New Results on Nucleosynthesis in Massive Stars; Nuclear Data Needs for Nucleosynthesis

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We review the current status of the nuclear reaction rates needed to study nucleosynthesis in massive stars. Results for the calculated nucleosynthesis of all stable species from Hydrogen to Bismuth in a completely evolved 25 $M_\odot$ star of initial solar metallicity will be presented. Special emphasis will be paid to two particular reactions, ^{12}C$(\alpha,\gamma)^{16}$O and ^{22}Ne$(\alpha,n)^{25}$Mg, and their effect on the structure of the star and resultant nucleosynthesis. Both have been measured many times, but the present range of experimental uncertainty translates into remarkable sensitivity of the calculated nucleosynthesis.

KEYWORDS: nucleosynthesis, nuclear reactions, abundances, supernovae - general

I. Introduction

Second only in scientific interest to the origin of the universe itself is the origin of the chemical elements therein. The near term goal of nuclear origins, or *nucleosynthesis*, seeks to develop a complete understanding of the origin of every isotope in nature in terms of their nuclear properties and astrophysical sites where they were assembled. Once known, this understanding can also be employed to calculate the chemical history, not only of the elements in our own sun and the Galaxy, but in older stars, future stars, and in distant galaxies.

Simulating nucleosynthesis in stars presents several problems for nuclear physics that are peculiar to the stellar environment. For many species of interest, the important nuclear flows move through target or product nuclei (sometimes both) that are frequently radioactive. Subsequently, many important reaction cross sections are not amenable to measurement. Further, neutron resonance analysis can often only be done on compound nuclear states one neutron removed from stability, and thus important quantities derived from such an analysis (average level spacings, neutron strength functions, etc.) are not available for input to reaction models on unstable nuclei. The potential for Rare Isotope Accelerators to address some of the more critical reactions is tantalizing, but due to shear numbers alone, most of our nuclear cross section needs for nucleosynthesis will necessarily be derived from theory.

Another complication is that the targets exist in a thermal distribution of excited states. Laboratory measurements (where available) cannot be directly applied to reaction networks. Further, reactions on long-lived or highly populated isomeric states are not included in stellar reaction networks used to calculate nucleosynthesis in massive stars (^{26}Al being the notable exception).

Finally, there are a lot of nuclei for which nuclear reaction rate information is needed, roughly 4600 bound nuclei exist from hydrogen to lead. Considering only binary reactions involving nucleons, alpha-particles, and photons, along with a potential ground state weak interaction (β^-, β^+, or electron capture), this translates into approximately 32,000 nuclear reactions (plus their inverses) if one considers all possible nuclear burning scenarios. In addition, a need for weak interaction rates at extreme values of temperature and density experienced in the late time evolution of massive stars increases these nuclear data requirements. Clearly, the development of reaction rate data bases to study nucleosynthesis in massive stars is a huge undertaking, drawing from the best elements of experiment, theory, and evaluation. That such efforts have only been made three times in the last 25 years should come as no surprise.(1–3)

This contribution will describe the current status of nuclear reaction rate information required to study nucleosynthesis in massive stars. Examples of nucleosynthesis in a 25 $M_\odot$ star of initial solar metallicity is given in §II. The required data will be broken into categories depending on reaction type and range of target nuclei, and their impact on the nucleosynthesis will be discussed (§III.) Sensitivity to key reaction rates will be presented for two specific cases (§III.2 and III.3). Weak rates are treated in §IV.

II. Nucleosynthesis in Massive Stars

Nucleosynthesis in stars has been reviewed many times.(4–6) To set the stage we present in **Table 1** the nuclear burning stages experienced by massive stars ($M \geq 11$ $M_\odot$). Shown are the major hydrostatic burning phases (H, He, C, Ne, O, and Si burning), their principle product(s), most important secondary products, and the approximate temperature and lifetimes during which a given fuel is burned. The general trends are evident: an abundant "fuel" burns, liberating energy which serves to support the star against gravitational contraction. Eventually the fuel is exhausted, the star contracts, the core heats up, and the "ash" of the previous burning stage serves as the "fuel" for the next one. A shell of material adjacent to the new burning core continues to burn by the same reaction mechanisms as in the previous core burning scenario, and the star develops an "onion-like" structure. To burn heavier fuels the temperature must increase to surmount the increas-

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ing coulomb charge barriers, and the lifetime for exhausting a given fuel decreases owing to: a) the very high temperature dependence of the reaction rates governing the energy release, and b) the ever mounting neutrino losses (which dominate beyond helium burning).

