Roles of Spin-dependent Transitions in Nuclei on Astrophysical Processes in Stars

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○ e-capture and β-decay rates in stellar environments

1. Weak rates in nuclei relevant to nuclear Urca processes
   ・A=23 and 25 nuclear pairs (sd-shell):
   cooling of ONeMg core of stars with 8-10$M_\odot$
   ・A=31 pair in the island of inversion and A=61 pair
   cooling of neutron star crusts

2. ・GT strength and e-capture rates in pf-shell nuclei by shell-model calculations
   ・Nucleosynthesis of iron-group elements in Type-Ia supernovae

In collaborations with Honma, Shimizu, Otsuka, Mori, and Kajino

e-capture rates

FFN: Fuller, Fowler, Newman, ApJ. 252, 715 (1982); ApJS. 48, 279 (1982)

simple shell-model

$$\lambda = \frac{\ln 2}{6146(s)} \sum_i W_i \sum_f \underline{B(\mathrm{GT}; i \to f)}$$

$$\underline{\times \int_{\omega_{\min}}^{\infty} \omega p (Q_{ij} + \omega)^2 F(Z, \omega) S_e(\omega) d\omega,}$$

$$Q_{if} = (M_p c^2 - M_d c^2 + E_i - E_f)/m_e c^2,$$

$$W_i = (2J_i + 1) e^{-E_i/kT} / \sum_i (2J_i + 1) e^{-E_i/kT},$$

$$B_{ij}(GT) = \left(\frac{g_A}{g_V}\right)^2 \frac{1}{2J_i + 1} |\langle f \| \sum_k \sigma^k t_\pm^k \| i \rangle|^2,$$

$$\rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar}\right)^3 \int_0^{\infty} (S_e - S_p) p^2 \, dp,$$

Y_e = No. electrons/No. baryons

$$S_e = \frac{1}{\exp\left(\frac{E_e - \mu_e}{kT}\right) + 1}, \qquad \mu_p = -\mu_e.$$

TABLE III. Electron chemical potential μ_e (in units of MeV) at high densities, $\rho Y_e = 10^7$–10^{10} g/cm^3, and high temperatures, $T = T_9 \times 10^9$ K.

ρY_e (g/cm^3)	T_9									
	1	2	3	4	5	6	7	8	9	10
10^7	1.200	1.133	1.021	0.870	0.698	0.534	0.404	0.310	0.244	0.196
10^8	2.437	2.406	2.355	2.283	2.192	2.081	1.952	1.808	1.653	1.493
10^9	5.176	5.162	5.138	5.105	5.062	5.010	4.948	4.877	4.797	4.708
10^{10}	11.116	11.109	11.098	11.083	11.063	11.039	11.011	10.978	10.940	10.898

As $\rho \uparrow$

$\Rightarrow S_e \uparrow$

$\Rightarrow$

$\lambda_e \uparrow$

$\lambda_\beta \downarrow$

β-decay

$$\Phi_{ij}^{\beta^-} = \int_1^{Q_{ij}} w p (Q_{ij} - w)^2 F(Z+1, w) \underline{(1 - S_e(w))}$$

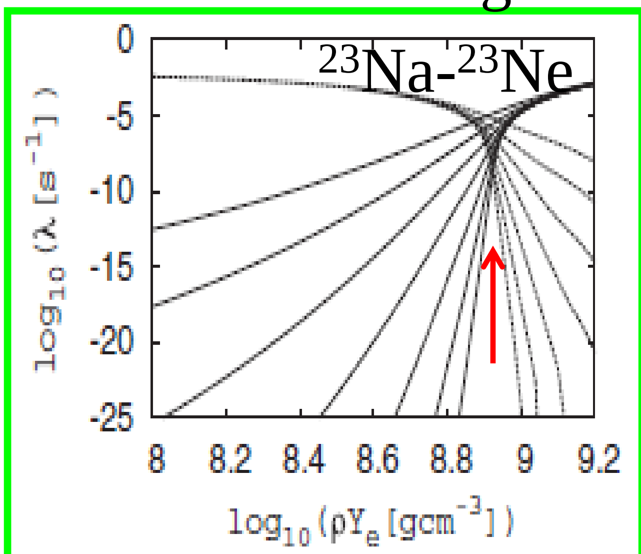
1. Weak rates for nuclei relevant to nuclear Urca processes

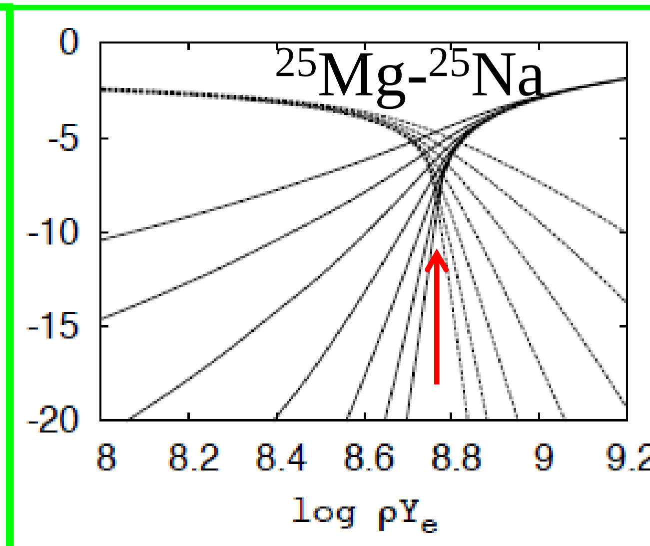
2a. Cooling of the ONeMg-core of 8-10M$_\odot$ stars by nuclear URCA processes

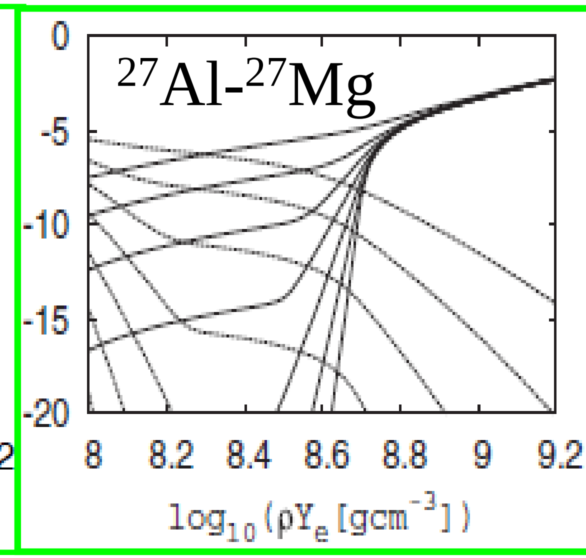
e-capture: ${}^{A}_{Z}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \nu$ rates increase as density increases

β-decay: ${}_{Z-1}^{A}Y \rightarrow {}^{A}_{Z}X + e^{-} + \bar{\nu}$ rates decrease as density increases

They occur simultaneously at certain density (URCA density) where both rates are balanced. Energy is lost from stars by emissions of ν and $\bar{\nu}$ $\rightarrow$ Cooling of stars $\rightarrow$ fate of the star after neon flash:







