Can ^{55}Co give us the desired prompt explosion of massive stars

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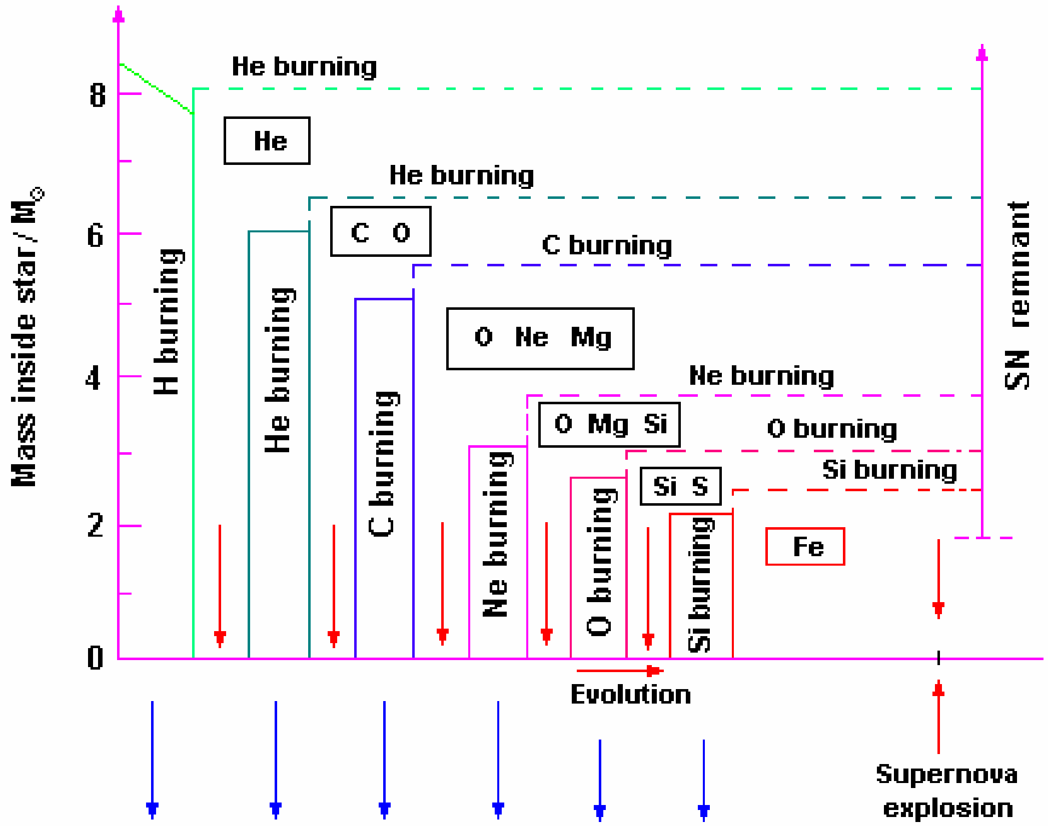
Introduction

- Weak interactions play a conclusive role in the evolution of massive stars at the presupernova stage and supernova explosions:
- They initiate the gravitational collapse of the core of stars
- They affect the formation of heavy elements above iron via the r-process
- Play a key role in neutronisation of the core material via electron capture by free protons and by nuclei.

Star Evolution



Temp. (K)	6×10^7	2×10^8	9×10^8	1.7×10^9	2.3×10^9	4×10^9
Density(g-cm^{-3})	5	700	2×10^5	4×10^6	1×10^7	3×10^7
Time (s)	2.2×10^{14}	1.6×10^{13}	1.9×10^{10}	1.6×10^7	5.2×10^5	8.6×10^4

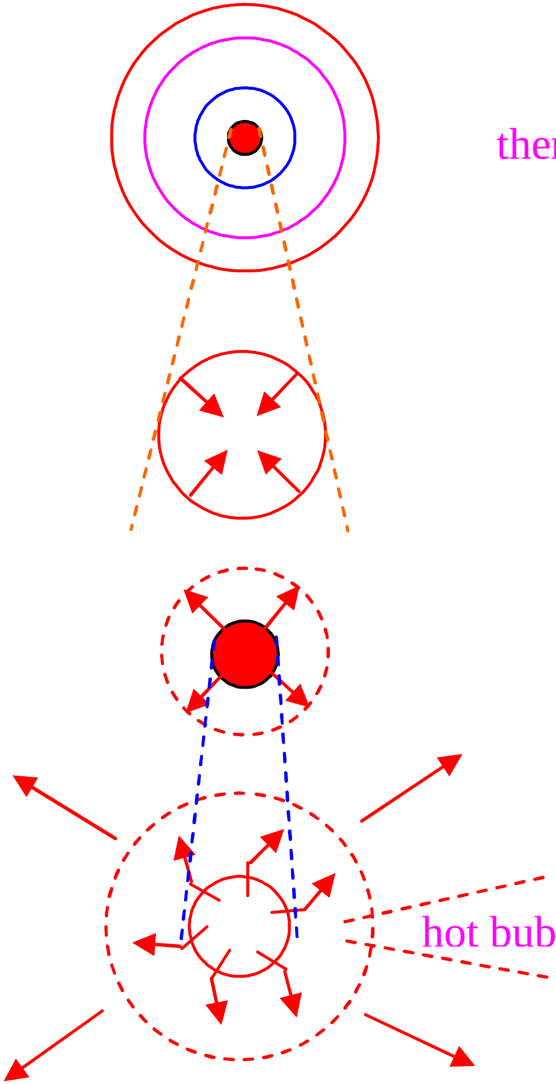
H-burning (CNO)
He-burning

Si-burning
Fe-core formed

contraction
neutronization
core collapse

proto-neutron star
core bounce
shock wave (stalled)

