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

CoCoNuT meeting

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LUTH (Laboratoire Univsers et Théories), Observatoire de Paris

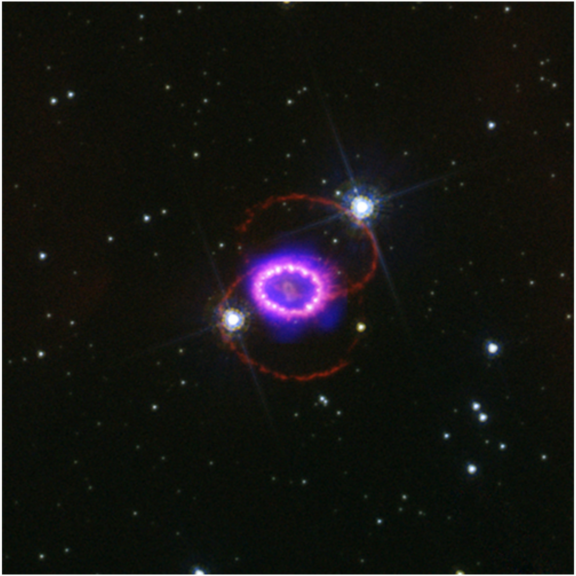


Figure 1: SN1987A remnant, in the large magellanic cloud (51.5 kpc).

Electrons captures

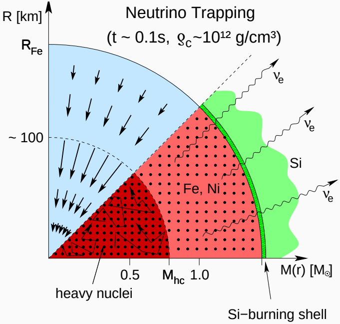
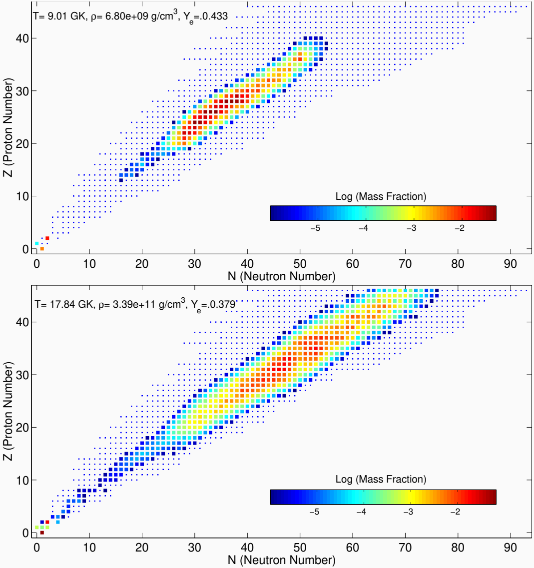


Figure 2: Core-collapse and electrons-captures, figure extracted from Janka (2012)

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

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

Evolution of the composition during the collapse



Typical nuclear abundances

at presupernova stage (top)

at neutrino trapping phase (bottom)

Janka (2012)

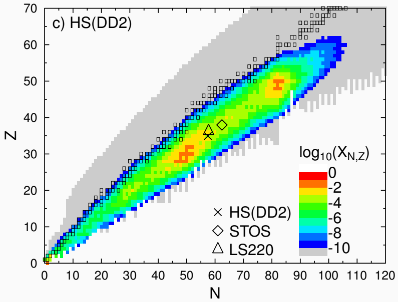
Influence of the SNA approximation

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)

Absorption and SNA approximation

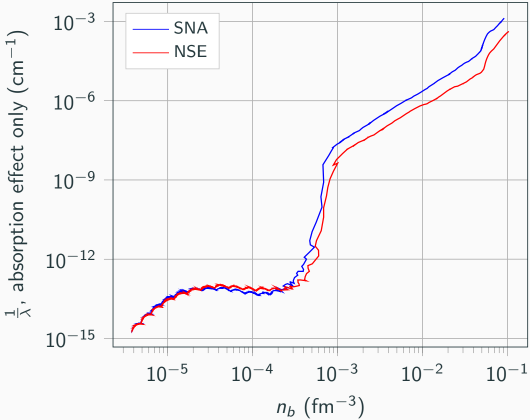


Figure 3: Evolution of the neutrino absorption opacity (Bruenn formula[1]), in the central element, along a collapse trajectory

[1] Bruenn 1985.

