



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

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Abstract

Massive stars are significant sites for the weak s-process (ws-process). In metal-rich stars, ^{22}Ne and ^{16}O are, respectively, the main neutron source and poison for the ws-process. In metal-poor stars, however, the abundance of ^{22}Ne is limited by metallicity, so the contribution of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction on the s-process is smaller. Conversely, the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction becomes more prominent in these stars because of the most abundant ^{16}O at all metallicities. In this study, we calculated the evolution of four metal-poor stars ($Z = 10^{-3}$) 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 $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rates from Wiescher et al. (2023). The yields of the s-process isotopes with the updated reaction rates are compared with the results using the default reaction rates from JINA REACLIB. We found that the new $^{17}\text{O}+\alpha$ reaction rates enhance the ws-process in all stages, whereas the new $^{22}\text{Ne}+\alpha$ reaction rates enhance the ws-process only in the 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 the new $^{17}\text{O}+\alpha$ reaction rates becomes more significant.

Keywords Massive stars · Supernovae · S-process · Nuclear reactions · Nucleosynthesis

1 Introduction

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

In massive stars with zero-age main-sequence (ZAMS) masses greater than $\sim 12 M_{\odot}$, the weak s-process (ws-process) is a key mechanism for producing neutron-rich

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isotopes, particularly those in the atomic mass range of $A = 60\text{--}90$ [1]. Early studies associated the ws-process primarily with core helium (He) burning [2–7]. Later research identified significant production during shell carbon (C) burning, which is characterized by higher temperatures and neutron densities [8–11]. More recent models include explosive nucleosynthesis during core-collapse supernovae (CCSNe), although these events have minimal impact on ws-process yields [12–16]. Limongi and Chieffi [14] and Tur et al. [15] showed that the yields of the ws-process are not strongly modified by supernova explosions.

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 [2, 5, 17–19]. ^{22}Ne in core He burning is produced via a sequence of reactions, $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+ \nu)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$. The ws-process is activated by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction once the temperature exceeds 2.0×10^8 K. During shell C burning, this reaction is re-activated by α produced by the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ channel [20].

^{22}Ne is primarily synthesized by α -capture involving ^{14}N , whose amount depends on the initial metallicity of stars. Consequently, one would expect the yields of the ws-process elements to be low in metal-poor stars [6, 21]. However, recent observations found that the ws-process elements in metal-poor stars are not as low as previously predicted [22–24]. 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 core of He burning and increase their production [16, 24, 25].

Moreover, uncertainties in $^{17}\text{O}+\alpha$ 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 $^{16}\text{O}(n, \gamma)^{17}\text{O}$ reaction [26–28]. 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 [25, 29, 30], 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 across all metallicities, the neutrons released by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction in metal-poor stars are possibly captured by ^{16}O , instead of attending the ws-process, followed by a large amount of production of ^{17}O . Therefore, the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction could play a more important role.

In this study, we investigate the ws-process in non-rotating massive stars, specifically comparing the new reaction rates suggested in recent references with those in JINA REACLIB [31]. We evaluate the implications of these new reaction rates on the ws-process, emphasize how variations in these rates influence the nucleosynthesis. In Sect. 2, we

Table 1 The reaction recipes used in this work

Case	$^{17}\text{O}+\alpha$	$^{22}\text{Ne}+\alpha$
1	REACLIB*	REACLIB
2	REACLIB	Wiescher et al. [40]
3	Best et al. [39]	REACLIB
4	Best et al. [39]	Wiescher et al. [40]

* The $^{22}\text{Ne}+\alpha$ reaction rates adopted in JINA REACLIB come from Longland et al. [19], while 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 NACRE [27] and CF88 [28], respectively

present the parameters of our stellar models and compare the results using the reaction rates from the new references with those from JINA REACLIB. In Sect. 3, 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 Sect. 4. In Sect. 5, we discuss uncertainties in the reaction rates, mixing, explosion, and other effects. We conclude the study in Sect. 6.

2 Models and input physics

We employ the Modules for Experiments in Stellar Astrophysics (MESA, version 12778; Paxton et al. [32–36], Jermyn et al. [37]) to follow various nuclear burnings and the structure evolution in stars from ZAMS until the Fe core collapse, when the infall velocity of the Fe core reaches 10^3 km s^{-1} . We only focus on nucleosynthesis before the explosion, as the final explosion makes only a slight modification of the ws-process abundance [15].

We calculate the evolution of four metal-poor stellar models of $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$ with MESA¹. The trajectories of these models are utilized in the WinNet code [38] to investigate the effects of the reaction rates on the ws-process. For the $^{17}\text{O}+\alpha$ reactions, we incorporate both competing reactions, $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ and $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$, as reported by Best et al. [39]. The reaction rates for $^{22}\text{Ne}+\alpha$, including both the (α, n) and (α, γ) reactions, are updated according to Wiescher et al. [40]. 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 are discussed in Sect. 2.1. Most physical parameters follow Xin et al. [41, 42] with some changes clarified in Sect. 2.2. Section 2.3 outlines the setup within the WinNet code.

¹ All these models are available on Zenodo at [10.5281/zenodo.17021896](https://zenodo.org/record/17021896)

2.1 Reactions for weak s-process

The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is active at $T \sim 0.2$ 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 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 Fig. 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 the temperature. In the top panel, the $(\alpha, n)/(\alpha, \gamma)$ ratio for $^{22}\text{Ne}+\alpha$, as recommended by Wiescher et al. [40], 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.

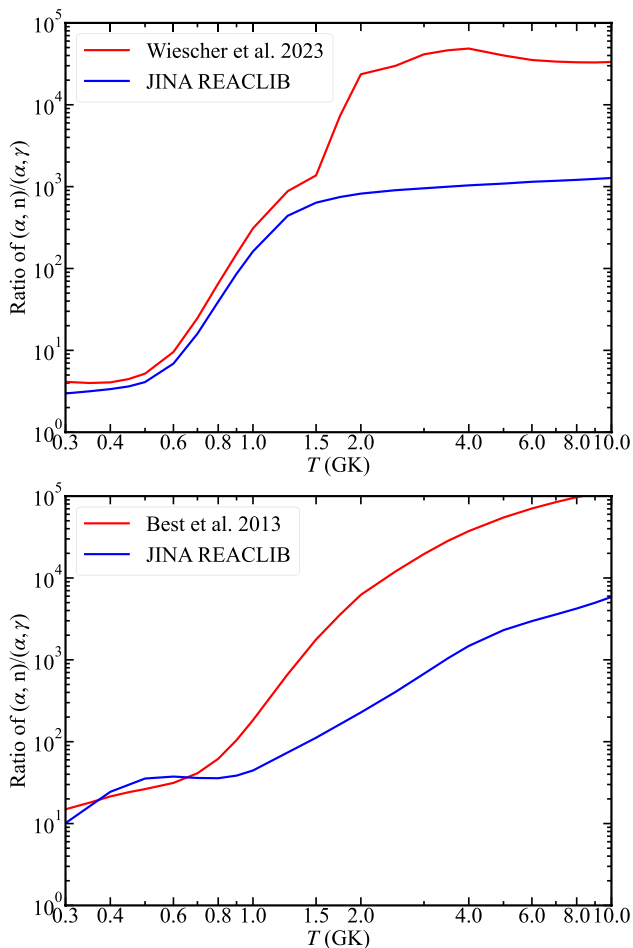


Fig. 1 (Color online) The $(\alpha, n)/(\alpha, \gamma)$ ratio as a function of temperature for $^{22}\text{Ne}+\alpha$ (top) and $^{17}\text{O}+\alpha$ (bottom) reactions

In the bottom panel, the $(\alpha, n)/(\alpha, \gamma)$ ratio for the $^{17}\text{O}+\alpha$ reaction suggested by Best et al. [39] is similar to REACLIB below 0.7 GK, where only He burns, but 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 the ws-process isotopes were significantly enhanced.

2.2 Input physics in MESA

To achieve the convergence of the model structures within approximately 10%, a nuclear network comprising at least 127 isotopes should be included [43]. In this study, we utilized 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 [44].

We enhanced both the temporal and spatial resolutions to ensure numerical convergence. The mass resolution is critical for accurately capturing changes in the stellar structure [43, 45]. The parameter `max_dq` controls the maximum fractional mass of a cell in the model, and we set `max_dq=5d-4`, which resulted in over 3,500 cells in the model. We adopted a minimum diffusion coefficient of $D_{\min} = 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ to ensure that the global mixing timescale ($\tau = L^2/D_{\min}$) was significantly longer than the lifetimes of

Table 2 Nuclides included in the nuclear reaction network of `mesa_161.net`

Element	$A_{\min}$	$A_{\max}$	Element	$A_{\min}$	$A_{\max}$
n	1	1	S	31	35
H	1	2	Cl	35	38
He	3	4	Ar	35	40
Li	7	7	K	39	44
Be ^a	7	10	Ca	39	46
B	8	8	Sc	43	48
C	12	13	Ti	43	51
N	13	15	V	47	53
O	14	18	Cr	47	57
F	17	19	Mn	51	57
Ne	18	22	Fe	51	61
Na	21	24	Co	55	63
Mg	23	26	Ni	55	64
Al	25	28	Cu	59	64
Si	27	31	Zn	60	64
P	30	33			

^aBe is not included

the stellar models. This allows us to neglect the effects of global mixing and smooth local composition gradients [45].