neutrino heating
hot-bubble formed
shock wave revived



(nuclear physics)
thermonuclear reactions
NSE

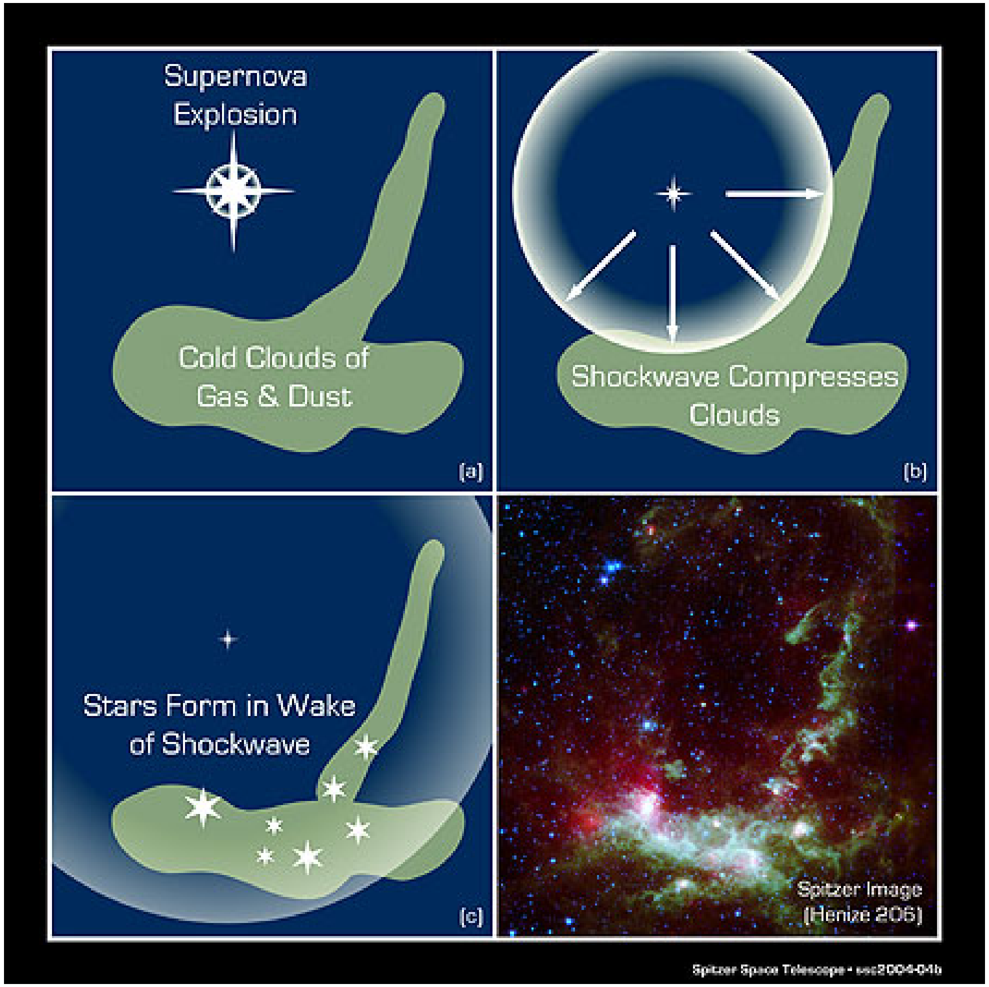
electron captures &
photodisintegrations

