Spin-dependent Modes in Nuclei and Astrophysical Processes

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Simplicity, Symmetry and Beauty of Atomic Nuclei
"in honor of Prof. Arima's 88 year-old Birthday"
Shanghai
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New shell-model Hamiltonians with proper inclusion of tensor components describe the spin modes in nuclei such as GT strength and M1 moments and transitions very well:

GT strength in ^{12}C, ^{14}C (p-shell), Ni and Fe isotopes (pf-shell)

Magnetic moments in p-shell nuclei, M1 strength in pf-shell nuclei

Roles of nuclear forces

tensor, 2body-LS, & 3-body forces

- shell evolutions in p-sd and sd-shell nuclei

  inversion of $0d_{5/2}$-$1s_{1/2}$: ^{17}O-^{15}C (tensor + 2-body LS)

  shell evolutions in C and O isotopes, dripline of O isotopes (3-body)

e-capture rates in stellar environments

- sd-shell: cooling of O-Ne-Mg core by nuclear URCA process
- pf-shell: type-Ia SNe and synthesis of iron-group elements

ν-nucleus reactions: $E_\nu \leq 100$ MeV

- low-energy ν-detection: SNν, solar ν, reactor ν

  Scintillator (CH, …), H_2O, Liquid-Ar, Fe
- nucleosynthesis of light elements in SNe

  ν-oscillation effects on nucleosynthesis and ν detection

● New shell-model Hamiltonians

1. SFO (p-shell; space p-sd shell)
2. SFO-tls, YSOX (p +p-sd shell)
3. GXPF1J (pf-shell)
4. V_MU (monopole-based universal interaction)

Suzuki, Fujimoto, Otsuka, PR C69, (2003) , Yuan, Suzuki, Otsuka .. PRC85 (2012)
Suzuki and Otsuka, PR C 78 (2008)
Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)
Otsuka, Suzuki, Honma, Utsuno et al., PRL 104 (2010) 012501

* important roles of tensor force

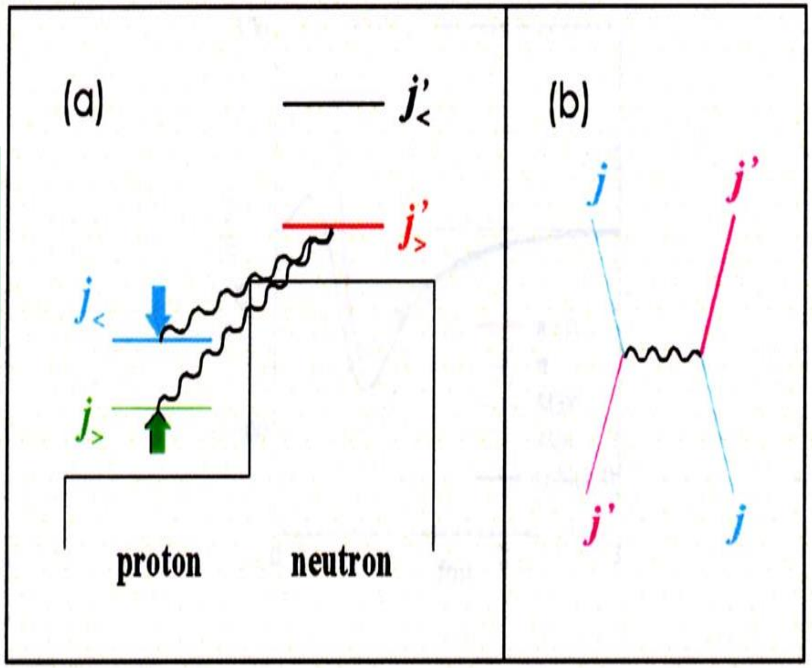
Monopole terms of V_{NN}

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

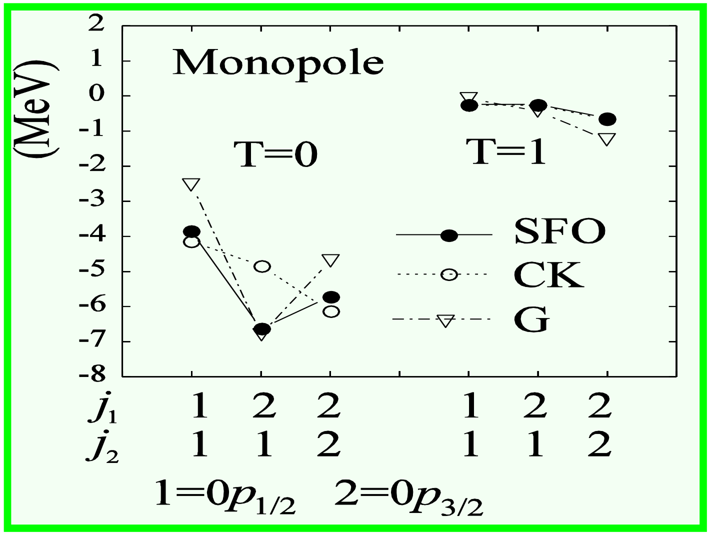
$j_> - j_<$: attractive

$j_> - j_>, j_< - j_<$: repulsive

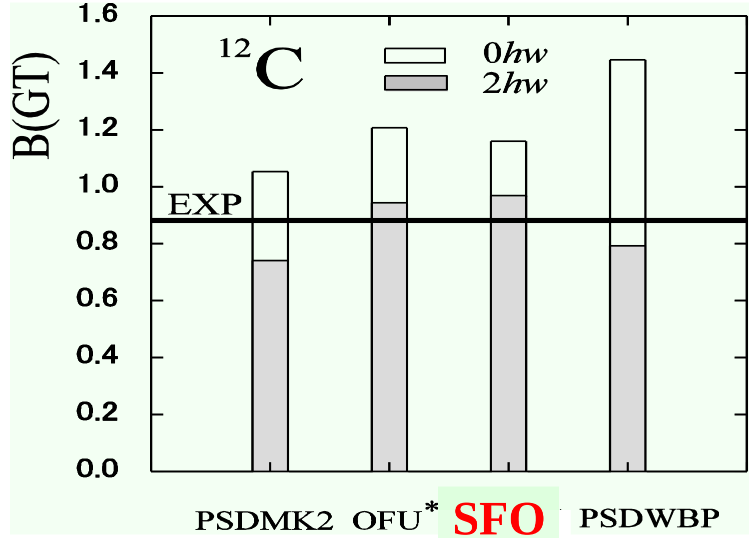
Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)



