Comparison of Updated Electron Capture Rates in the N=50 Region using 1D Simulations of Core-collapse Supernovae

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ABSTRACT
Recent studies have highlighted the sensitivity of core-collapse supernovae (CCSNe) models to electron-capture (EC) rates on neutron-rich nuclei near the $N = 50$ closed-shell region. In this work, we perform a large suite of one-dimensional (1D) CCSN simulations for 200 stellar progenitors using recently-updated EC rates in this region. For comparison, we repeat the simulations using two previous implementations of EC rates: a microphysical library with parametrized $N = 50$ rates (LMP), and an older single-nucleus approximation (SNA). We follow the simulations through shock revival up to several seconds post-bounce, and show that the EC rates produce a consistent imprint on CCSN properties, often surpassing the role of the progenitor itself. Notable impacts include the timescale of core collapse, the electron fraction and mass of the inner core at bounce, the accretion rate through the shock, the success or failure of revival, and the properties of the central compact remnant. We also compare the observable neutrino signal of the neutronization burst in a DUNE-like detector, and find consistent impacts to the counts and mean energies. Overall, the updated rates result in properties that are intermediate between LMP and SNA, and yet slightly more favorable to explosion than both.

1. INTRODUCTION
Massive stars ($\gtrsim 8 \, M_\odot$) are destined to undergo iron core-collapse, either imploding entirely into a black hole (BH), or violently ejecting their outer layers and leaving behind a proto-neutron star (PNS) in a core-collapse supernova (CCSN; reviews: Janka et al. 2007; Müller 2020). Of the myriad physical processes that contribute to these stellar deaths, the capture of electrons onto protons via the weak interaction plays a central role.

Electron-capture (EC) regulates the deleptonization of nuclear matter during collapse, and thus helps to set the initial conditions of the shock at core bounce (reviews: Langanke & Martínez-Pinedo 2003; Langanke et al. 2021). The uncertainties on electron capture rates can span orders of magnitude and produce larger variations in core-collapse properties than changes to the nuclear equation of state (EOS) or stellar progenitor (Sullivan et al. 2016; Pascal et al. 2020).

It is experimentally and computationally difficult to constrain electron-capture rates under astrophysical conditions, especially for the heavy, neutron-rich nuclei relevant to core-collapse. For this reason, CCSN simulations typically rely on parametrized approximations, particularly those of Bruenn (1985) and Langanke et al. (2003). Recent decades, however, have seen the continued development of tabulated rates for larger numbers of nuclei based on shell-model calculations (e.g., Oda et al. 1994; Langanke & Martínez-Pinedo 2000; Langanke et al. 2003; Suzuki et al. 2016).

A systematic study by Sullivan et al. (2016) showed that core-collapse simulations were most sensitive to changes in the electron capture rates of neutron-rich nuclei near the $N = 50$, $Z = 28$ closed shell region. The drawback is that most of these rates relied on the parametrization of Langanke et al. (2003), which is extrapolated from rates on nuclei near the valley of stability. In a follow-up study focusing on 74 nuclei in the high-sensitivity region, Titus et al. (2018) showed that
these rates are likely overestimated by up to two orders of magnitude, further emphasizing the need for updated rates. Using new experimental measurements of the $^{86}\text{Kr}(t,{}^3\text{He}+\gamma)$ charge-exchange reaction, Titus et al. (2019) calculated microphysical rates on 78 nuclei in this region, confirming that the parametrized rates are overestimated.

In the meantime, Raduta et al. (2017) improved upon the parametrization of Langanke et al. (2003) for neutron-rich nuclei by accounting for temperature, electron density, and odd-even effects. Comparing one-dimensional (1D) core-collapse simulations using this improved parametrization, Pascal et al. (2020) demonstrated the expected increase in core mass and electron fraction due to an average decrease in EC rates. Pascal et al. (2020) also performed a rate sensitivity study, independently verifying the findings of Sullivan et al. (2016) and Titus et al. (2018) that electron-capture rates in the $N = 50$ region remain the most crucial for CCSNe.

In this paper, we present simulations of core collapse supernovae through to shock revival/failure for 200 stellar progenitors using the updated $N = 50$ rates from Titus et al. (2019). We run corresponding simulations using the baseline rate library from Sullivan et al. (2016) with the improved approximation of Raduta et al. (2017), and a third set using the single-nucleus approximation of Bruenn (1985). By comparing the model sets, we investigate the impact of updated electron-capture rates on core collapse, shock revival, and neutrino emission across a variety of progenitors.

The paper is structured as follows. In Section 2 we describe our methods, including the electron-capture rate tables (§ 2.1), the setup of the CCSN simulations (§ 2.2), and the calculation of observable neutrino signals (§ 2.3). In Section 3, we compare the simulation results, with a detailed comparison of three reference progenitors (§ 3.1), the impact across the full progenitor population (§ 3.2), the compact remnants (§ 3.3), and the predicted neutrino signal (§ 3.4). In Section 4 we interpret our results and compare them to previous studies, and give concluding remarks in Section 5.

2. METHODS

To explore the impact of electron-capture rates on CCSNe, we run multiple large sets of 1D simulations using the FLASH code (Fryxell et al. 2000; Dubey et al. 2009). For initial conditions, we use 200 stellar progenitor models from Sukhbold et al. (2016) with zero-age main-sequence (ZAMS) masses between $9 - 120\,M_{\odot}$ (§ 2.2).

