Magicity evolution and electron capture rates toward the dripline and their impact on core-collapse

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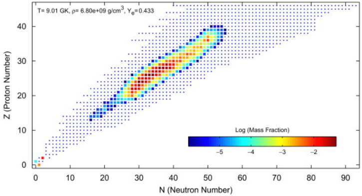
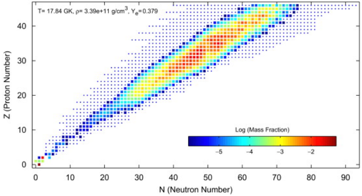
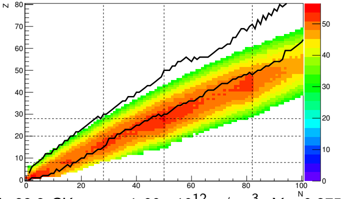
The Phases of Dense Matter, 17-23 July 2016, Seattle

Nuclear abundances during CC





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



T=23.2 GK, $n_B = 1.99 \cdot 10^{12}$ g/cm^3, Y_e=0.275

Raduta et al, PRC93, 025803 (2016)

wide nuclear distributions

As the collapse proceeds:

- wider distributions (increasing T)
- increasingly heavy nuclei (increasing n_B)
- increasingly n-rich nuclei (decreasing Y_e)
- at low Y_e experimental masses are not available

  $\rightarrow$ abundances are model dependent
- N magic numbers

Nuclear composition, EC rates and CC evolution

Core composition and collapse evolution depend on EC rates
[Aufderheide et al, ApJS **91**, 389 (1994), post-Si burning stage]
[Langanke et al, PRL **90**, 241102 (2003), core-collapse]

Finite-T: many configurations and possible, averaging over NSE distributions
Electron capture rate:

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

$$n(A,Z) \propto g_{A,Z}(T) \left(\frac{M_{A,Z} T}{2\pi} \right)^{3/2} \exp\left(\frac{-M_{A,Z}}{T} \right)$$

$$g_{A,Z}(T) = g_{A,Z}^{GS} + \int_0^{E_{max}} d\epsilon \rho(\epsilon) \exp(-\epsilon/T)$$

subject to major uncertainties coming from nuclear masses, excited states densities

Nuclear composition, EC rates and CC evolution

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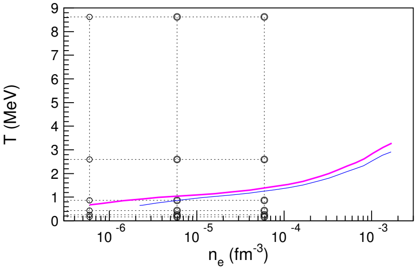
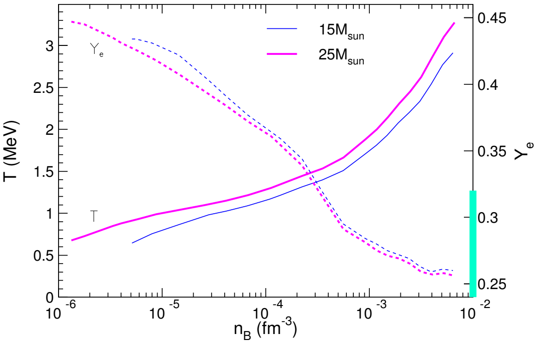


- λ_{EC} are known only for a limited number of nuclei (sd- and pf-shells) and limited thermodyn. conditions
- for CC, weak-int. tabulations are not sufficient too scarce in T not wide enough in n_e
- analytic param. are *probably* not appropriate for (T, n_e), nor representative for n-rich nuclei

Pre-bounce evolution

Thermodynamic conditions from Juodagalvis et al., NPA848, 454 (2010)
$0.05 M_\odot$ enclosed mass; $15 M_\odot$ and $25 M_\odot$ progenitors;

NSE, EC rates from shell model + RPA with param. single part. occ. numbers



- $T(n_B)$, $Y_e(n_B)$ have similar patterns, slight progenitor dependence
- more massive progenitors lead to higher T and n_B and lower Y_e
- for $Y_e < 0.32$ no exp. values exist for $B(A, Z)$

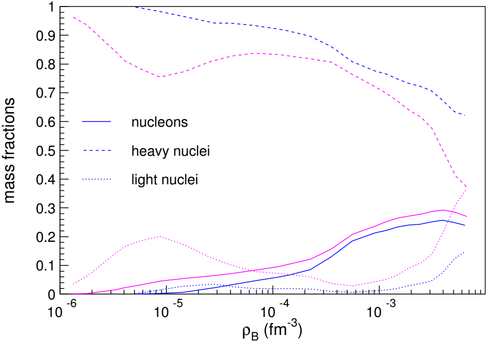
Matter composition - mass fractions

NSE model of Gulminelli and Raduta, PRC 92, 055803 (2015)

Nuclear masses from Audi et al., Chinese Physics C36, 1287 (2012); ibid. C36, 1603 (2012) + Duflo and Zuker, PRC **52**, R23 (1995);

level densities from von Egidy and D. Bucurescu, PRC 72, 044311 (2005), PRC 73, 049901 (2006).

