect through the Coulomb barrier, the reaction cross section $\sigma(E)$ drops almost exponentially with decreasing energy E:

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta) \tag{1}$$

where S(E) is the so-called astrophysical S-factor and $2 \pi \eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$. Z_1 and Z_2 are the electric charges of the nuclei, μ is the reduced mass (in a.m.u.), and E is the energy (in keV) in the center of mass system [14]. We point out that the astrophysical S-factor contains all the nuclear physics information. The relevant level scheme of ¹⁵O with the resonances in ¹⁴N(p, γ) can be seen in figure 3.

Adelberger et al. in the latest compilation [7] recommended the $S(0)=1.66\pm0.12$ keVb value for the solar temperature. While previous LUNA efforts [15] reached the lowest energy of 70 keV for the total cross section, this is still far above the burning energy in the Sun (between 20 and 35 keV). Therefore, R-matrix analysis is a must for



Figure 3: Energy levels of ¹⁵O. Taken from Adelberger et al. [7]

a reliable extrapolation and this requires nuclear physics ingredients obtained at higher energies. Below, we list the most important ingredients.

• Total cross section of ${}^{14}N(p,\gamma){}^{15}O$

This can be used to verify the consistency of the sum of the individual transitions, since the total cross section can be obtained typically with higher statistics. The standard in beam method uses a summing crystal with high efficiency [16]. The application of the so called activation method, i.e. counting the ¹⁵O nuclei through their decay, would require a dedicated set-up since the ¹⁵O half-life is rather short (about 2 minutes).

• Partial cross sections of ${}^{14}N(p,\gamma){}^{15}O$

This in-beam method uses high purity germanium detectors for detecting all the possible transitions leading to 15 O. While LUNA covered the low energy range [8, 17], at present only two data sets are available at higher energies [18, 19]. Another overground experiment (HZDR, Germany) is underway. It is obvious from the previous experiments that two transitions are very important: The transition to the 6.79 MeV state dominates the S(0), and the ground state transition becomes more important at very low energies according to R-matrix extrapolations (figure 4). Also, the experimental determination of the ground state transition can be affected by the so called summing problem, posing limitations on the detector geometry/volume [20].

• The lifetime of the ¹⁵O and ANC

The transition to the ground and 6.79MeV states are affected by the -0.506MeV subthreshold state that can be addressed by the Asymptotic Normalization Coefficient (ANC) and direct lifetime experiments of that state. Both approaches need high energy data, and especially the lifetime experiment demands a sophisticated



Figure 4: R-matrix based low energy extrapolation for the ${}^{14}N(p,\gamma){}^{15}O$. Taken from Wiescher et al. [24]

detection setup. Recent advances in gamma tracking detector technology (AGATA array) allowed a high precision experiment on the lifetime [21, 22].

• Elastic proton scattering ¹⁴N(p,p)

A recent experiment by the Notre Dame group in the US determined the angular distribution of elastically scattered protons up to 4.0MeV further constraining the R-matrix extrapolations [23]. According to the authors, while the scattering data lead to a more confident extrapolation of the ground state capture cross section other uncertainty contributions which are of equal or greater significance remain.

3.4 Improvements from the underground measurement

Since the Q value of the ¹⁴N(p,γ)¹⁵O reaction is relatively high (Q=7.297 MeV), especially for the ground state transition (probably the most important part to study) the suppression of the cosmic ray background at LNGS provides the ideal working conditions.

3.5 Experimental setup

Similar experiments at lower energies have been successfully performed at the LUNA 400kV at LNGS, and running now at higher energies in the US and Germany. The setups include various high purity Germanium detectors positioned at various angles. At LUNA MV the minimum requirement is to rebuild the setup of the previous LUNA experiments (solid state TiN targets combined with non-shielded high purity germanium detectors). However, a more granulated Germanium detector array would be an asset.

3.6 Possible background sources

In addition to laboratory background the intrinsic background coming from the gamma detectors should play a minor role. Again, experience with the same reaction at the LUNA 400kV energies can be used. At higher energies beam induced background can be expected: this requires a more detailed study taking into account the experience of the presently running overground experiments in the same energy region.

3.7 Expected beam time

The expected beamtime depends on the expected effect of the LUNA MV results on the S(0) value. This can be determined by a detailed R-matrix calculation taking into account the new values from the very recent [19] and still running overground experiments. In any case, a period of about four months of beamtime will be adeguate.

3.8 Risk analysis

The advantage of the ${}^{14}N(p,\gamma){}^{15}O$ experiment is the great experience gained with the previous studies of the reaction at the LUNA 400kV accelerator. In addition, the high expected yield guarantees relatively short experiments at each energy. Also, quite standard Germanium detectors can be used.

3.9 Conclusions

The ¹⁴N(p,γ)¹⁵O experiment can be regarded as a day zero experiment of LUNA MV. The gained experience of the LUNA team at previous ¹⁴N(p,γ)¹⁵O projects performed at the 400kV accelerator guarantees the feasibility of the solid TiN target production and purity. An experiment at energies overlapping with the previous data obtained at the LUNA 400kV accelerator would be able to connect the existing low energy data with the upcoming higher energy data. While the suggested experiment can be performed with a simple gamma detector setup, a more efficient granular detector array would certainly be an advantage. We point out that there is enough room to host an array of detectors.

Briefly, the expected result of the pilot experiment is twofold: verify the LUNA MV and surrounding solid target setup performance under realistic conditions and collect valuable data to reduce the error in the low energy extrapolation of the S-factor of ${}^{14}N(p,\gamma){}^{15}O$.

4 ${}^{12}C + {}^{12}C$

4.1 Abstract

The fusion reaction ${}^{12}C+{}^{12}C$ is critically important in nuclear astrophysics: it regulates the energy production and nucleosynthesis of the carbon burning phase and ultimately influences the global chemical evolution of the Universe. Previous cross section measurements of the proton and α channels of this process have been carried out, however, the existing data do not extend into the energy range relevant to astrophysical processes. Additionally, there is a great deal of uncertainty and disagreement in the existing data. In this section, after an overview of the astrophysical importance and of the state of the art for this reaction, the possibility of studying it with the LUNA MV accelerator in the very low background environment of the Gran Sasso Laboratory is described. An estimate of the beam time required is also given together with a brief analysis of the risks involved.

4.2 Astrophysical motivations

The ¹²C+¹²C reaction is the trigger of the carbon burning. The two main channels of this reaction release protons and α particles in a rather hot environment, thus allowing a complex chain of reactions to be activated involving a nuclear network extending from C to Si. Some of these reactions, e.g., the ¹³C(α ,n)¹⁶O and the ²²Ne(α ,n)²⁵Mg, may release neutrons and, in turn, activate neutron-capture nucleosynthesis in form of the a weak s-process, which is characterised by a slow neutron flux and a small neutron exposure, and produces the heavy elements from Cu to Sr. Only the more massive stars experience a hydrostatic C-burning phase. The threshold mass (M_{up}) is a fundamental parameter in astrophysics. After the He burning, the C-O core contracts and, because of the release of gravitational energy, heats up. In stars with M <M_{up}, however, as the density increases, the pressure of degenerate electrons coupled with an intense energy loss caused by the production of plasma neutrinos stops the heating of the core before the temperature becomes large enough for the activation of the ¹²C+¹²C (see Figure 5).

