

The impact of new (α , n) reaction rates on the weak s-process in metal-poor massive stars

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Date: 2025-07-16T00:00:00+00:00

Abstract

Massive stars are significant sites for the weak s-process (ws-process). ^{22}Ne and ^{16}O are, respectively, the main neutron source and poison for the ws-process. In the metal-poor stars, the abundance of ^{22}Ne is limited by the metallicity, so that the contribution of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction on the s-process is weaker. Conversely, the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction becomes more prominent in these stars due to the most abundant ^{16}O in all metallicities. In this work, we calculate the evolution of four metal-poor models ($Z=10^{-3}$) for the Zero-Age Main-Sequence (ZAMS) masses of $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$ to investigate the effect of reaction rates on the ws-process. We adopt the new $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ reaction rates suggested by Best et al. (2013) and $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ from Wiescher et al. (2023). The yields of the s-process isotope with updated reaction rates are compared with the results using default reaction rates from JINA REACLIB. We find that the new $^{17}\text{O}+\alpha$ reaction rates increase the ws-process mainly in all the stages, while the new $^{22}\text{Ne}+\alpha$ reaction rates only increase the ws-process in C and Ne burning stages. Updating these new reaction rates would increase the production of ws-process isotopes by tens of times. We also note that for more massive stars, the enhancement by new $^{17}\text{O}+\alpha$ reaction rates becomes more significant.

Full Text

Preamble

The Impact of New (α , n) Reaction Rates on the Weak s-Process in Metal-Poor Massive Stars

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Massive stars are significant sites for the weak s-process (ws-process). ^{22}Ne and ^{16}O are, respectively, the main neutron source and poison for the ws-process. In metal-poor stars, the abundance of ^{22}Ne is limited by metallicity, weakening the contribution of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction to the s-process. Conversely, the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction becomes more prominent in these stars due to the high abundance of ^{16}O at all metallicities.

In this work, we calculate the evolution of four metal-poor models ($Z = 10^{-3}$) with Zero-Age Main-Sequence (ZAMS) masses of $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$ to investigate the effect of reaction rates on the ws-process. We adopt the new $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ reaction rates suggested by Best et al. (2013) and the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ rates from Wiescher et al. (2023). The yields of s-process isotopes with these updated reaction rates are compared with results using default rates from JINA REACLIB. We find that the new $^{17}\text{O}+\alpha$ reaction rates enhance the ws-process at all evolutionary stages, while the new $^{22}\text{Ne}+\alpha$ rates only increase the ws-process during the C and Ne burning stages. Updating these reaction rates increases the production of ws-process isotopes by tens of times. We also note that for more massive stars, the enhancement from the new $^{17}\text{O}+\alpha$ reaction rates becomes more significant.

Keywords: massive stars, supernovae, s-process, nuclear reactions, nucleosynthesis

Introduction

Massive stars play a crucial role in galactic chemical evolution, synthesizing elements up to the iron group through charged-particle reactions during thermonuclear burning. The slow neutron capture process, or s-process, produces heavy elements in stars by allowing atomic nuclei to capture neutrons at a rate slow enough for unstable isotopes to undergo β -decay before capturing additional neutrons.

In massive stars with Zero-Age Main-Sequence (ZAMS) masses greater than approximately $12 M_{\odot}$, the weak s-process (ws-process) is a key mechanism for producing neutron-rich isotopes, particularly those in the atomic mass range $A = 60\text{--}90$ [?]. Early studies associated the ws-process primarily with core helium (He) burning [?, ?, ?, ?, ?, ?]. Later research identified significant production during shell carbon (C) burning, characterized by higher temperatures and neutron densities [?, ?, ?, ?]. More recent models include explosive nucleosynthesis during core-collapse supernovae (CCSNe), though these events have minimal

impact on ws-process yields [?, ?, ?, ?, ?]. Limongi and Chieffi [?] and Tur et al. [?] have shown that the yields of the ws-process are not strongly modified by the supernova explosion.

In contrast to the main s-process in asymptotic giant branch (AGB) stars, which relies on the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction, the ws-process in massive stars is driven by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction [?, ?, ?, ?]. The abundance of ^{22}Ne in the core He burning region is produced via the sequence $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$. The ws-process is activated by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction once the temperature exceeds 2.5×10^8 K ($T_9 = 0.25$). During shell C burning, this reaction is re-activated by α -particles produced via the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ channel [?]. Since ^{22}Ne is primarily synthesized through α -capture on ^{14}N , which itself derives from the initial metallicity of the star, one would expect the yields of ws-process elements to be low in metal-poor stars [?, ?]. However, recent observations by Aoki et al. [?, ?] and Chiappini et al. [?] found that ws-process elements in metal-poor stars are not as depleted as predicted. To account for this discrepancy, theoretical models have proposed that fast-rotating massive stars may enhance the production of ws-process elements. In these models, rotation can promote the mixing of ^{14}N from the H-rich envelope into the convective He-burning core, increasing the production [?, ?, ?].