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. [42]). To achieve finer granularity during evolution, we imposed limits on the changes in the logarithm of the central density and temperature. Specifically, we set $\delta_{\log \rho_c} < 10^{-3}$ and $\delta_{\log T_c} < 2.5 \times 10^{-3}$. Additionally, we restrict the change in the mass fraction of isotopes with $\text{d}X_{\text{nuc_drop_limit}} = 3 \times 10^{-2}$ and tightening this limit to $\text{d}X_{\text{nuc_drop_limit_at_high_T}} = 10^{-2}$ when $\log T_c > 9.45$.

2.3 Post-processing calculation with WinNet

The detailed nucleosynthesis in the stellar models was computed in post-processing using an extensive nuclear reaction network code, WinNet [38]. The network consists of approximately 2000 isotopes from neutron and proton to thorium ($Z = 90$). The reaction rates of (n, γ) , (n, p) , (p, γ) , (α, n) , (α, p) , (α, γ) , and their inverse reactions from the JINA REACLIB database [31] were included. Theoretical weak rates from Langanke and Martínez-Pinedo [46], electron chemical potentials from Timmes and Arnett [47], and screening corrections from Kravchuk and Yakovlev [48] were used.

For each stellar model, we mapped the initial composition and time evolution of the temperature and density from the MESA simulation on the trajectories. The nucleosynthesis calculation of these trajectories was performed until the onset of iron core collapse. The region inside the steepest density jump is expected to eventually collapse into a neutron star and does not contribute to the yield of the w -process nucleosynthesis. The steepest density jump occurs at the most active burning shell and has been defined by Xin et al. [42]. We briefly describe the MESA result in Sect. 3.

3 Pre-CCSN evolution and explodability

3.1 Evolution of massive stars

In Fig. 2, we show the central temperature against the central density for the evolution of stars with $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$. The gray dashed lines show the ignition lines of C, Ne, O, 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 owing to electron–positron pair creation (indicated as “pair instability”) (Ohkubo et al. [49]), general relativistic effects (“GR instability”) (see, for example, Osaki [50]), and the photo-disintegration of matter in nuclear statistical equilibrium (NSE) at $Y_e = 0.5$ (“photo-disintegration”) (Ohkubo et al. [49]).

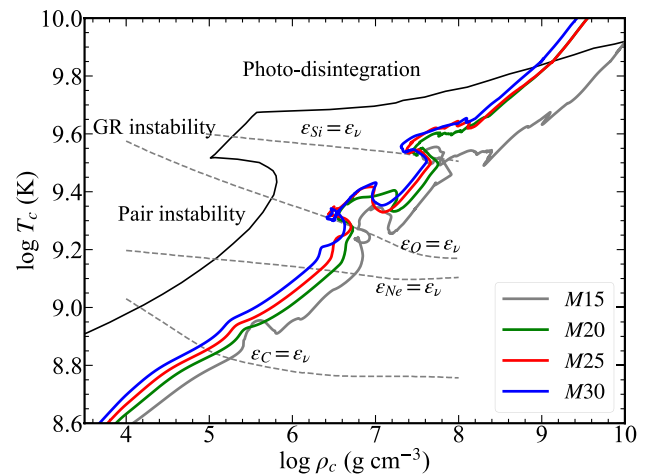


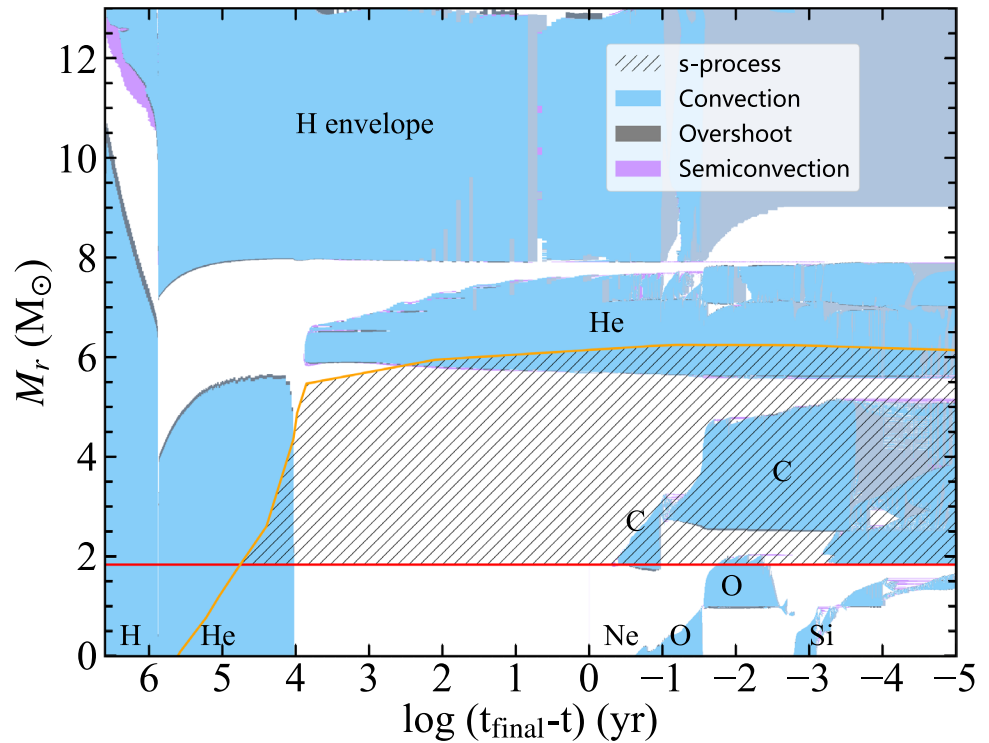
Fig. 2 (Color online) The central temperature against the central density for the evolution of stars with $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$. The gray dashed lines show the ignition lines of C, Ne, O, and Si burning, where the energy generation rate by nuclear burning equals the energy loss rate by neutrino emissions. In the region to the left of the black line, stars are dynamically unstable owing to electron–positron pair creation (indicated as “pair instability”) (Ohkubo et al. [49]), general relativistic effects (“GR instability”) (see, for example, Osaki [50]), and the photo-disintegration of matter in nuclear statistical equilibrium (NSE) at $Y_e = 0.5$ (“photo-disintegration”) (Ohkubo et al. [49])

(“photo-disintegration”) (Ohkubo et al. [49]). After core He burning, the mass fraction of ^{12}C in the center is smaller for larger $M(\text{ZAMS})$. Only the star with $M(\text{ZAMS}) = 15 M_{\odot}$ 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 with larger $M(\text{ZAMS})$ undergo contraction because the neutrino energy loss rate exceeds the energy production rate of C burning. After Si burning, the star with $M(\text{ZAMS}) = 15 M_{\odot}$ 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 study and will be discussed in future works.

More massive stars eject more materials but explode less frequently [51]. Considering the combined effects of ejected masses and event frequencies, stars with $M(\text{ZAMS}) = 25 M_{\odot}$ are regarded as the most significant contributors to the chemical enrichment of galaxies [21, 52]. Therefore, we select the model of $M(\text{ZAMS}) = 25 M_{\odot}$ as a typical example for discussing stellar nucleosynthesis.

In Fig. 3, we present the Kippenhahn diagram for the star with $M(\text{ZAMS}) = 25 M_{\odot}$, tracking its evolution from H burning to Fe core collapse. The central temperature reaches approximately 0.2 GK at $\tau = t_{\text{final}} - t = 10^{5.6}$ yr. Here, t is the time from the ZAMS and t_{final} denotes the time at the final stage of evolution, which is defined as the moment when the infall speed of the Fe core reaches 1000 km s^{-1} . The orange line indicates the isotherm at $T = 0.2 \text{ GK}$.

Fig. 3 (Color online) 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. Blue, gray, and pink represent the convection, overshoot, and semiconvection regions, respectively. The orange line is the isotherm line 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 considered



The ws-process is assumed to occur interior to this isotherm. After core He burning, this region extends to $M_r \sim 6.0 M_{\odot}$, and the He and CO core masses are 7.8 and $4.96 M_{\odot}$, respectively. C burning ignites off-center at $\tau = 10^{0.5}$ yr, nearly three years before the collapse. After $\tau = 10^{-3}$ yr (10 h 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), whereas the outer layers are ejected. Therefore, this study considers only the ws-process isotopes produced in the hatched region.