For each progenitor, we run simulations using three different implementations of EC rates, which include a single-nucleus approximation, microphysical calculations, and updated experimental rates (§ 2.1). For the $12, 20,$ and $40\,M_{\odot}$ progenitors, we also run simulations with the microphysical rates scaled by factors of 0.01 and 10. In total, this results in 612 supernova models evolved to between $1 - 5\,s$ post-bounce.

2.1. Electron-capture Rates

The first of our three electron-capture rate sets uses the single-nucleus approximation on a mean nucleus (SNA; Fuller et al. 1982; Bruenn 1985), also known as the independent particle approximation (IPA). These rates were used in the comparable FLASH simulations of Couch et al. (2020) and Warren et al. (2020). Crucially, SNA assumes that EC completely halts for nuclei with $N \geq 40$ due to Pauli blocking, thus only permitting captures on free protons at densities above $\sim 10^{10}\,g\,cm^{-3}$, where neutron-rich nuclei dominate the composition (Langanke et al. 2003).

The second set, which we label LMP, uses a library of microphysical rates compiled by the National Superconducting Cyclotron Laboratory (NSCL) Charge-Exchange Group\textsuperscript{1,2} (Sullivan et al. 2016; Titus et al. 2018). This library includes rates from Fuller et al. (1982); Oda et al. (1994); Langanke & Martínez-Pinedo (2000); Langanke et al. (2003); Pruett et al. (2003) and Suzuki et al. (2016). For nuclei that are not covered by the above calculations, the single-state parametrization from Raduta et al. (2017, Model 3) is used, which extends the approximation of Langanke et al. (2003) to account for temperature, electron density, and odd-even effects. By unblocking EC on neutron-rich nuclei, these modern calculations replace the assumption in SNA that deleptonization is dominated at high densities by EC on free protons (Langanke et al. 2003).

The third set, which we label LMP+N50, is the same as LMP except for updated microphysical rates in the region around $N = 50$, $Z = 28$, where core-collapse is known to be highly sensitive (Sullivan et al. 2016; Titus et al. 2018; Pascal et al. 2020). These new rates were calculated for 78 nuclei by Titus et al. (2019) using a quasi-particle random-phase approximation (QRPA) using constraints from their charge-exchange experiment on the $^{86}\text{Kr}(t,{}^3\text{He}+\gamma)$ reaction. The LMP set largely relies on the Raduta et al. (2017) parametrization for these rates, which appeared to be overestimated by up to two orders of magnitude due to their lack of Pauli-blocking effects (Titus et al. 2018, 2019). On the other hand, Dzhioev et al. (2020) recently argued that Pauli-unblocking at finite temperature may actually reduce or eliminate this gap. Indeed, during the preparation of our manuscript, Giraud et al. (2021) reported new finite-temperature calculations for the $N = 50$ region, which resulted in rates around an order of magnitude higher than LMP+N50 for $T \lesssim 10\,GK$ and $\rho Y_e = 10^{11}\,g\,cm^{-3}$, bringing them closer to the original LMP approximation. A fu-

\textsuperscript{1} https://github.com/csullivan/weakrates
\textsuperscript{2} https://groups.nscl.msu.edu/charge_exchange/weakrates.html
Figure 1. Post-bounce evolution of shock radius ($r_{sh}$) and neutrino heating efficiency in the gain region ($\eta_{\text{heat}}$) for three reference progenitors ($\S$ 3.1). The 0.01x and 10x models consist of the LMP and LMP+N50 rates systematically scaled by factors of 0.01 and 10 ($\S$ 2.1). Note the different $\eta_{\text{heat}}$ ranges.

Table 1. Neutrino detection channels used in the SNOWGLOBES analysis for a DUNE-like liquid argon detector

| Channel | Reaction | Flavor | (%) |
|---------|----------|--------|-----|
| $\nu_e$CC | $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}$ | $\nu_e$ | 70–80 |
| $\bar{\nu}_e$CC | $\bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}$ | $\bar{\nu}_e$ | $\lesssim 1$ |
| NC | $\nu + ^{40}\text{Ar} \rightarrow \nu + ^{40}\text{Ar}$ | $\nu_e, \bar{\nu}_e, \nu_x$ | 10–20 |
| ES | $\nu + e^- \rightarrow \nu + e^-$ | $\nu_e, \bar{\nu}_e, \nu_x$ | $\sim 7$ |

Note: The reaction channels are charged-current (CC), neutral current (NC), and electron scattering (ES). Also listed are the rough percentage contributions of each channel to our total counts, which vary by model and choice of flavor mixing.

Numerical Methods

To simulate the collapse and explosion of massive stars, we use the FLASH hydrodynamics code (Fryxell et al. 2000; Dubey et al. 2009) with the Supernova Turbulence

in Reduced-dimensionality (STIR) framework (Couch et al. 2020; Warren et al. 2020).

STIR enhances the “explodability” of 1D CCSN models by using time-dependent mixing-length theory (MLT) to approximate convective turbulence in 1D. We use a mixing length parameter of $\alpha_L = 1.25$, chosen to reproduce the convective velocities of 3D simulations (for details, see Couch et al. 2020).

We use a recently-implemented hydrodynamics solver (Couch et al. 2020), which uses a fifth-order finite-volume method-of-lines Runge-Kutta time integration.

For neutrino transport, we use the “M1” scheme, an explicit two-moment method with an analytic closure (described in O’Connor & Couch 2018), with three neutrino species ($\nu_e$, $\bar{\nu}_e$, and $\nu_x = \{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau\}$) and 18 logarithmically-spaced energy groups between 1 to 300 MeV.