Moreover, uncertainties in the $^{17}\text{O}+\alpha$ reaction rates significantly affect the yields of the ws-process, particularly in metal-poor stars where ^{16}O acts as a major neutron poison through the $^{16}\text{O}(n, \gamma)^{17}\text{O}$ reaction [?]. The subsequent competing reactions $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ determine whether neutrons are released or captured. Although recent studies have explored these effects in rotating stars [?, ?, ?], few have investigated the combined impact of $^{17}\text{O}+\alpha$ and $^{22}\text{Ne}+\alpha$ reactions in non-rotating metal-poor stars. Since ^{16}O is extremely abundant at all metallicities, the neutrons released by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction in metal-poor stars may be captured by ^{16}O instead of participating in the ws-process, leading to substantial production of ^{17}O . Therefore, the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction could play a much more important role.

In this study, we investigate the standard ws-process in non-rotating stars, specifically comparing these new reaction rates suggested in recent references with those in JINA REACLIB. We evaluate the implications of these new reaction rates on the standard ws-process, emphasizing how variations in these rates can significantly influence nucleosynthesis. In Section II, we present the parameters of our stellar models and compare the reaction rates from the new references with those from JINA REACLIB. In Section III, we use a model with $M(\text{ZAMS}) = 25 M_\odot$ as an example to illustrate the evolution of metal-poor stars. We further compare the effects of the $^{17}\text{O}+\alpha$ and $^{22}\text{Ne}+\alpha$ reactions on nucleosynthesis in Section IV. Finally, we conclude the study in Section VI.

II. Models and Input Physics

We employ the Modules for Experiments in Stellar Astrophysics (MESA, version 12778; Paxton et al. [?, ?, ?, ?, ?], Jermyn et al. [?]) to follow various nuclear burnings and the structural evolution of stars from ZAMS until Fe core collapse, when the infall velocity of the Fe core reaches 10^3 km s^{-1} . We focus only on nucleosynthesis before the explosion, as the final explosion makes only a slight modification to the ws-process abundance [?]. We calculate the evolution of four metal-poor stellar models with $M(\text{ZAMS}) = 15, 20, 25$, and 30 M using MESA. The trajectories of these models are utilized in the WinNet code [?] to investigate the effects of reaction rates on the ws-process. For the $^{17}\text{O}+\alpha$ reactions, we incorporate both competing channels, $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$, as reported by Best et al. [?]. The reaction rates for $^{22}\text{Ne}+\alpha$, including both the (α, n) and (α, γ) channels, are updated according to Wiescher et al. [?]. To assess the impact of these reactions, we compare four reaction recipes for each model, as listed in Table 1. The differences among these reaction rates will be discussed in Section II.A. Most physical parameters follow Xin et al. [?, ?] with some changes clarified in Section II.B. Section II.C will outline the setup within the WinNet code.

Table 1. The reaction recipes used in this work.

$^{22}\text{Ne}+\alpha$	$^{17}\text{O}+\alpha$
REACLIB	REACLIB*
REACLIB	Best et al. [?]
Wiescher et al. [?]	REACLIB
Wiescher et al. [?]	Best et al. [?]

JINA REACLIB Cyburt et al. [?].

Figure 1 [Figure 1: see original paper]. The $(\alpha, n)/(\alpha, \gamma)$ ratio as a function of temperature for $^{22}\text{Ne}+\alpha$ (top) and $^{17}\text{O}+\alpha$ (bottom) reactions.

A. Reactions for Weak s-Process

The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is active at $T = 0.2 \text{ GK}$ and 1.0 GK in He and C burning shells, respectively. This reaction competes with $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$, which consumes ^{22}Ne without releasing any neutrons. In these shells, ^{16}O is the most abundant isotope and acts as the main neutron poison through $^{16}\text{O}(n, \gamma)^{17}\text{O}$. Fortunately, the neutrons absorbed by ^{16}O can be released again via $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$. Therefore, the availability of neutrons for the ws-process is determined by the $(\alpha, n)/(\alpha, \gamma)$ ratio for both $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reactions.

In Figure 1, we show the $(\alpha, n)/(\alpha, \gamma)$ ratios for the $^{22}\text{Ne}+\alpha$ (top panel) and $^{17}\text{O}+\alpha$ (bottom panel) reactions as a function of temperature. In the top panel, the $(\alpha, n)/(\alpha, \gamma)$ ratio for $^{22}\text{Ne}+\alpha$, as recommended by Wiescher et al. [?], is

observed to be 1.2 to 2.0 times higher than the values provided by REACLIB below 1.5 GK, a range typically associated with He and C shell burning. Notably, this enhancement increases dramatically, reaching several tens of times above 1.5 GK. In the bottom panel, the $(\alpha, n)/(\alpha, \gamma)$ ratio for the $^{17}\text{O}+\alpha$ reaction suggested by Best et al. [?] is similar to REACLIB below 0.7 GK, where only He burns. However, this ratio rapidly increases to several tens of times in the C, Ne, and O layers. With these updated reaction rates, we anticipate an increase in neutron release from ^{22}Ne while reducing neutron consumption by ^{16}O . Consequently, the yields of ws-process isotopes are significantly enhanced.

