Stellar weak-interaction rates from deformed QRPA calculations

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COMEX6

Weak-decay rates

Problem :

- Weak-decay rates determine late stages of stellar evolution.
- Simulations: experimental extrapolations or theoretical predictions.

Reproduce exp. information on $T_{1/2}$ and BGT under terrestrial conditions.

Theoretical approach :

- Deformed HF+BCS+QRPA formalism with Skyrme forces and residual spin-isospin interactions in both ph and pp channels.

Results : Weak-decay rates at various (ρ,T) in stellar scenarios

- pf-shell nuclei. Main constituents of stellar core in presupernova formations: Sc, Ti, V, Mn, Fe, Co, Ni, Zn isotopes.
- Neutron-rich isotopes (Ge-Pd, rare earths): r process.
- Neutron-deficient waiting-point isotopes (Ni-Sn, Hg-Pb): rp process.

Weak-decay rates

$$\lambda = \ln 2 \left(T_{1/2}\right)^{-1} = \frac{\ln 2}{D} \sum_{if} P_i(T)\, B_{if}\, \Phi_{if}\left(\rho, T\right)$$

Initial states thermally populated

$$P_i(T) = \frac{2J_i + 1}{G} e^{-E_i/(kT)}, \quad G = \sum_i \left(2J_i + 1\right) e^{-E_i/(kT)}$$

$$P_{i=g.s.}(T=0) = 1$$

Nuclear structure

$$B_{if}(GT) = \left(\frac{g_A}{g_V}\right)_{\text{eff}}^2 \left\langle f \left\| \sum_k \sigma^k t_{\pm}^k \right\| i \right\rangle^2$$

Phase space factors :

β^+, **EC :** $\Phi_{if} = \Phi_{if}^{EC} + \Phi_{if}^{\beta^+}$

β^- **:** $\Phi_{if} = \Phi_{if}^{\beta^-}$

$\lambda\,(\rho,T)$ are different from laboratory (P_i, cEC)

Phase space factors

$$\Phi_{if}^{\beta^-} = \int_1^{Q_{if}} \omega\sqrt{\omega^2-1}(Q_{if}-\omega)^2 F(Z+1,\omega)\left[1-S_e(\omega)\right]\left[1-S_\nu(Q_{if}-\omega)\right]d\omega$$

$$\Phi_{if}^{\beta^+} = \int_1^{Q_{if}} \omega\sqrt{\omega^2-1}(Q_{if}-\omega)^2 F(-Z+1,\omega)\left[1-S_p(\omega)\right]\left[1-S_\nu(Q_{if}-\omega)\right]d\omega$$

$$\Phi_{if}^{cEC} = \int_{\omega_\ell}^{\infty} \omega\sqrt{\omega^2-1}(Q_{if}+\omega)^2 F(Z,\omega)S_e(\omega)\left[1-S_\nu(Q_{if}+\omega)\right]d\omega$$

$$\Phi^{oEC} = \frac{\pi}{2}\left[q_K^2 g_K^2 B_K + q_{L_1}^2 g_{L_1}^2 B_{L_1} + \cdots\right]$$

- q Neutrino energy
- g Radial components of the e-wf at r=0
- B Exchange and overlap corrections

$$Q_{if} = \frac{1}{m_e c^2}\left(M_p - M_d + E_i - E_f\right)$$

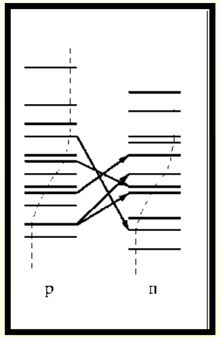
Distribution functions

$$S_e = \frac{1}{\exp\left[\left(\omega-\mu_e\right)/\left(kT\right)\right]+1}$$

$S_p=S_\nu=0$ S_e: Fermi-Dirac distribution

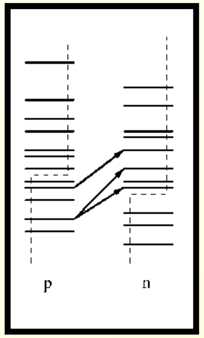
Nuclear Structure

Skyrme HF + def + BCS + QRPA (ph,pp)

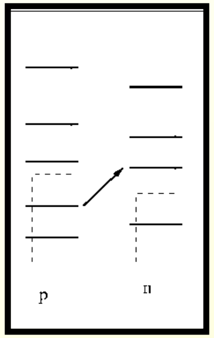


Redistribution and reduction of the strength

Smooth occupations
New excitations



Fragmentation



Skyrme HF

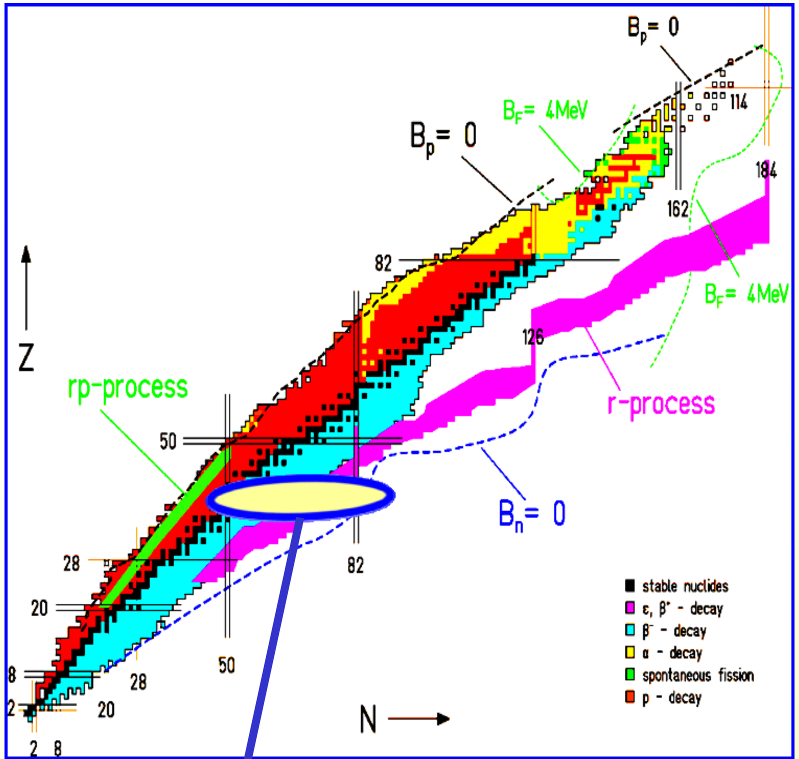
pnQRPA with separable forces

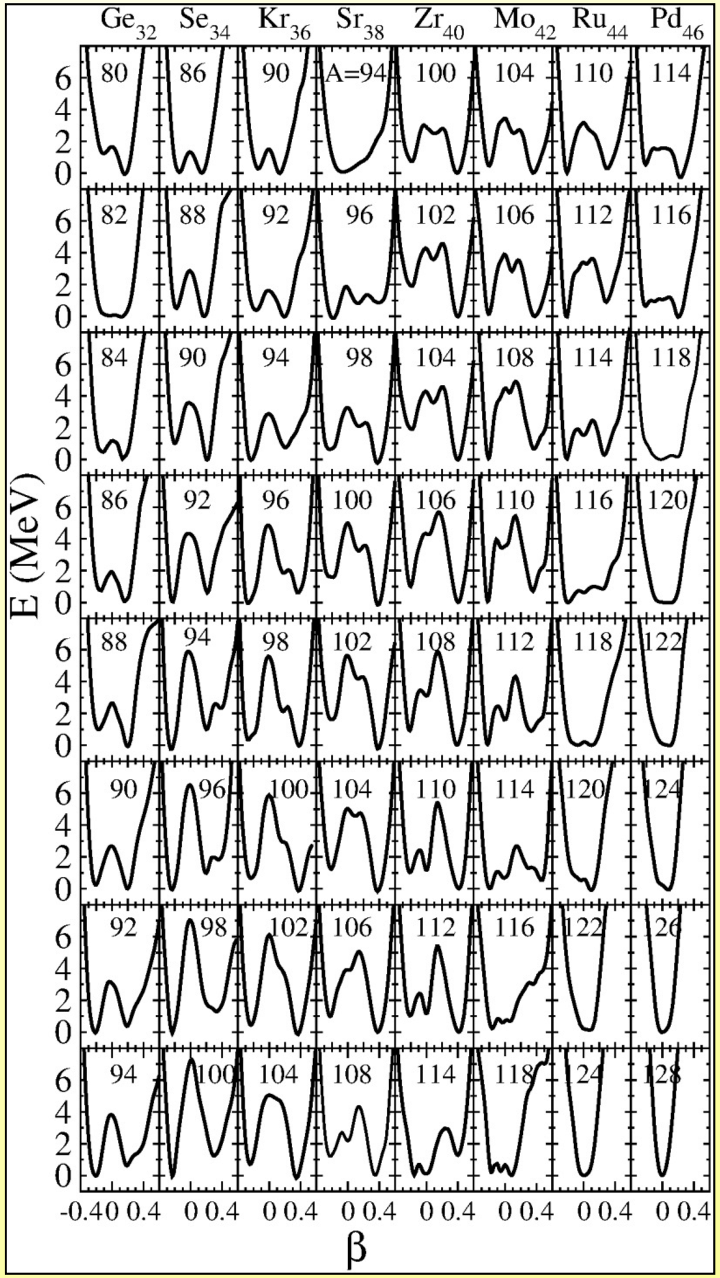
Transition amplitudes

$$\langle \omega_K | \sigma_K t^- | 0 \rangle = \sum_{\pi\nu} \left(q_{\pi\nu} X_{\pi\nu}^{\omega_K} + \tilde{q}_{\pi\nu} Y_{\pi\nu}^{\omega_K} \right)$$

$$\tilde{q}_{\pi\nu} = u_\nu v_\pi \Sigma_K^{\pi\nu}, \quad q_{\pi\nu} = v_\nu u_\pi \Sigma_K^{\pi\nu}, \quad \Sigma_K^{\pi\nu} = \langle \nu | \sigma_K | \pi \rangle$$