Nuclear equation
of state

Neutrino interactions

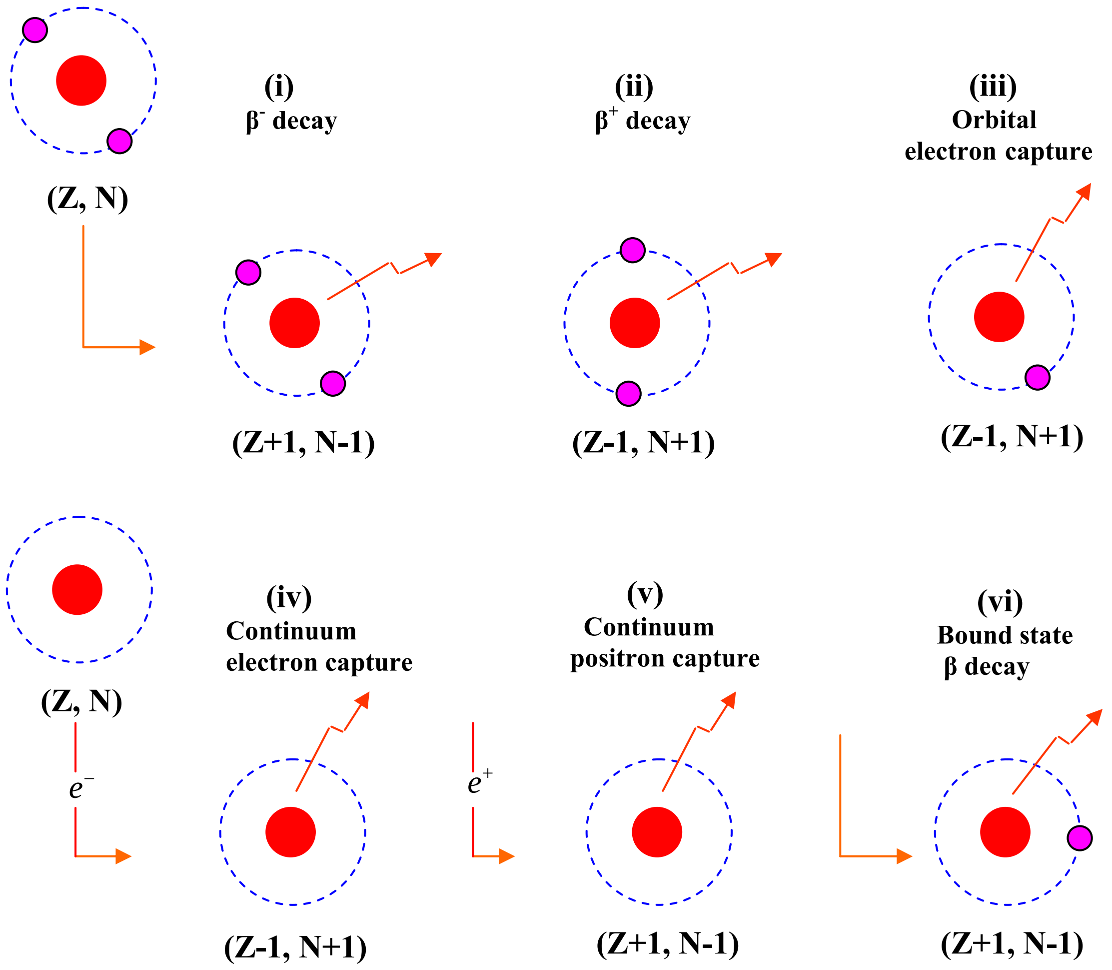
heavy elements
nucleosynthesis

This three-panel diagram shows the process of triggered star formation. In the first panel, a massive, dying star explodes or "goes supernova." In the second panel, the shock wave from this explosion passes through clouds of gas and dust (green). In the third panel, a new wave of stars is born within the cloud, induced by the shock from the supernova blast.



Spitzer Space Telescope • ssc2004-04b

The whole progression, from the death of one star to the birth of others, takes millions of years to complete.



(Z, N)

(i)
β^- decay

(Z+1, N-1)

(ii)
β^+ decay

(Z-1, N+1)

(iii)
Orbital
electron capture

(Z-1, N+1)

(Z, N)

e^-

(iv)
Continuum
electron capture

(Z-1, N+1)

e^+

(v)
Continuum
positron capture

(Z+1, N-1)

(vi)
Bound state
β decay

(Z+1, N-1)

Stellar Weak Interactions

- In domains of high temperature and density scales, weak rates are of decisive importance in studies of the stellar evolution.
- Beta decay and electron capture lead to:
- a change in the neutron-to-proton ratio
- cool the core to a lower entropy state
- determine the initial dynamics of the collapse
- determine the size of the collapsing-core
- determine the fate of shock wave released later

Role of ^{55}Co

- Aufderheide et. al. (Astrophy. J. Suppl. 91, 389 (1994)) compiled a list of important nuclides which affect the Y_e via electron capture processes.
- They ranked ^{55}Co as one of the most important nuclei w.r.t. its importance for electron capture process for the early presupernova collapse.
- Heger et al., (Phys. Rev. Lett. 86, 1678 (2001)) also discussed the importance of ^{55}Co relating to the dynamics of core collapse.

Calculation of electron capture rates of ^{55}Co

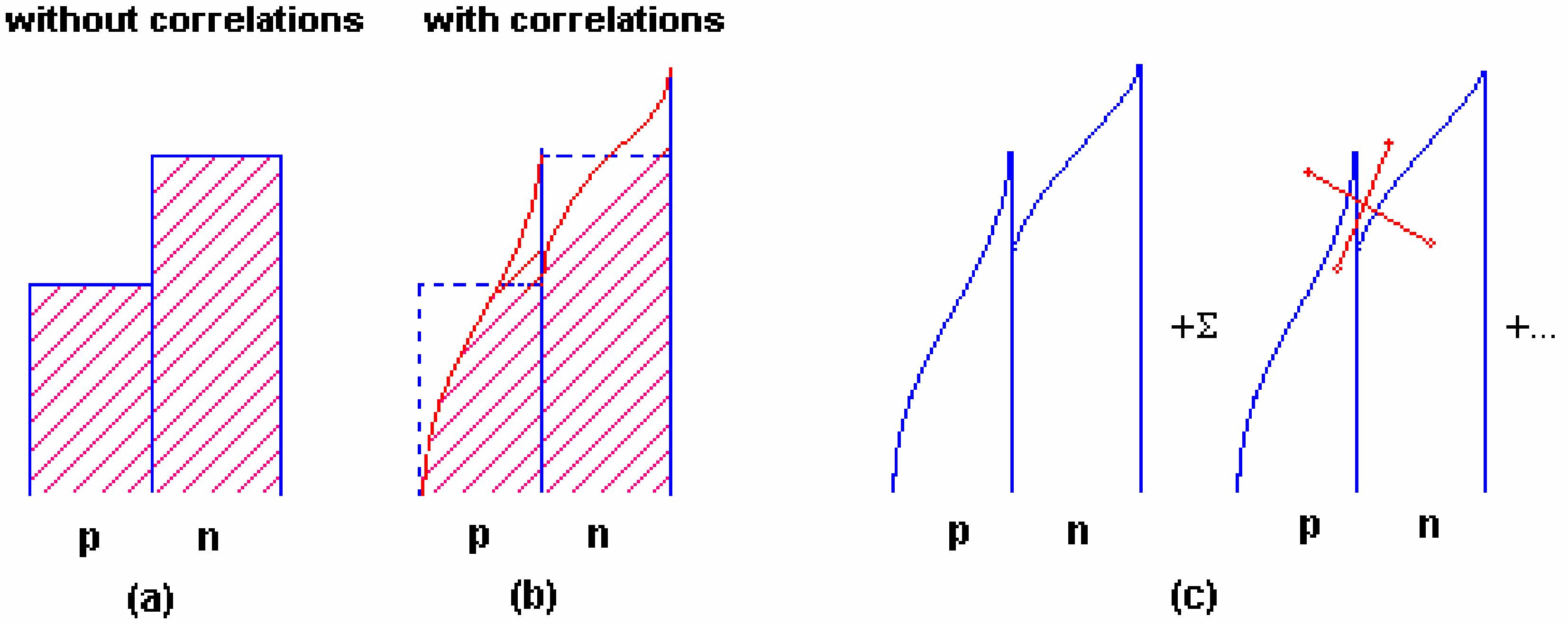
- pn-QRPA theory has a pretty good reputation for calculation of electron capture rates
- This microscopic theory puts more weight in correlations as compared to interactions
- Because of the large dimensionality of the space involved for the *pf*-shell nuclei and beyond, Hamiltonian diagonalization and calculation of beta decay strength is computationally a formidable task in Shell model calculations.