B. Input Physics in MESA

Table 2 . Nuclides included in the nuclear reaction network of mesa_{161}.net.

Element	A_{min}	A_{max}	Element	A_{min}	A_{max}
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C. Post-processing Calculation with WinNet

The detailed nucleosynthesis in the stellar models is computed in post-processing using the extensive nuclear reaction network code WinNet [?]. The network consists of approximately 2000 isotopes from neutron and proton to thorium ($Z = 90$). The reaction rates for (n, γ) , (n, p) , (p, γ) , (α, n) , (α, p) , (α, γ) , and their inverse reactions from the JINA REACLIB database [?] are included. Theoretical weak rates from Langanke and Martínez-Pinedo [?], electron chemical potentials from Timmes and Arnett [?], and screening corrections from Kravchuk and Yakovlev [?] are used.

For each stellar model, we map the initial composition and time evolutions of temperature and density from the MESA simulation onto trajectories. The nucleosynthesis calculation of these trajectories is performed until the onset of core-collapse at the center. The region inside the steepest-density jump is expected to eventually collapse into a neutron star and not contribute to the yield of ws-process nucleosynthesis. The steepest density jump occurs at the most active burning shell and has been defined in Xin et al. [?]. We will briefly describe the MESA results in Section III. ^8Be is not included.

III. Pre-CCSN Evolution and Explodability

To achieve convergence of the model structures within approximately 10%, a nuclear network comprising at least 127 isotopes should be included [?]. In this work, we utilize a more extensive nuclear network (mesa_{161}.net) that incorporates additional neutron-rich isotopes. Table 2 lists all the isotopes in mesa_{161}.net. We adopt a metallicity of $Z = 0.1 Z_{\odot}$ and assume solar metallicity ratios based on the work of Anders and Grevesse [?].

We have enhanced both the temporal and spatial resolutions to ensure numerical convergence. The mass resolution is critical for accurately capturing changes in stellar structure [?, ?]. The parameter $\max_dq$ controls the maximum fractional mass of a cell in the model, and we set $\max_dq = 5 \times 10^{-4}$, which results in over 3,500 cells in the model. We adopt a minimum diffusion coefficient of $D_{\min} = 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ to ensure that the global mixing timescale ($\tau = L^2/D_{\min}$) is significantly longer than the lifetimes of the stellar models. This allows us to neglect the effects of global mixing and to smooth local composition gradients [?].

After C burning, the core structure becomes more complex because of multi-shell burning, with the central entropy being significantly influenced by shell burning (see Xin et al. [?]). To achieve finer granularity during the evolution, we impose limits on the changes in the logarithm of the central density and temperature. Specifically, we set $\delta \log_c < 10^{-3}$ and $\delta \log T_c < 2.5 \times 10^{-3}$. Additionally, we restrict the change in the mass fraction of isotopes with $dX_{\{\{nuc\}\}\{drop\}}\{\{limit\}\} = 3 \times 10^{-2}$, tightening this limit to $dX_{\{\{nuc\}\}\{drop\}}\{\{limit\}\}\{at\}\{high\}T = 10^{-2}$ when $\log T_c > 9.45$.

A. Evolution of Massive Stars

After core He burning, the mass fraction of ^{12}C in the center is smaller for stars with lower initial mass. Only a star with $M(\text{ZAMS}) = 15 \text{ M}_\odot$ can ignite convective C burning in the center, as it has sufficient fuel with $X(^{12}\text{C}) \sim 0.2$. In contrast, other models undergo contraction because the neutrino energy loss rate exceeds the energy production rate of C burning, as shown in Figure 2 [Figure 2: see original paper]. After Si burning, the star with $M(\text{ZAMS}) = 15 \text{ M}_\odot$ exhibits distinct behavior compared to other models because shell Si burning is energetic. However, the effects of shell Si burning are not the focus of this work and will be discussed elsewhere.

More massive stars eject more material but explode less frequently [?]. Considering the combined effects of ejected masses and event frequencies, stars with initial masses of $M(\text{ZAMS}) = 25 \text{ M}_\odot$ are regarded as the most significant contributors to the chemical enrichment of galaxies [?, ?]. Therefore, we select the model with $M(\text{ZAMS}) = 25 \text{ M}_\odot$ as a typical example for discussing stellar nucleosynthesis.

In Figure 7 [Figure 7: see original paper], we present the Kippenhahn diagram for the star with $M(\text{ZAMS}) = 25 \text{ M}_\odot$, tracking its evolution from H burning to Fe core collapse. The central temperature reaches approximately 0.2 GK at $\tau = t_{\text{final}} - t = 10^{5.6} \text{ yr}$. Here t is the time from ZAMS and t_{final} denotes the time at the final stage of evolution, defined as the moment when the infall speed of the iron core reaches 1000 km s^{-1} . The orange line indicates the isotherm of $T = 0.2 \text{ GK}$.