Table 1 Advanced Nuclear Burning Stages

Fuel	Main Product	Secondary Products	Temp 10^9K	τ yr
H	He	^{14}N	0.03	10^7
He	C,O	^{18}O,^{22}Ne, $s-$process	0.2	10^6
C	Ne,Mg	Na	0.8	10^3
Ne	O,Mg	Al,P	1.5	$\sim 10^{-1}$
O	Si,S	Cl,Ar, K,Ca	2.0	~ 2
Si	Fe-group	Ti,V,Cr, Mn,Co,Ni	3.3	$\sim 10^{-2}$

Following core silicon-burning, the core collapses, and if a neutron star forms at the stars center (likely for stars less than 30 $M_\odot$), a Type II supernova explosion can occur. Ignoring the hydrodynamic and neutrino-transport issues, the outgoing shock wave heats the overlying shells of previously synthesized elements, and explosive nucleosynthesis can alter the composition of certain species. Additional nucleosynthetic processes can take place, including the $\nu-$process,7) the $p-$process,8) and possibly the $r-$process.9) For a comprehensive survey of massive star evolution and nucleosynthesis, see Woosley & Weaver.10) Galactic chemical evolution is explored in Timmes, Woosley, & Weaver.11)

The final nucleosynthesis (including mass loss) of a fully evolved solar metallicity 25 $M_\odot$ star12) is presented in **Figure 1**. The reaction network included all necessary isotopes through mass 210 and used reaction rates current as of 2001. Shown is the "production factor" vs. mass number. Isotopes of a given element are connected by solid lines. The dashed line is centered on ^{16}O, with the dotted lines representing a "success band" of ± 0.3 dex. With rare exception, all isotopes from oxygen through nickel are co-produced in solar proportions with a production factor of $\sim$ 15 (in this figure, the initial composition of the sun would be a set of points all lying on "1"; a production factor of 15 means that the suns complement of metals could be understood if 1/15 of its mass passed through conditions like those experienced in this 25 $M_\odot$ star). The $r-$, $s-$, and $p-$process isotopes are also well produced (perhaps a little over-produced) from nickel to about A=88. In a 15 $M_\odot$ star,13) the $s-$process yield is less. The yields of these "trans-iron" elements is also sensitive to a still poorly determined reaction rate for ^{22}Ne$(\alpha,n)^{25}$Mg (see §III.3). Above mass 90, nucleosynthesis in massive stars is mostly restricted to the $p-$ process, although a potential $r-$process contribution from a ν-driven wind9) is not included here.

