炭素、酸素核の構造とニュートリノ核反応への応用

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ν-detection

Scintillator (CH, …), H_2O, Liquid-Ar, Fe

ν-^{12}C, ν- ^{13}C, ν-^{16}O, ν-^{56}Fe, ν- ^{40}Ar

$E_\nu < 100$ MeV

ν-oscillation effects $\rightarrow$ ν mass hierarchy

MSW oscillations in SNe

SN neutrino detection by ν-^{12}C and ν-^{16}O reactions

(MSW + collective oscillations)

ν- ^{16}O reactions
Suzuki, Chiba, Yoshida, Takahashi, and Umeda,
Phys. Rev. C98, 034613 (2018)

Neutrino oscillations in ν- ^{16}O reactions
Nakazato, Suzuki, and Sakuda, PTEP 2018, 123E02 (2018)

ν-nucleus reactions with new shell-model Hamiltonians

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

Suzuki, Fujimoto, Otsuka, PR C69, (2003) , Suzuki and Otsuka, PRC878 (2008)
Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)
Suzuki, Honma et al., PR C79, (2009)
Otsuka, Suzuki, Honma, Utsuno et al., PRL 104 (2010) 012501
Suzuki and Honma, PR C87, 014607 (2013)
Yuan, Suzuki, Otsuka et al., PR C85, 064324 (2012)

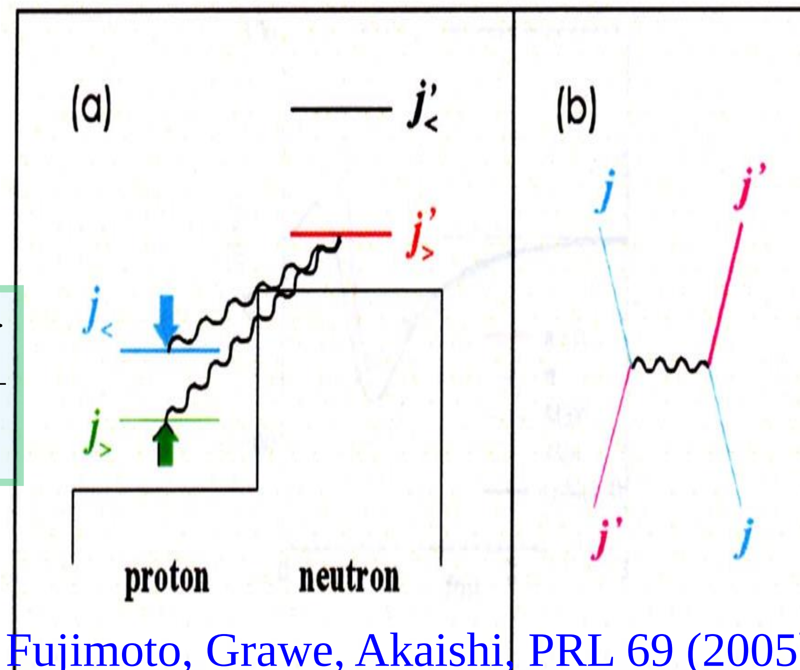
* important roles of tensor force

Monopole terms of V_{NN}

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

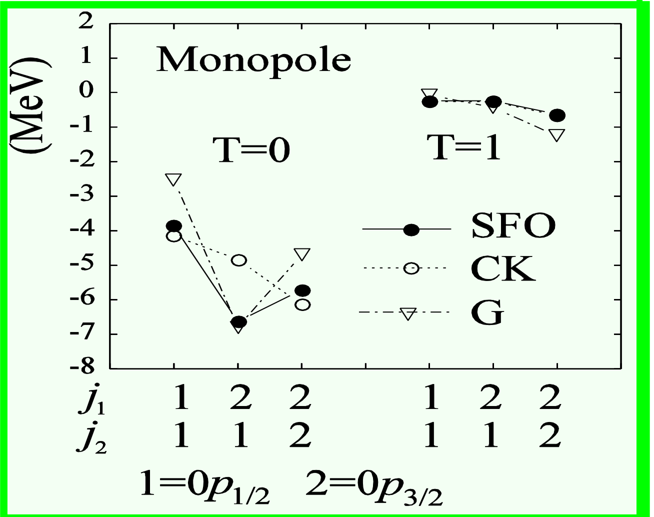
$j_> - j_<$: attractive

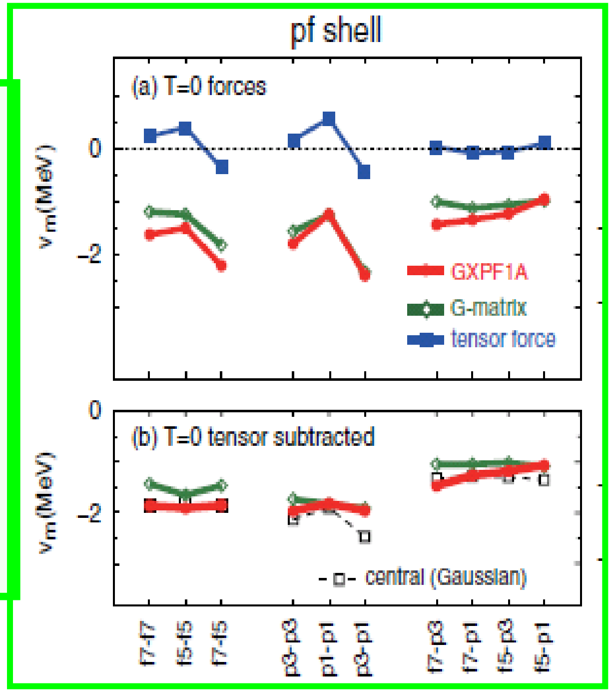
$j_> - j_>, j_< - j_<$: repulsive



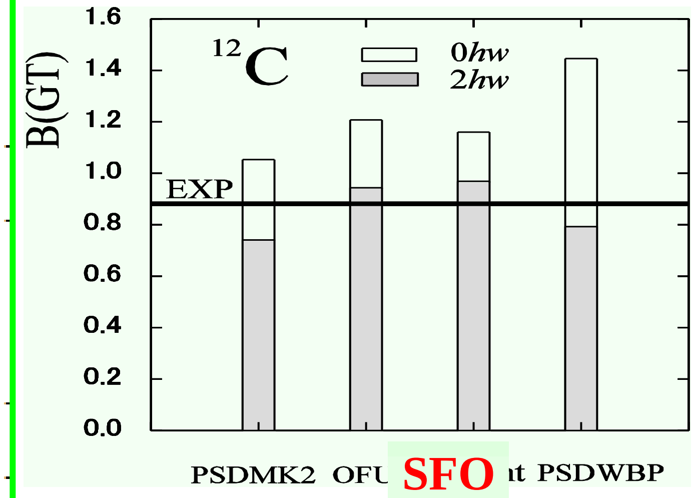
Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