SFO: p-sd shell



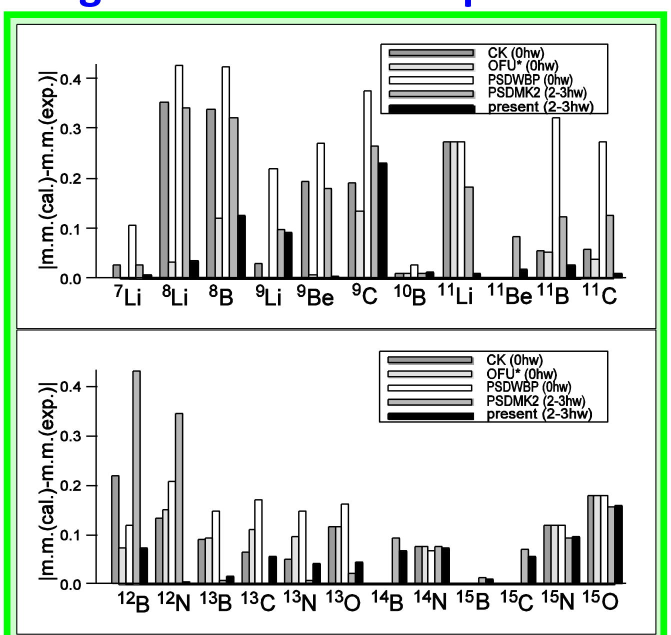
B(GT) for $^{12}C \rightarrow ^{12}N$



SFO: $g_A^{eff}/g_A = g_s^{IV, eff}/g_s^{IV} = 0.95$

B(GT: ^{12}C)_cal = experiment

Magnetic moments of p-shell nuclei

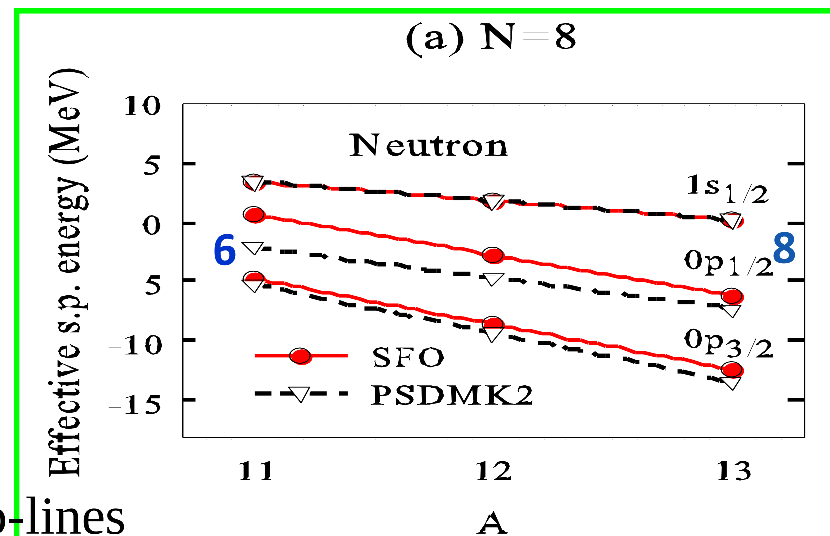


present = SFO space: up to 2-3 hw

Magic #
N=8→6

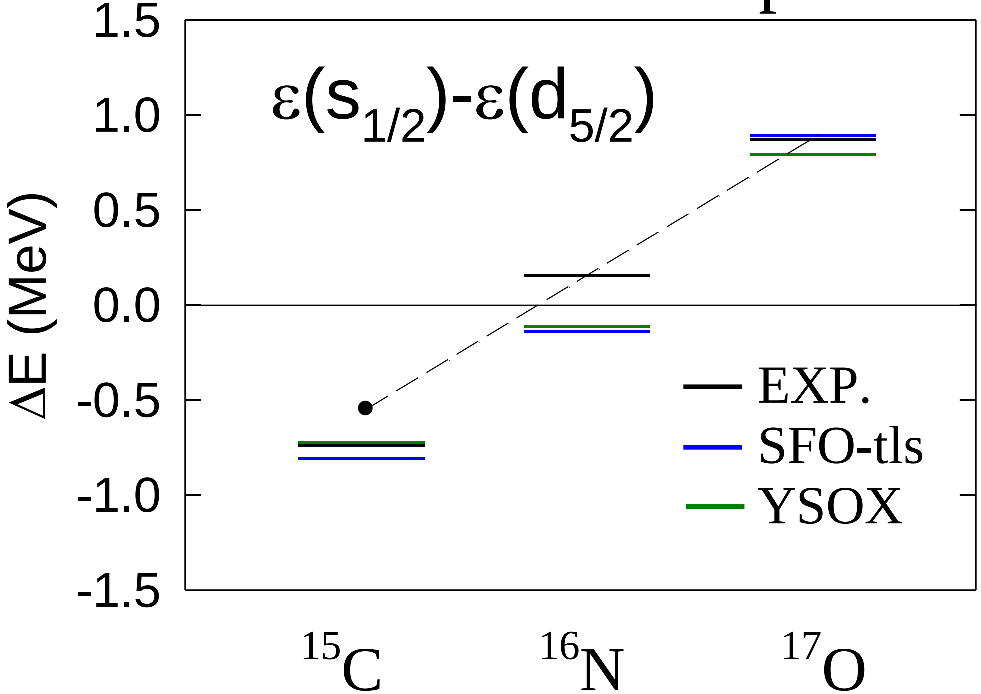
attraction
$\pi p_{3/2}$-$\nu p_{1/2}$
decreases
toward drip-lines

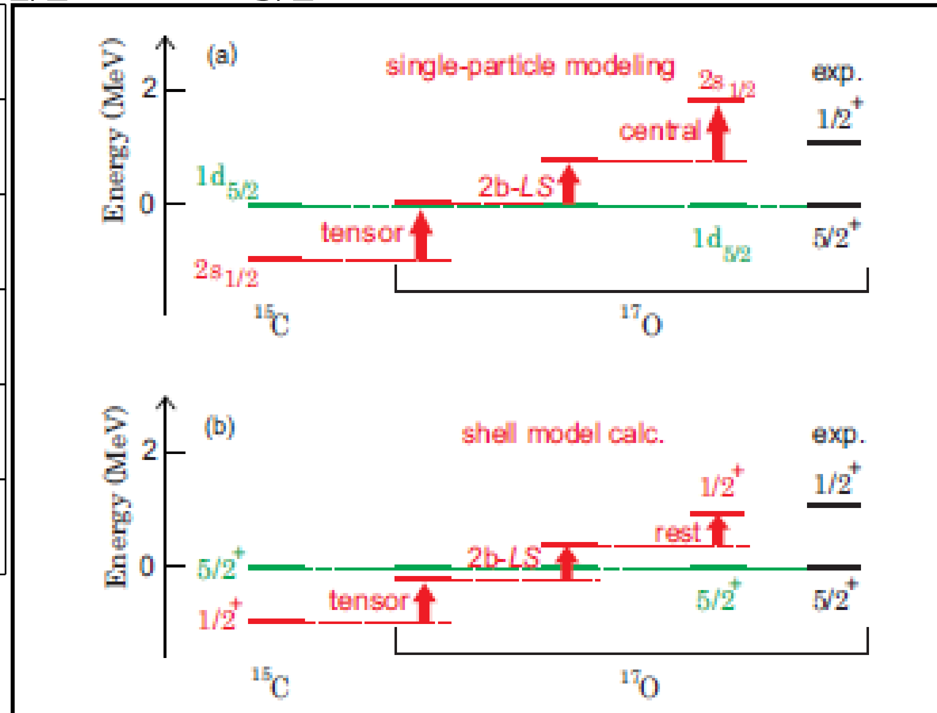
Shell evolution in N=8 isotone



Shell evolutions in p-sd and sd-shell nuclei

- Inversion of effective s.p.e of $s_{1/2}$ and $d_{5/2}$





Talmi and Unna, PRL 4, 469 (1960):
^{17}O, ^{16}N -> ^{15}C: linear extrapolation

Full inclusion of tensor in p-sd

p-sd: tensor ($\pi+\rho$), LS ($\sigma+\rho+\omega$)

tensor = attractive for $\pi p_{1/2}$-$\nu d_{5/2}$
= 0 for $\pi p_{1/2}$-$\nu s_{1/2}$
2-body LS = repulsive for $\pi p_{1/2}$-$\nu s_{1/2}$
Less # of $\pi p_{1/2} \rightarrow \nu d_{5/2}$ up, $\nu s_{1/2}$ down

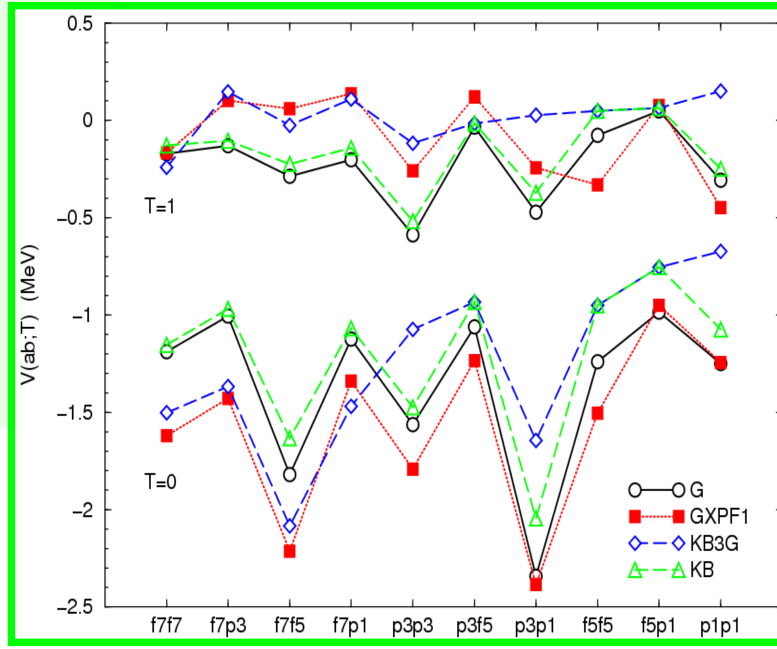
SFO-tls: Suzuki, Otsuka, PR C78, 061301(R) (2008)

YSOX: Yuan, Suzuki, Otsuka, Xu, Tsunoda, PR C85, 064324 (2012)
p-sd cross shell: VMU (monopole-based universal interaction)

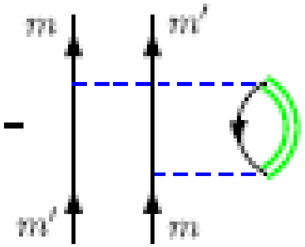
● 3 body forces induced by Δ excitations (Fujita-Miyazawa)

