OLD QUESTIONS AND NEW CHALLENGES IN NUCLEAR ASTROPHYSICS*

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Since 1957, astrophysics and nuclear physics have been working together to understand the evolution and nucleosynthesis of stars in our Galaxy. Today, this collaboration appears renewed by the investigation of exotic phenomena observed by the multi-messenger astronomy. However, important and challenging puzzles remain to be solved also in classical nuclear astrophysics. This paper deals with three case studies in which the solution to stellar physics problems is found in the nuclear physics of the studied environments. In particular, the influence of the $^{12}C + ^{12}C$ fusion rate on the exploitability of supernova progenitors is discussed along with how the $^{17}O + p$ reaction rate can help establish the stellar origin of certain dusts, and how precise data on β-decay in stellar plasmas are crucial to understand the neutron capture nucleosynthesis.

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1. Introduction

After many notable publications during the previous decades, such as *e.g.* the one by Bethe [1], the birth of nuclear astrophysics is traditionally traced back to 1957 when the B2FH paper [2] was published. In this famous work, the nuclear processes and the astrophysical sites responsible for the synthesis of each element were investigated to reproduce the element abundance distribution in the solar system. After decades of studies, the main processes driving the stellar evolution are quite well known, but many questions are still open, particularly about the late stages of stellar evolution and the exotic nuclear processes they host. In 2015, the observation

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of the first gravitational wave GW150914 has led to radical changes in the field of astronomy and astrophysics, changes so significant that someone has compared them to a second Copernican revolution. On the one hand, this discovery has greatly expanded the horizons of study, leading to the birth of multi-messenger astronomy and proposing new scenarios to investigate by astronomers and astrophysicists as well as by nuclear physicists. On the other hand, classical astrophysics continues to present unresolved questions, as *e.g.* will a star explode at the end of its life? Will an evolved star produce heavy nuclei by neutron captures? To answer such questions the role of (experimental) nuclear physics is crucial. In this paper, we will discuss three cases of study: *(i)* how a new measurement of the $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ reaction cross section may affect the final fate of massive stars, *(ii)* how the production site of some stellar dust "may change" considering different $^{17}\mathrm{O}+p$ reaction rates, and *(iii)* the need for measurements of β-decays in stellar plasma to predict yields of neutron capture nucleosynthesis.

2. The $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ nuclear reaction and the final fate of massive stars

The $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ reaction plays a crucial role in stellar evolution, particularly in stars with masses greater than approximately $8M_{\odot}$, where the carbon fusion produces heavier elements, such as O, Ne, and Mg, and affects their late evolutionary stages and final fate. A precise knowledge of the reaction rate is then essential for accurate modeling and understanding the stellar evolution and nucleosynthesis, as well as the dynamics of stellar remnants. However, carbon fusion in stars occurs at temperatures between 10^8 and 10^9 K, corresponding to energies of 10–300 keV. At these energies, the cross section for the $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ reaction is extremely small due the Coulomb barrier in between the 2 colliding nuclei, and its measurement by direct technique is extremely challenging, if not feasible.

In 2018, Tumino *et al.* [3] measured the $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ and $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reactions in the energies range of $0.8\ \mathrm{MeV} \leq E_{\mathrm{cm}} \leq 2.7\ \mathrm{MeV}$, and observed for the very first time a complex structure of several resonances below 300 keV, namely in the energy range critical for stellar burning. As a consequence, the reaction rates turned out to be 25 times larger than the reference values at $T \simeq 5\times10^8$ K [4]. This finding has profound implications for our understanding of the stellar carbon-burning, as it implies that carbon fusion may occur at a higher rate than previously thought, potentially altering the energy output and the timescale of the carbon-burning phase. For this reason, the paper by Tumino *et al.* has been followed by a number of subsequent studies, not only to evaluate the astrophysical implications, but also to debate the proper way to extract the reaction rates by the experimental data.

