Impact of electron capture cross sections on nuclei far from stability on core-collapse supernovae

Journée Physique Fondamentale et Ondes Gravitationnelles (PhyFOG)

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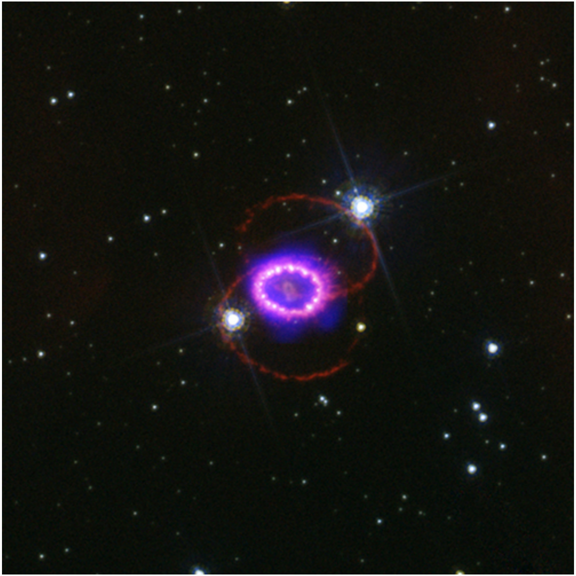

Figure 1: SN1987A remnant, in the large magellanic cloud (51.5 kpc).

The core-collapse mechanism (infall and early post-bounce)

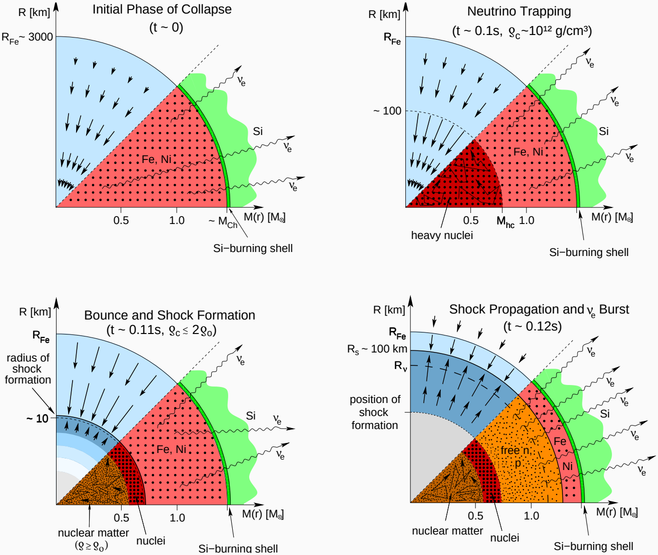

Figure 2: Core-collapse mechanism, figure extracted from Janka (2012)

Some simulation details

Progenitor : data from stellar evolution models[1]
mostly `s15` ($15\,\mathrm{M}_\odot$ with solar metallicity)
GR metric solver : `Lorene`[2]
GR hydrodynamic solver : `CoCoNuT`[3]
Equation of State : HS(DD2)[4]
Neutrinos transport scheme : Fast Multigroup Transport (FMT)[5]

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[1] Woosley, Heger, and Weaver 2002.
[2] Gourgoulhon, Grandclément, Marck, and Novak 1997-2012.
[3] Dimmerlmeier, Novak, and Cerdá-Durán 2001-2007.
[4] Hempel and Schaffner-Bielich 2010.
[5] Müller and Janka 2015.

