Study of equation of state for electron capture in core-collapse supernova

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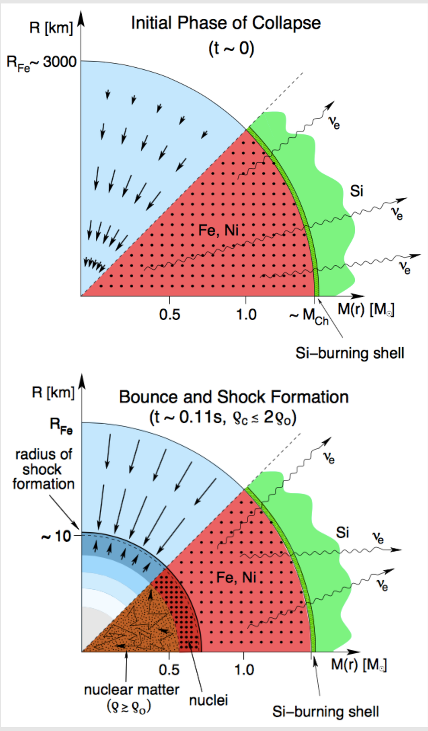
Introduction



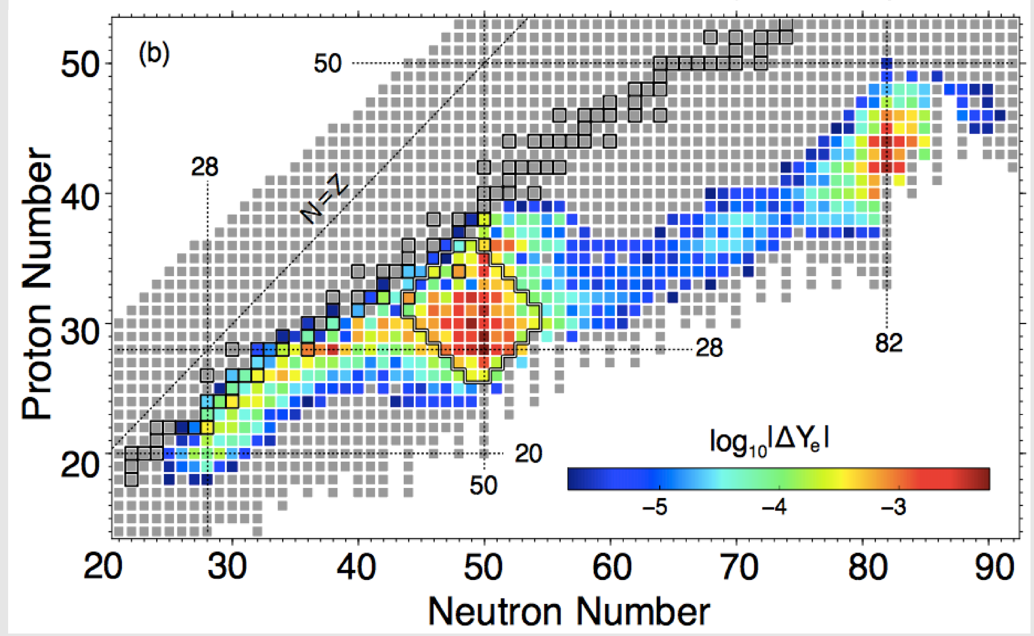
H.-Th. Janka, et al., Phys. Rep. 442, 38 (2007)

Despite the considerable advances since the first numerical simulations in the '60s, the best 3D models still fail to reproduce the characteristics of observed core collapse supernovae. Furthermore, the nuclear inputs such as the equation of state (EoS) and electro-weak processes play a fundamental role in these simulations. In particular, **the electron-capture process governs the neutronization of matter and determines the position of the formation of the shock wave**, which ultimately leads to the supernova explosion. In the early stage of the core-collapse the electron-capture rate on nuclei dominates. The proper way to obtain the total electron-capture rate is to fold the individual rates with the nuclear distribution. This is however not trivial, because most of the core-collapse codes use EoSs based on single nucleus approximation (SNA).

This motivated us to **implement a perturbative treatment of the extended Nuclear Statistical Equilibrium (NSE) model into the widely used Lattimer and Swesty (LS) EoS**. The NSE calculations depend on the masses of different nuclei, determined either experimentally or using a mass model.