- The QRPA approach gives us the liberty of performing calculations in a luxurious model space (as big as $7\mathrm{h}\omega$).

- The QRPA method considers the residual correlations among nucleons via one particle one hole (1p-1h) excitations in a large multi model space.

pairing correlations

ground state correlations in proton-neutron QRPA



(a) (b) (c)

Table:

The accuracy of the pn-QRPA model compared to experimental data (β^+/EC decay)

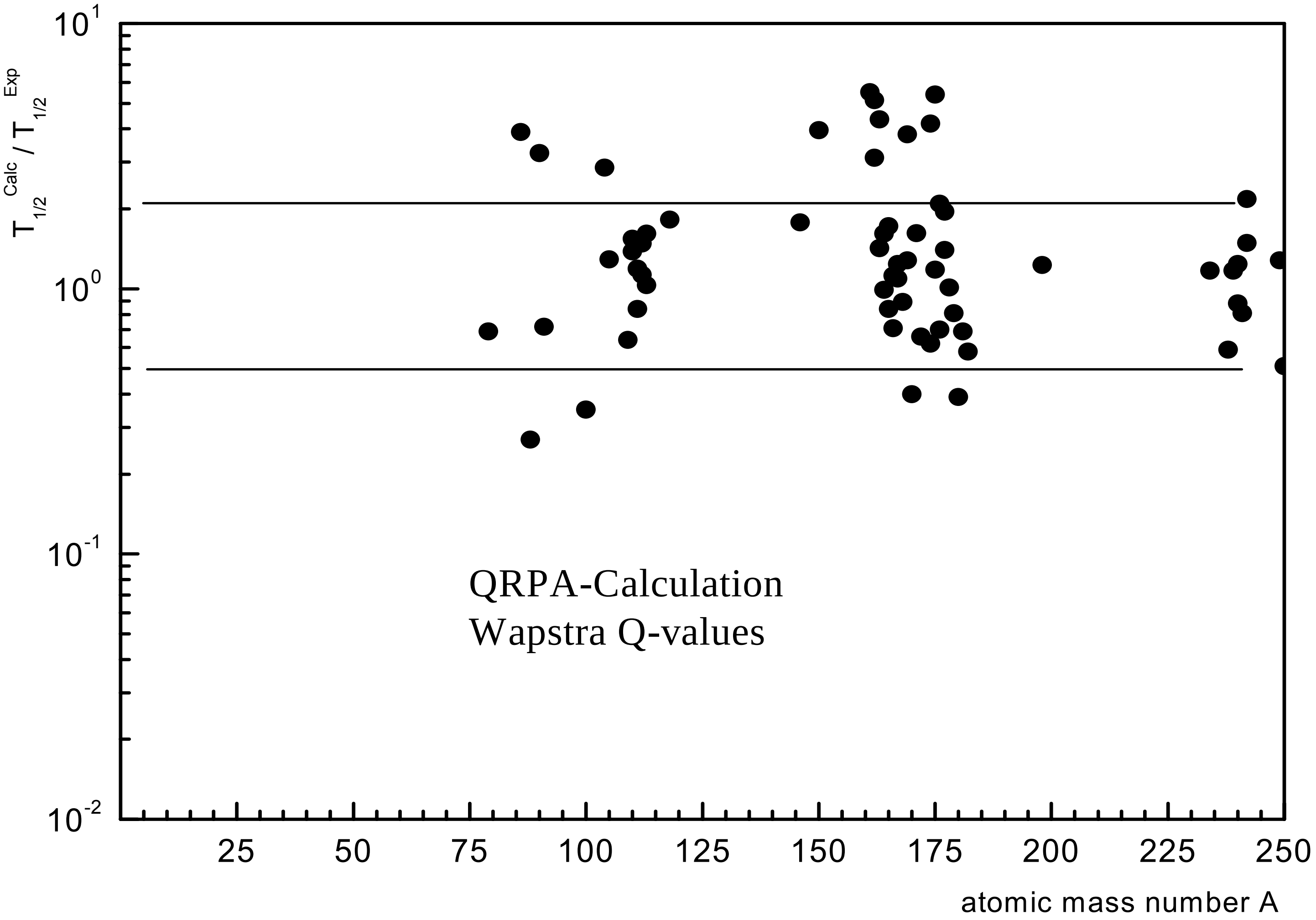
Conditions	$T_{1/2}^{\exp}(s) \leq$	N	n	n(%)	$\bar{x}$
$\forall x_i \leq 10$	10^6	894	706	79.0	2.057
	60	327	304	93.0	1.718
	1	81	78	96.3	1.848
$\forall x_i \leq 2$	10^6	894	489	54.7	1.363
	60	327	245	74.9	1.308
	1	81	59	72.8	1.230

N denotes the number of experimentally known half-lives shorter than the limit in the second column,
n is the number (and percentage) of isotopes reproduced under the condition given in the first column,
x bar is the average deviation.