URCA density at $\log_{10} \rho Y_e = 8.92$, A=23 pair

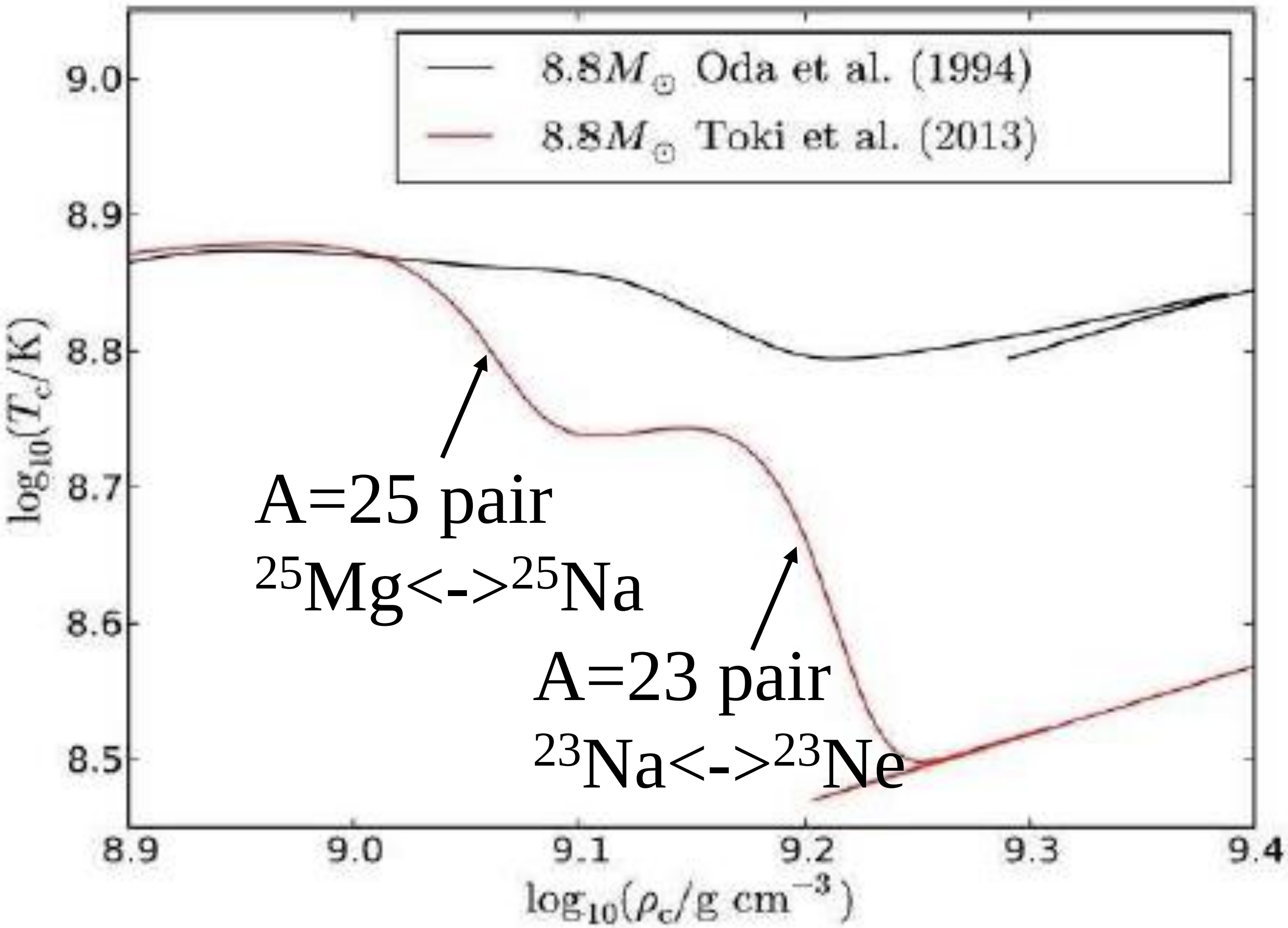
URCA density at $\log_{10} \rho Y_e = 8.78$, A=25 pair

g.s. $1/2^{+} \longleftrightarrow 5/2^{+}$ forbidden

No clear URCA density for A=27 pair

Suzuki, Toki and Nomoto, ApJ. 817, 163 (2016)

Cooling of the ONeMg core



Jones et al., ApJ 772, 150 (2013)

1b. Nuclei in the island of inversion

Cooling in neutron star crusts by nuclear URCA processes

Schatz et al, Nature 505, 65 (2014)

Table 1 | Electron-capture/β^--decay pairs with highest cooling rates

Electron-capture/β^--decay pair		Density†	Chemical potential†	Luminosity‡
Parent	Daughter*	(10^{10} g cm^{-3})	(MeV)	(10^{36} erg s^{-1})
^{29}Mg	^{29}Na	4.79	13.3	24
^{55}Ti	^{55}Sc, ^{55}Ca	3.73	12.1	11
^{31}Al	^{31}Mg	3.39	11.8	8.8
^{33}Al	^{33}Mg	5.19	13.4	8.3
56Ti	56Sc	5.57	13.8	3.5

Rates evaluated by QRPA
Shell-model evaluations are missing.

Island of inversion
Z=10-12, N = 20-22

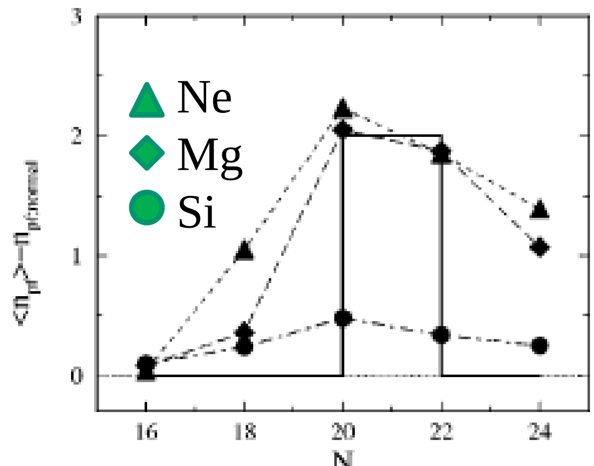
Neutron-rich Ne, Na, Mg isotopes

- Small shell-gap: $f_{7/2}$-$d_{3/2}$
- Small $E_x(2^+)$
- Large B(E2)

→ Large sd-pf admixture

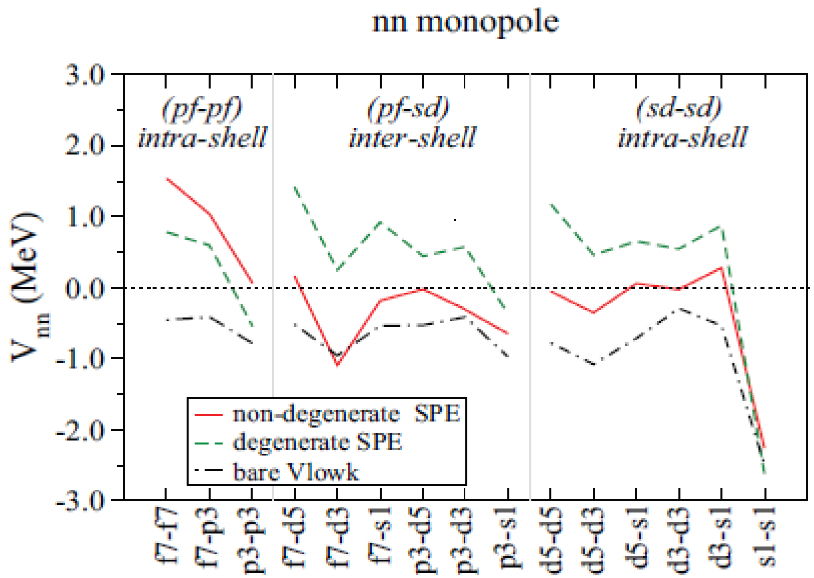
SDPF-M: Utsuno et al., PR C60, (1999)