Neutron-rich isotopes: Ge - Pd

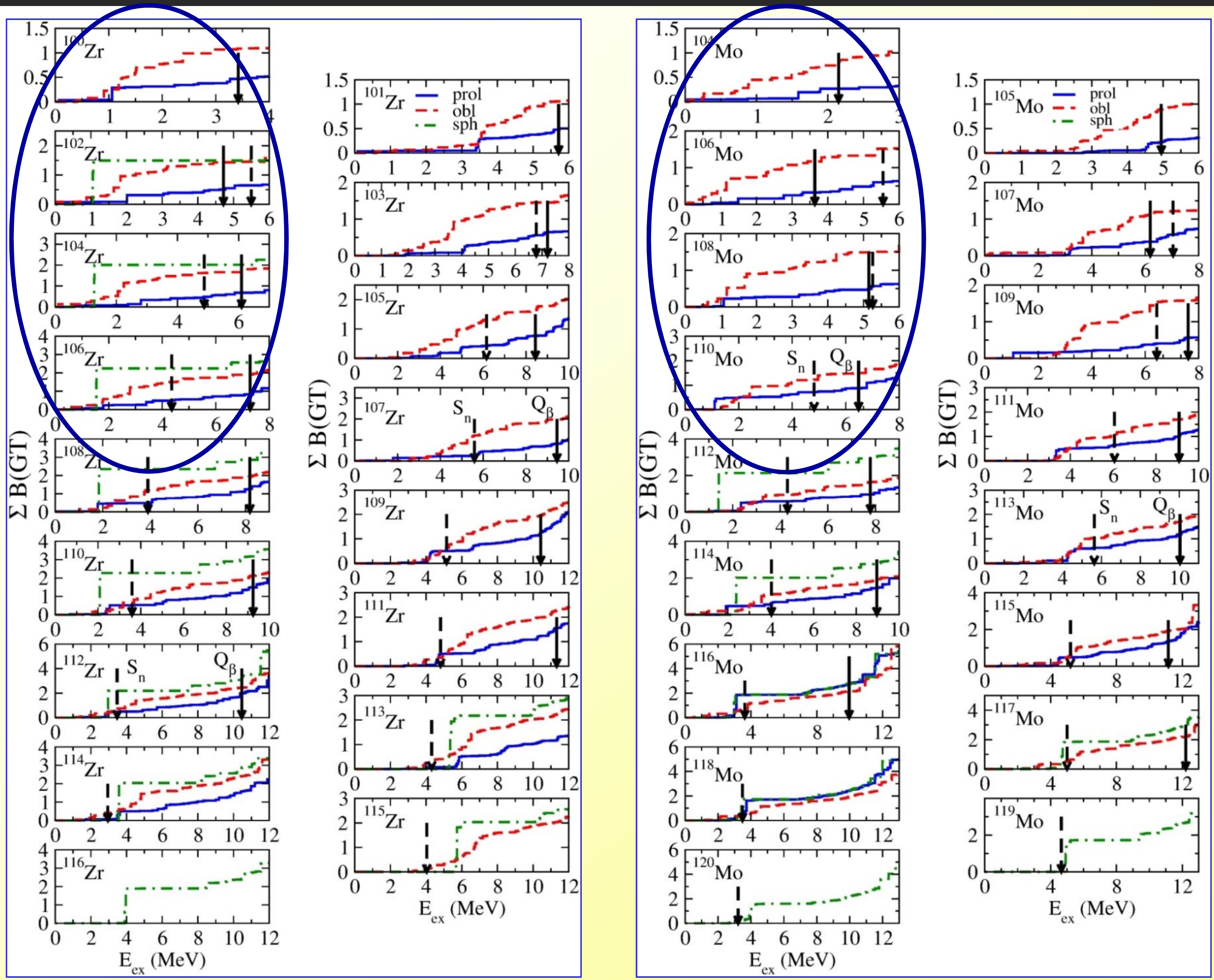




$^{80-94}$Ge, $^{86-100}$Se, $^{90-104}$Kr, $^{94-108}$Sr,
$^{100-114}$Zr, $^{104-118}$Mo, $^{110-124}$Ru, $^{114-128}$Pd

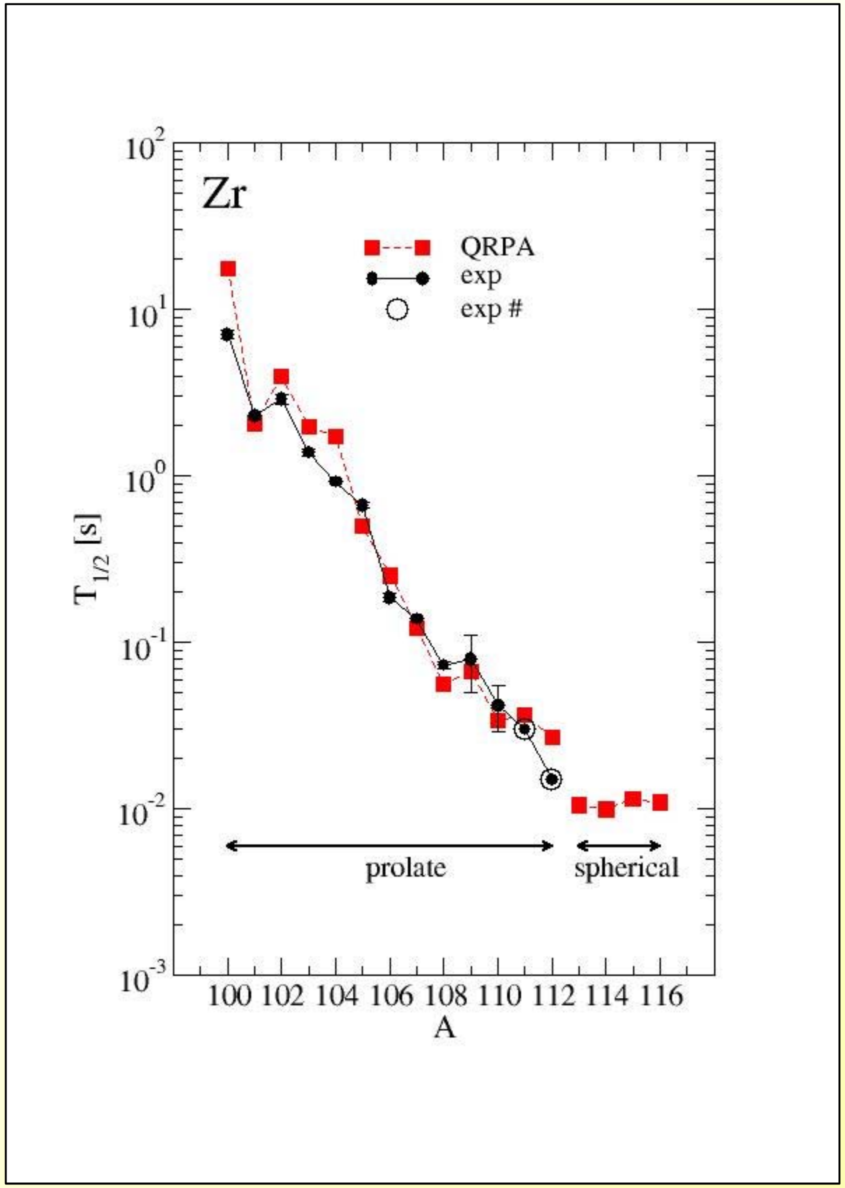
r-process: Nucleosynthesis of heavy elements. Supernovae, n-star mergers

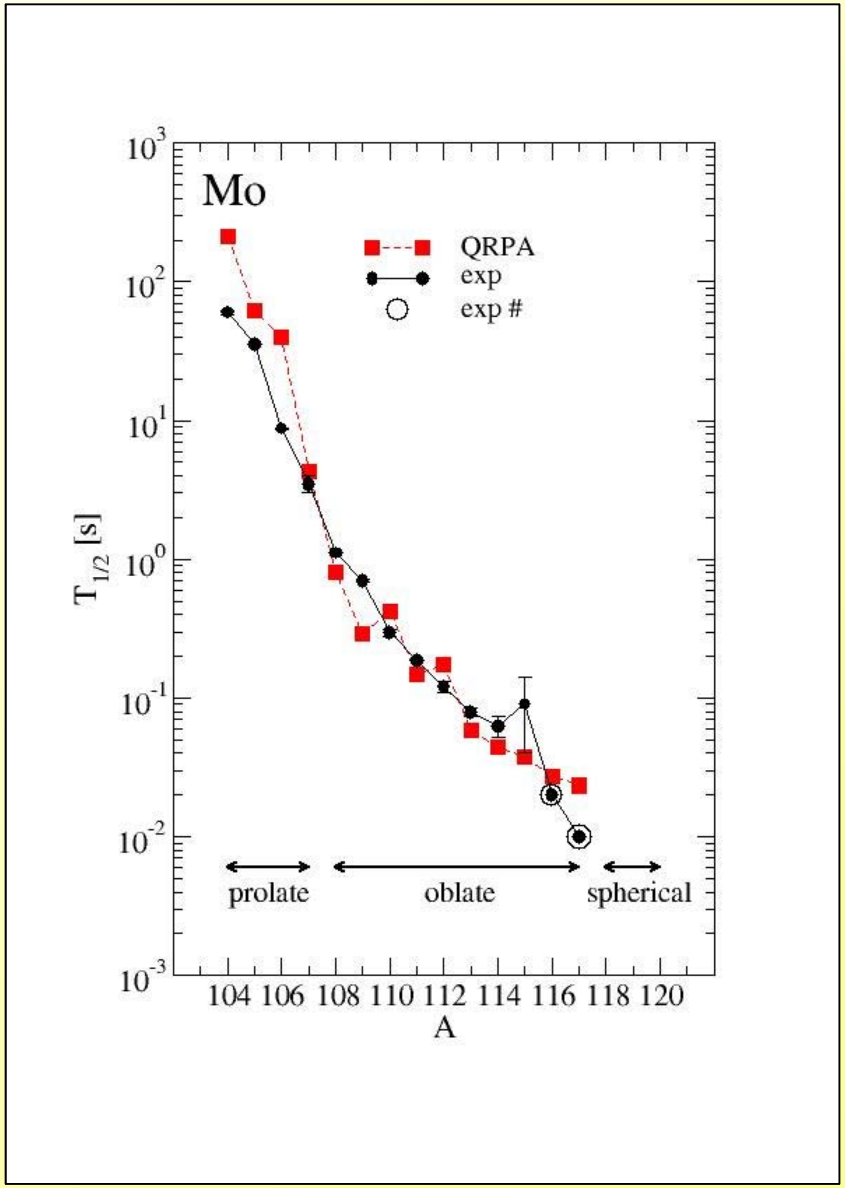
Zr-Mo B(GT)



