The Role of Nuclear Weak Rates on the Evolution of Degenerate Cores in Stars

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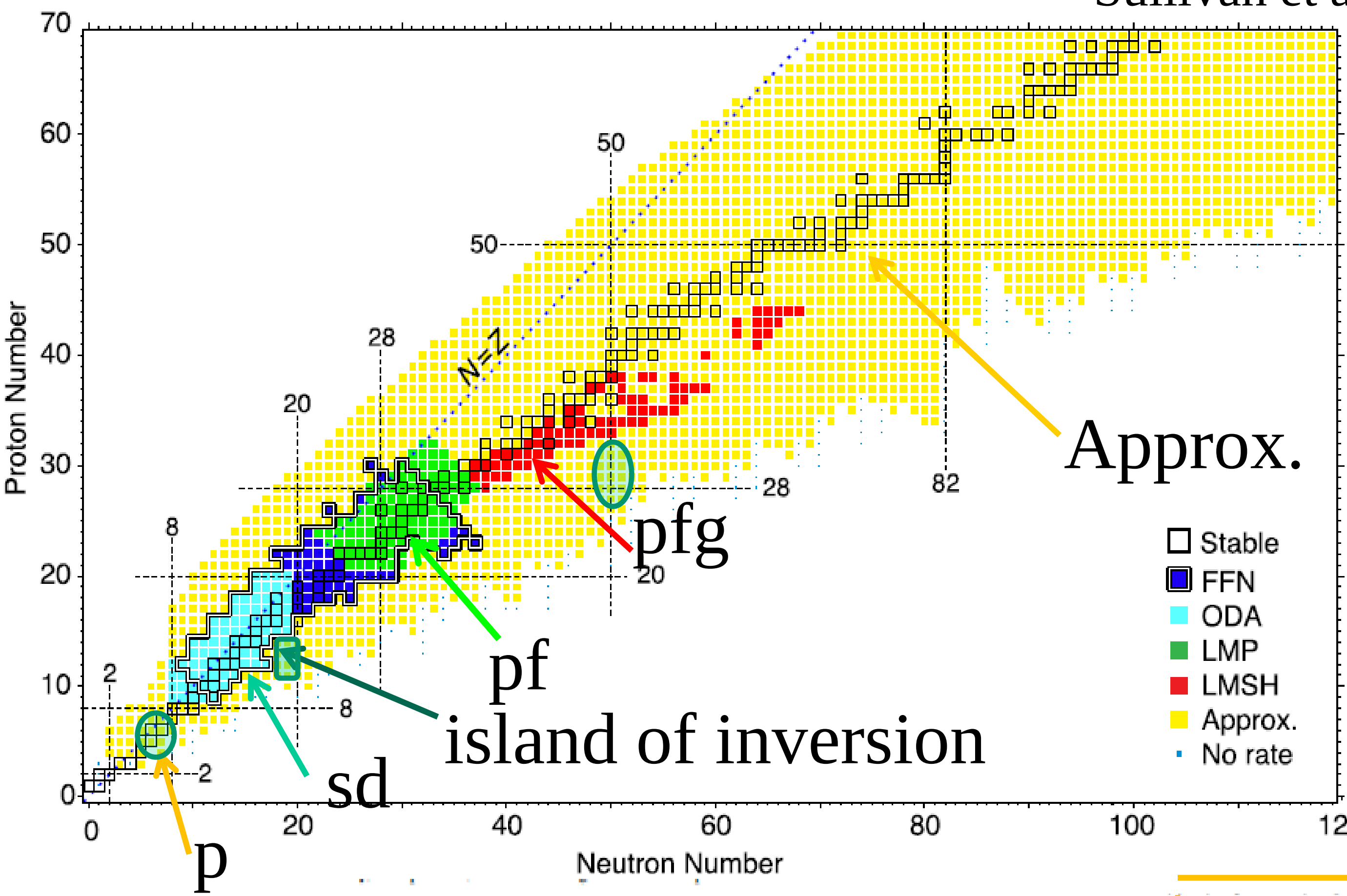
Standard electron-capture (weak) rates of nuclei available

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



Missing

- Island of inv. sd-pf
- ~^{78}Ni N=50 pf-gds
- p-shell

Approx.

B (=4.6) and ΔE (=2.5 MeV)

$$\eta = \chi + \mu_e/T,$$

$$\chi = (Q - \Delta E)/T,$$

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

$$F_k(\eta) = \int_0^\infty \frac{x^k}{\exp(x-\eta)+1}dx,$$

$$F_k(\eta) = -\Gamma(k+1)\mathrm{Li}_{k+1}(-e^\eta),$$

Table	Model Space					T (GK)	$\mathrm{Log}_{10}(\rho Y_e$ g cm$^{-3})$	Reference
	s	p	sd	pf	pfg/sdg			
FFN	x	...	x	x	...	0.01–100	1.0–11	Fuller et al. (1982)
ODA	x	...	x	...	...	0.01–30	1.0–11	Oda et al. (1994)
LMP	x	...	...	x	...	0.01–100	1.0–11	Langanke et al. (2003), Langanke (2001a)
LMSH	...	...	...	...	x	8.12–39.1	9.22–12.4	Hix et al. (2003), Langanke et al. (2001a)
Approx.	x	x	x	x	x	...	...	Langanke et al. (2003)

1. Weak rates of nuclei within one-major shells

- **sd**-shell nuclei with USDB and nuclear URCA processes in stars with O-Ne-Mg core
- **pf**-shell nuclei with GXPF1J and nucleosynthesis of iron-group nuclei in type Ia supernova explosions (SNe)

Suzuki, Toki and Nomoto, ApJ. 817, 163 (2016)
Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)
Mori, Famiano, Kajino, Suzuki, Hidaka, Honma, Iwamoto, Nomoto, and Otsuka, ApJ. 833, 179 (2016)

2. Weak rates of nuclei wth two-major shells

- **sd-pf** shell nuclei in the island of inversion important for nuclear URCA processes in neutron star crusts
- **pf-g** shell nuclei (~ ^{78}Ni) important for nucleosynthesis in core-collapse SNe

In collaboration with N.Tsunoda (CNS), N. Shimizu (CNS), Y. Tsunoda (CNS) and T. Otsuka (RIKEN)

1a. Weak Rates in sd-shell and Nuclear URCA process in O-Ne-Mg cores

- $M=8M_\odot \sim 10M_\odot$

  C burning → O-Ne-Mg core

  → (1) O-Ne-Mg white dwarf (WD)

  → (2) e-capture supernova explosion (collapse of O-Ne-Mg core induced by e-capture) with neutron star (NS) remnant

  → (3) core-collapse (iron-core collapse) supernova explosion with NS (neon burning shell propagates to the center)

Fate of the star is sensitive to its mass and nuclear e-capture and β–decay rates; Cooling of O-Ne-Mg core by nuclear URCA processes determines (2) or (3).

Nomoto and Hashimoto, Phys. Rep. 163, 13 (1988)
Miyaji, Nomoto, Yokoi, and Sugimoto, Pub. Astron. Soc. Jpn. 32, 303 (1980)
Nomoto, Astrophys. J. 277, 791 (1984); ibid. 322, 206 (1987)

- URCA processes in sd-shell nuclei

→ Cooling of O-Ne-Mg core in 8-10 $M_\odot$ stars

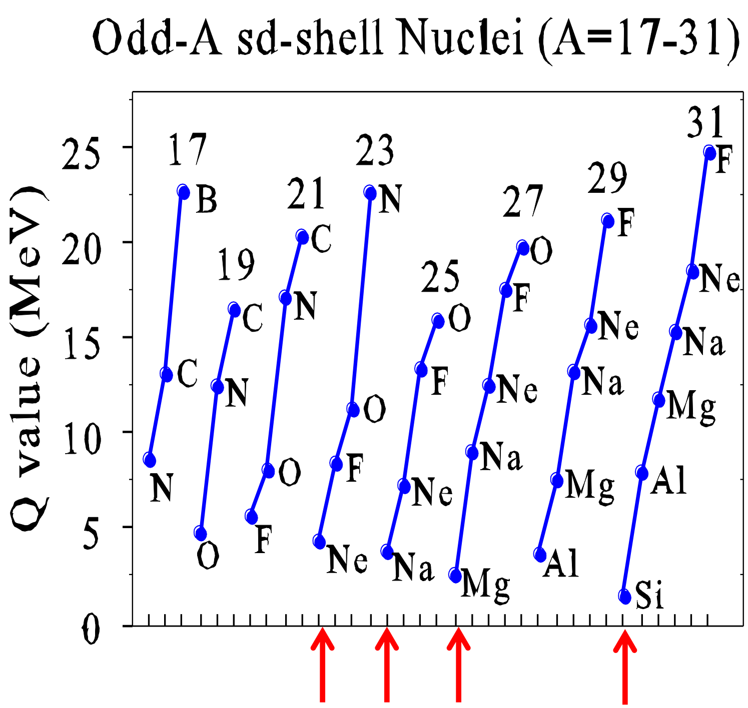
e-capture: $^{A}_{Z}X + e^- \to {}^{A}_{Z-1}Y + \nu$

β-decay: $^{A}_{Z-1}Y \to {}^{A}_{Z}X + e^- + \bar{\nu}$

They occur simultaneously at certain stellar conditions and energy is lost from stars by emissions of ν and $\bar{\nu}$ → Cooling of stars

How much star is cooled → fate of the star after neon flash:

- Beta-decay Q-values



A=23: Q=4.376 MeV
A=25: Q=3.835 MeV
A=27: Q=2.610 MeV

$^{23}Na + e^- \to {}^{23}Ne + \nu$

$^{23}Ne \to {}^{23}Na + e^- + \bar{\nu}$

$^{25}Mg + e^- \to {}^{25}Na + \nu$

$^{25}Na \to {}^{25}Mg + e^- + \bar{\nu}$

$^{27}Al + e^- \to {}^{27}Mg + \nu$

$^{27}Mg \to {}^{27}Al + e^- + \bar{\nu}$

▪ Nuclear weak rates in sd-shell

(1) New shell-model Hamiltonian: USDB cf. Oda et al., USD

(2) Fine meshes in both density and temperature

($\Delta \log_{10}(\rho Ye)=0.02$, $\Delta \log_{10} T=0.05$)

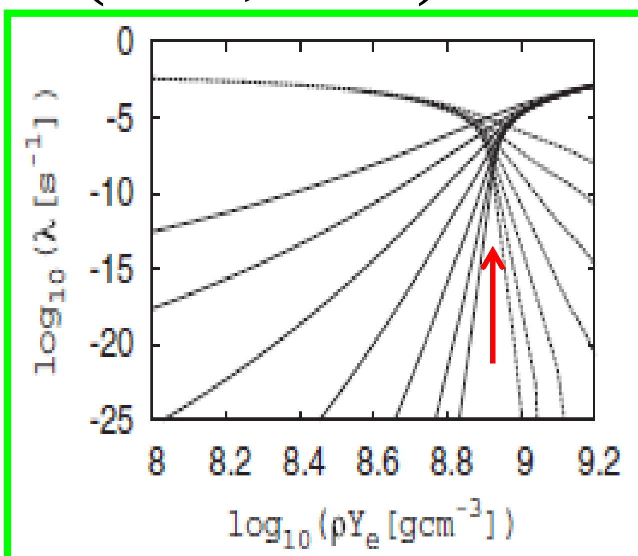
cf. Interpolation problem in FFN (Fuller-Fowler-Newman) grids