SFO: p-sd shell





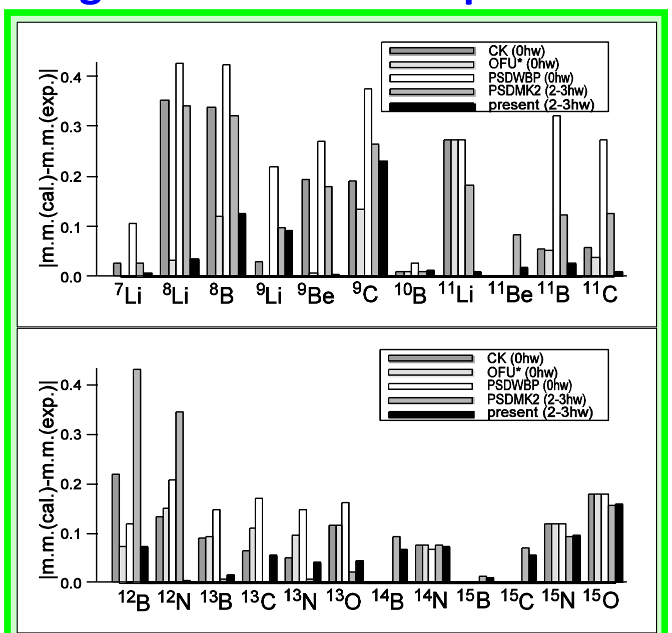
B(GT) for $^{12}C \rightarrow {}^{12}N$



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

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

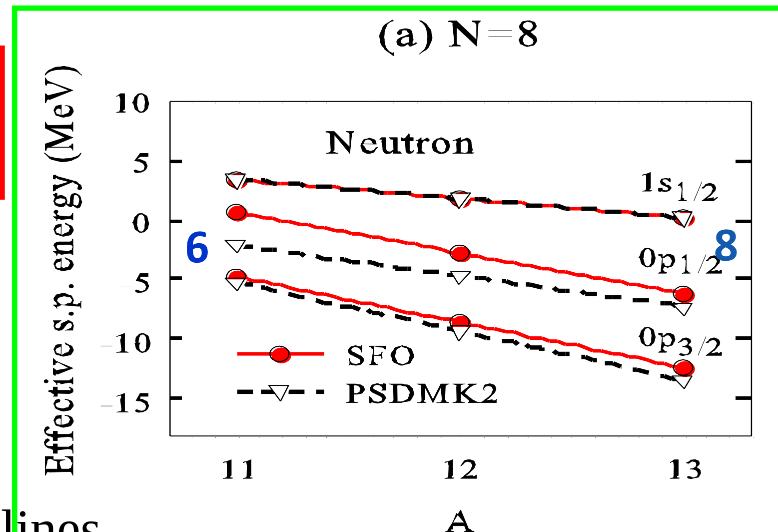
Magnetic moments of p-shell nuclei



present = SFO space: up to 2-3 hw

Shell evolution in N=8 isotone

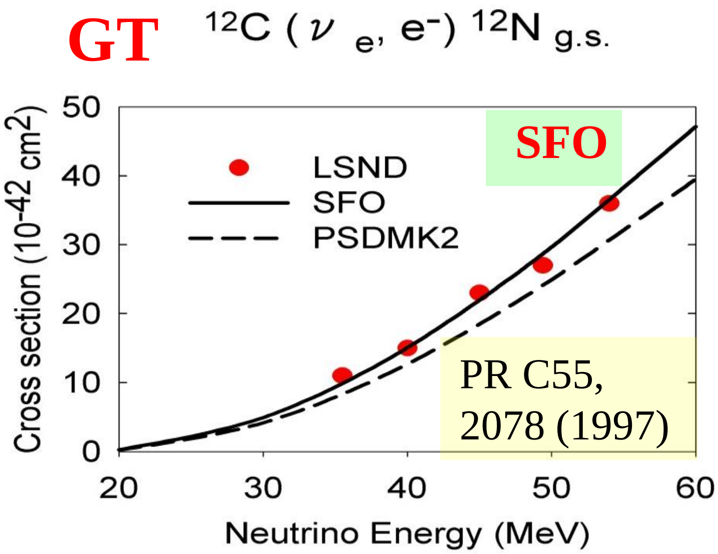
Magic #
N=8→6



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

・ν-nucleus reactions

p-shell: SFO



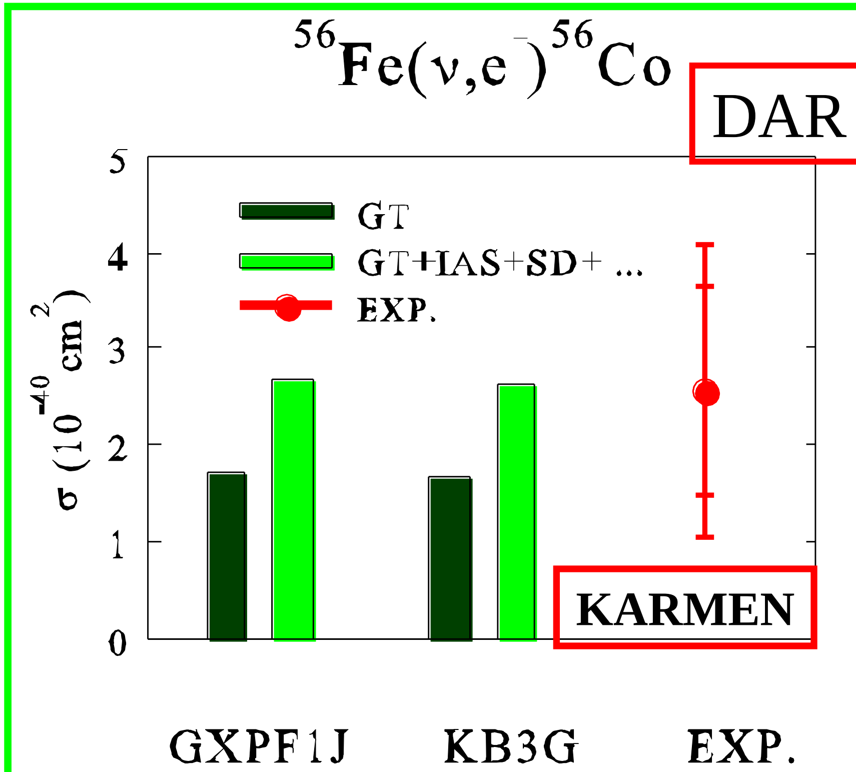
Suzuki, Chiba, Yoshida, Kajino, Otsuka, PR C74, 034307, (2006).

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

(ν, ν'), (ν_e, e^-) SD exc.
SFO reproduces DAR cross sections

pf-shell: GXPF1J (Honma et al.)

cf. **KB3** Caurier et al.



B(GT)=9.5 $B(GT)_{exp}$=9.9±2.4 $B(GT)_{KB3G}$=9.0

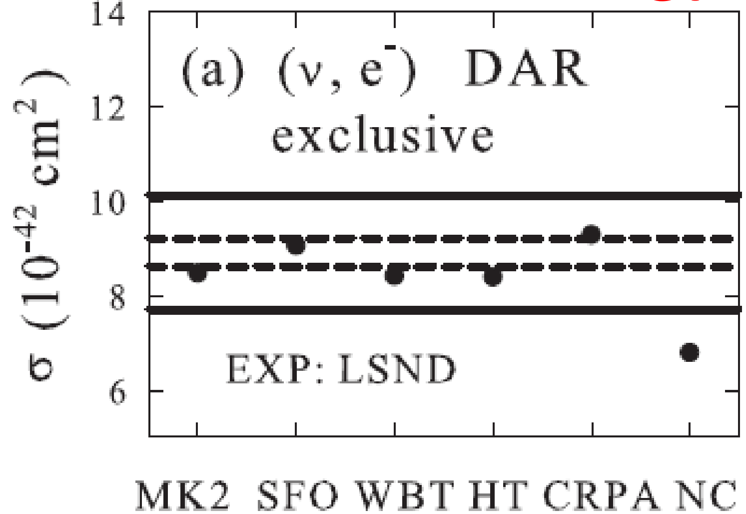
SD + … : RPA (SGII)

$$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}\ \mathrm{cm}^2.$$
$$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42}\ \mathrm{cm}^2.$$

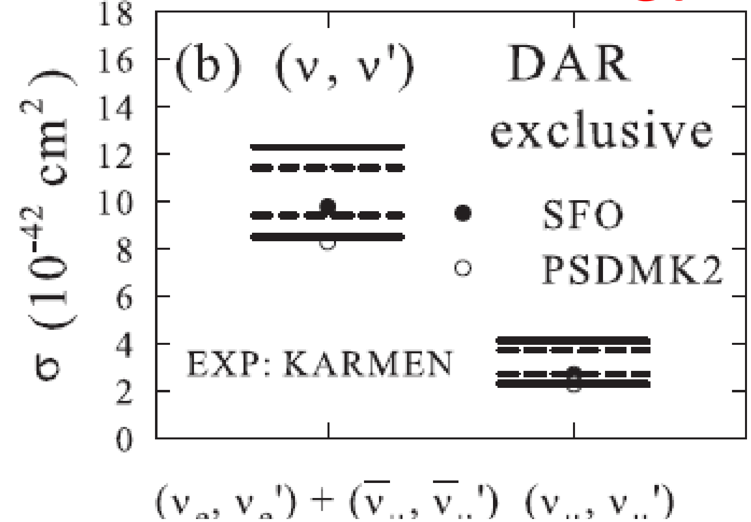
SM(GXPF1J)+RPA(SGII)	259 x10 $^{-42}$cm^2
RHB+RQRPA(DD-ME2)	263
RPA(Landau-Migdal force)	240

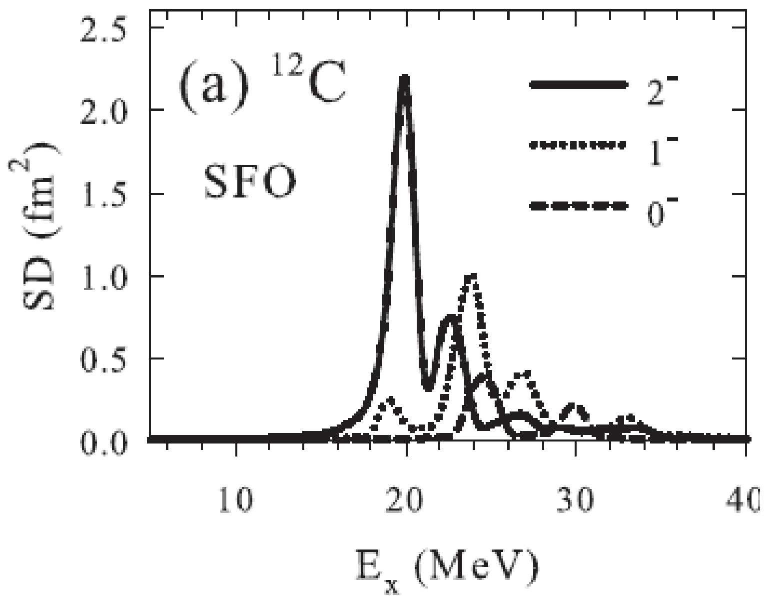
● ν-^{12}C

GT

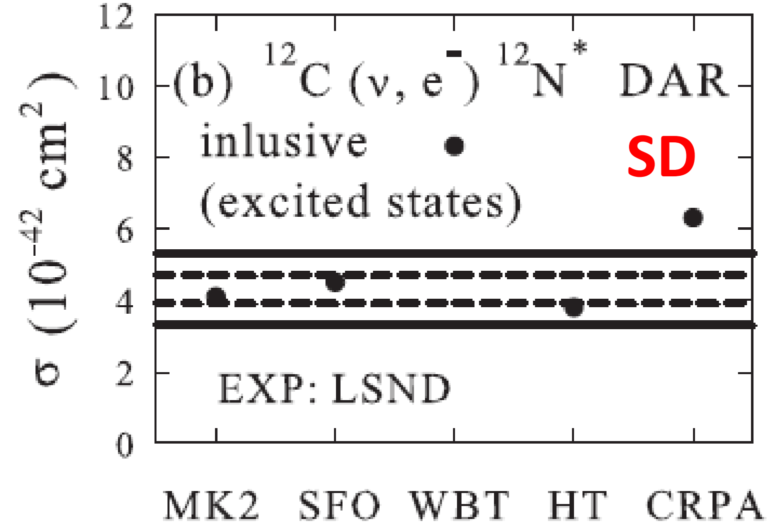


GT





Spin-dipole transitions



HT: Hayes-Towner, PR C62, 015501 (2000)
CRPA: Kolb-Langanke-Vogel, NP A652, 91 (1999)

Spin-dipole sum

$$B(SD\lambda)_{\mp} = \frac{1}{2J_i+1}\sum_f |< f \parallel S^{\lambda}_{\mp} \parallel i >|^2$$

$$S^{\lambda}_{\mp,\mu} = r[Y^1 \times \vec{\sigma}]^{\lambda}_{\mu} t_{\mp}$$

NEWS-rule: $S^{\lambda}_{-} - S^{\lambda}_{+} = \langle 0 \mid [\hat{S}^{\lambda}_{-}, \hat{S}^{\lambda}_{+}] \mid 0\rangle = \frac{2\lambda+1}{4\pi}(N\langle r^2\rangle_n - Z\langle r^2\rangle_p)$

$p_{3/2} \longrightarrow sd$ $\quad$ $[n(p_{3/2})=6,\ n(p_{1/2})=2]$

For [12]C; N=Z

$$S_{\lambda}(SD) = \sum_{\mu} |< \lambda,\mu \mid S^{\lambda}_{-,\mu} \mid 0 >|^2 = \frac{1}{2}\begin{cases} \frac{3}{4\pi}\frac{20}{3}b^2 = 4.28\ \mathrm{fm}^2, & \lambda^{\pi} = 0^-, \quad \frac{3}{4\pi}\frac{34}{12}b^2 \\ \frac{3}{4\pi}18b^2 = 11.56\ \mathrm{fm}^2, & \lambda^{\pi} = 1^-, \quad \frac{3}{4\pi}\frac{99}{12}b^2 \\ \frac{3}{4\pi}\frac{70}{3}b^2 = 14.98\ \mathrm{fm}^2, & \lambda^{\pi} = 2^-, \quad \frac{3}{4\pi}\frac{155}{12}b^2 \end{cases}$$

Energy-weighted sum

$$EWS^{\lambda}_{\pm} = \sum_{\mu} |< \lambda,\mu \mid S^{\lambda}_{\pm,\mu} \mid 0 >|^2 \,(E_{\lambda} - E_0),$$

$$EWS^{\lambda} = EWS^{\lambda}_{-} + EWS^{\lambda}_{+}$$

$$= \frac{1}{2} < 0 \mid [S^{\lambda\dagger}_{-}, [H, S^{\lambda}_{-}]] + [[S^{\lambda\dagger}_{+}, H], S^{\lambda}_{+}] \mid 0 > .$$

kinetic energy term (K) for $H = \frac{p^2}{2m}$

$$EWS_K^\lambda = \frac{3}{4\pi}(2\lambda+1)\frac{\hbar^2}{2m}A[1 + \frac{f_\lambda}{3A} < 0 \,|\, \sum_i \vec{\sigma}_i \cdot \vec{\ell}_i \,|\, 0 >]$$

$f_\lambda = 2$, 1 and -1 for $\lambda^\pi = 0^-$, 1^- and 2^-, respectively.