Figure 4 illustrates the mass distributions 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 the iron-group elements ranges from 10^{-4} to 10^{-5} . Additionally, the neutron excess, expressed as $\eta = 1 - 2Y_e$, of the ws-process region was observed to be 10^{-3} – 10^{-4} , as shown in Fig. 5. In the interior to $M_r = 1.84 M_{\odot}$, the neutron excess increases rapidly toward the center, reaching $\eta \sim 0.2$ at the center. This jump is primarily attributed to the reactions during O burning, including $^{16}\text{O}(^{16}\text{O}, n)^{31}\text{S}$ and the 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 $^{37}\text{Ar}(e^-, \nu)^{37}\text{Cl}$ [53].

3.2 The mass cut

In Fig. 5, prominent jumps in both the density and Y_e are observed near the mass coordinate $M_r = 1.84 M_{\odot}$. This layer corresponds to the base of shell O burning, which is the layer of peak energy generation. To measure the strength of shell burning, we use

$$\frac{V}{U} = -\frac{d \ln P}{d \ln M_r} = \frac{GM_r^2}{4\pi r^4 P} \quad (1)$$

where U and V are defined in earlier studies [54–57].

As explained in detail by Xin et al. [42], U is related to the degree of the density jump, and V/U is the pressure gradient against M_r . The mass coordinate at which V/U reaches its maximum is represented as $M(V/U_{\text{max}})$. The relationship between V/U and the strength of shell burning is straightforward. When shell O burning is more energetic, it produces higher energy to prevent the contraction and even to cause the expansion of outer layers, which makes 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 , that is, M_r at a specific entropy of $s = 4$ erg $\text{g}^{-1}\text{K}^{-1}$, which was previously used for the mass cut that would divide the inner proto-neutron star (PNS) and the outer ejecta in the explosion [58–61]. 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 [42].

Fig. 4 (Color online) The mass distribution of the main isotopes at $t = t_{\text{final}}$ from MESA. The two gray regions indicate where $M_r \leq 1.84 M_\odot$ and $T \leq 0.2$ GK, respectively

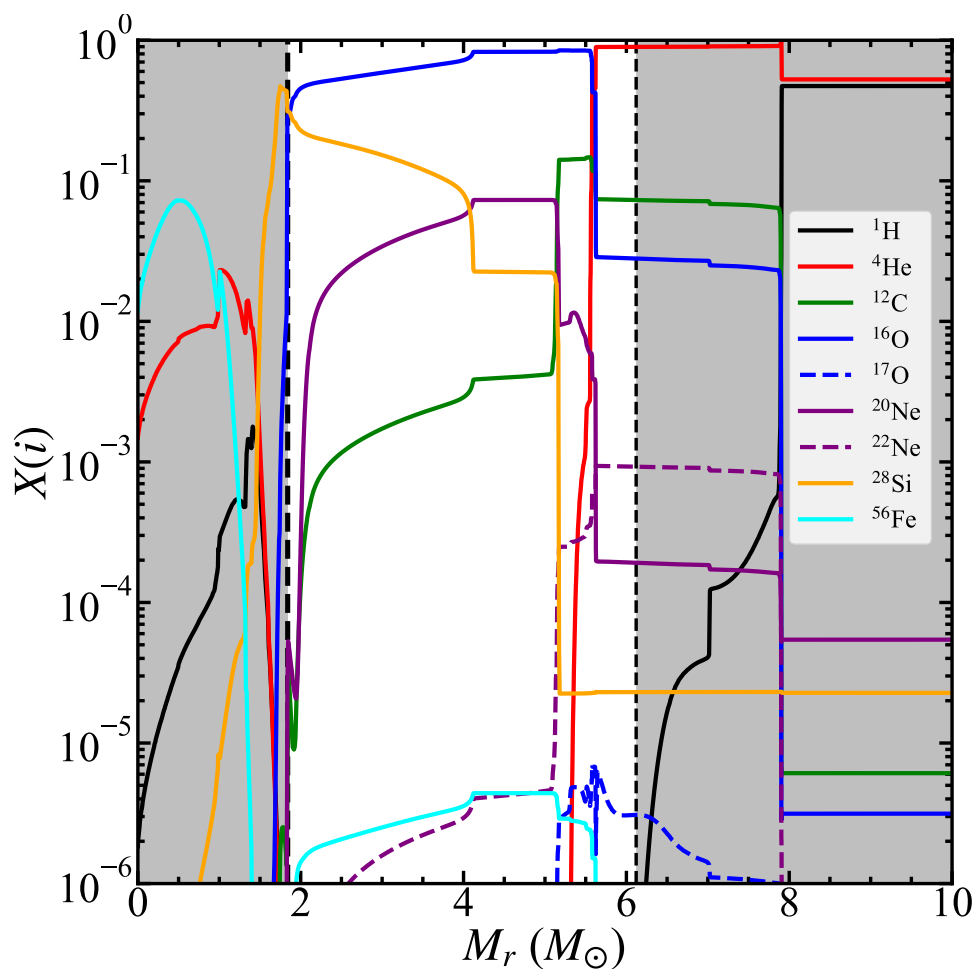
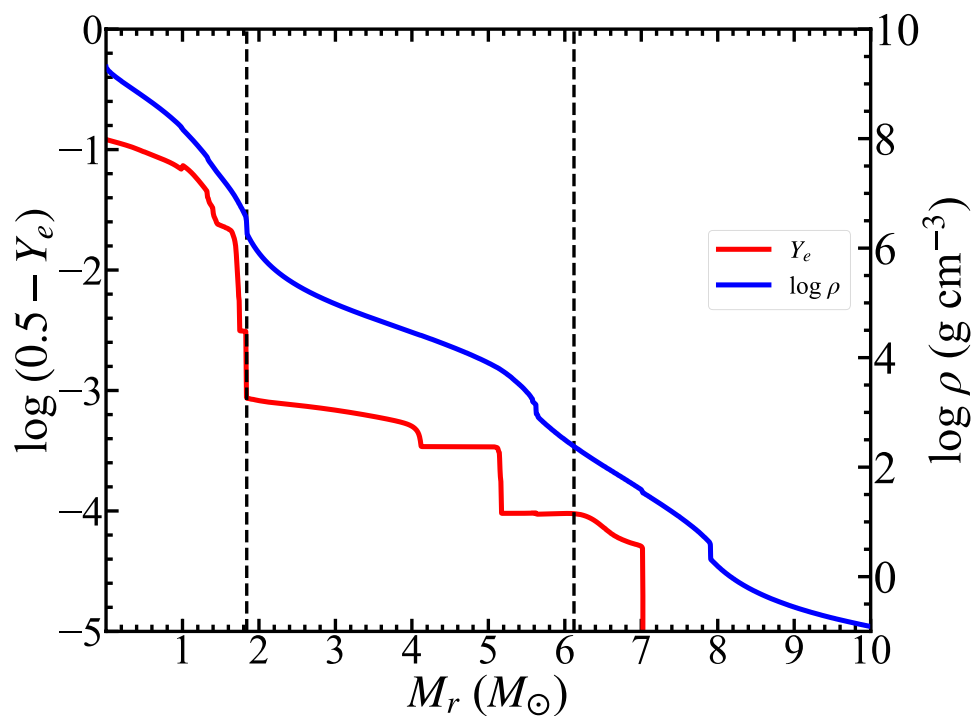


Fig. 5 (Color online) The mass distribution of the Y_e (red) and $\log \rho$ (blue) at $t = t_{\text{final}}$. The two black lines indicate where $M_r = 1.84 M_\odot$ and $T = 0.2$ GK, respectively



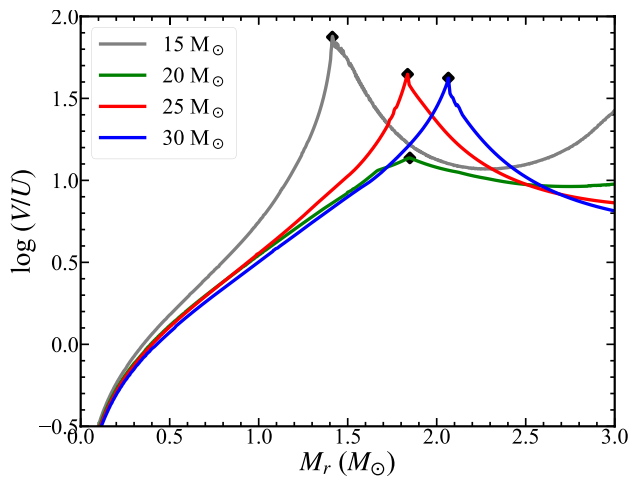


Fig. 6 (Color online) The mass distribution of $\log V/U$ at $t = t_{\text{final}}$. The black diamonds represent the location of M_4 , which is defined at the mass coordinate of specific entropy $s = 4 \text{ erg g}^{-1} \text{K}^{-1}$

The core masses and $M(V/U_{\text{max}})$ values for our models are listed in Table 3.

4 Nucleosynthesis and the effect of reaction rates

4.1 The nucleosynthesis in the $25 M_{\odot}$ model

In this section, we present the results of post-process nucleosynthesis and discuss the effects of the updated reaction rates.