FFN grids are rather scarce, especially for the density

(3) Effects of screening

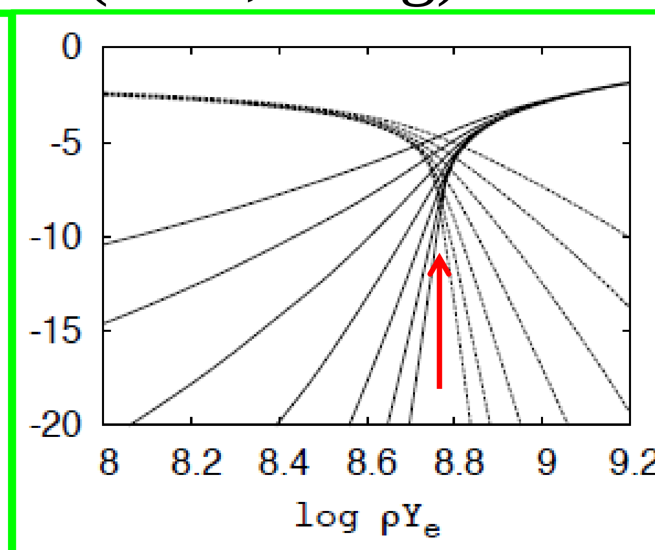
Suzuki, Toki and Nomoto, ApJ. 817, 163 (2016)

(^{23}Ne, ^{23}Na)



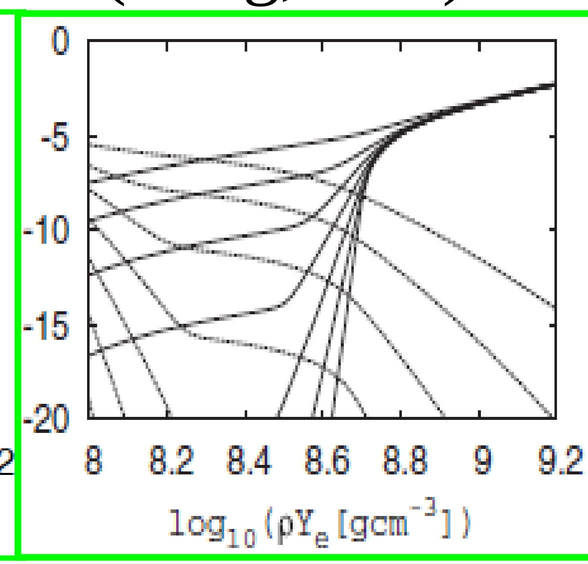
URCA density at $\log_{10} \rho Y_e = 8.92$

(^{25}Na, ^{25}Mg)



URCA density at $\log_{10} \rho Y_e = 8.78$

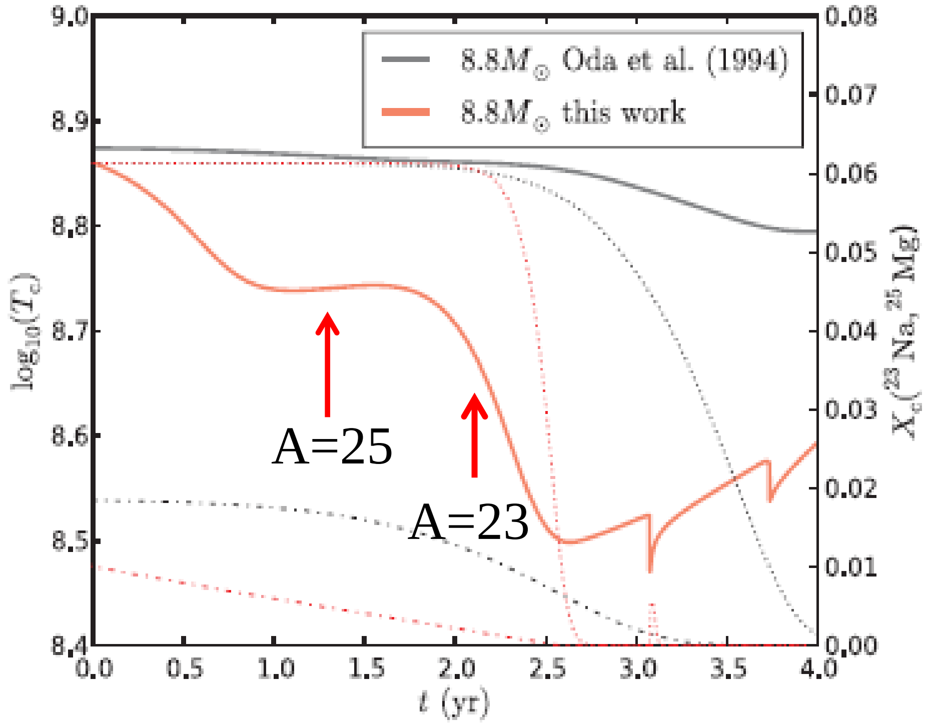
(^{27}Mg, ^{27}Al)



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

No clear URCA density for A=27 pair

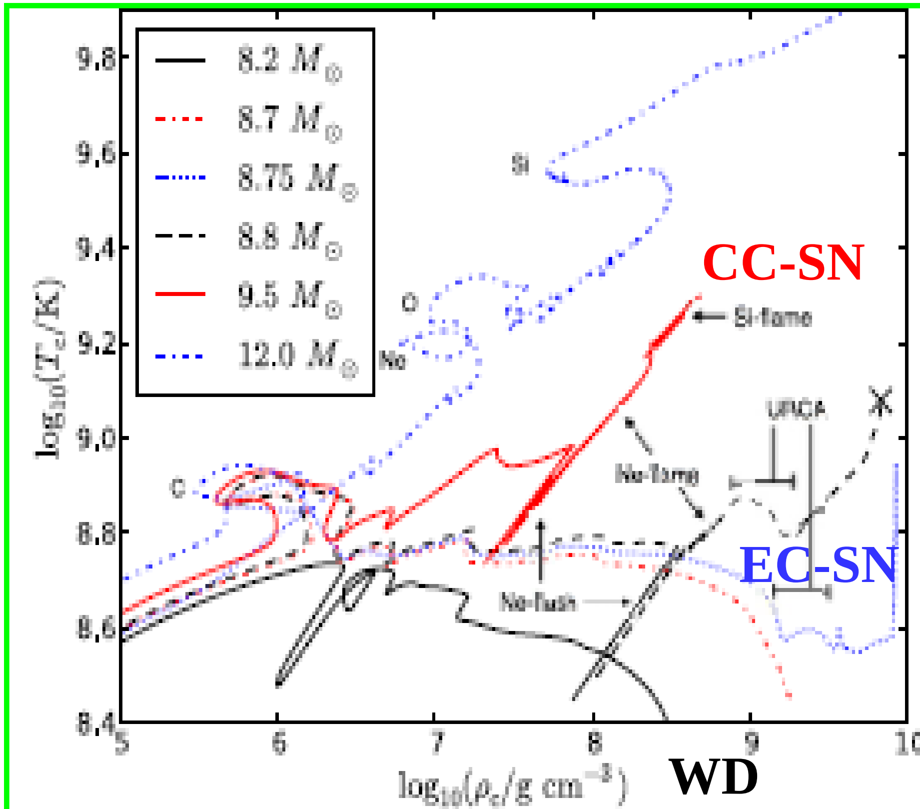
Cooling of O-Ne-Mg core by the nuclear URCA processes



8.8$M_\odot$ star collapses triggered by subsequent e-capture on ^{24}Mg and ^{20}Ne (e-capture supernova explosion)

Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)

Fate of 8-10$M_\odot$ stars



Border of CC-SN or EC-SN is at M～9$M_\odot$, which is quite sensitive to nuclear weak rates

Jones et al., Astrophys. J. 772, 150 (2013)

1b. GT strengts in pf-shell and e-capture rates at stellar environmemts

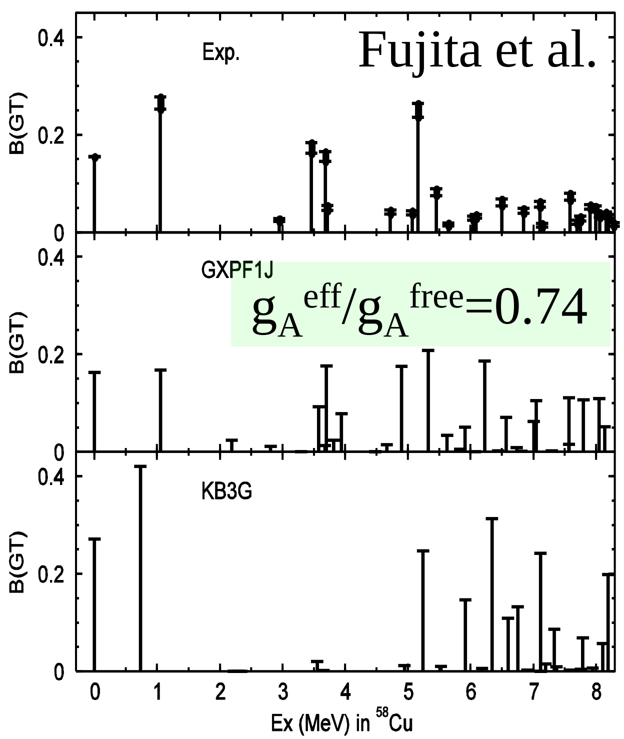
GXPF1: Honma et al., PR C65 (2002); C69 (2004); A=47-66

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

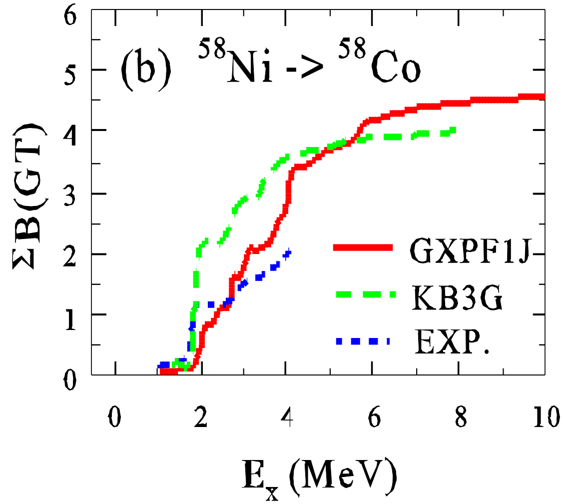
KB3G A = 47-52 G-matrix (KB) + monopole corrections