We generate neutrino opacity tables using the open source neutrino interaction library NuLIB (O’Connor 2015). The interaction rates largely follow Bruenn (1985) and Burrows et al. (2006), with corrections for weak magnetism and nucleon recoil from Horowitz (2002). Separate tables are cal-

3 https://github.com/evanoconnor/nulib
culated using the neutrino emissivities derived from each EC rate set described in Section 2.1. We note that our tables do not include the many-body effects and virial corrections to neutrino-nucleon scattering from Horowitz et al. (2017). These corrections aid explodability by enhancing neutrino heating in the gain region (O’Connor et al. 2017), and thus our simulations result in fewer explosions than the corresponding models in Couch et al. (2020) and Warren et al. (2020). Nevertheless, this does not impede our goal of a comparison study between the EC rates.

We use the SFHo equation of state (EOS) from Steiner et al. (2013), and assume nuclear statistical equilibrium (NSE) abundances everywhere in the domain. Self-gravity is included using an approximate general-relativistic effective potential (Marek et al. 2006; O’Connor & Couch 2018).

For initial conditions, we use 200 stellar progenitor models from Sukhbold et al. (2016), the same set used with FLASH+STIR in Couch et al. (2020) and Warren et al. (2020). These progenitors are spherically symmetric, solar-metallicity, non-rotating, and non-magnetic, with ZAMS masses ranging from 9 – 120 M\(_\odot\). The set spans core compactness values of 0 \(\lesssim\) \(\xi_{2.5}\) \(\lesssim\) 0.54 (as defined in O’Connor & Ott 2011) and iron core masses of 1.29 \(\lesssim\) \(M_{\text{Fe}}\) \(\lesssim\) 1.84 M\(_\odot\).

The simulation domain extends from the center of the star to \(r = 15,000\) km. The domain is divided into 15 adaptive mesh refinement blocks, each containing 16 zones. We allow up to nine levels of mesh refinement, resulting in a zone resolution of 62.5 km at the coarsest level and 0.244 km at the finest level. The adaptive mesh refinement results in a total of roughly 1000 zones.

2.3. Neutrino Observables

Following the approach used in Warren et al. (2020), we calculate simulated observations of the neutrino burst at core bounce using SNOWGLOBES\(^4\) (Scholberg 2012), which uses the GLOBES\(^5\) (Huber et al. 2005) framework to predict event rates for a given detector material.

As input for SNOWGLOBES, we calculate from our simulations the neutrino flux at Earth assuming a CCSN distance of 10 kpc and a pinched neutrino spectrum with a Fermi-Dirac parametrization (Keil et al. 2003). We include adiabatic neutrino flavor conversions from Mikheyev-Smirnov-Wolfenstein (MSW) matter effects (Dighe & Smirnov 2000). For each model, we apply three separate cases of flavor mixing: no flavor mixing, normal neutrino mass ordering, and inverted mass ordering (Appendix A).

We calculate detection events for a 40 kt liquid argon detector, representing the planned Deep Underground Neutrino Experiment (DUNE, Abi et al. 2021) capable of detecting large numbers of \(\nu_e\) from nearby CCSNe (Kato et al. 2017). Table 1 summarizes the different interaction channels: charged current (CC) reactions on \(^{40}\)Ar by \(\nu_e\) and \(\bar{\nu}_e\); neutral current (NC) reactions on \(^{40}\)Ar for all flavors; and electron scattering (ES) for all flavors. The \(\nu_e\)CC reaction channel accounts for approximately 70 – 80\% of the total counts in our models.

We capture the neutronization burst by integrating events over 100 ms centered on bounce, using 5 ms time bins and 0.2 MeV energy bins. For each model and flavor mixing case, we thus obtain the total neutrino counts and the mean detected neutrino energy, \(\langle E \rangle\), summed over all detection channels.

3. RESULTS

Our collection of 612 simulations can be sorted into three groups based on the explosion outcomes for each progenitor. Firstly, there are those models that, for a given progenitor, fail to explode for all three electron-capture rate sets. Secondly, there are those with mixed explosion outcomes between the rate sets. And thirdly, there are those that successfully explode for all three sets.

Of the 200 progenitors, 126 fail for all three rate sets, 29 have mixed explosion outcomes, and 44 explode for all sets. The 10.25 M\(_\odot\) progenitor simulations experience numerical crashes mid-shock revival, and are excluded from discussions of explosion outcome. Of the mixed-outcome group, the SNA models always fail, whereas LMP and LMP+N50 both explode in 26 cases, and LMP+N50 is the only explosion for the remaining three cases (22, 27.4, and 33 M\(_\odot\)). In summary, there are 44 successful explosions for SNA, 70 for LMP, and 73 for LMP+N50.

The data presented here, and the codes used to analyze it, are publicly available (Appendix B).

3.1. Reference Progenitors

We here present detailed simulation comparisons for the 12, 20, and 40 M\(_\odot\) progenitors. These progenitors are representative of the three groups of explosion outcomes, respectively: all EC rate sets fail to explode; mixed outcomes; and all successfully explode.

The evolution of the shock radius, \(r_{\text{sh}}\), and the neutrino heating efficiency, \(\eta_{\text{heat}}\), are shown in Figure 1. Here, \(\eta_{\text{heat}}\) is the fraction of the total \(\nu_e\) and \(\bar{\nu}_e\) luminosity absorbed in the gain region, which we estimate following O’Connor & Ott (2011). All 12 M\(_\odot\) models fail to explode and all 40 M\(_\odot\) models successfully explode. For the 20 M\(_\odot\) models, the LMP, LMP+N50, and both 10x models explode, whereas the SNA and both 0.01x models fail.