We selected a zone at $M_r = 2.3 M_{\odot}$ as a representative example to reveal the change in the mass fraction $X(i)$ of isotope i occurring during each burning stage after updating the (α, n) reaction rates. $X(\text{Ga-Zr})$ and $X(\text{Nb-Th})$ are the cumulative mass fractions of isotopes from Ga to Zr ($Z = 31 - 40$) and Nb to Th ($Z > 41 - 90$), respectively. The reaction rate recipes used in Fig. 7a–d correspond to cases 1–4 listed in Table 1. The chemical evolution of the main isotopes is depicted in the top panel of Fig. 7. The changes in

$X(n)$ and ${}^4\text{He}$ for the default rates are displayed in the bottom panel of Fig. 7a, while in Fig. 7b–d, the value is normalized by $X_{\text{def}}(i)$ in Fig. 7a to emphasize the effect of these reaction rates. Table 4 lists 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 are visualized in Fig. 8 by the ratios of ΔX to X_{ini} , where ΔX is the change in the mass fraction in each burning stage.

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

After Ne burning, the total enhancement of $X(\text{Ga-Zr})$ is estimated by the ratio of $(X_{\text{Ne-b}} - X_{\text{ini}})/X_{\text{ini}}$, where $X_{\text{Ne-b}}$ and X_{ini} are listed in Table 4. Compared with X_{ini} , $X(\text{Ga-Zr})$ increases by a factor of 6.56, 23.77, 31.58, and 113.62 for (a)–(d), respectively. The forthcoming O burning will not enhance but rather reduce their abundance because of the increased destruction at high temperatures [15].

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

With the new ${}^{17}\text{O} + \alpha$ reaction rates in Fig. 7c, more than 93% of the “Ga-Zr” elements are synthesized during the He and C burning stages, which is similar to (a). The final $X(\text{Ga-Zr})$ is enhanced by a factor of 4.81 compared to the 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 Sect. 5.1), $X({}^{17}\text{O})$ reaches a higher level at the end of He burning with the new rates. When the temperature exceeds 0.7 GK, the ratio of $(\alpha, n)/(\alpha, \gamma)$ increases significantly. Therefore, the new ${}^{17}\text{O} + \alpha$ reaction rates significantly enhanced the production of the “Ga-Zr” elements at all stages, although only slightly alter their contribution percentages.

Comparing Fig. 7a and b, the production of the “Ga-Zr” elements is enhanced by a factor of 23.8 using the new ${}^{22}\text{Ne} + \alpha$ reaction rates. This is smaller than the increase in using the new ${}^{17}\text{O} + \alpha$ reaction rates. Because the new ${}^{22}\text{Ne} + \alpha$ rates are smaller than those in REACLIB (see Fig. 14), ${}^{22}\text{Ne}$ is not exhausted until the core collapse. The $(\alpha, n)/(\alpha, \gamma)$ ratio of the new rates is 10 times higher than that of the default rates when the temperature exceeds 1.5 GK. A significant increase in neutron levels was observed six months

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

$M(\text{ZAMS})$ $M_{\odot}$	$M(\text{final})$ $M_{\odot}$	$M(\text{He})$ $M_{\odot}$	$M(\text{CO})$ $M_{\odot}$	$M(V/U_{\text{max}})$ $M_{\odot}$
15	14.88	4.66	2.39	1.41
20	19.79	6.25	3.85	1.85
25	24.73	7.80	4.96	1.84
30	29.50	9.86	6.76	2.07

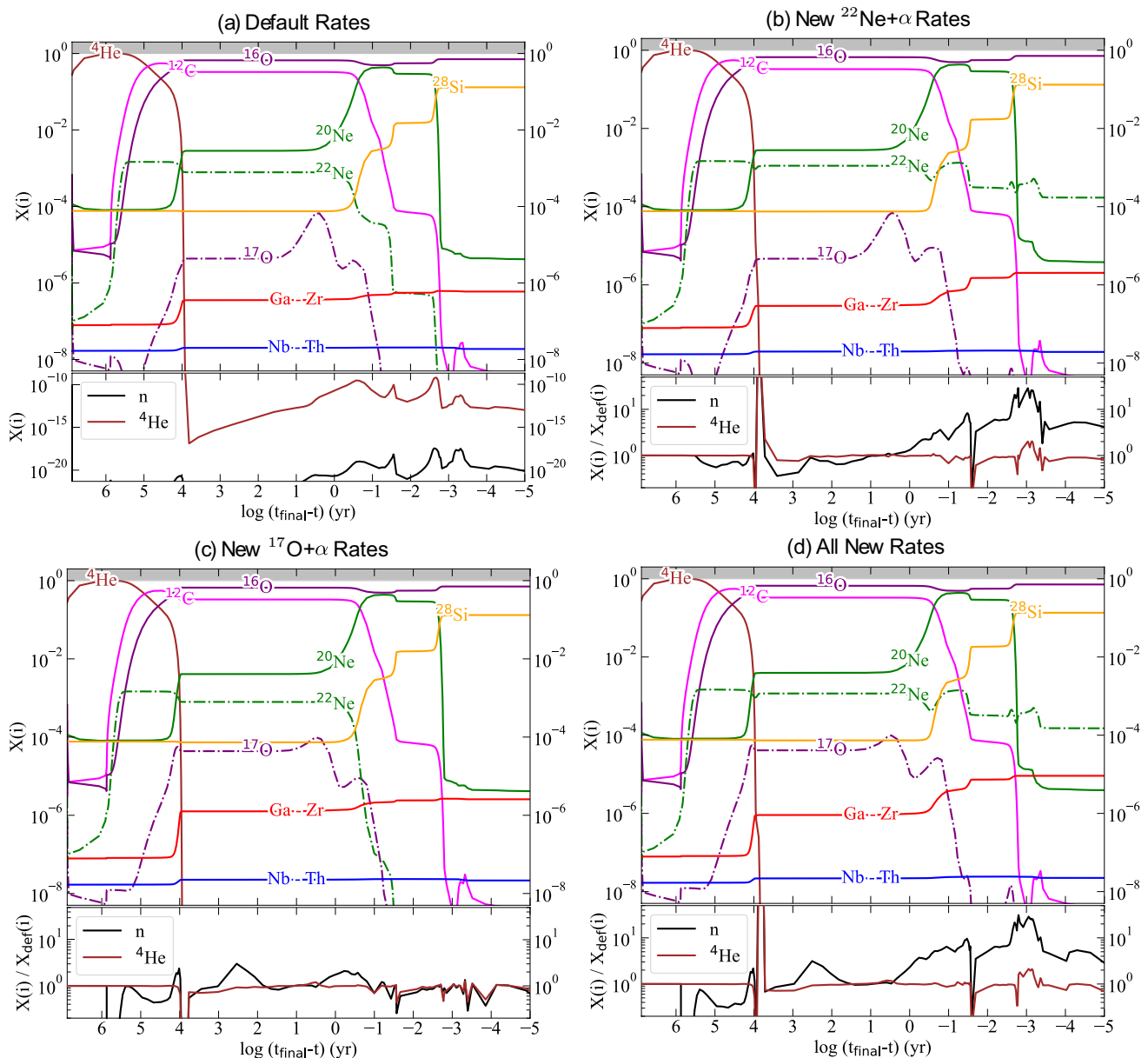


Fig. 7 (Color online) Chemical evolution in the OSi shell ($M_r = 2.3 M_\odot$). In the top panels of (a–d), changes in the mass fractions $X(i)$ of ^4He , ^{12}C , ^{16}O , and ^{20}Ne show the burning stages. $X(\text{Ga–Zr})$ and $X(\text{Nb–Th})$ are the cumulative mass fractions of the s-process isotopes from

Ga to Zr ($Z = 31 - 40$) and Nb to Th ($Z = 41 - 90$), respectively. In the bottom panel, the changes in $X_{\text{def}}(i)$ of neutrons and ^4He for the default rates are shown in (a). In (b–d) shown are the changes in the ratios $X(i)/X_{\text{def}}(i)$ between the “new” and default rates for n and ^4He

before the explosion. As a result, almost 89% of the “Ga–Zr” elements are synthesized during C and Ne burning.

In Fig. 7d, both the new $^{17}\text{O} + \alpha$ and new $^{22}\text{Ne} + \alpha$ reaction rates are updated. The production of the “Ga–Zr” elements was enhanced by more than one order of magnitude. However, the contributions of 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 isotope composition of the “Ga–Zr” elements. By

comparing (a, c) with (b, d), we can also determine whether Ne burning contributes significantly to the ws-process, depending on the $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rate.

