Charged Current Neutrino Interactions on Free Nucleons in MESA Simulated Core-collapse Supernovae

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Abstract

In the present work, approximate rates which emulate the charged-current neutrino interactions on free nucleons were implemented in the Modules for Experiments in Stellar Astrophysics (MESA) code. Changes to the 10398 release of MESA star have been made to accomplish this while still maintaining the full functionality of the original code. An example core-collapse supernova simulation from the MESA test suite was taken up with and without the implemented reactions and a qualitative difference in the innermost ejecta composition is observed. The potential for the use of this addition in the modeling of neutrino nucleosynthesis in MESA are discussed. In addition, the modified files which allow this functionality have been provided and made easily accessible to the user, meaning they can be readily changed and improved by users simulating different core collapse supernovae conditions.

Section I: Introduction

Sufficiently massive stars may end their lives in the cataclysmic events that are core collapse supernovae (CCSNe). When the iron core within these stars reaches sufficient mass, they are unable to withstand gravitational collapse. The collapse of the core is, in part, sped up by electron capture onto protons within it [8]. This process creates an intense but brief electron neutrino flux. More neutrinos and antineutrinos of all flavors are emitted on longer timescales by the cooling of the nascent neutron star in the collapsed core. When the collapsing core reaches nuclear density it rebounds and sends a shock front into the material above. The shock eventually stalls as it loses kinetic energy dissociating nuclei into free nucleons.

$p + \nu_e\text{-bar} \Rightarrow n + e^+$ (Reaction 1)

$n + \nu_e \Rightarrow p + e^-$ (Reaction 2)

The above charged-current neutrino interactions are thought to play an important role in both helping to revive the stalled shock front, and later influence the nucleosynthesis within the neutrino driven wind of core-collapse supernovae [7]. The motivation behind this work was to examine the qualitative difference between the electron mole fraction (Ye) and isotopic composition with and without an approximated neutrino flux using Modules for Experiments in Stellar Astrophysics (MESA) [1]. At the time of writing, MESA star does not model neutrino interactions such as reactions 1 and 2. Thus, modifications were made to the base code of MESA which gives approximate rates for reactions 1 and 2. Because the rates are approximate and rely on variables currently outside of the set which MESA calculates, the modifications are presented as an initial step towards a functionality which may prove useful as addition to MESA. The author hopes that, in accordance with the collaborative spirit of MESA development, interested parties will improve on the additions described in this work. In this vein, all changes to implement the charged-current neutrino interaction functionality are made available, either alongside this document or at **https://github.com/liam-kroll/MESA-Nu-Interactions**.

The outline of this work is as follows:

Section II describes how code within the MESA main directory was modified to implement these changes. Section III outlines the limitations and applicability of the addition. In Section IV, the MESA simulations that were performed to test the charged-current neutrino interaction functionality are described and the results presented. Lastly, in Section V a summary of the present work is given.

Section II: Procedure

To keep track of the changes made to MESA, any modified or added lines were placed between two commented brackets like:

```
!=====Changed=====
first_line_that_was_changed_or_added
second_line_that_was_changed_or_added
Nth_line_that_was_changed_or_added
!================
```

In some instances only one or two lines of code were changed and this practice was abbreviated to:

```
!===Changed below, XXXX======
```

Where XXXX gave a description of what was changed. This practice can be seen in the changed files provided alongside this work, or at **https://github.com/liam-kroll/MESA-Nu-Interactions**.

To simulate the charged current neutrino interactions, two reactions, called r_prot_wk_neut and r_neut_wk-minus_prot to symbolize reactions 1 and 2 respectively, were created. Nominally, MESA's rates module provides reaction rates based on the hydrodynamic variables and composition within each cell [1]. However for the reactions being considered it has been shown by Qian & Woosley that the reaction rate depends on the radial position of the cell from the center of the star, and the (anti-)neutrino energy and luminosity [6]. Therefore when implementing the reactions, instead of entering a standard rate function into raw_rates.f90, the raw rates were set to an arbitrary constant value; they would be discarded later. A simple routine called net_neu_reacy was written which calculated the rates for these reactions according to equations 65a and 65b of Ref [6]. The net_neu_reacy routine was placed in a modified run_stars_extra.f90 file which subsequently passed the calculated rates and Q values to the net_get routine from the net module. To be able to pass these values to the net_get routine several files had to be slightly modified for MESA to successfully compile. Where possible, any changes that were made were placed in run_star_extras.f90 so as to be accessible to the interested user without the need to recompile the main MESA directory. When all of these files had been changed, MESA was recompiled. When done these changes accomplish the following:

If the use_other_get_net control parameter is set to true in an inlist being called during a run, the rates for reactions 1 and 2 are flagged to be calculated. MESA's evolution routines proceed as normal. However, if the user has included the r_prot_wk_neut and r_neut_wk-minus_prot reactions in their reaction network, the net_neu_place routine will be called and will replace the null rate from raw_rate.f90 for one calculated by net_neu_reacy. This updated rate is then used by MESA's net module to calculate changes in composition for each cell like the other reactions in the network.

Table 1) Files modified to implement the described neutrino interaction functionality

File	Location within mesa-r10398
net_lib.f90	/net/public
net_approx21.f90	/net/private
net_approx21_plus_co56.f90	/net/private
net_approx21_plus_fe53_fe55_co56.f90	/net/private
net_approx21_procs.inc	/net/private
net_eval.f90	/net/private
net_derivs.f90	/net/private
net_burn.f90	/net/private
net_burn_const_density.f90	/net/private
net_burn_const_p.f90	/net/private
makefile	/net/make
test_net_support.f	/net/test/src
sample_net.f	/net/test/src
test_net_do_one	/net/test/src
other_net_get.f90	/star/other
net.f90	/star/private
reactions.list	/data/rates_data
raw_rates.f90	/rates/private
rates_names.f90	/rates/private
rates_def.f90	/rates/public
test_output	/rates/test
run_star_extras.f90	In the work directory of a project where the functionality is desired.

Table 2) Files added to implement the described neutrino interaction functionality

File	Location within mesa-r10398 where file was placed
net_neu_reac.f90	/net/private

In addition, the r_prot_wk_neut and r_prot_wk-minus_neut reactions were added to the approx21 series of hardwired nets for testing purposes because of the speed in which they can simulate CCSNe.

To enable the functionality as described above, the user needs only to replace the original files (a list is given in Tables 1 & 2) with the modified files included with this work or from **https://github.com/liam-kroll/MESA-Nu-Interactions**. MESA should then be recompiled. When the user wishes to include the charged-current neutrino interactions on nucleons (reactions 1 and 2) in a run, they should set the "use_other_net_get" control namelist parameter in their inlist to true. The user can then adjust the neutrino luminosity parameters from their inlist using the x_ctrls (see the modified run_star_extras.f file for a list of the neutrino luminosity parameters and their corresponding x_ctrl numbers)

Section III: Applicability and Limitations

With regards to the situations in which the described functionality is applicable, some remarks should be made. Because MESA cannot simulate a self-consistent core-collapse supernova the mass cut and energy injection methods (the details of which are described in Sections 6.2.2 and 6.1 of [3] and [4] respectively) are resorted to when simulating these events. Although reactions 1 and 2 play a role in reviving the shock front, these interactions cannot be used to investigate shock front revival in CCSNe simulations due to the artificial energy injection method of inducing an explosion. With an artificial energy source like this, the remaining correction from neutrino interactions becomes the composition change as opposed to the energy they deposit. For this reason, neutrino annihilations and neutrino scattering events are not considered in the present work as they have no effect on the material composition. The applicability of the added and modified code only pertains to the effect the charged-current interactions have on the nucleosynthesis within the neutrino driven wind.

In addition there were some simplifying assumptions which were adopted in the current net_neu_reacy routine. Namely:

1) The current functions which describe the electron neutrino and antineutrino mean energies and luminosities are general placeholders for testing purposes. These parameters are vital in calculating the rates as described above. However they depend on the EoS of the nuclear matter comprising the forming neutron star and the infall dynamics; both of these are intrinsically absent because the core of the supernova model is excised. That being said, all the calculations relevant to the rates are performed in run_star_extras.f90. Therefore if the user wishes they can modify these placeholders to functions which are more suitable for their specific progenitor or assumptions.

2) Because the rates are calculated using the expressions from Ref [6], they are subject to the same assumptions and approximations made by the authors in the work. Thus, the current routine gives rates that are an approximation and any numerical results should be regarded accordingly.