One-body spin-orbit potential term $\qquad V_{LS} = -\xi \sum_i \vec{\ell}_i \cdot \vec{\sigma}_i,$

$$EWS_{LS}^\lambda = \frac{3}{4\pi}(2\lambda+1)\frac{f_\lambda}{3}\xi < 0 \,|\, \sum_i (r_i^2 + g_\lambda r_i^2 \vec{\ell}_i \cdot \vec{\sigma}_i) \,|\, 0 >$$

$g_\lambda = 1$ for $\lambda^\pi = 0^-$, 1^- and $g_\lambda = -7/5$ for $\lambda^\pi = 2^-$.

For N=Z, $EWS^\lambda_- = EWS^\lambda_+$, and $EWS^2_-/5 < EWS^1_-/3 < EWS^0_-$

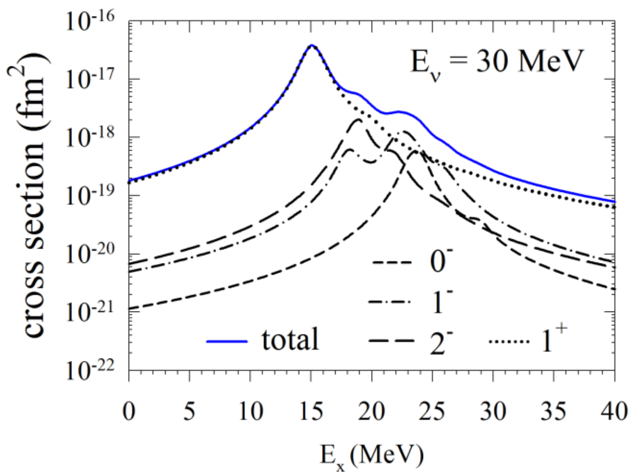
EWS-	0^-	1^-	2^-		
K+LS	48.0	116.6	117.2	MeV・fm^2	[n($p_{3/2}$)=6, n($p_{1/2}$)=2]
SFO	45.61	108.48	154.49		[n($p_{3/2}$)=6.42, n($p_{1/2}$)=1.44]
$E_{av}=EWS_-/S_-$					
K+LS	26.39	22.01	14.13	MeV	
SFO	25.71	25.22	21.50		

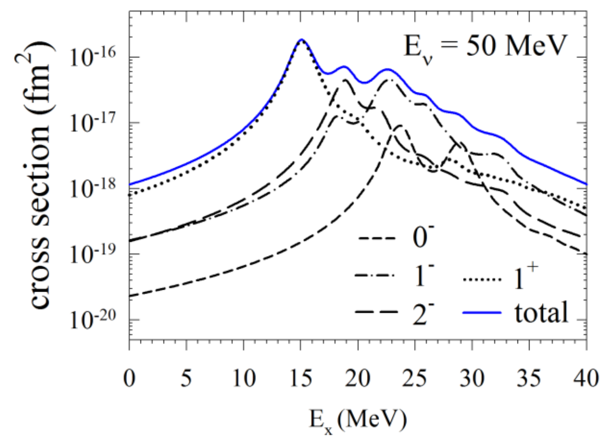
Hauser-Feshbach statistical model

Branching ratios for γ and particle emission channels (with multi-particle emission channels): γ, n, p, np (d), nn, pp, ^{3}H (nnp), ^{3}He (npp), α, αp, αn, αnn, αnp, αpp, ...

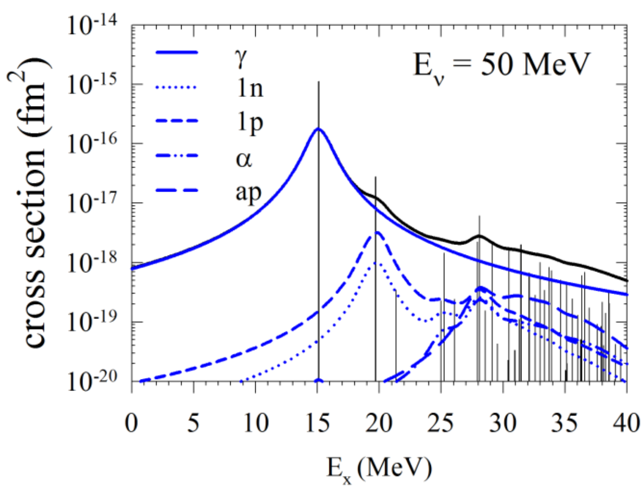
Isospin conservation is taken into account (S. Chiba)