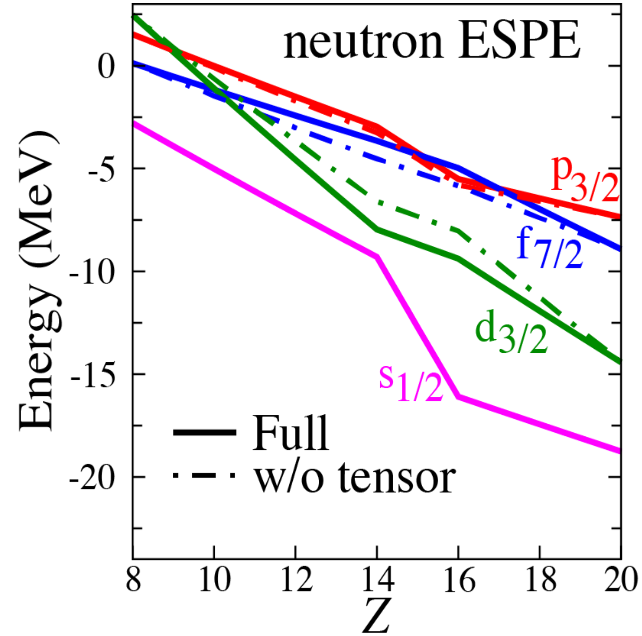
\# of nucleons in pf-shell

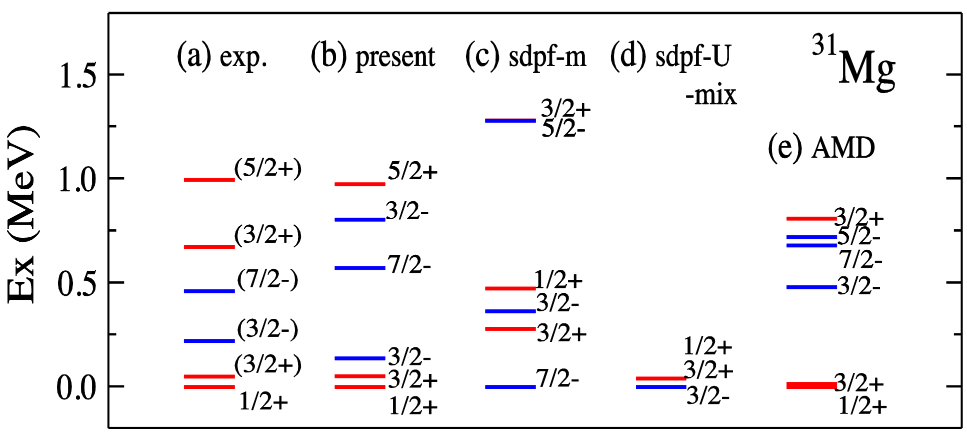


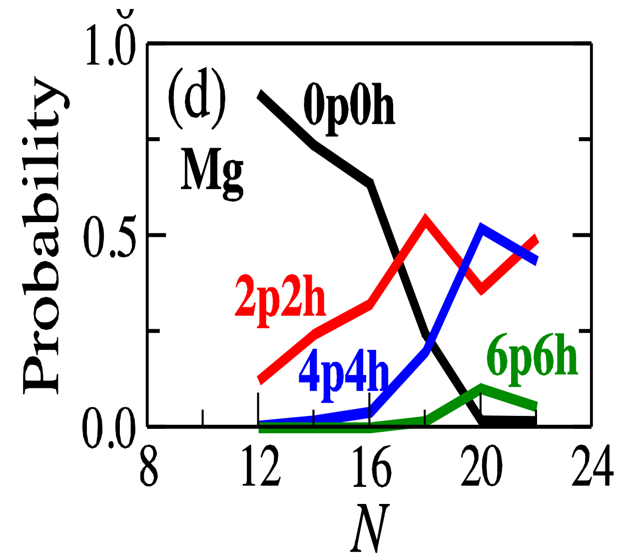
Neutron-rich isotopes in the island of inversion by EKK-method starting from chiral EFT interaction N^3LO+3N (FM)

Tsunoda, Otsuka, Shimizu, Hjorth-Jensen, Takayanagi and Suzuki, PRC 95, 021304(R) (2017)



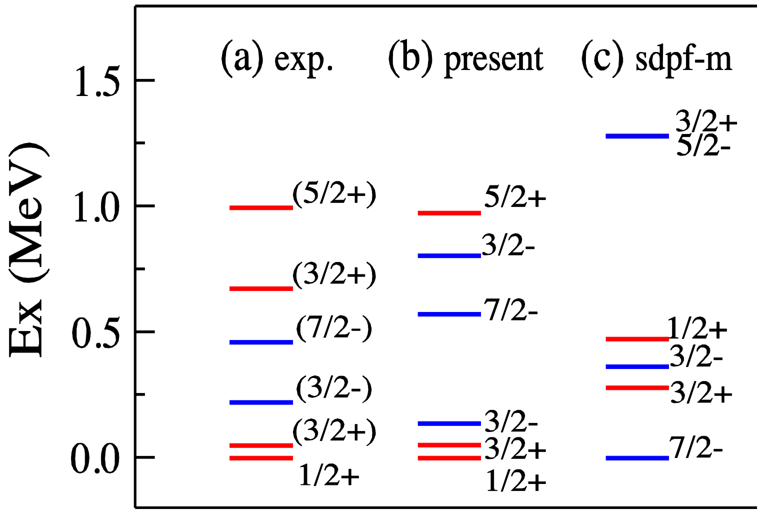


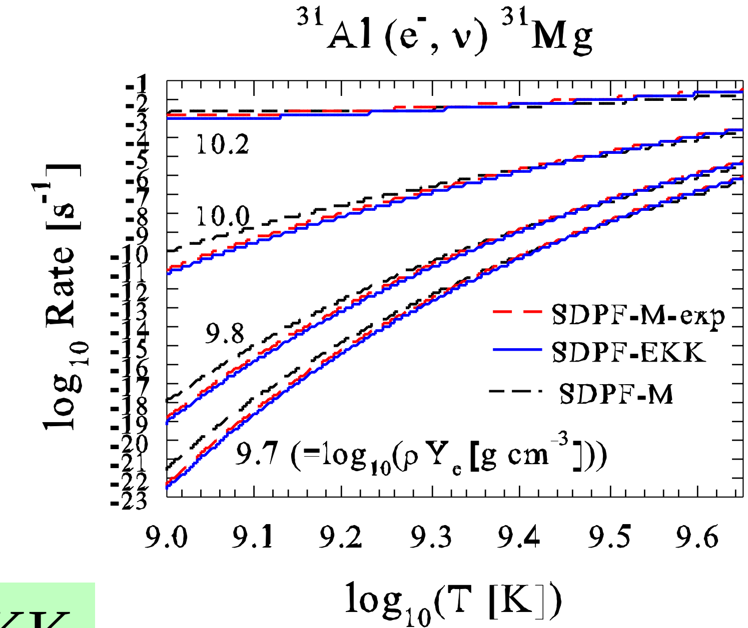




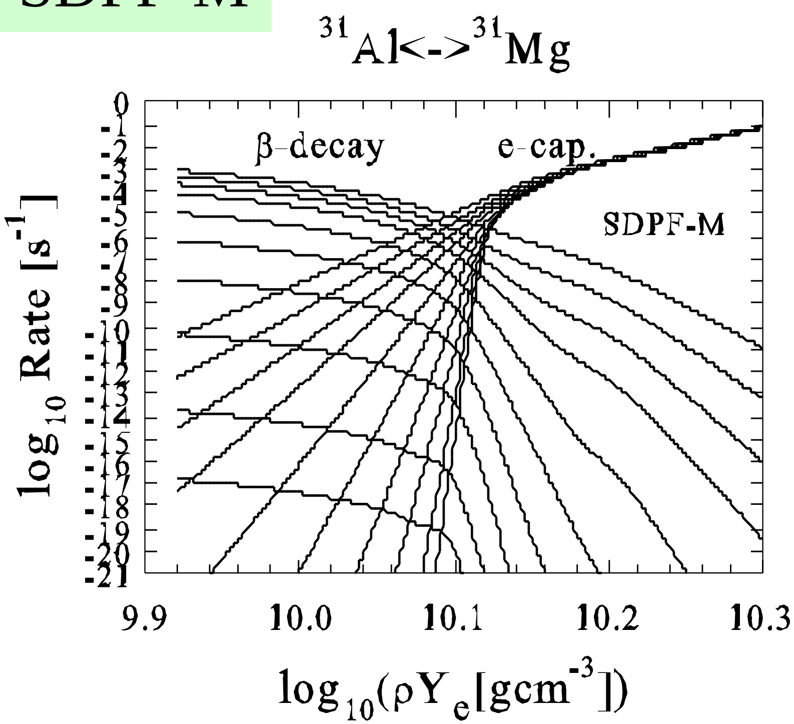
2p-2h+4p-4h

^{31}Mg

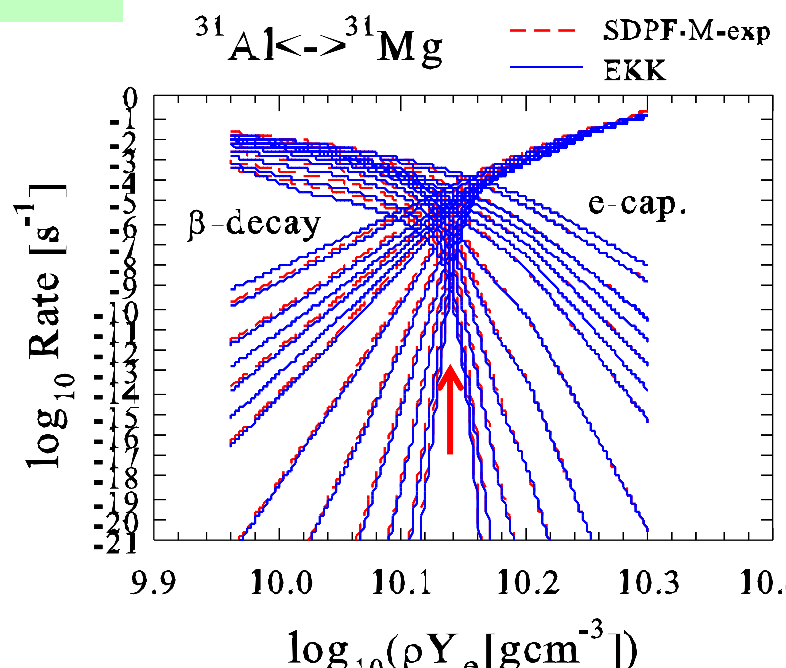




SDPF-M



EKK



1c. A=61 nuclear pair

β Decay of ^{61}V and its Role in Cooling Accreted Neutron Star Crusts

Ong et al. PHYSICAL REVIEW LETTERS 125, 262701 (2020)