$15 M_\odot$, $25 M_\odot$



- dep. on thermo conditions heavy ($Z \geq 20$) or light ($2 \leq A < 20$) nuclei and nucleons dominate
- heavy nuclei bound an important amount of matter and neutrons
  - if suject to uncertainties they can impact the evolution

Matter composition - average and most probable N and Z

NSE model of Gulminelli and Raduta, PRC 92, 055803 (2015)

Nuclear masses from Audi et al., Chinese Physics C36, 1287 (2012); ibid. C36, 1603 (2012) + Duflo and Zuker, PRC **52**, R23 (1995);

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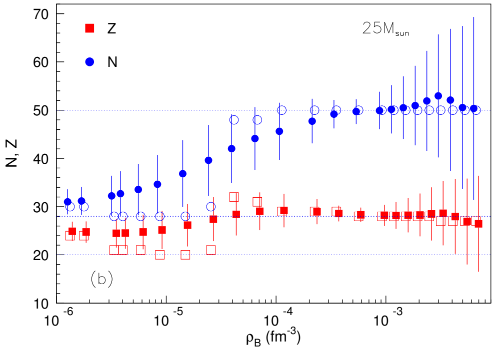
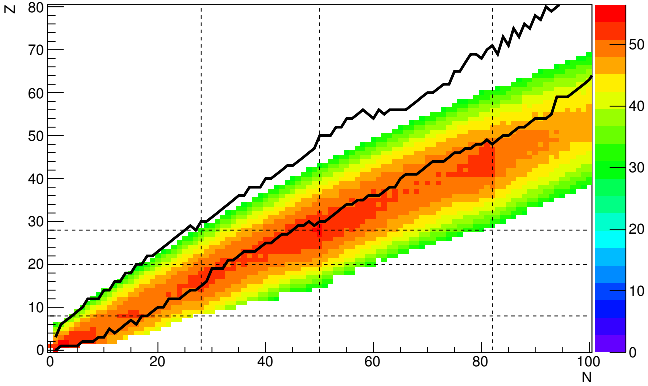


- increasing $\langle N\rangle$, $\langle Z\rangle$
- $\langle N\rangle$ increases faster than $\langle Z\rangle$
- large RMS
- $\langle N\rangle \neq N_{MP}$, $\langle Z\rangle \neq Z_{MP}$
- N_{MP}=28, 50; magic numbers
- competition of N-magic numbers

Matter composition - N magic numbers

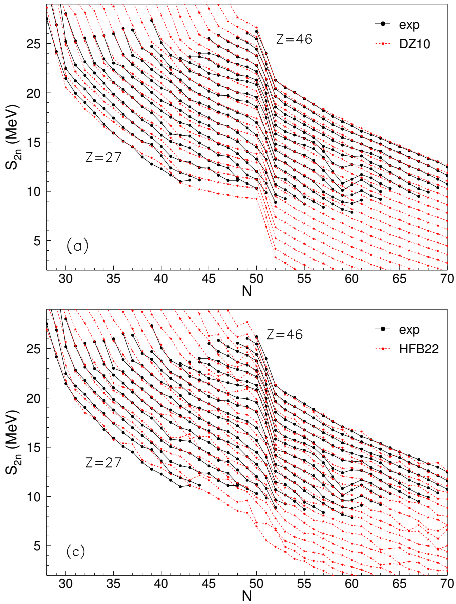
Nuclear masses from Audi et al., Chinese Physics C36, 1287 (2012); ibid. C36, 1603 (2012) + Duflo and Zuker, PRC **52**, R23 (1995);



points: abundances
lines: borders of exp masses

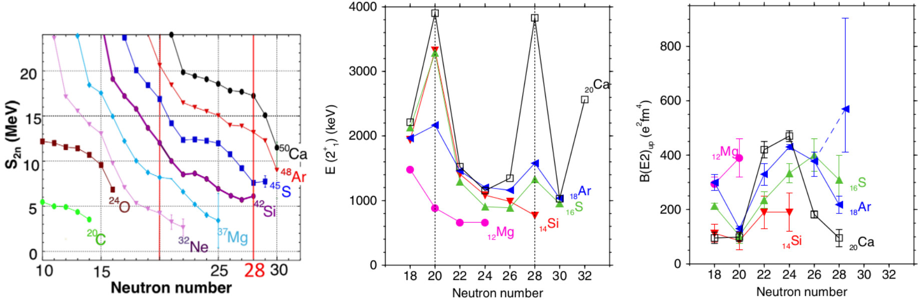
T=2 MeV, $n_B = 1.18 \cdot 10^{-3}$ fm^{-3}, $Y_e = 0.275$

Magicity evolution in n-rich nuclei



- HFB22 microscopic model predicts magicity quenching for $N = 50$
- at variance, HFB22 preserves magicity for $N = 82$
- phenomenological models (DZ, FRDM) do not account for magicity quenching

Magicity quenching in n-rich $N = 28$ nuclei



Sorlin and Porquet, Phys. Scr. T152, 014003 (2013)

Shell gap evolution due to NN interaction (central, SO, tensor, 3B)

Expected to occur also for $N = 50, 82$

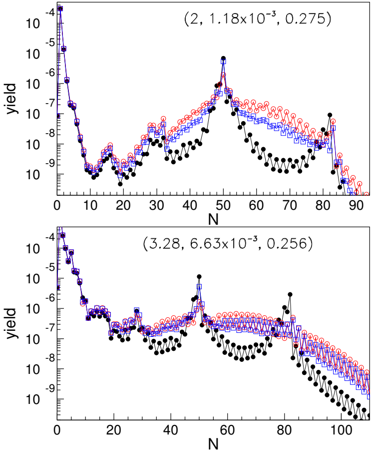
Controlled magicity quenching

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

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

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

$n(A,Z) \propto \exp\left(B(A,Z)/T\right)$ (Saha eqs.)