Figure 2 [Figure 2: see original paper]. The central temperature against

the central density for the evolution of stars with $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$. The grey dashed lines show the ignition lines of C burning, Ne burning, O burning, and Si burning, where the energy generation rate by nuclear burning equals the energy loss rate by neutrino emissions. In the region to the left of the black line, stars are dynamically unstable due to electron-positron pair creation (indicated as “pair instability”) [?], general relativistic effects (“GR instability”) (see, e.g., Osaki [?]), and the photo-disintegration of matter in nuclear statistical equilibrium (NSE) at $Y_e = 0.5$ (“photo-disintegration”) [?].

Figure 4 [Figure 4: see original paper]. The mass distribution of the main isotopes from MESA. The two grey regions indicate where $M_r \leq 1.84 M_{\odot}$ and $T \geq 0.2 \text{ GK}$.

Figure 3 [Figure 3: see original paper]. The Kippenhahn diagram of the star with $M(\text{ZAMS}) = 25 M_{\odot}$. The inner part of $M_r = 0-14 M_{\odot}$ is shown. The blue, grey, and pink regions represent convection, overshoot, and semiconvection, respectively. The orange line is the isotherm of 0.2 GK , and the red line shows the location of $M_r = 1.84 M_{\odot}$. Between these two lines, the hatched region indicates where the ws-process is taken into consideration.

The ws-process is assumed to occur interior to this isotherm. After core He burning, this region extends to $M_r \approx 6.0 M_{\odot}$, and the He and CO core masses are $7.8 M_{\odot}$ and $4.96 M_{\odot}$, respectively. C burning ignites off-center at $\tau = 100.5 \text{ yr}$, nearly 3 years before collapse. After $\tau = 10^{-3} \text{ yr}$ (10 hours before collapse), shell C burning merges with shell O burning at $M_r = 1.84 M_{\odot}$, marking the location of the highest energy generation rate as indicated by the red line. The inner part of this region is predicted to form a proto-neutron star (PNS), while the outer layers are ejected. Therefore, this paper considers only the ws-process isotopes produced in the hatched region.

Figure 4 illustrates the mass distribution of the main isotopes at $t = t_{\text{final}}$. The ws-process region extends from the Si/O interface to the bottom of the He burning shell, primarily composed of ^{16}O , ^{28}Si , ^{20}Ne , ^{12}C , and ^4He . The mass fraction of seed isotopes “Fe” ranges from 10^{-4} to 10^{-5} . Additionally, the neutron excess, expressed as $\eta = 1 - 2Y_e$, of the ws-process region is observed to be $10^{-3}-10^{-4}$, as shown in Figure 5. Interior to $M_r = 1.84 M_{\odot}$, the neutron excess increases rapidly toward the center, reaching $\eta \approx 0.2$ at the center. This jump is primarily attributed to reactions during O burning, including $^{16}\text{O}(^{16}\text{O}, n)^{31}\text{S}$ and weak interactions such as $^{30}\text{P}(e^+, \nu)^{30}\text{S}$, $^{33}\text{S}(e^-, \nu)^{33}\text{P}$, $^{35}\text{Cl}(e^-, \nu)^{35}\text{S}$, and $^{37}\text{Ar}(e^-, \nu)^{37}\text{Cl}$ [?].

Table 3 . The final mass, He core mass, CO core mass, and $M(V/U_{\text{max}})$ for each model. $M(\text{He})$ and $M(\text{CO})$ are defined at the layers where $X(\text{H})$ and $X(\text{He})$ fall below 10^{-4} .

$M(\text{ZAMS})$	$M(\text{final})$	$M(\text{He})$	$M(\text{CO})$	$M(V/U_{\text{max}})$
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IV. Nucleosynthesis and the Effect of Reaction Rates

A. The Nucleosynthesis in the 25 M Model

In this section, we present the results of the post-process nucleosynthesis and discuss the effects of updated reaction rates. We select a zone at $M_r = 2.3$ M as a representative example to reveal the changes in the mass fraction $X(i)$ of isotope i during each burning stage after updating these reactions. $X(\text{Ga-Zr})$ and $X(\text{Nb-Th})$ are the cumulative mass fractions of isotopes from Ga to Zr ($A = 31-40$) and Nb to Th ($A > 40$), respectively. The reaction rate recipes used in Figure 7 (a-d) correspond to cases 1-4 listed in Table 1. The chemical evolution of main isotopes is depicted in the top panel of Figure 7. The changes in $X(n)$ and ${}^4\text{He}$ for the default rates are displayed in the bottom panel of Figure 7(a), while in Figures 7(b)-(d), the values are normalized by $X_{\text{def}}(i)$ from Figure 7(a) to emphasize the effect of these reaction rates.

Table 4 . The total mass fraction of the “Ga-Zr” elements in the initial abundance (X_{ini}), after He burning ($X_{\text{He-b}}$), C burning ($X_{\text{C-b}}$), and Ne burning ($X_{\text{Ne-b}}$). The data is visualized in Figure 8 [Figure 8: see original paper] by the ratios of ΔX to X_{ini} , where ΔX is the change in mass fraction in each burning stage.