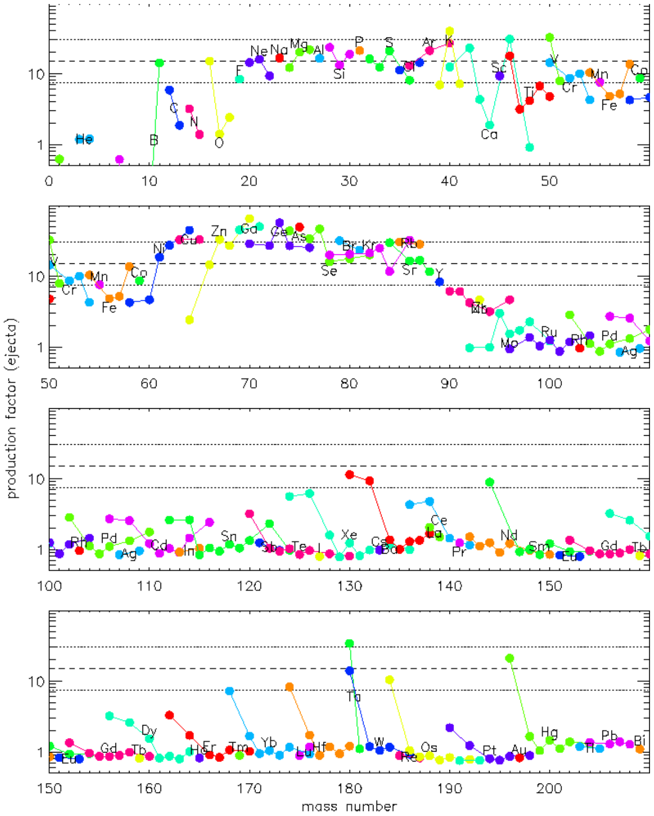

Fig. 1 Decayed, post-explosive production factors for a 25$M_\odot$ star of initial solar metallicity.

III. Strong and Electromagnetic Reaction Rates

We now describe the important nuclear physics ingredients needed to calculate stellar nucleosynthesis as displayed in **Figure 1**. The discussion breaks nicely into two distinct regions: reactions on targets lighter than silicon (where many of the key cross sections have been measured), and reactions on heavier targets (where the community must rely on statistical theory).

1. Critical Reactions for Energy Generation

Along with the 3α reaction rate, the heavy ion reactions ^{12}C+^{12}C, ^{12}C+^{16}O, and ^{16}O+^{16}O are the most important reactions for energy generation during hydrostatic helium, carbon, and oxygen burning. As such these reactions play a major role in determining stellar structure, and the production of all stable self-conjugate (Z=N) nuclei which constitute the most abundant species found in nature after hydrogen and helium (formed in the Big Bang). The current source for these reaction rates is Caughlan & Fowler,14) although the 3α reaction rate has recently been re-evaluated15) (little change resulted over the temperature range at which helium burning operates). These are probably adequate with the possible exception of ^{12}C+^{12}C and its electron screening rate.

2. ^{12}C$(\alpha,\gamma)^{16}$O

Possibly the most important nuclear burning scenario as far as nucleosynthesis is concerned is helium burning, being the only energy generation scenario in which two reactions, 3α and ^{12}C$(\alpha,\gamma)^{16}$O, compete on so nearly an equal basis in the consumption of a major fuel. It is here that a star has the ability to change its neutron excess and produce nuclei that have more neutrons than protons. In combination with 3α, the ^{12}C(α,γ) rate determines the ratio of carbon to oxygen at the end of core helium burning, with dramatic consequences for stellar structure, ultimately affecting the size and composition of the iron core, the possible nature of a compact remnant, and also the future of all subsequent phases of nuclear burning. Shown in **Figure 2** are the variations in core mass size for the advanced burning stages in a 25 $M_\odot$ star of solar metallicity as a function of a multiplier on the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate of Buchmann.[16)]

Although considered to be the most important reaction rate, its experimental value over the temperature range of interest (300 keV) is inadequately known. Determination of an accurate rate is experimentally challenging because it proceeds through two sub-threshold resonances whose critical alpha-widths must be determined indirectly.[16–18)] The rate is divided into three parts, a) the electric dipole part proceeding through the 1^- resonance, b) the electric quadrapole part proceeding through the 2^+ resonance, and everything else. The total rate is often expressed in terms of the S-factor at 300 keV, and the current uncertainties place its value in the range of 100 to 200 keV barns (but with a preference for 150 to 170 keV b with a temperature dependence similar to that described by Buchmann[16)]). This uncertainty is far to large for a rate of this importance. Based on nucleosynthesis arguments, a total S-factor of 170 ± 20 keV b co-produces nearly all stable species between oxygen and calcium.[19)] Uncertain stellar physics (semi-convection, and mass loss), also affects the total carbon and oxygen content in stars, but the current nuclear physics uncertainty is in utmost need of diminishment. Further experimental effort is highly encouraged.