Figure 9 shows the abundance distributions of the s-process elements. We observe two distinct bumps in the abundance of both “Ga–Zr” and “Nb–Th” in the region of $M_r = 2.2 - 5.9 M_\odot$. The first bump, located at $M_r = 2.0 - 3.6 M_\odot$, corresponds to the C, Ne, and O burning shells, while the second bump, found at $M_r = 5.0 - 5.9 M_\odot$, is associated

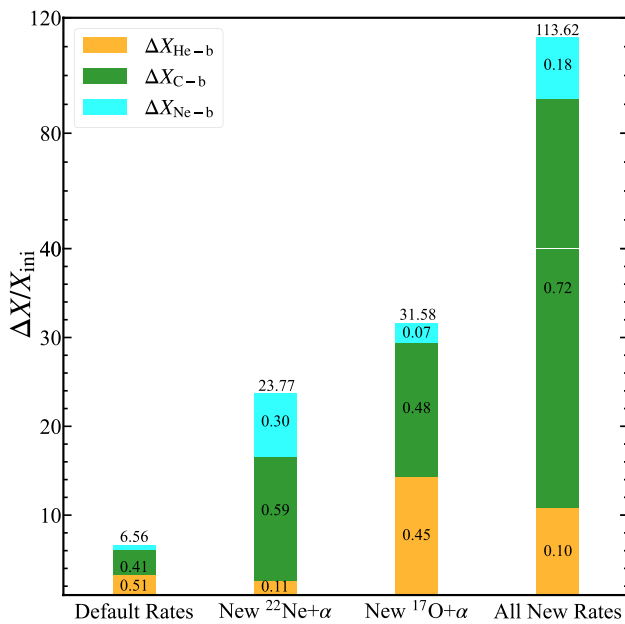


Fig. 8 (Color online) The total mass fraction of the ws-process isotopes from $A = 31 - 40$ after He, C, and Ne burning. All values are normalized by the initial abundance, $X_{\text{ini}} = 7.87 \times 10^{-8}$. The total value is written above each pillar, and the fractional contribution of each burning stage is written in the center of the box

Table 4 The total mass fractions of the ws-process isotopes of $Z = 31 - 40$ in the initial abundance, after He burning, C burning, and Ne burning stages, respectively, in Fig. 7

Figure	X_{ini}	$X_{\text{He-b}}$	$X_{\text{C-b}}$	$X_{\text{Ne-b}}$
7a	7.87×10^{-8}	3.42×10^{-7}	5.55×10^{-7}	5.95×10^{-7}
7b	7.87×10^{-8}	2.87×10^{-7}	1.38×10^{-6}	1.95×10^{-6}
7c	7.87×10^{-8}	1.21×10^{-6}	2.39×10^{-6}	2.56×10^{-6}
7d	7.87×10^{-8}	9.34×10^{-7}	7.34×10^{-6}	9.02×10^{-6}

with shell He burning. Between these two bumps, X (Ga-Zr) decreases owing to low α production in the unburned regions.

In Fig. 10, 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 enhanced X (Ga-Zr) only in the first bump, whereas the new $^{17}\text{O}+\alpha$ reaction rates positively affected X (Ga-Zr) across all the ws-process regions. Additionally, the new $^{17}\text{O}+\alpha$ reaction rates increase X (Nb-Th) by 50%, unlike the $^{22}\text{Ne}+\alpha$ reaction rates, because these elements are produced during the He burning stage. Notably, the sharp peak observed at $M_r = 1.84 - 2.0 M_\odot$ 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 the ws-process isotopes throughout the stellar evolution history and their mass distribution at the final stage for various reaction networks. We found that both the new $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates increased the production of ws-process isotopes.

(1) The new $^{17}\text{O}+\alpha$ reaction rates only increase neutron density by ~ 3 times during 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.

(2) The new $^{17}\text{O}+\alpha$ reaction rates does 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 that in the He burning stage.

(3) Before the explosion, the 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, and thus, little ^4He is released.

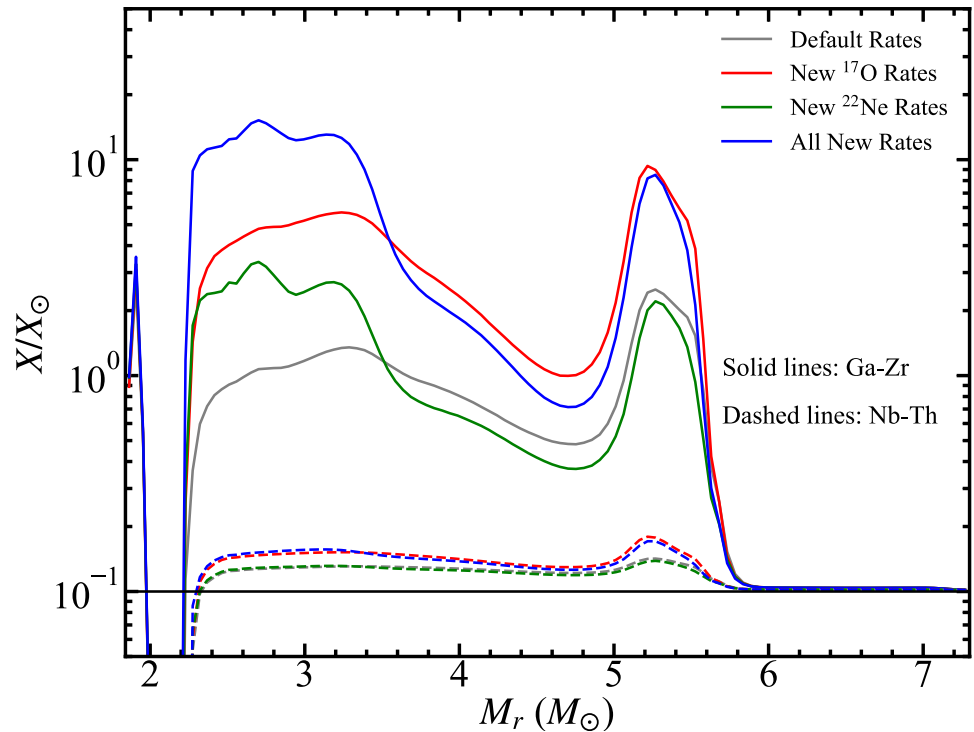
4.2 The integrated yields

As indicated in Fig. 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 integrated all isotopes in this region rather than the entire star. We assumed that the modifications of the ws-process yields in explosive nucleosynthesis can be ignored and that all radioactive isotopes decay into stable ones after the explosion. Such approximations are reasonable for investigating the sensitivity of the reaction rates.

In Figs. 11 and 12, we show the ratios between the yields with the new reaction rates ($\text{Yield}_{\text{new}}$) and those with the default reaction rates ($\text{Yield}_{\text{def}}$) for $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_\odot$, respectively.

(1) **From C to Zn:** With the new $^{22}\text{Ne}+\alpha$ reaction rates, we observe the increase in the yields of several neutron-rich isotopes of Ne, Mg, Si, S, Ar, and Ca, particularly those in ^{25}Mg , $^{29,30}\text{Si}$, ^{36}S , ^{40}Ar , and ^{46}Ca . The significant decrease in the $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rate at $T \simeq 1.5 - 2.0$ GK (during Ne burning) reduces the yield of ^{26}Mg . As a result, a greater amount of ^{22}Ne was converted to ^{25}Mg (see Sect. 5.1), leading to a significant increase in neutron production during Ne burning. Consequently, the yields of $^{21,22}\text{Ne}$ increase owing 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 [21]. In contrast, the new $^{17}\text{O}+\alpha$ reaction rates do not increase the number of neutrons in the Ne shell, thus leaving the yields of those isotopes

Fig. 9 (Color online) The abundance distributions of the ws-process elements at $M_r = 1.84\text{--}7.3 M_\odot$ in the He core of the $M(\text{ZAMS}) = 25 M_\odot$ star. The solid lines symbolize the “Ga–Zr” elements, while the dashed lines symbolize the heavier elements



unchanged. The iron peak isotopes remain unaffected by both the new $^{17}\text{O}+\alpha$ and $^{22}\text{Ne}+\alpha$ reaction rates, as they are primarily produced by the NSE process at $M_r \simeq 1.8\text{--}2.2 M_\odot$, which is affected by Y_c . However, Y_c is only altered by weak interactions.

(2) From Ga to Zr: The isotopes in this range are most significantly affected by the new reaction rates. The effect of

the new $^{17}\text{O}+\alpha$ rates differs significantly from that of the new $^{22}\text{Ne}+\alpha$ reaction rates. For the same element, the increases owing 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 were reduced. With enriched neutrons, the isotopic yields increase rapidly. As $M(\text{ZAMS})$ increases, the enhancement due to the new $^{17}\text{O}+\alpha$ reaction rates also increases, whereas the enhancement due to the new $^{22}\text{Ne}+\alpha$ reaction rates is not significantly affected by $M(\text{ZAMS})$.

(3) From Mo to Bi: The isotopes in this range were 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 $M(\text{ZAMS}) = 15 M_\odot$ models. The number of such isotopes increases only slightly for more massive models.