Overall, these reaction rates significantly alter the production of the “Ga-Zr” elements rather than the “Nb-Th” elements. We thus focus on the “Ga-Zr” elements in this section. The initial value of $X(\text{Ga-Zr})$ is $X_{\text{ini}} = 7.87 \times 10^{-8}$. Enhancements of $X(\text{Ga-Zr})$ are observed at four distinct times: at the end of He burning, the beginning of C burning, the end of C burning, and during Ne burning. These enhancements coincide with the neutron peaks and ${}^4\text{He}$ production shown in Figure 7.

After Ne burning, the total enhancement of $X(\text{Ga-Zr})$ is estimated by the ratio $(X_{\text{Ne-b}} - X_{\text{ini}})/X_{\text{ini}}$, where $X_{\text{Ne-b}}$ and X_{ini} are listed in Table 4. Compared with X_{ini} , $X(\text{Ga-Zr})$ increases by factors of 6.56, 23.77, 31.58, and 113.62 for cases (a)-(d), respectively. The forthcoming O burning will not enhance or may even reduce their production because of increased destruction at high temperatures [?].

When the default rates are used as in Figure 7(a), the “Ga-Zr” elements are mainly synthesized during the He (51%) and C (41%) burning stages (see Figure 8). Only 8% are synthesized during the Ne burning stage because the main neutron source isotope ${}^{22}\text{Ne}$ is almost exhausted.

With the new ${}^{17}\text{O} + \alpha$ reaction rates in Figure 7(c), more than 93% of the “Ga-Zr” elements are synthesized during the He and C burning stages, similar to case (a). The final $X(\text{Ga-Zr})$ is enhanced by a factor of 4.81 compared with default rates. Because both new ${}^{17}\text{O}(\alpha, n){}^{20}\text{Ne}$ and ${}^{17}\text{O}(\alpha, \gamma){}^{21}\text{Ne}$ reaction rates are lower than the default ones at temperatures below 0.7 GK (see Figure 15 [Figure 15: see original paper]), $X({}^{17}\text{O})$ reaches a higher level at the end of He burning with the new rates. When the temperature exceeds 0.7 GK, the $(\alpha, n)/(\alpha, \gamma)$

ratio increases. Therefore, the new $^{17}\text{O}+\alpha$ reaction rates significantly enhance the production of the “Ga-Zr” elements at all stages, though only slightly altering their contribution percentages.

Comparing Figure 7(a) and (b), the production of the “Ga-Zr” elements is enhanced by a factor of 23.8 when using the new $^{22}\text{Ne}+\alpha$ reaction rates. This is smaller than the increase obtained using the new $^{17}\text{O}+\alpha$ reaction rates. Since the new $^{22}\text{Ne}+\alpha$ rates are smaller than those in REACLIB (see Figure 14 [Figure 14: see original paper]), ^{22}Ne is not exhausted until core collapse. The $(\alpha, n)/(\alpha, \gamma)$ ratio of the new rates is 10 times higher than that of the default ones when the temperature exceeds 1.5 GK. A significant neutron rise is observed from six months before the explosion. As a result, almost 89% of the “Ga-Zr” elements are synthesized during C and Ne burning.

In Figure 7(d), both the new $^{17}\text{O}+\alpha$ and new $^{22}\text{Ne}+\alpha$ reaction rates are updated. The production of the “Ga-Zr” elements is enhanced by more than one order of magnitude. However, the contributions from He and Ne burning are only 10% and 18%, respectively, and most of the “Ga-Zr” elements are synthesized during the C burning stage, which should alter the isotopic composition of the “Ga-Zr” elements. Comparing (a, c) with (b, d), we also note that Ne burning contributes significantly to the ws-process only depending on the $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rate. Only when some ^{22}Ne still exists during the Ne burning stage can this occur.

Figure 9 displays the abundance distributions of s-process elements. We observe two distinct bumps in the abundance of both “Ga-Zr” and “Nb-Th” elements in the region $M_r = 2.2\text{--}5.9\text{ M}$. The first bump, located at $M_r = 2.0\text{--}3.6\text{ M}$, corresponds to the C, Ne, and O burning shells, while the second bump, found at $M_r = 5.0\text{--}5.9\text{ M}$, is associated with shell He burning. Between these two bumps, $X(\text{Ga-Zr})$ decreases due to low α -particle production in the unburned regions.

In Figure 10 [Figure 10: see original paper], the distribution of ^{21}Ne is similar to the “Ga-Zr” elements, while ^{22}Ne displays an opposite trend. Compared to the unburned shells, more ^4He is produced in the burning shells, which can consume ^{22}Ne and release more neutrons. The new $^{22}\text{Ne}+\alpha$ reaction rates enhance $X(\text{Ga-Zr})$ only in the first bump, whereas the new $^{17}\text{O}+\alpha$ reaction rates positively affect $X(\text{Ga-Zr})$ across all ws-process regions. Additionally, the new $^{17}\text{O}+\alpha$ reaction rates increase $X(\text{Nb-Th})$ by 50%, unlike the $^{22}\text{Ne}+\alpha$ reaction rates, since these elements are produced during the He burning stage. Notably, the sharp peak observed at $M_r = 1.84\text{--}2.0\text{ M}$ remains unaffected by both the $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates, as these “Ga-Zr” elements are generated through the NSE process.