A consistent hierarchy of \(r_{\text{sh}}\) evolution is seen across the reference progenitors. Overall, the SNA models reach

\(^4\) https://github.com/SNOwGLOBES/snowglobes

\(^5\) www.mpi-hd.mpg.de/personalhomes/globes
Figure 2. Radial matter profiles at core bounce versus enclosed mass for the 20 $M_\odot$ progenitor (left), and all 200 progenitors between 9–120 $M_\odot$ (right). From top to bottom: electron fraction ($Y_e$); specific entropy ($S$); density ($\rho$); and radial velocity ($v_r$). Differences between the EC rate are typically larger than differences between the progenitors. For the 20 $M_\odot$ progenitor, the SNA and 0.01x models fail to explode, whereas the LMP, LMP+N50, and 10x models successfully explode (Fig. 1).
Figure 3. Lepton fraction ($Y_l$) versus density ($\rho$) at core bounce for the $20 \, M_\odot$ progenitor. Of the baseline EC rate sets, SNA has the weakest deleptonization at densities $\gtrsim 10^{12} \, g \, cm^{-3}$, but the strongest at lower densities.

The smallest $r_{sh}$, experience the earliest shock recession (12 and $20 \, M_\odot$), and the latest shock revival ($40 \, M_\odot$), followed closely by the $0.01x$ models. The LMP and LMP+N50 models reach larger $r_{sh}$ before recession ($12 \, M_\odot$) and undergo earlier shock revival ($20$ and $40 \, M_\odot$). Finally, the $10x$ models reach the largest $r_{sh}$ before recession ($12 \, M_\odot$) and the earliest shock revivals ($20$ and $40 \, M_\odot$).

For the $20 \, M_\odot$ progenitor, LMP+50 appears to require a smaller heating efficiency for shock revival than LMP, suggesting more favorable explosion conditions. The $10x$ models experience a surge in $\eta_{\text{heat}}$ around 250 ms, which appears to contribute to an early shock runaway. In contrast, SNA does not reach sufficient $\eta_{\text{heat}}$ before its shock contracts, shrinking the available gain region for neutrino interactions.

The matter profiles at core bounce are shown in Figure 2 for the $20 \, M_\odot$ progenitor (left) and the full set of 200 progenitors (right). We define bounce as the moment when the peak entropy in the core reaches $3 \, k_B \, \text{baryon}^{-1}$. We also define the inner core mass at bounce, $M_{\text{core}}$, as the mass enclosed within this point (also known as the homologous core mass).

As with $r_{sh}$, the models maintain a consistent hierarchy, even across the entire population of progenitors. The SNA models have the largest inner core mass and electron fraction, entropy, density, and infall velocity. This trend is followed, in order, by the $0.01x$, LMP+N50, LMP, and finally $10x$ models. This ordering is reversed for the $Y_e$ outside the shock, where SNA is the lowest and $10x$ the largest.

In Figure 3, the lepton fraction is shown versus density at bounce for the $20 \, M_\odot$ progenitor. Above the neutrino-trapping densities of $\sim 10^{12} \, g \, cm^{-3}$, the $0.01x$ models have the largest $Y_l$, followed by SNA, LMP+N50, LMP, and $10x$.

Figure 4. Core bounce properties versus progenitor iron core mass, $M_{\text{Fe}}$, for all simulations (§ 3.2). From top to bottom: electron fraction at bounce in the $M = 0.1 \, M_\odot$ mass shell ($Y_e$); inner core mass at bounce ($M_{\text{core}}$); gravitational potential at the shock at bounce ($V_b$); and convergence time of the shock with the $\nu_e$-sphere, relative to bounce ($t_{\nu_e} - t_b$). The $0.01x$ and $10x$ rate-scaled models are marked by downward and upward-pointing triangles, respectively (appearing from left to right: 12, 20, and $40 \, M_\odot$). In most cases, the differences between EC rates are larger than the dependence on stellar progenitor.

3.2. Population Comparisons

A selection of properties at core bounce for all 200 progenitors are plotted versus the progenitor iron core mass, $M_{\text{Fe}}$, in Figure 4. These quantities in particular demonstrate large differences between the EC rates compared to differences between the progenitors.
The electron fraction of the inner core at bounce, $Y_e$, is taken at the $M = 0.1 \, M_\odot$ enclosed mass coordinate (see also Fig. 2). The SNA models have the largest $Y_e$ (i.e., weakest deleptonization), followed by LMP+N50 and LMP.

The extent of deleptonization translates directly into the inner core mass at bounce, $M_{\text{core}}$. The SNA rates produce systematically larger $M_{\text{core}}$ than LMP by around $0.08 \, M_\odot$ ($\approx 15\%$), whereas LMP+N50 are around $0.03 \, M_\odot$ ($\approx 5\%$) larger.

The density profile at bounce (Fig. 2) determines the gravitational potential at the shock, $V_s$. Following previous trends, SNA results in a potential around 15% deeper than LMP, compared to LMP+N50 which is consistently $\approx 5\%$ deeper.

Also shown is $t_{\nu_e}$, the time when the shock crosses the $\nu_e$-sphere immediately following bounce. SNA reaches $t_{\nu_e}$ consistently $\approx 1.5 \, \text{ms}$ earlier than LMP, while LMP+N50 is $\approx 0.5 \, \text{ms}$ earlier. This relatively small but persistent difference impacts the neutrino signal of the deleptonization burst (§ 3.4).