Section IV: Results

To test the functionality described above, a MESA work directory was created that was based off of the example_ccsn_IIp directory from the test_suite folder (r-10398). The run_star_extras.f routines from this test_suite example were ignored, as this file is mainly concerned with matching the simulated lightcurve to observed CCSN lightcurves in the later parts of the explosion [4].

The starting model which was used was 13M_vvc_0.0_wnd_1.0_ovr_010_mlt_3.0_z6m3.mod from the same test_suite directory. This starting model was not chosen because of any specific properties, but because it was an already evolved CCSN progenitor beginning core collapse, and thus no further inlists for the creation of a progenitor had to be made. As previously mentioned the procedure for simulating a CCSN in this work closely follows Sections 6.2.2 and 6.1 of [3] and [4] respectively. However a brief description of the method is described here for completeness. The core with entropy greater than $4k_B$ was removed. The material exterior to this mass cut was allowed to fall inwards. When the inner cell reached a radius of 200km, the inner boundary velocity was fixed to zero. When the inner cell's infall had been arrested, a total of 0.59×10^{51} ergs was injected evenly into the $0.01M_{sun}$ of material above the mass cut over a period of roughly 5ms. At this time the supernova was allowed to explode normally, or the neutrino interactions were turned on before the explosion with all other controls being equal. These represented the control and the test runs respectively. From this point the propagating shock was followed for the first 2.5 seconds after the completion of energy injection. The results from the end of energy injection to 2.5s afterwards are shown in Figs 1-6 and discussed in the remainder of this section.

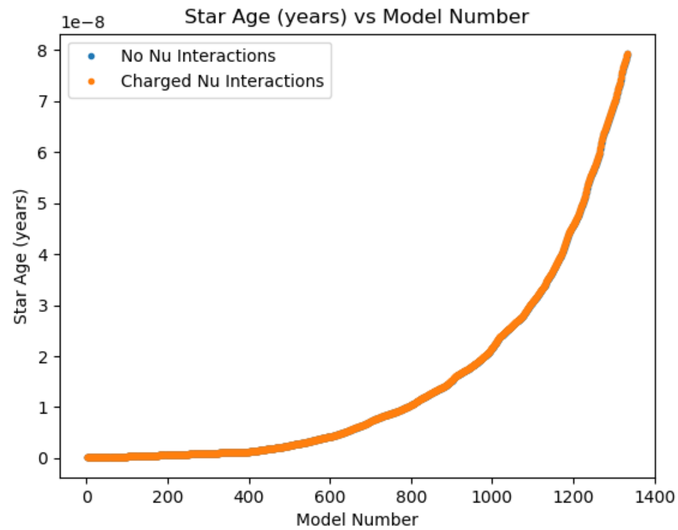
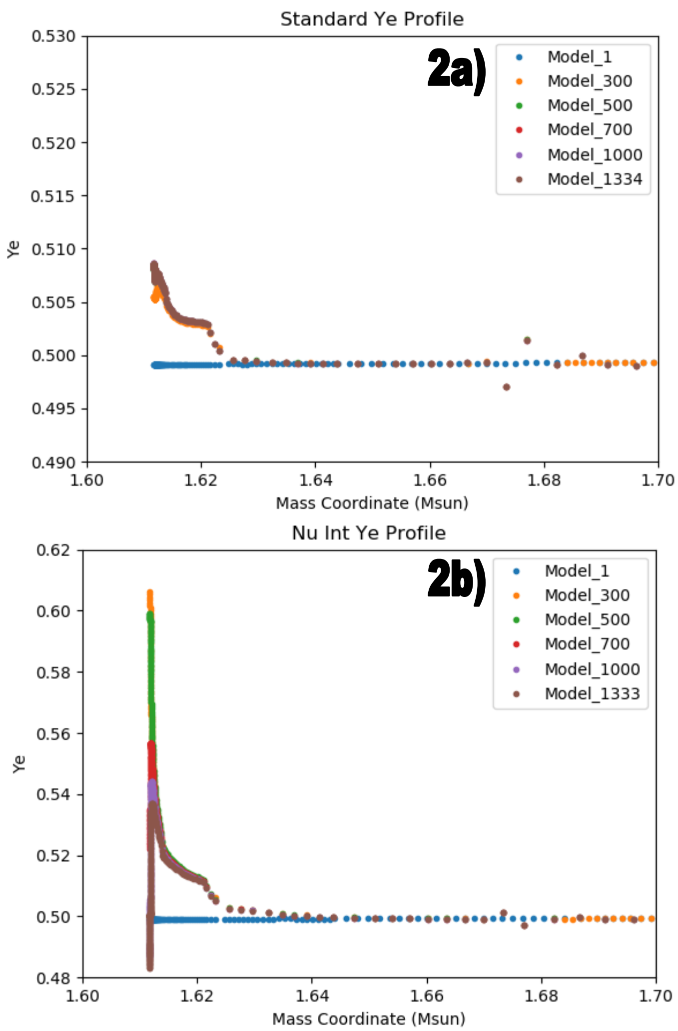