In this section, we follow the variation of ws-process isotopes throughout the stellar evolution history and their mass distribution at the final stage for various reaction rate recipes. We find that both new $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates increase the production of ws-process isotopes. (1) The new $^{17}\text{O}+\alpha$ reaction

rates only increase neutron density by 3 times during the He and C burning stages. In contrast, the new $^{22}\text{Ne}+\alpha$ reaction rates increase the neutron density by several tens of times during the C and Ne burning stages. (2) The new $^{17}\text{O}+\alpha$ reaction rates do not vary the contribution in each burning stage. In contrast, the new $^{22}\text{Ne}+\alpha$ reaction rates significantly increase the contribution in the C and Ne burning stages but decrease it in the He burning stage. (3) Before the explosion, ws-process isotopes are primarily concentrated in the burning shells, with their abundances decreasing in the outer layers of the CO core. This is because there is no C burning in the outer layers of the CO core, so little ^4He is released.

B. The Mass Cut

In Figure 5, significant jumps in both density and Y_e are observed near the mass coordinate $M_r = 1.84 M_\odot$. This layer corresponds to the base of the shell O burning and represents the layer of peak energy generation. To measure the strength of shell burning, we use $V/U = d\ln M_r / d\ln(4\pi r^4 P)$, where U and V are defined in earlier studies [?, ?, ?, ?]. As explained in detail in Xin et al. [?], U relates to the degree of the density jump and V/U is the pressure gradient against M_r . The mass coordinate where V/U reaches its maximum is represented as $M(V/U_{\text{max}})$. The relation between V/U and the strength of shell burning is straightforward. When shell O burning is more energetic, it produces more energy to prevent contraction and even cause expansion of the outer layers, making the gradients of entropy and pressure against M_r (i.e., V/U) larger.

Figure 6 shows the distribution of $\log(V/U)$ against M_r at $\tau = t_{\text{final}}$ for each model. We note that $M(V/U_{\text{max}})$ coincides with M_4 , i.e., M_r at a specific entropy of $s = 4 \text{ erg g}^{-1} \text{ K}^{-1}$, previously used for the mass cut which would divide the inner proto-neutron star (PNS) and the outer ejecta in the explosion [?, ?, ?, ?]. In the present study, we adopt $M(V/U_{\text{max}})$ as the mass cut because it is the location of the steepest gradients of pressure and density [?]. The core masses and $M(V/U_{\text{max}})$ for our models are listed in Table 3.

B. The Integrated Yields

As indicated in Figure 7, the ws-process isotopes produced between the mass cut and the top of the He burning shell may contribute to the overall enhancement. We integrate all the isotopes in this region rather than the entire star. We assume that modifications to the ws-process yields in explosive nucleosynthesis can be ignored and that all radioactive isotopes decay into stable ones after the explosion. To investigate the sensitivity to reaction rates, such approximations are reasonable.

In Figures 11 and 12, we show the ratios between the yields with new reaction rates ($\text{yield}_{\text{new}}$) and those with default reaction rates ($\text{yield}_{\text{def}}$) for

$M(\text{ZAMS}) = 15, 20, 25, \text{ and } 30 \text{ M}$, respectively.

- (1) **From C to Zn:** With the new $^{22}\text{Ne}+\alpha$ reaction rates, we observe increases in the yields of several neutron-rich isotopes of Ne, Mg, Si, S, Ar, and Ca, particularly ^{25}Mg , $^{29,30}\text{Si}$, ^{36}S , ^{40}Ar , and ^{46}Ca . In Figure 14(b), the significant decrease in the $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rate at $T = 1.5\text{--}2.0 \text{ GK}$ (during Ne burning) reduces the yield of ^{26}Mg . As a result, a greater amount of ^{22}Ne is converted to ^{25}Mg , leading to a significant increase in neutron production during Ne burning. Consequently, the yields of $^{21,22}\text{Ne}$ increase due to neutron capture on ^{20}Ne . Similarly, some $^{29,30}\text{Si}$ and most of the rare isotopes ^{36}S , ^{40}Ar , and ^{46}Ca are also produced in the Ne burning shell [?]. In contrast, the new $^{17}\text{O}+\alpha$ reaction rates do not increase neutrons in the Ne shell, thus leaving the yields of those isotopes unchanged. The iron-peak isotopes remain unaffected by both new $^{17}\text{O}+\alpha$ and $^{22}\text{Ne}+\alpha$ reaction rates, as they are primarily produced by the NSE process at $M_{\text{r}} = 1.8\text{--}2.2 \text{ M}$, which is affected by Y_{e} . However, Y_{e} is only altered by weak interactions.
- (2) **From Ga to Zr:** Isotopes in this range are most significantly changed by the new reaction rates. The effect of the new $^{17}\text{O}+\alpha$ rates differs significantly from that of the new $^{22}\text{Ne}+\alpha$ rates. For the same element, the increases due to the new $^{17}\text{O}+\alpha$ reaction rates in the isotopic yields are similar. However, for the new $^{22}\text{Ne}+\alpha$ reaction rates, the yields of some isotopes with fewer neutrons are reduced. With enriched neutrons, the isotopic yields increase quickly. As $M(\text{ZAMS})$ increases, the enhancement due to the new $^{17}\text{O}+\alpha$ reaction rates also increases, while the enhancement due to the new $^{22}\text{Ne}+\alpha$ reaction rates is not obviously affected by $M(\text{ZAMS})$.
- (3) **From Mo to Bi:** Isotopes in this range are not significantly altered by the new reaction rates. The new $^{22}\text{Ne}+\alpha$ reaction rates increase the yields of only a few isotopes for the $M(\text{ZAMS}) = 15 \text{ M}$ models. The number of such isotopes increases only slightly for more massive models.