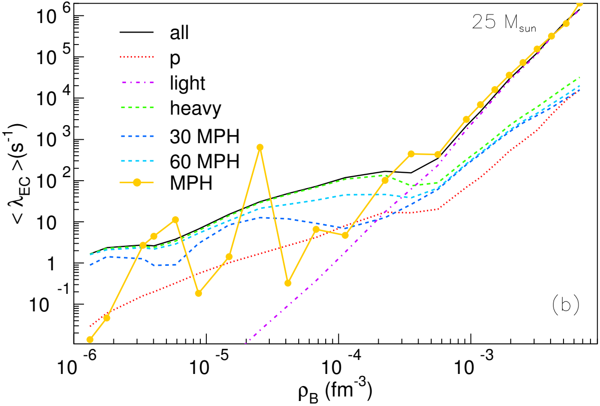


if the shell gap is reduced:

- diminised production of N-magic nuclei;
- more non-magic nuclei

Consequences of shell quenching on r-process nucleosynthesis [Pearson et al, PLB387, 445 (1996)]: better agreement with solar system abundances for $A \approx 110$

NSE-average EC rates



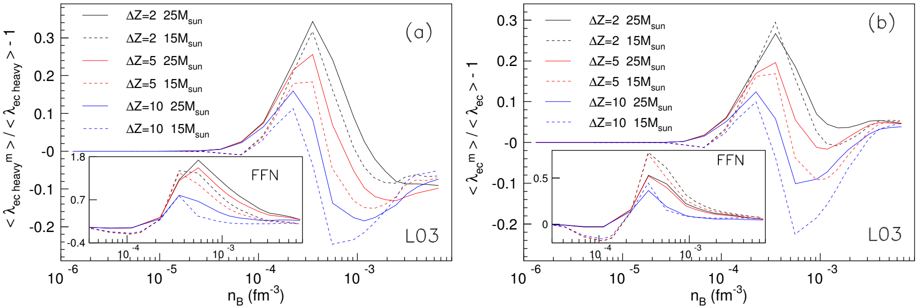
EC on protons (Fuller et al., Ap.J 1982)

EC on other species (PRL90, 241102 (2003))

$$\langle \lambda_{EC} \rangle = \sum_{A,Z} n(A,Z)\lambda(A,Z) / \sum_{A,Z} n(A,Z)$$

- NSE-average EC is the contribution of several tens of nuclei
- SNA is never acceptable

NSE-average EC rates

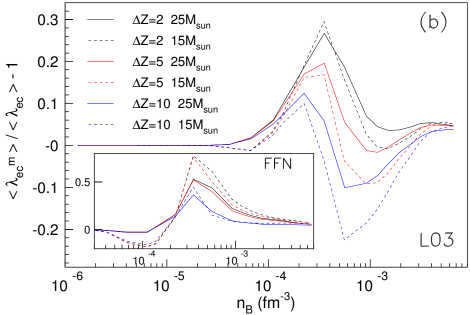


EC rates from Langanke et al, PRL90, 241102 (2003),

Fowler, Fuller, Newman, Astrophys. J. 293, 1 (1985)

- EC rates are modified by up to 30%
- stronger modif. if the unblocking effect of $N > 40$ nuclei is overestimated
- strong sensitivity to individual rates

NSE-average EC rates



non-monotonic evolution make the consequences on CC difficult to anticipate
need for experimental data on n-rich $N = 50, 82$ *nuclei*

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

Electron capture rates

$$\lambda^\alpha = \frac{\ln 2}{K} \sum_i \frac{(2J_i+1)\exp(-E_i/k_B T)}{G(A,Z,T)} \sum_j B_{ij}\Phi^\alpha_{ij}$$

accurate nuclear structure data

experimental uncertainties / EC rates at finite temperature [Cole et al., PRC86, 015809]

finite temperature and electron density: limited number of nuclei, on a finite grid

- $17 \leq A \leq 39$ Oda et al., ADNDT 56, 231 (1994);
- $45 \geq A \geq 65$ Langanke & Martinez-Pinedo, ADNDT 79, 1 (2001);
- $65 \leq A \leq 80$ Pruet et al., ApJS149, 189 (2003);
- $18 \leq A \leq 100$ Nabi et al., ADNDT 71, 149 (1999); ibid. 88, 237476 (2004);

analytic param. used otherwise

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

$\Delta E = 2.5$ MeV, B=4.6

Langanke et al, PRL90, 241102 (2003)

Electron capture rates

Question: how do the uncertainties on EC rates affect CC?