Fig 1) The elapsed time since completion of energy injection as a function of the run model number for the runs both including and excluding the neutrino interaction functionality.

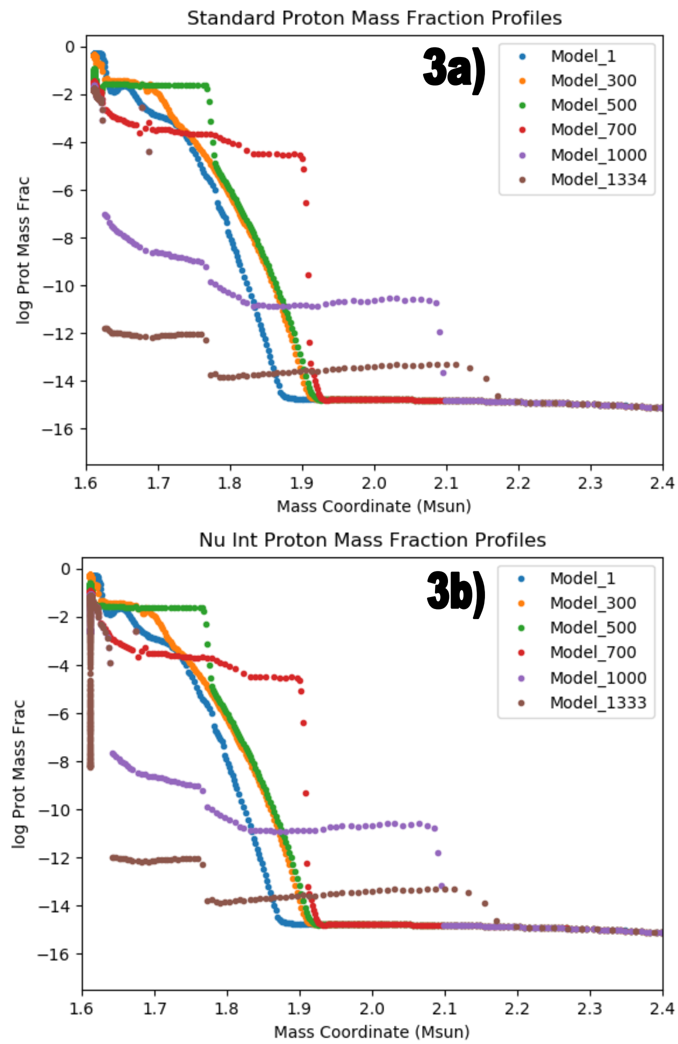
It can be seen from Fig 1, which plots the age of the star since the end of energy injection, that both the control and test simulations had a very similar age trajectory. In fact, the plots lay almost exactly one on top of each other. On one hand this is convenient; the same model numbers for each run correspond to the same time in the evolution of the CCSN which means they can be compared accordingly. On the other hand it shows that the test simulation is not requiring smaller timesteps and suggests (at least superficially) that the model is converging to a solution. For the present simulations, it took 1334 models and 1333 models to reach 2.5s post energy injection for the control and test runs respectively.

The Ye from the control and test runs was then investigated. The Ye profile from model numbers 1, 300, 500, 700, 1000, and ~1334 are plotted in Figs 2a&b. It can be seen in the standard run without the neutrino interactions that the innermost part of the Ye profile maintains a fairly constant, slightly proton rich, distribution throughout the simulation. This is not the case for the test run which includes the neutrino interactions. It can be seen that the innermost portion of the Ye profile in this simulation becomes very proton rich early on. This is to be expected from the initially large electron neutrino flux that was used to test the functionality. Over the course of the test run the initially very proton rich inner ejecta becomes mildly proton rich as the electron neutrino luminosity decays.