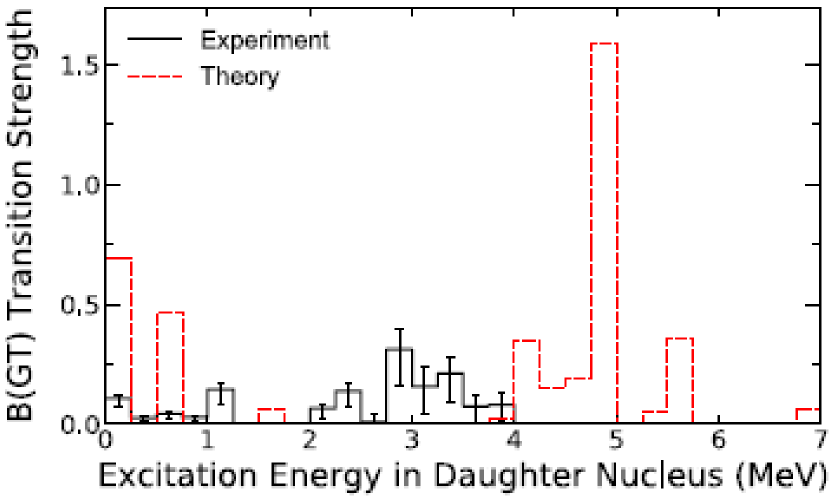


FIG. 2. B (GT) strength for the β decay of ^{61}V as a function of excitation energy in the daughter nucleus, deduced from the γ-ray data from this work (solid black line) and predicted by QRPA-fy (red, dashed line). Note that γ-ray data can only provide the strength function up to the neutron separation energy of 3.9 MeV.

^{61}V (g.s.) -> ^{61}Cr (g.s.)

Exp. log ft =5.5$\pm$0.2

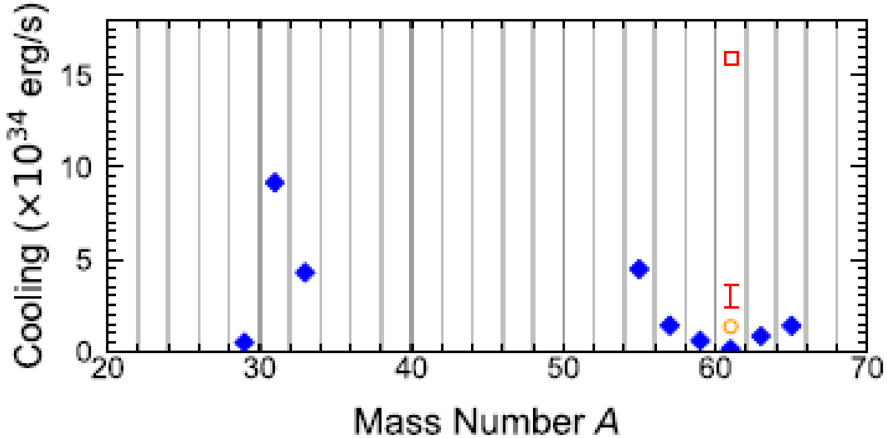
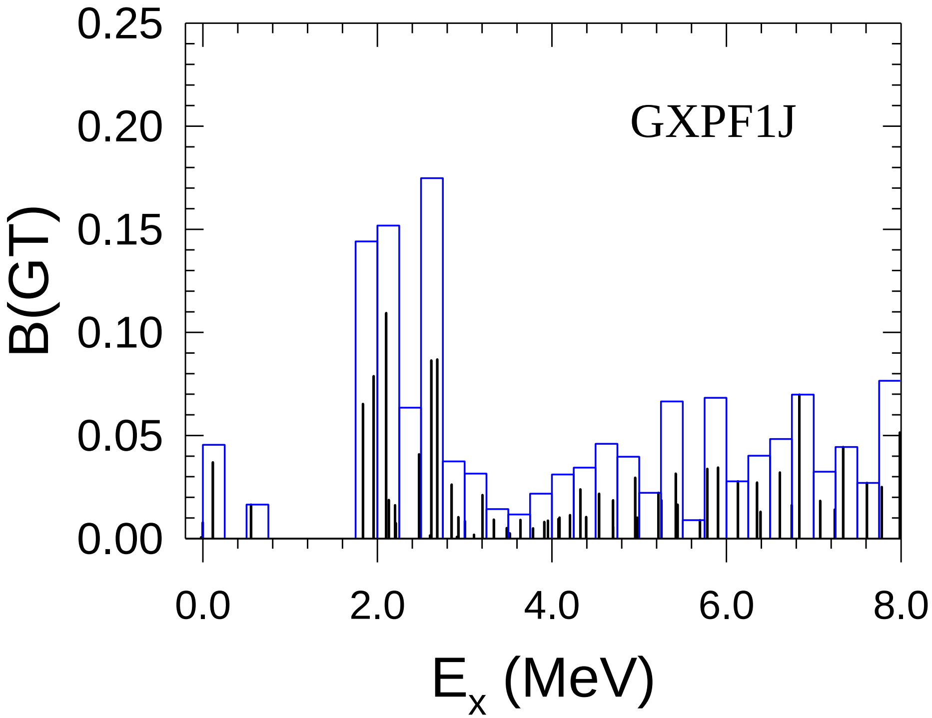
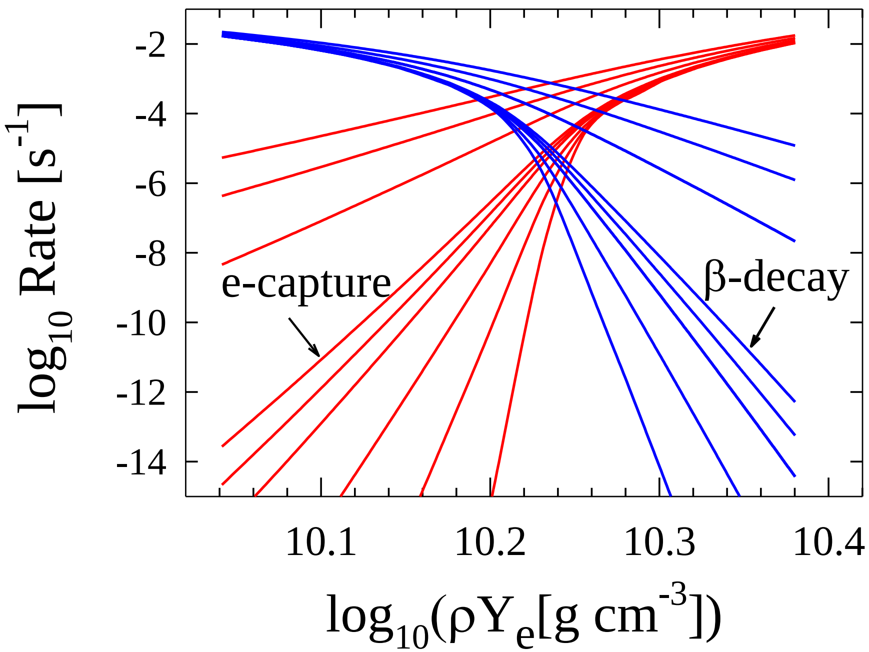


FIG. 3. The neutrino cooling contribution from individual mass chains for a neutron star crust made from rp-process ashes [14]. Predictions based on QRPA-fy (blue filled diamonds) are shown for the strongest cooling chains. For $A = 61$, we also show the QRPA-fy prediction when assuming the predicted 10 keV daughter state in ^{61}Cr populated by the β decay of ^{61}V is in fact the ground state (red open square, see text for more discussion). The $A = 61$ cooling rates based on experimental transition strengths are shown without the contribution from the ^{61}Cr-^{61}V Urca pair Letter (orange circle) and with the new data on ^{61}Cr-^{61}V from this Letter (red error bar). Results shown are for a neutron star radius $R = 12$ km and a temperature $T = 0.5$ GK and will scale with R^2T^5 for different physical parameters.

$^{61}V \rightarrow {}^{61}Cr$



$^{61}Cr \leftrightarrow {}^{61}V$



g.s. <-> g.s.

