Direct measurements of cross section of astrophysical interest

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Abstract. New direct experimental methods and techniques, combined with the development of new theoretical tools have opened new avenues to explore nuclear reactions of significance for nucleosynthesis at or near the actual temperatures of stellar burning. The main difficulty of direct measurements is determined by the background, which, together with the low cross sections, set a limit on the energy range that can be investigated with a simple setup on the earth's surface. Essentially there are three sources of background, cosmic rays, environmental radioactivity and beam-target induced nuclear reactions. Each of these sources produces background of a different nature and energy, so that each reaction studied needs special care to suppress the relevant background component. I will show different experimental approaches that have been used to study processes of astrophysical interest. In particular, I will focus my attention on underground experiments and the recoil mass separator approach.

1. Introduction
It is in the nature of astrophysics that many of the processes and objects one tries to understand are physically inaccessible. Thus, it is important that those aspects that can be studied in the laboratory are well understood. One such aspect are the nuclear fusion reactions. The theories of nucleosynthesis have identified the most important sites of element formation and also the diverse nuclear processes involved in their production. New precise astronomical observations and improvements in the knowledge of physics inputs for stellar evolution calculations allow us to enter into a new phase for our field: the era of precision.

Basic laws driving these events are obtained mainly from two branches of physics, astrophysics and nuclear physics. The synergic efforts in both theoretical and experimental research in these two domains have given rise, in the last decades, to the fascinating interdisciplinary field of nuclear astrophysics. Nuclear fusion reactions are at the heart of nuclear astrophysics: they influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation, neutrino luminosity, and evolution of stars ([1, 2]). A good knowledge of the rates of these reactions is thus essential for understanding the broad picture outlined above.

The aim of experimental nuclear astrophysics is to measure with high accuracy the nuclear reaction rate at the relevant astrophysical energies, which are very low. Indeed, in a stellar environment the energy available to nuclear species is very much lower than the Coulomb barrier, i.e. nuclear reactions take place via quantum tunnelling effect. For example, the central temperature of the sun is about $15\cdot10^6K$ and therefore the available energy is about 1 keV, much
lower than the Coulomb barrier (550 keV for the p+p system). For charged particle reactions it is possible to define the cross section as:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}$$  \hspace{1cm} (1)

where the exponential term takes into account the s-wave tunnelling probability, $\eta$ is the Sommerfeld parameter and the S-factor, $S(E)$, is a smoothly varying function in energy for non resonant reactions, which includes all the nuclear properties of the reaction \cite{1}. In a stellar plasma, to obtain the energy produced per second, one has to calculate the reaction rate, which is the averaged product between cross section and relative velocity distributed accordingly to the Maxwell-Boltzmann distribution:

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} \frac{1}{(KT)^{3/2}} \int_0^\infty \frac{S(E)}{E} e^{-2\pi\eta} e^{-E/\kappa T} dE$$  \hspace{1cm} (2)

While both the energy distribution function and the tunneling function through the Coulomb barrier are small, the convolution of the two functions results in a peak (the Gamow peak) near the energy $E_0 = \left(\frac{\kappa T}{2}\right)^{2/3}$, with $b = 0.989 Z_1 Z_2 \mu^{1/2}$, giving a sufficiently high probability to allow a significant number of reactions to occur. The energy of the Gamow peak is generally much larger than $\kappa T$.

For a given stellar temperature $T$, nuclear reactions are taking place mainly inside the Gamow peak. In the case of H-burning typical energies are of the order of tens of keV (for example about 25 keV for $^{14}$N(p,$\gamma$)$^{15}$O). Cross sections at the Gamow peak energy are of the order of $10^{-9}$ to $10^{-12}$ barn corresponding to experimental counting rates ranging from a few events per day to a few events per month under typical laboratory conditions. This means that in realistic experimental conditions, the expected counting rate is prohibitively low and the competition with cosmic background strongly hinders obtaining statistically significant results.

There are three sources of background: cosmic rays, environmental radioactivity and beam target impurity induced nuclear reactions. Each of these sources produces background of a different nature and energy, so that each reaction studied needs special attention in suppressing the relevant background component. A number of techniques have been developed to reduce the background component by improved detector configuration, event identification and background rejection techniques \cite{3, 4}. A major breakthrough was the development of the low energy underground accelerator facility LUNA in the Gran Sasso laboratory \cite{5}.

