Magicity evolution toward dripline and its impact on electron capture rates during core-collapse

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Overview

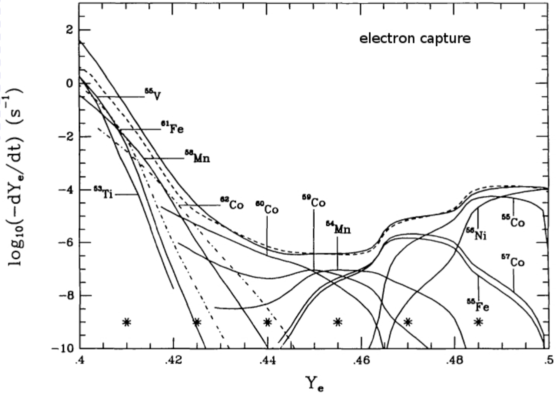
- **Introduction:** electron capture rates in stellar matter at finite T (post core Si burning in massive stars, core-collapse)
- **Matter composition and EC rates in n-rich environments:** late stage evolution of core collapse, unconstrained nuclear structure input, scenarios of magicity quenching, consequences for $\langle \lambda^{(NSE)} \rangle$
- **Conclusions:** extra mass measurements for n-rich N=50, 82 nuclei

Pulsars and their environments, 18-20 May 2016, Meudon

Weak interaction rates in the iron core prior to collapse

`[Aufderheide et al, ApJS 91,389(1994)]`

Thermo conditions for $15M_\odot$, $25M_\odot$ progenitors:
$7.5 \leq \rho \leq 12$ g/cc, $2 \leq T \leq 10$ GK, $0.4 \leq Y_e \leq 0.5$



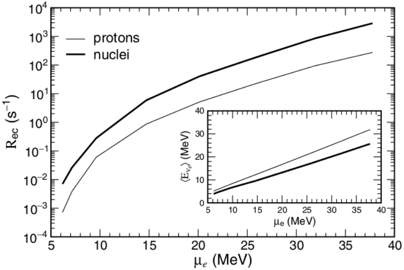
$$\langle \lambda^{(NSE)} \rangle = \frac{\sum \lambda(A,Z) n(A,Z)}{\sum n(A,Z)}$$

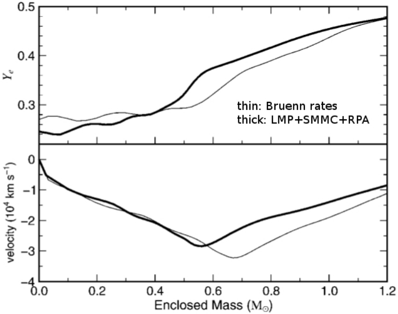
- folded up effect of many nuclei, not necessarily the most abundant nor the most reactive
- $\lambda(A,Z)n(A,Z)(\rho, Y_e, T)$
- accurate rates are needed

- similarly for β^--decay

Electron capture rates during core-collapse

`[Langanke et al., PRL 90, 241102 (2003)]`

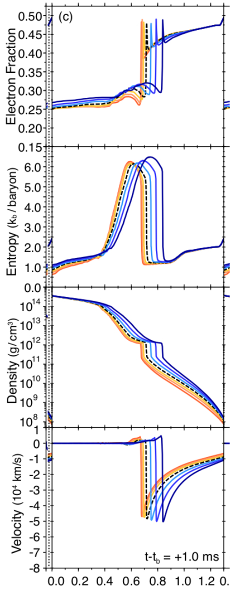




- $\lambda_{EC}^{(nuclei)} >> \lambda_{EC}^{(p)}$

- accurate λ_{EC} needed for dynamics and deleptonization

Electron capture rates during core-collapse



[Sullivan et al., ApJ 816, 44 (2016)]

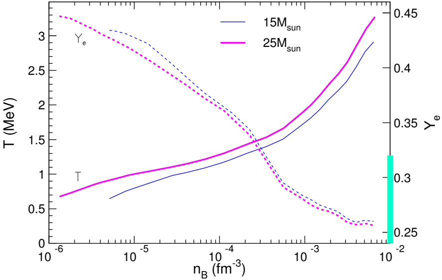
- present accuracy on EC is not sufficient
- CC evolution depends more on EC than on EoS and progenitor models
- systematic modif. of λ_{EC} within present error bars lead to modif. of $+16/\text{-}4\%$ on the inner core at bounce and $\pm 20\%$ on ν_e=peak luminosity
- statistical modif. of λ_{EC} produce smaller effects