$3/2_1^- \rightarrow 5/2_1^-$: log ft = 5.68

Cf. Exp. log ft =5.5±0.2
QRPA log ft =4.35

2a. GT strengts in pf-shell and e-capture rates at stellar environmemts

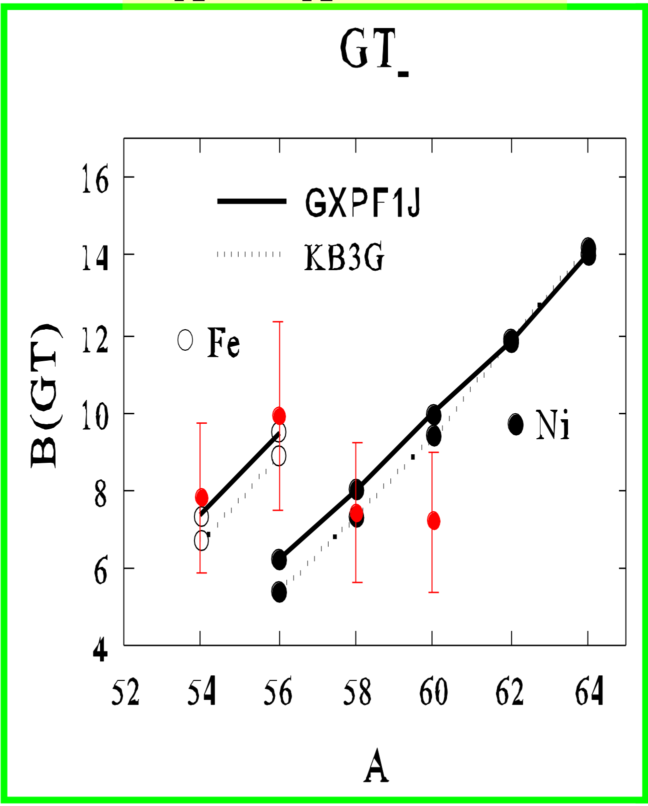
GXPF1: Honma et al., PR C65 (2002); C69 (2004); A=47-66

KB3: Caurier et al., Rev. Mod. Phys. 77, 427 (2005)

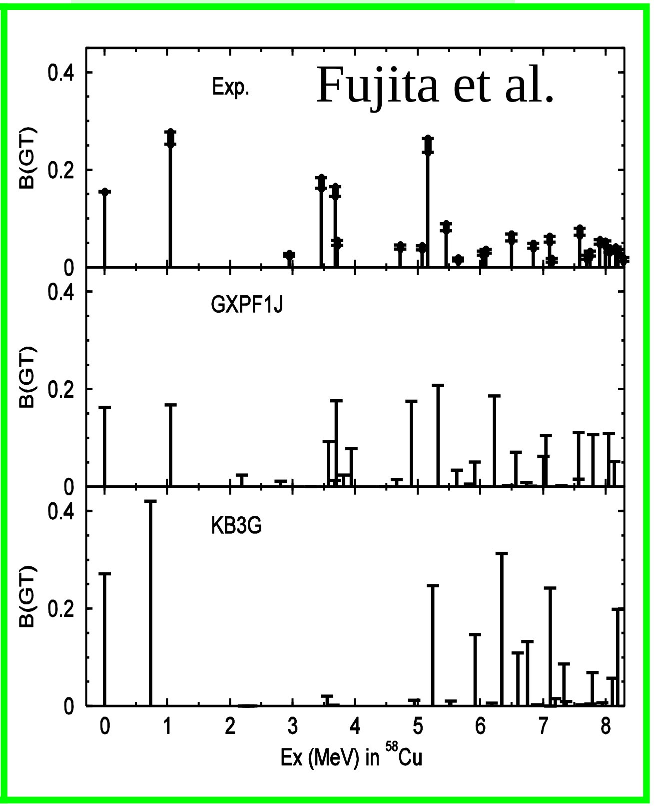
KB3G A = 47-52 G-matrix (KB) + monopole corrections

- **Spin properties of pf-shell nuclei are well described**

g_A^{eff}/g_A^{free}=0.74

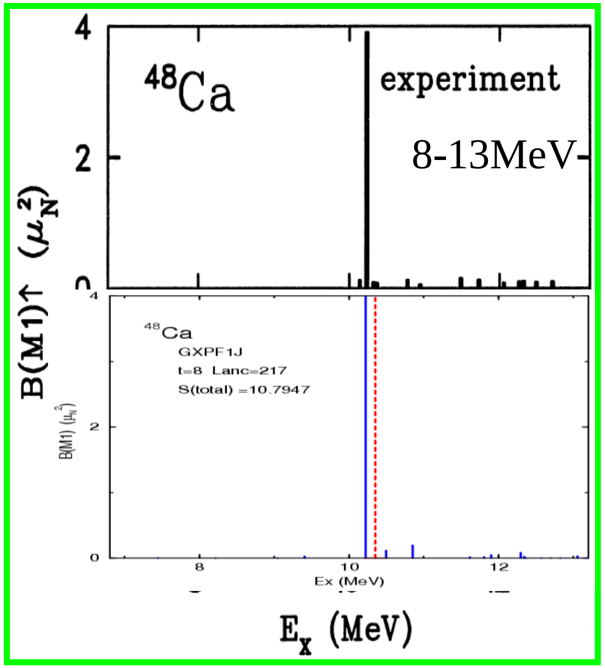


B(GT-) for ^{58}Ni

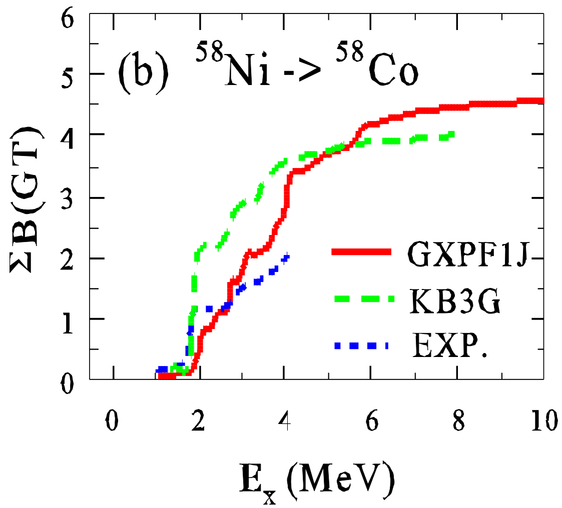


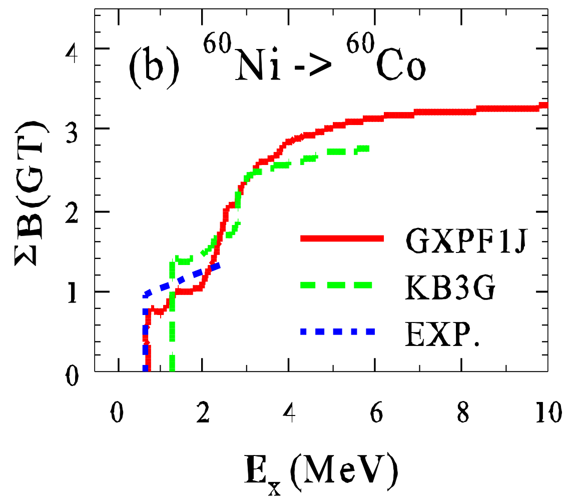
M1 strength (GXPF1J)