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

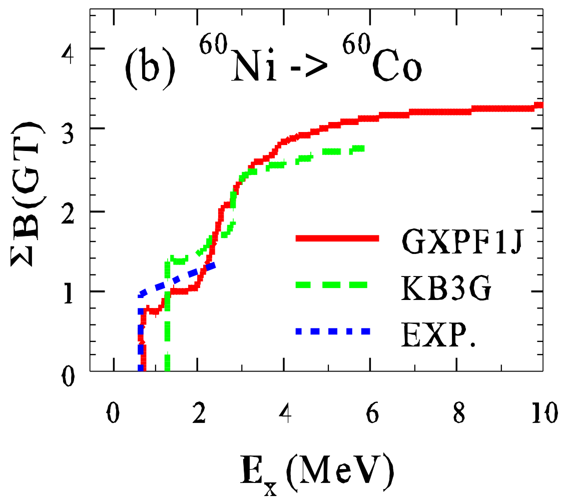
B(GT-) for ^{58}Ni



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



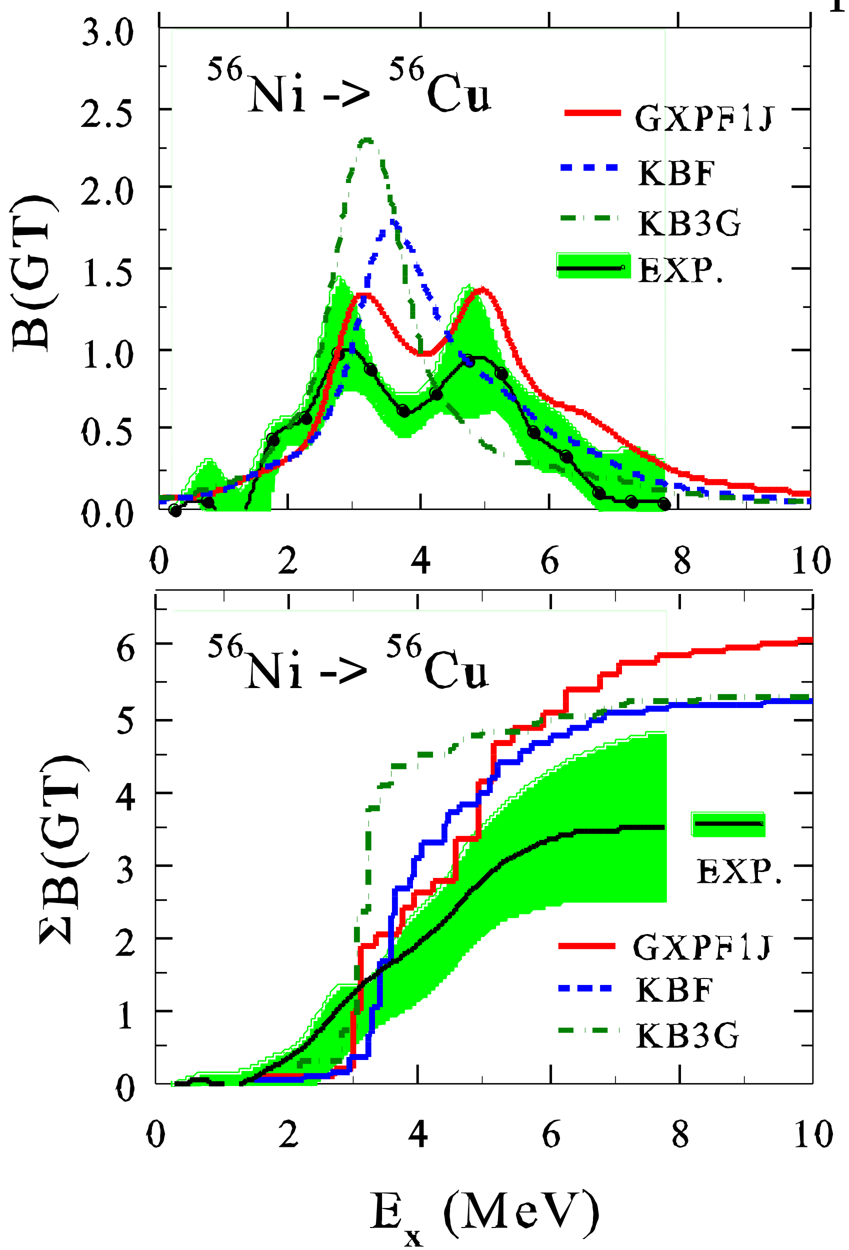
Exp: Hagemann et al., PL B579 (2004)



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

Comparison of e-capture rates: KB3G vs GXPF1A vs RPA Cole et al., PR C86, 015809 (2012)

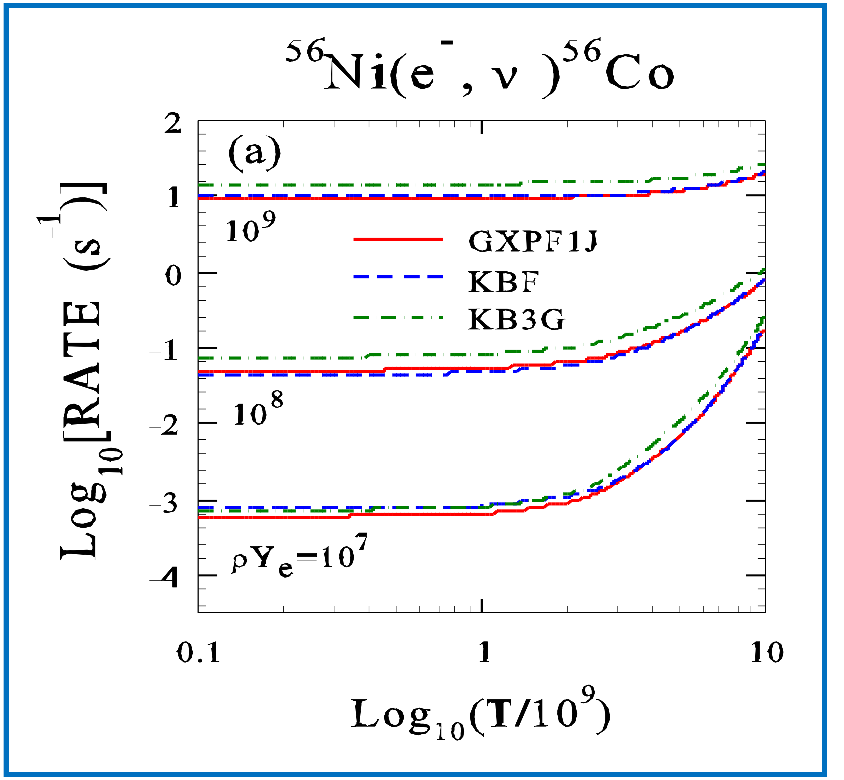
GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF



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:



・Type-Ia SNe and synthesis of iron-group nuclei

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass ≈ Chandrasekhar limit

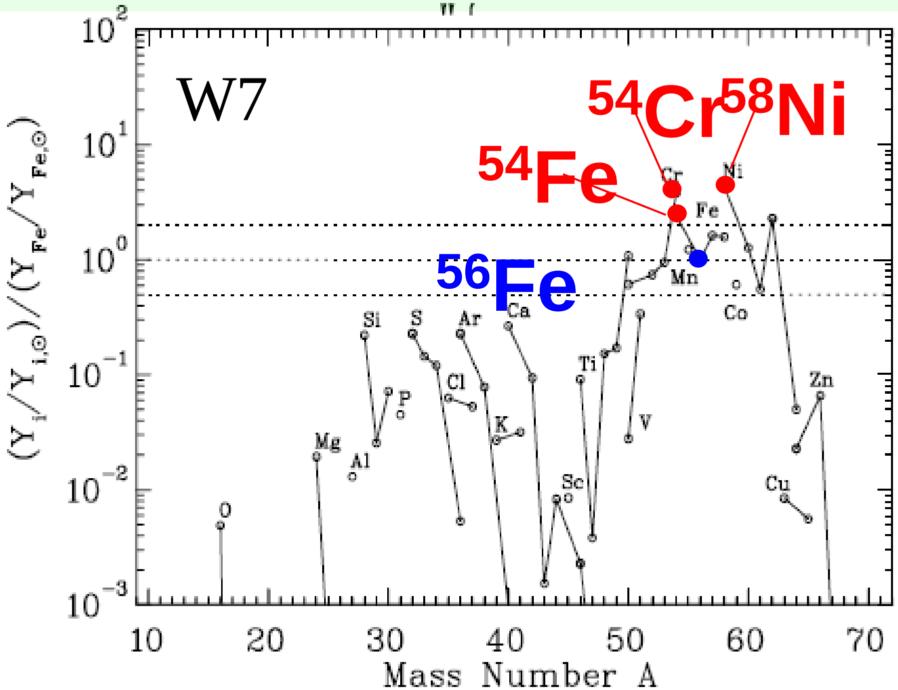
→ ^{56}Ni (N=Z)

→ ^{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

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)

Type-Ia SNe

W7 model : fast deflagration

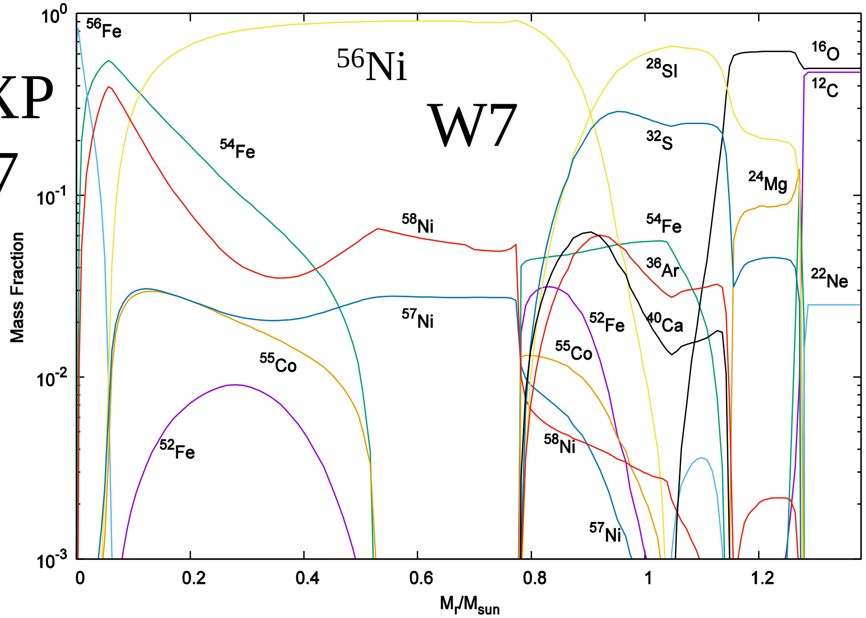
WDD2: Slow deflagration + delayed detonation