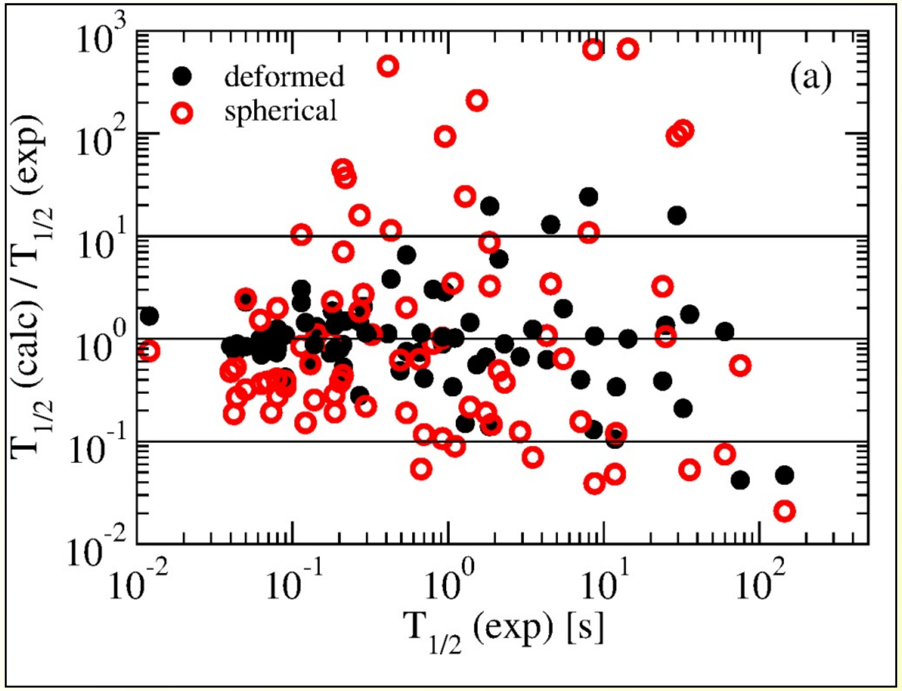
100Zr
102Zr
104Zr
106Zr
108Zr
110Zr
112Zr
114Zr
116Zr
101Zr
103Zr
105Zr
107Zr
109Zr
111Zr
113Zr
115Zr
104Mo
106Mo
108Mo
110Mo
112Mo
114Mo
116Mo
118Mo
120Mo
105Mo
107Mo
109Mo
111Mo
113Mo
115Mo
117Mo
119Mo
prol
obl
sph
Sn
Qβ
Σ B(GT)
Eex (MeV)

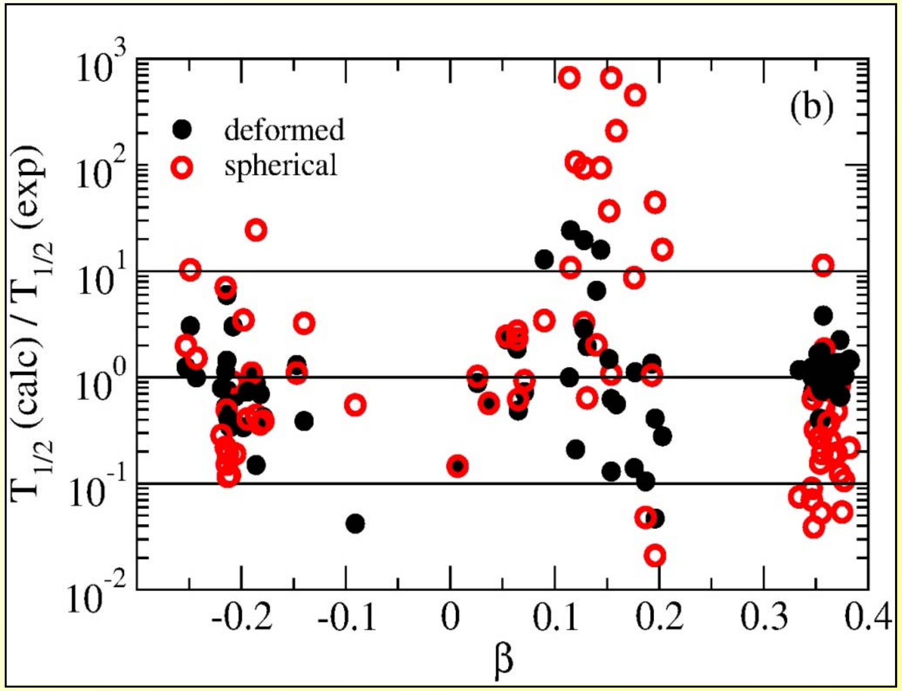
Zr-Mo Half-lives





Impact of deformation





Error analysis

$$r = \log_{10}\left[\frac{T_{1/2}(\mathrm{calc})}{T_{1/2}(\mathrm{exp})}\right]$$

Average position

$$M_r = \frac{1}{n}\sum_{i=1}^{n} r_i$$

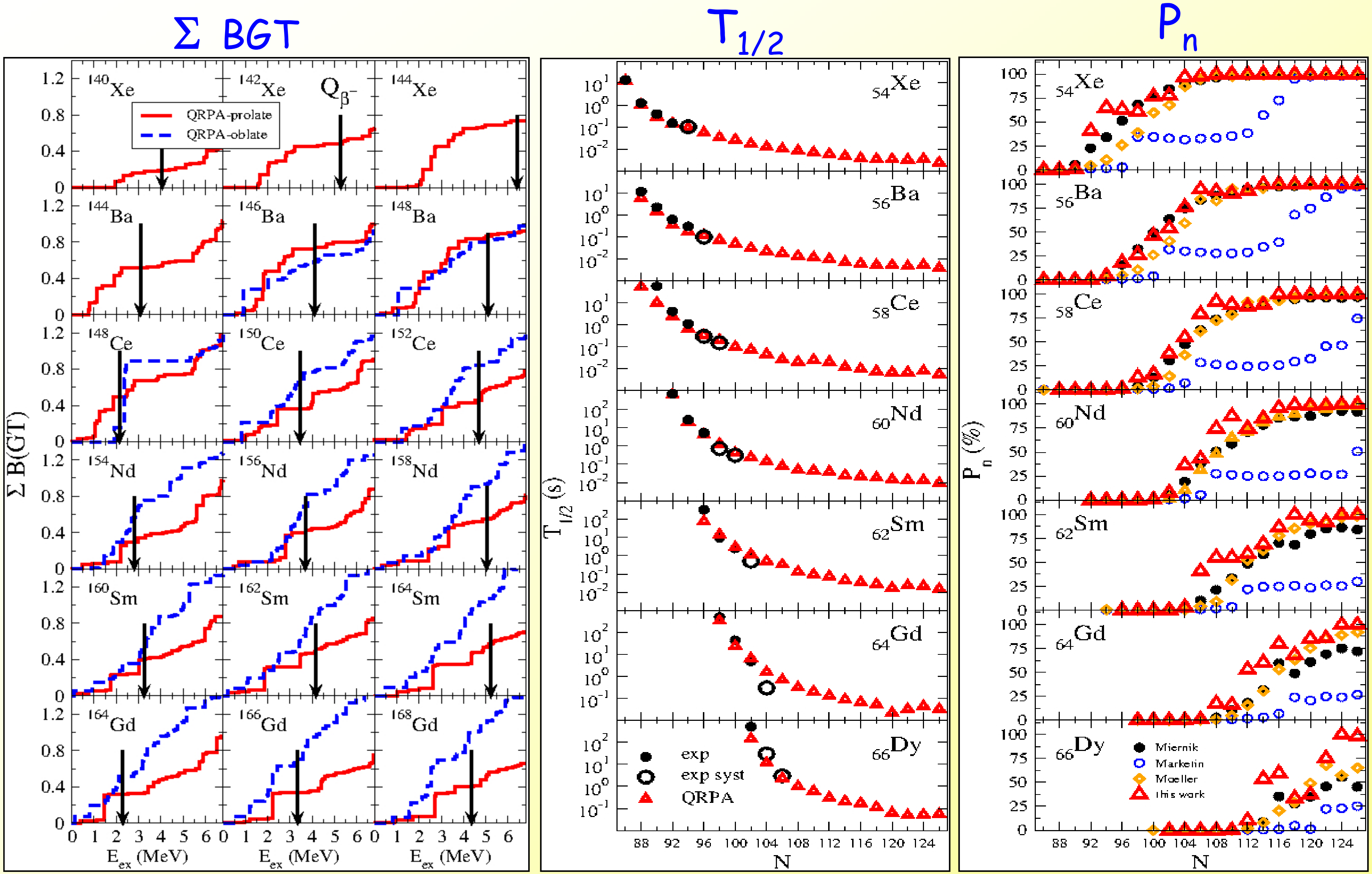
Mean square fluctuation

$$\sigma_r = \left[\frac{1}{n}\sum_{i=1}^{n}(r_i - M_r)^2\right]^{1/2}$$

		10^{M_r}	10^{σ_r}
Global	**Sph**	**1.105**	**10.213**
	def	**0.937**	**3.088**
0.25 < β < 4	sph	0.260	3.285
	def	1.062	1.518