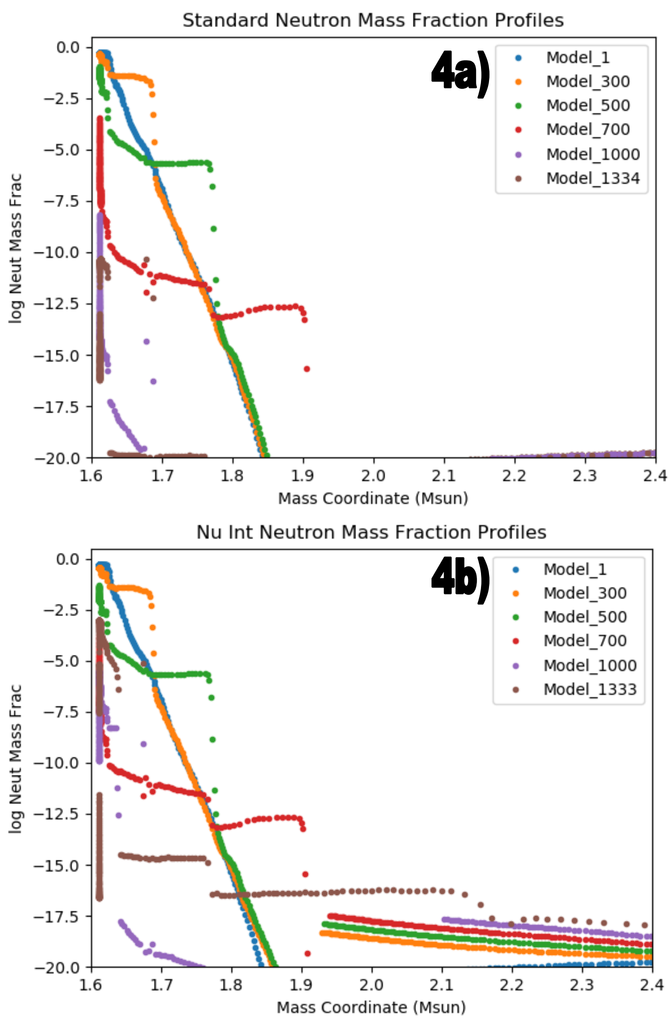
Figs 2a&b) Electron mole fraction profiles for model numbers 1, 300, 500, 700, 1000, and ~1334 of the control and test runs. a) plots the profiles from the control run (i.e. without neutrino interactions) and b) plots the profiles from the test run (i.e. with neutrino interactions).

The fact that a qualitative difference is observed in the Ye profiles of the two runs is promising. It shows that the implemented neutrino interactions are indeed being used by MESA and having an effect on the nucleosynthesis that is occurring in the CCSN ejecta. With the charged current neutrino interactions implemented, it was desired to investigate the potential for the modelling of nucleosynthetic pathways which was previously not feasible in MESA because of the lack of these neutrino interactions. In particular, it has been suggested that when reactions 1 and 2 are considered in the nucleosynthesis within the neutrino driven wind, the production of light p-nuclides through the so called νp-process may be possible [9]. This process occurs in the proton rich ejecta of CCSN where the electron anti-neutrino flux from the cooling neutron star creates a small but persistent neutron mass fraction through reaction 1. These neutrons are then captured by waiting point nuclei such as Ni-56, which then undergo a (p,n) reaction [9]. This sequence can repeat in the ejecta with a temperature range of roughly 1-3GK, eventually producing the light p nuclei [9].