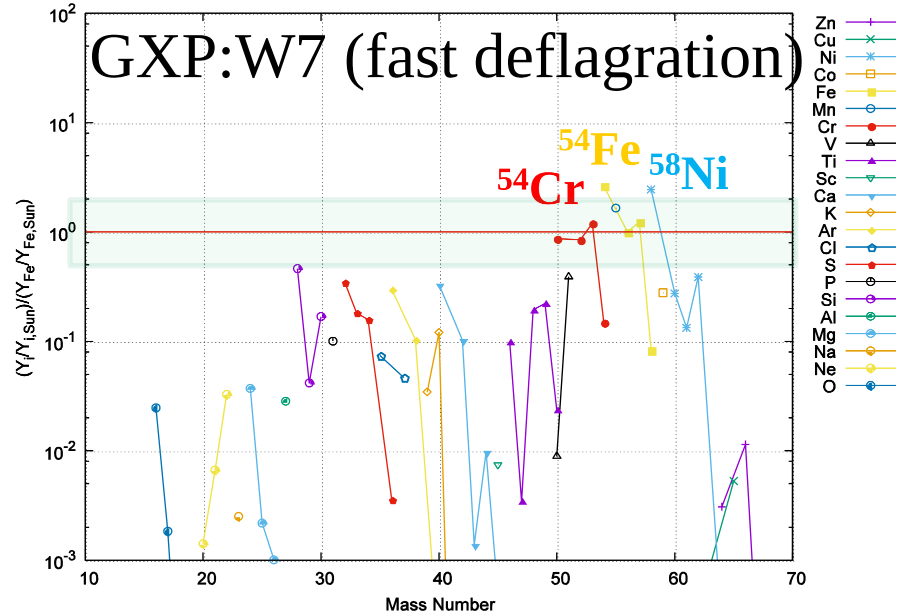
Initial: C-O white dwarf, $M=1.0M_\odot$

central; ρ_9=2.12, T_c=1x10^7K

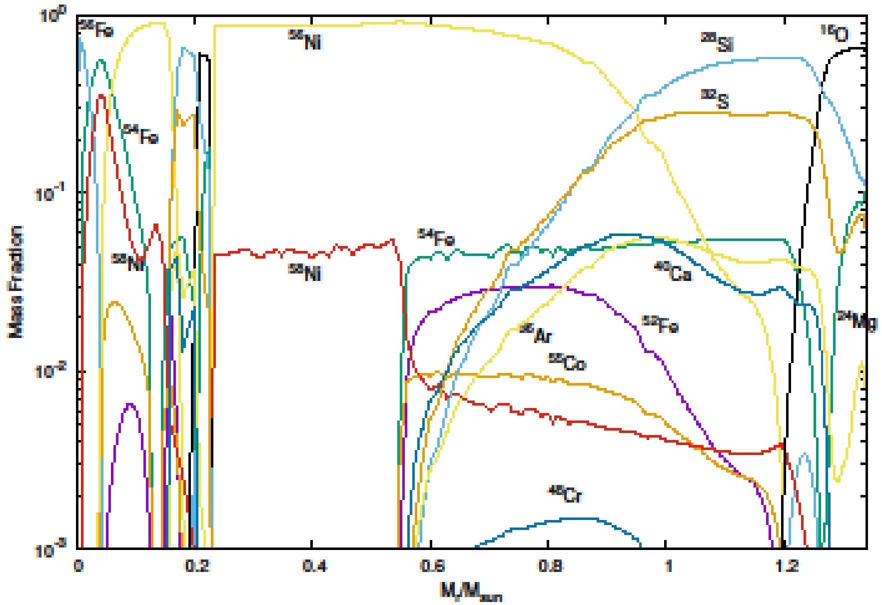
e-capture rates: GXP; GXPF1J (21≤Z≤32) and KBF (other Z)

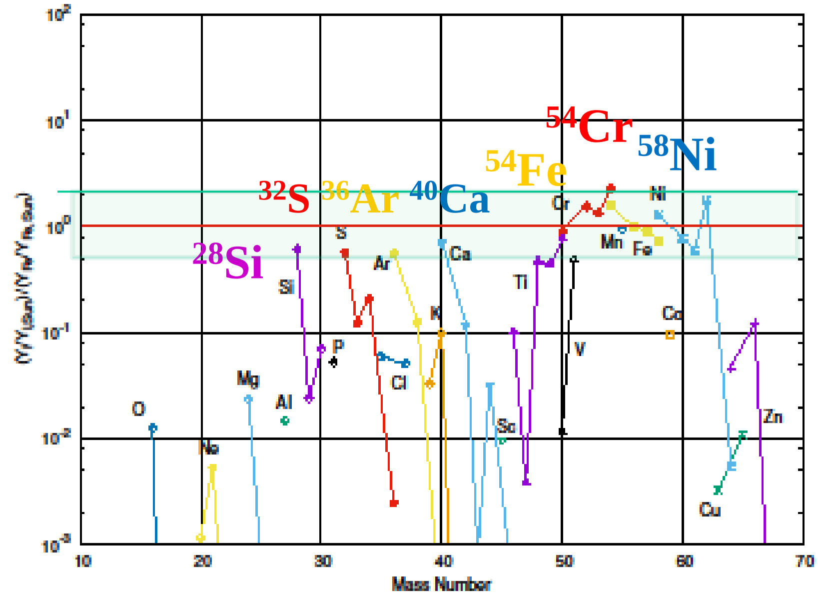
GXP
W7





GXP: WDD2 (slow deflagration + detonation)





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

2a. Weak rates for nuclei in the island of inversion

Nature 505, 65 (2014)
doi:10.1038/nature12757

Strong neutrino cooling by cycles of electron capture and β^- decay in neutron star crusts

H. Schatz[1,2,3], S. Gupta[4], P. Möller[2,5], M. Beard[2,6], E. F. Brown[1,2,3], A. T. Deibel[2,3], L. R. Gasques[7], W. R. Hix[8,9], L. Keek[1,2,3], R. Lau[1,2,3], A. W. Steiner[2,10] & M. Wiescher[2,6]

Rates evaluated by QRPA
Shell-model evaluations are missing.

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
^{57}Cr	^{57}V	1.22	8.3	1.6
^{57}V	^{57}Ti, ^{57}Sc	2.56	10.7	1.6
^{63}Cr	^{63}V	6.82	14.7	0.97
^{105}Zr	^{105}Y	3.12	11.2	0.92
^{59}Mn	^{59}Cr	0.945	7.6	0.88
^{103}Sr	^{103}Rb	5.30	13.3	0.65
^{96}Kr	^{96}Br	6.40	14.3	0.65
^{65}Fe	^{65}Mn	2.34	10.3	0.60
^{65}Mn	^{65}Cr	3.55	11.7	0.46

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

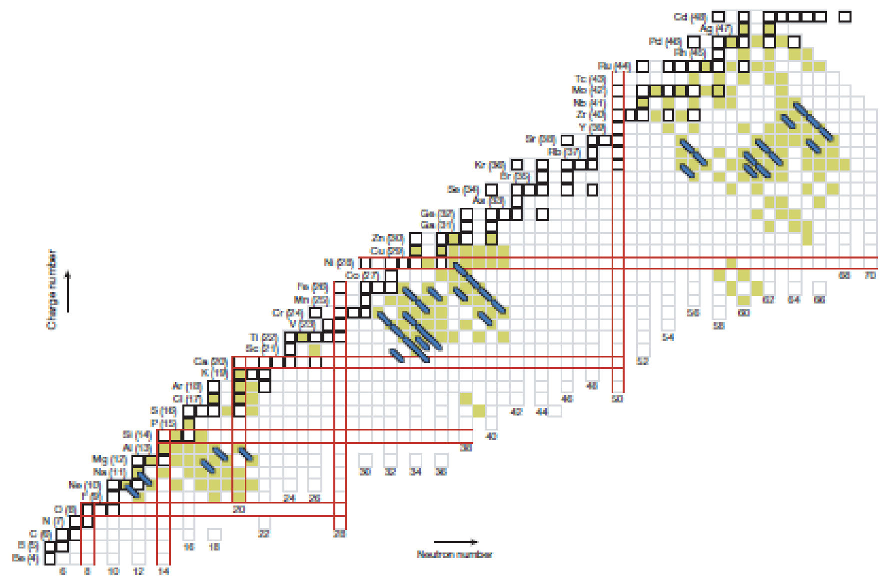
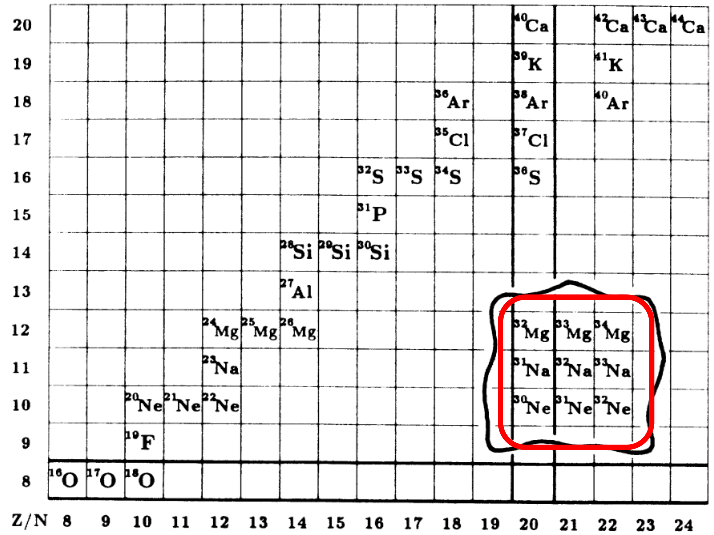


Figure 2 | Electron-capture/β^--decay pairs on a chart of the nuclides. The thick blue lines denote electron-capture/β^--decay pairs that would generate a strong neutrino luminosity in excess of 5×10^{34} erg s^{-1} at $T = 0.51$ GK for a composition consisting entirely of the respective electron-capture/β^--decay pair. They largely coincide with regions where allowed electron-capture and β^--decay transitions are predicted to populate low-lying states and subsequent electron capture is blocked (shaded squares, see also the discussion in ref. 3). These are mostly regions between the closed neutron and proton shells (pairs of horizontal and vertical red lines), where nuclei are significantly deformed (see Supplementary Information section 4). Nuclides that are β^--stable under terrestrial conditions are shown as squares bordered by thicker lines. Nuclear charge numbers are indicated in parentheses next to element symbols.