The nuclei that play the most important role during the core collapse because of their electron-capture rates are located around ^{78}Ni **and ^{128}Pd. An experiment, which aims to measure the masses of the nuclei of interest located around ^{78}Ni with the JYFLTRAP Penning trap mass spectrometer at the IGISOL facility (Jyväskylä, Finland), is planned for November 2017.**

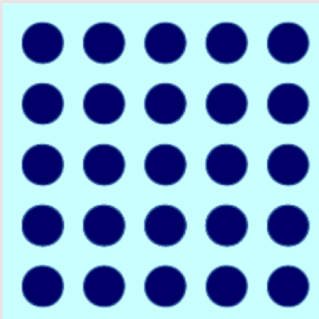
Variation of the electron fraction during the collapse



Sullivan et al. Apj 816, 44 (2016)

EoS

SNA :

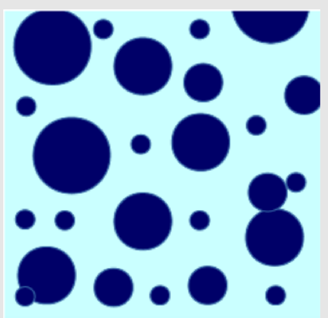


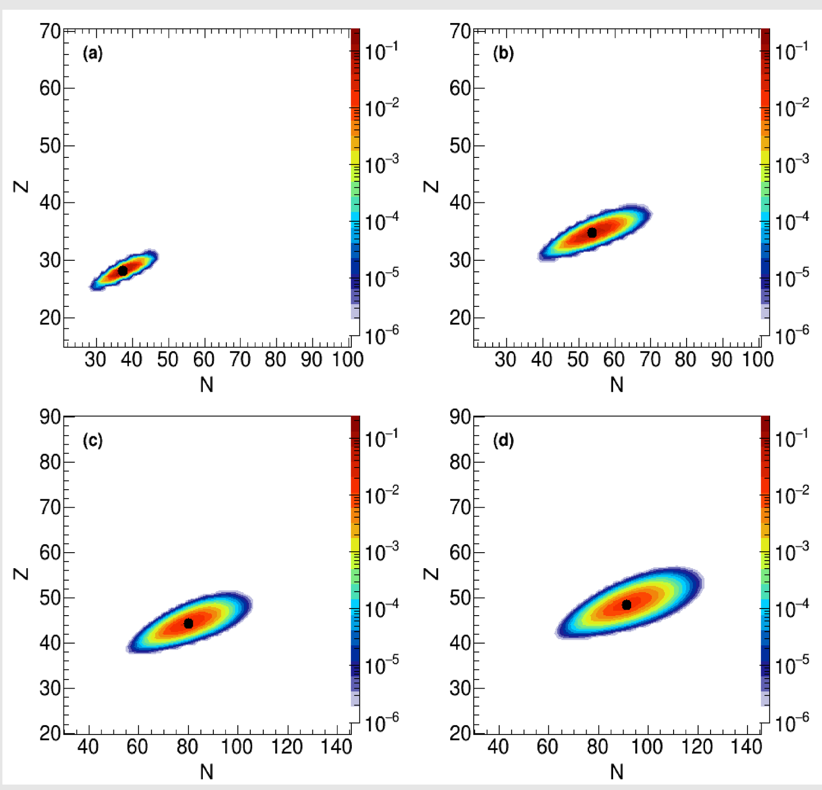
In the SNA, matter is divided into identical cells, each one containing one nucleus (the one that is energetically favoured) surrounded by a gas of free nucleons and a uniform non-interacting gas of photons and leptons. During the core collapse, at each thermodynamic condition (baryon density n_B , temperature T, and proton fraction Y_p), the EoS is obtained by minimazing the free energy of the system with respect to the variational variables (leptons and photons are treated separately), under baryon number and charge conservation.

NSE :

However, in core-collapse conditions, **at finite temperature, different microstates are expected to be populated.** Although the use of the NSE instead of the SNA does not affect very much the thermodynamic quantities, it can have a non-negligible impact on the electron-capture rates, thus possibly on the core-collapse dynamics.

We implemented an extended NSE model in a perturbative way on top the LS EoS based on the SNA.





(1) The average nucleus of LS EoS coincides with the most probable nucleus of the distribution. As the density and the temperature increase the nucleus become bigger and the distribution wider.

The probability p(A,Z) of having the nucleus (A,Z) is proportionnal to :

$$p(A,Z) \propto \exp(-F_{nuc}/T)$$

where

$$F_{nuc} = E_{nuc}(A,Z) - T.S(A,Z)$$

F_{nuc} the nucleus free energy, T the temperature, E_{nuc} (A,Z) the binding energy of the nucleus (A,Z), S(A,Z) the entropy.