Figure 13 [Figure 13: see original paper]. The production factors of the elements from Cu to Zr. Each element is integrated from 15 to 30 $M_{\odot}$ with the Salpeter IMF with $\gamma = -2.35$.

In principle, the abundance of elements in the solar system arises from the cumulative contributions of numerous generations of stars with varying metallicities. Typically, stars in the range $0.1Z < Z < Z_{\odot}$ contribute more than 90% to the solar abundance [?]. It is common to use production factors (PFs) to identify which elements are significantly contributed by a generation of stars. The PF of element i is defined as follows:

$$\text{PF}_i = \frac{\sum_k Y_{i,k}^*}{\sum_k Y_k^*} \bigg/ \frac{X_{i,\odot}}{X_{\odot}}$$

where $X_{\{i\}}$ denotes the solar mass fraction of element i , Y_k represents the yield of element i averaged by the initial mass function (IMF) from Salpeter [?] with $\gamma = -2.35$, and the denominator runs over all elements and Y_k^* .

Figure 13 shows the production factors of the elements from Cu to Zr. Using the default and new $^{22}\text{Ne}+\alpha$ reaction rates, most elements are underproduced (green lines). However, when the new $^{17}\text{O}+\alpha$ reaction rates are included, the PFs from Zn to Rb increase by more than a factor of 0.5 dex. The contribution of stars with $0.1 Z$ to the solar abundance should be limited, as approximately 50% of the solar abundance is produced from stars with $0.5 Z < Z < Z$. Nevertheless, accounting for both new reaction rates leads to overproduction of Ga, Ge, As, and Se. Therefore, it is worth calculating models with $0.5 Z$ and Z to verify whether the predictions concerning these elements align with observational data. Given the considerable uncertainties involved, it is essential to enhance the measurement accuracy of the (α, n) reaction rate, especially for the $^{17}\text{O}+\alpha$ reactions.

V. Discussion

The primary purpose of this work is to evaluate the effect of the new $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates. However, the size of the nuclear network used in MESA is limited to 300 isotopes, making it challenging to cover all s-process isotopes. Therefore, the evolution and trajectories are based on the MESA calculation, but the detailed nucleosynthesis is based on WinNet. In this section, we discuss some uncertainties related to our calculations.

A. The Effect of Mixing

Nucleosynthesis in each zone is calculated separately because WinNet is a one-zone code. Thus, the effect of convective mixing is not taken into consideration. Mixing affects our results mainly in two aspects. On one hand, as seen in Figure 10, ^{22}Ne and ^{17}O are exhausted only in burning shells in the CO core because the abundance of α -particles is quite small in the unburned shells. In contrast, Figure 4 shows that mixing can transport ^{22}Ne and ^{17}O from unburned shells to burning shells in the region $M_r = 2.5\text{--}5.1 M_\odot$. As a result, more neutrons should be released in MESA calculations. Similarly, the ^{17}O left in Figure 4 is quite small.

Convective mixing can also affect the locations of the C, Ne, O, and Si burning shells. With mixing, more fresh fuel is transported from the outer layers to the bottom of the burning shells, extending the lifetimes of the burning shells. Thus, the bottom of shell O burning is located at $M_r = 1.84 M_\odot$ in Figure 4, while it moves to $M_r = 2.10 M_\odot$ in Figure 10. Similarly, the bases of the C and Ne shells are at $M_r = 2.0 M_\odot$, but shift to $M_r = 2.6$ and $2.7 M_\odot$ without mixing in WinNet.