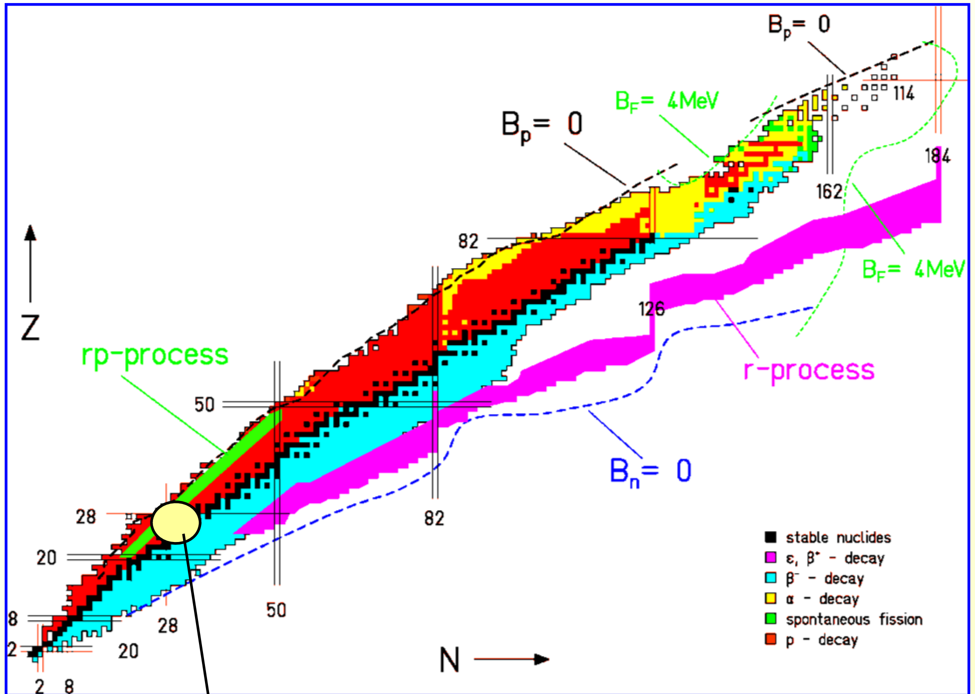
P.S. PRC 91, 044304 (2015)

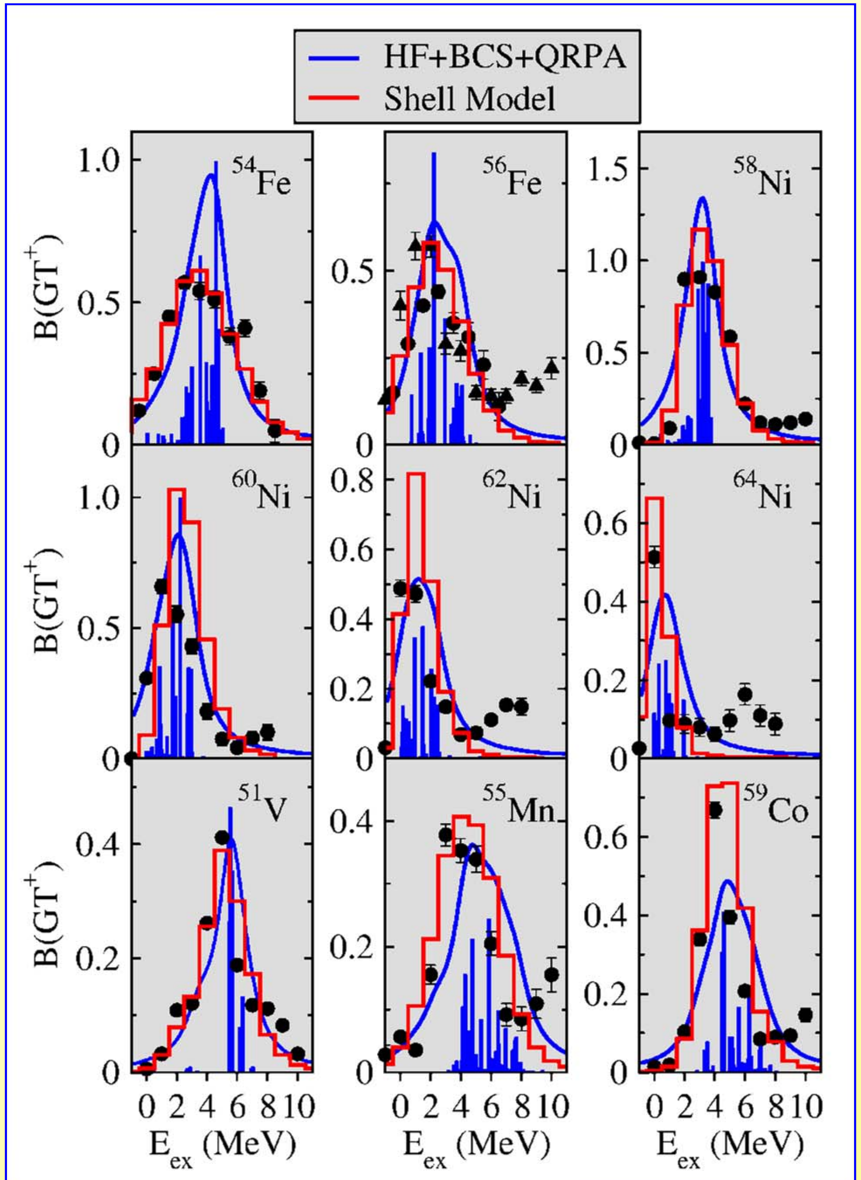
Neutron-rich isotopes: Rare-earth region



PRC 95, 014304 (2017)

Weak decay rates in pf-shell nuclei





Main constituents of stellar core in presupernovae. Comparison with :