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 $0.1 Z_\odot < Z < Z_\odot$ contribute more than 90% to the solar abundance [14]. It is general to use the production factors (PFs) to see which element is contributed significantly by a generation of stars. The PF of element i is defined as

$$P_i \equiv \frac{Y_i^*}{X_{i\odot} \cdot \sum_i Y_i^*}, \quad (2)$$

where $X_{i\odot}$ denotes the solar mass fraction of element i . $\sum_i Y_i^*$ runs over all elements and Y_i^* represents the yield of

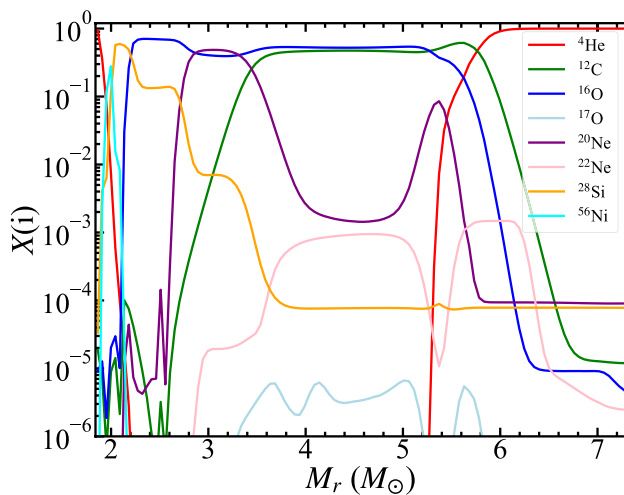
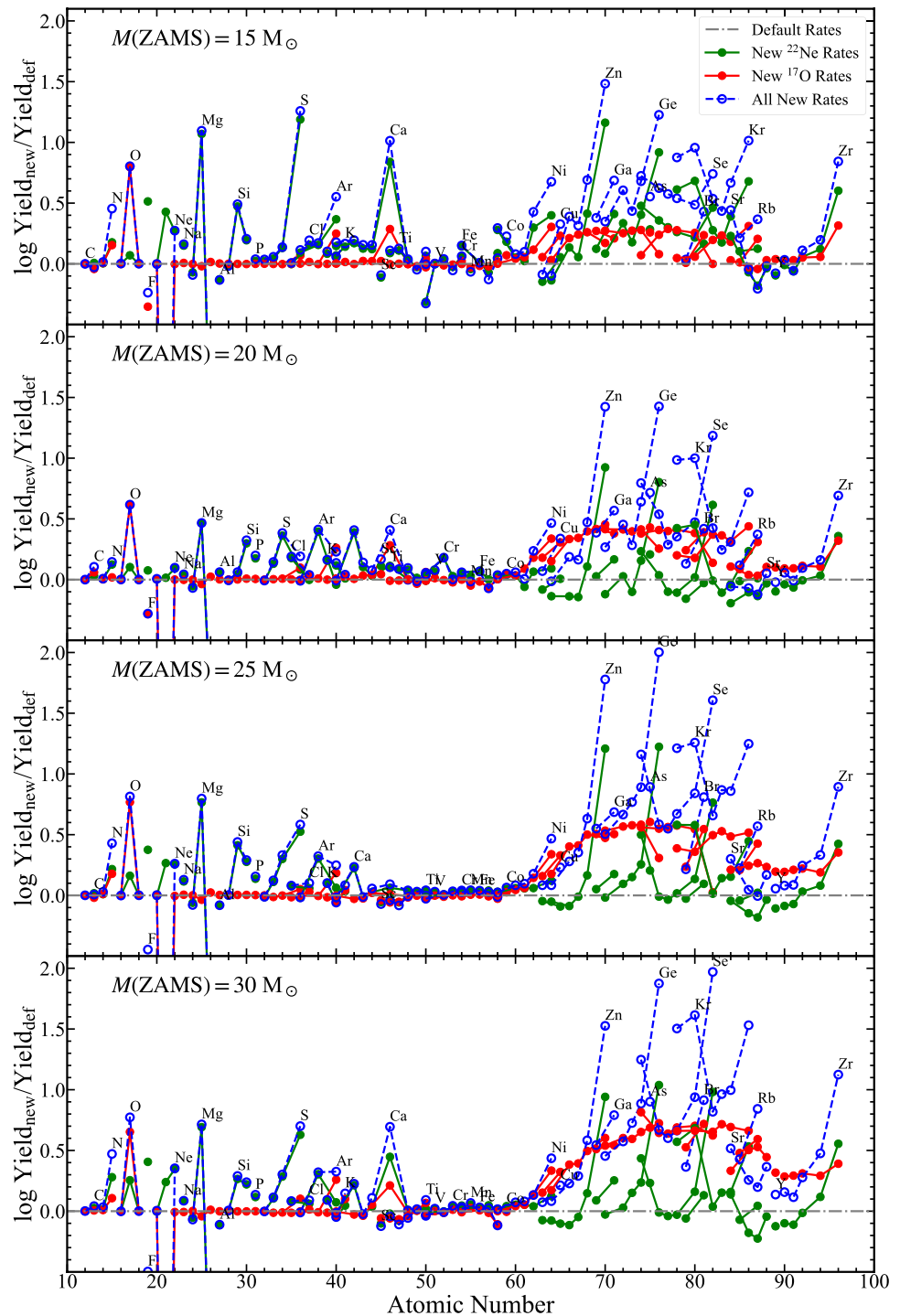


Fig. 10 (Color online) The distribution of the mass fractions of the main isotopes at $M_r = 1.84\text{--}7.3 M_\odot$ obtained from the post-processing calculation. Note that mixing is not considered in the post-processing calculation because WinNet is a one-zone code. A comparison between Figs. 10 and 4 is presented in Sect. 5.2

Fig. 11 (Color online) The ratios of isotopic yields (from C to Zr) between new rates and default rates for $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$, respectively

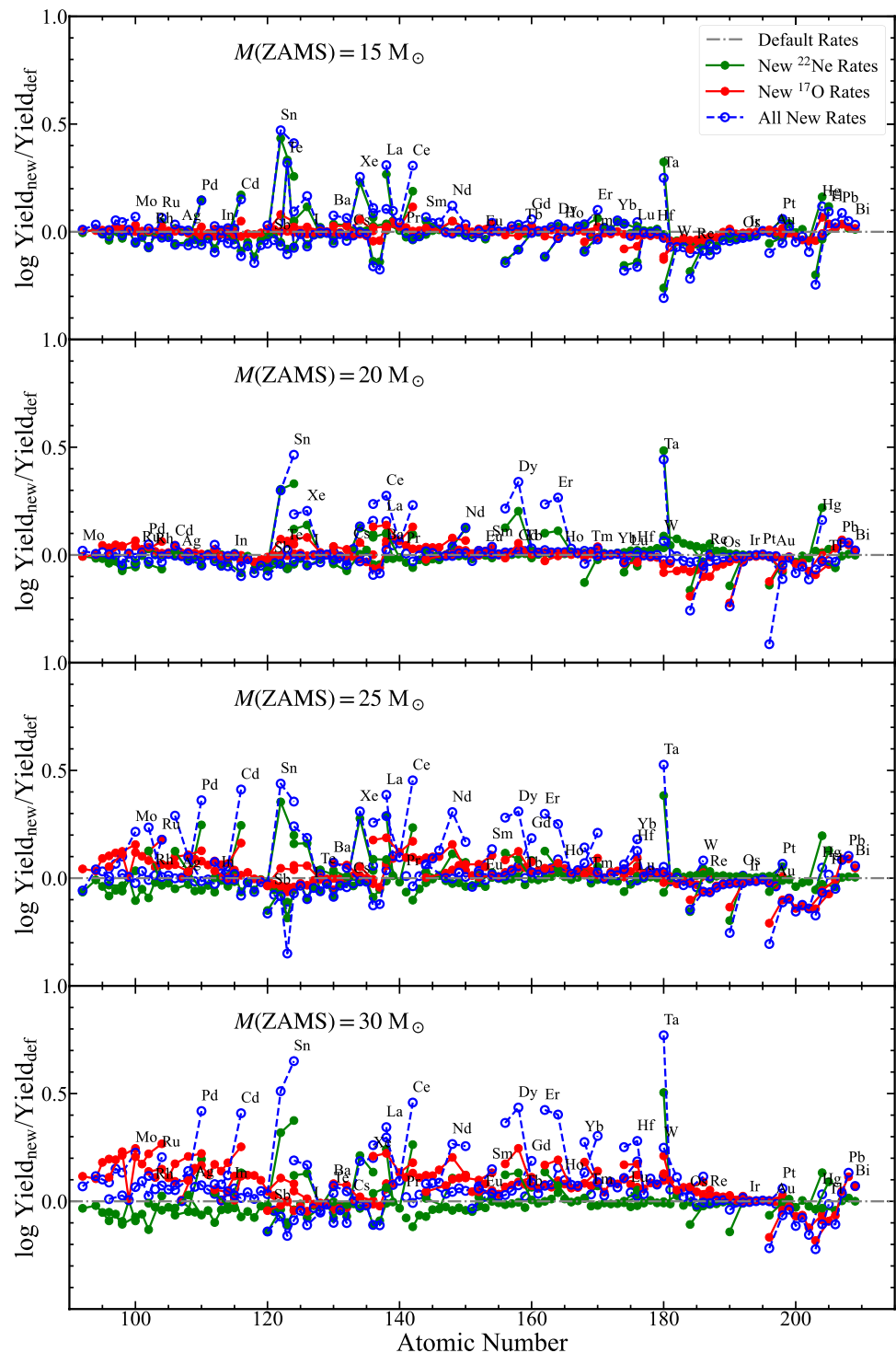


element i averaged by the initial mass function (IMF) from Salpeter [62] with $\gamma = -2.35$.