An alternative approach uses quite complex apparatuses to optimize the detection efficiency, selectivity and the background suppression. An example is Recoil Mass Separators (RMS) \cite{6, 7, 79}, that allow one to measure the cross section of radiative capture reactions by means of the detection of the residual nucleus. Gamma coincidence measurements can be added in order to gain informations on the transitions involved in the reaction.

Most of the presently used rates are based on the extrapolation of the existing low energy experimental data. In many cases the extrapolation is of insufficient accuracy because of the difficulties in taking full account of the complexities for the reaction mechanisms. Improved measurements both towards lower energies and at higher energies are needed to reduce the uncertainty of the extrapolation procedure.

2. Underground laboratory for nuclear astrophysics

Low-energy studies of thermonuclear reactions in a laboratory on the earth’s surface are hampered predominantly by background effects of cosmic rays in the detectors, leading typically to more than 10 events per hour in common detectors. Conventional passive or active shielding around the detectors can only partially reduce the problem. The best solution is to install an
accelerator facility in a laboratory deep underground, similar to the solar neutrino detectors. The excavation of the experimental halls of Laboratori Nazionali del Gran Sasso (LNGS) in Italy was completed in 1987. The Gran Sasso Mountain, with an average thickness of 1400 m of rock or 3800 mwe (metre water equivalent) above the laboratory halls, led to a reduction of the muon flux, the most penetrating component of the cosmic-rays, by a factor $10^6$ compared with the surface, thus providing a low background environment [5].

Thermonuclear reactions induced by charged particles are mainly studied by means of $\gamma$-ray or particle spectroscopy. The main sources of natural $\gamma$-ray background arise from several sources: i.e. radionuclides belonging to the natural radioactive series of uranium and thorium or long-lived natural radionuclides such as $^{40}$K. All these radionuclides lead to $\gamma$-ray background with signals below $E_\gamma = 3.5$ MeV. In comparison, the $\gamma$-ray background above $E_\gamma = 2.6$ MeV is mainly dominated by the effects of cosmic rays in the detectors, i.e. muon and neutron-induced events (figure 1). The rock shielding of LNGS leads, in a HPGe $\gamma$-ray detector, to about 3 orders of magnitude reduction in the $\gamma$-ray background signal above $E_\gamma = 2.6$ MeV (figure 2), i.e. the region above natural radioactivity.

![Figure 1. $\gamma$-ray background as observed with a HPGe detector placed above ground.](image1)

![Figure 2. $\gamma$-ray backgrounds as observed with a HPGe detector placed underground (gray line) and with a lead shielding and radon box (black line).](image2)

Therefore, the advantage of an underground environment is evident for high Q-value reactions such as $d(p,\gamma)^3$He and $^{14}$N($p,\gamma)^{15}$O [9], but appears less evident for low Q-value reactions. In a surface laboratory passive shielding such as lead can be placed around the detectors but it is limited to a certain thickness. One cannot add further shielding material since cosmic-ray muons interact with the material and create energetic neutrons which, in turn, create $\gamma$-rays in the lead. Clearly, this background component is dramatically reduced with the significantly suppressed muon flux in an underground laboratory. An additional $\gamma$-ray background component below $E_\gamma = 2.6$ MeV arises due to neutron-induced events. A separate treatment is needed for radon $^{222}$Rn, which is a short-lived radioactive gas and a daughter product of the uranium and thorium decay chains. A popular solution to this problem is to house the detector in a box with a small overpressure of flushing nitrogen (figure 2) [10, 11].

2.1. Laboratory Underground for Nuclear Astrophysics: LUNA I

As a pilot project for an underground accelerator facility, a home-made 50 kV accelerator was installed in the LNGS underground laboratory. This unique project, called LUNA I (Laboratory for Underground Nuclear Astrophysics) [5], was initiated in 1990. During the first phase of the experiment, the cross section of the nuclear processes $^3$He($^3$He,2$p$)$^4$He[15], d($^3$He,$p$)$^4$He [12, 13] and d($p,\gamma$)$^3$He [14] have been measured, reaching for the first time the relevant astrophysical energy of the Gamow peak. The presence of a low energy resonance in the $^3$He($^3$He,2$p$)$^4$He
was considered, before the SNO and Kamland results, as a possible nuclear explanation for the Solar Neutrino Problem. The LUNA experiment, measuring the cross section down to about 15 keV [15] covered all the solar Gamow peak and excluded the existence of any resonance in the Gamow energy region. This important result showed that the solution of the Solar Neutrino Problem was not in the uncertainty of the Standard Solar Model.