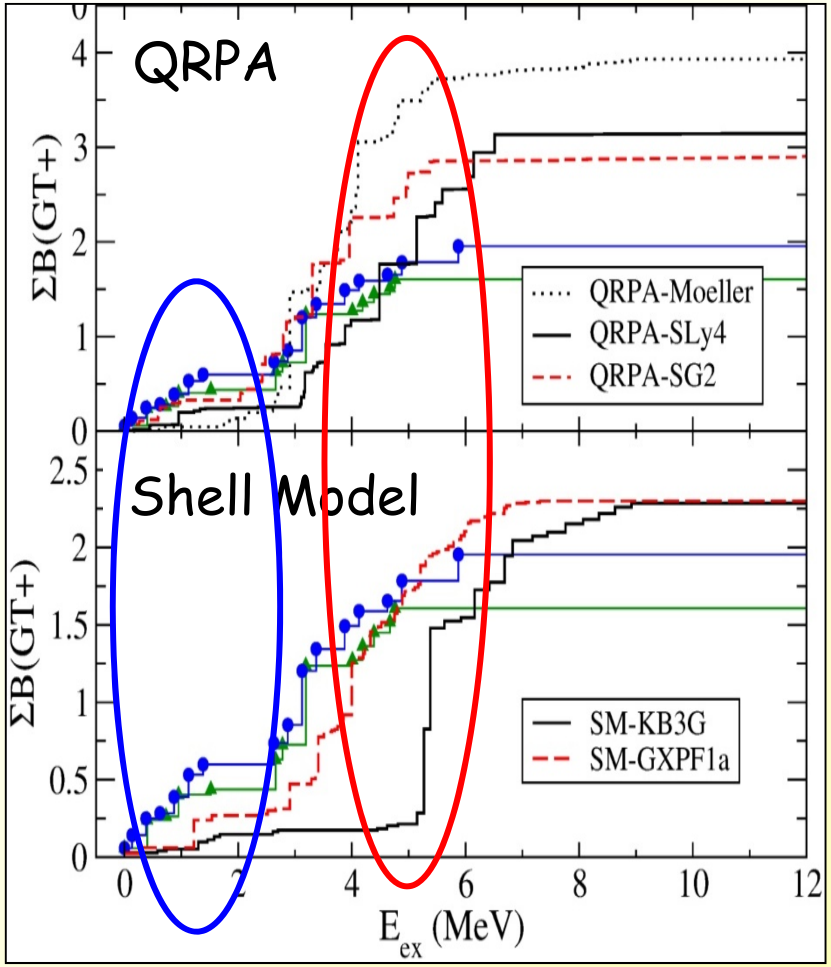
- exp. (n,p), (p,n)
- SM calculations

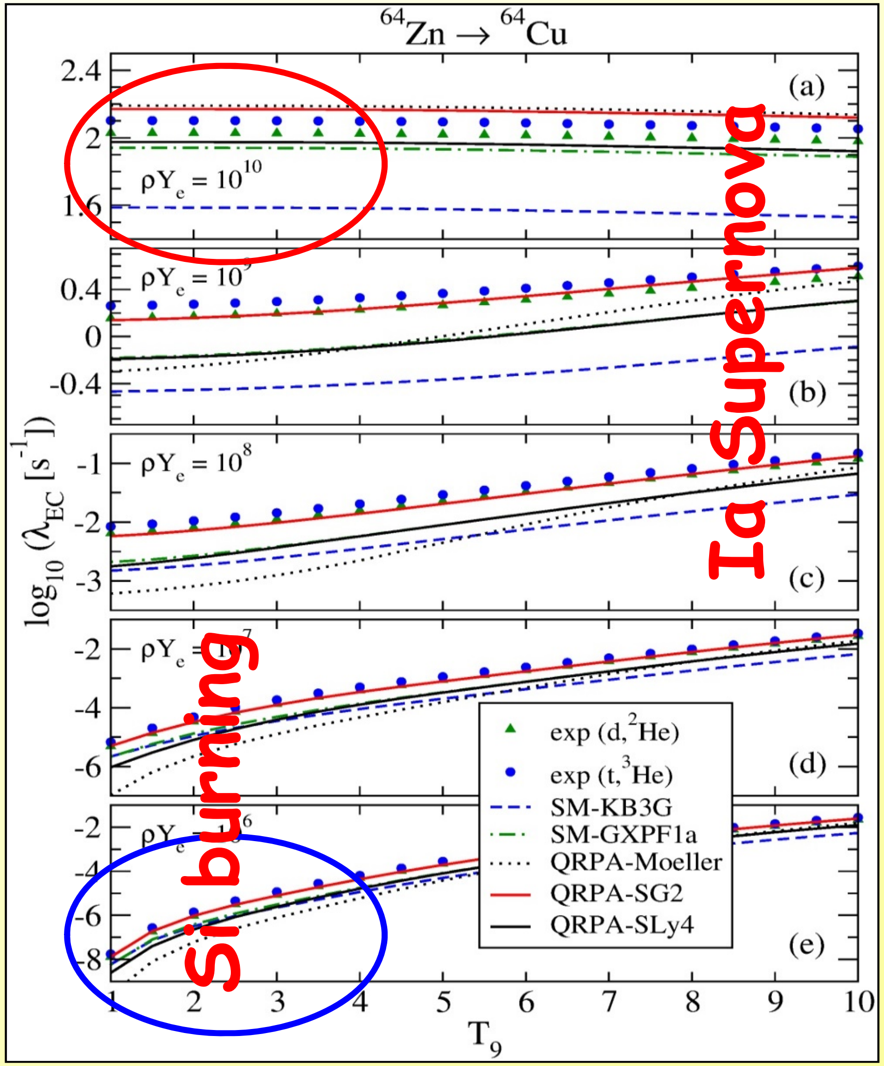
GT properties: Test of QRPA

SM: NPA 653, 439 (1999)
QRPA: NPA 716, 230 (2003

Weak decay rates in pf-shell nuclei

^{64}Zn -> ^{64}Cu



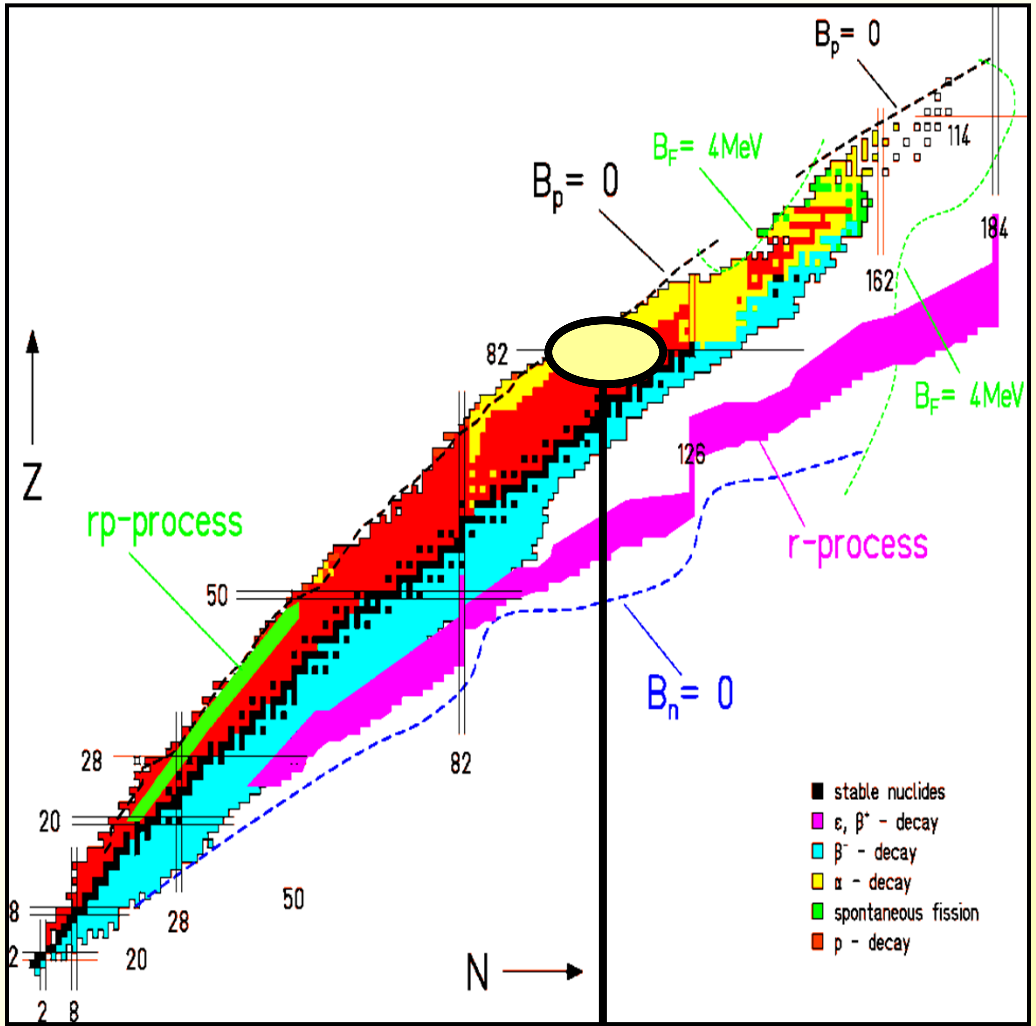


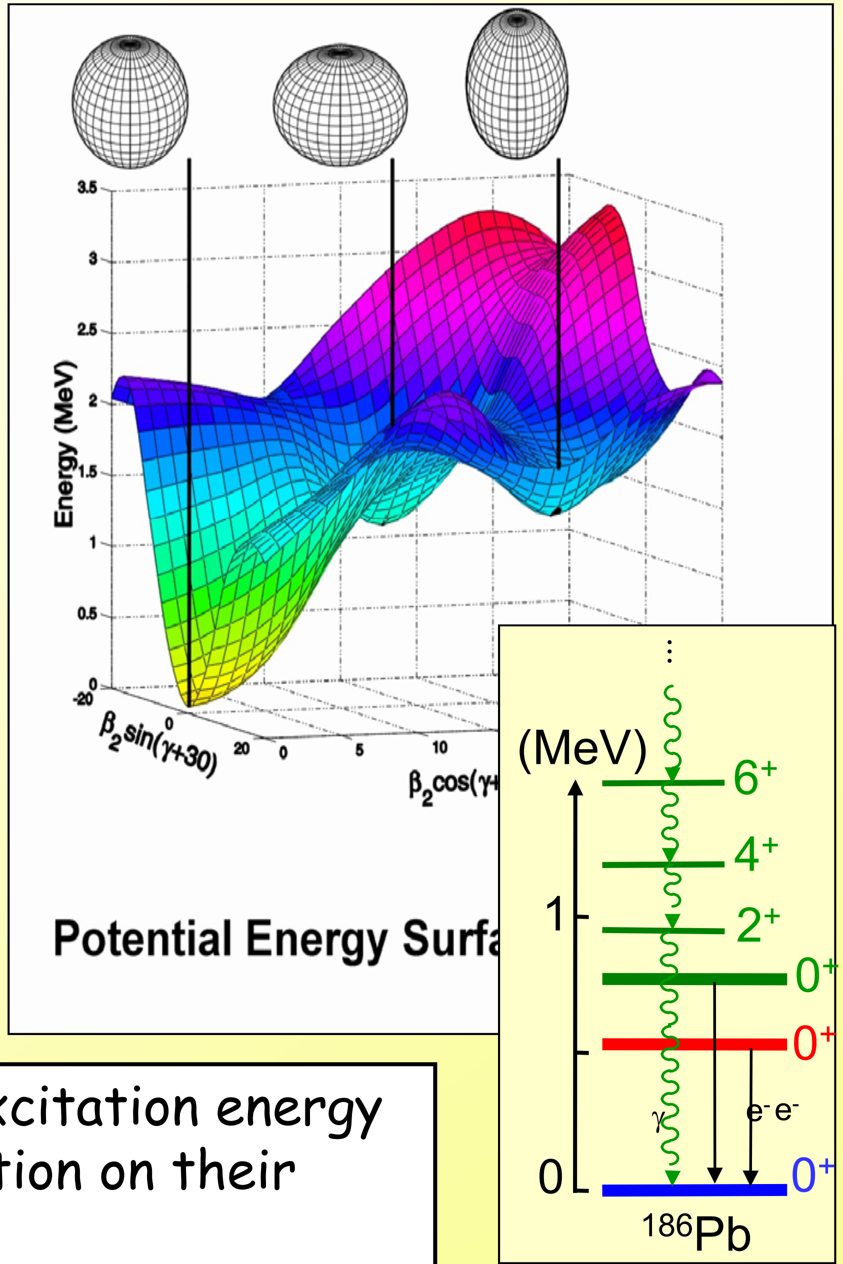
sensitive low-lying excitations (low ρ and T)

sensitive to global behavior (high ρ and T)

Cole PRC 86, 015809 (2012); P.S. PRC87, 045801 (2013); PRC93, 054309 (2016)