Such a breakthrough outcome was achieved thanks to the use of an indirect measurement technique: the Trojan Horse method (hereafter THM) [5]. Indirect methods are commonly employed in experimental nuclear astrophysics (see *e.g.* [6]), which often requires experimental access to very low energies. Among them, the THM is a very powerful tool to study fusion reactions between bare nuclei as they occur in stellar plasmas, without the distortions caused by electron screening that might occur in laboratory conditions using other measurement techniques. As the flip side, the theoretical background necessary for data analysis and for extracting the total cross section of the studied reaction is quite complex (see [7, 8] for details). By means of the THM the low-energy cross section of an $A(x,b)B$ reaction is investigated by measuring the quasi-free contribution of a specific $A(a,bB)s$ reaction, where the nucleus a (the TH nucleus) is chosen for its $x \oplus s$ cluster structure to transfer the particle x, and induce the $A(x,b)B$ reaction, while the particle s plays the role of spectator. In this way, the $A + a$ process occurs at the laboratory energy, well above the Coulomb barrier, allowing for the transfer of x in the nuclear field of A avoiding any Coulomb suppression or electron screening effects, and then the $A + x$ reaction takes place at the sub-Coulomb relative energy E_{cm}, because the excess energy of the $A + a$ system is consumed by the break-up of a and the momentum of s. The quasi-free reaction cross section is then extracted from experimental yields in arbitrary units and the normalization to data (at higher energy) in the literature is needed to obtain the cross section in absolute units. Therefore, the THM is very powerful in detecting resonances at energies not accessible to direct measurements, while the overall trend of the cross section can be determined by a scaling procedure.

Until 2018, the THM has been successfully applied only to study reactions where the x nucleus has $Z \leq 2$ and the charge of the TH nucleus is small too [9, 10]. This is not so in the case of the $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ and the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reactions, which were investigated employing $^{14}\mathrm{N}$ as nucleus a and by measuring the $^{12}\mathrm{C}(^{14}\mathrm{N},\alpha^{20}\mathrm{Ne})^{2}\mathrm{H}$ and $^{12}\mathrm{C}(^{14}\mathrm{N},p^{23}\mathrm{Na})^{2}\mathrm{H}$ three-body reactions, respectively [3]. Mukhamedzhanov *et al.* [11] raised doubts on the validity of the obtained results, claiming that a more complex procedure is needed to derive the astrophysical S-factor for the $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ case due to the larger charge of the TH nucleus. According to the cited authors, there are no doubts about the existence of the resonance structure at 0.9 MeV, but the high charge of the nucleus a generates strong Coulomb interactions in the initial and final states of the TH transfer reaction, and as a consequence, the cross section turns out to decrease, instead of increasing, as energy/temperature decreases. Such a Coulomb distortion effect has been identified as “hindrance”.

In any case, the presence of the resonance states at 0.9 MeV deeply affects the behavior of the ^{12}C + ^{12}C reaction in the energy range of the stellar C-burning. Bertulani *et al.* [12] provided a comprehensive study of the ^{12}C + ^{12}C reaction, focusing on the effects of resonances and their role in the fusion process. This work has been important for refining theoretical models of stellar nucleosynthesis and improving the accuracy of predictions for stellar explosion mechanisms. Among the stellar physics studies on the impacts of these new estimates of the ^{12}C + ^{12}C, Chieffi *et al.* [13] examined the impact of revised reaction rates on the evolution of massive stars. By comparing stellar models computed by the rates suggested in [3] with ones computed employing the reference values from [4], they demonstrated that the updated reaction rates alter the binding energy of the inner stellar regions. As a consequence, the compactness of the cores of the supernova progenitors is altered as long as the stellar exploitability, in other words, the onset of the core collapse is affected by the ^{12}C + ^{12}C reaction rates.