Figure 13 shows the production factors of 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 0.5 dex. The contribution of stars with $0.1 Z_{\odot}$ to the solar abundance should be

limited, as approximately 50% of the solar abundance is produced by stars with $0.5 Z_{\odot} < Z < Z_{\odot}$. Nevertheless, accounting for both the new reaction rates leads to the overproduction of Ga, Ge, As, and Se. Therefore, it is worth calculating the models with $0.5 Z_{\odot}$ and $Z_{\odot}$ and verifying whether the predictions concerning these elements align with observational data. Given the considerable uncertainties involved, it

Fig. 12 (Color online) Same as Fig. 11, but for elements from Mo to Bi



is essential to enhance the measurement accuracy of the (α , n) reaction rate, particularly for the $^{17}\text{O}+\alpha$ reactions.

5 Discussion

The primary purpose of this study is to evaluate the effects of the new $^{22}\text{Ne}+\alpha$ from Wiescher et al. [40] (hereafter, W23) and $^{17}\text{O}+\alpha$ reaction rates from Best et al. [39] (hereafter, B13). In fact, some other recent reaction rates were reported by Adsley et al. [63] (hereafter A21) and Hammache

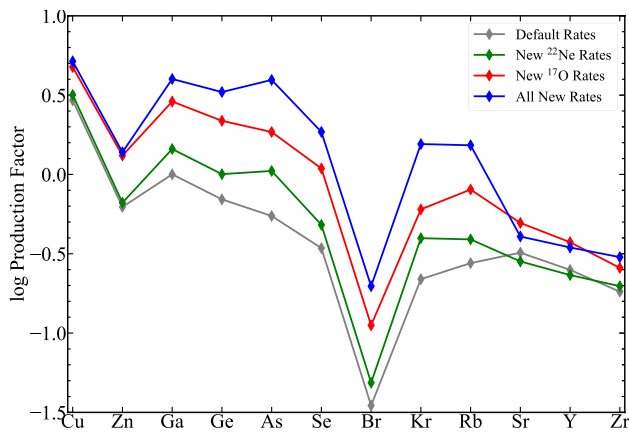


Fig. 13 (Color online) The production factors of the elements from Cu to Zr. Each element was integrated from 15 to 30 $M_{\odot}$ with the Salpeter IMF with $\gamma = -2.35$

et al. [64] (hereafter H24), which were not adopted in our evaluations. In Sect. 5.1, we briefly discuss the effects of differences in these reaction rates on our $M(\text{ZAMS}) = 25 M_{\odot}$ model. In addition, the size of the nuclear network used in MESA is limited to ~ 300 isotopes, which makes it challenging to cover all the 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.

5.1 Comparisons with results from other reaction rates

In Fig. 14a, we compare the $^{22}\text{Ne} + \alpha$ and $^{17}\text{O} + \alpha$ reaction rates used in JINA REACLIB with those reported in different references. As mentioned in Sect. 2.1, the $(\alpha, n)/(\alpha, \gamma)$ ratio of W23 increases quickly above 1.5 GK because the $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reaction rate decreases significantly. Compared with the default rates, the rates in W23 enhance the contribution of Ne burning in the ws-process (see Fig. 8). Related enhancement is also observed in the abundance of “Ga–Zr” elements in the region of $M_r = 2.2\text{--}3.5 M_{\odot}$ in Fig. 15.

Because A21 only provides reaction rates below 1.25 GK, in this trial, we switched to the rate from Longland et al. [19] at $T > 1.25$ GK. In Fig. 14b, A21 suggests a lower $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction rate at $T < 0.7$ GK. Consequently, the production of the “Ga–Zr” elements is reduced in both core and shell He burning, as shown in Fig. 15.

In Fig. 14c and d, H24 suggests a similar $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ reaction rate with the rate in B13 and a higher $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction rate at $T < 0.7$ GK. At $T > 1.0$ GK, we also switch to the rate in B13. As a result, the production of the “Ga–Zr” elements during core He burning was enhanced compared with the model with the B13 rate in Fig. 15.

In conclusion, the $^{22}\text{Ne} + \alpha$ reaction rates reported in different studies lead to variations in the yields of the ws-process elements by a factor of approximately 3–5. In contrast, the $^{17}\text{O} + \alpha$ reaction rates published in the literature produce order-of-magnitude differences in the ws-process elemental yields.

5.2 The effect of mixing

Nucleosynthesis in each zone was calculated separately because WinNet is a one-zone code. Thus, the effect of convective mixing was not considered. Mixing affects our results in two main aspects. As seen in Fig. 10, ^{22}Ne and ^{17}O are exhausted only in the burning shells in the CO core because the abundance of α particles is quite small in the unburned shells. In Fig. 4 in the region of $M_r = 2.5\text{--}5.1 M_{\odot}$, mixing can transport ^{22}Ne and ^{17}O from unburned shells to the burning shells. Consequently, more neutrons should be released in the MESA calculation. Similarly, the mass fraction of ^{17}O in Fig. 4 is quite low.

Convective mixing can also affect the locations of the C, Ne, O, and Si burning shells. With mixing, more fresh fuel was transported from the outer layers to the bottom of the burning shells. This would make the life of the burning shells longer. Thus, the bottom of shell O burning located at $M_r = 1.84 M_{\odot}$ in Fig. 4 would move to $M_r = 2.10 M_{\odot}$ in Fig. 10. Similarly, the bases of the C and Ne shells are at $M_r = 2.0 M_{\odot}$ would shift to $M_r = 2.6$ and $2.7 M_{\odot}$, respectively, without mixing in WinNet.

5.3 The effect of explosion

As mentioned in Sect. 3.2, we assume that the mass cut is located at $M(V/U_{\text{max}})$ and that the region of $M_r > M(V/U_{\text{max}})$ contributes to the chemical enrichment. We also assume that the ws-process isotopes produced in explosive nucleosynthesis are destroyed by the shock during the explosion. Thus, we did not calculate the explosive nucleosynthesis. The results from Tur et al. [15] show that explosive burning would reduce the ws-process isotopes by less than 15%. Limongi and Chieffi [14] mentioned that for the isotopes of ^{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 significantly changed by the shock wave. Because the exact explosion mechanism of core-collapse supernovae is not well understood, the explosion energy and choice of mass cut would also affect the final yields of these isotopes.

5.4 Other effects

The ws-process occurs mainly during the He, C, and Ne burning phases. The physical processes that affect these