→ repulsion in T=1 monopoles of valence particles

^{24}O=drip-line nucleus of oxygen isotopes



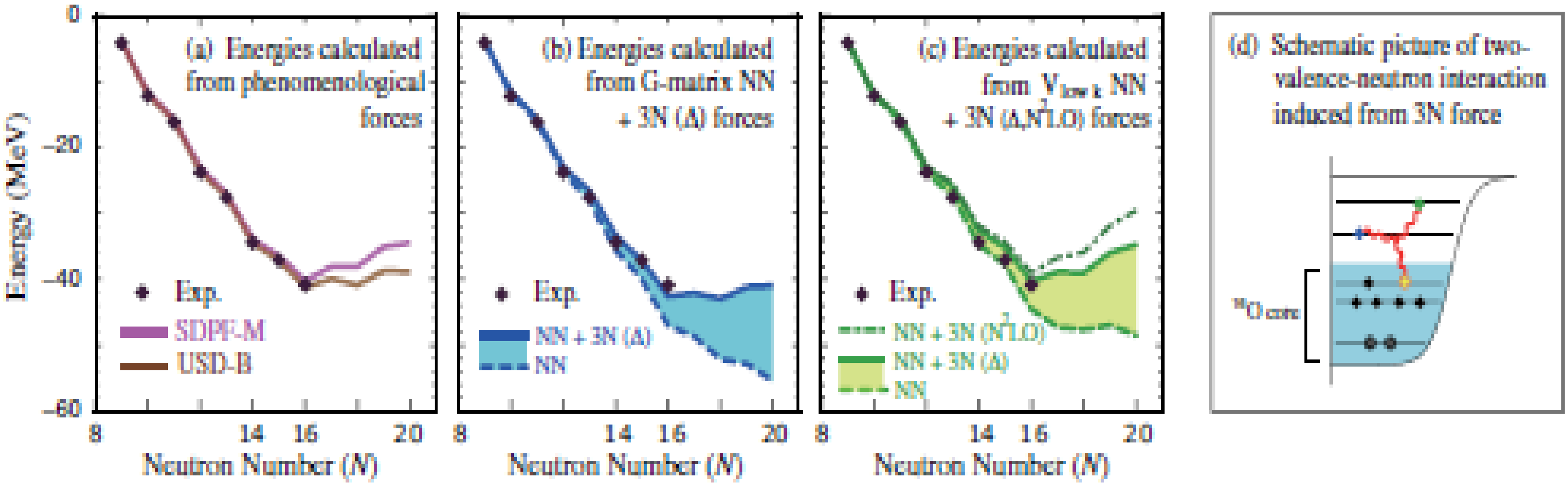
Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105 032501 (2010)



$$- \quad \Delta = \frac{1}{\Delta M}\sum_{h\Delta}|<mh|V|m'\Delta>|^2 > 0$$

more repulsion than G in T=1

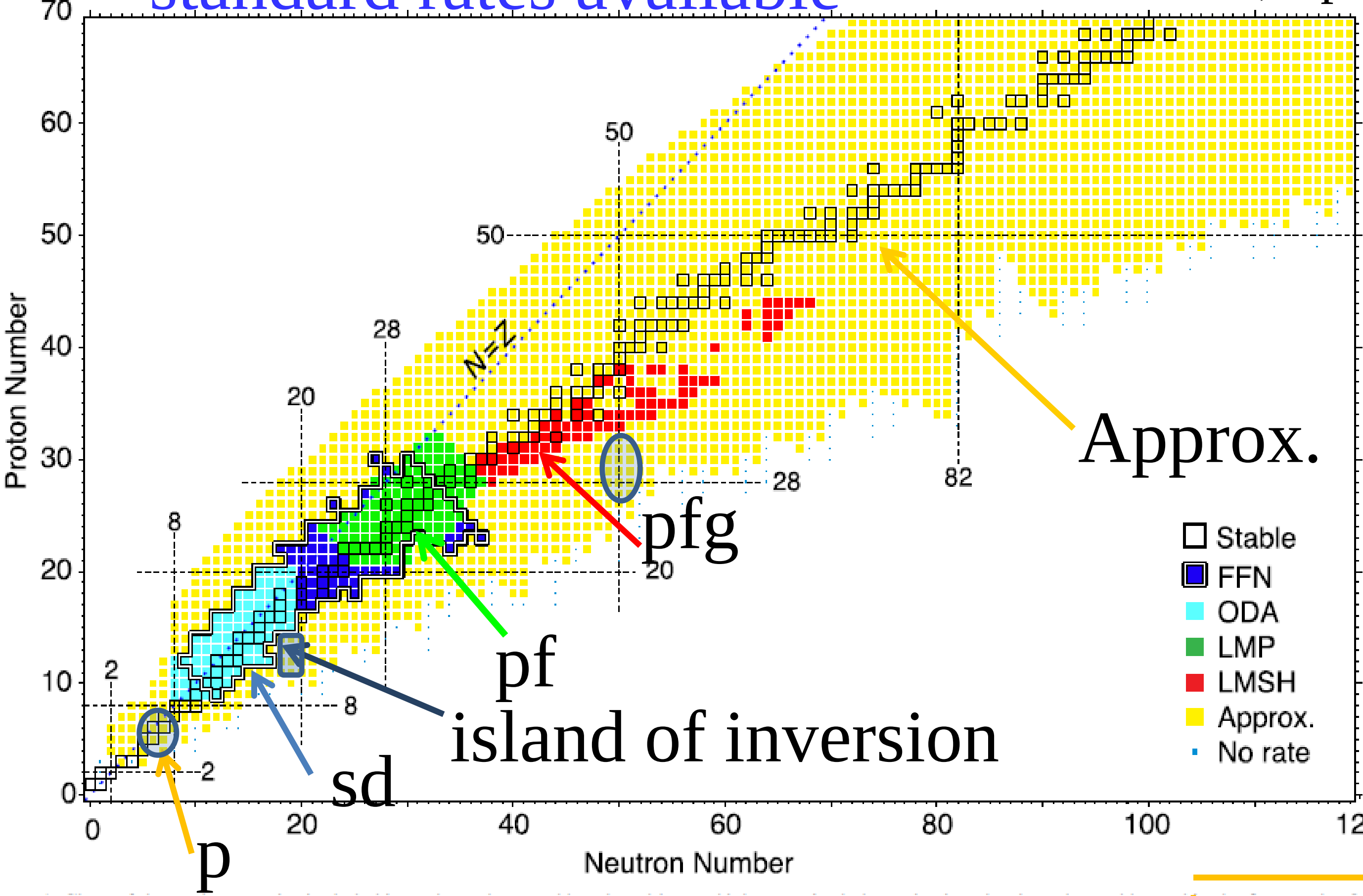
more attraction than G in T=0



Electron-capture (weak) rates in stellar environments

- standard rates available

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



- Missing
- Island of inv. sd-pf
- $\sim^{78}$Ni N=50 pf-gds
- p-shell

Approx.

B (=4.6) and ΔE (=2.5 MeV)

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

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

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

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

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

	standard	update
sd	ODA (USD)	Toki-Suzuki-Nomoto (USDB)
pf	LMP(KBF)	Honma & Suzuki (GXPF1J)
sd-pf	RPA	N. Tsunoda (EKK)
pf-g	LMSH	Y. Tsunoda (A3DA)

▪URCA processes in sd-shell nuclei (USDB)

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

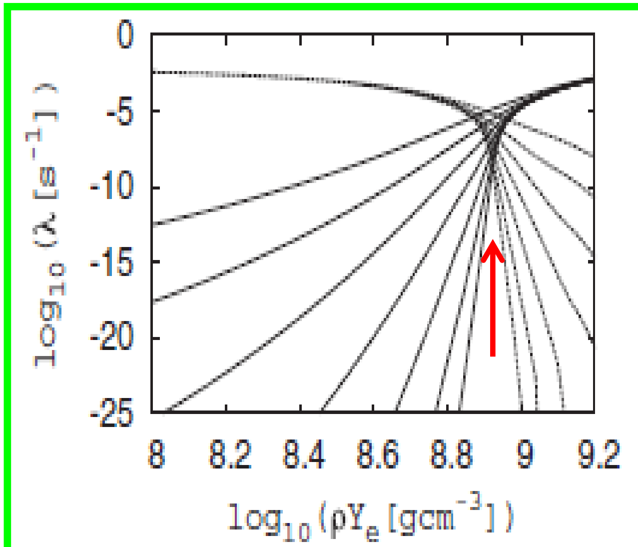
e-capture: ${}^{A}_{Z}X + e^- \rightarrow {}_{Z-1}^{\ \ A}Y + \nu$