^{12}C **Neutral current reactions** ^{12}C

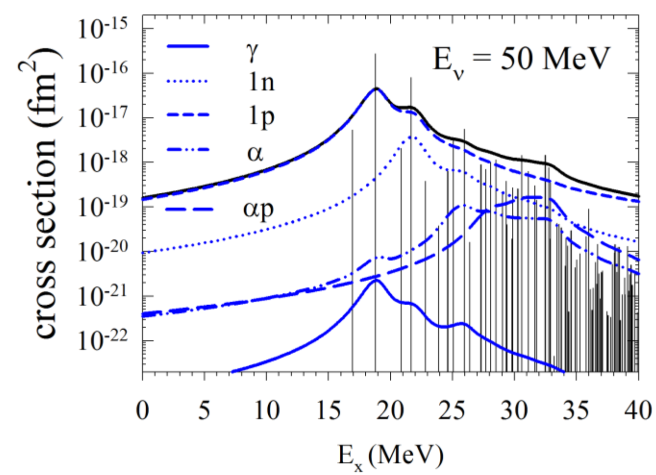




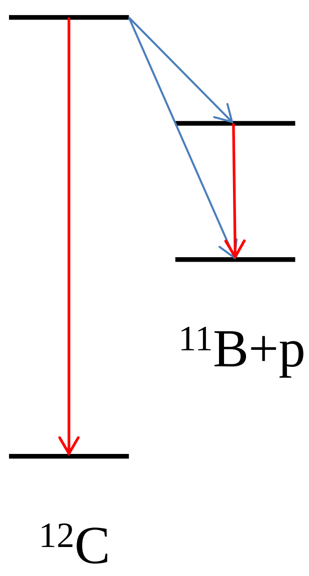
^{12}C 1$^+$

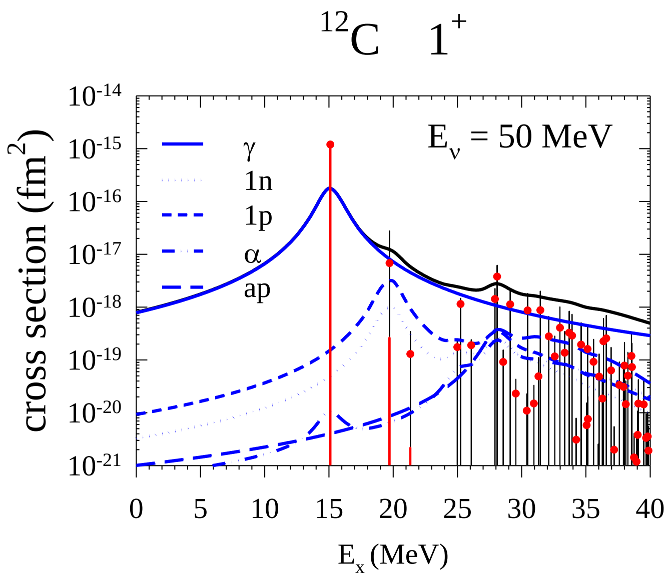


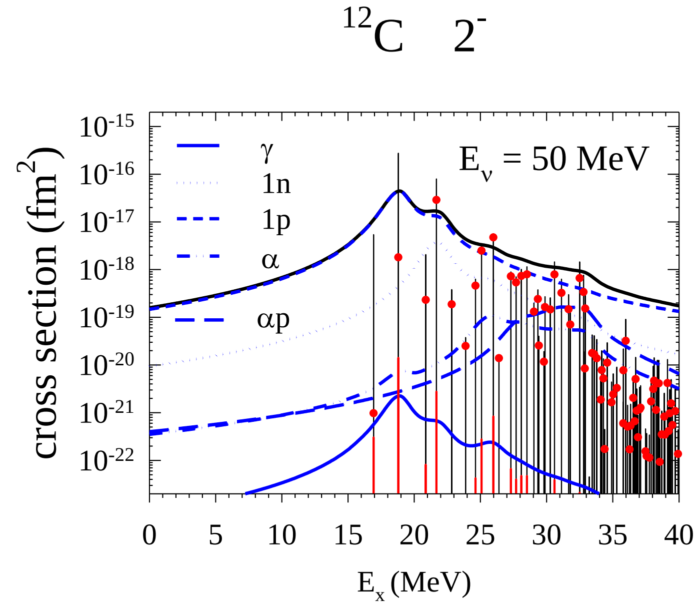
^{12}C 2$^-$



Gamma

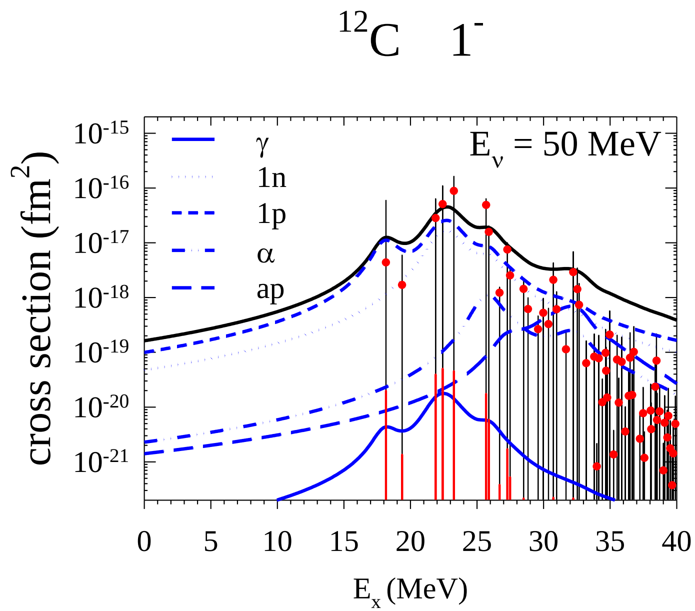


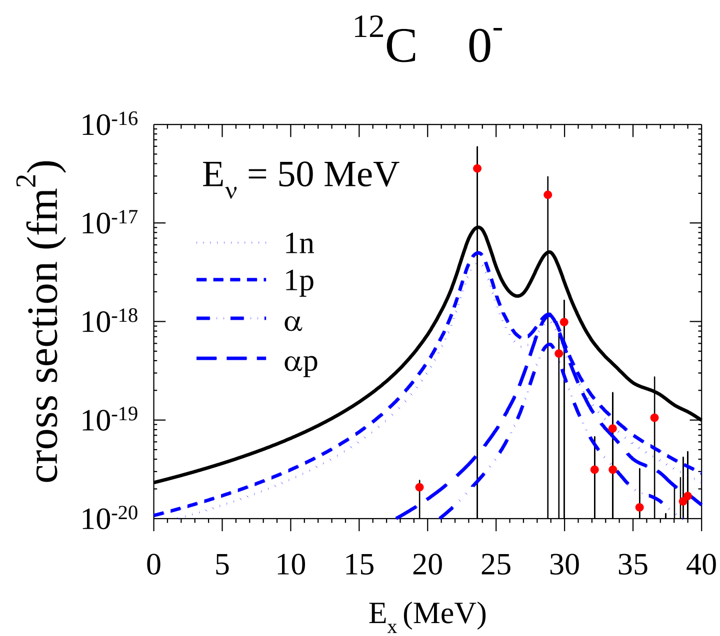




direct decay

direct
+ delayed
after particle
emissions





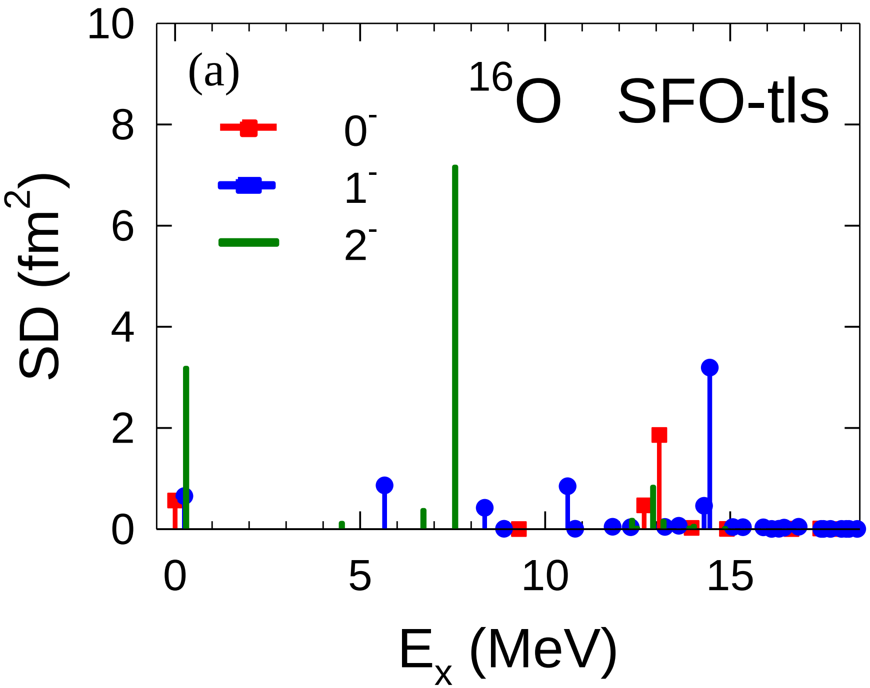
- **ν-induced reactions on ^{16}O**
- **Modification of SFO → SFO-tls**

  Full inclusion of tensor force

  - **p-sd: tensor-> π+ρ**

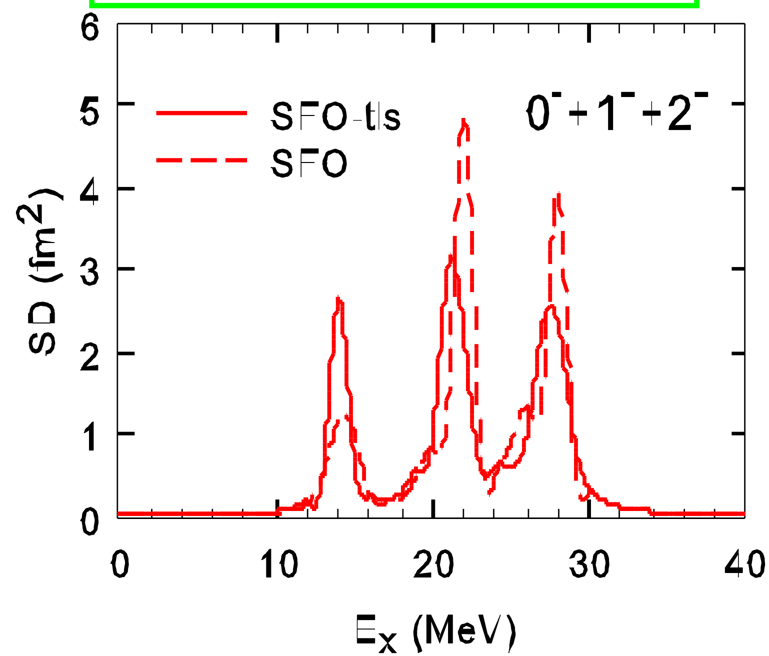
    LS -> σ+ρ+ω

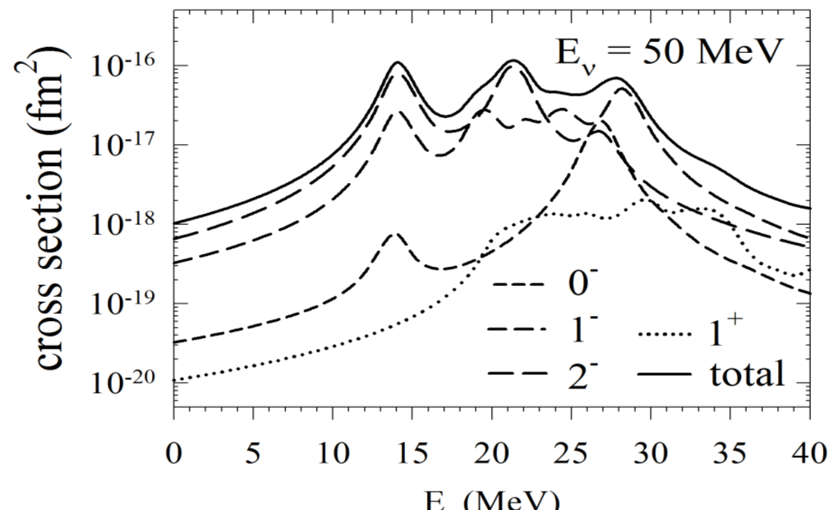
$$V = V_C + V_T + V_{LS}$$
$$V_T = V_\pi + V_\rho$$
$$V_{LS} = V_{\sigma+\omega+\rho}$$



Spin-dipole strength in ^{16}O

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





Spin-dipole sum

$$S_\lambda(SD) = \sum_\mu |< \lambda, \mu \,|\, S^\lambda_{-,\mu} \,|\, 0 >|^2 = \begin{cases} \frac{3}{4\pi} 4\mathrm{b}^2 = 2.99\mathrm{fm}^2 & \lambda^\pi = 0^- \\ \frac{3}{4\pi} 12\mathrm{b}^2 = 8.98\mathrm{fm}^2 & \lambda^\pi = 1^- \\ \frac{3}{4\pi} 20\mathrm{b}^2 = 14.96\mathrm{fm}^2 & \lambda^\pi = 2^- \end{cases}$$

$p \longrightarrow sd$

$\propto\ 2\lambda+1$

EWS^λ_-	0^-	1^-	2^-	
K+LS	56.4	144.1	155.9	MeV・fm^2
SFO-tls (/(K+LS)	73.0 (1.29)	173.2 (1.20)	246.5 (1.58)	
SFO (/(K+LS)	76.1 (1.35)	175.0 (1.21)	258.2 (1.66)	

$\bar{E}_\lambda = EWS^\lambda_- / \mathrm{NEWS}^\lambda_-$,	0^-	1^-	2^-	
SFO-tls	24.5	25.1	20.1	MeV
SFO	25.8	25.2	21.0	

Tensor interaction: attractive for 0^- and 2^-, & repulsive for 1^-

$$V_T(r) = F(r)\{[\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2]^{(2)} \times [r^2 Y_2(\hat{r})]^{(2)}\}^{(0)},$$

$$V_T(r) = F(r) \sum_\lambda \frac{\sqrt{4\pi}}{6} \left(\frac{10}{3}\right)^{1/2} \begin{Bmatrix} -2\sqrt{5} \\ \sqrt{15} \\ -1 \end{Bmatrix} \times \{r_1[\boldsymbol{\sigma}_1 \times Y_1(\hat{r}_1)]^{(\lambda)}$$

$$\times r_2[\boldsymbol{\sigma}_2 \times Y_1(\hat{r}_2)]^{(\lambda)}\}^{(0)}, \qquad \text{for } \lambda = \begin{Bmatrix} 0^- \\ 1^- \\ 2^- \end{Bmatrix}.$$

● μ-capture rate on ^{16}O and the quenching factor

The muon capture rate for ^{16}O (μ, ν_μ) ^{16}N from the 1s Bohr atomic orbit

$$\omega_\mu = \frac{2G^2}{1+\nu/M_T} \mid \phi_{1s} \mid^2 \frac{1}{2J_i+1}\left(\sum_{J=0}^{\infty} \mid< J_f \parallel M_J - L_J \parallel J_i >\mid^2 + \mid< J_f \parallel T_J^{el} - T_J^{mag} \parallel J_i >\mid^2\right),$$

$$\mid \phi_{1s} \mid^2 = \frac{R}{\pi}\left(\frac{m_\mu M_T}{m_\mu + M_T} Z\alpha\right)^3 \qquad R = 0.79$$