The final fate of stars whose mass is smaller than M_{up} is very different from that of the more massive objects. For stars with initial mass below M_{up} , the final fate is a C-O white dwarf (WD), a cool crystallized stellar structure representing the most common form of baryonic dark matter in the Universe. Mass accretion onto a WD in close binary systems may result in violent events, like cataclysm variables, novae or type Ia supernovae. The latter are triggered by C ignition in the degenerate core, when 1) the WD mass attains the Chandrasekhar limit or 2) two WD collide. Stars with mass above M_{up} are the progenitors of core-collapse supernovae, such as the type II and the less frequent types Ib, Ic. In most cases, the remnants of the evolution of stars with initial mass above M_{up} are neutron stars or black holes. If these compact remnants belong to close binaries, they may merge leading to extremely energetic explosions resulting in, e.g., gamma-ray bursts, and become promising emitters of detectable gravitational waves [25]. For all these reasons, the precise determination of M_{up} is a primary goal of modern astrophysics [26]. It critically depends on the value of the ${}^{12}C+{}^{12}C$ rate, at temperatures between 0.5 and 1 GK. Therefore, experimental investigations devoted to measure the low-energy cross section of this reaction are mandatory.

The ${}^{12}C+{}^{12}C$ is among the few nuclear reactions directly affecting the physical parameters that characterise stellar interiors: the larger the ${}^{12}C+{}^{12}C$ rate, the lower the temperature of C burning. As a consequence, the duration of C burning is modified by a variation of the ${}^{12}C+{}^{12}C$ rate with important effects on the advanced evolution of massive



Figure 5: C ignition curves with different ¹²C+¹²C as defined as the loci where the rate of nuclear energy production (¹²C+¹²C) is equal to the rate of plasma-neutrino energy loss (solid line). C burning occurs when the (T, ρ) in the stellar core cross this line. Different ¹²C+¹²C rate have been used: Caughlan and Fowler 1988 (CF88, black line) and CF88 plus the artificial contribution from a low energy (1.4 MeV) resonance. The dashed line show the evolutionary track of the maximum temperature layer in the core of a star with initial mass 7 M_{\odot} . For this particular model, the conditions for the C ignition are attained only if the artificial contribution to the ¹²C+¹²C rate is included.

stars and their nucleosynthesis. The current large uncertainty on the low-energy rate of the ${}^{12}C+{}^{12}C$ induces a large uncertainty in our knowledge of the final mass of the iron-core, on which depend both the total amount of electromagnetic and kinetic energy released by the explosion following the core collapse and the associated nucleosynthesis. Furthermore, the temperature obviously plays a fundamental role for nucleosynthesis during the C burning. For example, primary ¹³C can be produced by the ¹²C(p, γ)¹³N reaction followed by a β^+ decay. If enough ¹³C is produced, the ¹³C(α ,n)¹⁶O becomes an efficient source of neutrons for the s-process nucleosynthesis. However, with the existent rate of the ¹²C+¹²C, the C burning temperature is so high that most of the ¹³N photo-disintegrates, rather than decay into ¹³C. In this context, a faster ¹²C+¹²C would favour the s-process nucleosynthesis [27].

Finally, the ${}^{12}C+{}^{12}C$ rate also affects the outcomes of type Ia supernovae [28]. For instance, a variation of the rate would modify the extension of the convective core during the so-called "simmering" phase preceding the explosion and, in turn, the duration of this phase, the degree of neutronization, and the temperature at the beginning of the thermonuclear runaway. We recall that type Ia supernovae play a fundamental role in cosmology, allowing the measurements of distances and of the expansion rates of high redshift galaxies. These measurements revealed the acceleration of the cosmic expansion

4.3 State of the art

The ¹²C+¹²C reaction is characterized by a Coulomb barrier of about 6.7 MeV, and proceed through different channels corresponding to the emission of a photon, a neutron, a proton, an α particle or even two α particles or a ⁸Be nucleus. Of these channels, the two more relevant ones are the emission of protons and α particles. The neutron emission becomes effective only for energies (in the center of mass system, if not specified) larger than 2.6 MeV. The relevant energy range for the ¹²C+¹²C process depends on the astrophysical scenario: for quiescent C burning it is between 0.9 and 3.4 MeV while for type Ia supernovae energies as low as 0.7 MeV may become important. The Q-value for proton emission is 2.24 MeV while that for α emission is 4.62 MeV.

The proton and alpha channels can be measured either by detecting the charged particles or by revealing the gamma decay of the first excited state to the ground state of the ²³Na or ²⁰Ne residual nuclei, respectively. The energy of the two photons are 440 keV for the proton channel and 1634 keV for the alpha channel. Obviously, the latter technique cannot take into account α_0 and p_0 with the full energy, which leave the residual nucleus in the ground state, as well as the contributions from high energy states of the residual nuclei which de-excite directly to the ground state. Approximately, the decay of the first excited state to the ground state accounts for 50% of the total cross section. So far, many different experiments attempted to measure the ¹²C+¹²C reaction using one of the two above described techniques or both. The first experiment dates back to 1960 [31] while the most recent ones are that of Spillane et al. [32] and that presently ongoing at the CIRCE accelerator in Caserta, Italy [33]. A summary of the results in terms of the modified astrophysical S factor (which includes the first order correction to the penetrability since the charge of the two interacting nuclei are rather high) as a function of the energy is presented in Figure 6.

The lowest energy measured is 2.1 MeV [32]. The general structure is characterized by the presence of several resonances superimposed onto a flat background. The resonances have a typical width of 10 keV and are spaced by 300-500 keV. The lowest energy resonance observed (E = 2.14 MeV [32]) has a quite clear signature in the alpha channel but is unresolved in the proton channel due to the large uncertainties of the data at these energies. It is characterized by a relative large strength and its impact on the reaction rate is very relevant. A deeper investigation of the reaction with the main aims of re-measuring the 2.1 MeV resonance and looking for the eventual presence of other lower energy resonances is necessary.

4.4 Improvements from the underground measurement

The gamma-ray measurements of Spillane et al. [32] were limited only by the natural background since the issues related to the H contamination of the targets were solved. Their HPGe detector was surrounded by a 15 cm thick lead shield allowing a reduction of the natural background by a factor of 400 near E_{γ} = 1.6 MeV. As a matter of fact, in a laboratory on the Earth's surface, the shielding efficiency cannot be increased by adding more shield since the cosmic muons interact with the added material, creating more back-



Figure 6: Modified astrophysical S factor relative to the 1634 keV transition (i.e., the de-excitation of the first excited state of ²⁰Ne populated by the ¹²C(¹²C, α)²⁰Ne reaction).

ground. Of course, this problem is drastically reduced in the Gran Sasso underground laboratory where 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 . Indeed, in the case of the ${}^{3}\text{He}({}^{4}\text{He},\gamma)^{7}\text{Be}$ measurement [34], with a proper massive shielding of 0.3 m³ of copper and lead, surrounded by an anti-radon envelope of plexiglas flushed with N₂ gas, a background suppression of 5 orders of magnitude was reached for γ rays below 2 MeV, with respect to a background spectrum measured underground with no shielding. In particular, a background rate of 51.8 ± 1.4 counts/day and of 1.0 ± 0.2 counts/day have been measured in the relevant energy windows of 425-455 keV and of 1619-1649 keV, respectively [35]. Therefore, a deep underground measurement represents the only opportunity to reach the low energy domain of the ${}^{12}\text{C} + {}^{12}\text{C}$ reaction.