Normalized probabilities of the nucleus (Z,N), blue to red: from less to more probable. The black dot corresponds to the average nucleus of LS EoS.

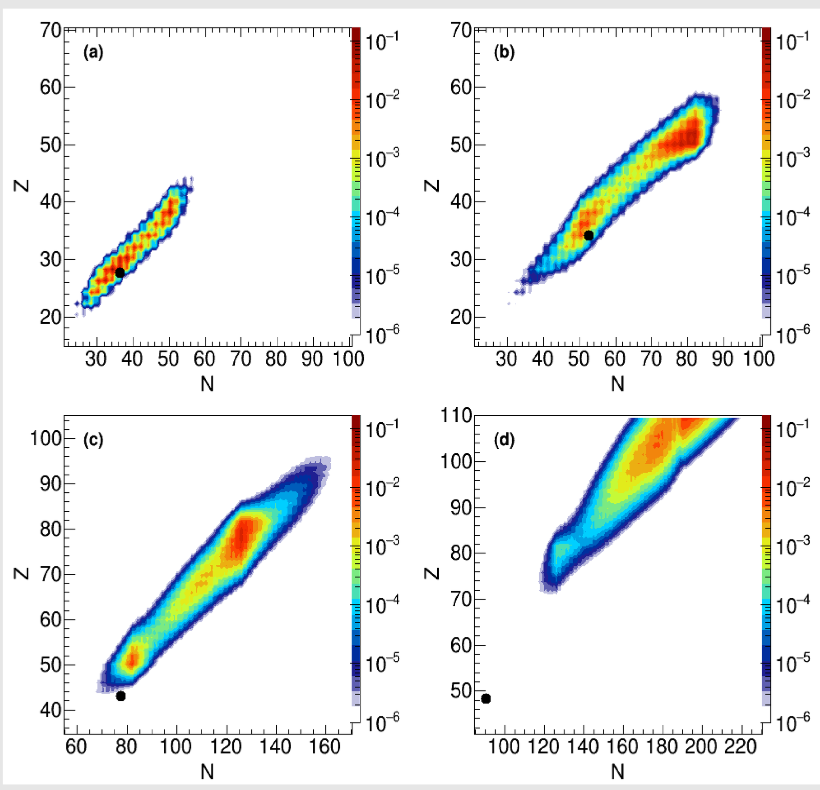
We compared the distributions obtained using different mass models :

(1) Liquid-drop like functional of the LS EoS

(2) Brussels-Montreal HFB-24 mass model

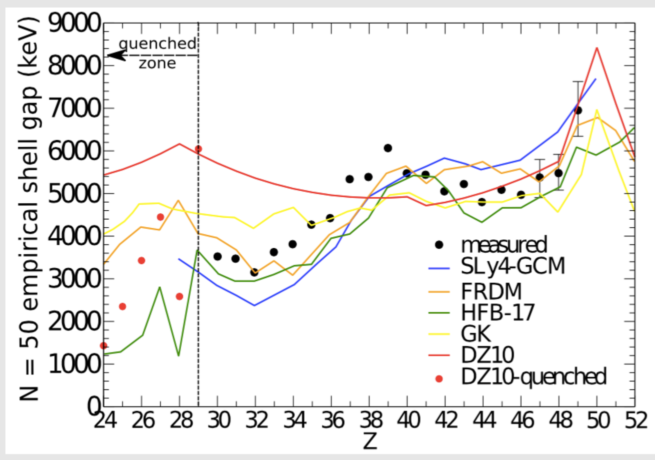
For different thermodynamic conditions along a collapse trajectory :

a) T =0.79 MeV ; Y_p =0.43 ; n_B =3.86e-06 fm^{-3}
b) T =1.51 MeV ; Y_p =0.38 ; n_B =3.35e-04 fm^{-3}
c) T =2.68 MeV ; Y_p =0.33 ; n_B =3.01e-03 fm^{-3}
d) T =3.33 MeV ; Y_p =0.31 ; n_B =5.85e-03 fm^{-3}



(2) There is bimodal distributions and the most probable nuclei are around the magic numbers. In particular, at the beginning of the collapse nuclei around Z = 28 and N = 50 are populated.