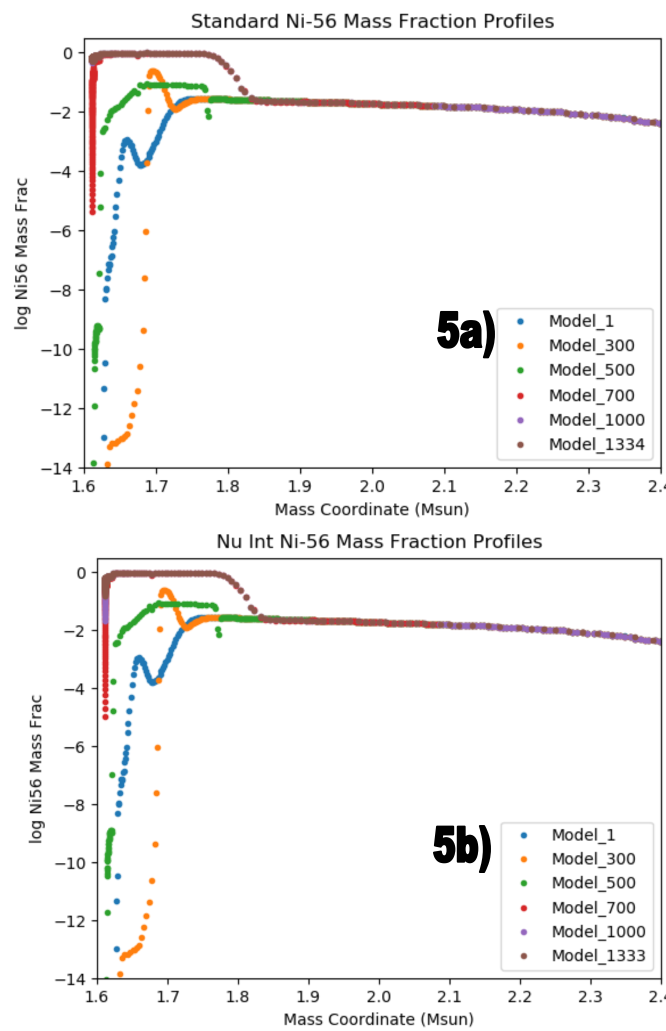
Figs 3a&b) Proton mass fraction profiles for model numbers 1, 300, 500, 700, 1000, and ~1334 of the control and test runs. a) plots the profiles from the control run (i.e. without neutrino interactions) and b) plots the profiles from the test run (i.e. with neutrino interactions).

Given the approximate nature of the rates, and the placeholder functions for the neutrino luminosities, at this time the author considered it inappropriate to perform a quantitative simulation for the light p-nuclide yields. Instead, the future potential for using the described charged current neutrino interactions in MESA to investigate νp-process nucleosynthesis in the neutrino driven wind is evaluated. This was done by observing the mass fraction and temperature profiles of the current control and test runs to determine if the necessary conditions are met. The mass fractions of protons, neutrons and Ni-56 at various points in the evolution of the CCSN are shown in Figs 3,4, and 5 respectively. As seen in Figs 3 and 5, the proton and Ni-56 mass fraction profiles for both the control and test runs are very similar for the duration of the simulation. However, it can be seen from Fig 4 that the test run shows a significant enhancement in the neutron mass fraction when compared to the control run. This enhancement is most pronounced in the innermost (roughly 1.6-1.65 M_{sun}) Lagrangian mass coordinates and during the later parts of the simulated CCSN.



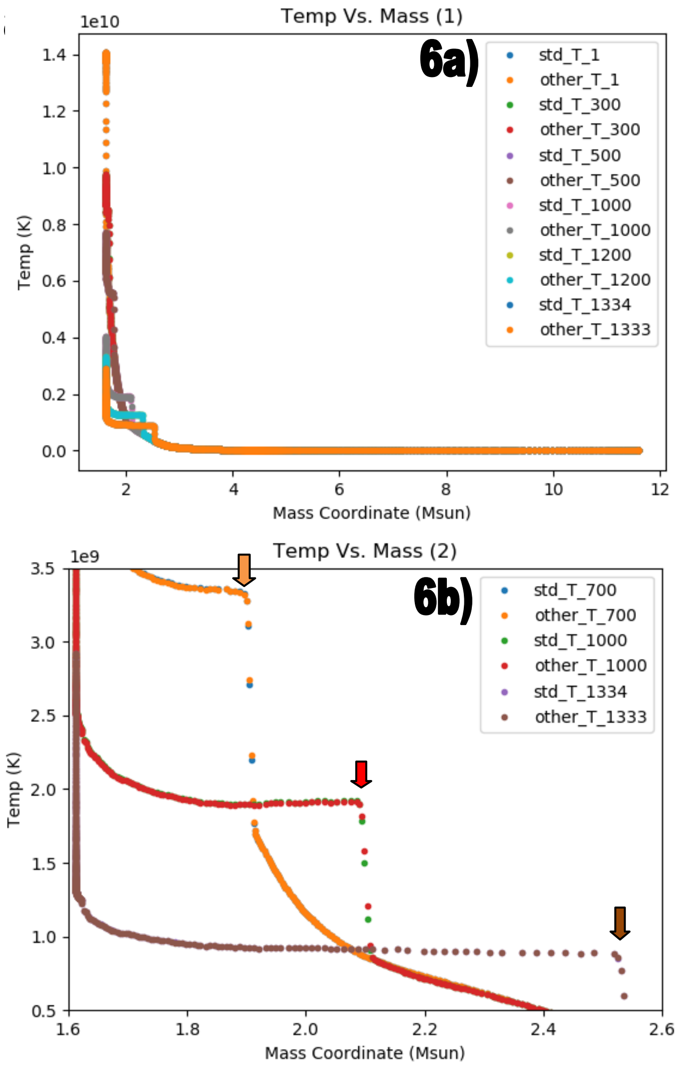
Figs 4a&b) Same as Figs 3a&b but for the neutron mass fraction profiles.