Quantities which have much more variation between progenitors than between the EC rates are illustrated in Figure 5. For clarity, we emphasize the changes due to EC rates by calculating the absolute difference relative to LMP for each progenitor. For a given quantity $X$, each SNA value is given by $\Delta X = X_{\text{SNA}} - X_{\text{LMP}}$, and likewise for LMP+N50.

The time of core bounce from the start of the simulation, $t_b$, illustrates the speed of collapse from a common starting point. SNA reaches core bounce around 10 – 17 ms earlier than LMP, whereas LMP+N50 is generally $\lesssim 2 \, \text{ms}$ later.

The mass accretion rate through $r = 500 \, \text{km}$ at bounce, $\dot{M}_b$, further illustrates the strength of collapse. Overall, SNA reaches accretion rates around $0.1 \, M_\odot \, \text{s}^{-1}$ larger than LMP, whereas LMP+N50 is around $0.1 \, M_\odot \, \text{s}^{-1}$ smaller.

The maximum shock radius reached for failed explosions, $\max(r_{\text{sh}})$, further supports the differences in shock evolution seen in the reference progenitors (Fig. 1). SNA reaches the smallest $r_{\text{sh}}$, generally around 5 – 20 km smaller than LMP, whereas LMP+N50 is around 0 – 5 km larger.

### 3.3. Compact Remnants

The compact remnant properties are compared in Figure 6 as the absolute difference relative to LMP, as used in Section 3.2.

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**Figure 5.** Absolute difference of LMP+N50 and SNA models relative to LMP for each progenitor (§ 3.2), versus progenitor iron core mass. The quantities compared, from top to bottom: time to bounce from start of simulation ($t_b$); accretion rate through $r = 500 \, \text{km}$ at bounce ($\dot{M}_b$); and maximum shock radius reached for failed explosion models ($\max(r_{\text{sh}})$). Note the grid resolution of the simulation limits the precision of $r_{\text{sh}}$ here to $\approx 0.5 \, \text{km}$.

**Figure 6.** Absolute difference of compact remnant properties relative to LMP (§ 3.3), versus progenitor iron core mass. Top: proto-neutron star mass at the end of the simulation ($M_{\text{PNS}}$) for exploding models. Bottom: time from bounce to black hole formation ($t_{\text{BH}}$).
The proto-neutron star mass at the end of the simulation, $M_{\text{PNS}}$, is compared for exploding models. SNA tends to produce a heavier PNS, with progenitors of $M_{\text{Fe}} \gtrsim 1.45 \, M_\odot$ around $0.02 - 0.1 \, M_\odot$ larger than LMP. On the other hand, LMP+N50 tends to produce a similar or slightly lighter PNS, at most up to $0.01 - 0.02 \, M_\odot$ lighter than LMP. All of the exploding models for $M_{\text{Fe}} \lesssim 1.45 \, M_\odot$ are within $0.02 \, M_\odot$ of LMP.

The post-bounce time to black hole formation, $t_{\text{BH}}$, is compared for the subset of models that reach PNS collapse. Not all failed-explosion models reach PNS collapse within the time simulated (between $1 - 5$ s post-bounce). For the handful of models that do allow comparison with LMP, SNA reaches black hole formation around 20 – 80 ms earlier, whereas LMP+N50 is only around 2 – 7 ms earlier.

Assuming the entire star is accreted, there would be no difference in the final BH mass between the EC rates.

3.4. Neutrino Signal

The neutrino emission at $r = 500 \, \text{km}$ is shown in Figure 7 for the $20 \, M_\odot$ progenitor. The three baseline sets reach similar peak electron-neutrino luminosities of $L_{\nu_e} \approx 5 \times 10^{53} \, \text{erg} \, s^{-1}$. The 0.01x luminosities peak roughly 10% higher, whereas the 10x peak roughly 10% lower. Additionally, the SNA and 0.01x models peak slightly earlier than the LMP, LMP+N50, and 10x models, which have $\nu_e$ emission spread out to later times. The mean neutrino energies, $\langle E_{\nu_e} \rangle$, follow a similar pattern. The $\bar{\nu}_e$ and $\nu_e$ emission is largely reversed, with SNA and 0.01x generally having the largest luminosities and mean energies, followed by LMP+N50, LMP, and 10x.

The predicted neutrino burst signal in a DUNE-like detector is shown for all 612 models across 200 progenitors in Figure 8. For all three MSW flavor-mixing cases, there are consistent differences in the detected neutrinos between the electron-capture rate sets.

Overall, LMP and LMP+N50 produce similar total neutrino counts and mean detected energies, $\langle E \rangle$, with larger differences for SNA, particularly in $\langle E \rangle$. When no flavor mixing is assumed, SNA results in the lowest counts and $\langle E \rangle$. The effect is reversed when flavor-mixing is included for both normal and inverted neutrino mass ordering. Overall, the inclusion of flavor mixing results in fewer counts and larger $\langle E \rangle$.

4. DISCUSSION

The choice of electron-capture rates has a clear impact on our simulations of core-collapse supernovae. Perhaps the starkest difference in outcome is whether the models undergo successful shock-revival and explosion. This variation in outcome can largely be traced to the pre-bounce core-collapse phase, where the EC rates control deleptonization and set the conditions at core bounce for the subsequent shock evolution. The EC rates also influence the formation of the compact remnant and the observable neutrino signals.