Mass measurements



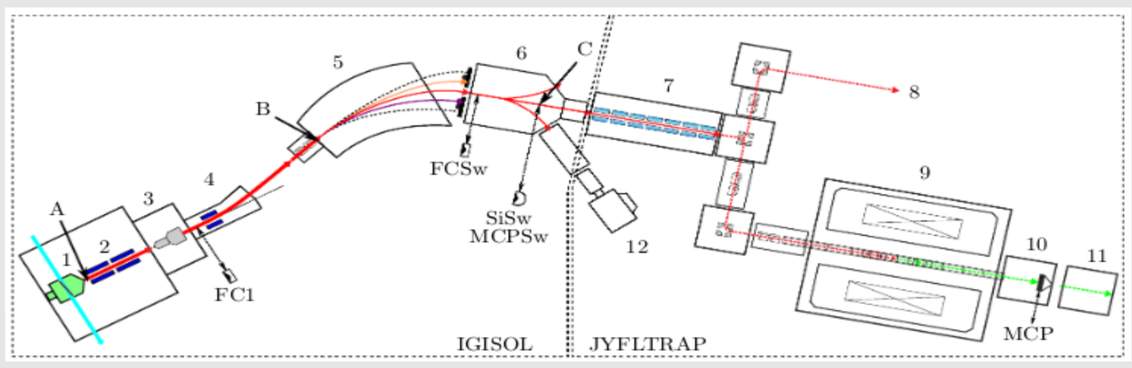
Ad. R. Raduta, Phys. Rev. C 93 (2016) 025803

For the N=50 isotones, the mass models increasingly deviate from each other while approaching the neutron drip-line.

Precise mass measurements (<100 keV precision) in the ^{78}Ni region will allow to constrain theoretical models and to have a more realistic EoS.

The I220 experiment, which aims to measure precisely the masses of isotopes in the region of interest (^{67,68}Fe, $^{68-71}$Co, ^{74,75}Ni, $^{76-79}$Cu, ^{81,82}Zn, ^{84}Ga, ^{79}Ge, ^{78}As, ^{84}Br), will take place at the **IGISOL facility using the JYFLTRAP** in November 2017.

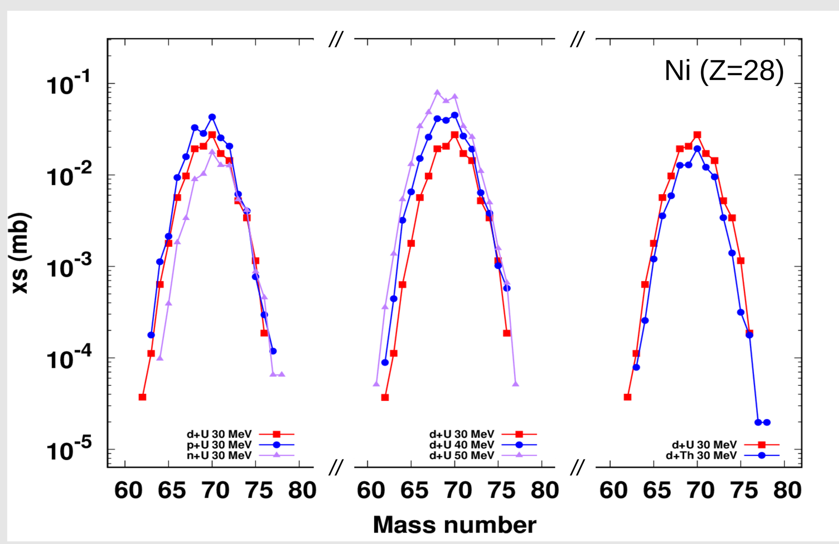
Setup :



1- Gas filled target chamber
2- Sextupole ion guide
3- Extraction electrodes
4- Beam bending plates
5- Dipole magnet
6- Switchyard
7- Radio frequency quadrupole (cooler-buncher)
8- Beam line towards laser spectroscopy setup
9- Double Penning trap (JYFLTRAP)
10- Microchannel plate detector
11- Post-trap spectroscopy setup
12- β-γ spectroscopy setup

Reaction choice:

- K. Kruglov et al. (2002) suggests that d+Th is the best projectile-target combination to produce the nuclei of interest.
- **GEF/Talys calculations :**