4.5 Experimental setup

The experiment will be performed using the intense C beam provided by the LUNA MV accelerator. As already underlined in Section 2, the expected intensity of the beam in the energy range 500-3500 keV is 150 μ A for the ${}^{12}C^+$ beam and 100 μ A (corresponding to 50 particle μ A) for the ${}^{12}C^{2+}$ beam. Since the energy in the center of mass system for the ${}^{12}C + {}^{12}C$ reaction is exactly one-half of the beam energy, the measurement can be performed with the more intense single charge state beam for $E_{cm} \leq 1750$ keV, approximately. For higher energies, only the ${}^{12}C^{2+}$ beam can be used.

The beam will impinge on a solid ¹²C target of natural composition with the lowest contamination due to hydrogen isotopes (see the following section). Infinitely thick targets (e.g., 1 mm thick) are preferable since they enhance counting rates and are more resistant. Thin carbon targets minimize auto absorption effects for proton and α particles but their thickness makes them very sensitive to carbon build-up effects which need to be carefully monitored. Larger systematic uncertainties are expected in this case. The detection system will consist of a high efficiency and ultra low intrinsic background HPGe detector, as that now in use at the LUNA 400 kV accelerator [35], placed at 0° with respect to the beam direction, complemented with four silicon detectors (or telescopes) at backward angles (placed at 135° with respect to the target, with azimuthal angles of 0°, 90°, 180° and 270°). This set up will allow for the measurement of both the γ -rays and the particles (protons and alphas). The use of telescopes for charged particles detection is preferable since it allows a better identification and background rejection but is not applicable for the detection of alphas which will be stopped in the ΔE detector. Ionization chambers (e.g. [33]) might be an alternative to thin silicon detectors. A massive lead shielding is necessary for the HPGe detector, ideally 25 cm thick [35].

4.6 Possible background sources

4.6.1 Backgrounds in the γ -ray experiment

The decays of the ²³Na and ²⁰Ne first excited states produce the dominant lines in the γ -ray spectrum at $E_{\gamma} = 440$ keV and 1634 keV, respectively. These energy peaks are severely doppler-shifted because the stopping time of the excited ²³Na and ²⁰Ne nuclei in the carbon target is comparable to their lifetimes.

Background in the γ -ray spectrum may arise both from beam-induced sources (e.g., interaction of the beam with impurities in the target) and from natural background. Beam-induced background is significant only if the reaction producing it has a cross section greater than or comparable to the ¹²C + ¹²C reaction. Due to the ease of forming bonds with carbon, hydrogen and deuterium are naturally found in carbon targets or are eventually deposited on the surface from the vacuum rest gas during measurements. Previous experimental works have identified the γ rays from the ²H(¹²C,p₁ γ)¹³C and ¹H(¹²C, γ)¹³N reactions as primary sources of beam induced background: they emit γ rays at 3.09 MeV and 2.36 MeV, respectively. At low beam energies, the Compton background of these peaks could completely dominate the carbon fusion γ -ray peaks, as evidenced by Kettner et al. [36] and Barron-Palos et al. [37].

Thus, it is very important to find extremely pure targets and, to reduce the contamination as much as possible before the low energy measurements. Spillane et al. [32] found a method to mitigate the hydrogen and deuterium content: they placed the target in a chamber under vacuum and exposed it to an intense ¹²C beam bombardment without any cooling. By heating up the target for 20 minutes at 700°C the contamination was reduced to a negligible level. In order to fulfil this procedure, thick targets are required to withstand the intense beam bombardment during the heating.

With the reduction or elimination of hydrogen and deuterium from the target, the primary background in the γ -ray spectrum derives from naturally occurring (i.e., non-beam-induced) sources, primarily from ubiquitous natural radioisotopes. This background is negligible at higher energies, but becomes significant below 3.0 MeV where the advantage of an underground measurement is very clear.

4.6.2 Backgrounds in the particle experiments

The most relevant sources of background for the detection of protons and α particles are beam induced events. Both the interaction of the ¹²C beam with impurities in the target

and the interaction of beam impurities (e.g., ¹³C) with the target carbon atoms may induce background particles. The ¹²C beam purity achieved so far is extremely high, with contaminations less than one part in 10^{12} . Thus we focus on reactions with impurities in the target. The Coulomb barrier criteria restricts background producing nuclei in the target to the isotopes of H, He, Li, Be, B and C. The cross sections of ${}^{12}C + {}^{13}C$ and ${}^{12}C$ + ¹²C have been shown to be comparable at energies near and below the Coulomb barrier. As the isotopic ratio of ${}^{13}C/{}^{12}C$ is 0.01, ${}^{12}C + {}^{13}C$ should not contribute meaningfully to the measured yield. Background due to isotopes of He, Li and B was investigated by Spillane et al. and found to be negligible. On the contrary, a small Be contamination was not completely ruled out [38]. Therefore, also for particle experiments the most significant source of background is given by interactions of the carbon beam with isotopes of hydrogen in the target. If the particle detectors are placed at backward angles, it is kinematically impossible to find protons in the carbon fusion region of interest (ROI) from nuclear reactions of ${}^{12}C$ with ${}^{1}H$ or ${}^{2}H$: the ${}^{1}H({}^{12}C,p){}^{12}C$ reaction will not produce protons at backwards angles, while the ${}^{2}H({}^{12}C,p){}^{13}C$ reaction produces protons with significantly lower energies than the carbon ROI. In the presence of deuterium a further two-step process can be initiated [39]. When deuterium is elastically scattered by carbon at forward angles, a secondary ${}^{12}C(d,p){}^{13}C$ reaction can take place in the target, kinematics whose allows protons to be detected directly in the relevant ROI. Thus it is of great importance to find targets with minimal exposure to H isotopes, as well as low intrinsic contamination. Furthermore, the rest gas must be monitored and controlled to reduce hydrogen isotope contamination. Moreover, periodic analysis of deuterium contamination is necessary for accurate background subtraction. The advantage of an underground measurement is much less evident in the case of particle detection even if a recent measurement performed at the LUNA 400 kV accelerator proved that detecting low energy alpha particles is 15 times easier in a deep underground laboratory than overground [40].

4.7 Expected beam time

The expected beam time can be estimated according to the following assumptions: a ¹²C beam current of 150 particle μ A for $E_{cm} \leq 1750$ keV and of 50 particle μ A for $E_{cm} > 1750$ keV; a ¹²C target of 1 mm thickness; a HpGe detector efficiency of 6.4% for $E_{\gamma} = 440$ keV and of 2% for $E_{\gamma} = 1634$, as obtained in the setup used for the ²H(α,γ)⁶Li reaction measurement at LUNA [41, 42]; the modified astrophysical S-factor reported by Spillane et al. [32], and a branching ratio for the population of the first excited state of 0.48 for the p channel and of 0.55 for the alpha channel, respectively. We used the data of Spillane et al. to calculate the yield of the infinitely thick target also at energies lower than those measured by Spillane et al. assuming no resonance was present and performing a fit of the existing data.