4.1. Collapse and Bounce

Due to the lack in SNA of forbidden transitions and thermal unblocking effects, the rates are limited to EC on free protons when the average nucleus has a neutron number of $N \gtrsim 40$ (Hix et al. 2003). Because protons are less abundant than neutron-rich nuclei at high densities, the total number of electron captures are suppressed, resulting in a larger $Y_e$ in the inner core at bounce compared to LMP and LMP+N50, which do allow EC for $N \gtrsim 40$. On the other hand, electron-captures are actually enhanced in SNA at low densities below the $N = 40$ threshold, because the rates are overestimated compared to the LMP-based tables (Lentz et al. 2012).

The combined effect is a larger $Y_e$ and $Y_l$ for SNA in the inner core region ($\rho \gtrsim 10^{12} \, \text{g} \, \text{cm}^{-3}$) and lower values in the outer core compared to LMP and LMP+N50 (Fig. 2 and 3). This enhanced deleptonization of matter passing through lower densities accelerates the collapse to core bounce, leading to stronger accretion rates, larger infall velocities, larger inner core mass, deeper gravitational potential, and higher densities (Fig. 4 and 5).

These bounce profile differences between the SNA and LMP-based rates are well-established in the literature, noted by Langanke et al. (2003) and Hix et al. (2003), and reproduced in subsequent studies (e.g., Lentz et al. 2012; Sullivan et al. 2016; Richers et al. 2017; Pascal et al. 2020).

4.2. Shock Evolution and Explosion Outcome

Initially, owing to the larger inner core mass, the SNA shock has more kinetic energy and less overlying material to pass through than LMP and LMP+N50. Competing with these favorable conditions, however, are the higher densities (and thus deeper gravitational potential), faster infall of the overlying material (Fig. 2 and 4), and stronger neutrino cooling. Despite rapid expansion at early times in SNA, the shock is soon overwhelmed by accretion and neutrino cooling, leading to earlier stalling at smaller radii (Fig. 5). Compounded by the smaller gain region now available for neutrino heating, the result is an earlier shock recession or a delayed explosion (Fig. 1). By contrast, LMP+N50 tends to have more favorable conditions for a successful explosion, with the slowest collapse to bounce and smallest accretion rates (Fig. 5).

The impact of the EC rates on shock evolution is borne out by the incidence of successful explosions. Of the 73 progenitors with at least one explosion among the EC rate sets, LMP+N50 explodes in all 73 and LMP explodes in 70. In contrast, SNA explodes in only 43 of these cases, and for no progenitor is SNA the sole explosion.

4.3. Compact Remnants
Figure 7. Neutrino emission at $r = 500$ km for the $20 \, M_\odot$ progenitor. Top row: neutrino luminosity, $L_\nu$. Bottom row: mean neutrino energy, $\langle E_\nu \rangle$. Left: electron neutrino ($\nu_e$) emission; Right: electron antineutrino ($\bar{\nu}_e$) and heavy-lepton neutrino ($\nu_x$) emission. Note the different time and $L_\nu$ ranges.

Figure 8. Neutrino burst signal in a DUNE-like liquid argon detector for all 200 progenitors, versus progenitor iron core mass. Top row: total neutrino counts. Bottom row: mean detected neutrino energy. From left to right are the adiabatic flavor mixing implementations: no flavor mixing, normal mass ordering, and inverted mass ordering. The signal is integrated over 100 ms centered on bounce ($\S$ 2.3), across all detection channels (Table 1), and assuming a distance of 10 kpc. The error bars show typical $1\sigma$ uncertainties due to Poisson counting statistics. Note the different $y$-axis ranges.
The EC rates also impact the formation of the compact remnant (§ 3.3). In successful explosions, the proto-neutron star mass, \( M_{\text{PNS}} \), is effectively determined by the total mass accreted through the shock before shock revival unbinds the remaining material. The two deciding factors are thus the accretion rate and the elapsed time before shock revival. SNA typically experiences both higher accretion rates (Fig. 5) and later shock revival (Fig. 1), resulting in the largest \( M_{\text{PNS}} \) (Fig. 6). The converse effects on LMP+N50 result in smaller \( M_{\text{PNS}} \).

In the case of failed explosions, the conditions at core bounce influence the evolution and eventual collapse of the PNS. The larger core \( Y_e \) and \( M_{\text{core}} \) in SNA results in a stronger initial shock, producing a larger PNS radius and stronger \( \nu_x \) radiation (Fig. 7). The subsequent cooling of the PNS results in SNA reaching collapse approximately 20 – 80 ms earlier than LMP (Fig. 6). LMP+N50 has only marginally more efficient PNS cooling than LMP, and collapses at most a few milliseconds earlier. A change in the BH formation time would alter the shut-off of multimessenger signals from neutrinos and gravitational waves.

4.4. Neutrino Emission

The effects of electron-capture on deleptonization and shock formation also manifest in the neutrino emission around bounce (§ 3.4). For SNA, a larger \( M_{\text{core}} \) at bounce and stronger initial shock, combined with smaller neutrinospheres due to lowered opacities, leads to a faster convergence of the shock with the \( \nu_e \)-sphere, producing an earlier peak in \( L_{\nu_e} \) (Fig. 7). The mean time between core bounce and the shock reaching the \( \nu_e \)-sphere was 1.8 ± 0.1 ms for SNA, 3.3 ± 0.1 ms for LMP, and 2.8 ± 0.1 ms for LMP+N50 (1\( \sigma \) standard deviation; Fig. 4). These differences in \( L_{\nu_e} \) have been noted in previous EC rate studies (e.g., Hix et al. 2003; Lentz et al. 2012; Sullivan et al. 2016; Pascal et al. 2020).