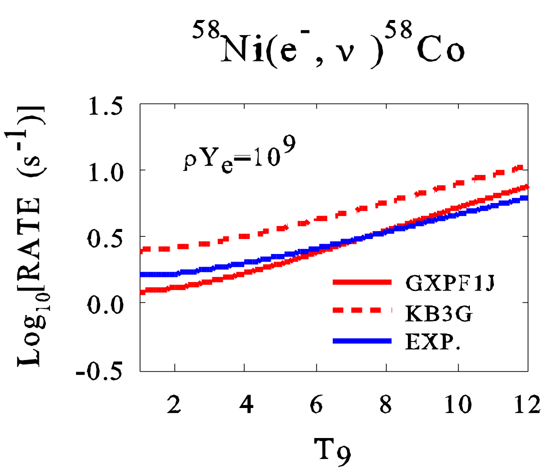
g_S^{eff}/g_S=0.75±0.2

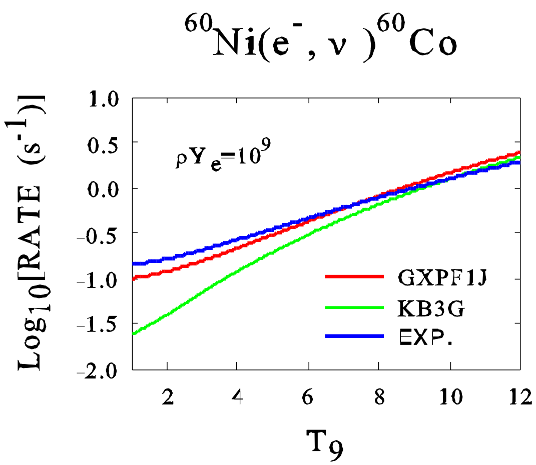


B(GT$_+$) and e-capture rates for ^{58}Ni and ^{60}Ni







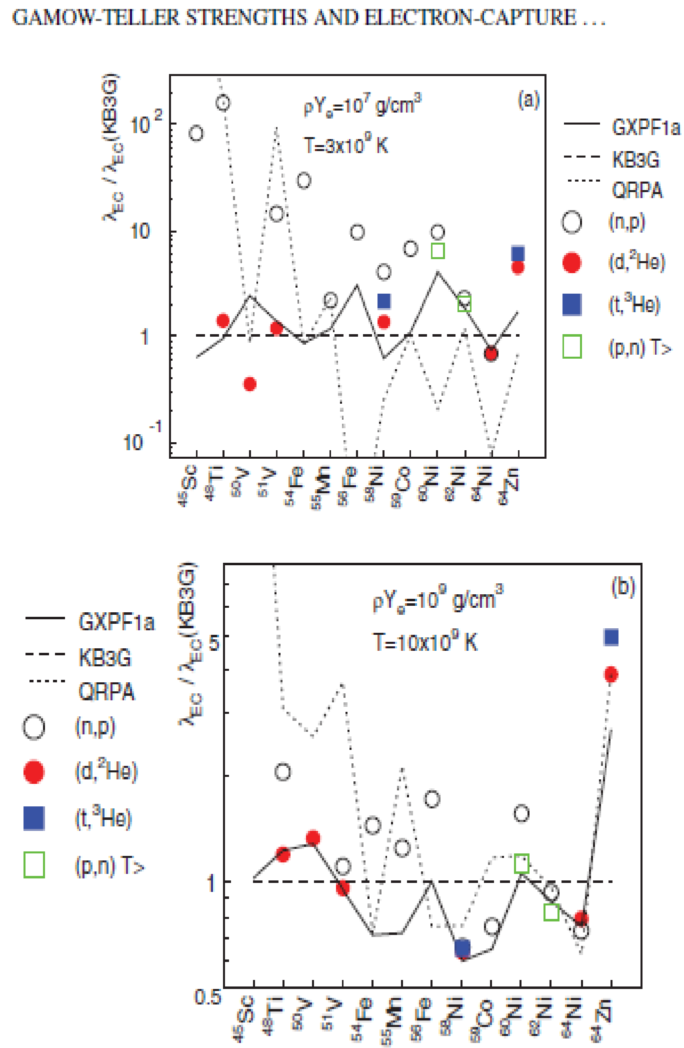


Exp: Hagemann et al.,
PL B579 (2004)

Exp: Anantaraman et al.,
PR C78 (2008)

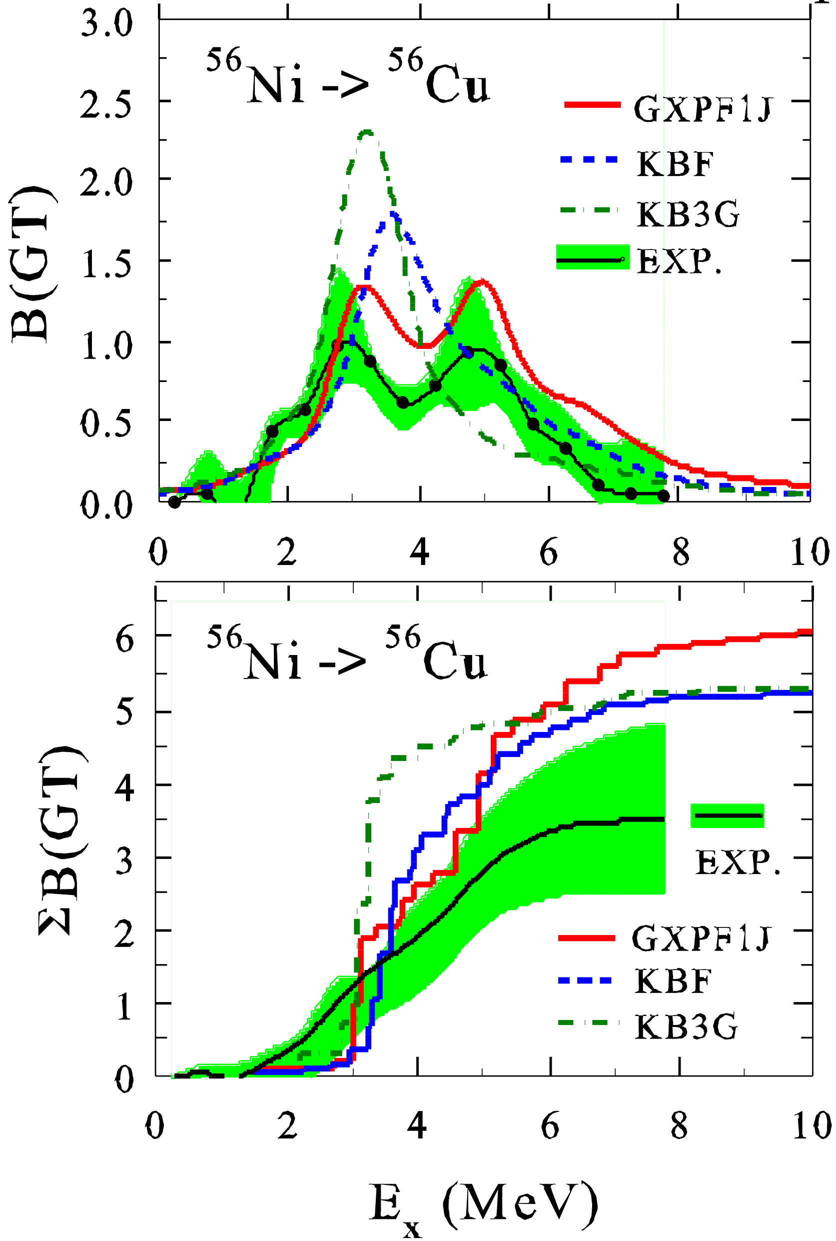
Suzuki, Honma, Mao, Otsuka, Kajino, PR C83, 044619 (2011)

KB3G vs GXPF1A



Cole et al., PR C86, 015809 (2012)

- fp-shell: GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF

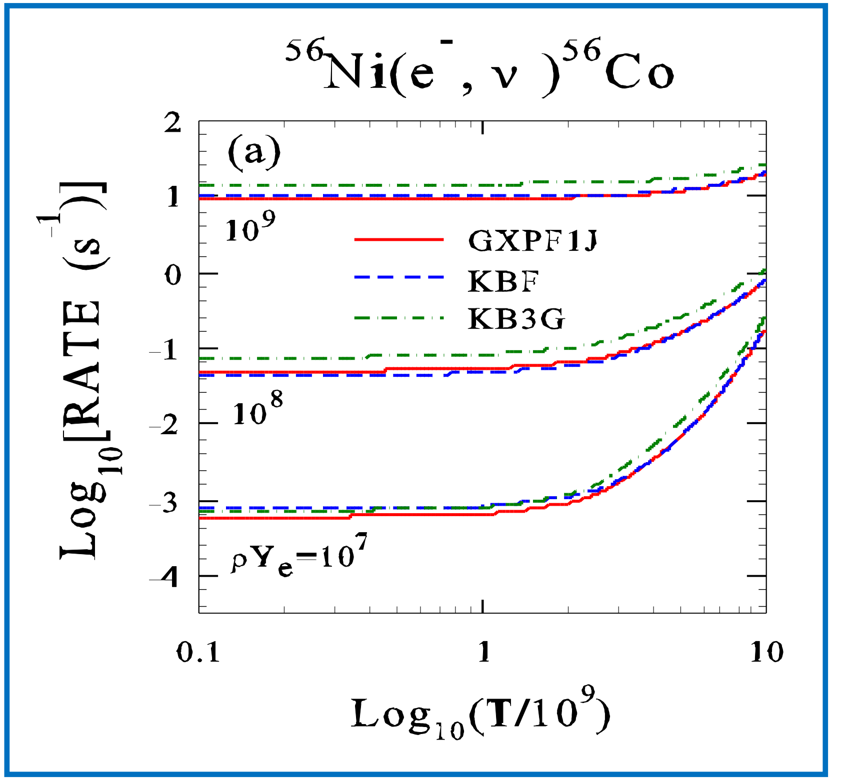


EXP: Sasano et al., PRL 107, 202501 (2011)