The reaction $d(\alpha,\gamma)^{3}\text{He}$ has been studied at LUNA I over the full energy range of the solar Gamow peak [14], i.e. as low as 2.5 keV. It represents the first case of a capture reaction studied underground, where the full advantage of an environment free of cosmic-ray induced background was exploited. The $pd$ reaction plays an important role in the theory of Big Bang Nucleosynthesis. The uncertainty in the $pd$ reaction in the relevant energy window (25-120 keV) propagates into uncertainties into the deuterium, $^{3}\text{He}$ and $^{7}\text{Li}$ abundances. Thanks to the LUNA I data this uncertainty was reduced by a factor of 2. Moreover, the new calculation of the ratio $\rho$ of nucleons to photons in the early universe done with LUNA I data together with other input parameters [16, 17] is in good agreement with that derived from the cosmic background radiation (WMAP) [18, 19].

2.2. LUNA II

With the scientific successes of LUNA I the collaboration decided to purchase a new accelerator. Thus a commercial high-current 400 kV accelerator, LUNA II, was installed at LNGS, which opened the possibility of improving our knowledge for other key reactions. It provides a H-beam current on target of up to 500 $\mu$A and a He-beam current of up to 1 mA [20, 5]. Other nuclear processes, i.e. $^{3}\text{He}(^{4}\text{He},\gamma)^{7}\text{Be}, ^{14}\text{N}(\alpha,\gamma)^{15}\text{O}, ^{15}\text{N}(\alpha,\gamma)^{16}\text{O}$ and $^{25}\text{Mg}(\alpha,\gamma)^{26}\text{Al}$, were studied with the 400 kV accelerator.

The first reaction studied was $^{14}\text{N}(\alpha,\gamma)^{15}\text{O}$ ($Q=7.297$ MeV), which is the slowest reaction in the CN cycle and therefore a key for understanding the timescale of the CNO cycles as well as the overall energy production and neutrino production associated with CNO burning [21]. The LUNA group, as the LENA one at TUNL [4] in a surface laboratory, measured this cross section detecting the prompt-capture $\gamma$-radiation [22, 23, 24]. In an additional measurement by the LUNA Collaboration [26, 25] the total cross section was determined. These recent experiments cover an energy range from 70 to 480 keV, still far from the solar Gamow window at $E_{0}=27$ keV. Additional information is provided by experiments which used indirect approaches such as the Doppler shift attenuation method [27, 28], Coulomb excitation [29] and asymptotic normalization coefficients (ANC) [30].

The goal of the first phase of the LUNA experiment was to study the single $\gamma$-transitions, in particular the ground state transition. Therefore a high resolution HPGe-detector was used making it possible to distinguish single decays. The primary $\gamma$ peaks were at energies higher than 5 MeV, so a clean signal could be detected, thanks to the background free energy spectra, down to 110 keV center of mass energy (figure 3). The price for using a high resolution germanium detector is the relatively low detection efficiency (about $10^{-4}$). To push the cross section measurements toward lower energies, a second phase of the experiment was started using a nearly 4$\pi$ BGO summing crystal. The absolute efficiency at 7 MeV was about 65%. Due to the insufficient energy resolution of the BGO detector it was not possible to have information on the single $\gamma$-transitions but the total cross section was measured down to 70 keV. This energy is at the upper edge of the solar Gamow peak ($E_{0}=27$ keV), but is within the Gamow peak for AGB stars (Asymptotic Giant Branch). The two different approaches were complementary and both took extreme advantage of the low background laboratory (see figure 4). The resulting reaction rate decreased by a factor of 2 from the previous determination [31] for temperatures lower than $150\cdot10^{6}$ K[5]. It should be pointed out that the reliable extrapolation of the LUNA data to the solar Gamow peak required the combination of low-energy and high-energy data. Therefore, the range of uncertainty in higher-energy data affects the low-energy extrapolation.
This suggests the need for improved measurements in the high-energy range [32].

