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). 22Ne and 16O are, respectively, the main neutron source and poison for the ws-process. In the metal-poor stars, the abundance of 22Ne is limited by the metallicity, so that the contribution of 22Ne(α, n)25Mg reaction on the s-process is weaker. Conversely, the 17O(α, n)20Ne reaction becomes more prominent in these stars due to the most abundant 16O 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(ZAMS) = 15, 20, 25, and 30 M to investigate the effect of reaction rates on the ws-process. We adopt the new 17O(α, n)20Ne and 17O(α, γ)21Ne reaction rates suggested by Best et al. (2013) and 22Ne(α, n)25Mg and 22Ne(α, γ)26Mg 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 17O+α reaction rates increase the ws-process mainly in all the stages, while the new 22Ne+α 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 17O+α 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, so the contribution of the ^{22}Ne(α, n)^{25}Mg reaction to the s-process is weaker. Conversely, the ^{17}O(α, n)^{20}Ne reaction becomes more prominent in these stars due to the abundance of ^{16}O at all metallicities.

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

In massive stars with Zero-Age Main-Sequence (ZAMS) masses greater than approximately 12 M , the weak s-process (ws-process) is a key mechanism for producing neutron-rich isotopes, particularly those in the atomic mass range of A = 60 to 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, characterized by higher temperatures and neutron densities [8–11]. More recent models include explosive nucleosynthesis during core-collapse supernovae (CCSNe), though these events have minimal impact on ws-process yields [12–16]. Limongi and Chieffi [14] and Tur et al. [15] 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}C(α, n)^{16}O reaction, the ws-process in massive stars is driven by the ^{22}Ne(α, n)^{25}Mg reaction [2, 5, 17, 18]. The abundance of ^{22}Ne in the core He burning is produced via the sequence ^{14}N(α, γ)^{18}F(β^+)^{18}O(α, γ)^{22}Ne. The ws-process is activated by the ^{22}Ne(α, n)^{25}Mg reaction once the temperature exceeds 2.5×10^8 K ($T_9 = 0.25$). During shell C burning, this reaction is reactivated by α particles produced via the ^{12}C(^{12}C, α)^{20}Ne channel [19]. Since ^{22}Ne is primarily synthesized by α-capture involving ^{14}N, which derives from the initial metallicity of stars, one would expect the yields of ws-process elements to be low in metal-poor stars [6, 20]. However, recent observations by Aoki et al. [21, 22] and Chiappini et al. [23] 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 and increase production [16, 23, 24].

Moreover, uncertainties in ^{17}O+α 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}O(n, γ)^{17}O reaction [25]. Subsequent competing reactions ^{17}O(α, n)^{20}Ne and ^{17}O(α, γ)^{21}Ne determine whether neutrons are released or captured. Although recent studies have explored these effects in rotating stars [24, 26, 27], few have investigated the combined impact of ^{17}O+α and ^{22}Ne+α reactions in non-rotating metal-poor stars. Since ^{16}O is extremely abundant across all metallicities, the neutrons released by the ^{22}Ne(α, n)^{25}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}O(α, n)^{20}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 [28]. 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(ZAMS) = 25 M as an example to illustrate the evolution of metal-poor stars. We further compare the effects of the ^{17}O+α and ^{22}Ne+α 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. [29, 30, 31, 32, 33], Jermyn et al. [34]) to follow various nuclear burnings and structural evolution in 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 ws-process abundances [15]. We calculate the evolution of four metal-poor stellar models with M(ZAMS) = 15, 20, 25, and 30 M using MESA. The trajectories of these models are utilized in the WinNet code [35] to investigate the effects of reaction rates on the ws-process.

For the ^{17}O+α reactions, we incorporate both competing channels, ^{17}O(α, n)^{20}Ne and ^{17}O(α, γ)^{21}Ne, as reported by Best et al. [36]. The reaction rates for ^{22}Ne+α, including both the (α, n) and (α, γ) channels, are updated according to Wiescher et al. [37]. 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. [38, 39] with some changes clarified in Section II.B. Section II.C will outline the setup within the WinNet code.