Aiming to resolve the ambiguities raised by the mentioned papers ([3] and [11]), the STELLA Collaboration investigated the ^{12}C + ^{12}C reaction with an advanced particle–gamma coincidence technique and the measured cross section seems to support the hypothesis of a hindrance effect at play at deep sub-barrier energies [14]. Monpribat *et al.* [15] investigated the astrophysical consequences of the hindrance-reduced reaction rates by analyzing two stellar models of 12 and $25 M_{\odot}$, respectively. The authors compared the output of models computed employing 3 different inputs for the ^{12}C fusion cross section: *(i)* the reference one from [4], *(ii)* the one measured by [14], and *(iii)* a third one computed by considering a resonance at 2.41 MeV (as proposed by [16]) on the top of the latter reaction rate. It turned out that the central C-burning takes place at temperatures that are 10% higher in models computed by using the *(ii)* hindrance-reduced rates; while using the reaction rates *(iii)* that consider the resonance at 2.41 MeV, the duration of the C-burning phase is reduced by a factor of 2 and the stellar core becomes degenerate earlier, with a modification in the timing of the pre-core collapse phase. From the nucleosynthesis point of view, the stellar models computed by the hindrance reaction rate produce up to 60% more neon, but the impact of the different rates on the slow neutron capture process occurring during the C-burning phase is modest. So the readjustment of the stellar structure triggered by the change in the rate of a reaction important for the stellar energy production prevents severe consequences for the whole stellar structure (even if the rates differ by more than an order of magnitude), while changes can be appreciated in the evolution of the stellar region where the C-burning takes place.

Recently, Dumont *et al.* [17] confirmed the impact of using the hindrance suppressed reaction rates on temperature and density, lifetime, size, convective or radiative regime of the C-burning core of massive stellar models. The authors also underlined the mass-dependent effect of the resonance at 2.14 MeV. Moreover, Dumont *et al.* noted that the effects of the nuclear physics inputs on the stellar nucleosynthesis (namely a reduction in the efficiency of the slow neutron capture processes) are amplified in rotating stellar models.

In all 3 cited papers [13, 15, 17], the $^{12}C + ^{12}C$ fusion reaction rates turn out to change the behavior of the core-carbon-burning phase with major changes in the nucleosynthesis and the final fate of the stars, therefore a common conclusion of the authors is that a correct and accurate determination of the nuclear reaction rates, affected or not by the hindrance and with a precise measurement of the low-energy resonances, is pivotal for a careful interpretation of evolution and nucleosynthesis of intermediate and massive stars.

3. The dust progenitor mass and the $^{17}O + p$ reaction rate

In this paragraph, we will analyze the quiescent hydrogen burning that occurs in a radiative shell below the stellar envelope in stars of the Asymptotic Giant Branch (AGB), an evolutionary phase typical of low-mass stars and/or intermediate ones, but not exceeding 6.5–$7M_\odot$. Due to the small mass of these objects, the CO core is degenerate, surrounded by a shell of He, undergoing periodically convective instabilities, and a radiative region rich in hydrogen, where thermonuclear fusion reactions fuel the star for the most of the AGB phase. An extended, convective envelope surrounds AGB stars and makes these objects the major source of dust in the Galaxy.

Among the tiny solids that might form in the stellar envelopes, there are the so-called presolar grains, which are refractory particles of a few microns or nanometers in diameters that are usually spread in the nearby interstellar medium by the stellar winds. Samples of them came to us as inclusions of pristine meteorites and, by mass spectrometer analysis, they reveal the chemical and isotopic composition of the star in which they were formed, with a precision not achievable through stellar spectroscopy observations. The recorded isotopic distribution in presolar grains is often the signature of the nucleosynthesis of the site where they had origin. Based on such abundances, the type of the progenitor star can be inferred, and in accordance with these, the grains are classified into groups and subgroups (see *e.g.* [18] for details).