Relevant weak processes occuring during core-collapse

Absorption/Emission via charge exchange

- $p + e^- \leftrightarrows n + \nu_e$
- $n + e^+ \leftrightarrows p + \bar{\nu}_e$
- ${}^{A}_{Z}\mathrm{X} + e^- \leftrightarrows {}_{Z-1}^{\ \ A}\mathrm{Y} + \nu_e$

Thermal pair production

- $e^- + e^+ \leftrightarrows \nu + \bar{\nu}$
- $\gamma^* \leftrightarrows \nu + \bar{\nu}$ (plasmon decay)
- $N + N \leftrightarrows N + N + \nu + \bar{\nu}$ (nucleon bremsstrahlung)

Scattering

- $N + \nu \leftrightarrows N + \nu$
- ${}^{A}_{Z}\mathrm{X} + \nu \leftrightarrows {}^{A}_{Z}\mathrm{X} + \nu$
- $e^\pm + \nu \leftrightarrows e^\pm + \nu$

(the color indicates which of the above processes are actually implemented in our models)

Influence of the electron capture cross section on nuclei prescription on the simulation results

Electrons captures (EC)

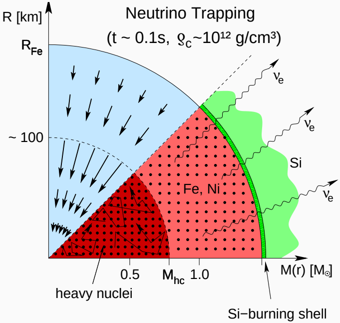

Figure 3: Core-collapse and electrons-captures, figure extracted from Janka (2012)

$$p + e^- \leftrightarrows n + \nu_e$$

$$^A_Z\mathrm{X} + e^- \leftrightarrows {}_{Z-1}^{\ \ A}\mathrm{Y} + \nu_e$$

⇒ deleptonization of the core

Composition of the medium

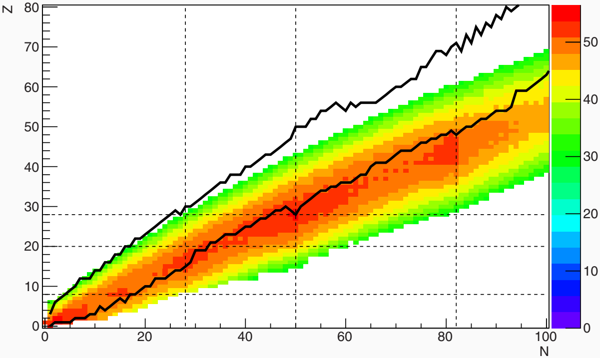

Figure 4: Typical nuclear abundance near the end of the collapse[6] (arbitrary unit), solid lines mark boundaries of experimental mass measurements, dashed lines mark magic numbers

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[6] Raduta, Gulminelli, and Oertel 2016.

3 models for electrons captures on nuclei

$$^{A}_{Z}\mathrm{X} + e^{-} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \nu_e$$

- Bruenn : approx. of independant particles[7]
- LMP (Langanke and Martínez-Pinedo) : fit on shell model results[8]
- LMP(3) : same fit but done with more parameters[9]

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Bruenn model

Calcul : weak interaction + shell model

+ approximation of independant particles

⇒ Predict no captures on nuclei with $N \geq 40$
(fewer captures at the end of the collapse, where neutron rich nuclei dominates the composition)

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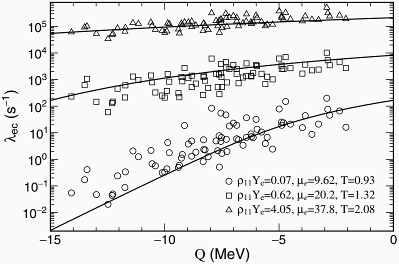
LMP model

Fit on results of nuclear shell models using the $Q - value$ dependance of the rate

$\Rightarrow$ all nuclei contributes to captures



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Raduta's improvement of LMP fit

Improvement of the previous fit, done with more parameters :

- the *Q-value* ($Q = M(A, Z-1) - M(A, Z)$)
- thermodynamic conditions : T, $n_e = Y_e n_b$
- nuclei parameters : $I = (N-Z)/A$ and pairing