A. Reactions for Weak s-Process

The ^{22}Ne(α, n)^{25}Mg reaction is active at T = 0.2 GK and 1.0 GK in He and C burning shells, respectively. This reaction competes with ^{22}Ne(α, γ)^{26}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}O(n, γ)^{17}O. Fortunately, the neutrons absorbed by ^{16}O can be released again via ^{17}O(α, n)^{20}Ne. Therefore, the availability of neutrons for the ws-process is determined by the (α, n)/(α, γ) ratio for both ^{22}Ne+α and ^{17}O+α reactions.

In Figure 1 [Figure 1: see original paper], we show the (α, n)/(α, γ) ratios for the ^{22}Ne+α (top panel) and ^{17}O+α (bottom panel) reactions as a function of temperature. In the top panel, the (α, n)/(α, γ) ratio for ^{22}Ne+α, as recommended by Wiescher et al. [37], 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 (α, n)/(α, γ) ratio for the ^{17}O+α reaction suggested by Best et al. [36] 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 lists the nuclides included in the nuclear reaction network mesa_{161}.net. To achieve finer granularity during evolution, we impose limits on the changes in the logarithm of central density and temperature. Specifically, we set δlog _c < 10^{-3} and δlogT_c < 2.5 × 10^{-3}. Additionally, we restrict the change in isotope mass fractions with dX_{{{nuc}}*{{drop}}*}{limit} = 3 × 10^{-2}, tightening this limit to dX_{{{nuc}}*{{drop}}*}{{{limit}}*{{at}}*}{high}T = 10^{-2} when logT_c > 9.45.

C. Post-processing Calculation with WinNet

Detailed nucleosynthesis in the stellar models is computed in post-processing using the extensive nuclear reaction network code WinNet [35]. The network consists of approximately 2000 isotopes from neutron and proton to thorium (Z = 90). Reaction rates for (n, γ), (n, p), (p, γ), (α, n), (α, p), (α, γ), and their inverse reactions from the JINA REACLIB database [28] are 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] 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 collapse into a neutron star eventually and not contribute to ws-process nucleosynthesis yields. The steepest density jump occurs at the most active burning shell and has been defined in Xin et al. [39]. We will briefly describe the MESA results in Section III. (Note: ^{8}Be is not included.)

III. Pre-CCSN Evolution and Explodability

To achieve convergence of model structures within approximately 10%, a nuclear network comprising at least 127 isotopes should be included [43]. In this work, we utilize a more extensive nuclear network (mesa_{161}.net) that incorporates additional neutron-rich isotopes. Table 2 lists all isotopes in mesa_{161}.net. We adopt a metallicity of Z = 0.1 Z and assume solar metallicity ratios based on Anders and Grevesse [44].

We have enhanced both temporal and spatial resolutions to ensure numerical convergence. Mass resolution is critical for accurately capturing changes in stellar structure [43, 45]. The parameter max_{dq} controls the maximum fractional mass of a cell in the model, and we set max_{dq} = 5 × 10^{-4}, which results in over 3,500 cells in the model. We adopt a minimum diffusion coefficient of D_{min} = 10^{-2} cm^{2} s^{-1} to ensure that the global mixing timescale (τ = 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 [45].

After C burning, the core structure becomes more complex because of multi-shell burning, with central entropy being significantly influenced by shell burning (see Xin et al. [39]).

A. Evolution of Massive Stars

After core He burning, the mass fraction of ^{12}C in the center is smaller for stars with smaller initial mass. Only a star with M(ZAMS) = 15 M can ignite convective C burning in the center, as it has sufficient fuel with X(^{12}C)   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(ZAMS) = 15 M 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 [51]. Considering the combined effects of ejected masses and event frequencies, stars with initial masses of M(ZAMS) = 25 M are regarded as the most significant contributors to galactic chemical enrichment [20, 52]. Therefore, we select the M(ZAMS) = 25 M model as a typical example for discussing stellar nucleosynthesis.