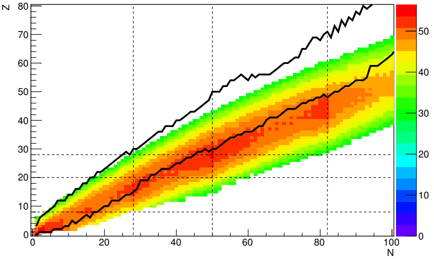
increased accuracy on key nuclei (^{78}Ni, ^{79}Cu, ^{79}Zn) might help

Extreme neutron-rich matter is populated in CC

most abundant nuclei are out of the stability valley,
their structure is **not known**

$n_B = 1.18 \cdot 10^{-3}\ \mathrm{fm}^{-3},\ Y_e = 0.275,\ T = 2\ \mathrm{MeV}$

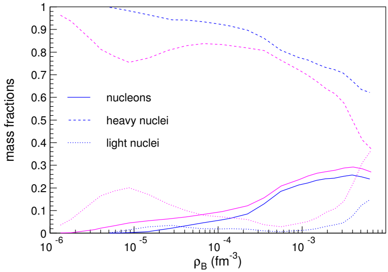




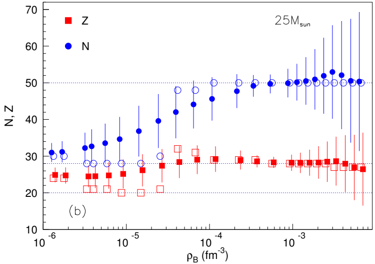
[Juodagalvis et al., NPA848, 454 (2010)]

- similar pattern, slight progenitor dependence
- more massive progenitors lead to more exotic matter, higher T

Matter composition along the CC trajectories



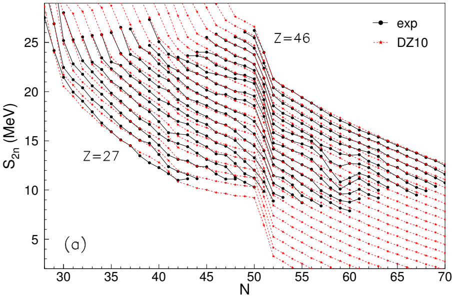
- because of finite T, many nuclei are populated
- $n(A, Z)$ distrib. are multi-peaked
- $X_{A\geq 20} \geq 0.4$

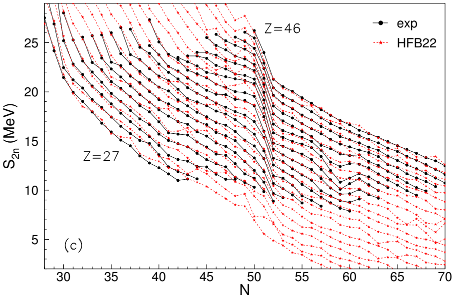


- $\langle N\rangle \neq N_{prob.}$, $\langle Z\rangle \neq Z_{prob.}$
- $\sigma_{N,Z}$ is large
- $Z_{prob.} = 20$, $N_{prob.} = 50$
- $\sigma_N \approx 20$, competition of a second magic number

[AR, Gulminelli, Oertel, PRC93, 025803 (2016)]

Magicity far from stability





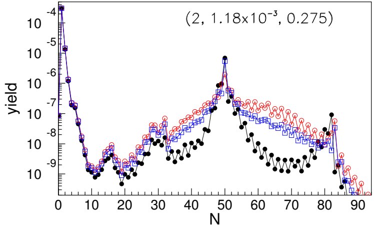
- beyond stability, binding energies are not known
- predictions of phenomenological or microscopic mass models are used
- correlations and reduced n-p residual interaction, quench magicity in asymmetric nuclei (experimental data exist for $N = 20$)
- magicity quenching might occur also for $N = 50$ and $N = 82$