Answer: Sullivan et al, Ap.J 816, 44 (2016) modified EC rates by by factors ranging from 0.1 and 10 (present exp. error bars)

- systematic modifications
- statistic modifications

Conclusions:

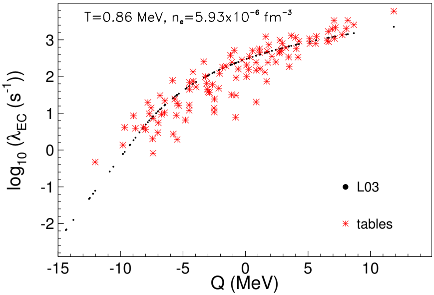
- *Systematic modif.* impact by $+16$/-4% the mass of the inner core at bounce and by $\pm 20\%$ the ν_e luminosity-peak
- no effect

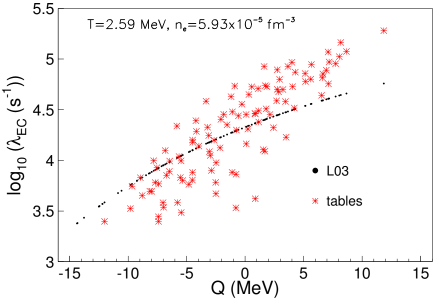
.... very nice but unrealistic
.... maybe a significant deviation monotonically dependent on X would be more realistic and make an effect
e.g.: $X = (N - Z)/A$

EC rates on n-rich nuclei at high (T, n_e)

- no microscopic calculations
- analytic param. [Langanke et al, PRL90, 241102 (2003)] fitted on *pf-nuclei* and (T, n_e)-*values too low* for CC are used

Question: Could λ_{EC}^{n-rich} depart from λ_{EC}^{pf} such as to obtain, globally, an effect similar to the one of Sullivan et al, Ap.J 816, 44?





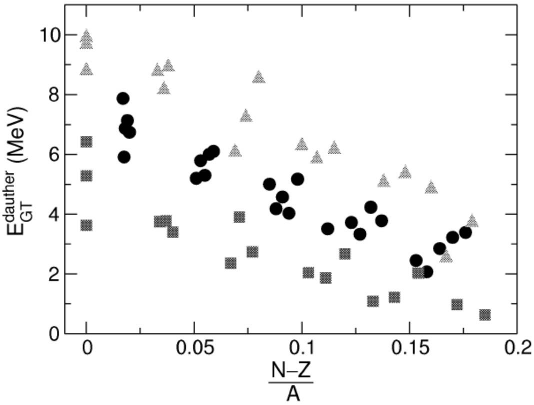
$45 \leq A \leq 65$ **L03 is not that good at high** (T, n_e)

Langanke and Martinez-Pinedo, ADNDT 79, 1 (2001).

$\Delta E(I, \delta)$

GT_+ centroid energy depends linearly on $I = 1 - 2Z/A$,
it manifests odd-even effects

square: EE; circles: O; triangles: OO (pairing effect)



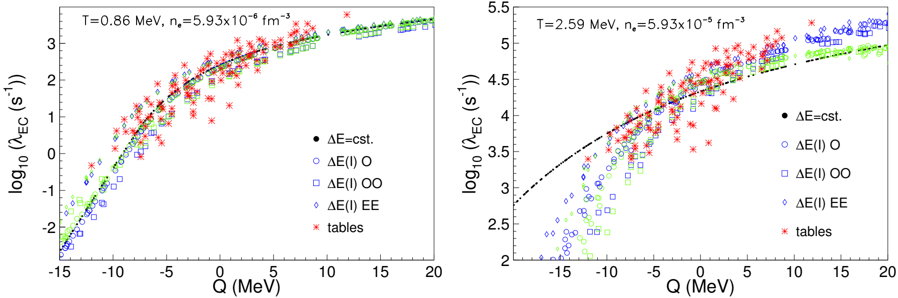
Langanke, Martinez, NPA (2000)

similar effect in experimental data

$\Delta E = E_f - E_i$, E_f assimilated with the centroid of GT_+

$\Delta E(I, \delta)$

GT$_+$ centroid energy depends on $I = 1 - 2Z/A$, it manifests odd-even effects
$\Delta E = E_f - E_i$, E_f assimilated with the centroid of GT$_+$

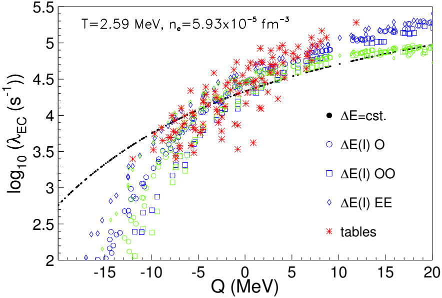


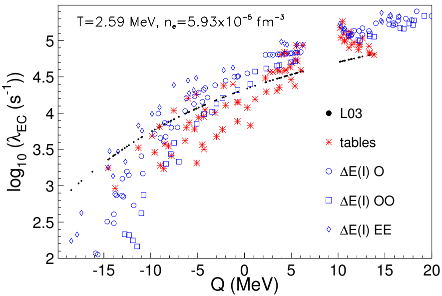
$45 \leq A \leq 65$

improved agreement (linear vs. quadratic I-dependence)

lower λ_{EC} for n-rich nuclei; *the most important nuclei according to Sullivan 2016*
λ_{EC} reduction not systematic but progressive; though expected to play a role

$\Delta E(I, \delta)$





$45 \leq A \leq 65$
Langanke & Martinez-Pinedo, ADNDT (2001)