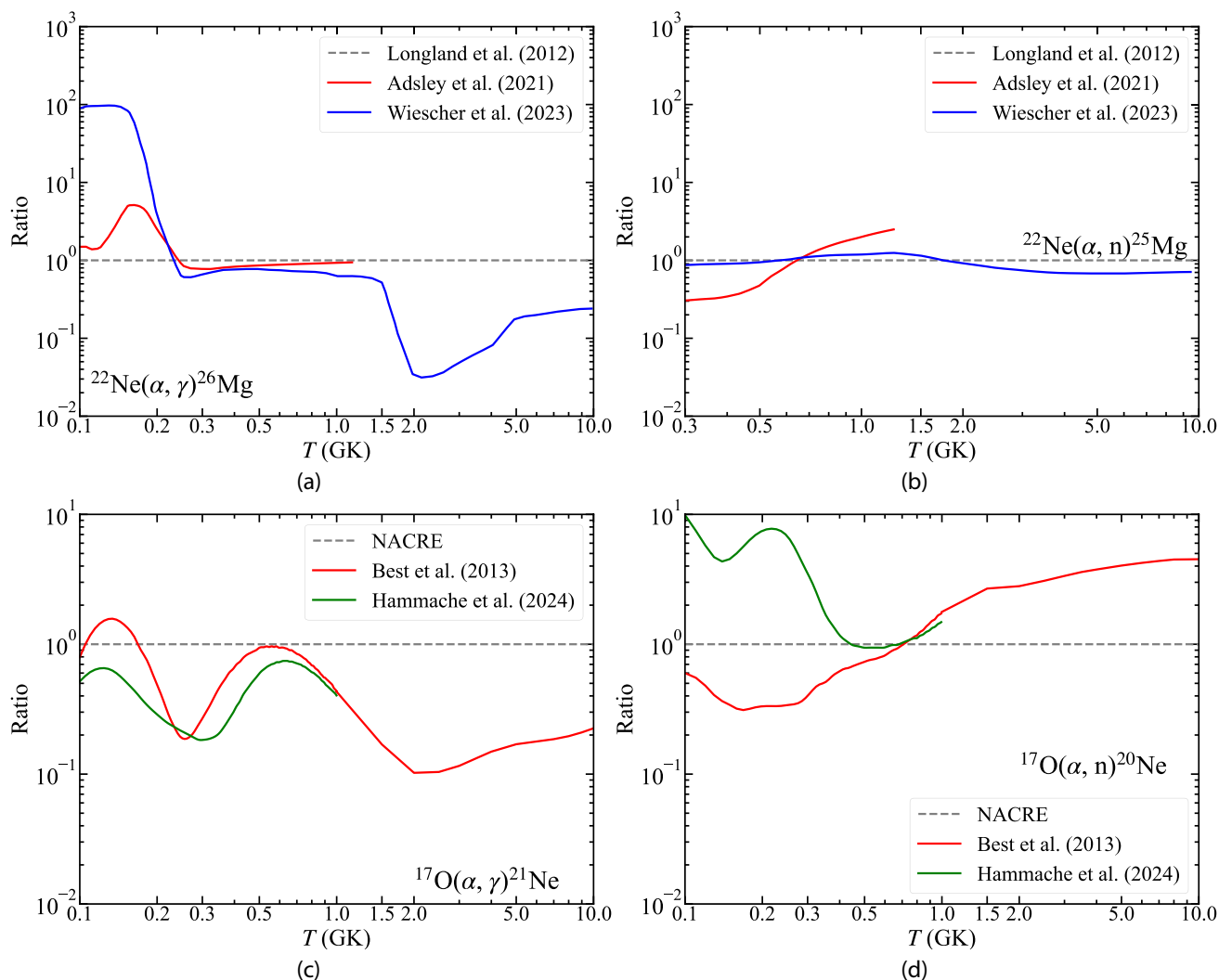


Fig. 14 (Color online) Top: $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ and $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction rates from different references. The gray dashed line shows the default rates in JINA REACLIB from Longland et al. [19]. The red and blue lines represent the reaction rates reported by Adsley et al. [63] and Wiescher et al. [40]. Bottom: $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ and $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction rates from different references. The gray dashed lines

burning phases may also affect the ws-process yields, such as reaction rates, convection, rotation, and magnetic fields [65]. Tur et al. [15] showed that a 15% change in the 3α and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rates may change the yields of the ws-process isotopes by more than a factor of 2. Limongi and Chieffi [16] presented many rotating massive star models, including ws-process nucleosynthesis. Their models involved $M(\text{ZAMS}) = 13\text{--}120 M_{\odot}$ and metallicity of $-3 \leq [\text{Fe}/\text{H}] \leq 0$. They found the interplay between the He core and the H burning shell, which is triggered by rotation-induced instabilities, enhances the products of CNO (especially for ^{14}N) and produces more neutrons. Consequently, the ws-process should be significantly enhanced in rotating models.

show the default rates in JINA REACLIB, which are from CF88 and NACRE. The red and green lines represent the reaction rates reported by Best et al. [39] and Hammache et al. [64]. To show the difference, all the rates shown here are normalized by the default rate in JINA REACLIB

6 Conclusion

In this study, we investigate the impact of the new $^{17}\text{O}+\alpha$ reaction rates from Best et al. [39] and new $^{22}\text{Ne}+\alpha$ reaction rates from Wiescher et al. [40] in comparison with the default reaction rates in JINA REACLIB. We calculate the nucleosynthesis of approximately 2000 isotopes, ranging from neutron and proton to thorium ($Z = 90$), using the one-zone code WinNet and the stellar models are calculated with MESA for an initial metallicity of $Z = 0.1 Z_{\odot}$ and $M(\text{ZAMS}) = 15, 20, 25$, and $30 M_{\odot}$. All models are evolved from ZAMS to the Fe core collapse, where the infall speed of the Fe core reached 10^3 km/s. We assume that the corrections by explosive nucleosynthesis to the yields are minor and that the isotopes lying in the outer layer of the mass cut

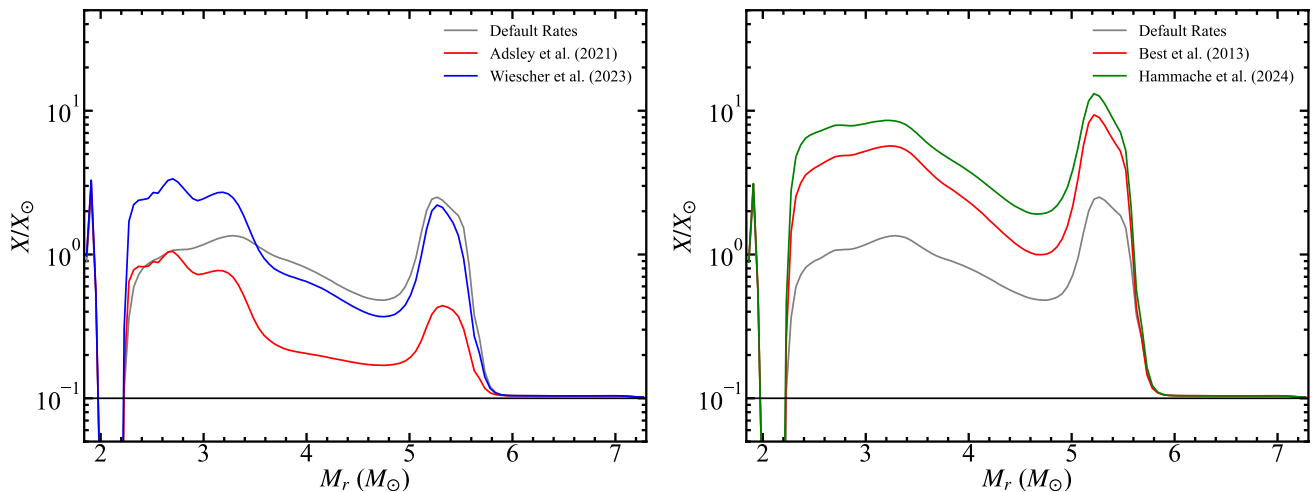


Fig. 15 (Color online) Same as Fig. 9, but only for the abundances of “Ga–Zr” elements. The effects of $^{22}\text{Ne}+\alpha$ reaction rates in different references are compared in the left panel, while the effects of $^{17}\text{O}+\alpha$ reaction rates in different references are compared in the right panel

($M_r > M(V/U_{\text{max}})$) would 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, whereas the new $^{17}\text{O}+\alpha$ reaction rates have the opposite effect. Both enhance the ws-process significantly during C and Ne burning. Using the reaction recipes listed in Table 1, $X(\text{Ga–Zr})$ increases by a factor of 6.56, 23.77, 31.58, and 113.62, respectively, after Ne burning (see Fig. 8).

(2) Without considering the effect of mixing, the mass distribution of the ws-process isotopes provided by WinNet shows a two-bump shape (see Fig. 9). This is because unburned layers release fewer neutrons than burning shells. This results in an underestimation of the yields of the ws-process isotopes. If the nucleosynthesis of the ws-process is calculated by coupling with evolution instead of 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 reaction rates for $^{22}\text{Ne}+\alpha$ significantly enhance only the yields of the most neutron-rich isotopes (see Fig. 11).

(4) We averaged these four initial masses with Salpeter’s IMF and showed the production factors (PFs) of the elements from Cu to Zr. The new $^{17}\text{O}+\alpha$ reaction rates enhanced the PFs more significantly than the new $^{22}\text{Ne}+\alpha$ reaction rates, particularly for Ga, Ge, As, and Se. Considering such a significant impact that the reaction rates from Best et al. [39] and JINA REACLIB have on the PFs of these elements, it is crucial to improve the accuracy and reliability of the measurement of the $^{17}\text{O}+\alpha$ reaction rates. Additionally, further investigations are necessary to ascertain which reaction rates can explain astronomical observations.

(5) We compared the results from the $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates used in JINA REACLIB with those reported in different references. We conclude that the $^{22}\text{Ne}+\alpha$ reaction rates reported in different studies lead to variations in the yields of the ws-process elements by a factor of approximately 3–5. In contrast, the $^{17}\text{O}+\alpha$ reaction rates published in the literature produce order-of-magnitude differences in the ws-process elemental yields. Because both the $^{22}\text{Ne}+\alpha$ and $^{17}\text{O}+\alpha$ reaction rates have important contributions to the ws-process after core He burning, we suggest that researchers conducting experimental or theoretical studies of nuclear reaction rates provide reaction rates spanning the temperature range of 0.1–10 GK.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Wen-Yu Xin, Chun-Ming Yip, Ken’ichi Nomoto, and Xian-Fei Zhang. The first draft of the manuscript was written by Wen-Yu Xin, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability The data that support the findings of this study are openly available in <https://www.doi.org/10.5281/zenodo.17021896>.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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