KBF: Table by Langanke and Martinez-Pinedo,

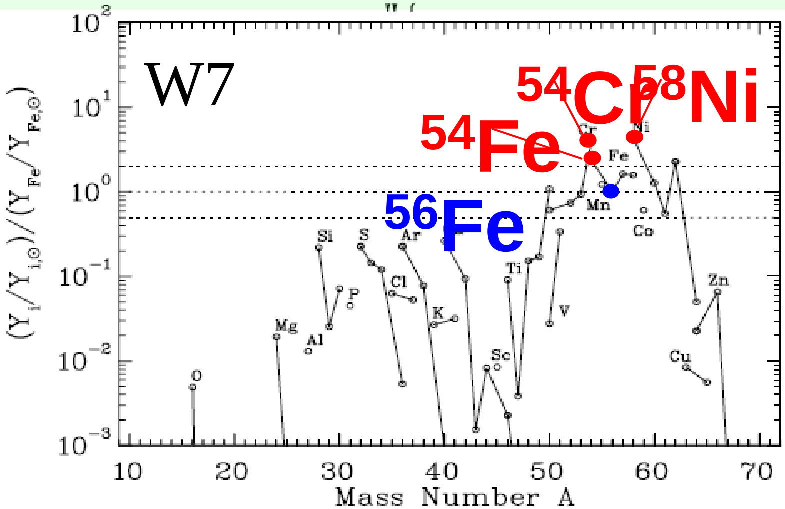
At. Data and Nucle. Data Tables 79, 1 (2001)

- fp-shell nuclei: KBF Caurier et al., NP A653, 439 (1999)
- Experimental data available are taken into account: Experimantal Q-values, energies and B(GT) values available
- Densities and temperatures at FFN (Fuller-Fowler-Newton) grids:



2b.Type-Ia SNe and synthesis of iron-group nuclei

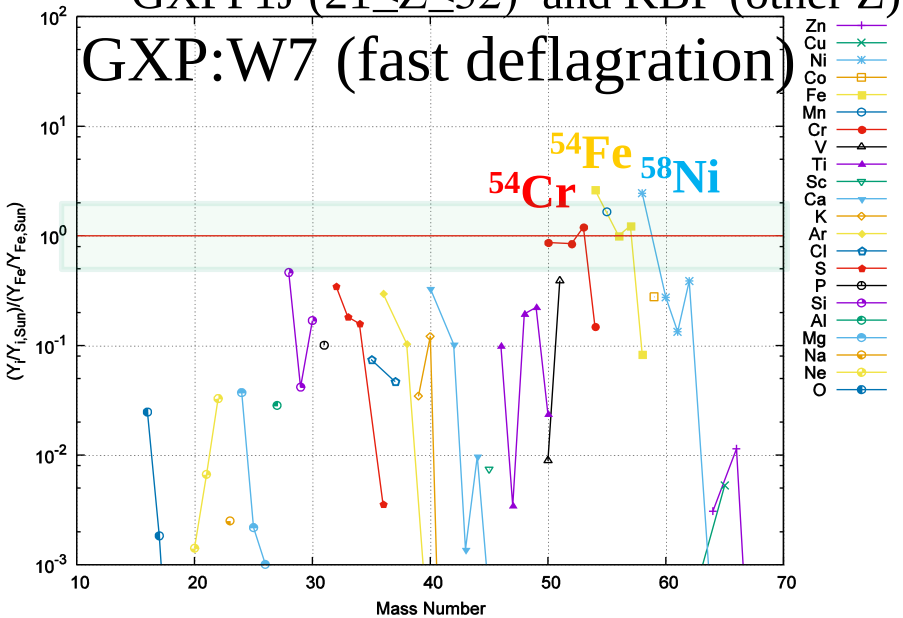
Problem of over-production of neutron-excess iron-group isotopes such as ^{58}Ni, ^{54}Cr … compared with solar abundances



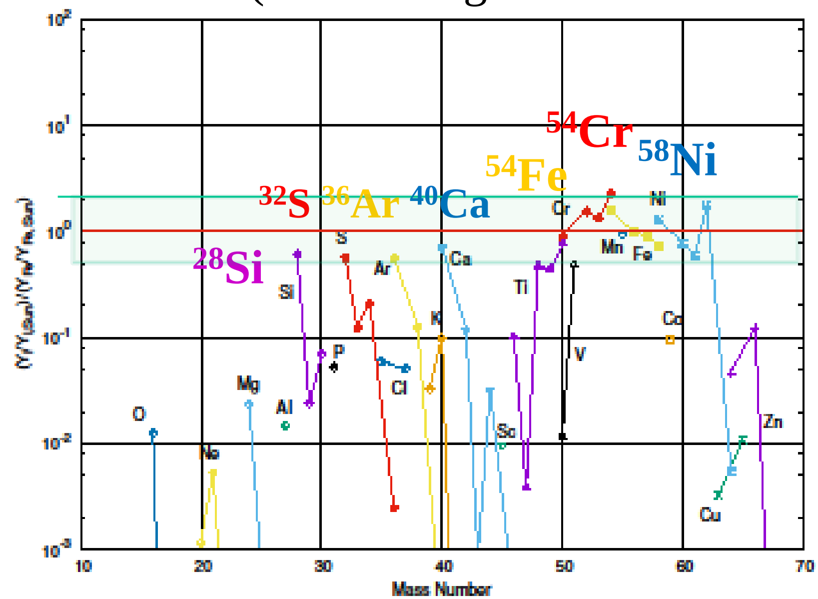
Iwamoto et al., ApJ. Suppl, 125, 439 (1999)

e-capture rates with FFN (Fuller-Fowler-Newman)

e-capture rates: GXP;
GXPF1J (21≤Z≤32) and KBF (other Z)



GXP: WDD2 (slow deflagration + detonation)



Accretion of matter to white-dwarf from binary star
→ SN explosion when WD mass ≈ Chandrasekhar limit
→ ^{56}Ni (N=Z) → ^{56}Ni (e^-, ν) ^{56}Co
Y_e =0.5 → Y_e < 0.5 (neutron-rich)
→ production of neutron-rich isotopes; more ^{58}Ni
Decrease of e-capture rate on ^{56}Ni
→less production of ^{58}Ni and larger Y_e

Mori, Famiano, Kajino, Suzuki, Hidaka, Honma, Iwamoto, Nomoto, Otsuka, ApJ. 833, 179 (2016)

Coulomb corrections: screening effects

1. Screening effects of electrons

$V(r)$ with screening effects of relativistic degenerate electron liquid

$$V(r) = -\frac{Ze^2}{2\pi^2}\int \frac{e^{i\vec{k}\vec{r}}}{k^2\epsilon(k,0)}d^3k = -\frac{Ze^2 2k_F}{2k_F r}\frac{2}{\pi}\int \frac{\sin(2k_F q r)}{q^2\epsilon(q,0)}dq.$$

$$V_s(r) = V(r) - \left(-\frac{Ze^2}{r}\right) = Ze^2(2k_F)J,$$

Juodagalvis et al., Nucl. Phys. A 848, 454 (2010).
Itoh et al, Astrophys. J. 579, 380 (2002).

