ν-nucleus reactions on oxygen and carbon for SN ν detection

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NuInt2018, GSSI, L’Aquila
Oct. 18, 2018

- ν-detection

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

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

  ν-^{12}C: GT(Gamow-Teller)+SD(spin-dipole)

  ν-^{16}O: SD

  $E_\nu \leq 100$ MeV

- ν-oscillation effects → ν mass hierarchy

  MSW oscillations in SNe

  Collective +MSW 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, arXiv: 1809.08398

● 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)

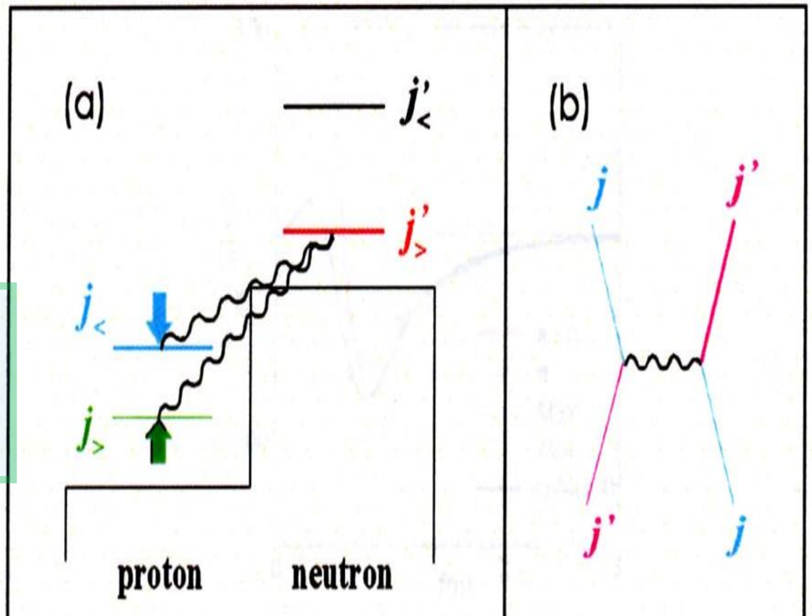
* important roles of tensor force