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

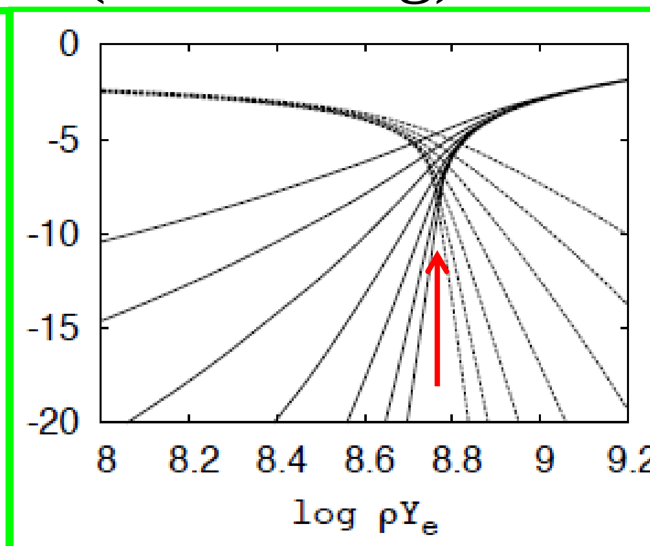
They occur simultaneously at certain stellar conditions and energy is lost from stars by emissions of ν and → Cooling of stars

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

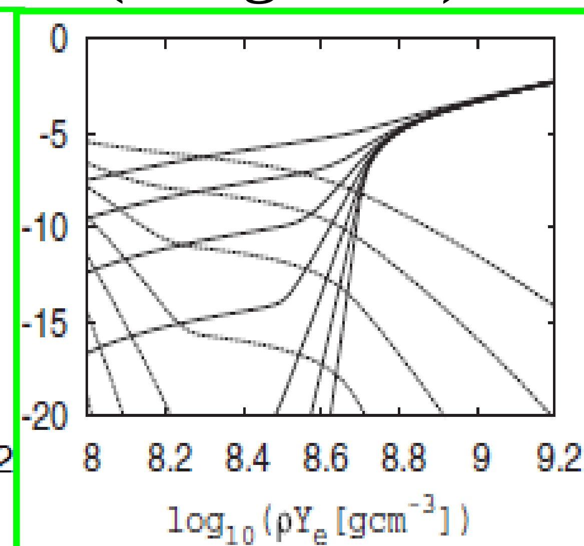
(^{23}Ne, ^{23}Na) (^{25}Na, ^{25}Mg) (^{27}Mg, ^{27}Al)



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



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



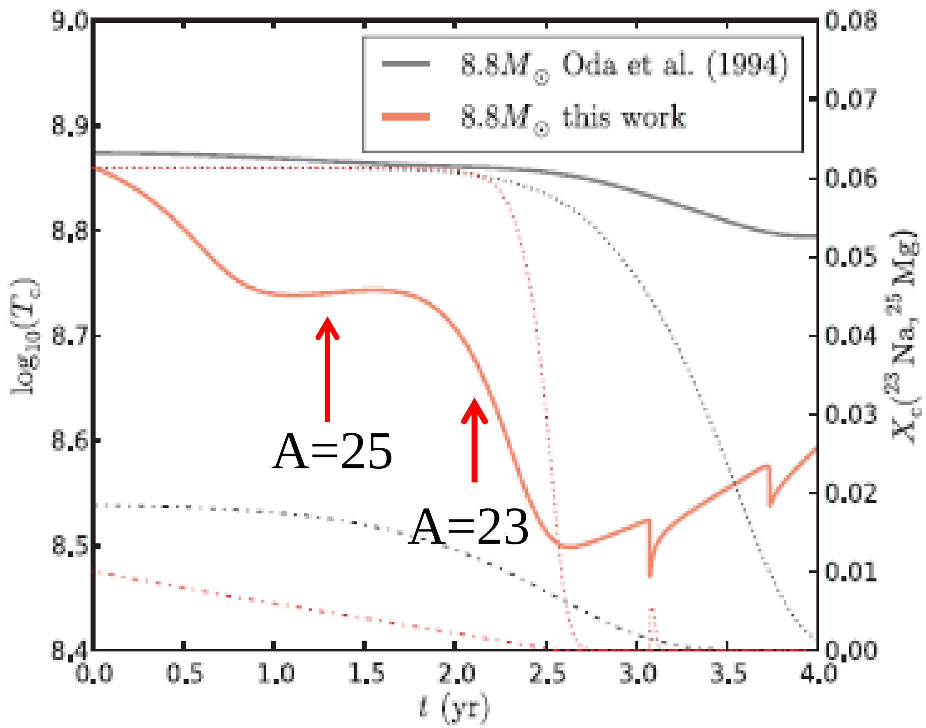
g.s. $1/2^+ \longleftrightarrow 5/2^+$ forbidden

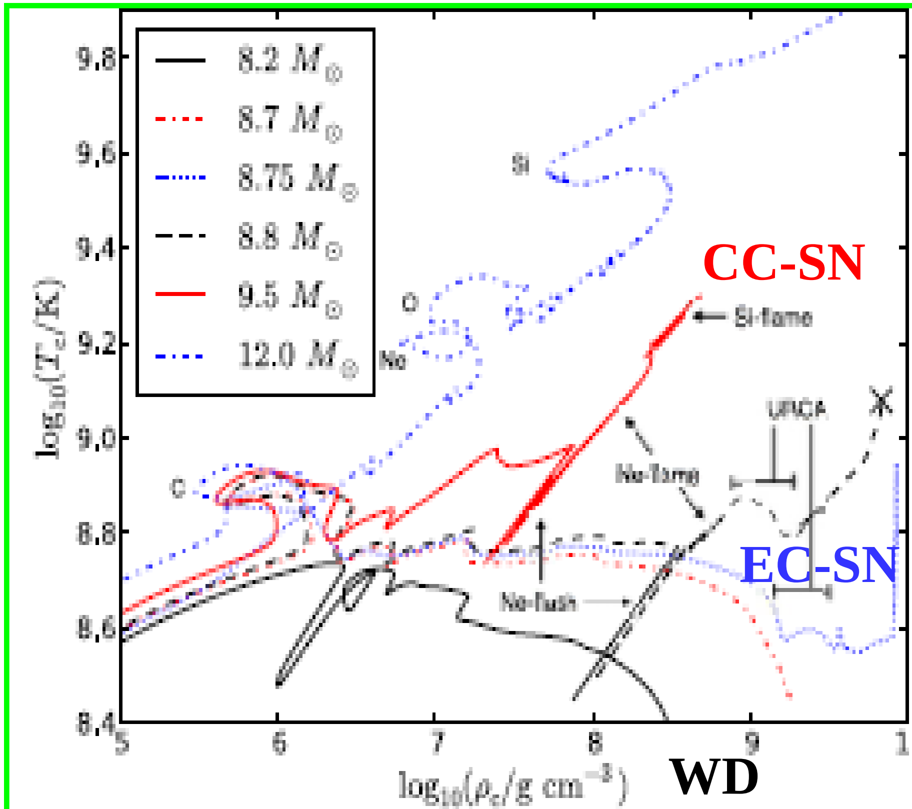
No clear URCA density for A=27 pair

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

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

Fate of 8-10$M_\odot$ stars





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

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

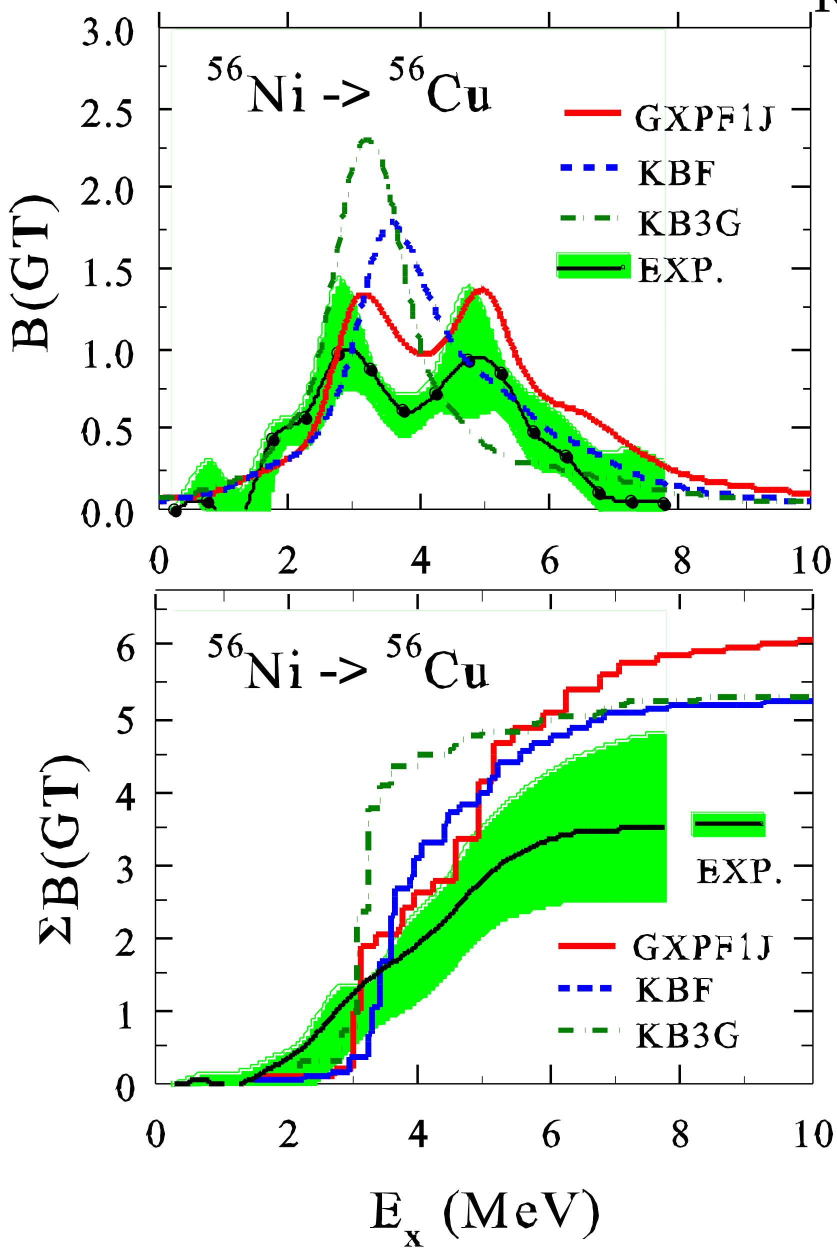
Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)