A bit more challenging is the identification of the origins of group 2 oxide grains (see [18] for the classification of oxide grains). These dust particles form in oxygen-rich environments, *i.e.*, where $C/O < 1$, and are composed almost exclusively of oxygen, aluminum, and traces of Mg, with $A = 26$ produced by the *in situ* decay of ^{26}Al. These chemical abundances suggest origins in environments where hydrogen burning occurs, but they are seemingly devoid of features that can be immediately linked to a specific stellar site in a unique way. In particular, groups 1 and 2 oxide grains are thought to originate in red giant stars (hence evolved with low mass) because their ^{17}O/^{16}O ratio typically has values greater than the solar one (and not reproducible by the abundant production of ^{16}O typical of massive stars), as observed in these stars [19]. However, group 2 grains also show a significant reduction in the ^{18}O/^{16}O ratio and an enrichment in the ^{26}Al/^{27}Al ratio (the latter inferred from the overabundance of ^{26}Mg, see [20]) that hint to a relatively high temperature of H-burning ($T \sim 7$–8×10^7 K). In principle, the value of the ^{17}O/^{16}O isotopic ratio can be used as a thermometer for the stellar environment in which each grain was formed [19]. This is because, assuming it originated in the H-shell of a red giant star (whether AGB or RGB), the equilibrium value of this ratio, determined by the burning of the CNO cycle at a given temperature T, is set by the rates of proton capture reactions on ^{17}O and ^{16}O. Group 2 oxide grains show $4 \times 10^{-4} \leq {}^{17}\mathrm{O}/{}^{16}\mathrm{O} \leq 2 \times 10^{-3}$ consistent with a stellar progenitor of about $2M_\odot$, but AGB with this mass are C rich, namely in their envelope C/O ≥ 1, which hampers the formation of oxide dust. Moreover, the surface abundances by which the object climbs the giant branch do not account for the recorded abundances of ^{18}O and ^{26}Al.

To reproduce the isotopic abundance pattern shown by the grains of group 2, while maintaining the hypothesis that their progenitors are AGB stars, it is necessary to assume the occurrence of mixing mechanisms (non-canonical) that allow for a direct connection between the inner regions of the H-burning shell and the convective envelope of the star, where the dust forms (see [21, 22] and references therein). These processes must be efficient but should not affect the stellar luminosity. This is compatible with two scenarios: an AGB star with masses between 4–$7M_\odot$ affected by the Hot Bottom Burning (HBB) [23, 24], or an AGB star with masses $< 1.5M_\odot$ where the Cool Bottom Process (CBP) is at work [25], or rather a mixing process of an advanced nature [26], in both cases the stellar envelope has C/O < 1. In the HBB, the temperature at the base of the convective envelope is high enough to allow for a few proton capture reactions to occur so that the surface material can be enriched in ^{26}Al and depleted in ^{17}O and ^{18}O (temperatures are too low to lead to appreciable modification in the amounts of ^{16}O and ^{27}Al). The CBP or extra-mixing refers to non-convective material transport processes between the H-burning shell and the stellar envelope, which can occur in stars with masses $< 3M_\odot$. In the last years, an advective mixing triggered by the ascent of "hot" material bubbles has been shown to be more effective than a traditional "conveyor belt" CBP in explaining the surface anomalies of CNO isotopes in AGBs since it has a reduced risk of feedback on the stellar luminosity [26].

Palmerini *et al.* [27, 28] showed that the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ isotopic ratios recorded in group 2 oxide grains are better reproduced by the AGB models with masses $< 1.5M_\odot$ and advective mixing at plays, or by models with masses between 4.5 and $7M_\odot$ with the HBB (as proposed by [24]), but in the latter case, only for a specific set of nuclear physics inputs used in the calculations. In particular, using the reaction rates for $^{17}O + p$ indirectly measured via the THM, low-mass stars appear to be the most realistic progenitors for group 2 grains, whereas using the reaction rates measured underground by the LUNA Collaboration, the most realistic scenario involves somewhat more massive progenitors with the HBB. These reaction rates are different due to the different width measured for the 64.5 keV resonance, which in the first case is found to be smaller than previously estimated, and in the other, larger. The largest disagreement is for the (p, α) channel of the reaction, in this case, in the temperature range from 0.02 to 0.9 GK, the underground rate [29] is three times higher than the THM one [30], while the two reaction rates are in agreement, within their uncertainties, at both higher and lower energies. For details on the set of the reaction rates employed in calculation, see Table 1 of [27] and references therein.