The counting rate (Fig. 7) can be easily derived from the yield assuming the current and efficiencies above and is compared with the expected natural background rate of a well shielded setup at LNGS [35]. The expected beam time can be calculated assuming to explore the energy range of 1730 keV $< E_{cm} < 2500$ keV for the proton channel and the energy range of 1920 keV $< E_{cm} < 2500$ keV for the alpha channel, with 5 keV spacing to search for resonances with width of about 10 keV. Assuming to measure each energy with a statistical uncertainty lower than 30%, the total time needed is 445 days full time, meaning approximately 2 years. Lower energies are meaningless because the expected signal-to-noise ratio is lower than 1/10 (for the alpha channel) or the counting rate is too small and/or the total time needed too long (for the proton channel). However, it has to be



Figure 7: Counting rate expected at LUNA MV with a γ measurement, for the proton channel (top panel) and the α particle channel (bottom panel). See text for details.

underlined that this estimate of the expected beam time is actually an upper limit since it is based on a non-resonant astrophysical S-factor. The presence of one or more resonances at low energy could dramatically enhance the counting rate.

4.8 Risk analysis

The possibility of performing this measurement relies on three important factors: the ¹²C current obtainable by the LUNA MV accelerator and the background obtainable using a well shielded set up for gamma detection underground, which have not been tested so far; and the possibility of reducing the beam induced background due to hydrogen isotopes contamination by heating the ¹²C target, which should be feasible, as demonstrated by

Spillane et al.. An intense preparatory phase is planned to clarify these potential issues.

4.9 Conclusions

The investigation of the ¹²C + ¹²C reaction at low energies represents a crucial step forward for astrophysics and cosmology. The deep underground location of the LUNA MV accelerator and its capability of producing an intense carbon beam offer a unique opportunity to perform such a measurement. The search for low energy resonances with a HPGe detector will benefit from the low γ -ray background obtainable with a shielded setup underground. The possibility of also using silicon detectors/telescopes will allow us to obtain a full picture of the reaction, at least at the higher energies where particle detection is easier, with the final aim to obtain a reliable reaction rate for this high-impact process.

5 13 **C**(α ,n) 16 **O**

5.1 Abstract

The ¹³C(α ,n)¹⁶O reaction takes place in thermally pulsing, low-mass, asymptotic giant branch (AGB) stars at Gamow energies¹ E = 140 - 230 keV ($T = 90 \times 10^6$ K). In surface laboratories the high neutron background induced by cosmic rays hampers direct measurements of cross section at such low energies. Extrapolations from higher energy data differ by more than a factor of 3 and it remains unclear whether, and to what extent, the $E_{\rm R} = -2.3$ keV sub-threshold state in ¹⁷O contributes to the reaction cross section. This section provides an overview of the astrophysical importance of this reaction as the main neutron source for the s-process and the nucleosynthesis of heavy elements. After a summary of the current knowledge, a proposal for improved measurements underground is presented, together with indications of expected beam times for its execution and an analysis of the risks involved.

5.2 Astrophysical motivations

The cosmic creation of roughly half of all elements heavier than iron, including industrial metals, such as W and Pd, as well as rare earth, seed of technology elements, such as La and Nd, occurs in AGB stars, where the neutrons necessary to drive the slow neutroncapture (s-) process are released by the ${}^{13}C(\alpha,n){}^{16}O$ reaction [44, 45]. Clearly, the operation of this major cosmic source of neutrons crucially depends on the determination of its stellar rate. In particular, the rate determines whether the ¹³C nuclei burn in radiative conditions or are ingested in the convective thermal pulses driven by He burning. If ¹³C is ingested in the convective region, the ¹³C(α ,n)¹⁶O reaction becomes also an energy source, which affects the development and structure of the thermal pulse itself [46, 47]. In addition, in convective conditions at temperatures ≈ 200 MK, the relative timescale of the $^{13}C(\alpha,n)^{16}O$ and the $^{14}N(\alpha,\gamma)^{18}F$ reactions determines the net amount of free neutrons resulting from the competing processes of neutron production and neutron absorption by the $^{14}N(n,p)^{14}C$ reaction [48]. The number of free neutrons in AGB stars determines the final model results, not only in terms of the absolute abundances of elements heavier than iron, but also in terms of the relative abundance patterns, both elemental and isotopic [49]. The accuracy of model predictions affects the interpretation of many s-process astrophysical observables: from spectroscopically derived abundances of single and binary stars [50] and of old and young stellar clusters [51], to the laboratory analysis of meteoritic rocks [52] and inclusions such as pre-solar dust [53].

The ${}^{13}C(\alpha,n){}^{16}O$ reaction is also the best neutron-source candidate to drive a new type of neutron-capture process: the *intermediate* neutron-capture (*i*) process [54]. This is also believed to occur in AGB stars and is required to explain some peculiar abundance patterns observed in post-AGB stars [55], in meteoritic stardust grains [56], and in the oldest stars in our Galaxy [57, 58]. The investigation of the *i* process is a fast-expanding research topic, which again requires accurate knowledge of the neutron source ${}^{13}C(\alpha,n){}^{16}O$ reaction.

In summary, the accurate and precise (at the level of 10%) knowledge of the ${}^{13}C(\alpha,n){}^{16}O$ reaction at stellar temperatures in the range 80 to 250 million K is the essential ingredient to investigate the s- and the i-processes. Current estimates are mostly based on indirect measurements and extrapolations to low energies, and constitute a collection of relatively

¹All energies are given in the centre of mass systems unless otherwise stated.

precise ($\sim 20\%$ uncertainty) but highly inconsistent values (see Table 1 of [59]). These inconsistencies raise the question of how accurately currently available rates represent the actual stellar rate, and prevent us from firmly addressing open questions on the identification and contribution of the s- and the i-processes to cosmic chemistry, from the galactic halo to the solar proto-planetary disk.

5.3 State of the art

The ¹³C(α ,n)¹⁶O reaction (Q = 2.216 MeV) has been studied over a wide energy range by several direct measurements [60–66]. The current situation is summarised in Figure 8, which shows the astrophysical S factor as a function of centre of mass energy. A couple of features are worth mentioning: 1) there exist no data at the energy of astrophysical interest (dark area - where measurements should ideally be made) because of the severe limitations imposed by the high neutron background in surface laboratories; 2) the lowest energy data (mostly by Drotleff *et al.* [64]) are affected by uncertainties that are too large to constrain extrapolations of higher energy data to astrophysical energies; and 3) discrepancies exist between different data sets both in energy dependence and absolute values. The extrapolation of experimental data to lower energies is further complicated by the unknown influence of three sub-threshold states and their possible interferences with higher energy resonances. In particular, the $1/2^+$ state at E = 6.356 MeV in ¹⁷O, just 2.3 keV below the α -particle threshold, is expected to provide the largest impact, but its contribution remains highly debated despite numerous indirect attempts at measuring its properties (see [67] for a recent overview). Note also that a recent study [43] reports on an excitation energy value E = 6.363 MeV which would change this level from a sub-threshold state to a E = 4.7 keV resonance.

The R-matrix extrapolation to low energies obtained by Heil et al. [66] (red curve in Fig. 8) assumes a constructive interference with the $1/2^+$ sub-threshold state; if this contribution is omitted, the extrapolated curve (green line) differs by up to a factor of 4. Clearly, new and improved measurements are needed to better constrain the astrophysical rate of this important reaction.