For LMP and LMP+N50, the extended emission of \( \nu_e \) at larger \( L_{\nu_e} \) and \( \langle E_{\nu_e} \rangle \) results in higher detected neutrino counts and energies in a DUNE-like liquid argon detector when no flavor mixing is assumed (Fig. 8).

When MSW flavor mixing is included with normal neutrino mass ordering, approximately 98% of the emitted \( \nu_e \) are converted to \( \nu_x \), and vice versa. This reduces the number of \( \nu_e \) available for detection in the dominant \( \nu_e \)-CC channel (Table 1), resulting in fewer total counts. There is also a shift to larger \( \langle E \rangle \) because most of the \( \nu_x \) that are now detected originate as high-energy \( \nu_x \). Because SNA has larger emitted \( L_{\nu_e} \) and \( \langle E_{\nu_e} \rangle \), it now has the highest counts and \( \langle E \rangle \).

The inverted mass ordering case is somewhat intermediate, with only 70% of the emitted \( \nu_e \) converted to \( \nu_x \), and vice versa. These favorable survival probabilities result in overall counts and \( \langle E \rangle \) that are between the previous two cases. This appears to roughly coincide with the “cross-over” point, where all three EC rates produce very similar counts.

The large error bars, especially for \( \langle E \rangle \), suggest that these differences between the EC rates would be difficult to detect under these assumptions. The uncertainties may be improved by considering additional parts of the neutrino lightcurve (e.g., Segerlund et al. 2021), combining measurements from multiple neutrino detectors, or if the supernova were nearer than the assumed 10 kpc.

5. CONCLUSION

We have produced a suite of 612 one-dimensional core-collapse supernova simulations, using three sets of electron-capture rates and 200 stellar progenitors between 9 – 120 \( M_\odot \).

The three EC rate sets were (§ 2.1): a single-nucleus approximation (SNA; Bruenn 1985); a microphysical library with parametrized rates in the high-sensitivity \( N = 50 \) region (LMP; Sullivan et al. 2016; Titus et al. 2018); and the same library with updated \( N = 50 \) rates (LMP+N50; Titus et al. 2019).

Of the 200 progenitors, there were 43 successful explosions for the SNA set, 70 for LMP, and 73 for LMP+N50. In general, the SNA models reached smaller shock radii and exploded later than their LMP and LMP+N50 counterparts (§ 3.1). Of the latter two, LMP+N50 appeared marginally more favorable to explosion, with larger shock radii and earlier shock runaway than LMP.

At core bounce, SNA typically had the largest inner core mass, electron fraction, density, accretion rate, infall velocity, and gravitational potential (Fig. 2, 4, and 5). The next largest values were generally LMP+N50 followed by LMP, although LMP+N50 swapped places with LMP for the collapse time and accretion rate (Fig. 5). The standard ordering was also reversed for \( Y_e \) in the outer core, where SNA had the lowest values and LMP the highest (Fig. 3).

For exploding progenitors, SNA produced an initial PNS mass around 0.02 – 0.1 \( M_\odot \) larger than LMP due to higher accretion rates and delayed shock revival, and LMP+N50 was typically \( \lesssim 0.02 \ M_\odot \) smaller (Fig. 6). For failed explosions, enhanced PNS cooling in SNA resulted in a collapse to BH roughly 20 – 80 ms earlier than LMP, whereas LMP+N50 was at most a few milliseconds earlier.

Without flavor mixing, the extended \( \nu_e \) emission of LMP and LMP+N50 following bounce (Fig. 7) resulted in higher detected counts and mean energies than SNA in a DUNE-like liquid argon detector (Fig. 8). Conversely, when adiabatic flavor mixing is included, the enhanced \( \nu_x \) emission in SNA is converted to \( \nu_e \), resulting in higher counts and energies than LMP and LMP+N50. Given only \( \sim 10^2 \) counts, however, these differences were typically smaller than the estimated uncertainties.
All of these results largely stem from the total rate of electron captures at different densities during collapse (§ 4.1). For SNA, the total EC rate is overestimated at lower densities, but subsequently underestimated at higher densities due to Pauli blocking on a mean nucleus of $N \geq 40$. The LMP-based rates unblock EC for neutron-rich nuclei, and so deleptonization proceeds further than SNA during collapse. The updated $N = 50$ rates in LMP+N50 are lower than the parametrized rates in LMP, producing an intermediate case between LMP and SNA (Fig. 4).

It is important to emphasize the limitations of our study. While our STIR framework (Couch et al. 2020) approximates the effects of turbulence in 1D, there is ultimately no substitute for multi-dimensional simulations. Only high-fidelity 3D simulations can hope to fully capture the interplay between fluid instabilities, magneto-hydrodynamics, and neutrino transport in CCSNe (e.g., Hanke et al. 2013; Lentz et al. 2015; Summa et al. 2018; O’Connor & Couch 2018; Müller et al. 2019). Our progenitors from Sukhbold et al. (2016) were 1D, solar-metallicity, non-rotating, and non-magnetic, and do not represent the full variety of stellar populations. The progenitor models also used microphysical EC rates, and so the sudden transition to approximate rates in our SNA models is somewhat artificial. Although we accounted for adiabatic flavor mixing when calculating neutrino signals, there remains copious uncertainty around the effects of flavor oscillations, which were not included in our simulations.