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Evolution of capture rates

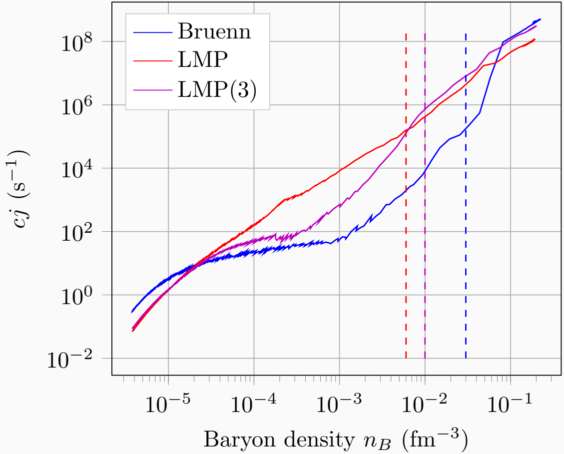


Figure 5: Evolution of the electron capture rates (on nuclei and free protons), in the central element, during the collapse. The vertical dashed lines show when β-equilibrium sets in (Pascal et al in prep.)

Evolution of electron fraction

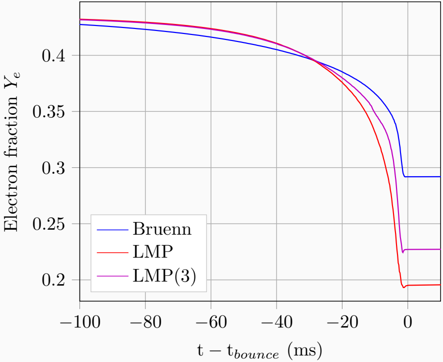


Figure 6: Evolution of the electron fraction in the central element (Pascal et al in prep.)

Model	Bruenn	LMP	LMP(3)
BC mass	0.45	0.31	0.4

Table 1: Mass of inner bouncing core (units of $M_\odot$)

$$Y_e \nearrow \quad \Rightarrow \quad P_{nuc} \searrow \quad \Rightarrow \quad M_{BC} \nearrow$$

(weaker nuclear pressure because nuclear matter is more symmetric)

Dynamic of the shock

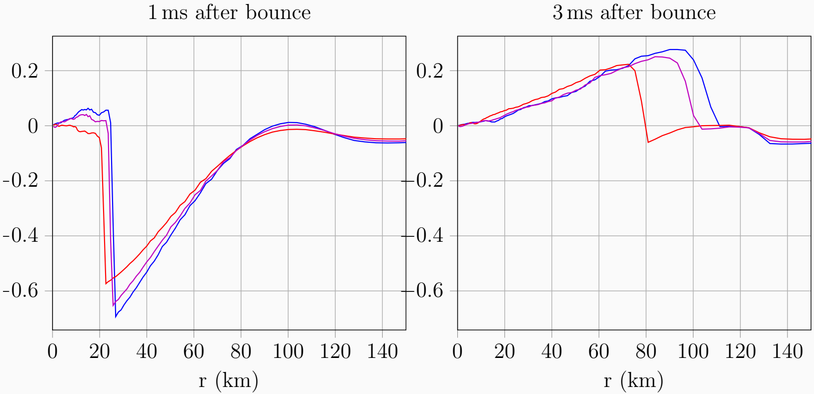


Figure 7: Radial velocity profiles in the early post-bounce phase (Pascal et al in prep.)

Neutrino luminosity

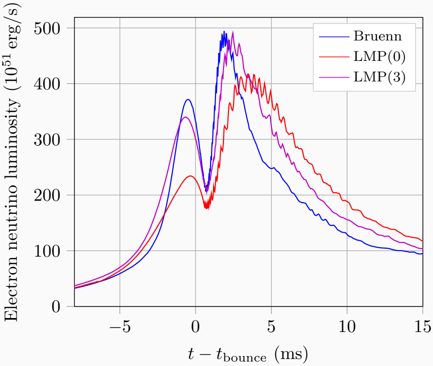
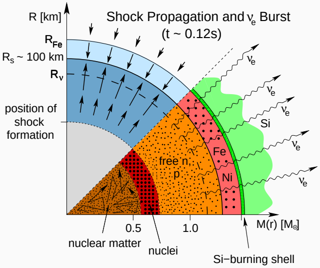


Figure 8: Electron neutrino luminosity, as a function of time after bounce (Pascal et al in prep.)