This reduction has already had several astrophysical implications. In the sun, the CNO cycle contributes only 2% (instead of 4%) [33] to the total energy production and thus the corresponding portions of solar neutrinos is reduced by this factor. This is highly relevant for the Borexino neutrino detector [35, 36]. Globular Clusters represent the oldest resolved stellar populations. Their age closely coincides with the time elapsed since the epoch of the formation of the first stars in the Universe and provides an independent check on the reliability of cosmological models. With the present determination of the reaction rate, the main astrophysical consequence is that the age of the Globular Clusters increases by about 1 Gyear, i.e. about 14 ± 1 Gyears depending on the metallicity [37]. This value is compatible with the results of the WMAP experiment [38]. The last consequence is related to the contribution of AGB stars to the chemical evolution of galaxies. There existed a long standing problem between observation and stellar models, i.e. an over-production of all chemical elements above carbon by a factor of 2 or more. This discrepancy has been resolved by the lower rate of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ [39].

The next experiment that has been performed at LUNA is the measurement of $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$. Also in this case, the experiment has been divided into low efficiency high resolution low and high efficiency resolution phases. The setups are similar to those of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ experiment.

Observations from satellites [40, 41] have discovered a $\gamma$-ray line at 1809 keV, which arises from the $\beta$-decay of $^{26}\text{Al}$ to $^{26}\text{Mg}$ ($T_{1/2} = 7 \times 10^5$ yr). The intensity of the line corresponds to about 3 solar masses of $^{26}\text{Al}$ in our galaxy. Moreover, the presence of $^{26}\text{Al}$ in the interstellar medium has been determined from the observation of $^{26}\text{Mg}$ isotopic enrichment (extinct $^{26}\text{Al}$) in carbonaceous meteorites [42]. While the observations from COMPTEL and INTEGRAL provided evidence that $^{26}\text{Al}$ nucleosynthesis is still active on a large scale, the Mg isotopic variations show that $^{26}\text{Mg}$ must have been produced within the last 4.6 billion years (the time of the condensation of solar-system material). Any astrophysical scenario for $^{26}\text{Al}$ nucleosynthesis must be concordant with both observations.

The nuclide $^{26}\text{Al}$ is produced mainly via the $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ capture reaction. The most important site for the activation of this reaction is the hydrogen-burning shell (HBS), which may be active in off main sequence stars of any mass. The existence of an active HBS is a common feature in stellar evolution and different classes of stars can have these characteristics: low
mass AGB, massive AGB, Novae, Core Collapse Supernovae and Wolf-Rayet stars for example. Stellar nucleosynthesis studies predict that about 30 to 50% of $^{26}$Al is produced in the HBS of massive stars (core collapse supernovae or WR-stars). The source of the remaining contribution is unknown and a more precise knowledge of the relevant reaction rates certainly will help in reducing the range of free parameters.

The reaction $^{25}$Mg$(p,\gamma)^{26}$Al ($Q = 6.306\text{ MeV}$) is dominated by narrow resonances. These resonances have been experimentally verified down to a resonance energy of $E_R = 190\text{ keV}$. From the known level structure of $^{26}$Al, one expects low-lying resonances at $E_R = 93, 109, \text{and } 130\text{ keV}$, among which the 93 keV resonance appeared most important. Indeed, the 93 keV resonance was discovered at LUNA II using the $4\pi$ BGO crystal and a $^{25}$Mg solid target. For the 130 keV resonance a new upper limit will be available. This new information allowed for improved astrophysical calculations of the origin of the 1809 keV line as well as of the chemical evolution of galaxies. The precision and reliability of the absolute values for the resonance strength measurement requires unusual efforts in the determination of all quantities entering the experiment. In particular the target stoichiometry is a critical parameter. Small, unknown admixtures of oxygen in the chemically enriched $^{25}$Mg target resulting from the evaporation procedure already have a large effect on the determination of the resonance strength. This difficulty can be partly solved for the low energy resonances, if the strengths of these resonances are determined relative to a precise known resonance at higher energies, where one might study the stoichiometry by a different method. The case of the $^{25}$Mg$(p,\gamma)^{26}$Al reaction allows for such a normalization by the measurement of the strong $E_R = 304\text{ keV}$ resonance with a natural Mg target [43].