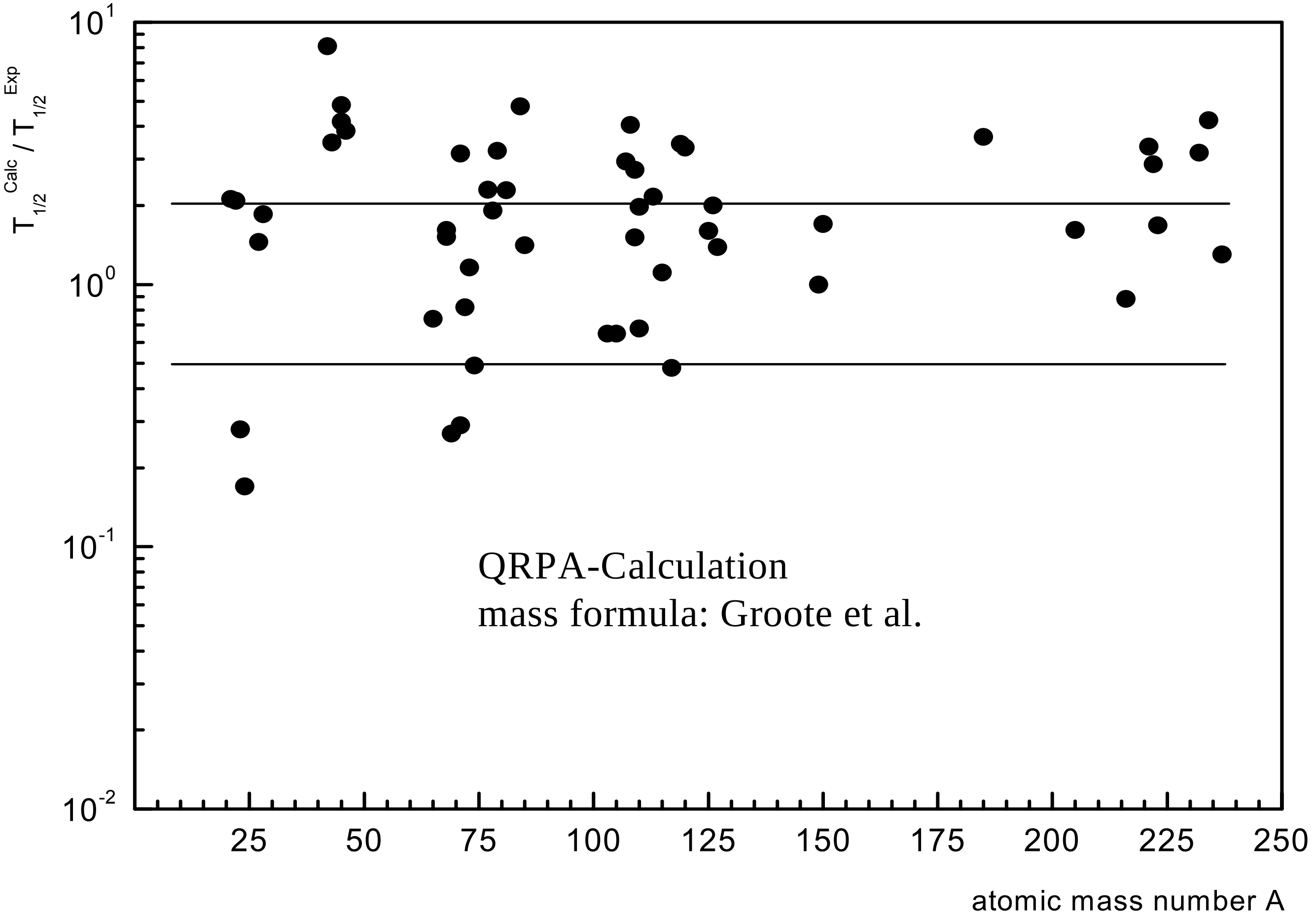
Table:

The accuracy of the pn-QRPA model compared to experimental data (β^- decay)