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

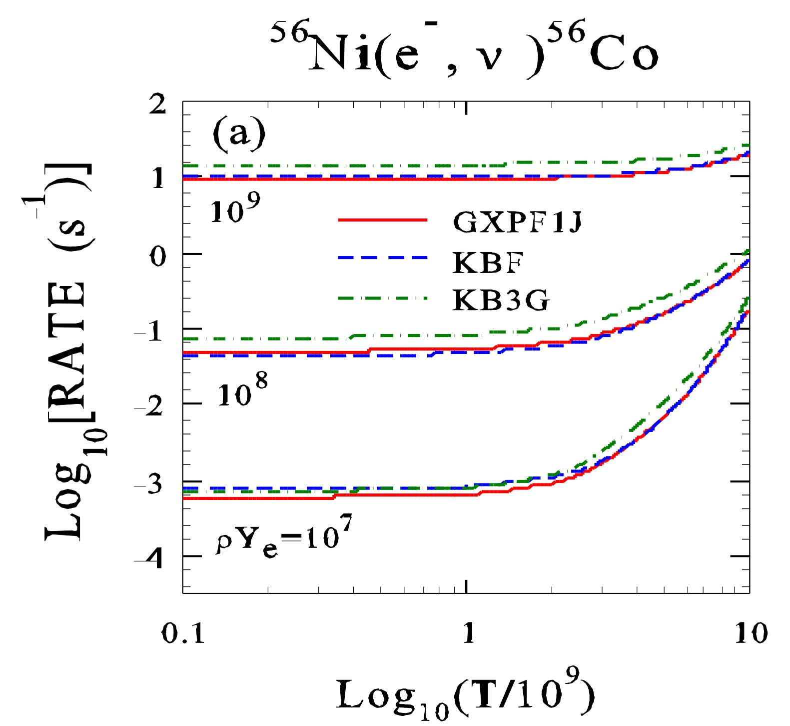
▪pf-shell: GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF

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:

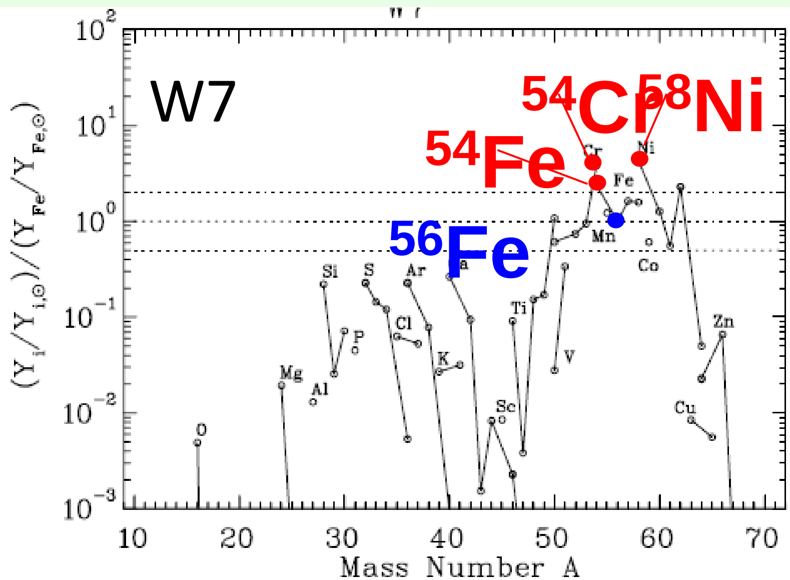


EXP: Sasano et al., PRL 107, 202501 (2011)



Type-Ia SNe and synthesis of iron-group nuclei

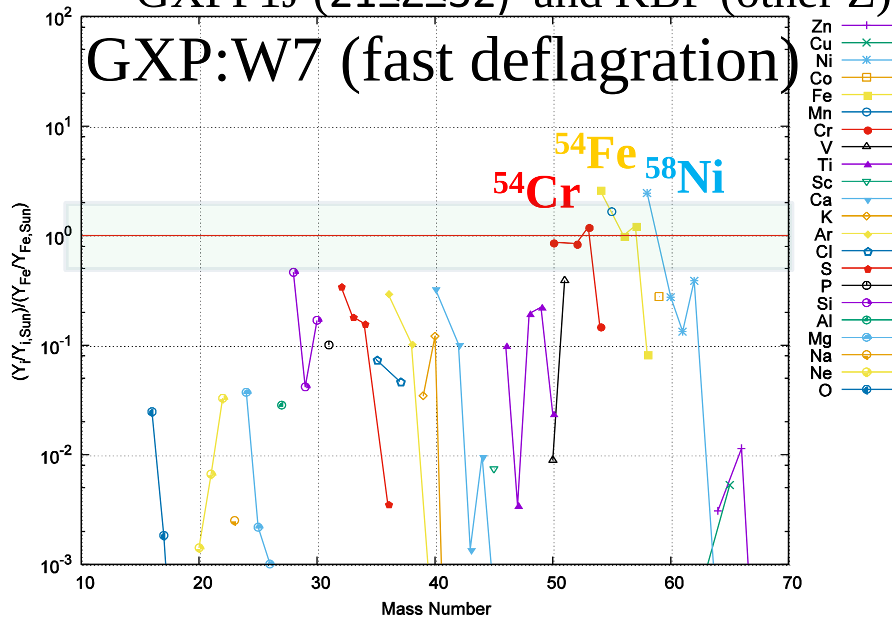
Problem of over-production of neutron-excess iron-group isotopes such as ^{58}Ni, ^{54}Cr … compared with solar abundances



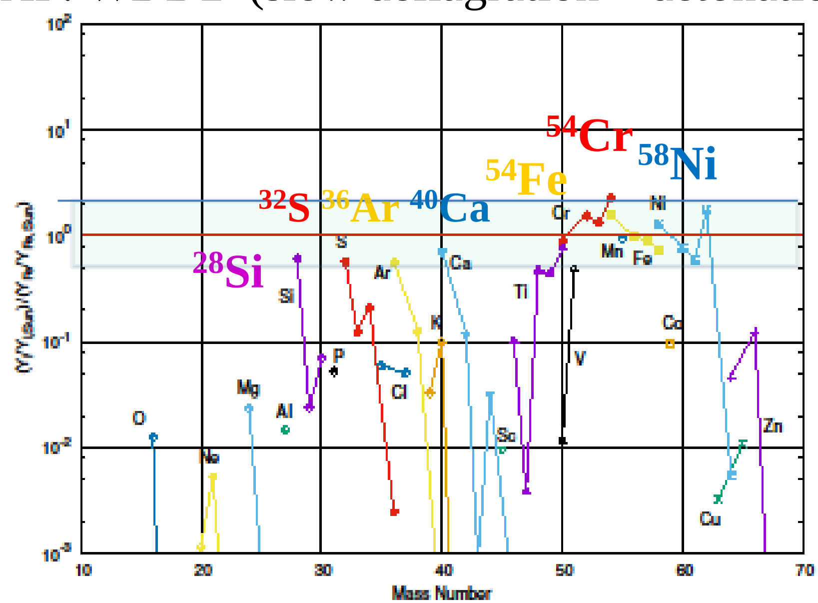
Iwamoto et al., ApJ. Suppl, 125, 439 (1999)

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

$Y_e = 0.5 \rightarrow Y_e < 0.5$ (neutron-rich)