The last experiment that was performed at LUNA was the measurement of the $^{15}$N$(p,\gamma)^{16}$O reaction rate. The proton capture of $^{15}$N is relevant since the compound nucleus $^{16}$O can decay into the $\alpha$ particle channel as well as into the $\gamma$ channel to the ground state of $^{16}$O. This introduces a reaction branch linking the first CNO or CN cycle with the second CNO, or NO cycle. The branching has always been a matter of debate since both reactions are characterized by strong low energy resonances [44]. Indirect studies suggest a cross section significantly lower that would translate into a lower rate [45, 46]. High precision experiments performed at higher energies in a wide energy range are extremely important, since they become complementary to low energy data, when direct measurements are not possible. Following this idea a collaboration was started between the Nuclear Science Laboratory at the University of Notre Dame and LUNA. We studied, with the same experimental setup, the $^{15}$N$(p,\gamma)^{16}$O reaction over a wide energy range. The energies covered by the experiment range from 2 MeV using the KN accelerator at ND, down to 100 keV using the 400 kV LUNA accelerator (figure 5). These studies confirm that the cross section is about a factor of 2 lower than previously thought [31], which translates into a reduced leakage rate from the CN to the NO cycle in stellar burning [47].

3. Recoil Mass Separator

The use of a recoil mass separator is an effective way to measure the cross section in cases where beam induced background or some problem of normalization occurs. With such an experimental approach, it is possible to measure the total cross section of the process by counting the number of recoil particles arising from the reaction. The difficulties are to collect all the recoils, which have angular and momentum dispersion due to the kinematics of the reaction and to separate the recoil from the incident beam, which is many orders of magnitude more intense. To discuss the potentialities of this approach, I will discuss the measurements of two particular reaction rates done by the ERNA and DRAGON collaborations.

The nuclear cross section of $^3$He$(^4$He, $\gamma)^7$Be is presently one of the largest uncertainties in the prediction of the solar neutrino flux. A better estimate of this parameter is needed to use solar neutrino fluxes as a probe to study the Standard Solar Model (SSM). In fact, the recent
downward revision in the metal content of the convective zone [34] prompts interest in a check of the standard solar model. The new metal abundances significantly alter the agreement between SSM and helioseismology in the temperature region below the solar convective zone. In this framework it is of particular interest to study the nuclear reactions which yield beryllium in the sun. Beryllium is produced during the pp chain via the $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ reaction, which is the second most probable way to destroy the $^3\text{He}$ (14%). It, in turn, decays predominantly via electron capture (99.89%), producing a monochromatic neutrino of 0.86 MeV ($^7\text{Be}(e^-\nu_e)^7\text{Li}$), which has been recently detected in the BOREXINO experiment [35, 36]. Beryllium can capture a proton nucleus (0.11%), which yield the unstable $^8\text{B}$, that $\beta$ decays emitting a high energy neutrino. This neutrino has been detected in the SuperKamikande and Sudbury Neutrino Observatory (SNO) experiments. The $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ reaction has also important implications on Big Bang nucleosynthesis (BBN), where the predicted abundance of $^7\text{Li}$ is a factor of 2 to 3 larger than observation. Therefore, an accurate evaluation of this cross section is the basis for possible solutions of the $^7\text{Li}$ problem.

During the last decades, many efforts have been devoted to the determination of this cross section at the relevant energies for Big Bang nucleosynthesis and stellar core hydrogen burning. All the experiments have used the detection of prompt gamma-rays as well as the observed radioactivity of the residual nuclei $^7\text{Be}$ (electron capture to $^7\text{Li}$ with $T_{1/2} = 53$ days), while in a few cases both techniques were used [48, 49, 50, 51, 52]. One of these experiments was
The cross section was measured at $E_{cm} = 127$ and 148 keV using the activation technique only. At $E_{cm} = 93, 106$ and 170 keV the cross section was obtained using both techniques (activation and prompt $\gamma$-ray) (figure 6). The results from the two methods were consistent and did not show any discrepancy at the level of the achieved accuracy (4%). Agreement between the two techniques was also found by a recent experiment [48] where the $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ reaction was measured in the energy region between $E_{cm} = 0.35$ and 1.2 MeV.