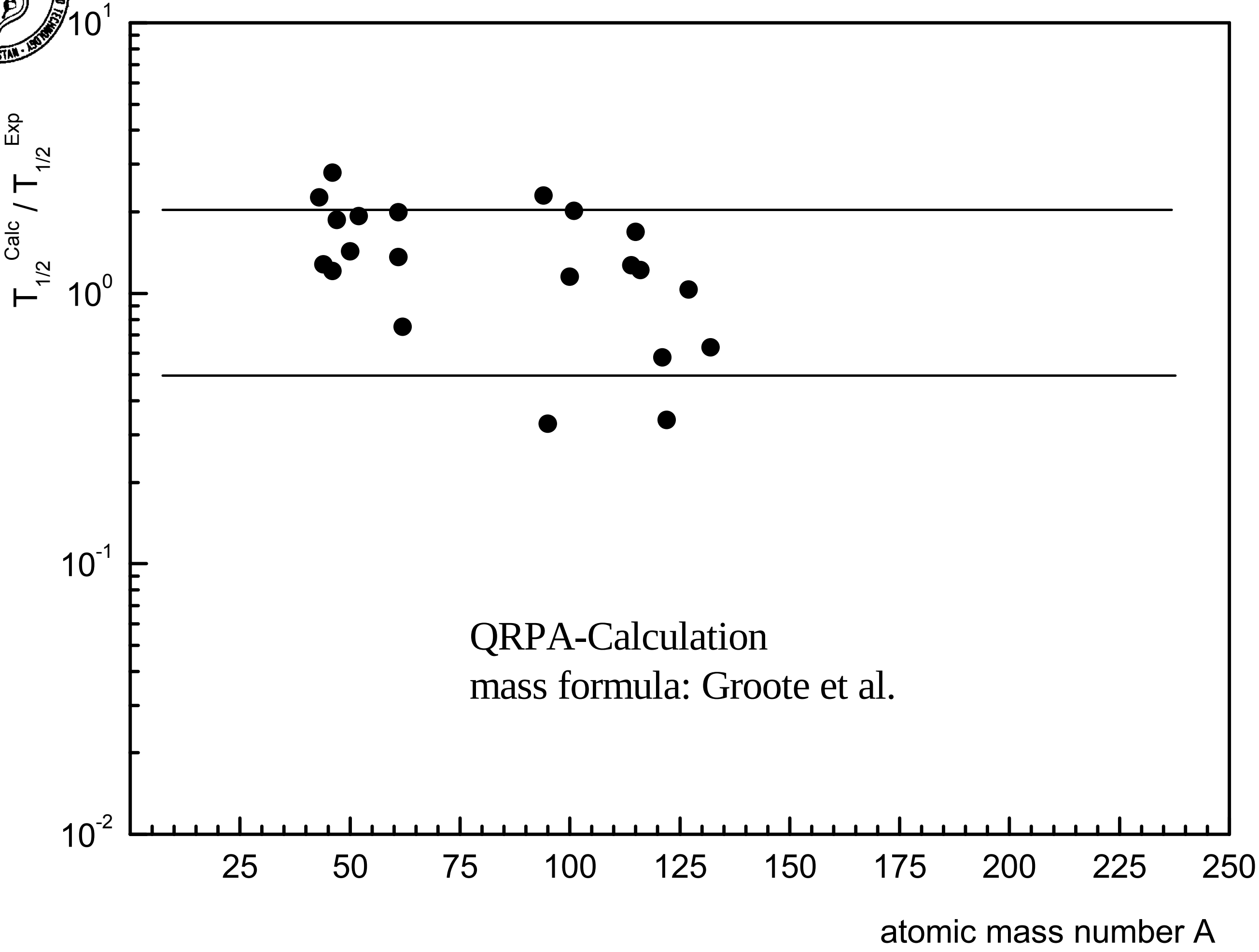
Conditions	$T_{1/2}^{\exp}(s)\le$	N	n	n(%)	$\bar{x}$
$\forall x_i \le 10$	10^6	654	472	72.2	1.85 ± 1.21
	60	325	313	96.3	1.67 ± 1.02
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \le 5$	10^6	654	456	69.7	1.68 ± 0.76
	60	325	307	94.5	1.56 ± 0.66
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \le 3$	10^6	654	420	64.2	1.50 ± 0.46
	60	325	295	90.8	1.46 ± 0.43
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \le 2$	10^6	654	369	56.4	1.37 ± 0.29
	60	325	267	82.2	1.36 ± 0.29
	1	106	96	90.6	1.35 ± 0.27



Predictive power of the pn-QRPA theory. Here the ratios of the calculated β+/(EC) decay half-lives and measured ones are shown as a function of mass numbers. The measured values were obtained *after* the calculations



The predictive power of the pn-QRPA theory for neutron rich nuclei (β- decays). The measured values were obtained *after* the calculations.



The predictive power of the pn-QRPA theory for proton rich-nuclei (β^+/EC). The measured values were obtained *after* the calculations.

- We calculated the electron capture rates over a wide temperature ($0.01\times10^{9} – 30\times10^{9}$ K) and density ($10 – 10^{11}$ g/cm^{3}) domain. (J.-U. Nabi and M. Rehman, PLB 190, (**612**), 2005)