Island of inversion: sd<->pf



Warburton, Becker, Brown, PR C41, 1147 (1990)

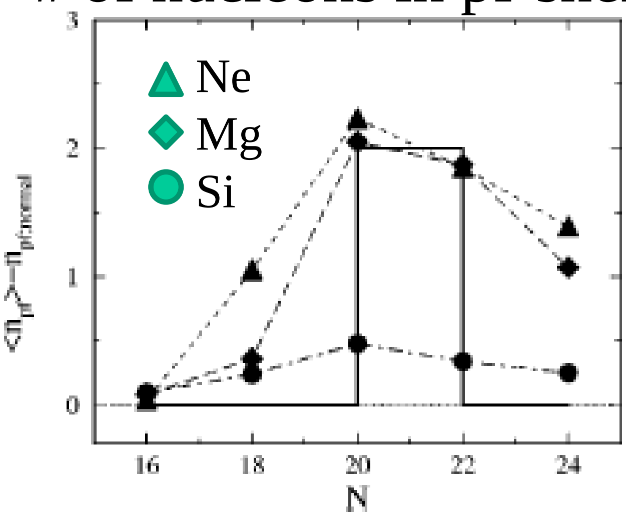
- Small shell-gap: $f_{7/2}$-$d_{3/2}$
- Small $E_x(2^+)$
- Large B(E2)

→ Large sd-pf admixture

Neutron-rich Ne, Na, Mg isotopes

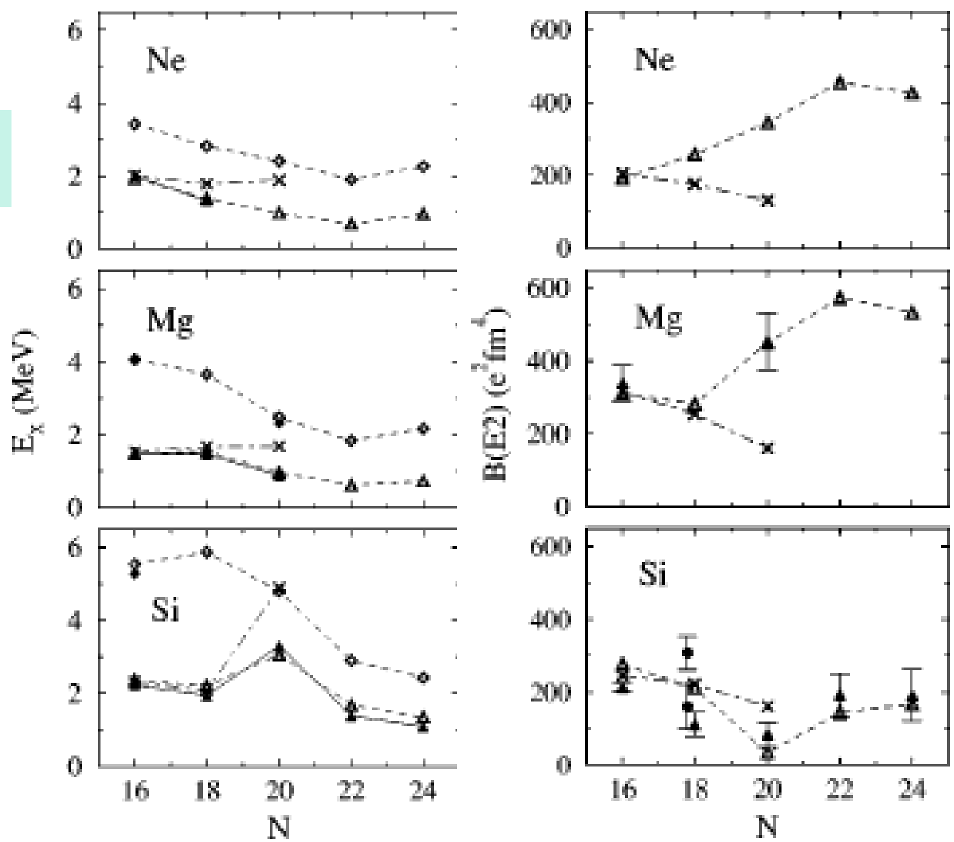
SDPF-M: Utsuno et al., PR C60, 054315 (1999)

# of nucleons in pf-shell



E_x: 2^+, 4^+

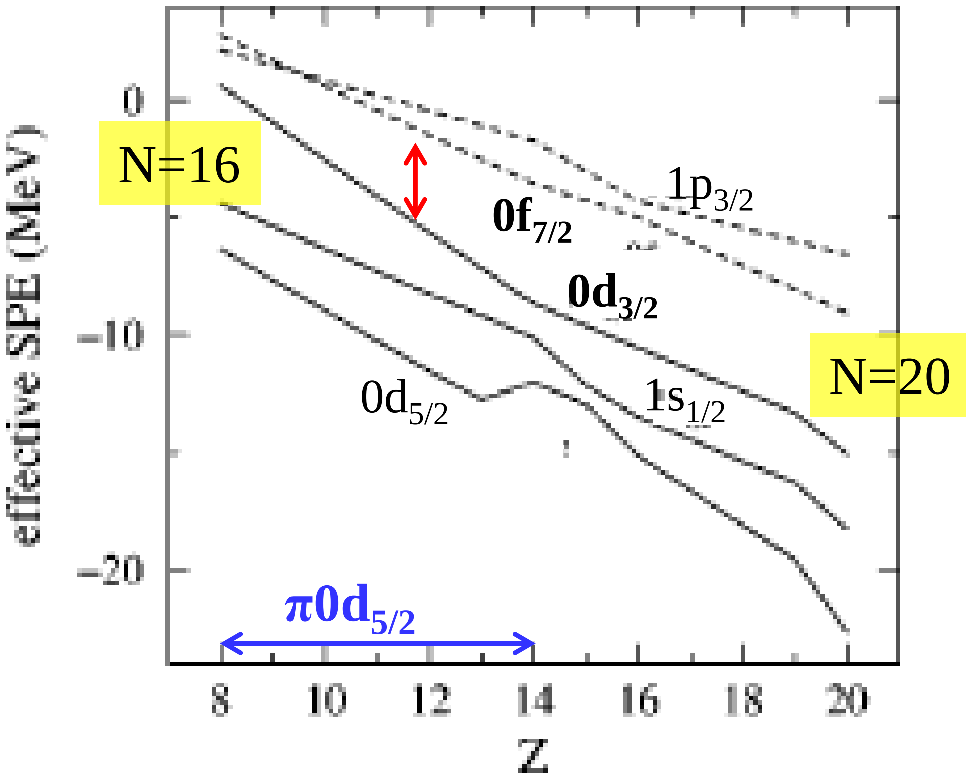
B(E2)



filled =exp.

× = sd only

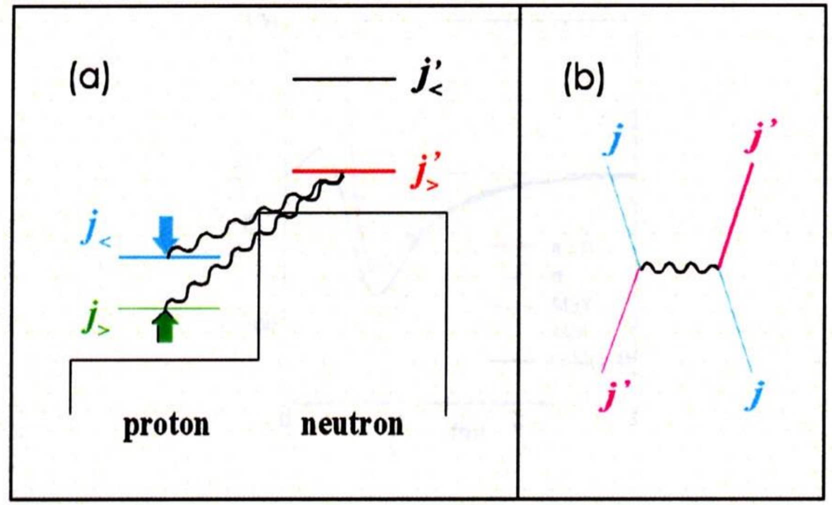
Neutron ESP for N=20 isotones



SDPF-M: Utsuno et al., PR C60, 054315 (1999)

Shell-gap ($\nu d_{3/2}$-$\nu f_{7/2}$) decreases for less protons in $d_{5/2}$-shell → Magic number changes from N=20 to N=16

Effects of Tensor Force on Shell Evolution



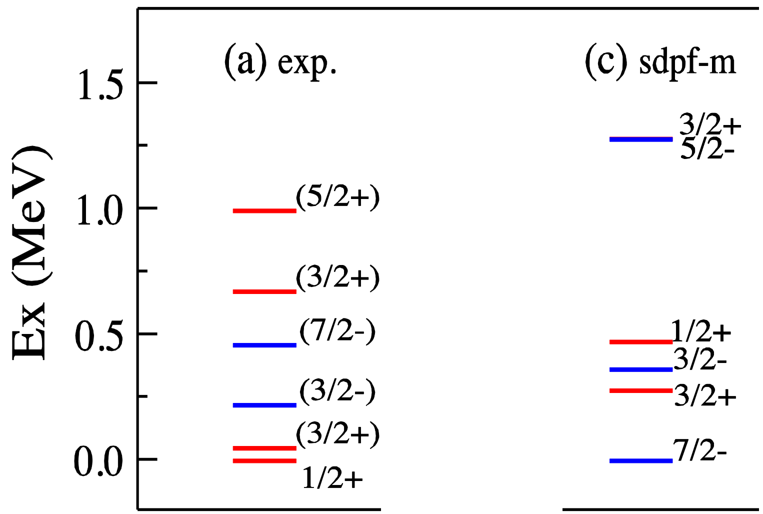
$\pi d_{5/2}$-$\nu d_{3/2}$: attraction
$\pi d_{5/2}$-$\nu f_{7/2}$: repulsion

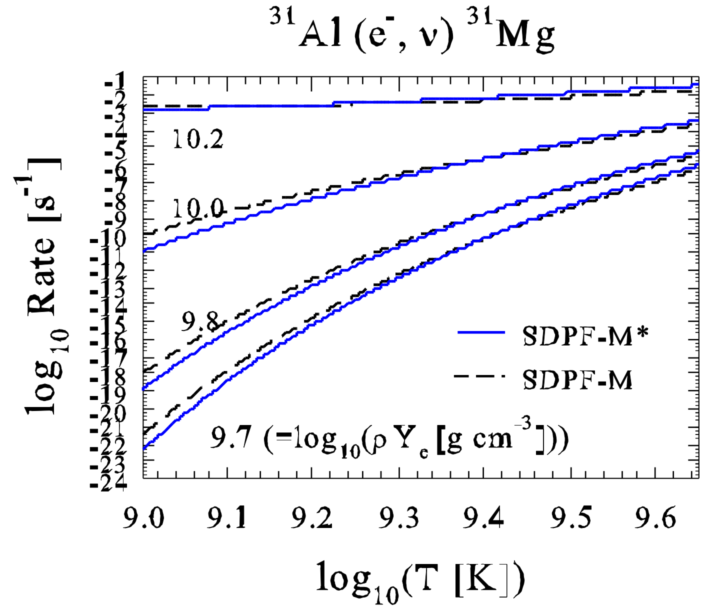
Monopole terms

$$V_M^T(j_1 j_2) = \frac{\sum_J (2J+1) < j_1 j_2; JT | V | j_1 j_2; JT >}{\sum_J (2J+1)}$$