(Janka (2012))

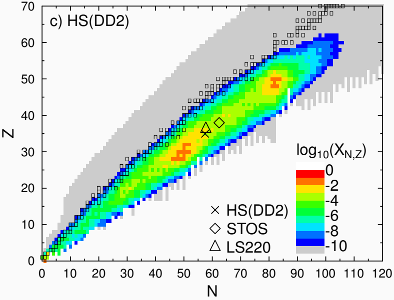
Influence of other parameters

SNA approximation

- SNA (Single Nucleus Approximation) : represent the heavy nuclei population by a single mean nuclei
- NSE (Nuclear Statistical Equilibrium) : compute the equilibrium distribution of nuclei

SNA is quite good for $n_b \leq 10^{-4}\,\mathrm{fm}^{-3}$ (the medium is mainly composed of nuclei from the iron peak)

But it does not represent well the composition in the last few ms of the collapse.



Oertel, Hempel, Klähn, and Typel (2017)

Influence of the SNA approximation on mean free paths

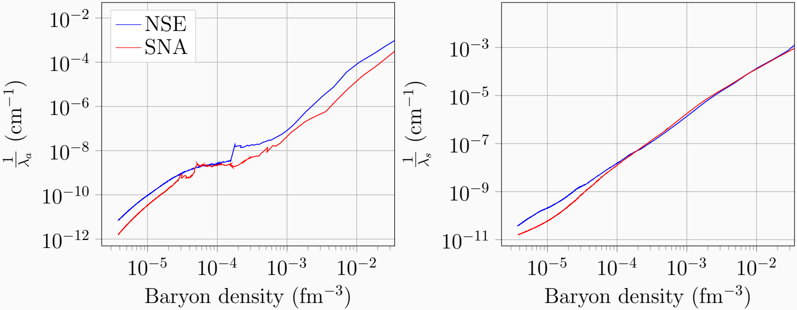


Figure 9: Evolution of the neutrino mean free paths for absorption and scattering, in the central element, during the collapse (Pascal et al in prep.)

Listing the most relevant nuclei

Nuclei of interest for the EC rate

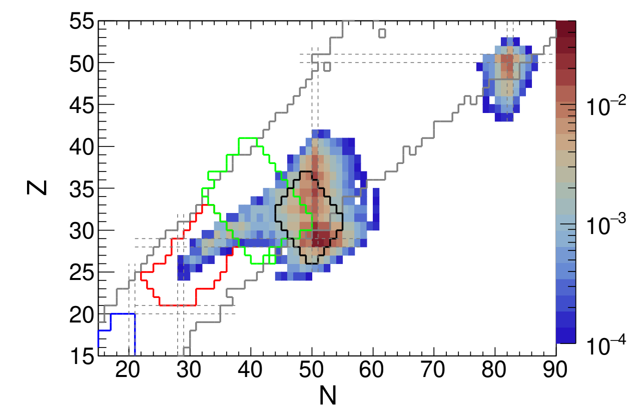


Figure 10: Time integrated relative deleptonization rate (LMP). Grey lines shows experimental mass measurements. (Pascal et al in prep.)

Conclusion

- Electron captures in CCSne mainly occurs during the last few ms before bounce on heavy neutron-rich nuclei
- the model of electron capture rates on those nuclei is of great influence on the results of core-collapse simulation and leads to 30% of variation on the electron fraction Y_e
- this influence is bigger than the one of other parameters such as the EoS, the choice of pregenitor, the nuclei mass model or the use of SNA approximation

$\Rightarrow$ this work allows to single out which nuclei are relevant in CCSne simulations, and microspic calculation can therefore focus on thoses nuclei in order to get more and more accurate EC rates