5.4 Improvements from the underground measurement

The main obstacle to low-energy measurements stems from a comparatively high neutron background, partly due to neutrons produced by cosmic-rays and partly to neutrons arising from (α ,n) reactions following the α -decay of long-lived radionuclides (*e.g.*, U and Th) in the laboratory environment. At LNGS, the neutron background is typically 2-3 orders of magnitude lower than on surface laboratories, with actual values depending on the exact location underground. Recent measurements [68] report a thermal neutron flux of $(0.32 \pm 0.09_{\text{stat}} \pm 0.04_{\text{sys}}) \times 10^{-6} \text{cm}^{-2} \text{s}^{-1}$, in good agreement with the neutron flux reported by [69]. Additional sources of neutron background come from beam-induced reactions on target impurities or along the beam line (e.g., on slits, collimators, etc.). These are discussed in Section 5.6. Thanks to the reduction in neutron background, we will be able to access the energy region of astrophysical interest for the first time and to establish a new standard in the knowledge of this crucial reaction.



Figure 8: Astrophysical S factor for the ${}^{13}C(\alpha,n){}^{16}O$ reaction. No data exists in the energy region of astrophysical interest (dark area) and discrepancies remain among different data sets, both in energy dependence and absolute value. The extrapolation to low energies (continuos red curve) is based on an R-matrix fit [66] assuming constructive interference with the E = -2.3 keV sub-threshold state in ${}^{17}O$, with uncertainties indicated by dashed lines. If contributions from this state are omitted, the green curve is obtained instead.

5.5 Experimental setup

With this experiment at LUNA MV we aim to: 1) cover a wide energy range, up to E = 1 MeV for improved low-energy extrapolations and global data analysis, to address the issue of normalization discrepancies; 2) access the energy of astrophysical interest; and 3) minimize overall statistical and systematic uncertainties.

First measurements of the ¹³C(α ,n)¹⁶O reaction are planned in 2017-18 at the LUNA 400 kV accelerator. Much of the setup devised for those first measurements will probably be employed at LUNA MV and we also expect to make changes if required, on the basis of the experience gained. Thus, the final choice of the target system and detector setup at LUNA MV will be made at a later stage. In the following, we report about the different available options.

5.5.1 Direct kinematics

The 3.5 MV accelerator is capable of delivering intense $(300 - 500 \ \mu\text{A}, \text{charge state } 1^+)$ α -particle beams over a wide energy region. For the energy range that we intend to explore, E = 220 - 1060 keV, the required beam energy is $E_{\alpha} = 0.3 - 1.4$ MeV. For the ¹³C-enriched targets, either solid or gas targets can be used. Solid targets of various thicknesses can be obtained by implantation onto a Ta or Au substrate, by electron gun evaporation, or as synthetic diamonds. The main issue relates to their degradation and possible carbon deposition during extensive high-intensity beam bombardment. For example, significant degradation was reported by Heil *et al.* [66] after 1C of charge deposition on target. Monitoring targets against degradation will be achieved using high-energy resonances in the ¹³C(α ,n)¹⁶O reaction and/or well-known resonances in the ¹³C(p, γ)¹⁴N reaction. This latter requires, however, changing to a proton beam. Alternatively, a ¹³C-enriched gas target (e.g., ¹³CH₄ or ¹³CO) can be used. Either gas is subject to strict regulations for their use underground. Note that the CH₄ gas has the same risk category as deuterium; while CO is toxic. A gas target prevents issues with target degradation but requires recirculation of the ¹³C-enriched gas to limit costs and its density needs to be chosen in order to minimize beam heating effects [14]. Initial calculations show optimal values for a target of 10 cm length at a pressure P = 1 mbar, corresponding to a target density $N_t = 2.4 \times 10^{17}$ atoms/cm². A feasibility study aimed at assessing the best option is currently ongoing.

In the energy region of interest, $E_{\alpha} = 0.3 - 1.4$ MeV neutrons are emitted with energies $E_{n} = 2.0 - 3.5$ MeV thus requiring moderation before detection. Options for a possible neutron detector are presented in section 5.5.3.

5.5.2 Inverse kinematics

The same energy range of interest, E = 220 - 1060 keV, can be covered in inverse kinematics using a ¹³C beam with energies $E_{^{13}C} = 0.9 - 4.5$ MeV with expected currents from 50 to 150 μ A. A ⁴He gas target with the same length (L = 10 cm) and pressure (P = 1 mbar) of the ¹³C target would be used. Higher bombarding energies in inverse kinematics lead to correspondingly higher neutron energies, $E_n = 2 - 5$ MeV, with a likely forward-focussed emission.

5.5.3 Neutron detector

Both direct and inverse kinematics require appropriate quantities of a suitable moderator material to thermalize the emitted neutrons before they can be detected. Two options are being considered: an array of ³He tubes embedded in a polyethylene moderator and a ⁶Li-loaded plastic scintillator surrounding a polyethylene-grafite moderator. In the first case [64][65] moderated neutrons ($E_n \le 0.025 \text{ eV}$) initiate a ³He(n,p)³H reaction (Q =0.764 MeV) in the counter. The proton and the triton deposit their energy in the ³He gas, resulting in a characteristic pulse height spectrum. Like for any thermal neutron detector, however, information on the initial neutron energy is lost. A possible geometry of the detector would consist of 15 3 He counters embedded in a moderating polyethylene matrix. A detection efficiency of about 40% for 2 MeV neutrons can be achieved by optimizing the arrangement of the counters inside the moderator, the ³He pressure in the tubes, and the amount of moderator between target and counters. In principle, different geometries can be used to maximize detection efficiency, i.e. count rates at different beam energies. A limiting factor may come from the intrinsic α -particle activity from long-lived radioisotopes in the tube material (Al or steel). To minimize this problem low-activity tubes will be necessary. The overall cost of this detector is estimated around 120-150k euros.

The second approach is based on the use of a plastic scintillator consisting in a homogeneous matrix of fine ⁶LiF particles and zinc sulphide phosphor ZnS:Ag compactly dispersed in a colourless binder. Here, thermal neutrons give rise to the ⁶Li(n, α)³H reaction (Q = 4.78 MeV) with a cross section $\sigma = 940$ b. The scintillation radiation induced by the recoiling α particles and tritons in the scintillator is collected by a standard photomultiplier tube (PMT). A prototype detector [70] consisting in two thin ($0.32 \times 51 \times 500$ mm³) layers of ⁶Li-doped scintillators (EJ-416, [71]) mounted on each



Figure 9: Rise-time traces from three different sources (micro-discharge, alpha particle, and neutron events) for data taken with commercial ³He tubes [74].

side of an inert plastic scintillator acting as a wavelength shifter $(20 \times 51 \times 500 \text{ mm}^3)$, EJ-280 [71]) has been recently acquired. Preliminary tests above ground have led to an intrinsic γ -ray sensitivity lower than 2×10^{-7} at the 95% confidence level [72]. Tests underground to assess the intrinsic and ambient background activity are currently ongoing at LNGS. Initial simulations with MCNPX indicate that optimum efficiency is obtained by using a moderator consisting of 7 cm polyethylene and 23 cm graphite [73]. A total efficiency of about 30% could be obtained with five $40 \times 40 \text{ cm}^2$ panels arranged around a $30 \times 30 \times 30 \text{ cm}^3$ cubic moderator. Further simulations for different geometries are being implemented. The overall cost of this detector is around 50k euros [70].