PCAC

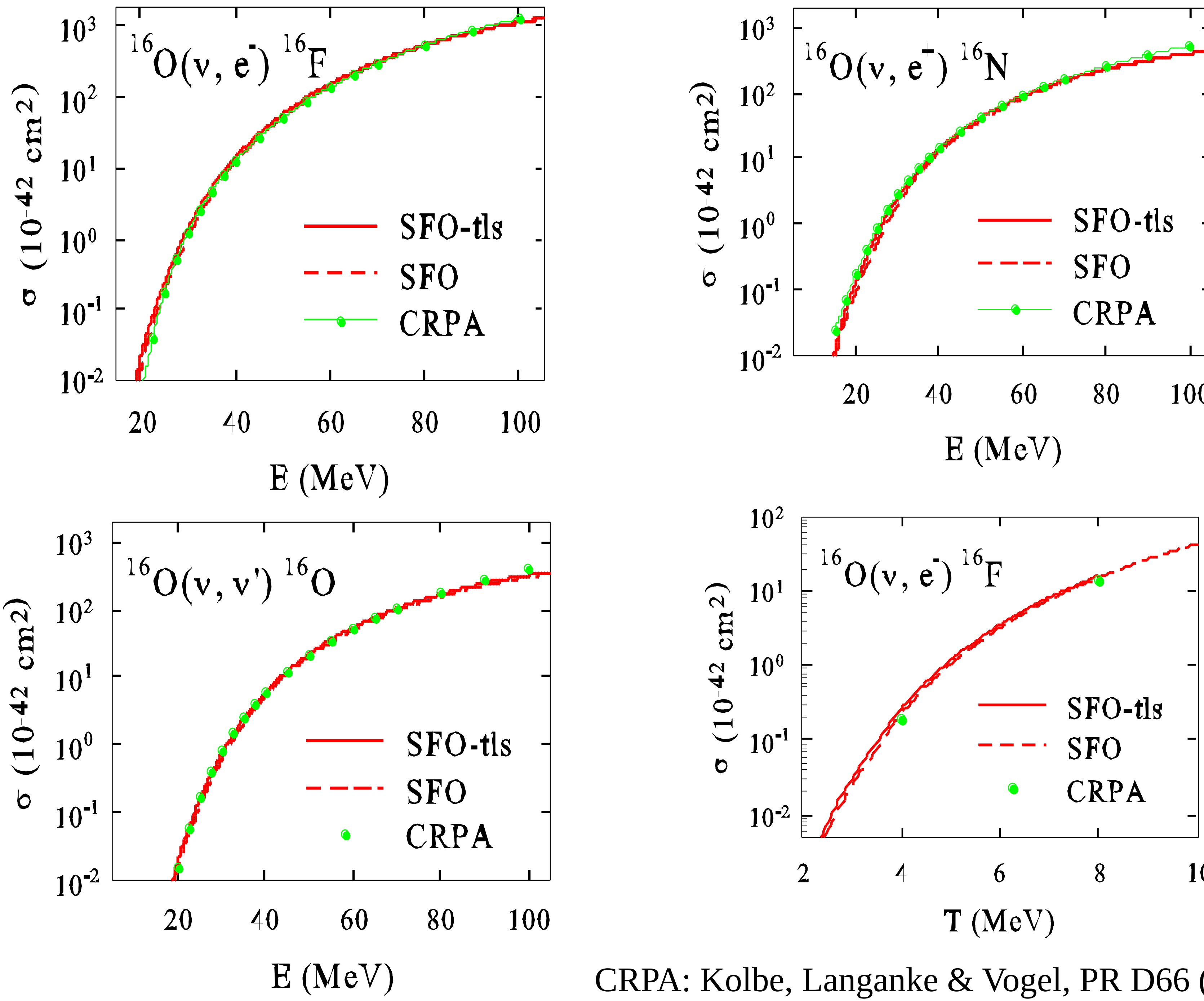
Induced pseudo-scalar current $F_P(q_\mu^2) = \frac{2M_N}{q_\mu^2 + m_\pi^2} F_A(q_\mu^2)$

Goldberger-Treiman

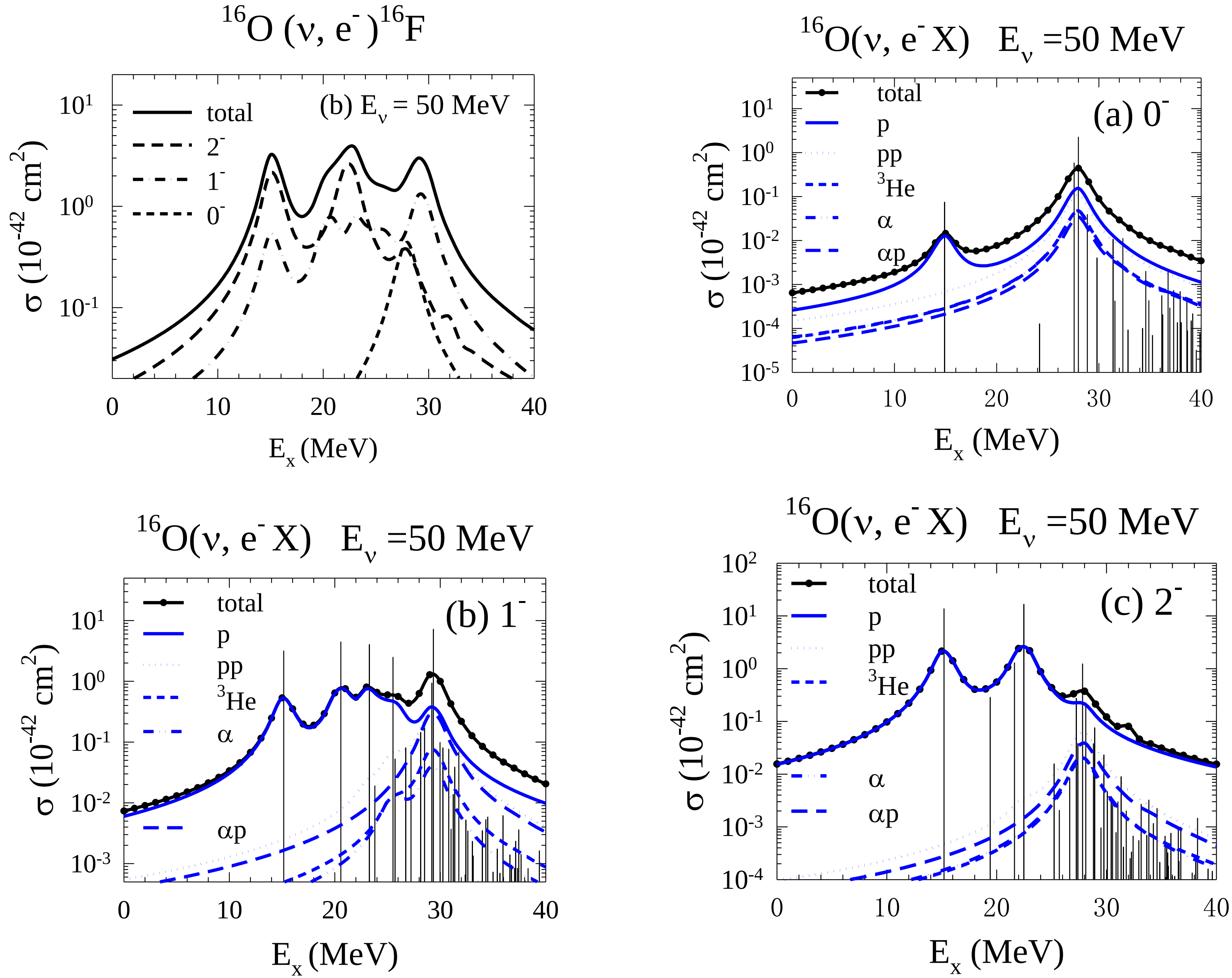
$$-2M_N F_A = \sqrt{2} g_\pi F_\pi$$

f $= g_A^{eff}/g_A = 0.95$

SFO	10.21×10^4 s^{-1}	(SFO/exp =0.995)
SFO-tls	11.20×10^4 s^{-1}	(SFO-tls/exp=1.092)
Exp.	10.26×10^4 s^{-1}	

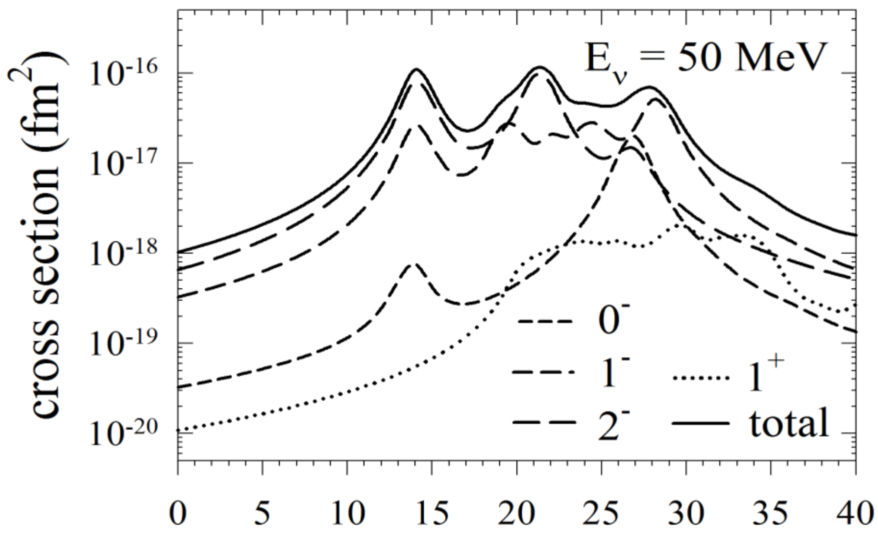


CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

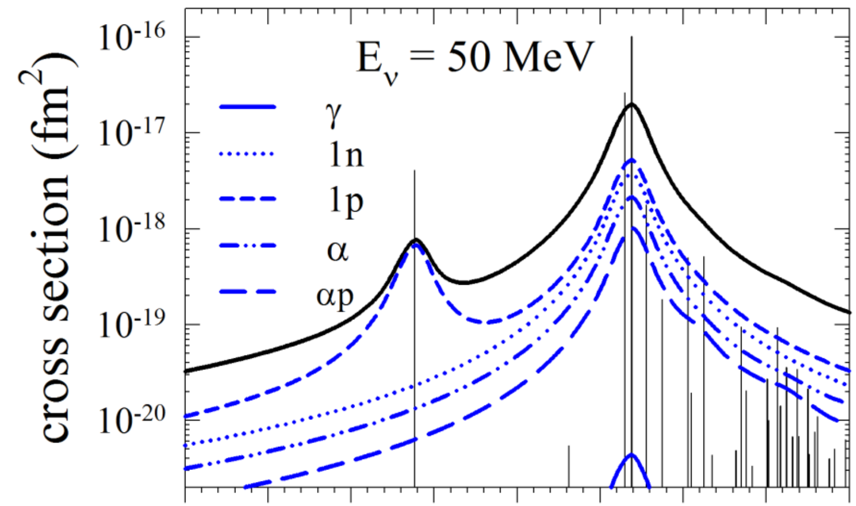


^{16}O (ν, e$^-$)^{16}F
total
2$^-$
1$^-$
0$^-$
(b) E$_ν$ = 50 MeV
σ (10^{-42} cm^2)
E$_x$ (MeV)
^{16}O(ν, e$^-$ X) E$_ν$ =50 MeV
(a) 0$^-$
(b) 1$^-$
(c) 2$^-$
total
p
pp
^{3}He
α
αp