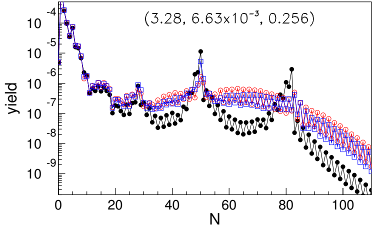
Magicity quenching far from stability

$$B_m(A,Z) = B_{LDM}(A,Z) + f(\alpha,\Delta Z)\left[B_{DZ}(A,Z) - B_{LDM}(A,Z)\right]$$

$$f(x,\Delta Z,\alpha) = \exp\left[\alpha x/\Delta Z\right],\ \alpha < 0$$

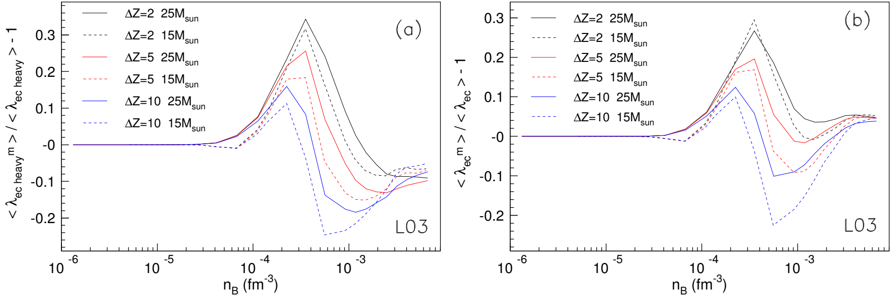
$$\color{blue}{\Delta Z = 10},\ \color{red}{\Delta Z = 5},\ \alpha = \log(10^{-2})$$





- magic peaks are much reduced;
- production of non-magic nuclei is much increased

Magicity quenching and EC rates



$$\lambda_{EC} = \frac{\ln 2 \cdot \mathcal{B}}{K} \left(\frac{T}{m_e c^2} \right)^5 \left[F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta) \right]$$

[Langanke et al, PRL90, 241102 (2003)]

- structure beyond drip impacts up to 30% on EC;
  exact values depend of EC rates and assumed scenario of magicity quenching
- enhanced ν-cooling, accelerated collapse, higher inner core at bounce

[AR, Gulminelli, Oertel, PRC93, 025803 (2016)]

Conclusions

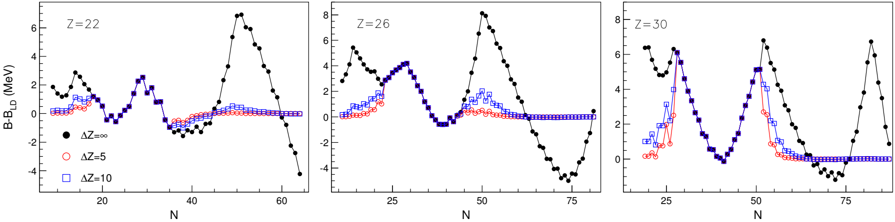
- the consequences of a possible quenching of the $N = 50$ and $N = 82$ shell closures on electron capture rates during core-collapse have been examined

- two trajectories corresponding to the pre-bounce evolution of the central element of CC progenitors with $15M_\odot$ and $25M_\odot$ are considered `[Juodagalvis et al., NPA848, 454 (2010)]`

- we found that the properties of very exotic nuclei around $N = 50$ and $N = 82$ represent a key microscopic information

Setup

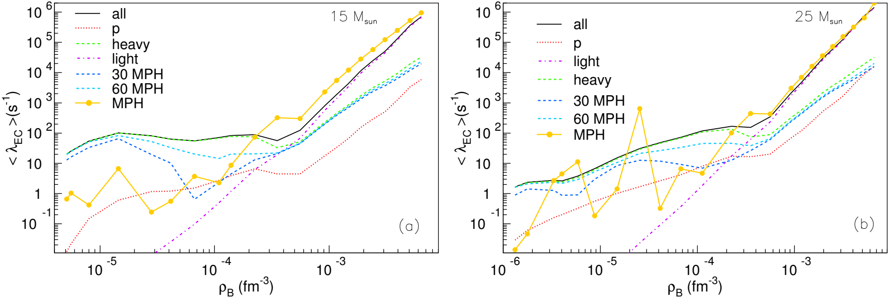
- exp. masses + Duflo-Zuker
  exp. masses + “magicity quenched” Duflo-Zuker
  $B_m(A,Z) = B_{LDM}(A,Z) + f(\alpha,\Delta Z)\left[B_{DZ}(A,Z) - B_{LDM}(A,Z)\right]$
  $f(x,\Delta Z,\alpha) = \exp\left[\alpha x/\Delta Z\right]$, $\alpha < 0$



large/small $\Delta Z \Rightarrow$ slow/steep quenching

EC rates

$$\bar{\lambda}_{EC} = \frac{\sum_{A,Z} n(A,Z)\lambda_{EC}(A,Z)}{\sum_{A,Z} n(A,Z)}$$



- EC by Langanke et al., PRL 2003
- many nuclei contribute to the EC
- SNA approx. is not good