Scattering and SNA approximation

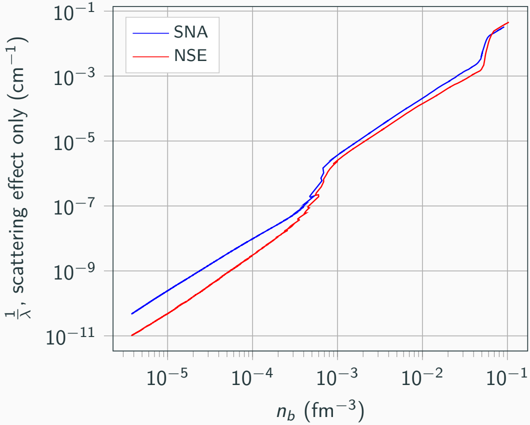


Figure 4: Evolution of the neutrino scattering opacity (Bruenn formula[2]), in the central element, along a collapse trajectory

[2] Bruenn 1985.

Influence on the electron fraction evolution

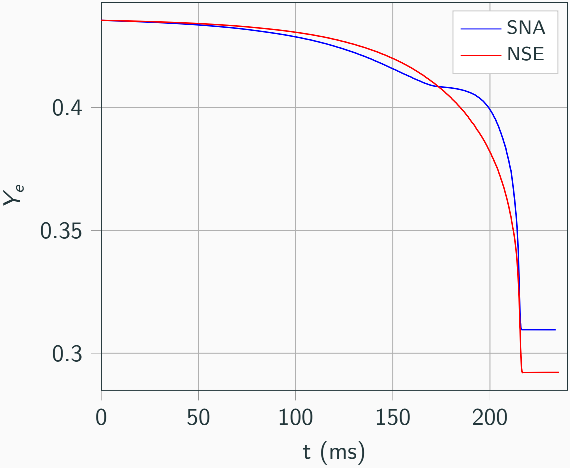


Figure 5: Evolution of the electron fraction in the central element

Models for electrons captures rates on nuclei

Nuclei of interest

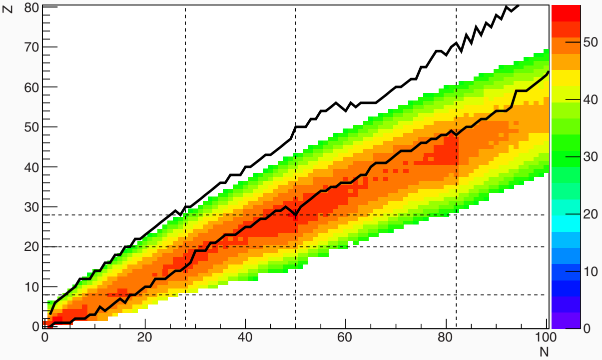


Figure 6: Typical nuclear abundance near the end of the collapse[3] (arbitrary unit), solid lines mark boundaries of experimental mass measurements, dashed lines mark magic numbers

[3]Raduta, Gulminelli, and Oertel 2016.

3 models for electrons captures on nuclei

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

- Bruenn : approx. of independant particles[4]
- LMP (Langanke and Martínez-Pinedo) : fit on shell model results[5]
- LMPR : same fit but done with more parameters[6]

[4] Bruenn 1985.

[5] Langanke et al. 2003.

[6] Raduta, Gulminelli, and Oertel 2017.

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Bruenn model

Calcul : weak interaction + shell model
+ approximation of independant particles

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

[4]Bruenn 1985.
[5]Langanke et al. 2003.
[6]Raduta, Gulminelli, and Oertel 2017.

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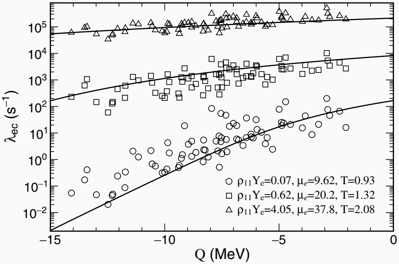
LMP model

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*
- thermodynamics conditions : T, $n_e = Y_e n_b$
- nuclei parameters : $I = (N - Z)/A$ and pairing

[4]Bruenn 1985.

[5]Langanke et al. 2003.