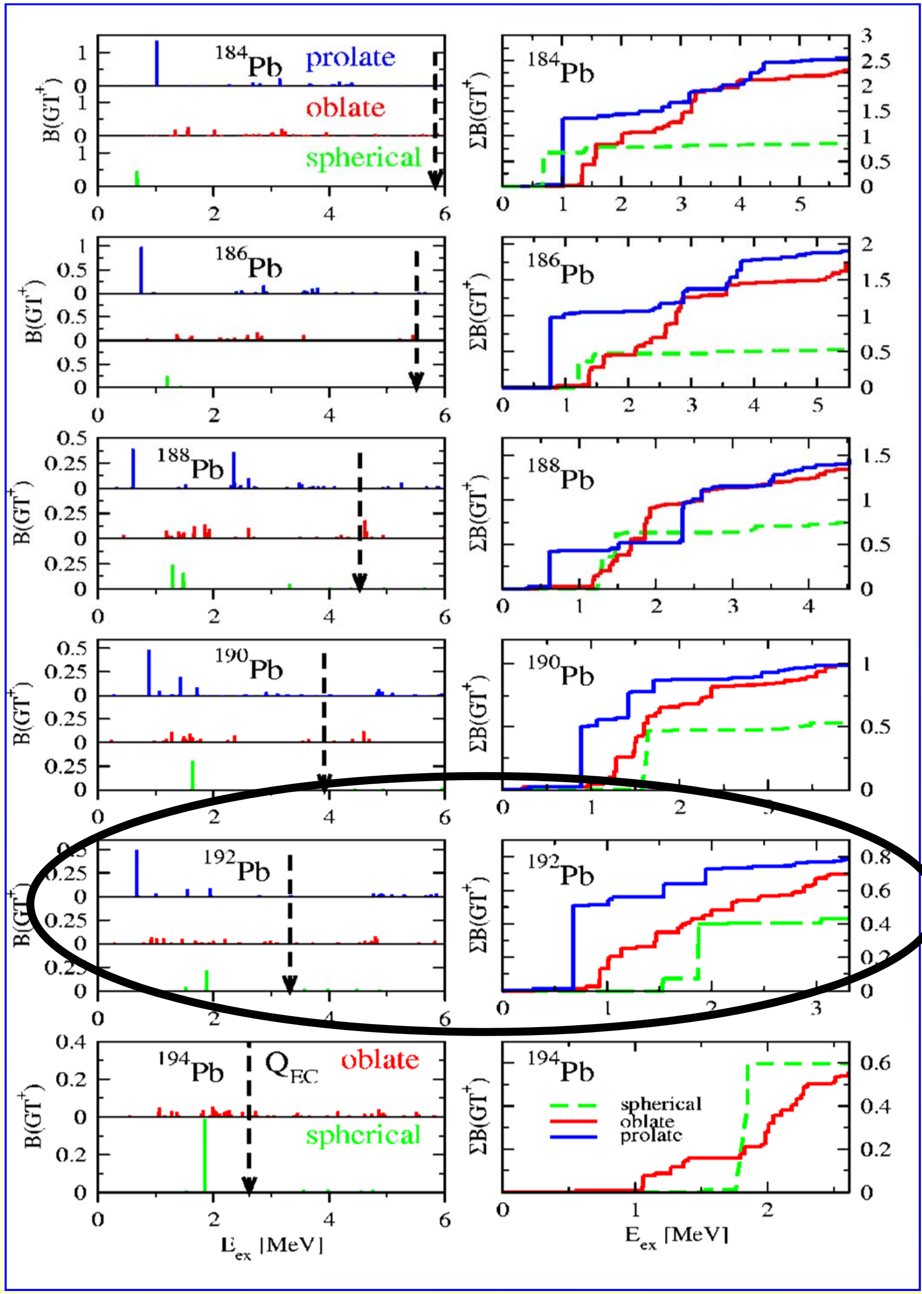
Neutron-deficient Hg, Pb, Po isotopes





- Triple shape coexistence at low excitation energy
- Search for signatures of deformation on their beta-decay patterns

Shape dependence of GTdistributions in neutron-deficient: Pb isotopes

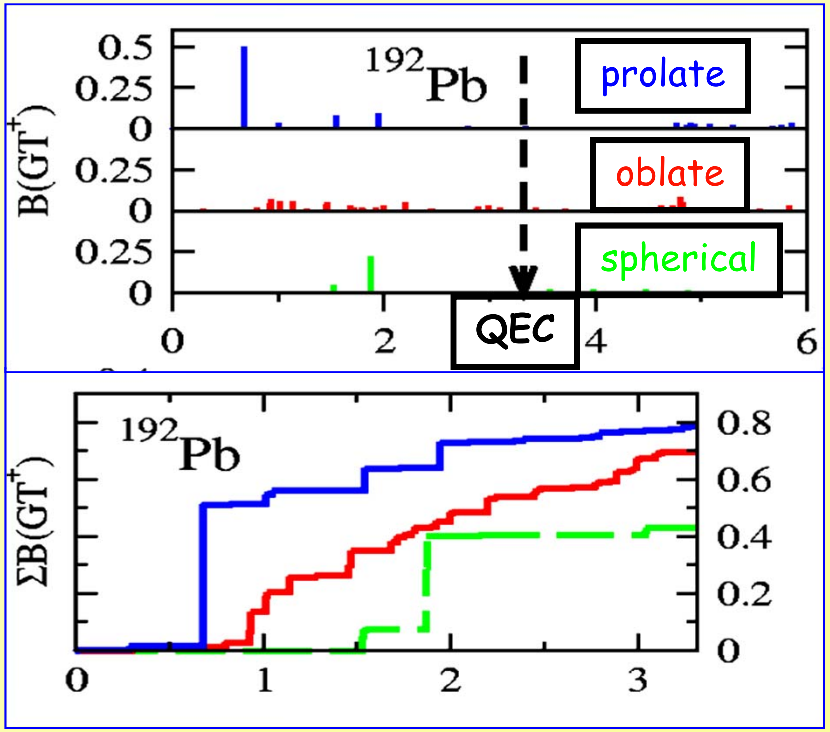


B(GT) strength distributions

- Not very sensitive to : Skyrme force and pairing treatment
- Sensitive to : Nuclear shape

Signatures of deformation

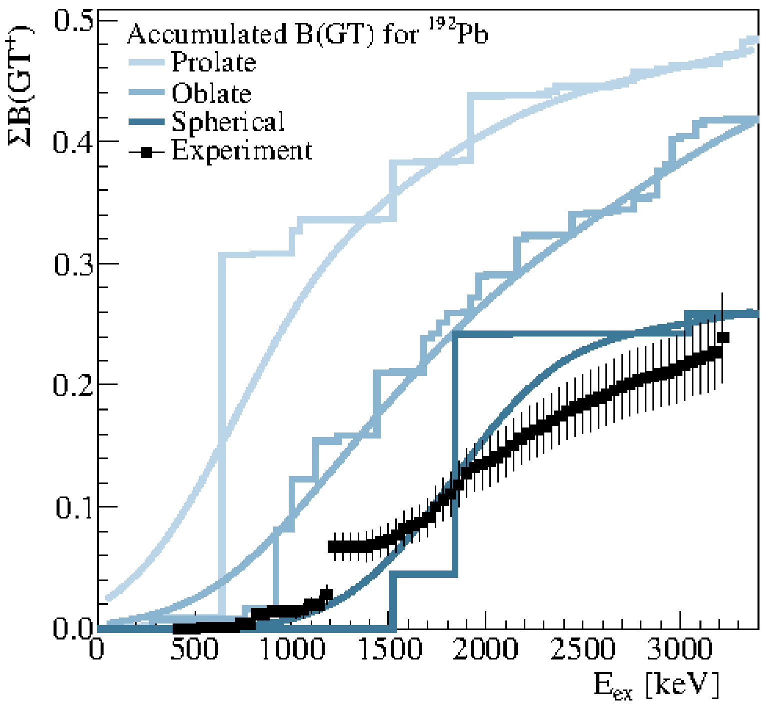
PRC 72, 054317 (2005), PRC 73, 054302 (2006)