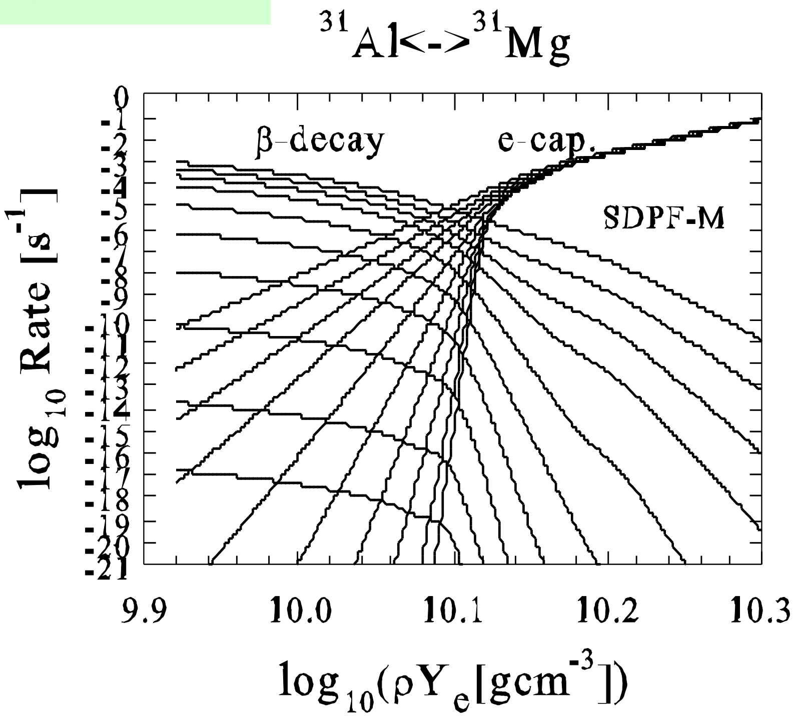
Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

^{31}Mg

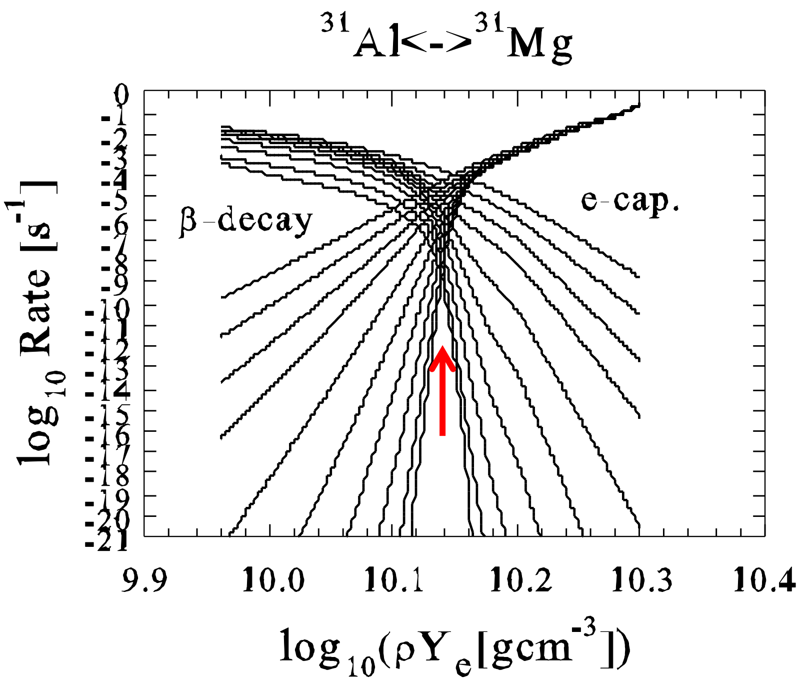




SDPF-M



SDPF-M*: E_x & B(GT) = exp.

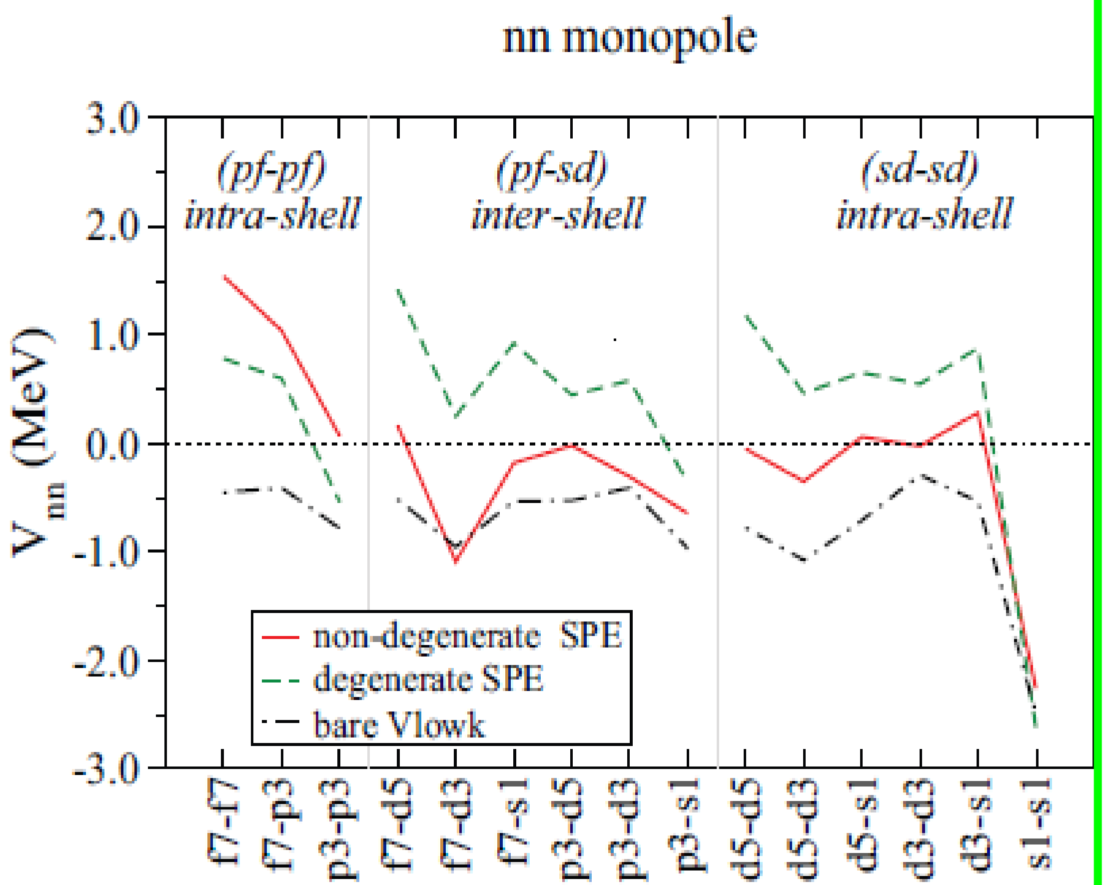


sd-pf shell

Non-degenerate treatment of sd and pf shells by
EKK (extended Kuo-Krenciglowa) method

Tsunoda, Takayanagi, Hjorth-Jensen and Otsuka, Phys. Rev. C 89, 024313 (2014)

Cf: monopoles with non-degenerate vs degenerate method



Kuo-Krenciglowa method

$$V_{\mathrm{eff}}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\mathrm{eff}}^{(n-1)}\}^k,$$

$$P H_0 P = \epsilon_0 P.$$

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP,$$

$$\hat{Q}_k(E) = \frac{1}{k!}\frac{\mathrm{d}^k \hat{Q}(E)}{\mathrm{d}E^k}.$$

Extended Kuo-Krenciglowa method

$$\tilde{H} = H - E$$

$$\tilde{H}_{\mathrm{eff}}^{(n)} = \tilde{H}_{\mathrm{BH}}(E) + \sum_{k=1}^{\infty} \hat{Q}_k(E)\{\tilde{H}_{\mathrm{eff}}^{(n-1)}\}^k,$$

$$\tilde{H}_{\mathrm{eff}} = H_{\mathrm{eff}} - E, \quad \tilde{H}_{\mathrm{BH}}(E) = H_{\mathrm{BH}}(E) - E,$$

$$H_{\mathrm{BH}}(E) = PHP - PVQ\frac{1}{E - QHQ}QVP.$$

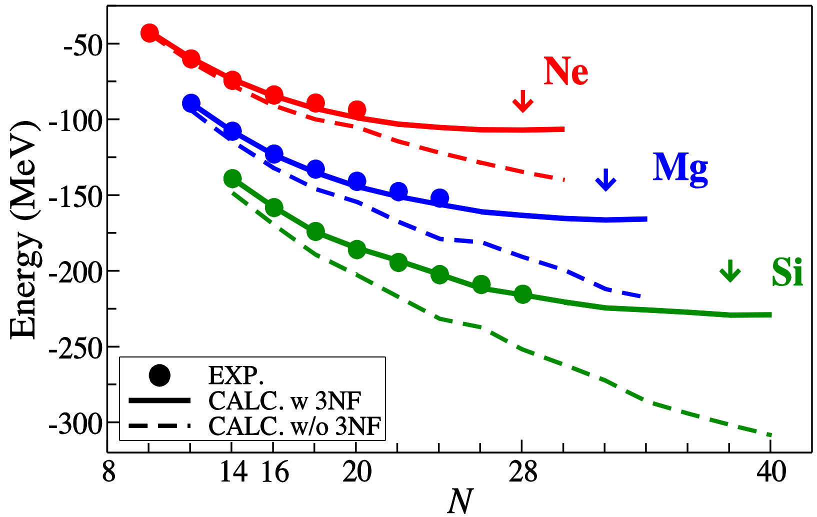
$$V_{\mathrm{eff}} = H_{\mathrm{eff}} - PH_0P.$$