In Figure 7 [Figure 7: see original paper], we present the Kippenhahn diagram for the M(ZAMS) = 25 M star, tracking its evolution from H burning to Fe core collapse. The central temperature reaches approximately 0.2 GK at τ = t_{final} - t = 10^{5}.^{6} yr, where 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 GK. The ws-process is assumed to occur interior to this isotherm. After core He burning, this region extends to M_r   6.0 M , and the He and CO core masses are 7.8 and 4.96 M , respectively. C burning ignites off-center at τ = 100.5 yr, nearly 3 years before collapse. After τ = 10^{-3} yr (10 hours before collapse), shell C burning merges with shell O burning at M_r = 1.84 M , 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 ws-process isotopes produced in the hatched region.

Figure 4 [Figure 4: see original paper] illustrates the mass distribution of the main isotopes at t = t_{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 ^{4}He. The mass fraction of seed isotopes "Fe" ranges from 10^{-4} to 10^{-5}. Additionally, the neutron excess, expressed as   = 1 - 2Y_e, of the ws-process region is observed to be 10^{-3} - 10^{-4}, as shown in Figure 5 [Figure 5: see original paper]. Interior to M_r = 1.84 M , the neutron excess increases rapidly toward the center, reaching   0.2. This jump is primarily attributed to reactions during O burning, including ^{16}O(^{16}O, n)^{31}S and weak interactions such as ^{30}P(e^{+},)^{30}S, ^{33}S(e^{-},)^{33}P, ^{35}Cl(e^{-},)^{35}S, and ^{37}Ar(e^{-},)^{37}Cl [53].

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 . 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 = dlnM_r/dln($4\pi r^4$P), where U and V are defined in earlier studies [54-57]. As explained in detail in Xin et al. [39], U relates to the degree of the density jump and V/U represents the pressure gradient against M_r. The mass coordinate where V/U reaches its maximum is designated M(V/U_{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 outer layers, making the gradients of entropy and pressure against M_r (i.e., V/U) larger.

Figure 6 [Figure 6: see original paper] shows the distribution of log(V/U) against M_r at τ = t_{final} for each model. We note that M(V/U_{max}) coincides with M$_4$, i.e., M_r at a specific entropy of s = 4 erg g^{-1} K^{-1}, previously used for the mass cut which 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_{max}) as the mass cut because it marks the location of the steepest gradients of pressure and density [39]. The core masses and M(V/U_{max}) for our models are listed in Table 3 .

IV. Nucleosynthesis and the Effect of Reaction Rates

A. The Nucleosynthesis in the 25 M Model

In this section, we present the results of post-process nucleosynthesis and discuss the effects of updated reaction rates. We selected a zone at M_r = 2.3 M as a representative example to reveal changes in the mass fraction X(i) of isotope i during each burning stage after updating these reactions. X(Ga-Zr) and X(Nb-Th) represent 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 [Figure 7: see original paper]. The changes in X(n) and ^{4}He for the default rates are displayed in the bottom panel of Figure 7(a), while in Figures 7(b)-(d), values are normalized by X_{def}(i) from Figure 7(a) 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_{He}-b), C burning (X_C-b), and Ne burning (X_{Ne}-b). The data are 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 during 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(Ga-Zr) is X_{ini} = 7.87×10^{-8}. Enhancements of X(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, respectively. These coincide with neutron peaks and ^{4}He production shown in Figure 7.

After Ne burning, the total enhancement of X(Ga-Zr) is estimated by the ratio (X_{Ne}-b - X_{ini})/X_{ini}, where X_{Ne}-b and X_{ini} are listed in Table 4. Compared with X_{ini}, X(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 more destruction at high temperatures [15].

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}Ne is almost exhausted.