Both detectors can be used in connection with Pulse Shape Discriminator electronics to distinguish neutron from non-neutron events, which may also in part alleviate the problem of intrinsic activity in the ³He tubes. Pulse shapes from a recent study [74] are shown in Figure 9 for data taken with commercial ³He counters; the difference in rise time between alpha- and neutron-induced pulses was used to reject 99% of the alpha background while still accepting 50% of the neutron events [74]. The exact cut settings can be tailored to achieve a favorable signal-to-noise ratio depending on the specific experimental application.

5.6 Possible background sources

In addition to the ambient neutron background, an important source of background arises from beam-induced reactions on target contaminants and on collimators along the beam line. The importance of such reactions is greater the lower the ¹³C(α ,n)¹⁶O reaction yield and careful consideration should be placed on any possible source of background especially at low astrophysical energies.

In direct kinematics, at ⁴He-beam energies below 400 keV the main sources of background are expected from reactions with ⁹Be and ^{10,11}B impurities in the solid target or along the beam line. If a gas target is used (e.g., CH₄ or CO), other sources of background might be possible, which require carefeul investigation. In inverse kinematics, the relatively higher beam energy implies a large number of open two- and three-body reaction channels that produce neutrons. Of these, three-body reactions are potentially more problematic as they give rise to neutrons with a continuum energy spectrum, and thus more easily moderated and detected. An estimate of such contributions is difficult because of the need of taking into account how the cross section of these reactions compare with that of the ¹³C(α ,n)¹⁶O reaction as a function of energy. It can be expected that most such reactions will take place on collimators along the beam line and not on the target itself. Shielding against these background neutrons might be possible; extensive simulations are required to ascertain this. Finally, the number of neutrons produced by the ¹³C(α ,n)¹⁶O reaction itself must also be kept below a maximum allowed rate of 2×10^3 n/s. To achieve this, measurements at energies above $E \sim 500$ keV will be performed with reduced beam currents.

5.7 Expected beam time

To calculate expected neutron yields and provide an estimate of the overall time required for a measurement over a wide energy region we have used experimental cross section data (corrected for electron screening) by Drotleff [64] for $E \ge 300$ keV and the Rmatrix extrapolation of Heil [66] for E < 300 keV. Expected yields and run times are given in Table 2 for a beam current of 150 μ A (either ⁴He or ¹³C) and a gas target with L = 10 cm and P = 1 mbar ($N_t = 2.4 \times 10^{17}$ atoms/cm²). Expected run times at each energy assume a neutron detection efficiency of 30% and an ambient background of 70 neutrons/h as determined from preliminary measurements using available ³He tubes [75]. The attainable statistical precision at each data point is also quoted. Note that the centreof-mass energy reported in the table represents the effective energy of the interaction. Conversion to the lab system requires taking into account beam energy losses in the target not considered here.

5.8 Risk analysis

As anticipated, a number of decisions will be taken based on the outcome of the work and experience on the ${}^{13}C(\alpha,n){}^{16}O$ experiment that will be performed at LUNA 400 before LUNA MV becomes operational. Main risks are related to the choice of the target and of the neutron detector. Feasibility studies are currently ongoing to address both issues. The main issues with solid targets stem from their inability to withstand long time measurements with high beam currents. Being able to access the target station easily for frequent target replacement may pose challenges to the overall design of the neutron detector. Gas targets would offer the advantage of being insensitive to deterioration issues but represent an expensive option, even assuming gas re-circulation. Their design is also likely to impact on the detector geometry and associated efficiency. Simulations are required in both cases and will be carried out during the end of 2016 and the start of 2017.

Risks associated with the detectors are of a different nature: for the ³He-tubes array, the main risk is associated with its high cost and the availability of appropriate funding. They provide, however, a tried and tested technology. The ⁶Li-based scintillators, on the other hand, are much cheaper but their suitability for this application is still to be proved by further underground tests.

Table 2: Neutron production yields and expected run times as a function of energy, assuming a beam current of 150 μ A ($N_{\rm proj} = 9.3 \times 10^{14}$ pps of either ⁴He or ¹³C), a gas target of L = 10 cm and P = 1 mbar ($N_{\rm target} = 2.4 \times 10^{17}$ atoms/cm²), an overall detection efficiency of 30%, and an ambient background of 70 neutrons/h. Cross section values are from the R-matrix extrapolation of Heil *et al.* (E < 300 keV) or from experimental data of Drotleff *et al.* ($E \ge 300$ keV). Centre-of-mass energies represent effective interaction energies. No energy losses have been taken into account.

$E_{\rm cm}$	σ	produced neutrons	precision	significance	run time [$\eta = 30\%$]
[keV]	[barn]	[n/h]	[%]	[sigma]	[days, mins, sec]
220	3.5×10^{-13}	0.3	90	1.11	490 d
240	1.9×10^{-12}	1.6	50	2	52 d
260	8.7×10^{-12}	7	50	2	3 d
280	3.4×10^{-11}	28	50	2	4.5 h
300	1.7×10^{-10}	140	30	3	43 m
320	3.9×10^{-10}	320	10	10	110 m
340	1.1×10^{-9}	900	10	10	28 m
1020	4.3×10^{-3}	1.2×10^{7a}	1	100	10 s
1060	1.5×10^{-3}	4.1×10^{6a}	1	100	5 m

^{*a*)}We point out that this requires a beam current of 1 μ A to keep the neutron production rate at acceptable levels and a ¹³C beam charge state of 2⁺.

5.9 Conclusions

In summary, the proposed experiment will allow to perform the first direct measurement of the ${}^{13}C(\alpha,n){}^{16}O$ reaction in the Gamow window for AGB stars. The lowest accessible energy will depend on the detector efficiency and the overall background (intrinsic, ambient, and beam-induced). The options for a study in direct or inverse kinematics have been proposed. The final decision will be taken based on the outcome of ongoing feasibility studies.

6 22 Ne(α ,n) 25 Mg

6.1 Abstract

The study of the ²²Ne(α ,n)²⁵Mg with the LUNA MV accelerator is discussed in the 470 < E_{cm} (keV)< 1200 energy range. This reaction is the main source of neutrons in massive stars and it contributes to the neutron production in AGB stars. Presently the rate of ²²Ne(α ,n)²⁵Mg reaction at temperature below ~300 MK is very uncertain because experimental nuclear data provide only an upper limit of σ < 10 pb at E_{lab} < 800 keV [76]. The present uncertainties can be reduced by increasing the experimental sensitivity in this energy region. A complete study also foresees measurements at higher energies, to accurately compute the reaction rate also for the s process occurring in the C burning shell of massive stars. The natural way to improve the knowledge of the ²²Ne(α ,n)²⁵Mg cross section is a measurement with LUNA MV, exploiting the very low neutron background at the underground Gran Sasso laboratory.