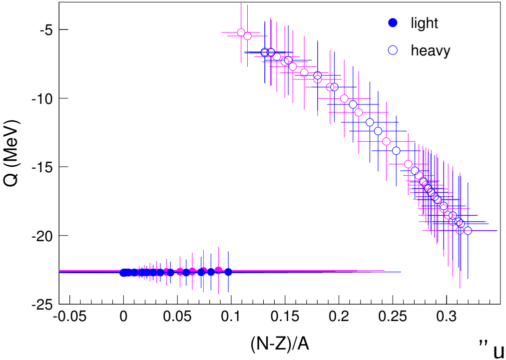
$17 \leq A \leq 39$
Oda et al., ADNDT (1994)

improved agreement

fitting param. depend on T, n_e

ee/o/oo ordering is the same as in Langanke and Martinez-Pinedo, NPA673, 481

Nuclear abundances: $I - Q$

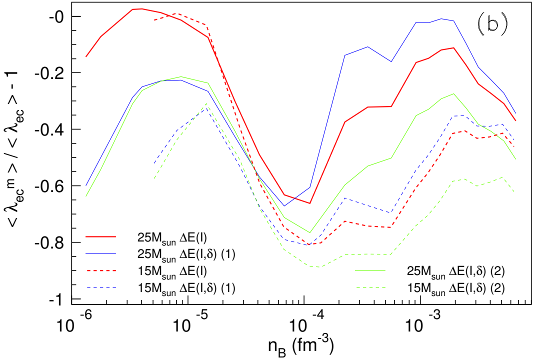


- $A \geq 20$, $-5 < \langle Q \rangle < -21$ MeV
- $2 \leq A \leq 19$, $\langle Q \rangle \approx -23$ MeV; is $\lambda_{EC}(Q)$ accurate enough?

"universality" does not hold when inclusive distrib. are considered

Nucl. abundances are dominated by the binding energies, strong correlation between I and Q, similar $T(n_B)$, $Y_e(n_B)$

NSE-average EC rates

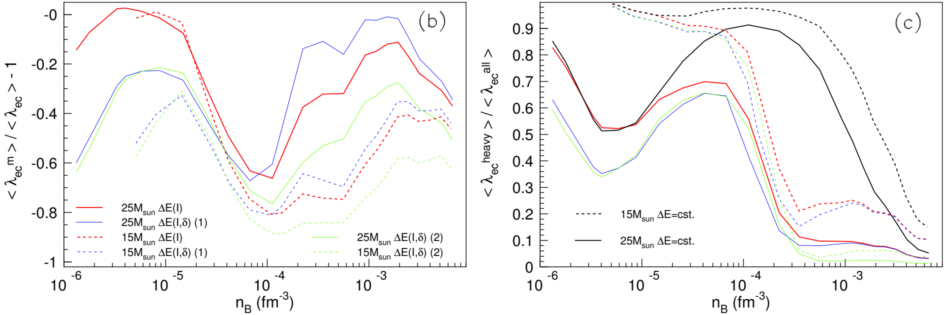


qualitative results,
highly sensitive to individual rates

`preliminary results`

- systematic reduction of EC
- non monotonic over the trajectory
- EC rates are more important than magicity quenching; not always in the same direction
- the net effect will be given by simulations (in progress...)
- identification of most important nuclei; *are they exp. accessible?*

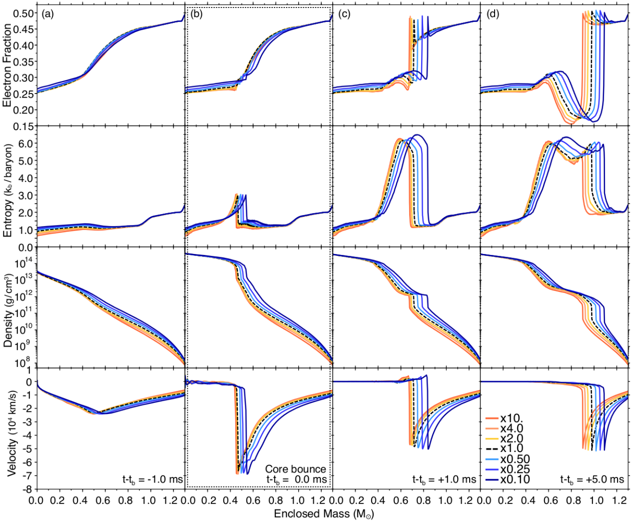
NSE-average EC rates



preliminary results

light nuclei are important as well despite the low Q-values and λ_{EC}

NSE-average EC rates and CC evolution



lower EC rates:

larger mass of the inner core at bounce (up to 16%)

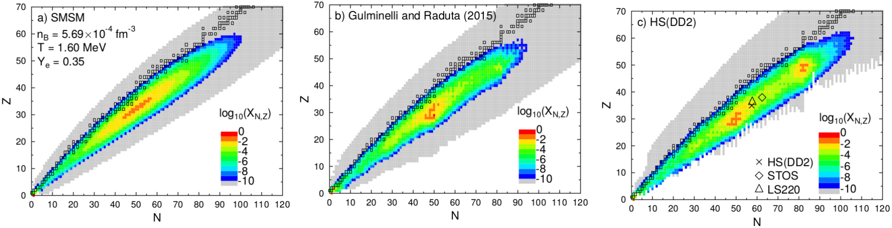
larger ν_e luminosity peaks (up to 20%)

${}^{78}_{28}$Ni, ${}^{79}_{29}$Cu, ${}^{79}_{29}$Zn - the most important

Sullivan et al, ApJ 816, 44 (2016)

Modeling dependence

Nuclear abundances within (extended) NSE courtesy of M. Oertel



interactions between unbound nucleons:

no | yes | yes

binding energies:

LDM | exp+DZ10 | exp+FRDM

upper excitation energy:

B | $\min(S_n, S_p)$ | B

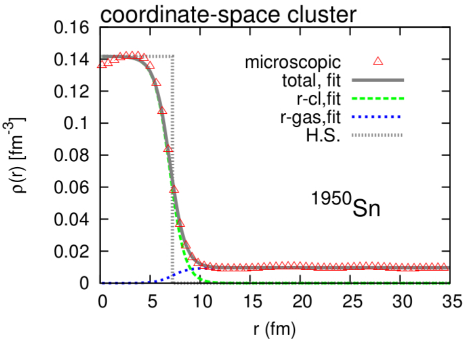
nucleon-cluster interaction:

excluded volume | excl. vol+ e-clusters | excl. vol.

electron screening (Wigner-Seitz)

significant model depencence

Nucleus in a nucleon gas



the nucleus is the **high density** component!

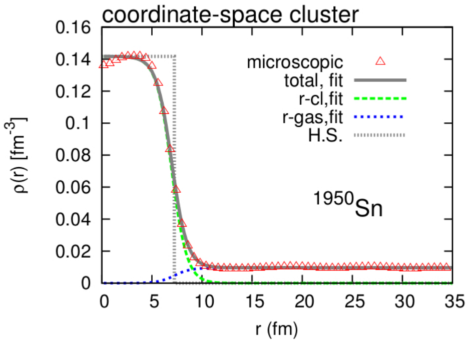
$$\rho^{WS}(r) = \rho_0 / \left[1 + \exp\left((r - R^{ws})/a\right)\right] + \rho_{gas} / \left[1 + \exp\left(-(r - R^{ws})/a\right)\right]$$

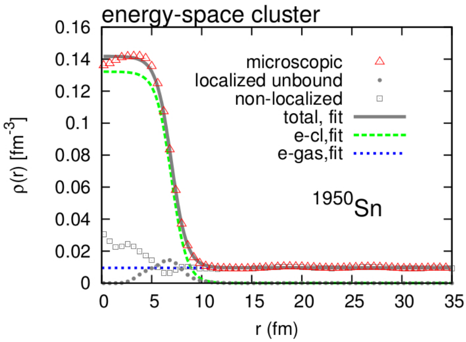
$$\rho^{WS}(r) = \rho^{WS}_{r-cl}(r) + \rho^{WS}_{r-gas}(r);$$

$$A^{WS} = A^r + \rho_g \left(V^{WS} - \mathcal{V}_{cl}\right),$$

$$E^{WS} = E^r + \epsilon_g \left(V^{WS} - \mathcal{V}_{cl}\right).$$

Nucleus in a nucleon gas





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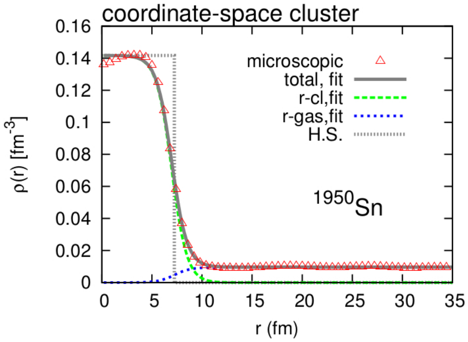
$$\rho^{WS}(r) = \rho^{WS}_{r-cl}(r) + \rho^{WS}_{r-gas}(r);$$
$$A^{WS} = A^r + \rho_g\left(V^{WS} - \mathcal{V}_{cl}\right);$$
$$E^{WS} = E^r + \epsilon_g\left(V^{WS} - \mathcal{V}_{cl}\right);$$

the nucleus is the **bound** component!

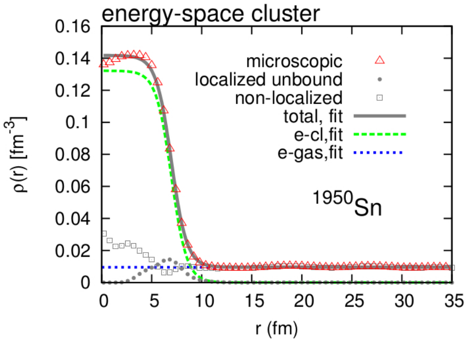
$$\left(\rho_0 - \rho_{gas}\right)/\left[1+\exp\left((r-R^{ws})/a\right)\right] + \rho_{gas}(r),$$

$$\rho^{WS}(r) = \rho^{WS}_{e-cl}(r) + \rho^{WS}_{e-gas}(r);$$
$$A^{WS} = A^e + \rho_g V^{WS},$$
$$E^{WS} = E^e + \epsilon_g V^{WS},$$

Nucleus in a nucleon gas



the nucleus is the **high density** component!



the nucleus is the **bound** component!

$$A^e = A^r\left(1 - \rho_{gas}\mathcal{V}_{cl}\right),$$
$$E^e = E^r\left(1 - \epsilon_{gas}\mathcal{V}_{cl}\right),$$

similar to an excluded volume correction

at $T = 0$: mapping between r- and e-clusters
Papakonstantinu et al., PRC 88, 045805 (2013)

Extended NSE models

Souza et al., PRC 79, 054602 (2009)
Heckel et al., PRC80, 015805 (2009)
Botvina and Mishustin, NPA 843, 98 (2010)
Hempel, Schaffner-Bielich, NPA 837, 210 (2010)
AR and Gulminelli, PRC82, 065801 (2010)
Blinnikov et al., A&A. 535, A37 (2011)