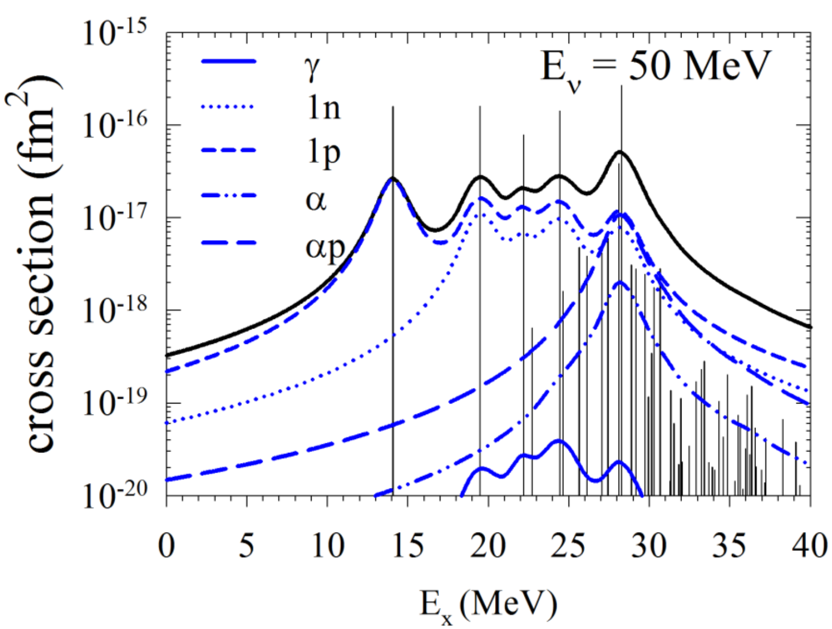
^{16}O Neutral current reactions



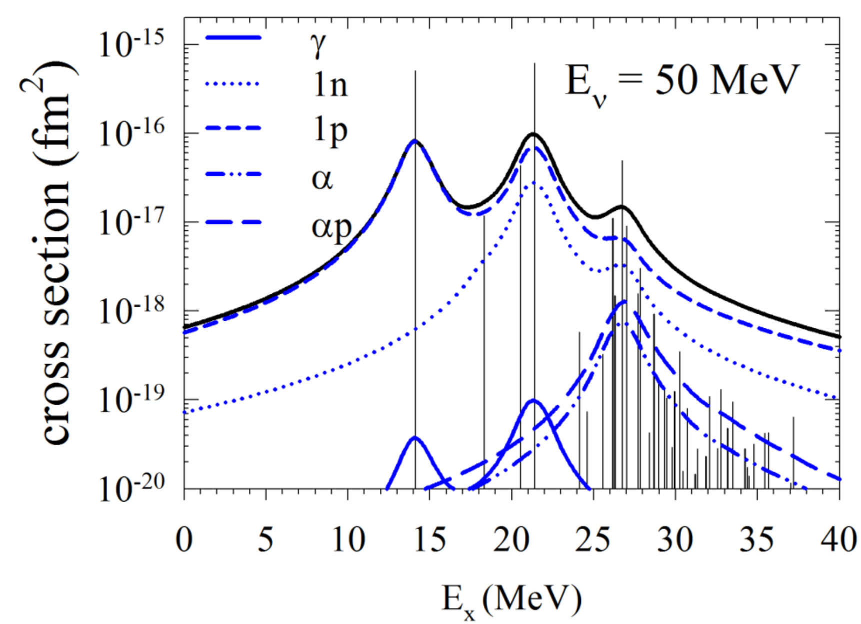
^{16}O 0^-



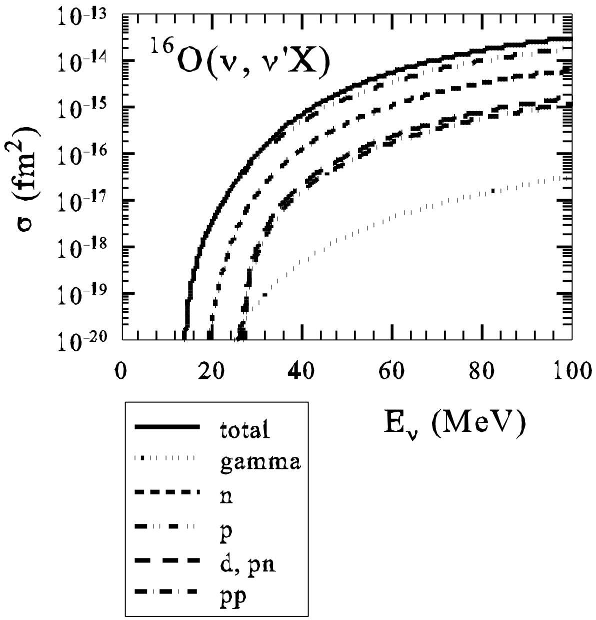
^{16}O 1^-

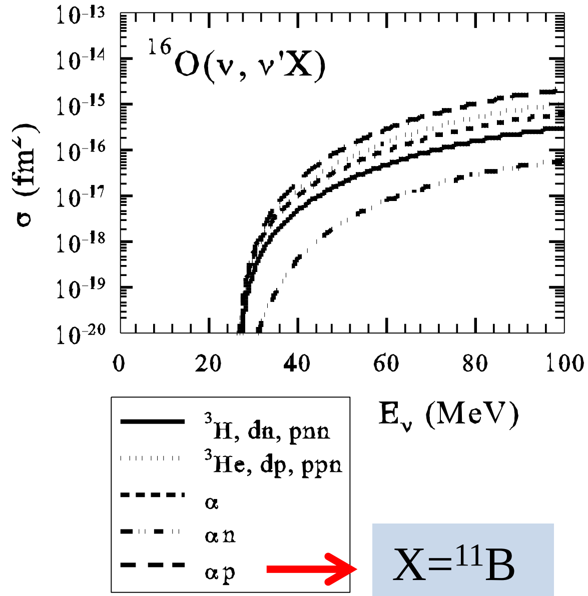


^{16}O 2^-

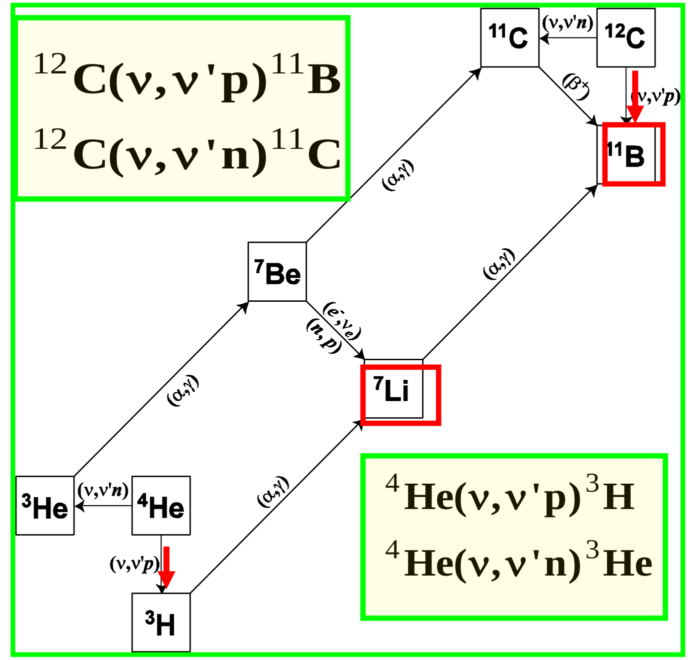


Synthesis of ^{11}B and ^{11}C in SNe





X=^{11}B



$$\frac{\sigma(^{16}\mathrm{O}(\nu,\nu'\alpha p)^{11}\mathrm{B})}{\sigma(^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B})} \approx 10\%$$

Case1: previous branches used in ^{16}O (γ, n, p, α-emissions) and HW92 cross sections

Case2: previous branches, and new cross sections

Case3: multi-particle branches and new cross sections

Production yields of ^{11}B and ^{11}C ($10^{-7} M_\odot$)

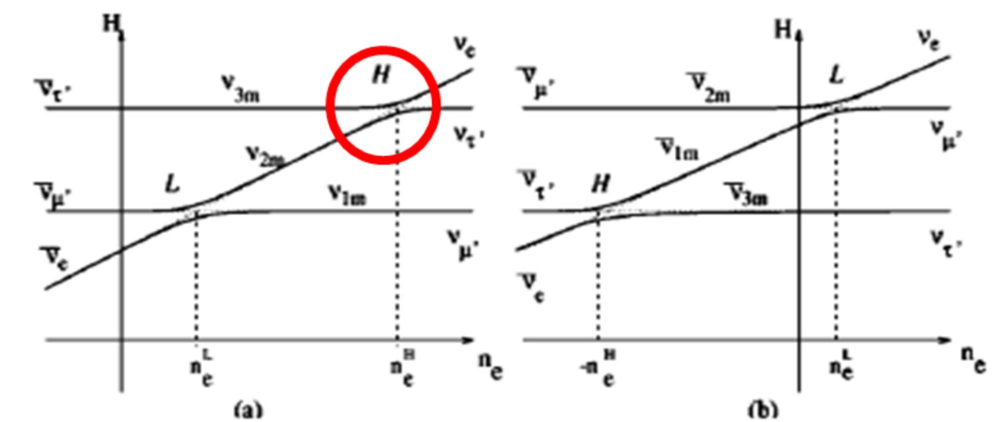
	$15M_\odot$ モデル			$20M_\odot$ モデル		
核種生成量	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}\mathrm{C})$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}\mathrm{B}+^{11}\mathrm{C})$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

ν oscillation effects $\rightarrow$ ν mass hierarchy

MSW ν oscillations

Normal hierarchy	Inverted hierarchy



$$\text{Normal}-\text{hierarchy}: \nu_\mu, \nu_\tau \rightarrow \nu_e$$

$$\text{Inverted}-\text{hierarchy}: \bar{\nu}_\mu, \bar{\nu}_\tau \rightarrow \bar{\nu}_e$$

Resonance condition

$$\rho Y_e = N_e = \frac{\Delta}{2\sqrt{2}EG_F}\cos 2\theta$$

$$= 6.55\times 10^6 \left(\frac{\Delta m_{ij}^2}{1\mathrm{eV}^2}\right)\left(\frac{1\mathrm{MeV}}{E_\nu}\right)\cos 2\theta_{ij} \quad \mathrm{g\cdot cm^{-3}}$$