3. Neutron Sources and Sinks

Secondary to energy generation, but no less important to nucleosynthesis, are the reactions that operate during helium burning to control the neutron budget. They directly affect the production of many species, most importantly those above the iron group made via the $s-$process. In massive stars the ^{22}Ne$(\alpha,n)^{25}$Mg reaction, (in close competition with ^{22}Ne$(\alpha,\gamma)^{26}$Mg), provide the neutrons required to synthesize stable species with $60 \leq \mathrm{A} \leq 88$, or the so-called "weak-component" of the $s-$process.[20)] The ^{22}Ne is produced by two alpha-captures on ^{14}N produced in the hydrogen burning CNO cycle. These reactions operate predominantly during core helium burning, although they also operate (supplemented by ^{26}Mg$(\alpha,n)^{29}$Si) at later times in shell helium burning. The bulk of the $s-$process nuclei (with $\mathrm{A} \geq 88$) are synthesized during shell helium burning in low mass AGB stars, where the principle neutron source reaction is ^{13}C$(\alpha,n)^{16}$O.

The status of both ^{22}Ne alpha-capture reactions is highly uncertain owing to the large experimental difficulty in determining the strength of the 633 keV resonance in the ^{22}Ne$+\alpha$ channel.[21)] Various choices for the parameters of this resonance give quite different strengths for the neutron exposure in the $s-$process, though none so powerful as to move the $s-$process peak much above A=90. Recent studies[22)] suggest a diminished role for this reaction rate to a level no higher than the "lower-bound" recommended by Käppeler.[21)] **Figure 3** shows the sensitivity of the nucleosynthesis to variations in the ^{22}Ne$(\alpha,n)^{25}$Mg rate that arise using the same stellar model that produced the results of **Figure 1**.

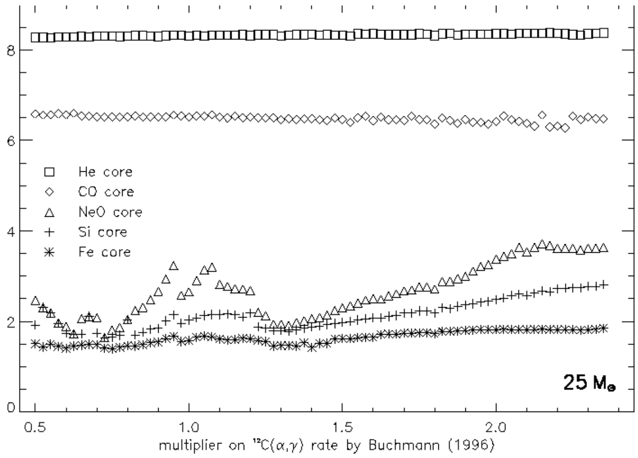

Fig. 2 Helium (*squares*), carbon-oxygen (*diamonds*), neon-oxygen (*triangles*), silicon (*crosses*), and "iron" (*asterisks*) core masses as a function of a multiplier on the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate of Buchmann.[16)]

The current sources of these and other important (α,n) and (α,γ) reactions on targets lighter than Si are drawn from many experimental efforts.[20)] Compilations do exist,[14,15)] but the current uncertainties warrant further experiment, especially for the reactions involving ^{18}O and ^{22}Ne.

In addition to the neutron source reactions, neutron capture reactions on all targets heavier than sodium are required to predict the $s-$process abundances in low and high mass stars. Fortunately, the reaction rate situation here is well in hand, in that nearly all of the important cross sections are measured in the temperature range of interest ($\sim 25 - 100$ keV). Various compilations are available.[23)] There are however many important (n,γ) reactions on unstable targets that affect $s-$process branching which must be calculated by theory.[3)]

Finally, the nucleus ^{60}Fe, a potential candidate for gamma-line detection, is also made during helium burning in massive stars. Its synthesis is currently dependent on theoretical cross sections.[24)] RIA measurements that provide either cross section or level density information pertaining to the (n,γ) rates on ^{59,60}Fe would be most welcome.