Finally, the updated rates in LMP+N50 do not include temperature dependence effects (Dzhioev et al. 2020). Very recently, Giraud et al. (2021) reported new finite temperature calculations for the $N = 50$ region, with rates around an order of magnitude higher than LMP+N50. Their simulations suggest that CCSN properties would be intermediate between the LMP and LMP+N50 models presented here, which are already in relatively good agreement compared to the commonly-used SNA rates. Work is underway to incorporate these new rates into NuLIB so that they can be freely used in future CCSN simulations.

Electron capture plays a central role in deleptonization, shock formation, and neutrino production during core-collapse. Our study has explored the effects of updated EC rates in the high-sensitivity $N = 50$ region, including a detailed comparison between microphysical rates and a simple single-nucleus approximation. By producing simulations across 200 progenitors, we have shown there are clear, systematic impacts of EC rates on the core structure, shock dynamics, and neutrino signals throughout the core-collapse supernovae mechanism.

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**Software:** FLASH$^6$ (Fryxell et al. 2000; Dubey et al. 2009), NSCL Weak-rate Library v1.2 (Sullivan 2015), NuLIB (O’Connor 2015), SNOWGLOBES (Scholberg 2012), GLOBES (Huber et al. 2005), MATPLOTLIB$^7$ (Hunter 2007), NUMPY$^8$ (Harris et al. 2020), SCIPY$^9$ (Virtanen et al. 2020), YT$^{10}$ (Turk et al. 2011), PANDAS$^{11}$ (Pandas development team et al. 2022), XARRAY$^{12}$ (Hoyer & Hamman 2017; Hoyer et al. 2020), ASTROPY$^{13}$ (Astropy Collaboration et al. 2013, 2018), FLASHBANG$^{14}$ (Johnston 2022a), FLASH_SNOWGLOBES$^{15}$ (Johnston 2022b).

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$^6$ https://flash.rochester.edu/site/
$^7$ https://matplotlib.org
$^8$ https://www.numpy.org
$^9$ https://www.scipy.org
$^{10}$ https://yt-project.org
$^{11}$ https://pandas.pydata.org
$^{12}$ https://xarray.pydata.org
$^{13}$ https://www.astropy.org
$^{14}$ https://github.com/zacjohnston/flashbang
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APPENDIX

A. NEUTRINO FLAVOR MIXING

When calculating detectable neutrino counts with SNO\textsc{W}GL\textsc{O}BES (§ 2.3), we account for adiabatic neutrino flavor conversions due to MSW matter effects (Dighe & Smirnov 2000). Following similar approaches in Nagakura (2021) and Segerlund et al. (2021), we calculate the neutrino flux at Earth, \(F_i\), for each neutrino flavor \(i\), using

\[
F_e = pF^0_e + (1 - p)F^0_x, \quad (A1)
\]

\[
\bar{F}_e = \bar{p}F^0_e + (1 - \bar{p})F^0_x, \quad (A2)
\]

\[
F_x = \frac{1}{2}(1 - p)F^0_e + \frac{1}{2}(1 + p)F^0_x, \quad (A3)
\]

\[
\bar{F}_x = \frac{1}{2}(1 - \bar{p})F^0_e + \frac{1}{2}(1 + \bar{p})F^0_x, \quad (A4)
\]

where \(p\) and \(\bar{p}\) are the survival probabilities, and \(F^0_i\) are the emitted fluxes for each flavor \(i\). Under normal neutrino mass ordering, the survival probabilities are given by

\[
p = \sin^2 \theta_{13} \approx 0.02, \quad (A5)
\]

\[
\bar{p} = \cos^2 \theta_{12} \cos^2 \theta_{13} \approx 0.69, \quad (A6)
\]

and under inverted mass ordering by

\[
p = \sin^2 \theta_{12} \cos^2 \theta_{13} \approx 0.29 \quad (A7)
\]

\[
\bar{p} = \sin^2 \theta_{13} \approx 0.02, \quad (A8)
\]

where we use mixing parameters of \(\sin^2 \theta_{12} = 0.297\) and \(\sin^2 \theta_{13} = 0.0215\) (Capozzi et al. 2017). The no-mixing case is equivalent to \(p = \bar{p} = 1\). Note that our simulations use the combined heavy-lepton species \(\nu_x = \{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau\}\), and thus we assume

\[
F^0_x = F^0_x \propto \frac{1}{4}L_{\nu_x}, \quad (A9)
\]

where \(L_{\nu_x}\) is the heavy-lepton neutrino luminosity from the simulation (Fig. 7). The separated heavy-flavor inputs to SNO\textsc{W}GL\textsc{O}BES are then

\[
F_\mu = F_\tau = F_x, \quad (A10)
\]

\[
\bar{F}_\mu = \bar{F}_\tau = \bar{F}_x. \quad (A11)
\]

The code used for these calculations is publicly available as a \texttt{Python} package, \textsc{flash_snowglobes} (Johnston 2022b).

B. DATA AVAILABILITY

The data for all simulations presented in this work are publicly available in a Mendeley Data repository (Johnston et al. 2022). The dataset includes summarized simulation results, radial profiles at core bounce, time-dependent quantities (e.g., shock radius and neutrino luminosities), and time-binned SNO\textsc{W}GL\textsc{O}BES neutrino counts and energies.

Much of the model analysis and plotting was performed using our publicly available \texttt{Python} package \textsc{flashbang} (Johnston 2022a).