NSE with e-clusters [Gulminelli and Raduta, PRC 92, 055803 (2015)]

$$Z^{cl}_{\beta\mu_B\mu_3} = \sum_k \exp\left[-\beta \sum_i n_i^{(k)} G^e_{\beta\mu_B\mu_3}(i)\right] = \prod_i \sum_{n=0}^{\infty} \frac{\left[\exp\left(-\beta G^e_{\beta\mu_B\mu_3}(i)\right)\right]^n}{n!}$$
$$= \prod_i \exp \omega_{\beta\mu_B\mu_3}(i).$$

cluster multiplicities

$$< n_i >_{\beta,\mu_B,\mu_3} = \omega_{\beta\mu_B\mu_3}(i) = \exp\left[-\beta\left(F^e_\beta(A,\delta,\rho_g,y_g,\rho_p) - \mu_B A_e - \mu_3 I_e\right)\right].$$

Advantages:

- in the limit $T \to \infty$, NSE $\to$ SNA

Conclusions

- n-rich nuclei with unconstrained masses and EC rates might impact the CC evolution
- identify the most important nuclei and propose experiments/theoretical calculations

Ongoing work:

- CC simulations,
- systematic EC rates calculations within QRPA
  A. F. Fantina, E. Khan, G. Col, N. Paar, and D. Vretenar PRC86, 035805;
  N. Paar, G. Colo, E. Khan and D. Vretenar, PRC80, 055801 (2009);

Collaborators: F. Gulminelli (Caen, France), M. Oertel (Meudon, France)

Partial support from NewCompStar, COST Project MP1304

Weak interaction rates

$$\lambda^{\alpha} = \frac{\ln 2}{K} \sum_i \frac{(2J_i+1)\exp(-E_i/k_B T)}{G(A,Z,T)} \sum_j B_{ij}\Phi_{ij}^{\alpha}$$

$$K = \frac{2\pi^3 \ln 2\hbar^7}{G_F^2 V_{ud}^2 g_v^2 m_e^5 c^4} = const.$$

G_F=Fermi cc

V_{ud} = the up-down element of the quark mixing matrix

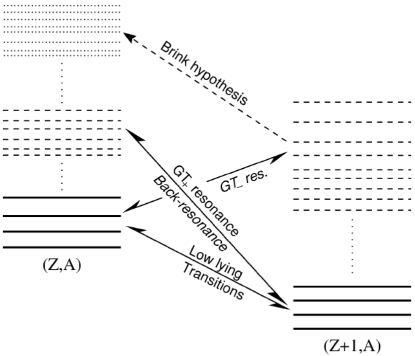
g_v =the weak vector cc =1

partition fct. of the parent:
$G(A,Z,T) = \sum_i \exp\left(-E_i/k_B T\right)$

reduced trans. prob. of the transition:
$B_{ij} = B_{ij}(F) + B_{ij}(GT)$

Phase space integral:
$\Phi_{ij}^{EC} = \int_{w_e}^{\infty} wp\left(Q_{ij}+w\right)^2 F(Z,w) S_e(w)(1 - S_{\nu}(Q_{ij}+w))dw$

K. Langanke, G. Martínez-Pinedo / Nuclear Physics A 673 (2000) 481–508



EC rates: Analytical expressions

$\lambda_{EC} = \log < ft > I_e$ Fuller, Fowler, Newman, Astrophy.J 293, 1 (1985)

for $Q_n > -m_e c^2$, $\tilde{\eta}_e = \eta_e^F - \eta_e^L$, $\eta_e^F = \mu_e/T$, $\eta_e^L = m_e c^2/T$

$$I_e = \left(\frac{T}{m_e c^2}\right)^5 F_4(\tilde{\eta}_e) + \left(4\eta_e^L + 2\zeta_n\right) F_3(\tilde{\eta}_e) + \left[6\left(\eta_e^L\right)^2 + 6\eta_e^L\zeta_n + (\zeta_n)^2\right] F_2(\tilde{\eta}_e)$$
$$+ \left[4\left(\eta_e^L\right)^3 + 6\left(\eta_e^L\right)^2\zeta_n + 2\eta_e^L(\zeta_n)^2\right] F_1(\tilde{\eta}_e) + \left[\left(\eta_e^L\right)^4 + 2\left(\eta_e^L\right)^3\zeta_n + \left(\eta_e^L\zeta_n\right)^2\right] F_0(\tilde{\eta}_e)$$

for $Q_n < -m_e c^2$, $\eta_e^L = |\zeta_n|$,$\zeta_n = Q_n/T$ (threshold case)

$$I_e = \left(\frac{T}{m_e c^2}\right)^5 \left[F_4(\tilde{\eta}_e) + 2|\zeta_n|F_3(\tilde{\eta}_e) + \zeta_n^2 F_2(\tilde{\eta}_e)\right]$$