These experiments directly covered the energy range of BBN (180 keV $< E < 400$ keV), on the other hand the Gamow energy ($E_0 = 22$ keV) in the Sun was not reached, and models have to be used to extrapolate the data. The results show an overall fair agreement, in the energy dependence of the cross section ($\sigma(E)$), while they disagree in their absolute values. A global analysis of their results [53] shows that discrepancies are still present. Finally, one should note that, at energies above 1 MeV, there exists essentially only one data set [54]. Consequently, these data have a large influence on the determination of $\sigma(E_0)$, since they provide a strong test of the adopted model and, thus, determine the energy dependence in the extrapolation. Therefore, new data were needed, aiming at a precise and accurate determination of $\sigma(E)$, at energies up to at least $E_{cm} = 2$ MeV. Recently a new determination of this cross section has been obtained by the direct detection of the $^7\text{Be}$ recoils using the recoil separator ERNA at the Dynamitron Tandem Laboratory of the Ruhr-Universitaet Bochum, Germany [55]. During the experiment a $^4\text{He}$ ion beam, emerging from the tandem, impinged onto a $^3\text{He}$ re-circulating windowless gas target. The number of projectiles impinging on the target was determined from the elastic scattering yield observed in two collimated silicon detectors. After the gas target is the separator, consisting of a quadrupole triplet, a Wien filter, a quadrupole singlet, a dipole magnet, a quadrupole doublet, another Wien filter, and a detector for the recoiling nuclei. Different end-detectors were used, depending on the recoil ion energy. The $\sigma(E_{eff})$, at the effective interaction energy $E_{eff}$, is given by comparing the number of recoils with the number of projectiles. The total cross section was measured in the energy range $E = 700 - 3200$ keV. In comparison with previous works, there is a significant discrepancy of both the absolute scale and the energy dependence of the S-factor in the energy range $E > 1000$ keV. The direct capture model does not provide a good description of the observed energy dependence of the S-factor above 1 MeV, where it should still be accurate (figure 6). The best extrapolation, with the present data and nuclear models, leads to a value, at astrophysically relevant energy, with an uncertainty of about 10%. This is still a much larger uncertainty than required by the astrophysics community [55, 53].

![Figure 6. Comparison of the results of the data of the present experiment and recent works with different model calculations fitted at $E < 2$ MeV (solid black line [57], solid grey line [58], dotted line [59]).](image)

The reaction $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ ($Q = 7.16$ MeV) takes place during helium burning. The cross
section at the relevant Gamow-energy, $E_0 \simeq 0.3$ MeV, determines, together with the convective mechanism in the helium stellar core, the abundances of carbon and oxygen at the end of helium burning. This, in turn, influences the nucleosynthesis of elements up to the iron region for massive stars [60] and the composition of C/O White Dwarfs in the case of intermediate mass stars [61]. The unknown rate of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is responsible for one of the most important uncertainties in nuclear astrophysics today. The primary reaction of He-burning is the triple-$\alpha$ process. It starts after the stellar core temperature exceeds $10^8$ K. The synthesized $^{12}\text{C}$ can capture another $\alpha$ particle forming an oxygen nucleus. The Q-values of both processes are very similar, but the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction consumes only one $\alpha$ particle and, thus, determines the ashes of this phase: the larger the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate, the longer the He-burning time and, consequently, the amount of $^{16}\text{O}$. The final carbon abundance at the end of helium burning has important consequences for the following astrophysical scenarios. The intermediate-light elements Ne, Na, Mg and Al ejected during the type II Supernova explosion scale directly with the C abundance left by He-burning, while the elements produced by the explosive burning phases, i.e. complete and incomplete explosive Si-burning, explosive O-burning and explosive Ne-burning, scale inversely [60, 62, 63]. The maximum luminosity and the kinetic energy of type I SN are driven by the $^{56}\text{Ni}$ abundance which is again proportional to the C abundance. Therefore, the lower the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate, the faster and brighter the light curve [64]. CO white dwarfs undergo stable pulsations during their long cooling time. These pulsations, observed as variations in brightness, in principle provide constraints on the internal structure of these condensed objects, e.g. the chemical profile [65]. However, large uncertainties in the efficiency of convection induced mixing make predictions of the central oxygen mass fraction rather uncertain. An accurate knowledge of the reaction rate could improve our understanding of the convection processes [61].