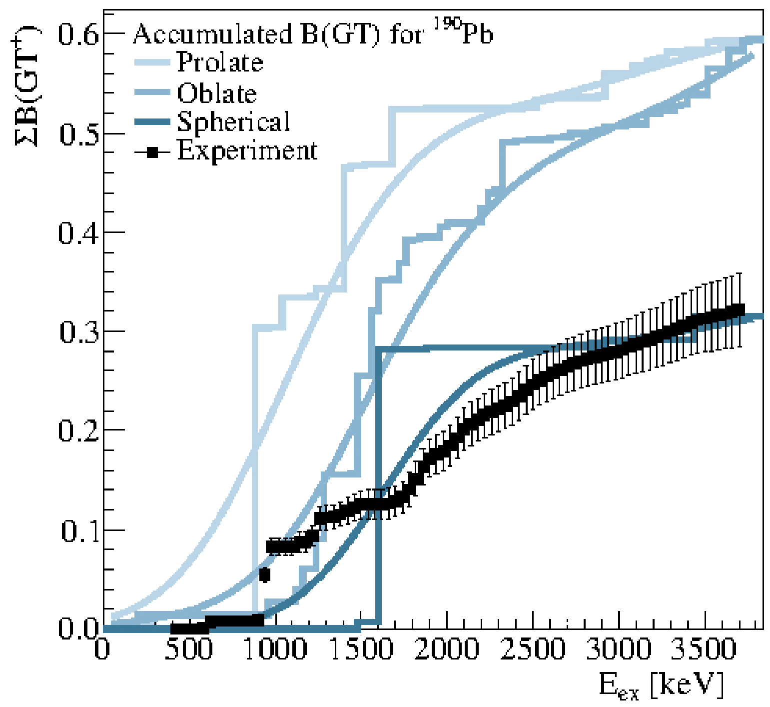


β–decay patterns: Theory vs. Experiment

^{192}Pb

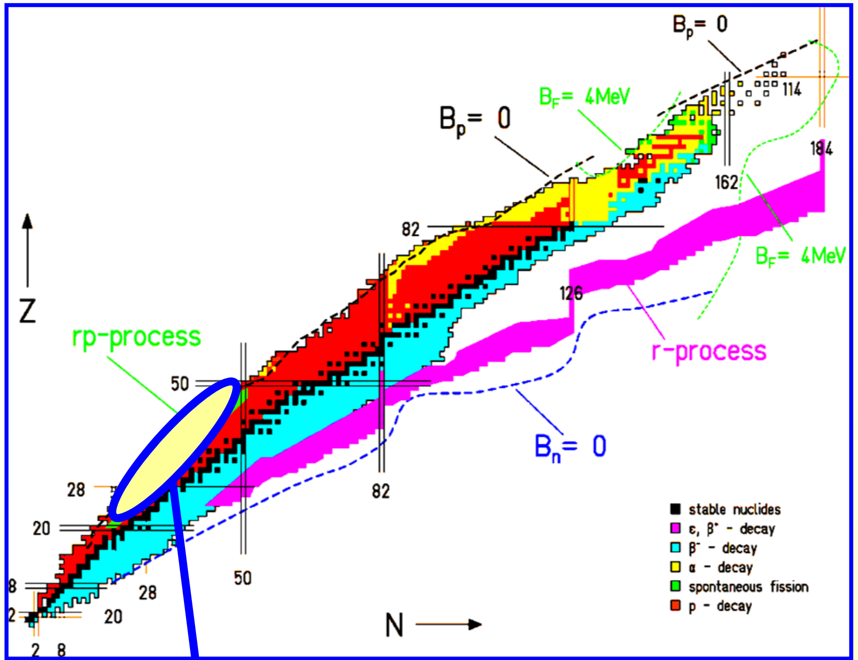
^{190}Pb

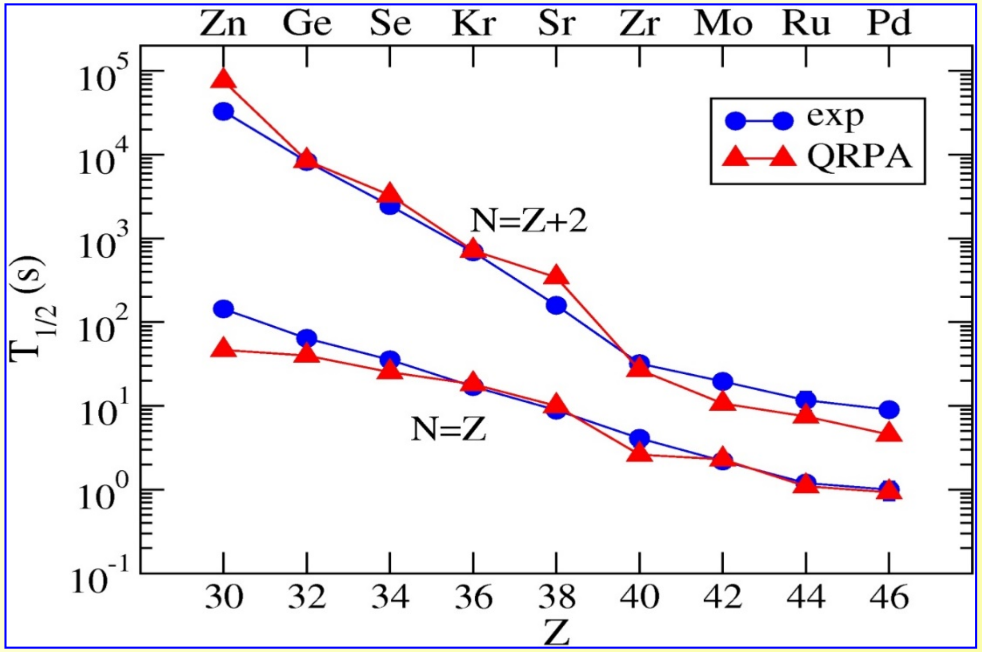




Exp: TAS (ISOLDE/CERN) PRC 92, 044321 (2015)

Medium-mass neutron-deficient isotopes





Good agreement with experiment:
Reliable extrapolations to high ρ and T

Waiting point nuclei in rp-processes

Shape coexistence

Beyond full Shell Model

$$T_{1/2}^{-1} = \frac{(g_A/g_V)^2_{\rm eff}}{6200} \sum_f \Phi^{\beta^+/EC} \left| \left\langle f \left\| \beta^+ \right\| i \right\rangle \right|^2$$

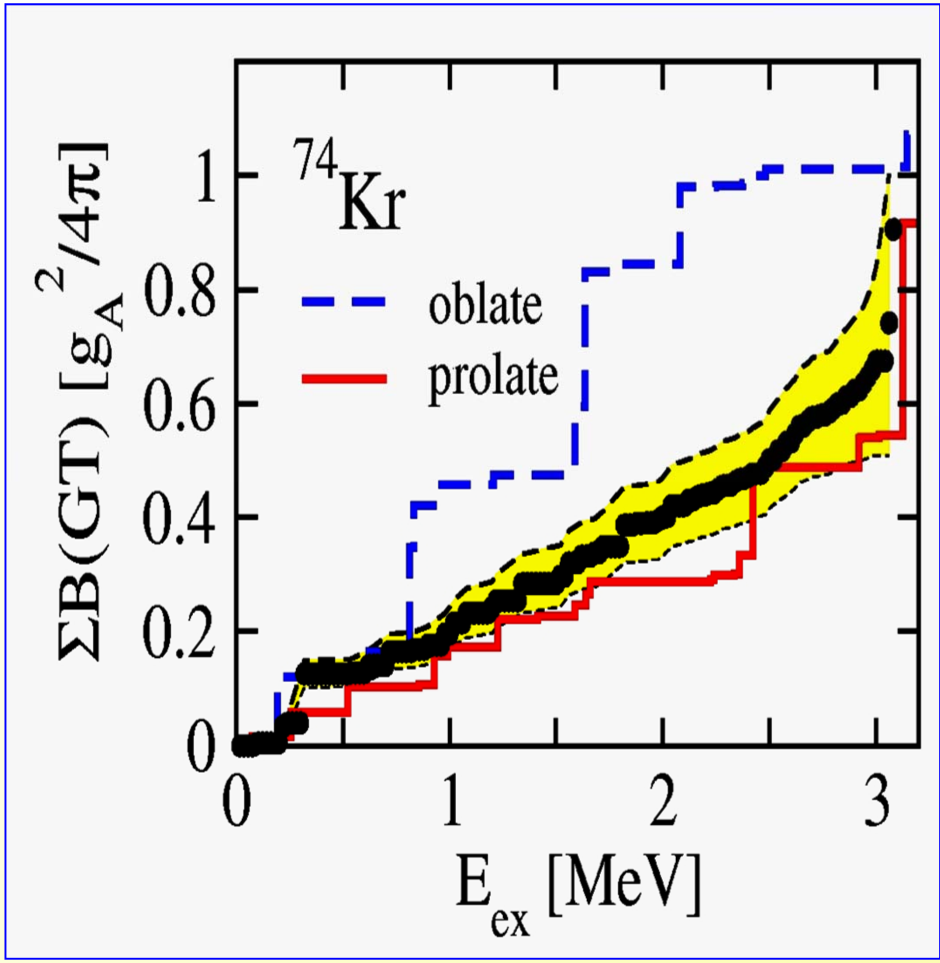
Ni,Zn,Ge,Se,Kr,Sr,Zr,Mo,Ru,Pd,Cd,Sn

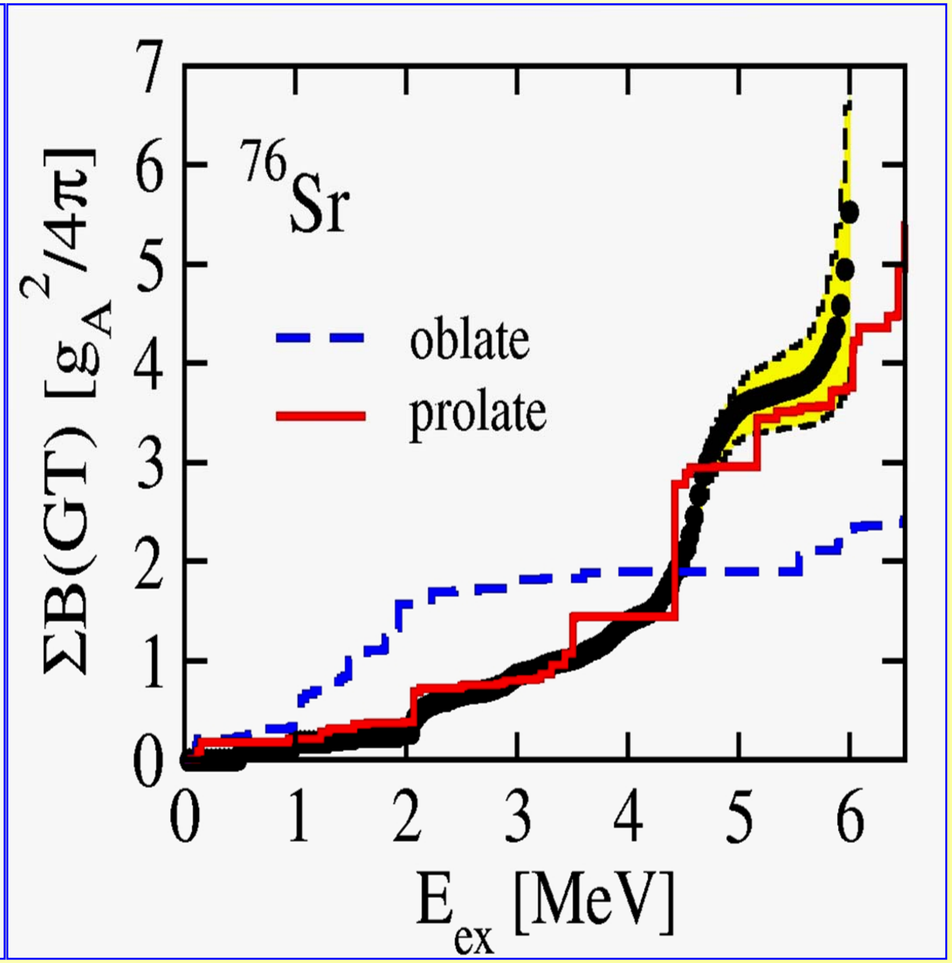
(N=Z and neighbors)

$$(g_A/g_V)_{\rm eff} = 0.74 (g_A/g_V)_{\rm bare}$$

Gamow-Teller strength: Theory and Experiment

ISOLDE: Total absorption spectroscopy



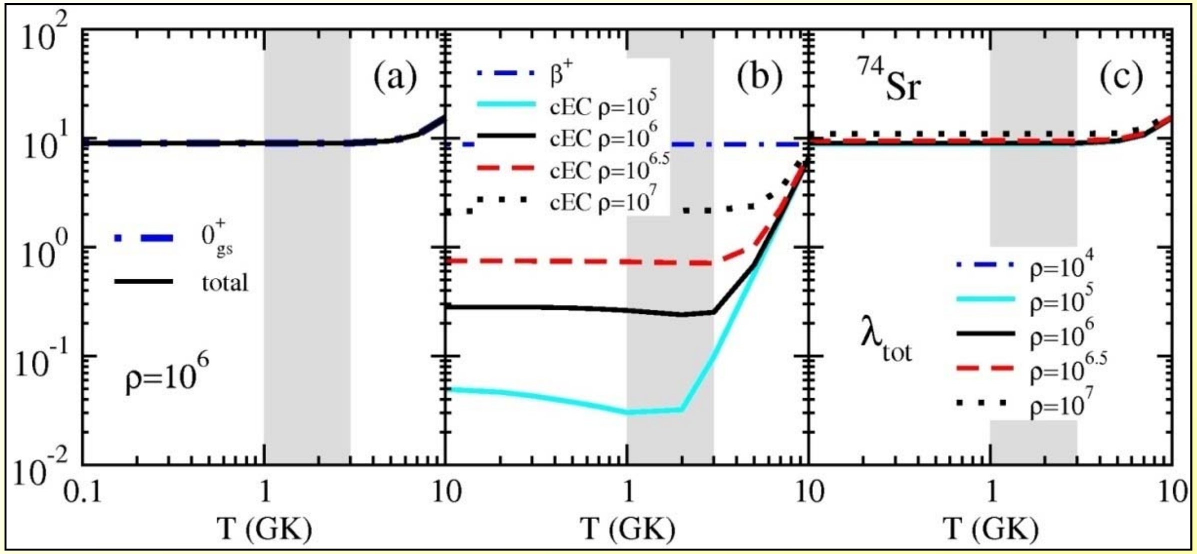


Exp: PRC69, 034307 (2004)