The neutron mass fraction enhancement is crucial as it is the first step in the νp-process past the waiting point nuclei. However, the neutron mass fraction enhancement from the neutrino interactions must also occur in the 1-3GK range to allow subsequent (p,n) reactions to carry the waiting point nuclei to higher Z. For this reason the temperature profiles of the control and test runs are plotted. It can be seen from Fig 6 that the temperature profiles for both the control and test runs are the same for any given model number. This was expected as the energy production from reactions was turned off for both runs similar to what was done in section 6.1 of Ref [4]. In Fig 6b the mass location of the shock front has been labeled with a colored arrow corresponding to that model number. The cells with a mass location below these arrows are where the νp-process can occur for each model number, as the shock front has dissociated some nuclei into free nucleons. Of the model numbers plotted, it can be seen that for model number 1000 the post shock mass elements in the range of roughly 1.6-2.1M_{sun} lie where the (p,n) reactions can occur.



Figs 5a&b) Same as Figs 3a&b but for the Ni-56 mass fraction profiles.

If the reader refers back to Fig 4, it can be seen that model number 1000 of the test run shows an enhanced neutron mass fraction versus model number 1000 of the control run, particularly in the area of roughly 1.6-1.65M_{sun}. Given these two mass ranges overlap, the waiting point nuclei in these cells will undergo neutron capture reactions and subsequent (p,n) reactions at a comparatively faster rate than in the simulations without the neutrino interactions. Because the window of time that these reactions can take place is quite short, the increased rate means a higher total yield of the light p-nuclei may be achieved when these neutrino interactions are taken into account. As discussed previously, the quantitative yields are not investigated further in this work as the currently implemented rates are approximations based on placeholder functions for the electron neutrino luminosities and mean energies.



Figs 7a&b) Temperature profiles at various model numbers of the control and test simulations. The legends in the top right show the profiles corresponding to each model number, with "std" and "other" representing the control and test runs respectively. a) plots the entire model profile while b) plots only the region where the ejecta is between 1-3GK. The steep temperature gradients which the arrows in b) point to are the mass locations of the shock front during the corresponding color coded model number.

However, the present analysis has highlighted the potential for using the described functionality to give composition corrections to MESA simulations where neutrino interactions cannot be neglected.

Section V: Summary

In this work reactions which simulate the charged current neutrino interactions on free nucleons have been implemented in MESA using the approximate rates from Qian & Woosley [6]. These new reactions were added to the approx21 series of reaction networks and then used to simulate a core collapse supernova by the mass cut and energy injection method. A qualitative enhancement in the neutron mass fraction was observed when the neutrino interactions were included versus when they were not. By observing the temperature and mass fraction profiles for the simulated explosions it was determined, that with further refinement, the present addition has the potential to allow MESA to model nucleosynthetic pathways which rely on charged current neutrino interactions. The code and MESA star test inlists used in this work are made available to the interested reader with the hope for further improvement from the MESA community's expertise.

Acknowledgements:

The author acknowledges helpful correspondence with the MESA developers and community. The author also acknowledges the use of the nugripy plotting software [5], with thanks to the NuGrid Collaboration. This work was supported by the Natural Sciences and Engineering Research Council of Canada.

References

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Ref[3] B.Paxton et al. 2015 ApJS 220 1

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