With the new ^{17}O+α reaction rates in Figure 7(c), more than 93% of the "Ga-Zr" elements are synthesized during He and C burning stages, similar to case (a). The final X(Ga-Zr) is enhanced by a factor of 4.81 compared with default rates because both new ^{17}O(α, n)^{20}Ne and ^{17}O(α, γ)^{21}Ne reaction rates are lower than the default ones at temperatures below 0.7 GK (see Figure 14 [Figure 14: see original paper]), allowing X(^{17}O) to reach a higher level at the end of He burning with the new rates. When the temperature exceeds 0.7 GK, the (α, n)/(α, γ) ratio increases. Therefore, the new ^{17}O+α 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 using the new ^{22}Ne+α reaction rates, which is smaller than the increase when using the new ^{17}O+α reaction rates. Since the new ^{22}Ne+α rates are smaller than those in REACLIB (see Figure 14), ^{22}Ne is not exhausted until core collapse. The (α, n)/(α, γ) 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}O+α and new ^{22}Ne+α reaction rates are updated. The production of the "Ga-Zr" elements is enhanced by more than one order of magnitude. However, the contributions of He and Ne burning are only 10% and 18%, 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 whether Ne burning contributes significantly to the ws-process depends on the ^{22}Ne(α, γ)^{26}Mg reaction rate. Only when this rate is favorable can some ^{22}Ne still exist during the Ne burning stage.

Figure 9 [Figure 9: see original paper] 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 of M_r = 2.2-5.9 M . The first bump, located at M_r = 2.0-3.6 M , corresponds to the C, Ne, and O burning shells, while the second bump, found at M_r = 5.0-5.9 M , is associated with shell He burning. Between these two bumps, X(Ga-Zr) decreases due to low α production in 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 unburned shells, more ^{4}He is produced in burning shells, which can consume ^{22}Ne and release more neutrons. New ^{22}Ne+α reaction rates enhance X(Ga-Zr) only in the first bump, whereas the new ^{17}O+α reaction rates positively affect X(Ga-Zr) across all ws-process regions. Additionally, the new ^{17}O+α reaction rates increase X(Nb-Th) by 50%, unlike the ^{22}Ne+α reaction rates, since these elements are produced during the He burning stage. Notably, the sharp peak observed at M_r = 1.84-2.0 M remains unaffected by both the ^{22}Ne+α and ^{17}O+α 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 stellar evolution history and their mass distribution at the final stage for various reaction recipes. We find that both new ^{22}Ne+α and ^{17}O+α reaction rates increase the production of ws-process isotopes: (1) The new ^{17}O+α reaction rates only increase neutron density by 3 times during He and C burning stages. In contrast, the new ^{22}Ne+α reaction rates increase neutron density by several tens of times during C and Ne burning stages. (2) The new ^{17}O+α reaction rates do not vary the contribution in each burning stage. Conversely, new ^{22}Ne+α reaction rates significantly increase contributions in C and Ne burning stages but decrease that in the He burning stage. (3) Before the explosion, ws-process isotopes are primarily concentrated in burning shells, with their abundances decreasing in the outer layers of the CO core because there is no C burning in these outer layers, so little ^{4}He is released.

V. Discussion

The primary purpose of this work is to evaluate the effects of the new ^{22}Ne+α reaction rates from Wiescher et al. [37] (hereafter W23) and ^{17}O+α reaction rates from Best et al. [36] (hereafter B13). In fact, other recent reaction rates have been reported by Adsley et al. [63] (hereafter A21) and Hammache et al. [64] (hereafter H24), which are not adopted in our evaluations. In Section V.A, we briefly discuss the effects of differences in these reaction rates on our M(ZAMS) = 25 M model. Additionally, 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 calculation.

A. Comparisons with Results from Other Reaction Rates

In Figure 14 [Figure 14: see original paper], we compare the ^{22}Ne+α and ^{17}O+α reaction rates used in JINA REACLIB with those reported in different references. As mentioned in Section II.A, the (α, n)/(α, γ) ratio of W23 increases quickly after 1.5 GK because the ^{22}Ne(α, γ)^{26}Mg reaction rate decreases significantly. Compared with the default rates, the rates in W23 enhance the contribution of Ne burning to the ws-process (see Figure 8). Related enhancement is also observed in the abundance of "Ga-Zr" elements between M_r = 2.2-3.5 M in Figure 15 [Figure 15: see original paper].