→ production of neutron-rich isotopes; more ^{58}Ni

Decrease of e-capture rate on ^{56}Ni

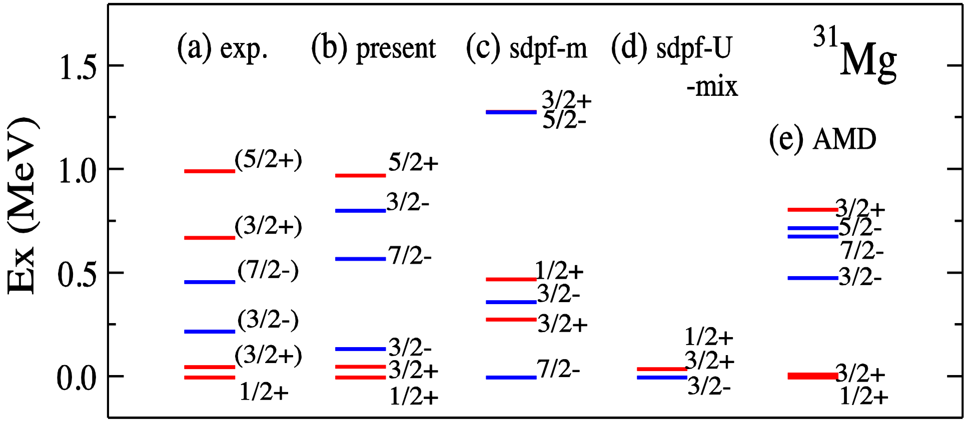
→less production of ^{58}Ni and larger Y_e

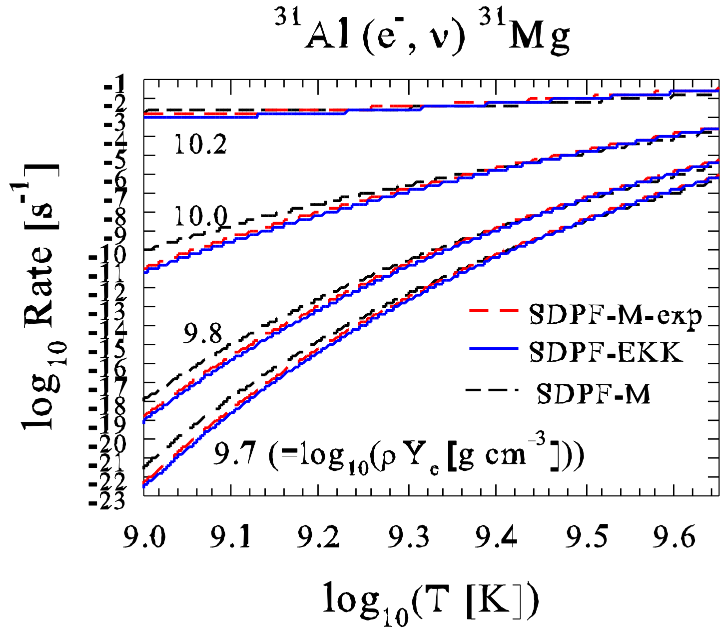
Mori, Famiano, Kajino, Suzuki, Hidaka, Honma, Iwamoto, Nomoto, Otsuka, ApJ. 833, 179 (2016)

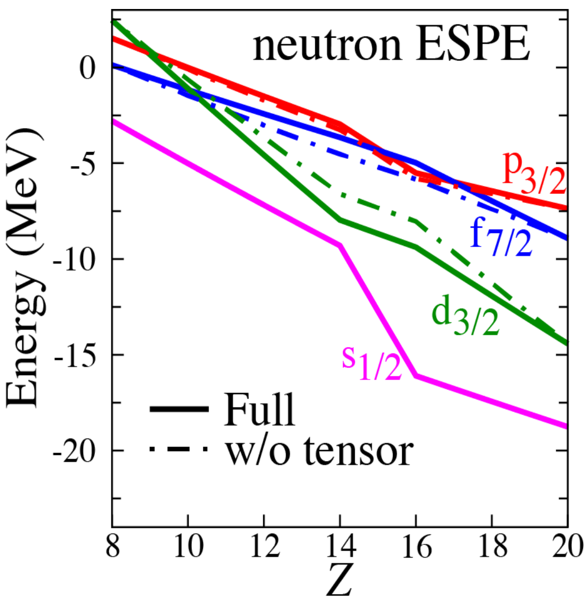
Neutron-rich isotopes in the island of inversion by EKK-method starting from chiral EFT interaction N^3LO+3N (FM)

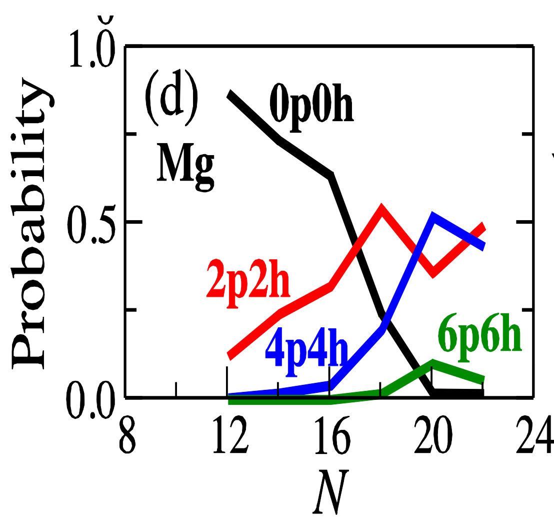
Tsunoda, Otsuka, Shimizu, Hjorth-Jensen,
Takayanagi and Suzuki, PRC 95, 021304(R) (2017)