6.2 Astrophysical motivations

The fundamental significance of the ${}^{22}Ne(\alpha,n){}^{25}Mg$ reaction in astrophysics derives from its role as source of free neutrons during hydrostatic stellar burning. The reaction is activated in AGB stars when temperatures above ~300 MK are reached during the episodical activation of the He-burning shell. Because the ramping up of He burning occurs within short timescales, energy transport requires the formation of a convective shell extending over the whole He-rich region. Together with energy generation, the temperature at the base of the shell also increases steeply with time, reaching the value required to activate the ${}^{22}Ne(\alpha,n){}^{25}Mg$ reaction within relatively short timescales, of the order of a few months. This results in a neutron burst with neutron densities up to 10^{12} cm⁻³, with implications on a large number of astrophysical observables.

In AGB stars of initial masses higher than roughly 5 solar masses the ²²Ne(α ,n)²⁵Mg reaction is the main source of neutrons, and its rate affects the total abundances of the elements heavier than Fe. The abundances of the elements Rb and Zr have been reported for these bright AGB stars [77–79]. The observations qualitatively confirm the role of the ²²Ne(α ,n)²⁵Mg reaction as the main neutron source, however, both models and observational uncertainties have hampered a firm, quantitive comparison with model predictions [80]. While observational uncertainties are currently being addressed [81], model uncertainties both from stellar physics and from the rate of ²²Ne(α ,n)²⁵Mg reaction remain troublesome [82]. This is also hampering investigation of massive AGB stars as the source of the mysterious abundance anomalies observed in ancient globular clusters [83]. It is difficult to constrain the models independently using the elements produced by the *s* process also because the rate of the neutron source reaction, the ²²Ne(α ,n)²⁵Mg, in these stars is not well known.

Also for AGB stars of lower initial masses (~3 solar masses), where the ${}^{13}C(\alpha,n){}^{16}O$ reaction is the main neutron source (Section 5), sensitivity studies have shown that the ${}^{22}Ne(\alpha,n){}^{25}Mg$ neutron burst impacts the abundances of almost 200 nuclei on the path of the *slow* neutron-capture process [59, 84]. This is due to their location nearby branching points on the path of neutron captures, which are extremely sensitive to the high neutron densities.

Observables to which the models must be compared range from elemental compositions derived from the spectra of low-mass AGB stars, their companions, and their planetary nebula progeny [85] to isotopic signatures measured in Solar System materials, from meteoritic to planetary samples. The interpretation of the latter affects our understanding of the formation of the Solar System [86].

Finally, the ²²Ne(α ,n)²⁵Mg reaction is also the main neutron source for the s process occurring during the hydrostatic burning of massive stars (with initial mass greater than 10 solar masses) [87], which is responsible for the cosmic production of the elements between the Fe peak and Sr, and even beyond in metal-poor fast-rotating massive stars, where efficient mixing can boost the amount of ²²Ne [88].

As the current knowledge of the 22 Ne(α ,n) 25 Mg reaction is incomplete and imprecise, it is not possible to address these many open questions with confidence. Current estimates of the rate [59] are mostly based on experimental evaluations of the dominant resonance at 832 keV and provide the rate with an uncertainty of 20-30%, while less than 5% is required for accurate model predictions. Furthermore theoretical extrapolations to low energies of the reaction measured at high energies may be affected by the unknown influence of low-energy resonances just below the neutron threshold, casting doubts on the accuracy of the values currently adopted in the stellar models.

6.3 State of the art

The most sensitive experiment of the ${}^{22}Ne(\alpha,n){}^{25}Mg$ reaction reported in literature has been performed at the 4 MV Dynamitron accelerator of the Institut für Strahlenphysik at Stuttgart (see Jaeger et al. for details [76]). Figure 10 shows the excitation function of the 22 Ne $(\alpha,n)^{25}$ Mg reaction as measured by Jaeger *et al.* [76] together with the results of previous experiments [64, 89, 90]. The excitation function was measured only at relatively high energies, and below E_{α} < 800 keV only an upper limit of about σ < 10 pb was obtained. For this reason, current calculations of the rate of the ${}^{22}Ne(\alpha,n){}^{25}Mg$ reaction are based on the measured resonance at $E_R = 832$ keV, the resonance with the lowest energy ever detected for this reaction (see Figure 10). As a consequence, the reaction rates reported in literature (and their uncertainties) strongly depend on theoretical assumptions related to the possible existence of unknown low-energy states for $E_{\alpha} < 800$ keV. The reaction rate recommended by Jaeger et al. and a more recent calculation by Longland et al. [91] are shown in Figure 11 (see also Table 3 for the comparison with previous rates). It is worth pointing out that both the calculations are based on the same data sets, but with different theoretical assumptions (see also Table 3). In conclusion, the rate at $T \leq 3 \times 10^8$ K, i.e., at typical temperatures of AGB stars, is affected by a large and model dependent uncertainty due to the lack of data at low energy that derives from the relatively high background level of neutrons induced by cosmic rays. A direct measurement at LNGS, where the neutron flux is about 3 orders of magnitude lower than on the surface, is mandatory.

6.4 Experimental setup

The proposed study of the ²²Ne(α ,n)²⁵Mg process (Q=-478 keV) at LUNA MV is based on the use of an intense ⁴He⁺ beam impinging on a windowless gas target of 99.9% enriched ²²Ne surrounded by a 4 π neutron detector. Since enriched ²²Ne gas is rather expensive a re-circulation system is foreseen to be implemented with a cryogenic trap at liquid nitrogen temperature, a zeolite trap, and a getter purifier to ensure gas target purity during the data taking. The foreseen pressure for the gas target ranges from 0.1 to 5 mbar, controlled by a Baratron feed-back system. The set-up will be implemented with a dedicated neutron detector for which three possible options are under consideration (see Section

Reference	recommended rate $(10^{-11} \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1})$
Caughlan and Fowler	1.86
NACRE	$4.06^{+192}_{-3.37}$
Käppeler et al. [92]	$9.09\substack{+14.4 \\ -4.14}$
Jaeger et al. [76]	$2.69^{+3.20}_{-2.63}$
Longland et al. [91]	$3.36^{+4.15}_{-2.74}$
Bisterzo et al. [59]	$2.24^{+2.92}_{-1.99}$

Table 3: The ²²Ne(α ,n)²⁵Mg rate at $T = 3 \times 10^8$ K, as estimated by several authors. Rates and their upper/lower limits are derived by experimental data and theoretical assumptions.



Figure 10: Excitation function of 22 Ne $(\alpha,n)^{25}$ Mg from [76]. Data from Refs.[64, 76, 89, 90] are reported. The grey area is kinematically excluded. The black arrow indicates the energy region for $T = 3 \times 10^8$ K.



Figure 11: Reaction rate and uncertainty of ${}^{22}Ne(\alpha,n){}^{25}Mg$ normalized to the recent calculation of Longland et al. [91]. The black contours represent the 68% uncertainties of the Longland calculation; the dashed blue lines are relative to the Jaeger paper [76]. The relevant temperatures for helium and carbon-shell burning are shown with the labels He and C respectively.