Because A21 only provides reaction rates below 1.25 GK, in this trial we switch to the rate from Longland et al. [40] at T > 1.25 GK. In Figure 14(b), A21 suggests a lower ^{22}Ne(α, n)^{25}Mg reaction rate at T < 0.7 GK. As a result, the production of "Ga-Zr" elements is reduced in both core and shell He burning, as shown in Figure 15.

In Figures 14(c) and (d), H24 suggests a similar ^{17}O(α, γ)^{21}Ne reaction rate to that in B13 and a higher ^{17}O(α, n)^{20}Ne reaction rate at T < 0.7 GK. At T > 1.0 GK, we also switch to the rate in B13. Consequently, the production of "Ga-Zr" elements during core He burning is enhanced compared with the model using the B13 rate in Figure 15.

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

B. 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. First, 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 unburned shells. In contrast, Figure 4 shows that from M_r = 2.5-5.1 M , mixing can transport ^{22}Ne and ^{17}O from unburned shells to burning shells. As a result, more neutrons should be released in the MESA calculation. Similarly, ^{17}O left in Figure 4 is quite small.

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

C. 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. Results from Tur et al. [15] show that explosive burning would reduce ws-process isotopes by less than 15%. Limongi and Chieffi [14] mentioned that for isotopes such as ^{70}Zn, ^{76}Ge, ^{74},^{77},^{82}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 choice of mass cut will also affect the final yields of those isotopes.

D. Other Effects

Since the ws-process takes place 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 [65]. Tur et al. [15] have shown that a 15% change in the 3α and ^{12}C(α, γ)^{16}O reaction rates may change the yields of ws-process isotopes by more than a factor of 2. Limongi and Chieffi [16] presented a large number of rotating massive star models including ws-process nucleosynthesis. Their models involve M(ZAMS) = 13-120 M and metallicities of $-3 \leq$ [Fe/H] ≤ 0. They find that the interplay between the He core and the H burning shell, triggered by rotation-induced instabilities, enhances CNO products (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}O+α reaction rates from Best et al. [36] and new ^{22}Ne+α reaction rates from Wiescher et al. [37] 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 Z and M(ZAMS) = 15, 20, 25, and 30 M . All models evolved from ZAMS to Fe core collapse, where 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 exterior to the mass cut (M_r > M(V/U_{max})) contribute to galactic chemical enrichment. The results are summarized as follows:

1. The new ^{22}Ne+α reaction rates slightly suppress the ws-process during He burning, while the new ^{17}O+α 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(Ga-Zr) increases by factors of 6.56, 23.77, 31.58, and 113.62, respectively, after Ne burning (see Figure 8 [Figure 8: see original paper]).

2. Without considering mixing effects, the mass distribution of ws-process isotopes provided by WinNet shows a two-bump shape (see Figure 9 [Figure 9: see original paper]) because unburned layers release fewer neutrons than burning shells. This results in underestimation of ws-process isotope yields. If ws-process nucleosynthesis were calculated coupled with stellar evolution instead of through post-processing, the enhancement would be more significant.

3. The new ^{17}O+α reaction rates can increase the yields of all isotopes from Cu to Zr, with enhancement being more pronounced in more massive stars. Conversely, the new ^{22}Ne+α reaction rates only significantly enhance the yields of the most neutron-rich isotopes (see Figure 11 [Figure 11: see original paper]).

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}O+α reaction rates enhance the PFs more significantly than the new ^{22}Ne+α reaction rates, especially for Ga, Ge, As, and Se. Considering the significant impact that reaction rates from Best et al. [36] and JINA REACLIB have on the PFs of these elements, it is crucial to improve the accuracy and reliability of measurements of the ^{17}O+α reaction rates. Additionally, further investigations are necessary to ascertain which reaction rate best explains astronomical observations.

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

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