EKK vs EXP

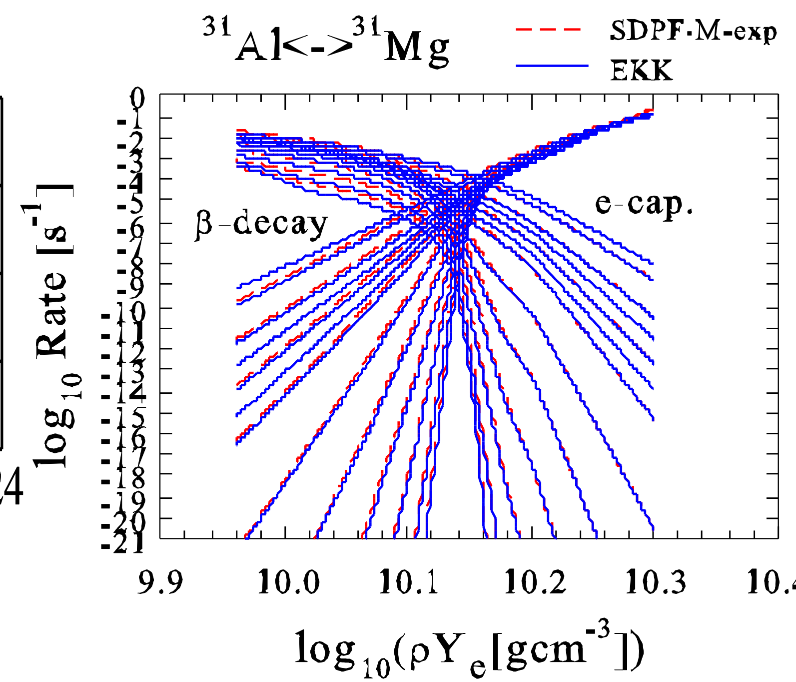








2p-2h+4p-4h



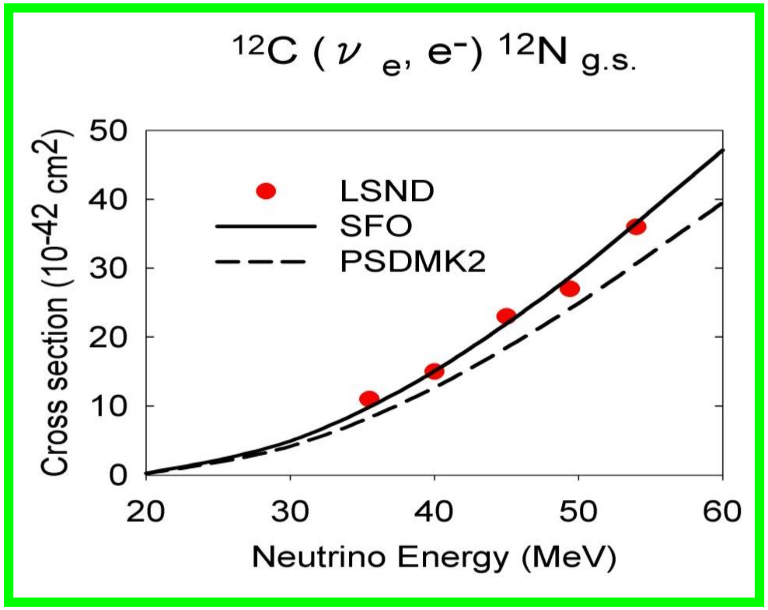
● ν-nucleus reactions

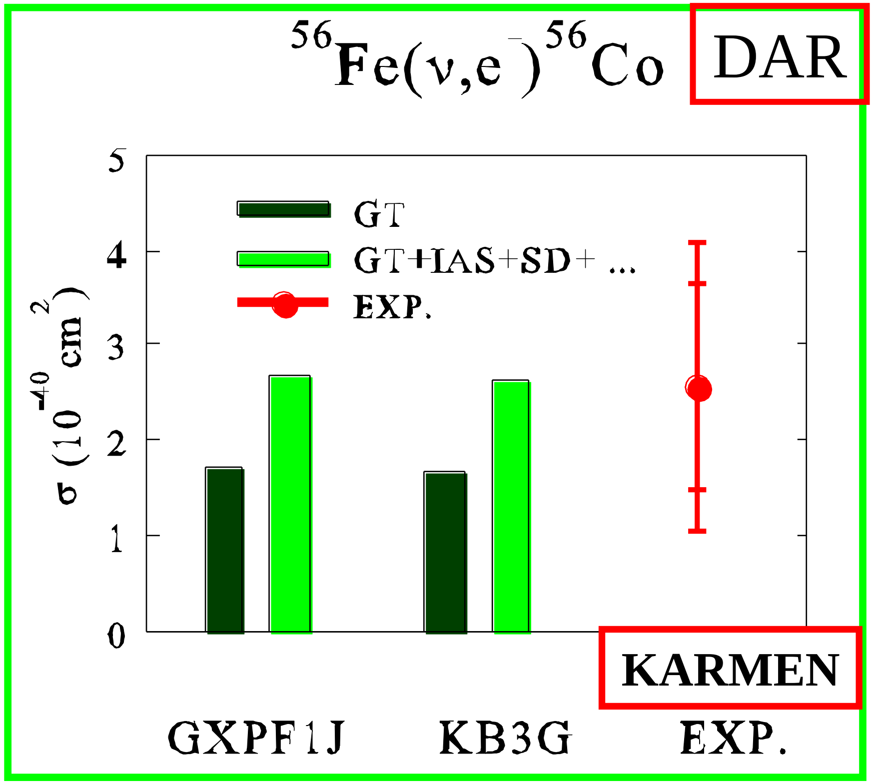
1. ν-^{12}C, ν- ^{13}C: SFO (p-shell)
2. ν-^{16}O, . ν-^{18}O: SFO-tls, YSOX (p +p-sd shell)
3. ν-^{56}Fe, ν-^{56}Ni: GXPF1J (pf-shell)
4. ν-^{40}Ar: VMU (sd-pf)+SDPF-M (sd) +GXPF1J (pf)

B(GT)=9.5 $B(GT)_{exp}=9.9\pm2.4$
$B(GT)_{KB3G}=9.0$

SD + … : RPA (SGII)

Suzuki, Chiba, Yoshida, Kajino, Otsuka, PR C74 (2006)
Suzuki, Balantekin, Kajino, PR C86 (2012)
Suzuki, Honma et al., PR C79, (2009)
Suzuki and Honma, PR C87, 014607 (2013)

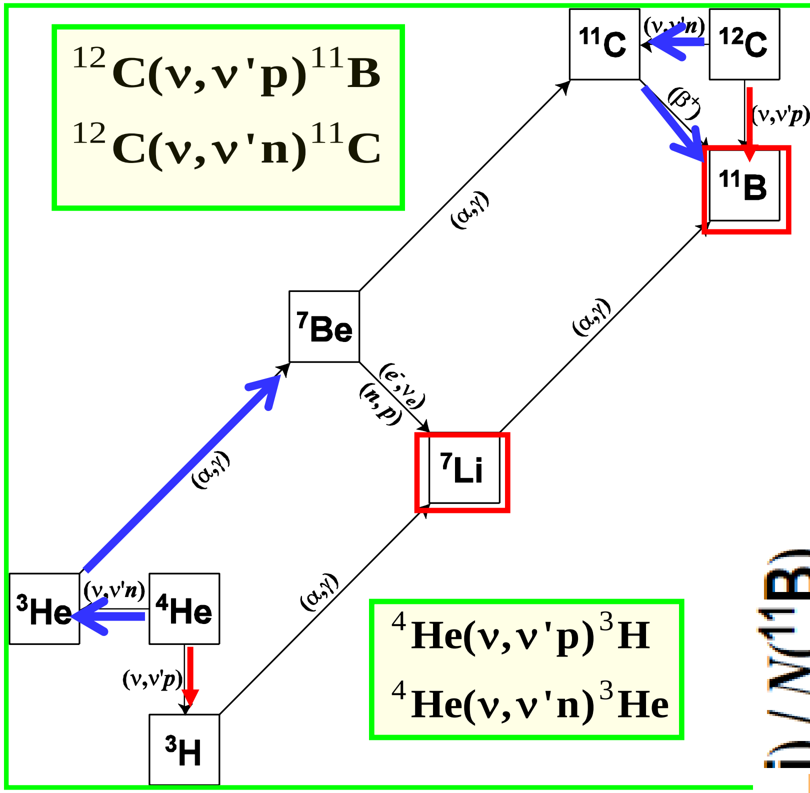




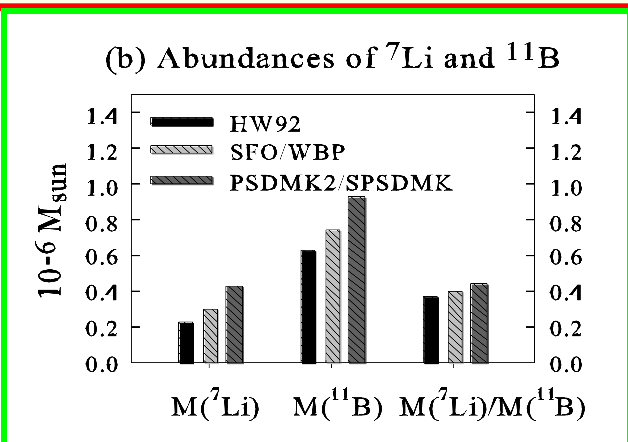
SFO: $g_A^{eff}/g_A=0.95$
B(GT: 12C)_cal = experiment

$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}$ cm^2.
SM(GXPF1J)+RPA(SGII) 259 x10 $^{-42}$cm^2

▪Nucleosynthesis processes of light elements in SNe



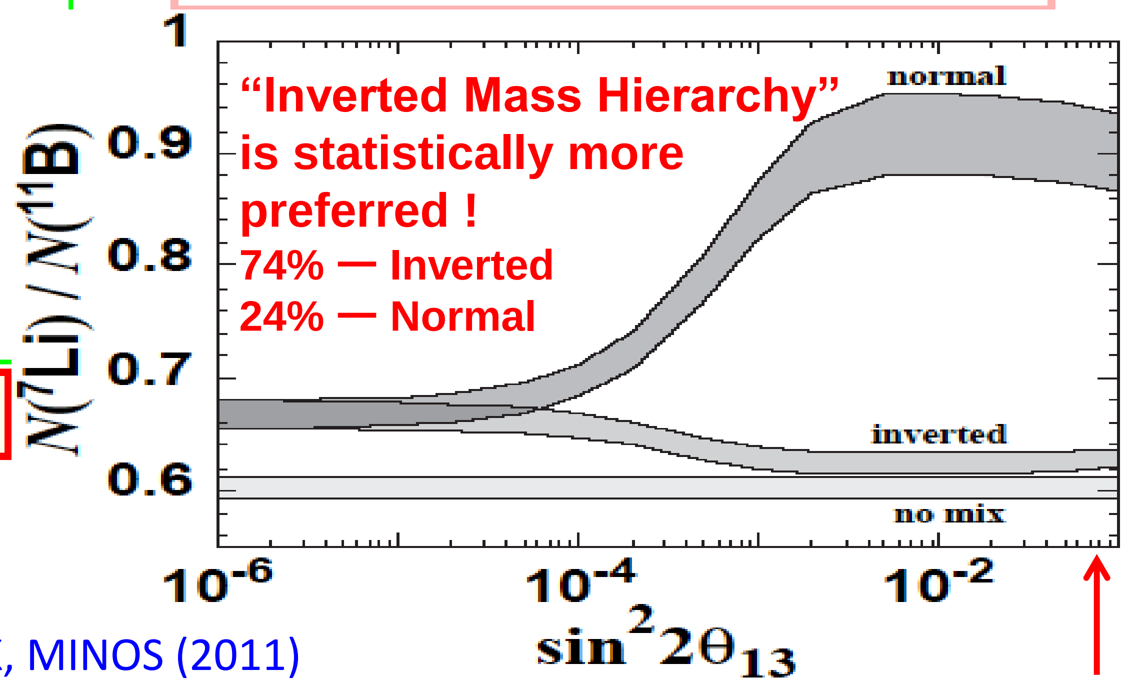
Enhancement of ^{11}B and ^{7}Li abund.