Figure 12: Expected reaction rate for the 22 Ne(α ,n) 25 Mg at LUNA MV under conservative assumptions (see text for details)

5.5.3). The first is a neutron detector composed by a set of ³He proportional counters surrounding the gas target and embedded in a polyethylene cylinder acting as moderator for the produced neutrons. This kind of detector is very insensitive to γ -rays. A possible background is represented by alpha particles emitted by the inner surface of proportional tubes. Therefore, R&D activity is necessary in this respect. A second possibility is the use of thin ⁶Li-glass scintillator panels as active elements. This solution allows in principle a moderate cost and a good solid angle acceptance. Direct underground measurement are ongoing to evaluate and minimize the background level of this option. Finally, a third detector based on the use ¹⁰B-loaded liquid scintillator is presently being investigated. The liquid scintillator acts as moderator and active element at the same time. The background reduction is based on the pulse shape analysis technique. Tests at Gran Sasso are in progress.

6.5 Improvements from the underground measurement

The advantage of LUNA MV with respect to surface experiments is due to the low neutron flux measured at Gran Sasso (see [93] and reference therein). As a matter of fact, the Gran Sasso mountain provides a six orders of magnitude reduction in the cosmic-ray muon flux, leading to 2-3 orders of magnitude reduction in neutrons induced by cosmic muons. The remaining dominant source of neutrons arises from (α ,n) reactions on light elements (A =12-28) due to α -particles produced in the rocks and concrete walls of the experimental hall from the ²³⁸U and ²³²Th decay chains. A passive shield surrounding the neutron detector, consisting on layers of suitable materials (e.g. paraffin, boron, cadmium), is under study.

6.6 Possible background sources

A possible source of background is due to the (α,n) reactions of the ⁴He⁺ beam with the material surrounding the beam line, such as ¹¹B which produces neutrons through ¹¹B $(\alpha,n)^{14}$ N. The beam induced background will be evaluated and minimized through tests dedicated to the selection of high purity materials and/or by plating the components exposed to the ⁴He⁺ beam (i.e., collimators, beam stopper, and reaction chamber) with inert material (e.g., gold or tantalum). As a matter of fact, the background level must be well known in order to extract the ²²Ne $(\alpha,n)^{25}$ Mg signal from the data. In-beam measurements with a target enriched with ²⁰Ne are foreseen. Note that the ²⁰Ne target gives rise to the same stopping power and straggling for the ⁴He projectiles without producing neutrons since ²⁰Ne $(\alpha,n)^{23}$ Mg is below threshold (Q =-7.22 MeV). In summary, a proper configuration and material selection is expected to limit the background at the level of 10 neutrons/day, i.e., well below the irreducible background level of 2000 neutrons/day of [76], predominantly produced by cosmic ray interactions.

6.7 Expected beam time and time schedule

The very low rate of the ²²Ne(α ,n)²⁵Mg reaction at low energy suggests the use of a gas target at relatively high pressure. Assuming a gas target length of 10 cm (extended gas target) and a pressure of 5 mbar, the resulting ²²Ne thickness is 1.25×10^{18} atoms/cm² (at 293 K). The energy loss along the gas target in these experimental conditions is about ΔE_{beam} =56 keV. This remarkable energy loss suggests measurements at low energies (550 < E_{beam} (keV)< 800) by varying the beam energy in steps of about 50 keV. If the

resulting count rate exceeds the background level measured with the same working conditions but with a target of ²⁰Ne instead of ²²Ne, then the pressure is properly decreased to perform measurements addressed to better determine the resonance parameters (energy, width, and strength).

It is worth pointing out that even in the case of no signal evidence the LUNA MV measurement will strongly improve the accuracy of the neutron production rate in AGB stars, since the contribution of resonances below the experimental sensitivity would be negligible.

In relation to the hotter environments corresponding to the C-burning shell of massive stars ($T \approx 10^9$ K), a renewed study of the excitation function above $E_{beam} = 800$ keV is foreseen. The relatively high rate above $E_{beam} = 800$ keV this study at low pressure (e.g., 0.1 mbar), with the advantage of reducing systematic uncertainties related to beam heating effects and energy straggling. Figure 12 shows the expected count rate considering the gas target features described above and making conservative assumptions for the detection efficiency, 10%, and the beam current, 100 μ A. The blue-line shows the expected count rate including the hypothetical resonance at 552 keV, with the current upper-limit value of 60 neV for the resonance strength [76]. The reaction rate without the resonance is expected to be 20 counts/day at $E_{cm} = 618.3$ keV and 1 count/day at $E_{cm} = 553.1$ keV. The horizontal dashed lines show the background level obtained by Jaeger *et al.* and estimated rate for the proposed experiment.

In summary, most of the beam time will be devoted to measurements at low energy. Assuming 50% duty cycle for in-beam measurements, about 3 months are necessary for the energy region below $E_{beam} = 800$ keV. An extra time of about 2 months is necessary if a counting excess is detected in this energy region. The measurements at $E_{beam} > 800$ keV are relatively fast and a total time of 2 months seems to be adequate.

The R&D activity is largely a common task with the ¹³C(α ,n)¹⁶O experiment and it has already started since that reaction will be investigated already with the LUNA 400 kV accelerator. In particular, design and tests concerning neutron detector, passive shield, and material selection are in progress. The construction of the gas target chamber and of the recirculation system will take advantage of the experience gained during previous LUNA experiments, such as the ²²Ne(α , γ)²⁶Mg reaction. The setup installation and validation is estimated to require about 3 months.

6.8 Risk analysis

Neutron production is limited to about 10 neutron/s at the highest energies. The recirculation system makes gas consumption and dispersion in the LUNA site negligible. The possible use of Cadmium in the passive shield and the relative safety issues must be investigated. No other source of risk has been found.

6.9 Conclusions

A renewed study of 22 Ne $(\alpha,n)^{25}$ Mg process with LUNA-MV will allow us to pindown nucleosynthesis in AGB and massive stars, and to compare meaningfully the predicted abundance of s-process isotopes with observations. A beam time of about 8 months is necessary.

7 Summary

We have described the scientific activity we propose to perform during the first 5 year running time of the new 3.5 MV single-ended accelerator which will be installed under Gran Sasso at the beginning of 2018. The accelerator will provide hydrogen, helium and carbon (also doubly ionized) high current beams and it will be devoted to the study of those thermonuclear reactions that determine and shape both stellar evolution and the nucleosynthesis of most elements in the Universe.

In particular, we are planning to start by measuring a reaction we have already studied with the 400 kV accelerator: ${}^{14}N(p,\gamma){}^{15}O$. It is the bottleneck reaction of the CNO cycle and its precise extrapolation within the solar Gamow peak will allow to infer the metallicity of the central region of the Sun from the forthcoming measurement of the CNO neutrino flux.

 ${}^{12}C+{}^{12}C$ is the flagship of this 5 year program. This reaction is the trigger of the C burning in stars. In particular, its rate determines the lower stellar-mass limit for the C ignition. This limit separates the progenitors of white dwarfs, novae and type Ia supernovae, from those of core-collapse supernovae, neutron stars and stellar-mass black holes.

 ${}^{12}C+{}^{12}C$ will be measured on one of the two beam lines at the completion of the ${}^{14}N(p,\gamma){}^{15}O$ study, alternating in time with the measurement of ${}^{13}C(\alpha,n){}^{16}O$ on the other beam line. The other reaction responsible for neutron generation inside stars, ${}^{22}Ne(\alpha,n){}^{25}Mg$, will then be the last measurement foreseen by this proposal.

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