4. Charged-particle Reactions on Z≤ 14

Reactions involving protons [(p,γ), (α,p), (p,α)] and nuclei lighter than silicon are also important, especially those that are involved in the energy generation cycles that operate

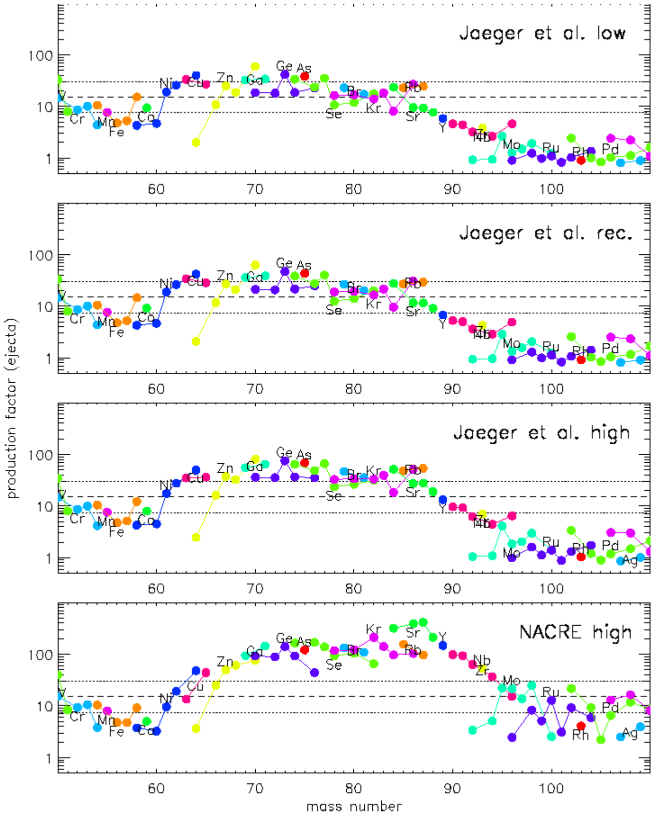

Fig. 3 Sensitivity of the production factors for different $^{22}Ne(\alpha, n)^{25}Mg$ rates in a 25 $M_{\odot}$ star. The first three panels give the results for the lower limit, recommended value, and upper limit of Jaeger et al.[22] The bottom panel uses the evaluated reaction rate set from NACRE[15] with their upper limit for the $^{22}Ne(\alpha, n)^{25}Mg$ rate.

during hydrogen burning (PPI, PPII, and PPIII in low mass stars; the CNO cycle and its bi-cycles in massive stars). Such reactions determine the synthesis of the important species ^{13}C, $^{14,15}N$, $^{17,18}O$, ^{21}Ne, ^{23}Na, and especially ^{26}Al (observed via $\gamma-$line decay). Of these low-mass stars make most of the ^{13}C, ^{14}N, and some of the ^{23}Na (through incomplete CNO processing and the Ne-Na cycle). It is estimated[11] that massive stars produce about one-fifth of the ^{14}N in the sun. The production of ^{15}N is relegated to novae. Controversy currently exists on how much of the observed 2 $M_{\odot}$ of ^{26}Al present in the Galaxy[25] is attributed to either massive stars,[26,27] or novae,[28] although massive stars can easily account for all of it.[11] Until recent revisions to the key reaction rates affecting ^{17}O synthesis,[29] massive stars were thought to be able to produce the solar abundance.[11] Should these new measurements be confirmed, production of ^{17}O may be relegated to low mass stars or novae.[30] Proton capture reactions on targets with $N \leq Z$ are also crucial for break-out of the hot-CNO cycle in x-ray bursts.

Sources for these reaction rates are varied.[14,15,31] Although the reactions involving energy generation are adequately determined,[32] further experiment is needed.

5. Charged-particle Reactions on $Z > 14$

The nucleosynthesis of nearly all species from silicon to the iron group are produced in the latter stages of stellar burning in massive stars. Many are made in either partial or complete nuclear statistical equilibrium,[33] where the absolute values of individual reaction rates are not as important as Q-values and partition functions.[24] But for the $p-$process nuclei (**Figure 1**), accurate rates are required to predict the nucleosynthesis of these rare species.