B. The Effect of Explosion

As mentioned in Section III.B, we assume that the mass cut is located at $M(V/U_{\{\max\}})$ and that the region with $M_r > M(V/U_{\{\max\}})$ contributes to chemical enrichment. We also assume that ws-process isotopes produced in explosive nucleosynthesis would be destroyed by the shock during the explosion. Thus, we do not calculate explosive nucleosynthesis. The results from Tur et al. [?] show that explosive burning would reduce ws-process isotopes by less than 15%. Limongi and Chieffi [?] mentioned that for isotopes such as ^{70}Zn , ^{76}Ge , $^{74,77,82}\text{Se}$, ^{78}Kr , ^{87}Rb , and ^{84}Sr , more than 50% of the yields are produced during explosive burning. These isotopes should be changed significantly by the shock wave. Since the exact explosion mechanism of core-collapse supernovae is not well understood, the explosion energy and the choice of mass cut will also affect the final yields of those isotopes.

C. Other Effects

Since the ws-process occurs mainly during the He, C, and Ne burning phases, physical processes that affect these burning phases may also influence ws-process yields, such as reaction rates, convection, rotation, and magnetic fields [?]. Tur et al. [?] have shown that a 15% change in the 3α and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rates may change the yields of ws-process isotopes by more than a factor of 2. Limongi and Chieffi [?] presented a large number of rotating massive star models including ws-process nucleosynthesis. Their models cover $M(\text{ZAMS}) = 13\text{--}120\text{ M}_{\odot}$ and metallicities of $-3 \leq [\text{Fe}/\text{H}] \leq 0$. They find that the interplay between the He core and the H burning shell, triggered by rotation-induced instabilities, enhances the products of CNO cycling (especially ^{14}N) and produces more neutrons. As a result, the ws-process should be more significantly enhanced in rotating models.

VI. Conclusion

In this work, we investigate the impact of new $^{17}\text{O}+\alpha$ reaction rates from Best et al. [?] and new $^{22}\text{Ne}+\alpha$ reaction rates from Wiescher et al. [?] in comparison to the default reaction rates in JINA REACLIB. We calculate nucleosynthesis of approximately 2000 isotopes, ranging from neutron and proton to thorium ($Z = 90$), using the one-zone code WinNet and stellar models calculated with MESA for an initial metallicity of $Z = 0.1\text{ Z}_{\odot}$ and $M(\text{ZAMS}) = 15, 20, 25$, and $30\text{ M}_{\odot}$. All models evolved from ZAMS to Fe core collapse, when the infall speed of the Fe core reaches 10^8 cm s^{-1} . We assume that corrections from explosive nucleosynthesis to the yields are minor and that isotopes lying outside the mass cut ($M_r > M(V/U_{\{\max\}})$) contribute to the chemical enrichment of the Galaxy. The results are summarized as follows:

- (1) The new $^{22}\text{Ne}+\alpha$ reaction rates slightly suppress the ws-process during He burning, while the new $^{17}\text{O}+\alpha$ reaction rates have the opposite effect. Both significantly enhance the ws-process during C burning and Ne burn-

ing. Using the reaction recipes listed in Table 1, $X(\text{Ga-Zr})$ increases by factors of 6.56, 23.77, 31.58, and 113.62, respectively, after Ne burning (see Figure 8).

- (2) We note that without considering the effect of mixing, the mass distribution of ws-process isotopes provided by WinNet shows a two-bump shape (see Figure 9). This is because unburned layers release fewer neutrons than burning shells, resulting in underestimation of ws-process isotope yields. If ws-process nucleosynthesis were calculated coupled with stellar evolution instead of through post-processing, the enhancement of the ws-process should be more significant.
- (3) The new $^{17}\text{O}+\alpha$ reaction rates can increase the yields of all isotopes from Cu to Zr, with the enhancement being more pronounced in more massive stars. Conversely, the new $^{22}\text{Ne}+\alpha$ reaction rates only significantly enhance the yields of the most neutron-rich isotopes (see Figure 11).
- (4) We average these four initial masses with Salpeter's IMF and show the production factors (PFs) of elements from Cu to Zr. The new $^{17}\text{O}+\alpha$ reaction rates enhance the PFs more significantly than the new $^{22}\text{Ne}+\alpha$ reaction rates, especially for Ga, Ge, As, and Se. Considering the significant impact that the reaction rates from Best et al. [?] and JINA REACLIB have on the PFs of these elements, it is crucial to improve the accuracy and reliability of measurements of the $^{17}\text{O}+\alpha$ reaction rates. Additionally, further investigations are necessary to ascertain which reaction rate can best explain astronomical observations.

Appendix A: Reaction Rates from References

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Figure 14 [Figure 14: see original paper]. $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rates from different references. The blue line and light-blue shaded region represent the recommended reaction rate and uncertainties from Wiescher et al. [?]. The grey dashed line and grey region represent the recommended reaction rate and uncertainties from Longland et al. [?], which is adopted in the JINA REACLIB database. To show the difference, all data shown here are normalized by the recommended reaction rate from Longland et al. [?].

Figure 15 [Figure 15: see original paper]. $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ reaction rates from different references. The red line represents the recommended reaction rate from Best et al. [?], normalized by the default reaction rate in JINA REACLIB. The $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ reaction rates used in JINA REACLIB come from the NACRE database and CF88 database, respectively.

Note: Figure translations are in progress. See original paper for figures.

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