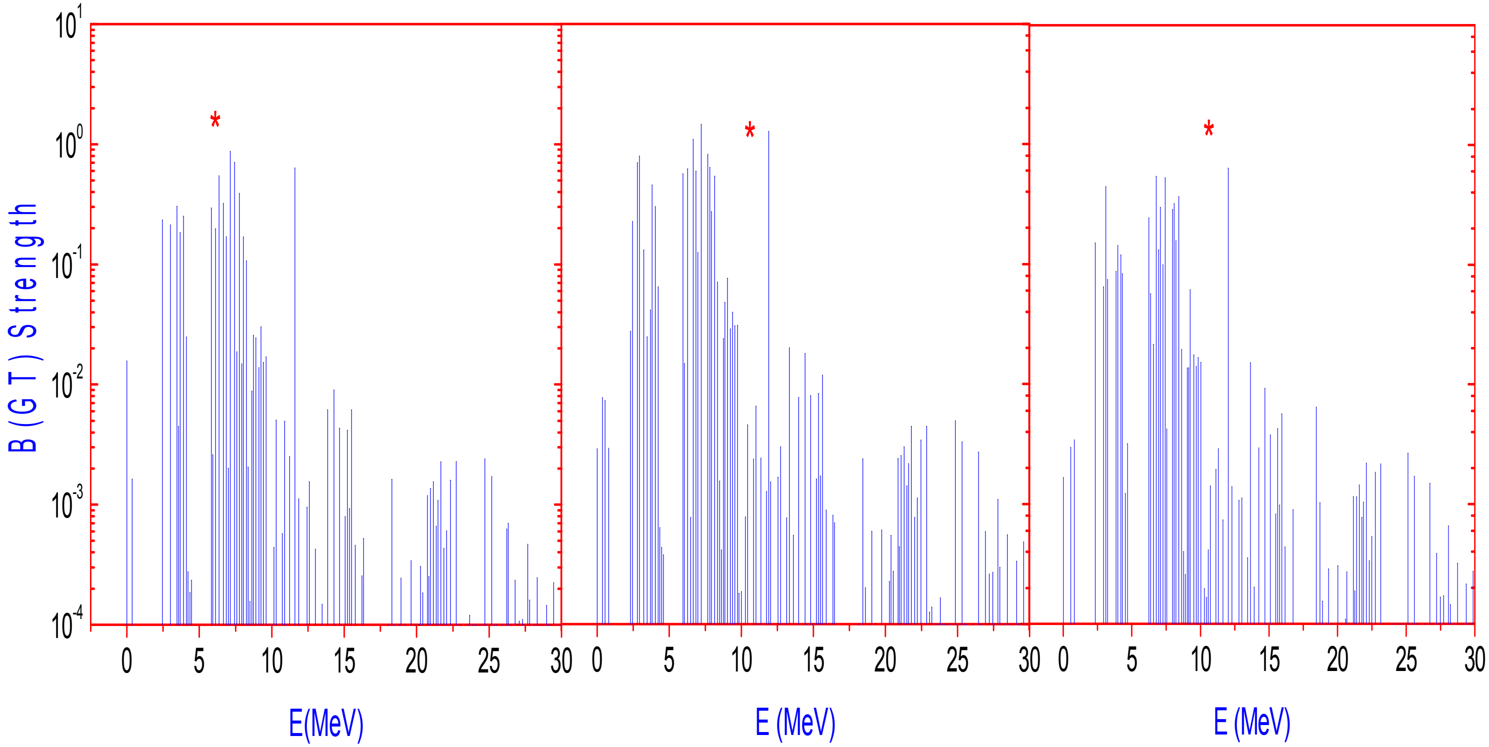
- The weak decay rate from the *i*th state of the parent to the *j*th state of the daughter nucleus is given by

$$\lambda_{ij} = \ln 2 \, \frac{f_{ij}(T, \rho, E_f)}{(ft)_{ij}}$$

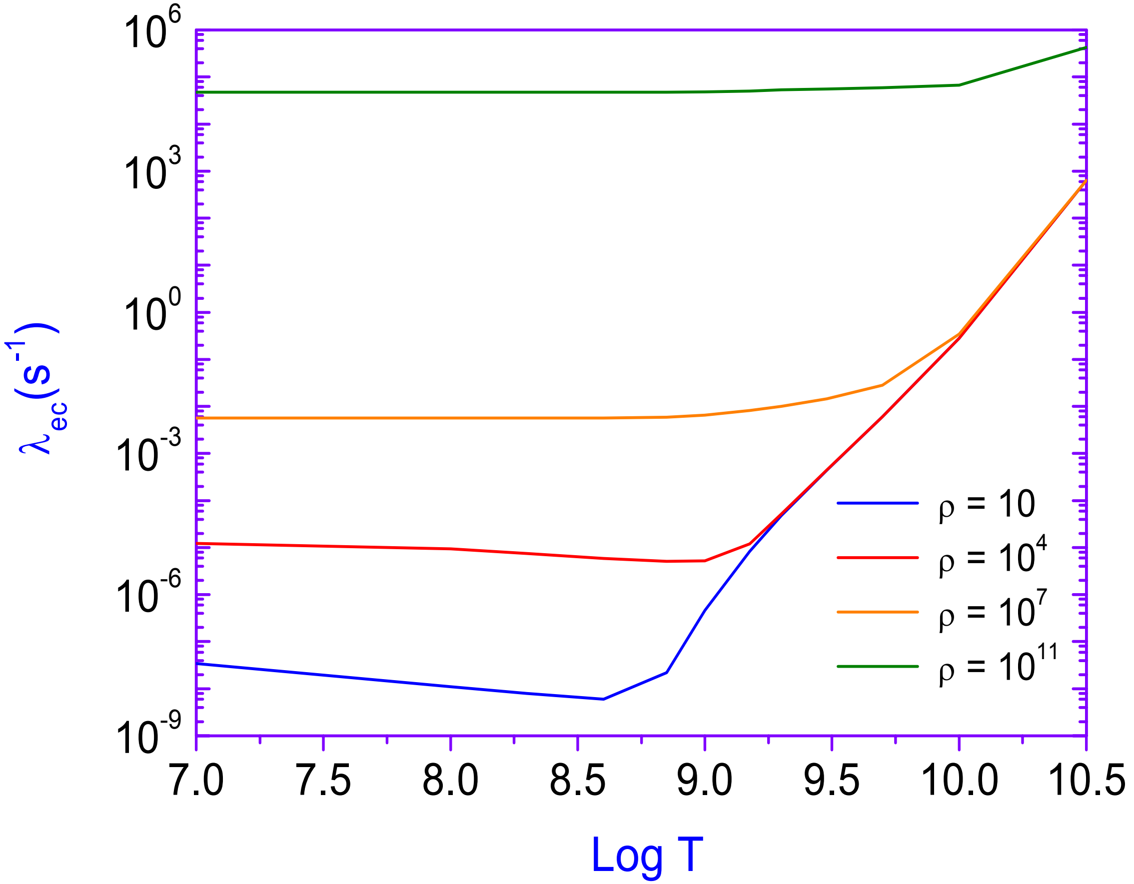
$$(ft)_{ij} = D / B_{ij}$$

D is a constant and B_{ij} are the sum of reduced transition probabilities of the Fermi and GT transitions.