H – resonance: θ_{13}

$$\rho Y_e = 300 - 3000 \;\; \mathrm{g\cdot cm^{-3}}$$

He/C layer

L – resonance: θ_{12}

$$\rho Y_e = 4 - 40 \;\; \mathrm{g\cdot cm^{-3}}$$

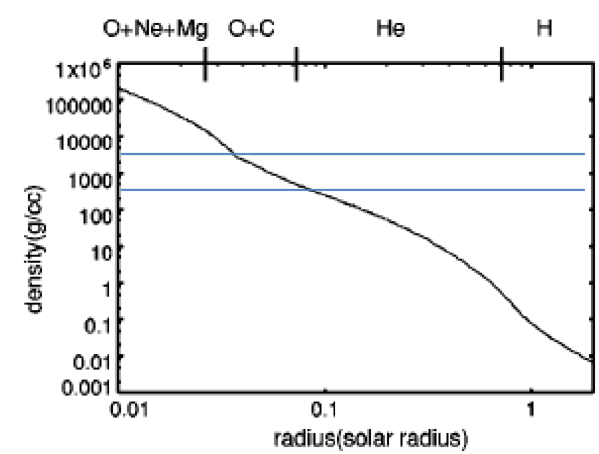
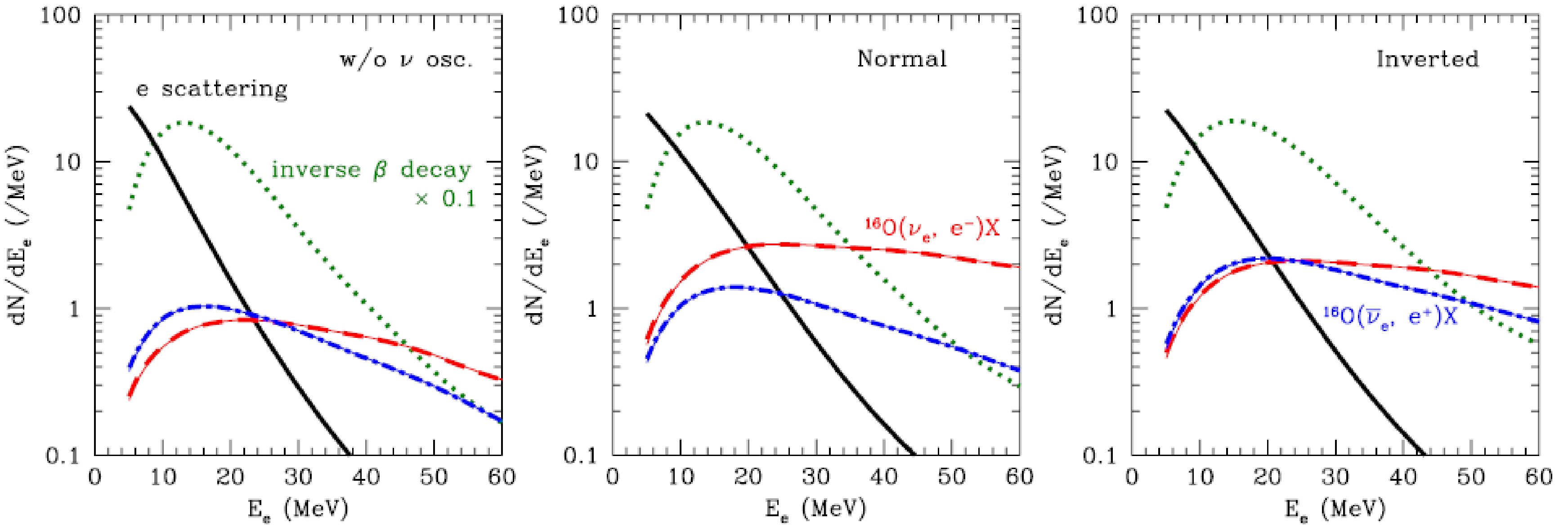


FIG. 3. Density profile of the presupernova star model used in the paper [20]. The progenitor mass is set to be $15M_\odot$.

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]

PTEP 2018, 123E02 (2018)



(M, Z) =(20M$_\odot$, 0.02) Z = metalicity

<E_ν_e> = 9.32 MeV, <E_$\bar{\nu}_e$> = 11.1 MeV, <E_ν_x> =11.9 MeV

Nakazato et al., ApJ. Suppl. 205, 2 (2013)

$N(\nu_e) = P*N^0(\nu_e) + (1-P)*N^0(\nu_x)$

$N(\text{anti-}\nu_e) = P'*N^0(\text{anti-}\nu_e) + (1-P')*N^0(\nu_x)$

Normal hierarchy: (P, P') = (0, 0.68) Dighe and Smirnov, PR D62, 033007 (2000)

Inverted hierarchy: (P, P') = (0.32, 0)

Table 6 Expected event numbers with a threshold energy of $E_e = 5$ MeV for the models in Table 5.

	ordinary supernova			black hole formation		
reaction	no osc.	normal	inverted	no osc.	normal	inverted
$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$	41	178	134	2482	2352	2393
$^{16}\mathrm{O}(\bar{\nu}_e, e^+)\mathrm{X}$	36	58	103	1349	1255	1055
electron scattering	140	157	156	514	320	351
inverse β-decay	3199	3534	4242	17525	14879	9255
total	3416	3927	4635	21870	18806	13054

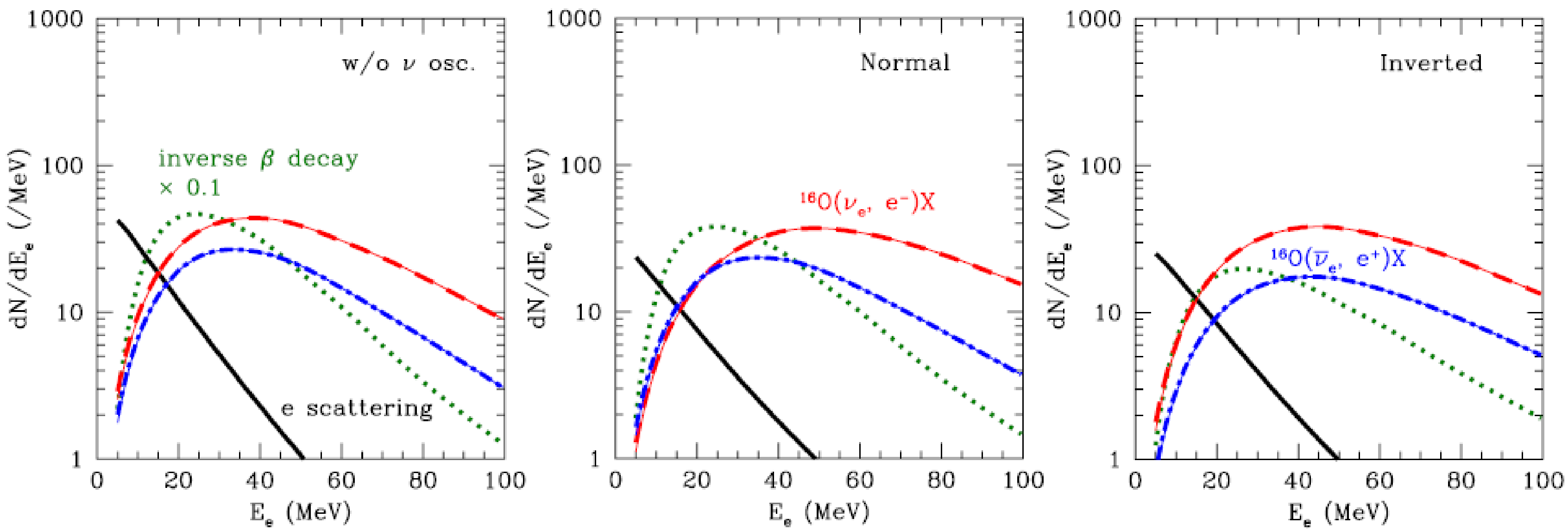
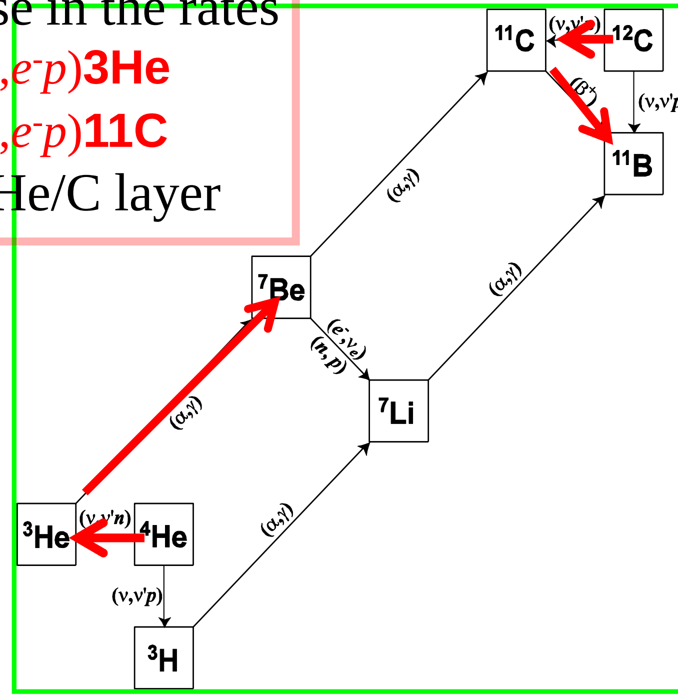


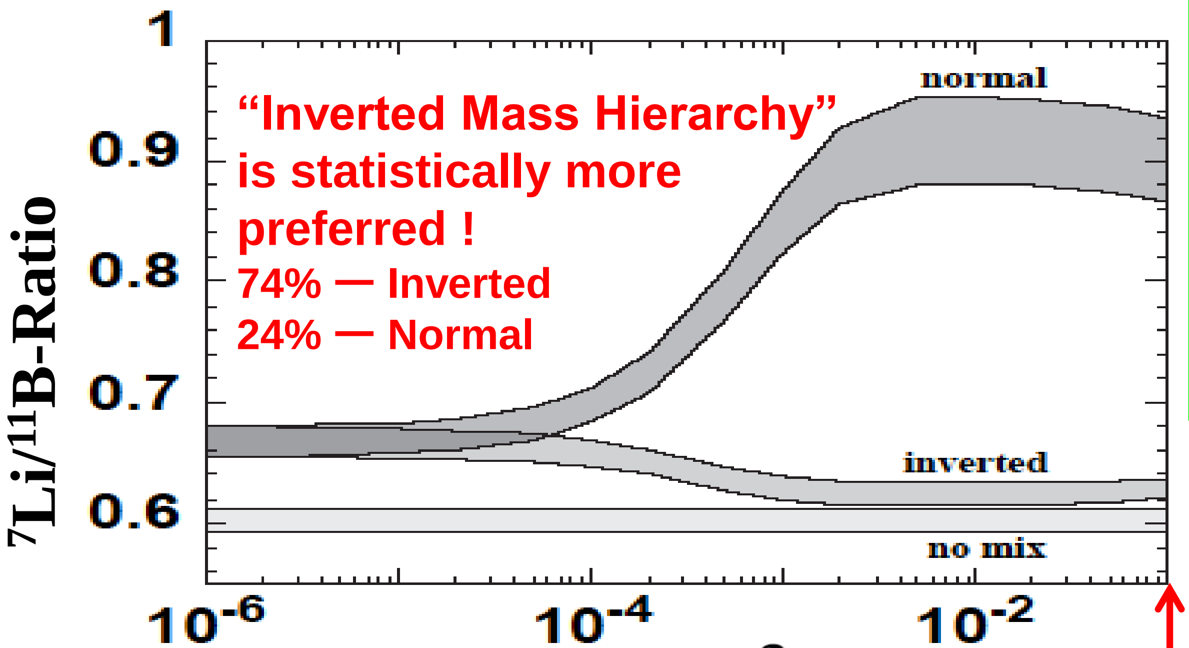
Fig. 5 Same as Fig. 4 but for the model with $(M, Z) = (30M_\odot, 0.004)$, which corresponds to a black-hole-forming collapse.