Effects of MSW ν oscillations

Normal – hierarchy : $\nu_\mu, \nu_\tau \rightarrow \nu_e$

Increase in the rates in the He/C layer:
$^{4}He(\nu_e, e^- p)^{3}He$
$^{12}C(\nu_e, e^- p)^{11}C$



- ▪T2K, MINOS (2011)
- ▪Double CHOOZ, Daya Bay, RENO (2012)

$\sin^2 2\theta_{13} = 0.1$

Bayesian analysis:
Mathews, Kajino, Aoki and Fujiya, Phys. Rev. D85,105023 (2012).1

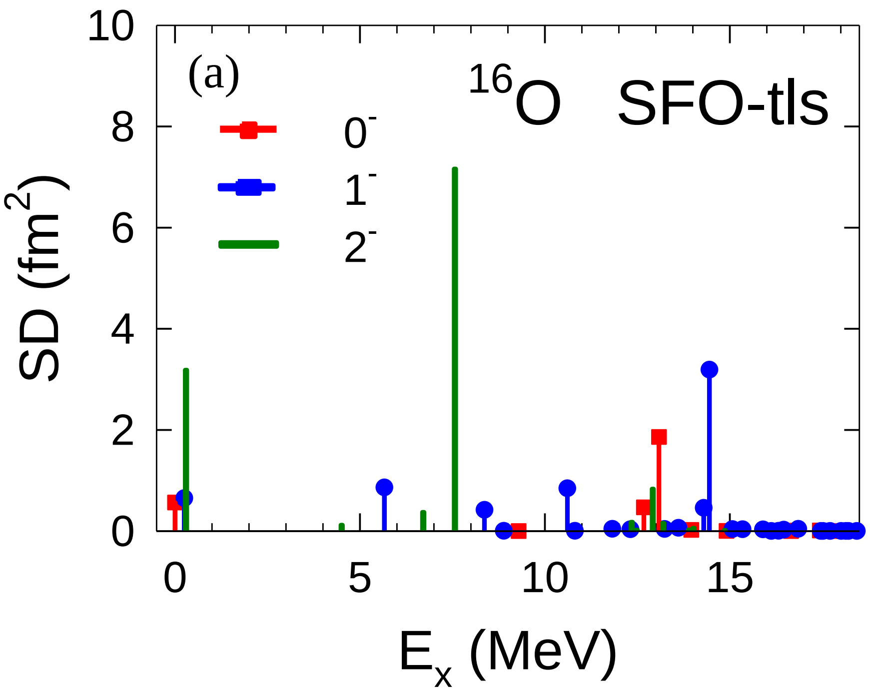
- ν-induced reactions on ^{16}O
- **Modification of SFO → SFO-tls**

Full inclusion of tensor force

- p-sd: tensor-> π+ρ

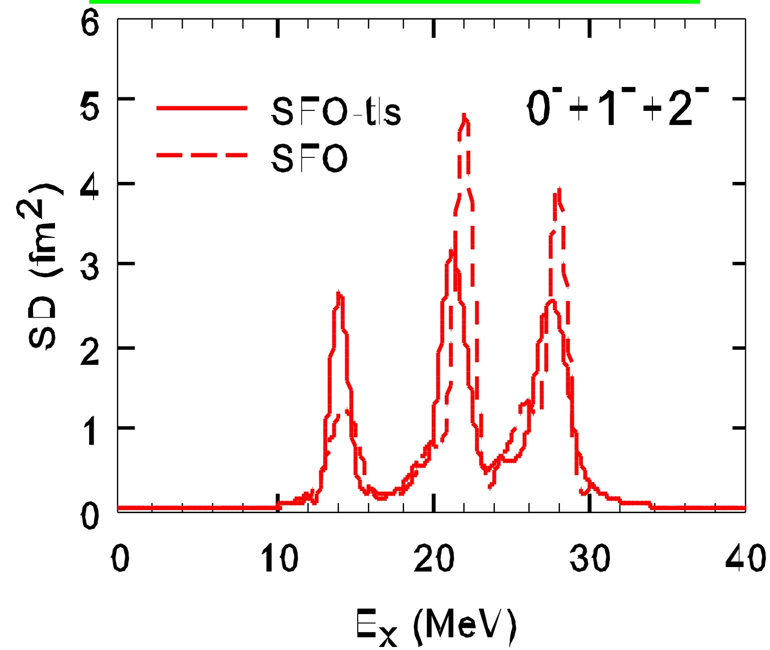
LS -> σ+ρ+ω

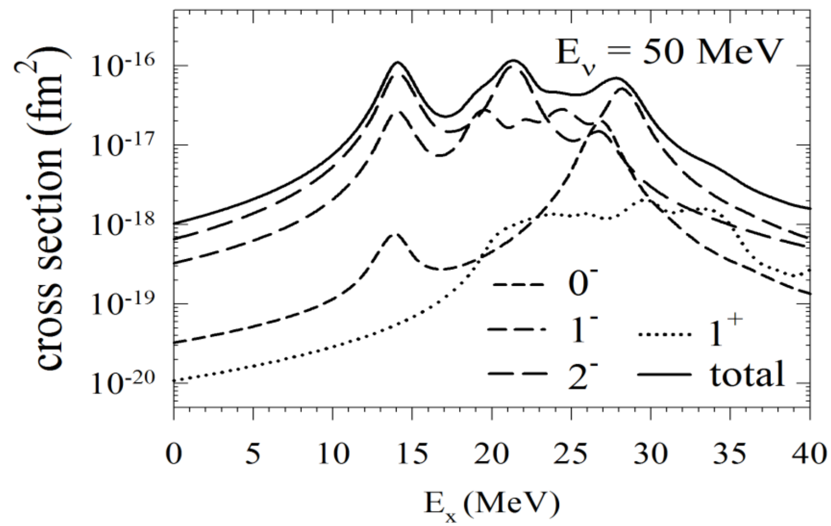
$$V = V_C + V_T + V_{LS}$$
$$V_T = V_\pi + V_\rho$$
$$V_{LS} = V_{\sigma+\omega+\rho}$$



Spin-dipole strength in ^{16}O

$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$





Charged current scattering off ^{16}O nucleus as a detection channel of supernova neutrinos

Ken'ichiro Nakazato[1], Toshio Suzuki[2], and Makoto Sakuda[3]

Cross sections for $^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$ and $^{16}\mathrm{O}(\bar{\nu}_e, e^+)\mathrm{X}$ induced by supernova neutrinos are evaluated as a function of recoil electron/positron energies.
Cases with/without neutrino oscillations are compared.
Dependence on neutrino mass hierarchies are studied, and counting rates for Super-Kamiokande detectors are estimated.

See arXiv: 1809.08398 for the details.

Summary

Shell-model Hamiltonians with proper spin-dependent components lead to proper shell evolution and good description of spin-dependent modes in nuclei

Evaluations of e-capture and β-decay rates at stellar environments and ν-nucleus reaction cross sections

Nuclear URCA processes and cooling of O-Ne-Mg core of 8-10 solar-mass stars

Nucleosynthesis of iron-group elements in Type Ia SNe.

Nucleosynthesis of light elements by ν-processes in SNe

Effects of ν-oscillations (MSW):

Mass-hierarchy dependence of the production yields of ^{7}Li and ^{11}B in SNe and charged ν-^{16}O cross sections

“Core-polarization and meson-exchange current effects on the magnetic form factor of ^{17}O”

T. Suzuki, Doctor thesis (1979).
A. Arima, Y Horikawa, H. Hyuga and T. Suzuki, PRL 40, 187 (1978).

12C: Sagawa, Suzuki, Hyuga and Arima, Nucl. Phys. A322, 361 (1979).
13C: Suzuki, Hyuga, Arima and Yazaki, Phys. Lett. B 106, 19 (1981).
205Tl, 207Tl, 207Pb, 208Pb, 209Bi:
Suzuki, Oka, Hyuga and Arima, Phys. Rev. C 26, 750 (1982);
Suzuki and Hyuga, Nucl. Phys. A402, 491 (1983).

Core-polarization (configuration mixing) ←→ quenching
2-body exchange current
spin-dependent mode (magnetic form factor)

温故知新

祝米寿
有馬先生

Much progress has been achieved in the effective interactions in nuclei

“Three-body forces and the structure of the sd-shell”
Arima, Onishi, Inoue, Akiyama and Suzuki,
Nucl. Phys. A 459, 286 (1986).
An early attempt to compromize saturation and energy levels


有馬朗人先生の文化勲章ご受章を祝う会

Collaborators

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