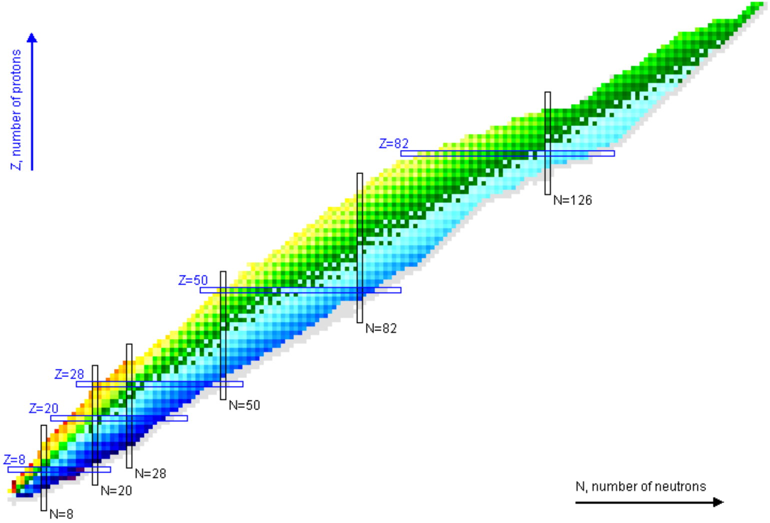
Langanke et al., PRL90, 241102 (2003)

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

$K = 6146$ s, $\chi = (Q - \Delta E)/T$, $\eta = \chi + \mu_e/T$,

$\mathcal{B} = 4.6$ MeV and $\Delta E = 2.5$ MeV (from fit of microsc. results)

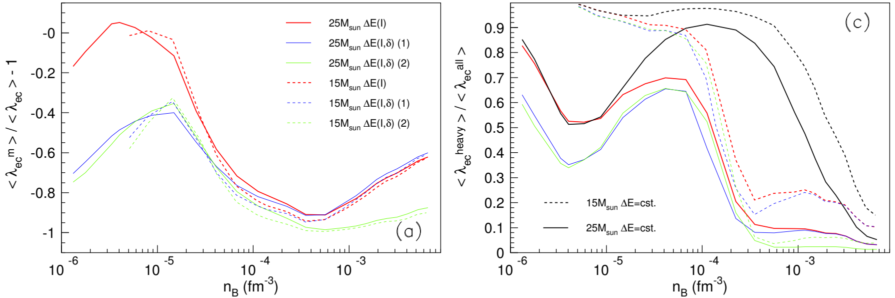
Q_{EC}


Z, number of protons
Z=82
Z=50
Z=28
Z=20
Z=8
N=126
N=82
N=50
N=28
N=20
N=8
N, number of neutrons

Improved $\lambda_{EC}(Q)$

T	n_e	ΔE=cst.		$\Delta E(I) = a_1 I + a_0$			$\Delta E(I,\delta) = a_1(\delta) I + a_0(\delta)$			$\Delta E(I,\delta) = a_1(\delta) I^2 + a_0(\delta)$		
(MeV)	(fm^{-3})	ΔE	χ^2	a_1	a_0	χ^2	a_1	a_0	χ^2	a_1	a_0	χ^2
0.86	$5.93 \cdot 10^{-6}$	2.96	20.8	2.01	2.71	20.8	-1.23	3.52	6.52	-20.8	3.72	6.43
							-10.0	6.30	3.74	-70.0	6.37	3.42
							-1.31	1.54	1.92	-20.7	1.73	1.87
0.86	$5.93 \cdot 10^{-5}$	3.81	11.4	56.3	-2.33	7.25	57.7	-2.23	3.50	259	0.40	3.89
							50.8	0.09	1.68	193	3.00	1.89
							56.4	-3.92	1.30	239	-1.16	1.47
2.59	$5.93 \cdot 10^{-6}$	2.35	7.75	26.3	-0.298	6.32	22.6	0.18	1.99	93.5	1.30	2.17
							23.9	2.38	1.55	88.1	3.74	1.67
							19.9	-1.84	0.69	82.8	-0.87	0.75
2.59	$5.93 \cdot 10^{-5}$	2.44	9.23	73.1	-4.84	5.11	70.7	-4.55	2.31	334	-1.64	2.66
							70.6	-2.46	1.36	295	1.03	1.58
							70.1	-6.39	0.86	323	-3.41	0.99

Average-NSE EC rates



Preliminary results

Evolution of neutron shell gaps

- the mechanism that creates the large SO N=28 shell gap between $f_{7/2}$ and $p_{3/2}$ is probably due to 3B forces [Holt et al., JPG 2012; Hagen et al., PRL2012]
  - also the $d_{5/2}$-$s_{1/2}$ sub-shell gap in N=14 comes from SO
  - SO shell gap expected also $N = 50$ ($g_{9/2}$-$d_{5/2}$) (Sorlin and Porquet, Phys. Scr. T 2013, effective monopole terms $V_{nn}^{g_{9/2}g_{9/2}}$=-200 keV, $V_{nn}^{g_{9/2}d_{5/2}}$=+130 keV extracted from ^{88,90}Zn spectroscopy)
  - SO shell gap expected also in $N = 82$ ($h_{11/2}$-$f_{7/2}$) but probably hard to see because of pairing with neutrons on $s_{1/2}$, $d_{3/2}$.
- SO magic numbers N=14, 28 and 50 disappear far from stability, while $N = 82$ does not; $N = 82$ does not come from $h_{11/2}$ and $f_{7/2}$; $h_{11/2}$ lower than $d_{3/2}$. (Phys. Scr. T 2013)
- nucl.-potential is more diffuse towards the drip line; low-l orbits more bound than high-l orbits; level inversion; all N-magic numbers are expected to vanish in n-rich nuclei.
- n-p interaction modified due to reduced overlap between n (loosely bound) and p (deeply bound) wave functions.