In spite of experimental efforts over nearly 30 years, we are still far from this goal. All previous efforts have focused on the observation of the capture $\gamma$-rays, including one experiment that combined $\gamma$-detection with coincident detection of the $^{16}\text{O}$ recoils. Due to the low cross section and various backgrounds depending on the exact nature of the experiments, $\gamma$-ray data with useful, but still inadequate, precision were limited to center-of-mass energies $1.2$ MeV $< E_{cm} < 3.2$ MeV [66, 67, 68, 69, 70, 71, 72, 73].

The use of a recoil mass separator to detect the $^{16}\text{O}$ ions produced in the reaction is one possible way to improve the situation. In fact, this method allows direct measurement at the total cross section of the process, regardless of the details of the reaction mechanism. The detection efficiency is determined by the probability of the selected ion’s charge state in the recoil separator, which is typically of the order of 30%. Moreover, heavy ion detectors do not suffer from environmental background problems, as gamma detectors, and the kinematic conditions set by the mass separator remove most of the beam induced background on target impurities. On the other hand, the experimental apparatus is quite complex because of the need to use a helium gas target in combination with a carbon beam to produce recoils emerging from the gas target that are kinematically focused, and to achieve an efficient transport system of recoil ions and beam suppression factor, which must be higher than $10^{10}$. The ERNA (European Recoil separator for Nuclear Astrophysics) collaboration reached, for the first time, the suppression factor and acceptance value needed to measure the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ [74, 75, 76, 77, 78]. The equipment was installed at the Tandem of the Ruhr Universitaet Bochum, Germany. In this way it was possible to measure the total cross section of the reaction in the energy range $E_{cm} = 1.9$-$5.0$ MeV [6]. These results have helped to establish the parameters of the R-matrix in the high energy region with high precision. A new transition through the excited state of $^{16}\text{O}$ ($E_X = 6.02$ MeV, $J^\pi = 0^+$) [79] has been detected by an experiment performed at the DRAGON separator. This new transition is likely the most important cascade contribution [79].

Finally, the estimated rate of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ is still affected by an uncertainty exceeding...
30%, which, as mentioned, is not an adequate input for stellar models. In any case it has been shown that, using mass separators, it will be possible to determine the rate of this reaction with adequate quality. It will then be possible to extend the measurements to energies below 1.5 MeV. The ERNA Collaboration decided to move the separator to the Circe laboratory [80], managed by the Department of Environmental Sciences of the Second University of Naples. The re-installation of the facility represents a unique opportunity to modify the design of the separator, including a stage for selecting the charge state immediately after the target. This will solve the problems of overfocusing, with a limited reduction of the separator acceptance.

4. Outlooks
There has been substantial progress over the last decade in our understanding of the nuclear reactions of astrophysical interest. In particular, new measurements have been performed mapping the cross sections of many of the critical hydrogen burning reactions with higher accuracy over a wide energy range. Particular efforts have been made to expand the experiments towards lower energies, close to the Gamow window using complementary experimental techniques to reduce the background by either passive shielding in an underground environment or active shielding by event identification and active background rejection. Presently used rates are mostly based on the extrapolation of existing low energy experimental data. In many cases the extrapolation is of insufficient accuracy because of the difficulties in taking full account of the complexities of the reaction mechanisms. Therefore, it is very important, if possible, to study the reactions using a recoil mass separator over a wide range of energies.

There exist proposals for new underground laboratories in England, Spain, Romania, and the USA. While the recoil separator ERNA is presently remounting at CIRCE laboratory of Caserta and a new separator is in the phase of commissioning at the Nuclear Science Laboratory of the University of Notre Dame.

Acknowledgments
The work described in this paper has been mainly done in the framework of the ERNA and LUNA experiments. The author would thank all the members of these international collaborations.

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