From the stellar physics point of view, both low-mass and intermediate-mass models have free parameters that need to be fixed, but overall, both are solid. The HBB models may have a slight additional weakness, namely the need to consider dilution effects in order to best reproduce the grain abundances [24]. Therefore, there seems to be an impasse regarding the identification of the stellar progenitor of group 2 grains, or rather its mass, as it does not appear possible to determine which set of reaction rates included in the calculations is the most reliable.

The puzzle solution is provided by the need to reproduce the values of $^{26}Al/^{27}Al$ present in the samples, which can reach values of 0.1. High values of $^{26}Al/^{27}Al$ are attributed to an enrichment in ^{26}Al, which is synthesized in hydrogen-rich environments through the $^{25}Mg(p, \gamma)^{26}Al$ reaction. Since the cross section of this reaction at temperatures of $\sim 10^7$ K is smaller than that of proton capture on ^{17}O and ^{18}O, the temperatures at the bottom of the convective envelope in the AGB stars with masses of 4.5–$7M_\odot$ are too low to allow for a very efficient production of ^{26}Al. Therefore, the HBB is not the appropriate scenario for producing group 2 oxide grains, at least those enriched in ^{26}Al. On the contrary, a deep advective mixing active in the AGB stars with masses $< 1.5M_\odot$ is able to produce a sufficient increase in the surface abundances of ^{26}Al, making low-mass AGB stars the most plausible site for the production of the studied presolar grains [28]. Currently, no experimental data regarding the ^{25}Mg$(p,\gamma)^{26}$Al reaction contradict this hypothesis or suggest alternative formation sites for the grains.

4. β-decays effects on neutron capture nucleosynthesis

As the final case study of this review, we will now discuss the importance of knowing the neutron capture cross sections of radioactive isotopes and their β decay (and electron capture) rates in plasmas, for the study of nucleosynthesis of elements heavier than iron. To highlight the effects of uncertainties in nuclear physics inputs, we once again describe a relatively simple astrophysical environment: the AGB stars, as described in the previous paragraph, and their slow neutron capture nucleosynthesis. That is, the s-process, which shares with the r-process (rapid neutron capture) the synthesis of elements heavier than iron in the Galaxy.

The processes are classified as r (rapid) and s (slow) on the basis of the comparison between the timescale of neutron captures and the mean lifetime of the species involved. In the s-process, neutron fluxes are usually lower (10^5–10^{10} n/cm^{-3}), so an unstable nucleus is more likely to decay rather than undergo a further neutron capture. In contrast, during the r-process, the neutron fluxes are much higher ($\geq 10^{20}$ n/cm^{-3}), and unstable and increasingly heavier isotopes of the same element are produced before a cascade of β-decays begins. Although less common, the i-process (intermediate) can occur in astrophysical environments with peculiar conditions where neutron densities are $\sim 10^{15}$ n/cm^{-3}. The r-process nucleosynthesis occurs in exotic and explosive environments, such as type II supernovae and neutron star mergers, where very intense neutron fluxes are released over short timescales ($\tau \sim 1$ s). While the r-process path runs along the neutron-drip line, producing exotic species, the s-path takes place close to the valley of stability, driven by less intense but longer-lasting ($\tau \sim 10^4$ yr) neutron fluxes in more quiescent environments, such as the AGB stars or central or shell C-burning in more massive objects.

Due to its relative simplicity, the s-process nucleosynthesis exhibits characteristics strongly tied to the nuclear physics of the processes involved. Indeed, the abundance distribution of s-process isotopes and elements in the solar system reflects the trend of (n,γ) capture cross sections, with abundance peaks occurring for nuclei near shell closures and magic neutron numbers (as discussed in [31]). Crucial points in the s-process are found in key regions of the chart of nuclei, such as around $A = 50$ and $A = 82$, where branching points occur. In these points, unstable nuclei are synthesized, and their decay and neutron capture rates compete due to their close timescales. As a result, the nucleosynthesis path may continue toward the $A+1$ isotope of the same element or "jump" to the A isotope of the $Z+1$ element via a β-decay. The path followed by nucleosynthesis is determined by the decay rate, the neutron capture rate, and/or by the available neutron flux, which determine whether neutron capture or decay is more likely. Therefore, the isotopic ratios in the yields of nucleosynthesis are clear indicators of the physical conditions of the environment in which nucleosynthesis occurred.