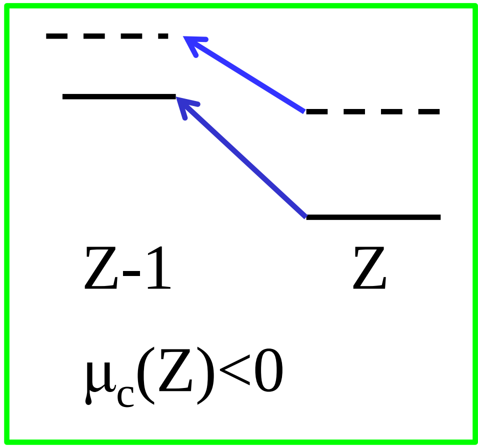
Vs(0)>0 → reduce (enhance) e-capure (β-decay) rates

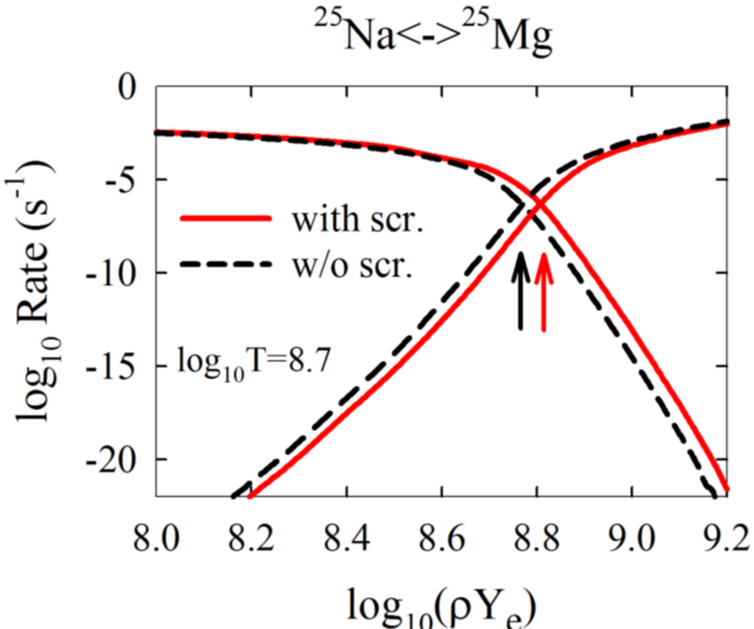
2. Change of threshold energy

$$\Delta Q_C = \mu_C(Z-1) - \mu_C(Z),$$

$\mu_C(Z)$ =the correction of the chemical potential of the ion with Z

ΔQ_c → reduce e-capture rates & enhance β-decay rates





Slattery, Doolen, DeWitt, Phys. Rev. A26, 2255 (1982).
Ichimaru, Rev. Mod. Phys. 65, 255 (1993).

$$\rho Y_e = 8.78 \rightarrow 8.81$$

URCA density → higher density region

Screening Effects on Electron Capture Rates and Type Ia Supernova Nucleosynthesis

Kanji Mori[1,2,8], Toshio Suzuki[2,3], Michio Honma[4], Michael A. Famiano[2,5], Toshitaka Kajino[1,2,6], Motohiko Kusakabe[6], and A. Baha Balantekin[2,7]

The Astrophysical Journal, 904:29 (6pp), 2020

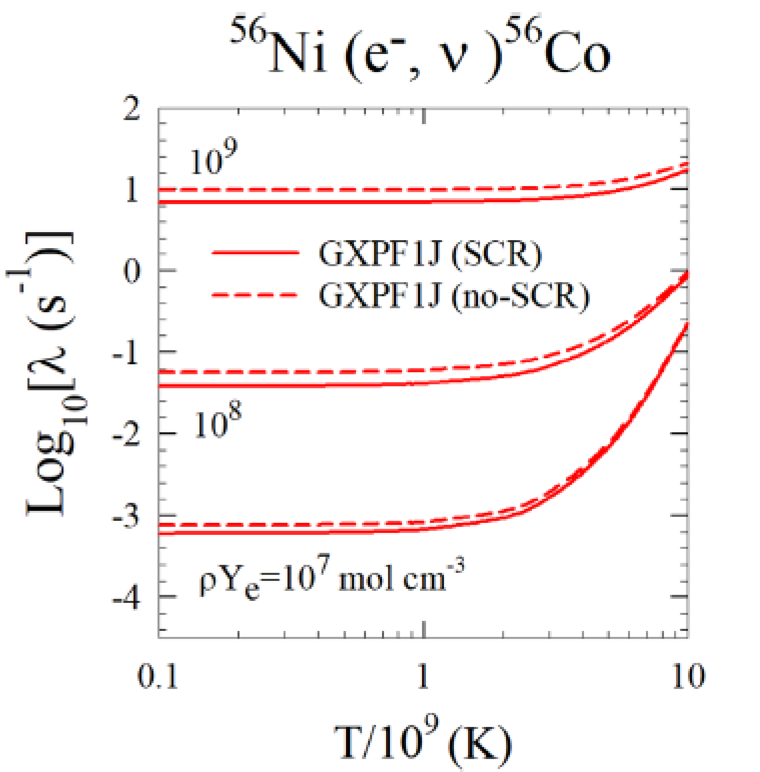


Figure 1. Comparison of calculated *e*-capture rates for ^{56}Ni (e^-, ν) ^{56}Co obtained with the GXPF1J at densities $\rho\, Y_e = 10^7$, 10^8, and 10^9 mol cm^{-3} for temperatures $T = 10^8$–10^{10} K. Solid and dashed curves denote the rates with and without the screening effects, respectively.

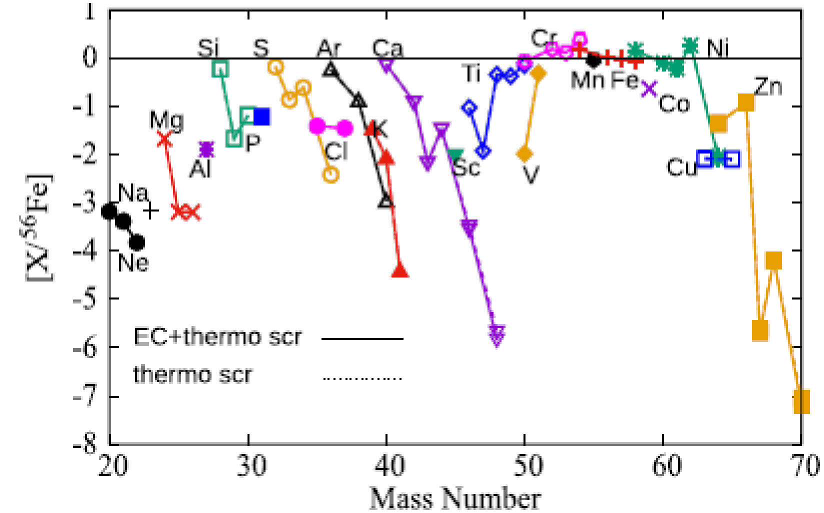


Figure 7. Abundances normalized by the solar and ^{56}Fe abundances. The solid lines adopt screening on ECs and the broken lines do not. WDD2 is adopted as an SN Ia model.

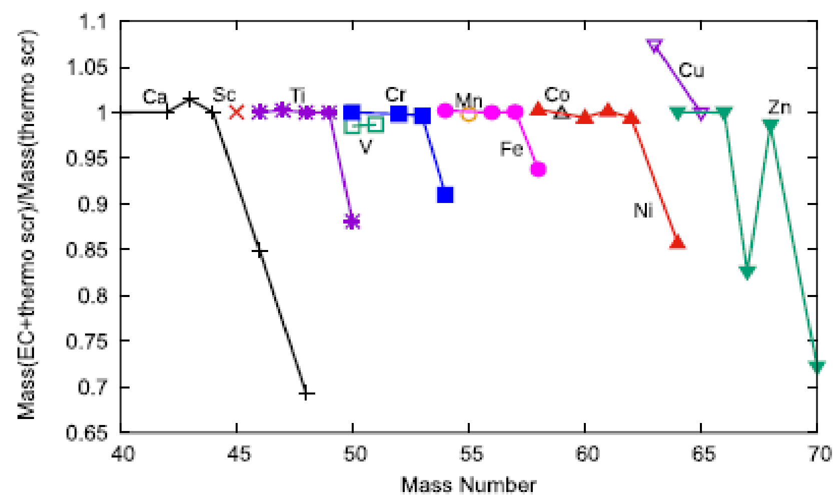


Figure 6. Abundance ratios between the cases with and without screening on ECs. WDD2 is adopted as an SN Ia model.

Summary

- **Spin responses in nuclei are well described by new shell-model Hamiltonians.**
- **Weak rates updated in sd-shell, sd-pf shell, pf-shell are applied to nuclear Urca processes in stars**

A=23, 25 pairs → cooling of ONeMg cores

A=31 pair → cooling of neutron-star crusts

A=61 pair → moderate cooling effect

- **A new shell model Hamiltonian GXPF1J in pf-shell describes the GT strengths and electron capture rates in Ni and Fe isotopes quite well.**

Updated weak rates are applied to nucleosynthesis of iron-group elements in Type Ia SN.

Over-production problem of neutron-excess iron-group isotopes in Type Ia SNe is suppressed with the updated e-capture rates.

- **Accurate evaluation of the weak rates is important for the study of evolution of stars and nucleosynthesis.**