Current nucleosynthesis calculations rely heavily on theoretical model calculations for nearly all of these cross sections.[3] This is troubling for some critical (α, γ), (α, p), and (p, γ) reactions on self-conjugate nuclei, which are difficult to measure (and predict) due to suppression of the photon transmission function due to uncertain isospin mixing.[34] Further problems exist due to the use of a poorly known global optical model α-particle potential. This area is in desperate need of experimental work that either measures the most important cross sections or derives important structure data for use in calibrating the Hauser-Feshbach reaction models, especially for targets with $A > 60$.

IV. Weak Interaction Rates

1. Ground State Weak Rates

Prior to carbon-burning, the use of ground state decay rates calculated from measured laboratory half-lives and branching ratios are adequate (in most instances) to predict stellar nucleosynthesis, including the $s-$process. These are the default source of weak reaction data for all species in modern reaction networks,[35] and are currently the only source of data beyond $A \sim 60$.

Of particular interest are the weak decay rates that affect the production of gamma-line species, particularly ^{22}Na (2.6 yr), ^{26}Al (7.5×10^5 yr), ^{44}Ti (60 yr), $^{56,57}Ni$ (6.1d, 1.5d), $^{56,57,60}Co$ (77.1 d, 271 d, 5.27 yr), and ^{60}Fe (1.5×10^5 yr). Of these ^{26}Al has been observed in the Galatic plane and in individual supernova remnants.[27] The shorter lived ^{44}Ti has been observed in CasA[25] and the Ti, Ni, and Co isotopes in SN 1987A.[25] Both ^{22}Na and ^{60}Fe are principle candidates for detection by the upcoming INTEGRAL mission. The lifetime for ^{44}Ti to decay to ^{44}Ca has been a subject of much experimental uncertainty over the last thirty years, with a half-life that has steadily increased from 45 to 70 yr. The most recent measurements seem to be converging on the presently accepted value of 60 yr.[36]

2. Temperature Dependent Weak Rates

For the extreme conditions encountered in stellar collapse, temperature and density dependent weak rates[37,38] are required. These play a central role in determining the nucleosynthesis of many important $\gamma-$line species ($^{56,57}Ni$, ^{44}Ti), the stellar structure after oxygen burning, the electron mole number (Y_e), and in determining the requisite conditions for an $r-$process to occur in the $\nu-$wind of Type II supernova cores.[42]

Some important changes in the stellar models are due to recently revised weak rates,[38] the largest changes become apparent during core silicon burning and thereafter. Typically, they lead to an increase of the central Y_e (the electron mole number, or number of electrons per baryon) at the onset of core collapse by 2 to 3 % and this difference tends to increase with increasing stellar mass.[39)] Perhaps more important for the explosion mechanism of core collapse supernovae is an increase of the density in the mass range of $m = 1.5$ $M_\odot$ to 2 $M_\odot$ by $30 - 50$ % relative to the same models computed with the previous set of weak rates.[10)] This may significantly affect the dynamics of the core collapse. The evolution of the central Y_e, the net weak flow, and their sensitivity to the choice of weak reaction rates is presented in (**Figure 4**) for a 15 $M_\odot$ star.

3. Neutrino Loss Rates

Neutrino losses are a critical aspect of stellar evolution in massive stars beginning with carbon burning. The dominant losses before silicon burning are due to thermal processes (chiefly pair-annihilation), which provide a loss term that is very roughly proportional to T^9 in the range of interest for advanced burning stages.[40)] This temperature sensitivity, combined with the need to burn heavier fuels at higher temperatures to surmount the increasing charge barriers, is what leads to the rapid decrease in lifetime to burn a given fuel reflected in (**Figure 1**), with obvious consequences for nucleosynthesis. The theory is well developed.[41)]