As discussed in the previous section, detecting isotopic abundances (particularly of trace elements) through direct observations of stellar spectra is essentially impossible, especially for stars with cool envelopes like AGB stars, which emit primarily in the infrared. In this case as well, the lack of observational data is compensated by analyses of presolar grains found in ancient meteorites. For s-process nucleosynthesis products, the reference presolar grains are the SiC grains — silicon carbide grains, which include atoms of other elements within their lattice structure. Unlike oxide grains, the stellar origins of SiC, which form in carbon-rich stellar environments (C/O ≥ 1), are easily identifiable. The most populous group of SiC grains is the so-called MainStream (MS), which contains over 10,000 samples enriched in s-process elements [18]. It is precisely the presence of these elements that proves the AGB origins of those dusts. The AGB stars are, in fact, the exclusive site of production for the main component of the s-process, and the need for carbon-rich envelopes narrows the mass range of the progenitors of MS-SiC grains to $1.5M_\odot \leq M_\star \leq 3_\odot$, with solar metallicity or lower.

Among the isotopic abundances of MS-SiC grains, the ones for Sr are among the most difficult to reproduce. In particular, it is challenging to match the experimental data (the grains) with stellar model predictions in the so-called three-isotope plot, *i.e.* ^{88}Sr/^{86}Sr *versus* ^{84}Sr/^{86}Sr [32]. The problems are essentially twofold: *(i)* obtaining Sr isotopic ratios in the models that match those measured in the grains, and *(ii)* reproducing the grains abundances by models with C/O ≥ 1 (during the AGB phase, in fact, the surface C/O ratio increases, and often a star approaches the asymptotic giant branch with an oxygen-rich envelope, which then transforms into a carbon-rich over time). The stable isotopes of Sr belong to the region with $N=50$, and the s-process nucleosynthesis path downstream of Sr crosses two important branching points: the ^{86}Rb and, especially, the ^{85}Kr. The latter isotope, which can be populated both in its ground state and isomeric state, represents the most famous branching of the s-process. If the physical conditions favor the production of isomeric ^{85}Kr and/or low neutron fluxes, the ^{85}Kr produced by the s-process will predominantly decay into ^{85}Rb, and the nucleosynthesis path will proceed as $^{85}\mathrm{Kr} \to {}^{85}\mathrm{Rb} \to {}^{86}\mathrm{Rb} \to {}^{86}\mathrm{Sr} \to {}^{87}\mathrm{Sr}$. On the other hand, in the case of higher neutron fluxes, the nucleosynthesis path will proceed with a neutron capture on ^{85}Kr, following the sequence $^{85}\mathrm{Kr} \to {}^{86}\mathrm{Kr} \to {}^{87}\mathrm{Kr} \to {}^{87}\mathrm{Rb} \to {}^{88}\mathrm{Rb} \to {}^{88}\mathrm{Sr}$, and the ^{86}Sr and ^{87}Sr are bypassed (see figure 4 in [33]). Therefore, grains richer in ^{86}Sr and in ^{87}Sr than ^{88}Sr originate from cooler stellar environments (or, in any case, from regions with lower neutron densities), while grains poorer in ^{87}Sr come from stars with higher neutron densities.