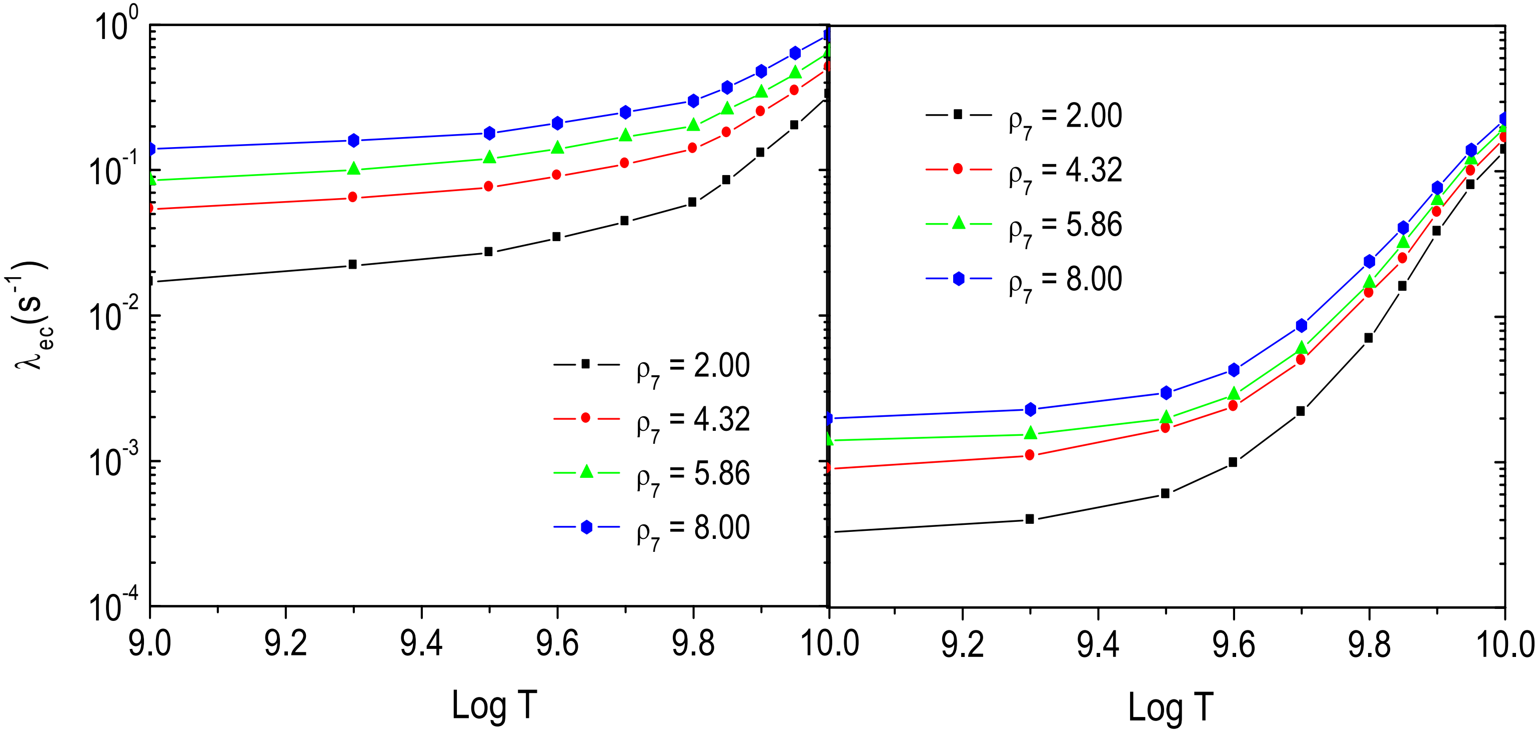
- We summed the partial rates over 200 initial and as many final states (to ensure satisfactory convergence) to get the total capture rate.
- For details please refer to Nabi & Klapdor (ADNDT, 237 (**88)**, 2004) **.**



Gamow-Teller (GT+) strength distribution for electron captures on ^{55}Co. The left panel shows GT strength for ground state, and middle and right panels show GT strength for 1st and 2nd excited states. The energy scale is the excitation energies in daughter ^{55}Fe.



Electron capture rates on ^{55}Co as function of temperature for different selected densities. Densities are in units of g cm^{-3}.



Electron capture rates on ^{55}Co as function of temperature for different densities (left panel). The right panel shows the results of PLB 436(1998)19, for the corresponding temperatures and densities.

Implications of the rates on the dynamics of core collapse

- The nuclei which cause the largest change in Ye are the most abundant ones *and* the ones with the strongest rates.
- Our calculation certainly points to a much more enhanced capture rates as compared to the shell model results (Langanke and M.-Pinedo, PLB **436** (1998) 19).

- According to Aufderheide et.al. the rate of change of lepton-to-baryon ratio changes by about 50% alone due to electron capture on 55Co.
- Authors in Hix et. al. (PRL 91(2003)201102) do point towards the fact that the spherically symmetric core collapse simulations, taking into consideration electron capture rates on heavy nuclides, still do not explode because of the reduced electron capture in the outer layers slowing the collapse and resulting in a shock radius of slightly larger magnitude.

- It will be very interesting to see if our enhanced electron capture rates are in favor of a prompt collapse of the core.

- We are in a process of finding the affect of inclusion of our rates in stellar evolution codes and hope to soon report our results (J.-U. Nabi and M.-U. Rahman, submitted to PRC (2006))

THANK YOU