MSW ν oscillations

$$\text{Normal}-\text{hierarchy}: \nu_\mu, \nu_\tau \rightarrow \nu_e$$

Increase in the rates
4He(ν_e,e^-p)3He
12C(ν_e,e^-p)11C
in the He/C layer





Yoshida et al.,PRL 96 (2006)

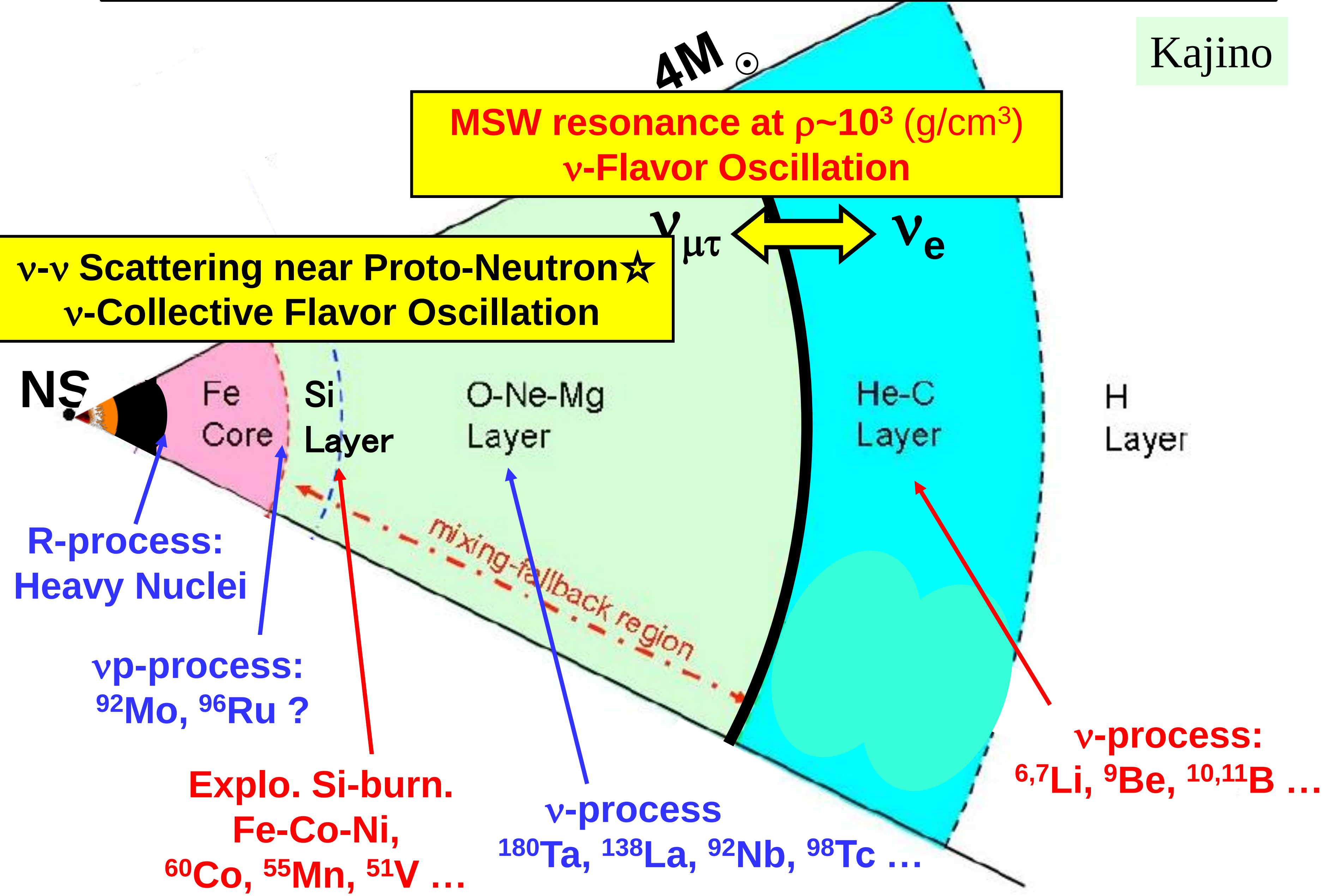
- T2K, MINOS (2011)
- Double CHOOZ, Daya Bay, RENO (2012)

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

First Detection of ^{7}Li/^{11}B in SN-grains in Murchison Meteorite
W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).

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

Various roles of ν's in SN-nucleosynthesis



Spectrum with ν-oscillations

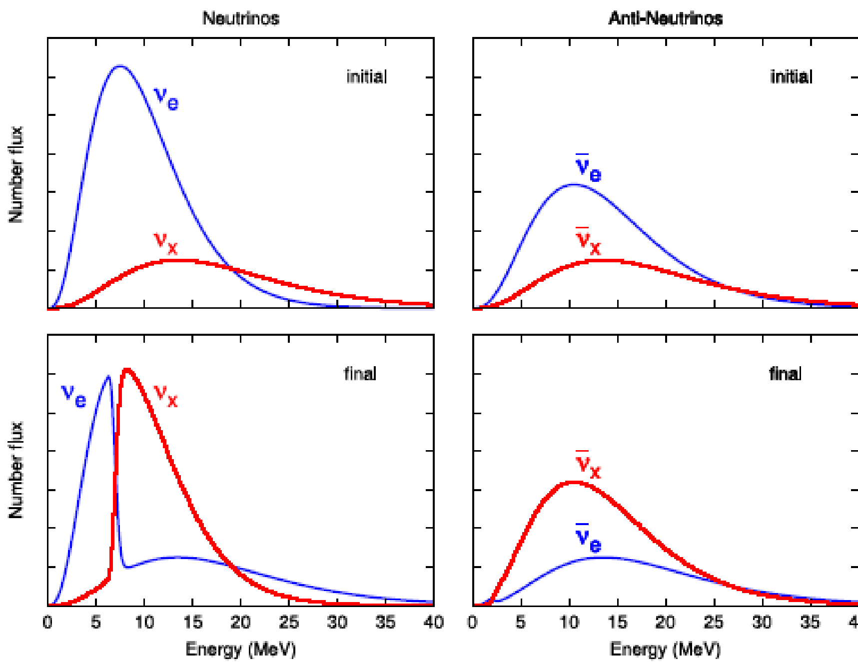
$\langle E_{\nu_e}\rangle = 10,\ \langle E_{\bar{\nu}_e}\rangle = 14$ and $\langle E_{\nu_x}\rangle = 18$ MeV.

- With collective oscillation effects

G.G. Raffelt / Progress in Particle and Nuclear Physics 64 (2010) 393–399

Normal

Inverted



$A: \quad F_{\nu_e}(E) = F_{\nu_x}(E)$

A: MAA instability (Zaizen)

$F_{\nu_e}(E) = \sin^2\theta_{12} F_{\nu_x}(E)$

$+\cos^2\theta_{12} F_{\nu_e}(E) \quad (E < E_{split})$

$F_{\nu_e}(E) = F_{\nu_e}(E) \quad (E > E_{split})$

B:

$F_{\nu_e}(E) = \sin^2\theta_{12} F_{\nu_e}(E)$

$+\cos^2\theta_{12} F_{\nu_x}(E) \quad (E < E_{split})$

$F_{\nu_e}(E) = F_{\nu_x}(E) \quad (E > E_{split})$

- With collective and MSW effects

$$F_{\nu_e}(E) = p(E) F^0_{\nu_e}(E) + [1 - p(E)] F^0_{\nu_x}(E),$$

Survival probabilities including collective effects for the scenario described in the text.

Scenario	Hierarchy	$\sin^2\Theta_{13}$	$p(E < E_{split})$	$p(E > E_{split})$	$\bar{p}(E)$	Earth effects
A	Normal	$\gtrsim 10^{-3}$	0	0	$\cos^2\Theta_\odot$	$\bar{\nu}_e$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2\Theta_\odot$	0	$\cos^2\Theta_\odot$	$\bar{\nu}_e$
C	Normal	$\lesssim 10^{-5}$	$\sin^2\Theta_\odot$	$\sin^2\Theta_\odot$	$\cos^2\Theta_\odot$	ν_e and $\bar{\nu}_e$
D	Inverted	$\lesssim 10^{-5}$	$\sin^2\Theta_\odot$	0	0	–

Cross sections folded over the spectra

- Target = ^{13}C

$\langle E_{\nu_e} \rangle = 10,\ \langle E_{\bar{\nu}_e} \rangle = 14$ and $\langle E_{\nu_x} \rangle = 18$ MeV.

$E_\nu \le 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\,\mathrm{MeV}$

Natural isotope abund. = 1.07%

	A (normal)	B (inverted)
no oscillation	8.01	8.01 ($10^{-42}cm^2$)
collective osc.	8.01 39.44	39.44 (39.93)
collective +MSW	39.31 8	39.35 (39.53)

- Target = ^{48}Ca $Q(^{48}Ca\text{-}^{48}Sc)$=2.8 MeV $E(1^+;\ ^{48}Sc)$ = 2.5 MeV

	A (normal)	B (inverted)
no oscillation	73.56	73.56 ($10^{-42}cm^2$)
collective osc.	73.56 303.4	303.4
collective +MSW	302.6 73	302.8

Cross sections are enhanced by oscillations.

E_{split} is too small to distinguish the ν-mass hierarchy in case of Collect.+MSW oscillations ( ): E_{split} =15 MeV

Summary

1. ・ ν-^{12}C GT + SD shell-model with SFO
   ・ ν-^{16}O SD shell-model with SFO-tls
   ・ Partial cross sections for particle and γ emission channels with Hauser-Feshbach statistical model
   ・ Synthesis of ^{11}B: ^{12}C (ν, ν'p) ^{11}B, ^{16}O (ν, ν'αp) ^{11}B
   ^{11}C: ^{12}C(ν, e$^-$p) ^{11}C, ^{16}O (ν, e$^-$$\alpha$p) ^{11}C

2. MSW ν oscillation effects
   Mass hierarchy dependence:
   Production ratio of ^{11}B/^{7}Li in SNe
   Cross sections of ^{16}O (ν, e$^-$) X and ^{16}O ($\bar{\nu}$, e$^+$) X

MSW+collective oscillations

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