To date, the (n,γ) capture cross sections for both $^{85}\mathrm{Kr}^g$ and $^{85}\mathrm{Kr}^m$ used in s-process nucleosynthesis calculations are not experimentally known but are estimated theoretically using software such as TALYS [34]. Similarly, the β-decay rates in plasmas are those reported in the theoretical compilation by Takashi and Yokoi [35]. Palmerini *et al.* [33] showed how the agreement between the measured Sr abundances in MS-SiC grains and the yields from the AGB model worsens if the latter is calculated, by keeping the stellar physics parameters unchanged, but using the state-of-the-art (as of [36]) cross sections for ^{84}Kr and ^{85}Kr, rather than those from a previous release of the Kadonis database [37]. This was due to the use of the most recent nuclear data set 60% of the nuclei captured on ^{84}Kr populate $^{85}\mathrm{Kr}^m$, then ^{86}Sr and ^{87}Sr are more efficiently synthesized than by employing the cross sections of [37], which lead instead to a branching of 40% and thus on a larger production of ^{88}Sr. It should be noted, however, that the same effect (*i.e.*, a better agreement between observational constraints and models) can also be achieved by using the most recent (and hopefully more precise) cross sections, but varying the decay rate of ^{85}Kr (for which, as a reminder, we only have a theoretical estimate from 1987).

Another crucial point on the s-process nucleosynthesis path is in the region with $N = 82$, from which one of the most typical products of the s-process comes from: the barium. Such an element is, in fact, mainly produced by slow neutron capture nucleosynthesis in the AGB stars, but despite a common agreement in the scientific community on its galactic source, the Ba isotopic distribution recorded in presolar grains is not so easy to be accounted for by nucleosynthesis models [38]. Among the main uncertainties affecting the prediction of Ba nucleosynthesis, there are the correct estimations of the Cs isotope time of life in stellar plasma conditions. The s-process nucleosynthesis paths to Ba indeed pass through the Cs isotopes, which are all unstable but the one with $A = 133$ (see figure 6 in [33]). In particular, ^{134}Cs, ^{135}Cs, and ^{136}Cs can be populated both in the ground state and in the isomeric state, and represent three successive branching points of the s-process. As a consequence, the relative abundances of ^{134}Ba, ^{135}Ba, ^{136}Ba, ^{137}Ba, and ^{138}Ba significantly reflect the physical conditions of the environment in which nucleosynthesis occurred. In addition to their uncertainties in the neutron capture cross sections (theoretically estimated but not measured) because they are unstable nuclei, the half-lives of ^{134}Cs and ^{135}Cs vary significantly with the temperature. For ^{134}Cs, the half-life in laboratory conditions is about 2 years, but at 3×10^8 K (a typical temperature of stellar environments where the s-process occurs), is enhanced by a factor of about 200 [35].

By two independent approaches, Taioli *et al.* [39] and Li *et al.* [40] demonstrated how the agreement between theoretical predictions and isotopic abundances in MS-SiC grains in the three-isotope plots of barium can be significantly improved by using new estimates for the mean lifetimes of ^{134}Cs and ^{135}Cs in stellar plasmas. Supporting the hypothesis that the key to solving the puzzle of barium isotopic abundances lies in nuclear physics, and most likely in the correct estimation of the mean lifetime of Cs isotopes at high temperatures, is the fact that the aforementioned authors arrive at similar results using a different approach to calculate the decay rates of the radioisotopes. Moreover, the stellar models used for the nucleosynthesis calculations are different and independent.

5. Conclusions

This paper presents three astrophysical case studies in which the nuclear physics inputs significantly affect the predictions of stellar evolution and nucleosynthesis. To emphasize the importance of the effects due to nuclear physics, as opposed to stellar physics, the examples refer to relatively simple astrophysical contexts that are easier to be studied and modeled, rather than exotic ones like neutron star mergers.

Nevertheless, it is evident that in the era of multimessenger astronomy, there are still classic topics of astrophysics that require new and more accurate data from experimental nuclear physics to be clarified. In particular, debates such as the presence (or absence) of a hindrance effect in the $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ fusion reaction require new experimental campaigns. Likely, direct underground measurements as the ones that will be carried out by LUNA at the Bellotti Facility at the Laboratori Nazionali del Gran Sasso [41], will provide the definitive answer. In the same way, the advent of RIBs facilities is enabling the measurement of neutron capture cross sections on unstable nuclei [42], often by indirect techniques, and storage rings and plasma traps like PANDORA at the Laboratori Nazionali del Sud [43, 44] will soon allow for the measurement of mean lifetimes in plasmas for many unstable isotopes, enabling the confirmation or refutation of the temperature dependence of their mean lifetimes.

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