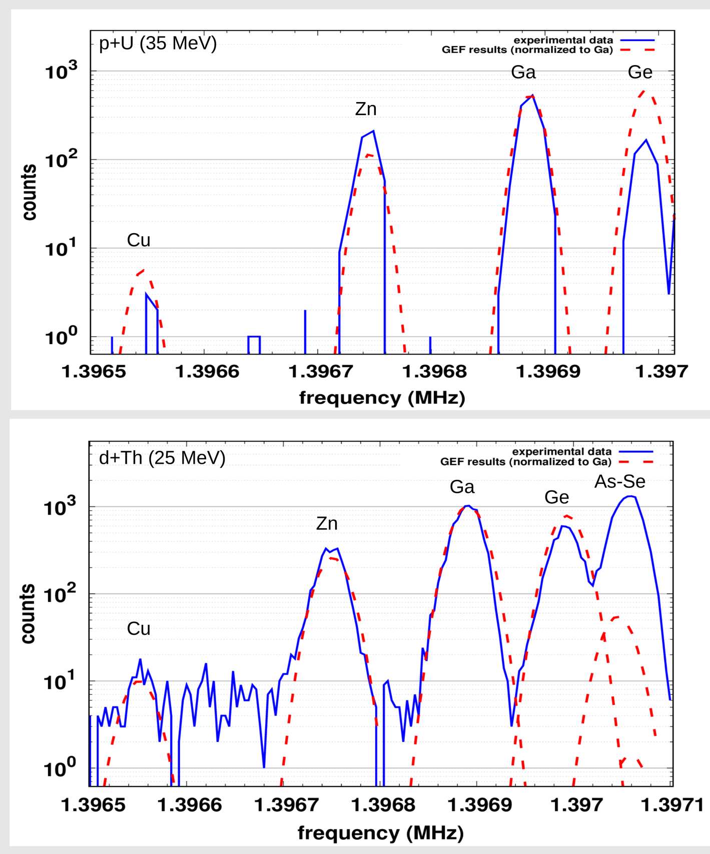


- n,d projectiles produce more n-rich isotopes than p
- U target has higher cross section than Th
- The higher the incident energy the better

➔ **d+U at high energy (≥25MeV)**

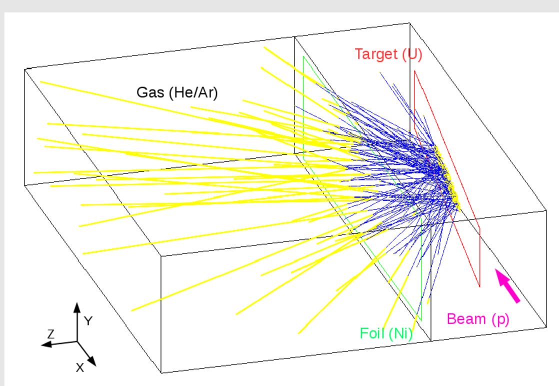
Experimental test results:

- **Mass scan** of neutron-rich isobars A=77 :



- Experimental results (in blue) are in agreement with the GEF code based estimations (in red).
- The preliminary results tend to confirm that d+U is the best combination.

Gas-cell simulation:



Geant4 simulation (adapted from K. Jansson et al. (Uppsala University)) gives an **efficiency of the gas-cell lower than 1%. We could improve this efficiency by changing the buffer gas properties** :

- The higher the pressure the better : with He gas at 100 torr the efficiency is about 0.5 % and 0.8 % at 200 torr.
- The heavier the element the higher the efficiency : at 200 torr the efficiency is about 0.8 % with He and 3.6 % with Ar.

Conclusion-Outlooks

- **Implemented perturbatively the NSE model into a very used EoS** (Lattimer & Swesty EoS).
- **Obtained the distribution of the nuclei** expected to be present along a collapse trajectory, using different mass formula (LDM, HFB24*, Duflo-Zuker 10). Magic nuclei are favoured.

➔ Integrate the LS EoS modified into a 1D core-collapse code**
➔ Compare the outputs of the CC code before and after the modification of the EoS.
➔ Use of new exp masses to defined a better mass functional used in the EoS.

- Comparison of different target-projectile couples to optimize the production of isotopes for the I220 experiment using the GEF code : **d+U at E≥25 MeV** seems the best combination => in contradiction with K. Kruglov et al. (2002).
- **Test run in June 2017 at IGISOL : online results are in agreement with the GEF code predictions**.
- **Simulation of the gas cell** to optimize the efficiency, high pressure regime and heavier buffer gas seem better. But need to quantify neutralisation and decay losses.

➔ Fine analysis of the test experiment and publication of the results.
➔ Perform and analyze the mass measurement experiment expected in November 2017 at IGISOL.

* S. Goriely, et al. (2013) PRC 88, 024308 ** Originally developed by Valencia group and also by A. Fantina