Exp: PRL92, 232501 (2004)

Weak decay rates in rp-process

^{74}Sr

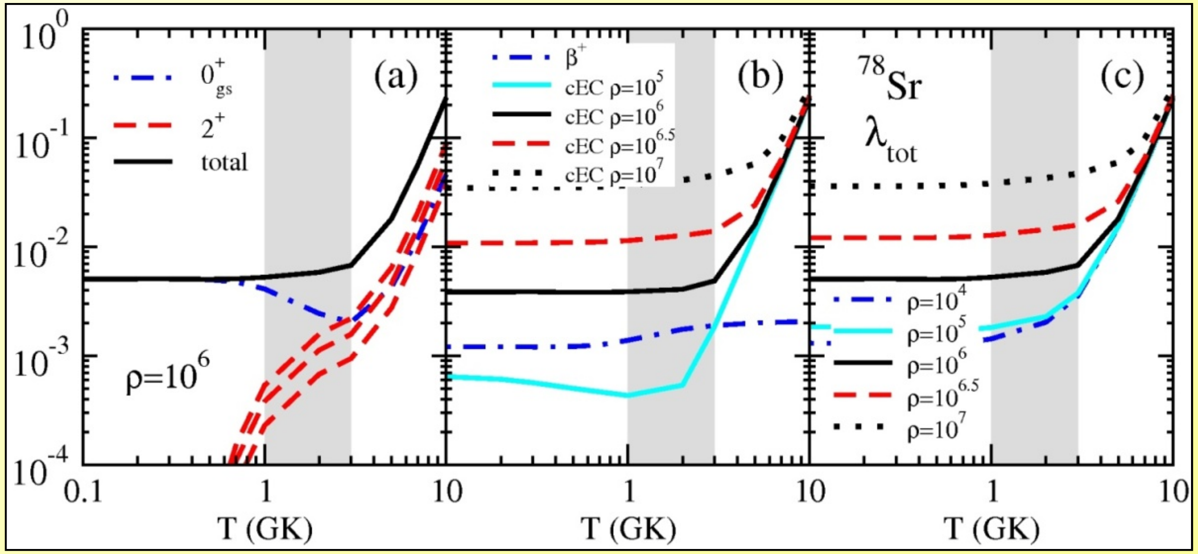


Deformed pn-QRPA

B(GT) and $T_{1/2}$: Good agreement with experiment

Competition β+/EC

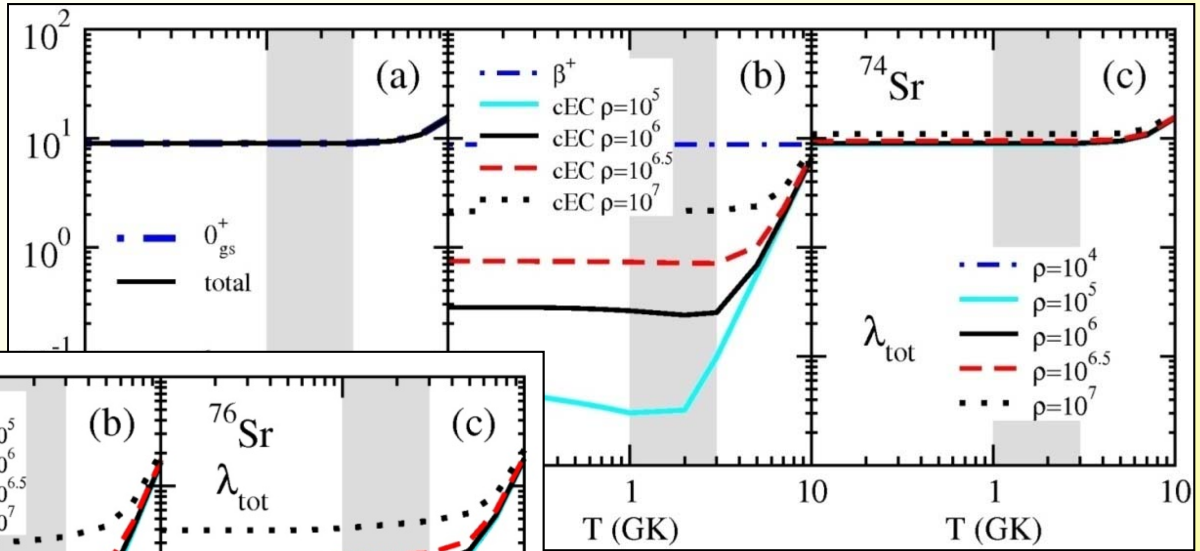
P.S. PRC83, 025801 (2011)

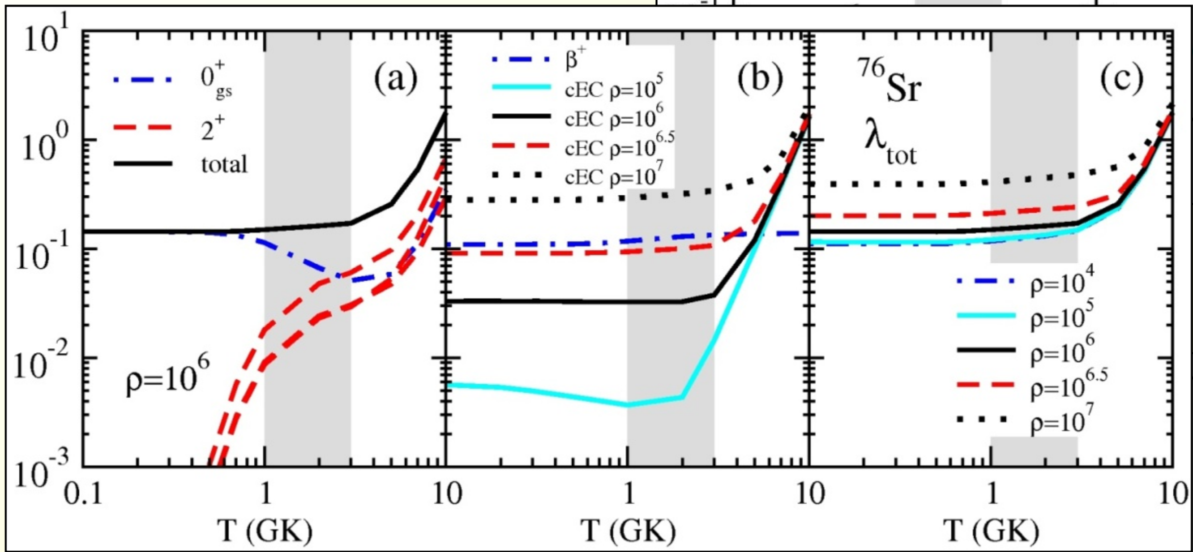


^{78}Sr

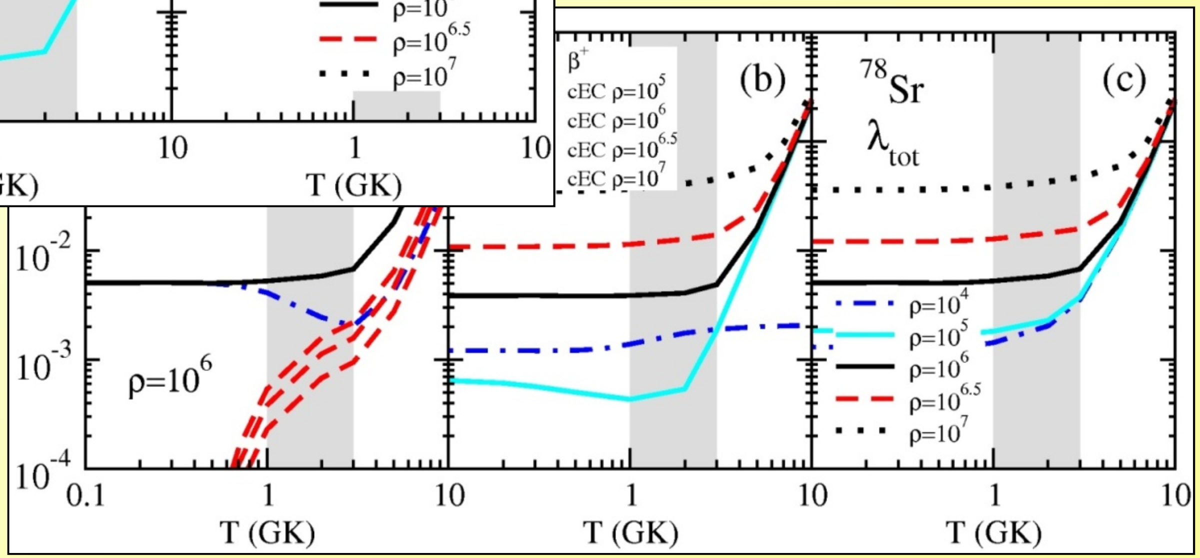
Weak decay rates in rp-process

^{74}Sr





^{76}Sr (WP)



P.S. PRC83, 025801 (2011)

^{78}Sr

Conclusions

Nuclear structure model (deformed Skyrme HF+BCS+QRPA)

- Study of decay properties in different mass regions. Astrophysical applications.
- Reproduce half-lives and main features of GT strength distributions extracted from beta-decay and/or charge exchange reactions.
- Weak-decay rates at (ρ,T) typical of astrophysical scenarios:
  - pf-shell nuclei (presupernova): EC rates from QRPA comparable quality to benchmark SM calculations.
  - Neutron-rich isotopes (r process).
  - Neutron-deficient WP nuclei (rp-process): EC/β^+ competition