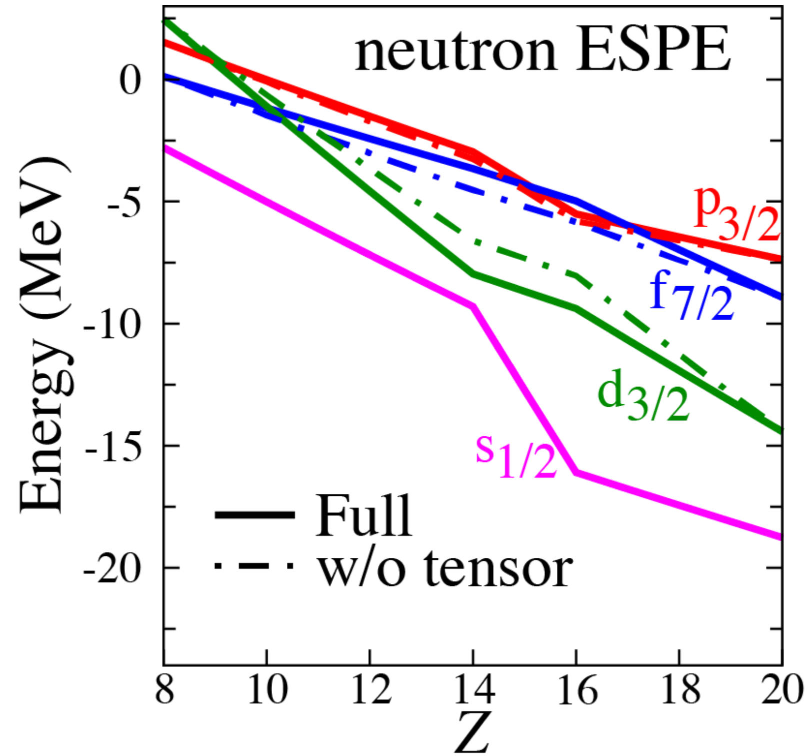
energy indpendent

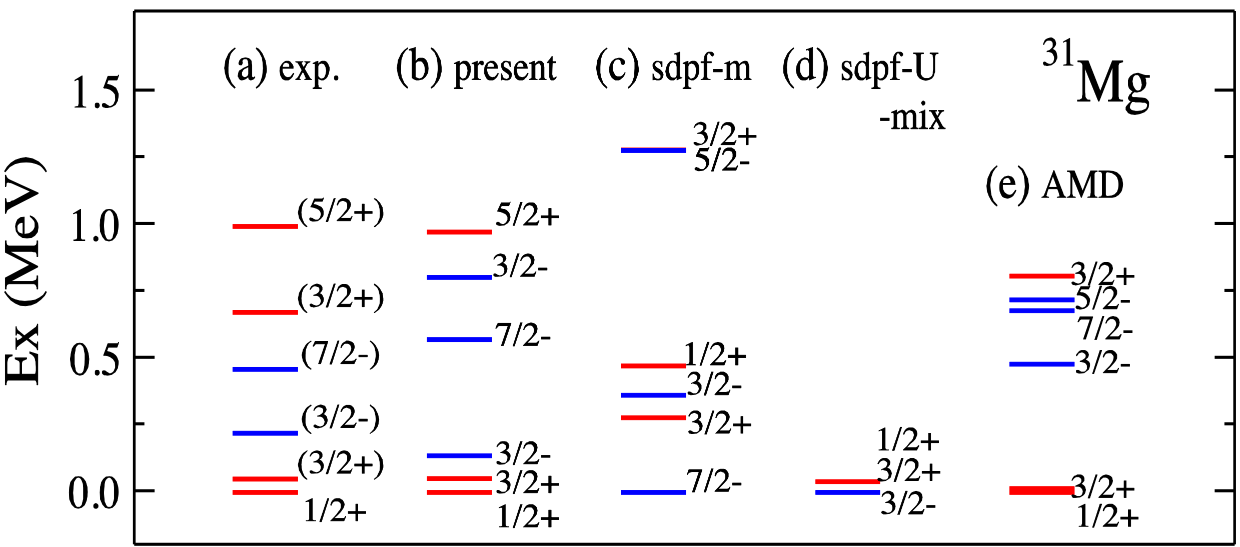
K. Takayanagi, Nucl. Phys. A **852**, 61 (2011).
K. Takayanagi, Nucl. Phys. A **864**, 91 (2011).

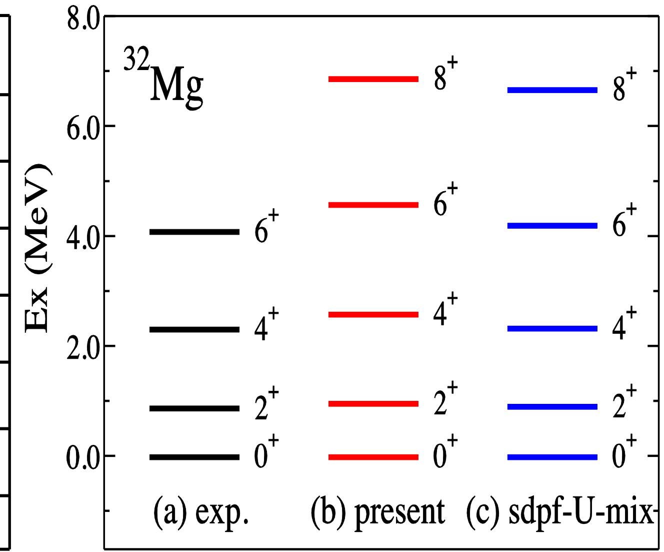
Neutron-rich isotopes in the island of inversion by EKK-method starting from chiral EFT interaction N^3LO+3N (FM)