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Evolution of capture rates

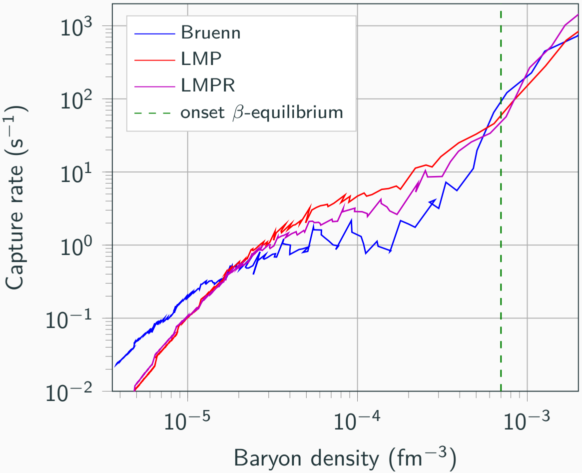


Figure 7: Evolution of the electron capture rates (on nuclei and free protons), in the central element, along a collapse trajectory

Evolution of electron fraction

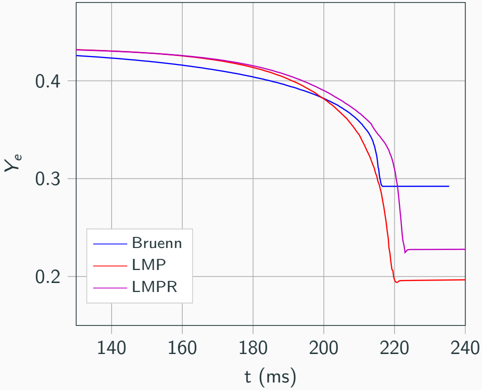


Figure 8: Evolution of the electron fraction in the central element

Model	Bruenn	LMP	LMPR
BC mass	0.29	0.19	0.26

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

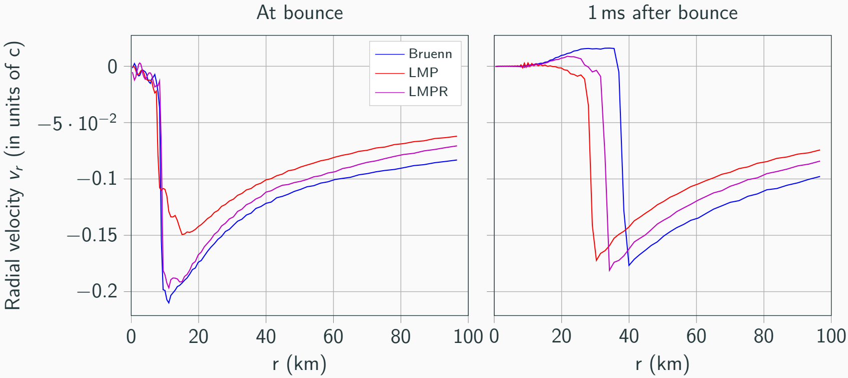
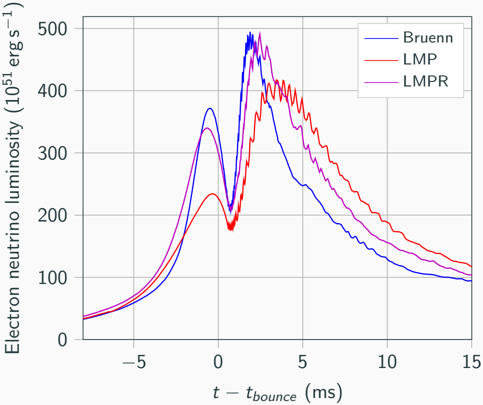
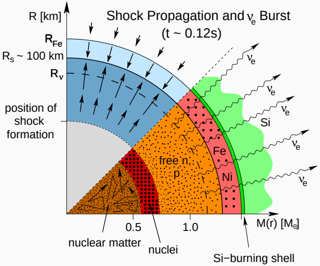


Figure 9: Radial velocity profiles at core bounce





(Janka (2012))

Figure 10: Electron neutrino luminosity, as a function of time after bounce

Conclusion

- the model of electron capture rates is of great influence on the results of core-collapse simulation
- this influence is bigger than the one of other parameters such as the EoS or the choice of pregenitor

$\Rightarrow$ it is important to get more and more realistic interaction rates in order to have core-collapse simulations that reproduces observations

Some simulation details

Progenitor : data from stellar evolution models[7]
mostly `s15` ($15\,M_\odot$ with solar metallicity)
GR metric solver : `Lorene`[8]
GR hydrodynamic solver : `CoCoNuT`[9]
Equation of State : HS(DD2)[10]
Neutrinos transport treatment :

- Leakage scheme[11]
- Fast Multigroup Transport scheme (FMT)[12]

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[7] Woosley, Heger, and Weaver 2002.
[8] Gourgoulhon, Grandclément, Marck, and Novak 1997-2012.
[9] Dimmerlmeier, Novak, and Cerdá-Durán 2001-2007.
[10] Hempel and Schaffner-Bielich 2010.
[11] Peres 2013.
[12] Müller and Janka 2015.