4. Neutrino-interaction Rates and Branching Ratios

Following Type II core collapse, a nascent neutron star liberates its gravitational binding energy ($\sim 3 \times 10^{53}$ erg) over a Kelvin-Helmholtz contraction time scale ($\sim$ 10 s) via neutrino emission, providing for the passage of a huge flux of neutrinos through the overlying shells of matter. This can cause an interesting transmutation of several rare elements by exciting abundant species to particle unbound levels through neutral current neutrino scattering.[7)] Based on an extensive grid of supernova models[10)] and a survey of galactic chemical evolution,[11)] the most affected species are ^{7}Li, ^{11}B, and ^{19}F. Several other species (^{15}N, ^{26}Al, and the rarest naturally occurring elements ^{138}La and ^{180}Ta) show modest enhancement over their production via more conventional nucleosynthetic processes. Neutral and charged current neutrino interaction cross sections and branching ratios are calculated from theory.[7,43)]

V. Conclusion

The field of nucleosynthesis has come a long way since the seminal papers of 1957,[4)] but certain key nuclear quantities still have unacceptably large uncertainties. Chief among them are the reaction rates for ^{12}C$(\alpha,\gamma)^{16}$O and ^{22}Ne$(\alpha,n)^{25}$Mg. Much experimental work has been done to improve the situation,[14,15,31)] but much more remains to be done. A major challenge will be to reduce the previously acceptable "factor of two" accuracy ascribed to reaction rates derived from nuclear modeling.[24)] Such goals are worthy in light of the wealth of new and highly accurate observational data from a variety of astrophysical systems.

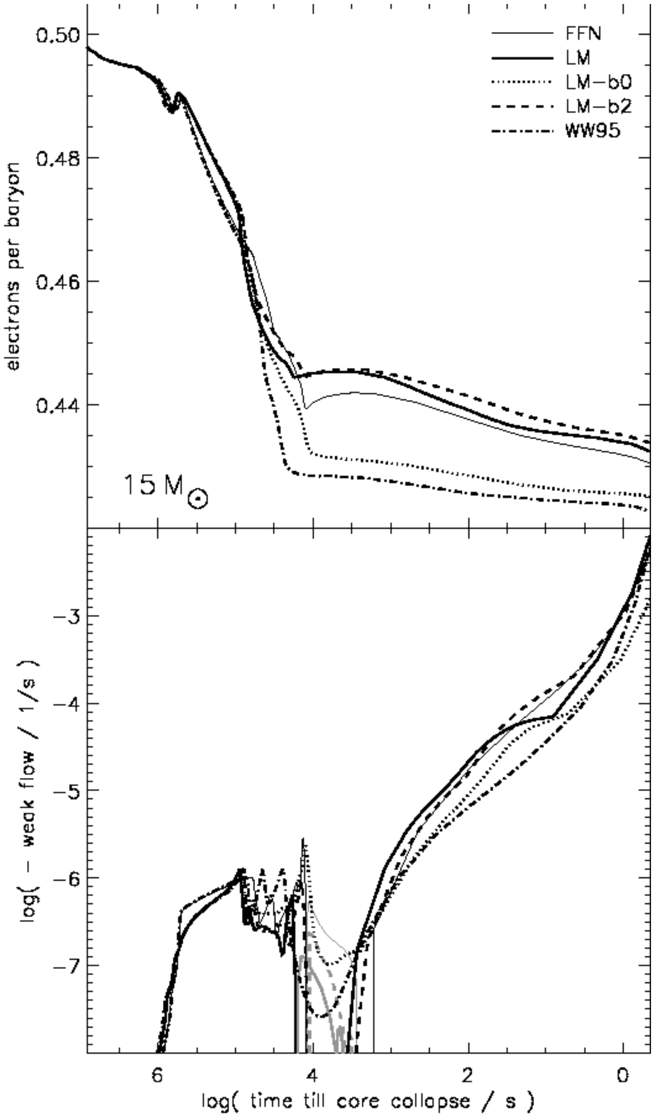

Fig. 4 Evolution of Y_e and the net weak flow in the center of a 15 $M_\odot$ star followed from central oxygen depletion till the onset of core collapse. Five choices of weak interaction rate sets are used, FFN[37)] (the previous standard), and three sets from Langanke & Martinez-Pinedo.[38)] LMP is the recommended set, the -b0 and -b2 lines indicate rate sets that multiplied the recommended beta-decay rates by zero and two respectively. The last simulation (WW95) is the result from a previous stellar model[10)] that used FFN rates.

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