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

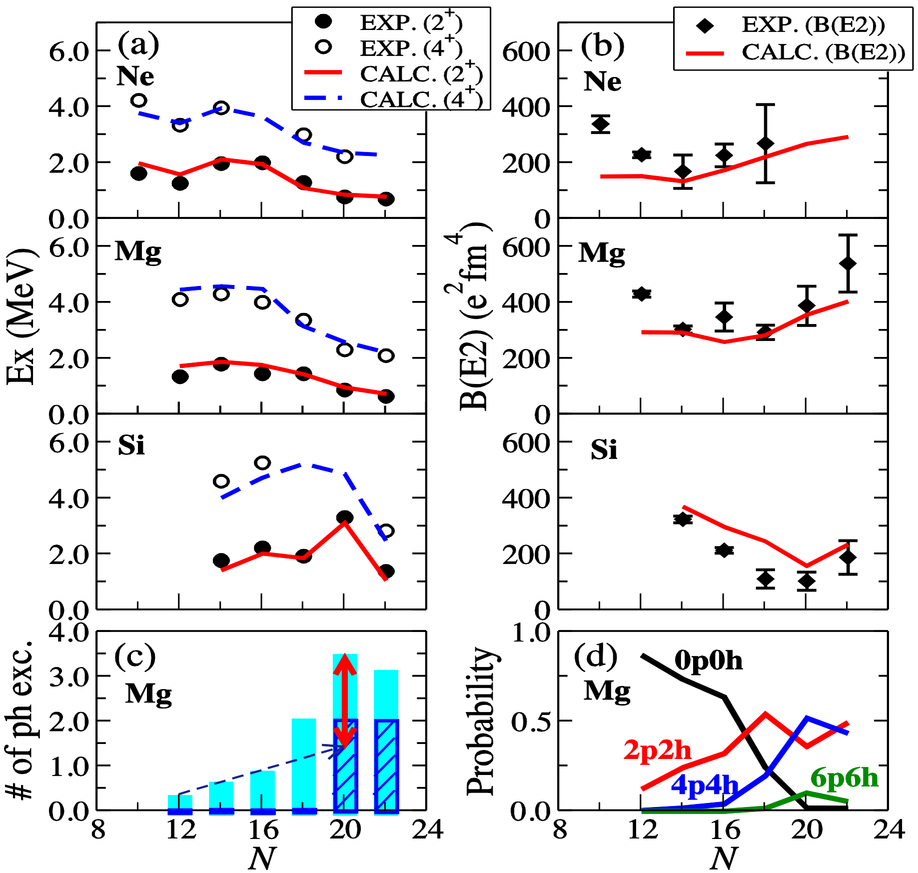




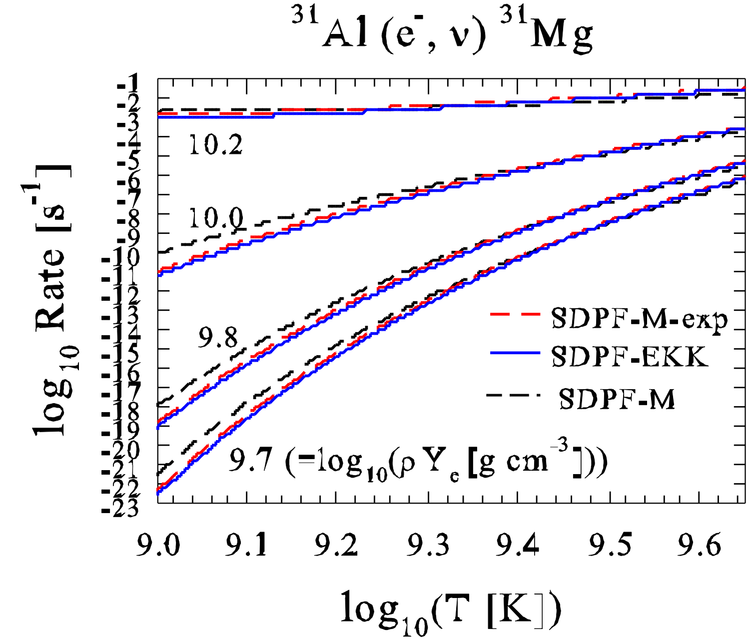


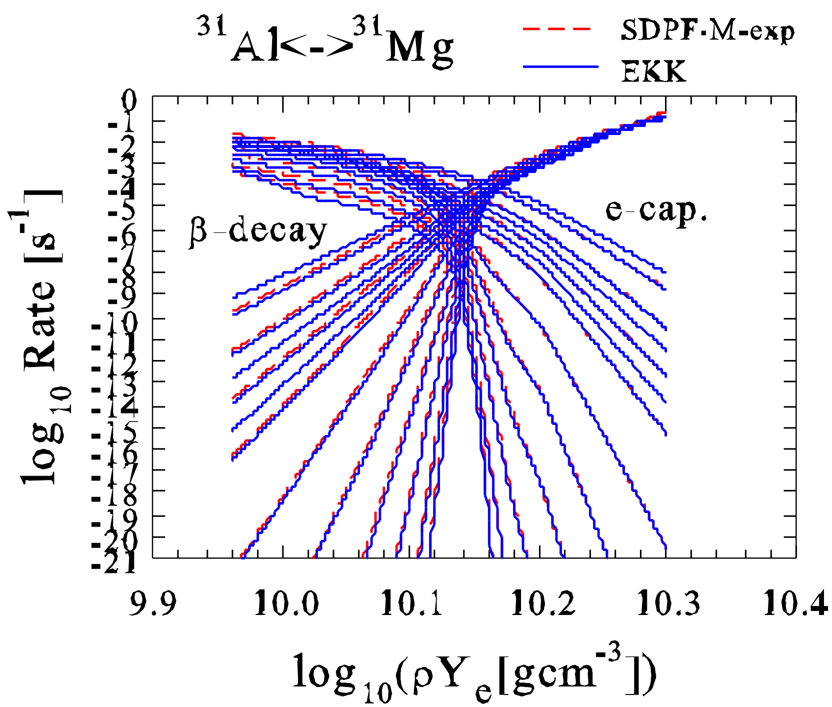


EKK vs EXP



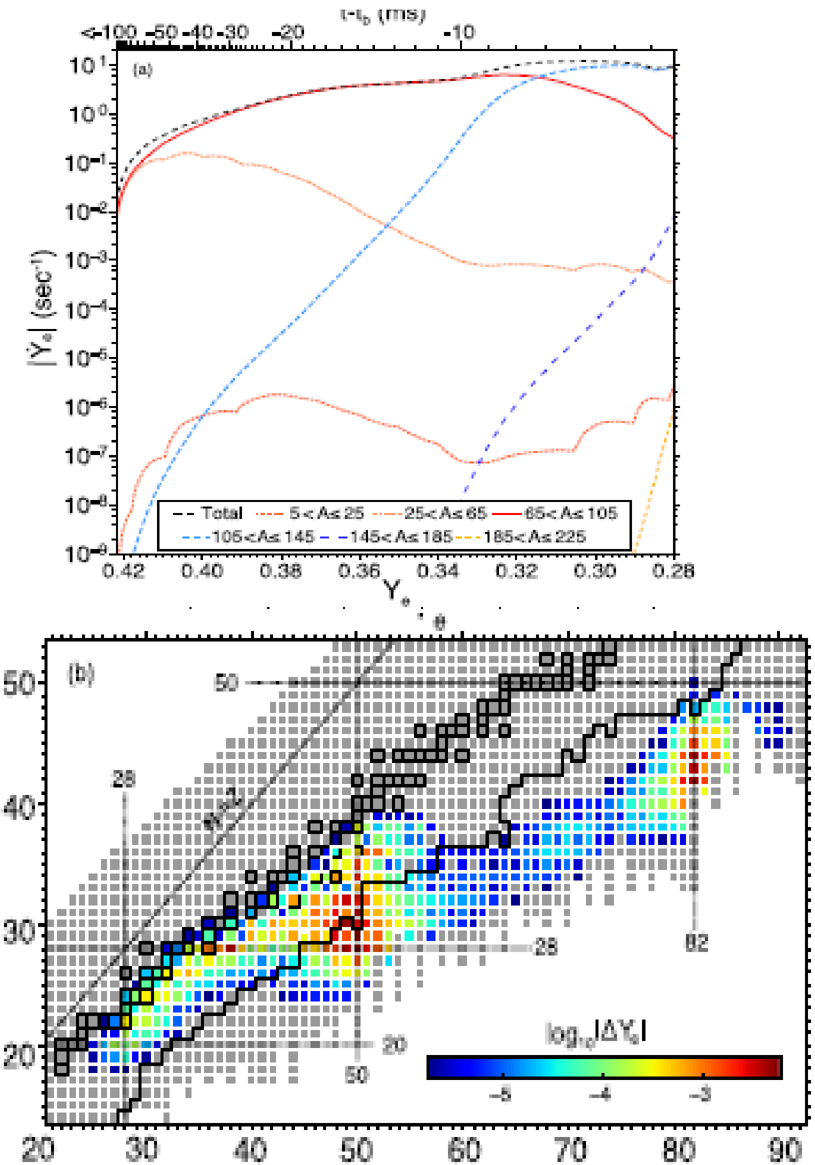
2p-2h+4p-4h





2b. Weak rates of pf-g shell nuclei and core-collapse SNe

Which nuclei affect $\dot{Y}_e$(change of Y_e) most in core-collapse process?



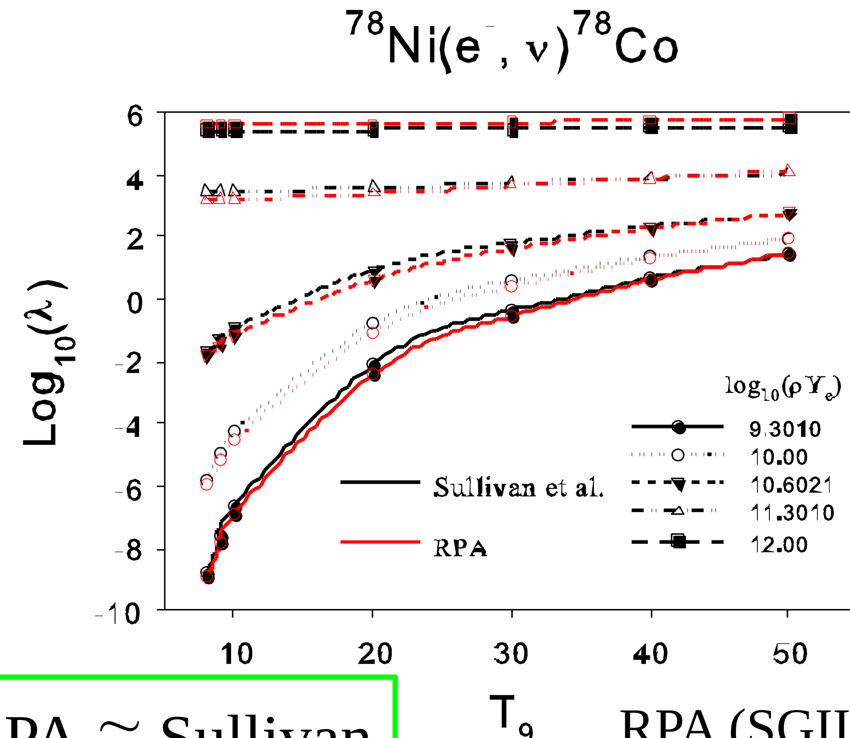
Sullivan et al., ApJ. 816, 44 (2016)

^{78}Ni

- Approx. rates of Sullivan et al.
- RPA
- SM (pf-$g_{9/2}d_{5/2}$; modified A3DA)

Q= -18.88 MeV (set to be HFB21's)

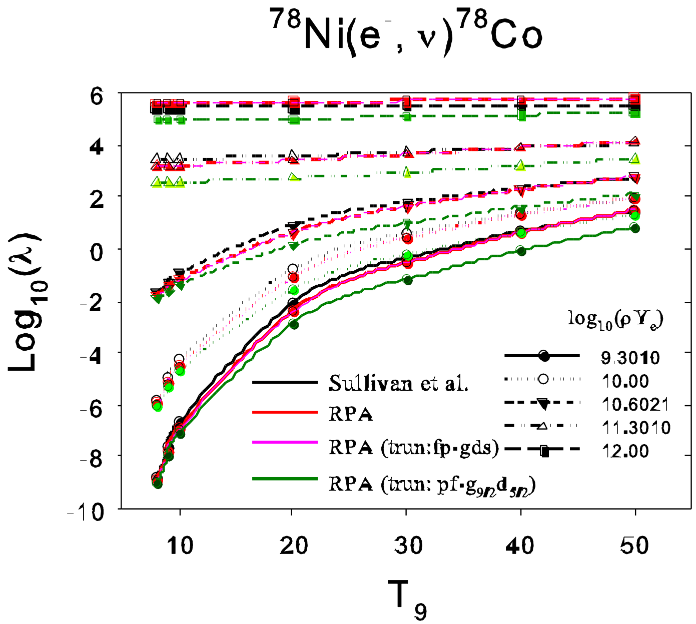
g_A^{eff}/g_A=0.74 (1.0) for GT (other multipoles)



RPA (SGII)

RPA ≈ Sullivan

Effects of truncation of space



pf-gds is enough, pf-$g_{9/2}d_{5/2}$ is not enough

Sum of the strengths

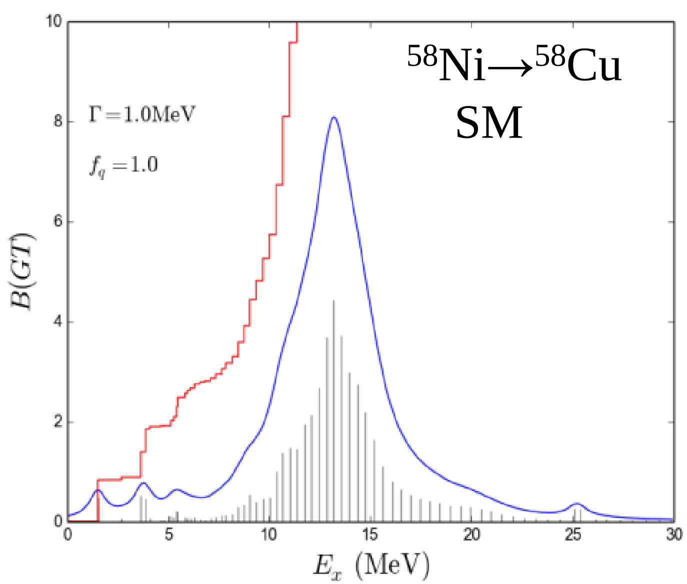
S=Σ_i<g.s. |O^+ |i><i|O|g.s.>

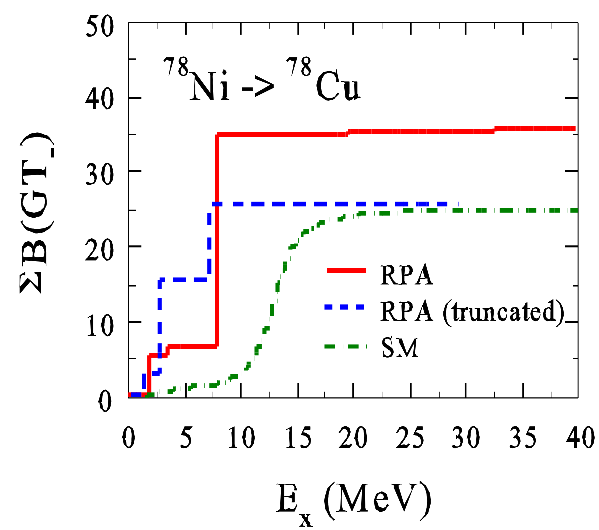
	SM(pfg9d5)	SM(pfgds)	RPA (full)
GT	0.0078	0.0804	0.3711
E1	3.202	4.368	4.231
SD0	0.046	12.083	12.378
SD1	1.603	20.241	20.683
SD2	2.616	14.098	15.995

SM: |g.s.> = |pfg9d5>

SM: modified A3DA; pf-$g_{9/2}d_{5/2}$
Y.Tsunoda et al., PRC 89, 031301R (2014)
$E_x(2^+)$ = 2.8 MeV
Up to 5p-5h outside filling config. of ^{78}Ni

SM with pf-gds in progress





Summary

1. Weak rates for one-major shell nuclei

○New weak rates for sd-shell from USDB

Evolution of 8-10 solar-mass stars is sensitive to e-capture and β-decay rates in sd-shell nuclei, especially for A=23 and 25 Urca nuclear pairs.

Nuclear URCA processes determine the fate of stars with ∼9$M_\odot$ whether they end up with e-capture SNe or core-collapse SNe.

○New weak rates for pf-shell from GXPF1J

Nucleosynthesis of iron-group elements in Type Ia SNe.

GXPF1J gives smaller e-capture rates compared with KBF, KB3G and FFN, and leads to larger Y_e with less neutron-rich isotopes, and thus can solve the over-production problem in iron-group nuclei.

New weak rates for sd-shell based on USDB, and pf-shell based on GXPF1J are tabulated.

2. Weak rates for two-major shell nuclei

○ **Nuclear weak rates for sd-pf shell nuclei in the island of inversion, which are important for Urca processes in neutron star crusts, are evaluated with EKK mehod starting from chiral EFT interaction N3LO +3N (FM).**
e.g. $^{31}Al\ (e^-, \nu)^{31}Mg$, $^{31}Mg(,e^- \nu)^{31}Al$

○ **Electron-capture rates for ^{78}Ni are evaluated by RPA and SM with pf-$g_{9/2}d_{5/2}$ configurations.**
RPA ≈ Sullivan's formula (g_A^{eff}/g_A for SD transitions =1.0)
SM: need for extension to fp-gds configurations; in progress

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