Monopole terms of V_{NN}

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

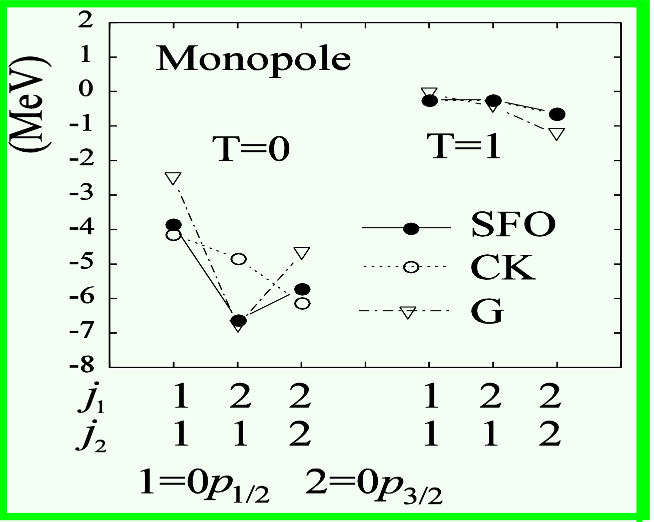
$j_> - j_<$: attractive

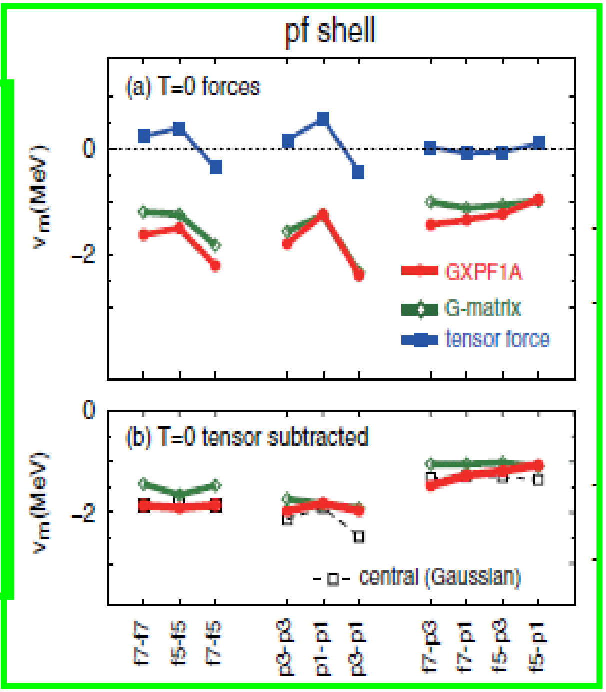
$j_> - j_>, j_< - j_<$: repulsive



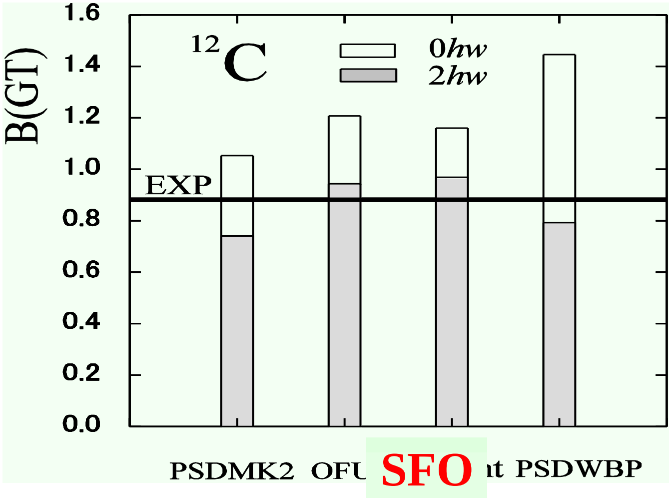
Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

SFO: p-sd shell





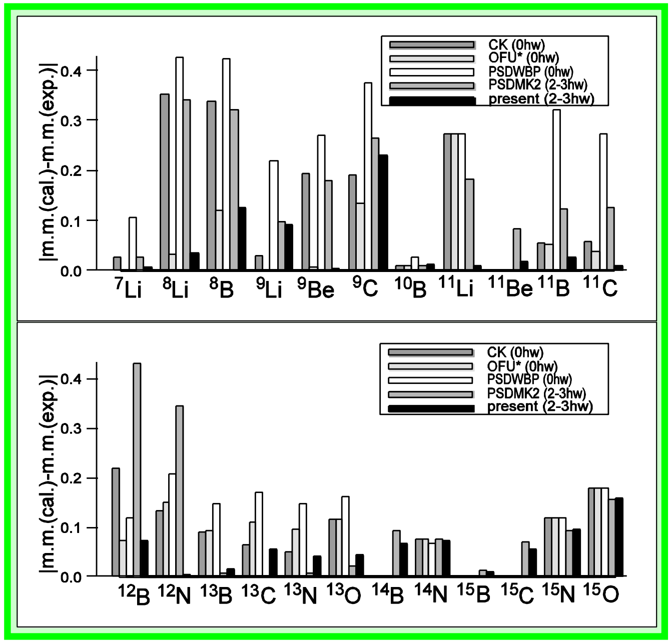
B(GT) for ^{12}C → ^{12}N



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

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

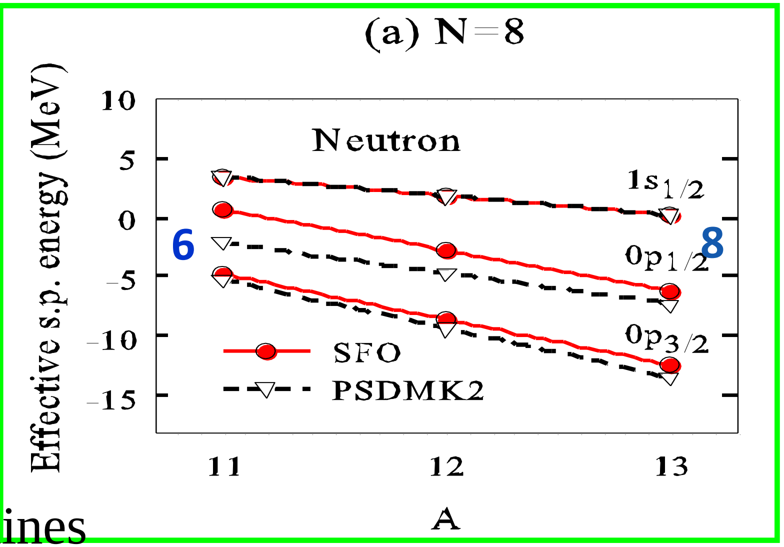
Magnetic moments of p-shell nuclei



present = SFO space: up to 2-3 hw

Shell evolution in N=8 isotone

Magic #
N=8→6



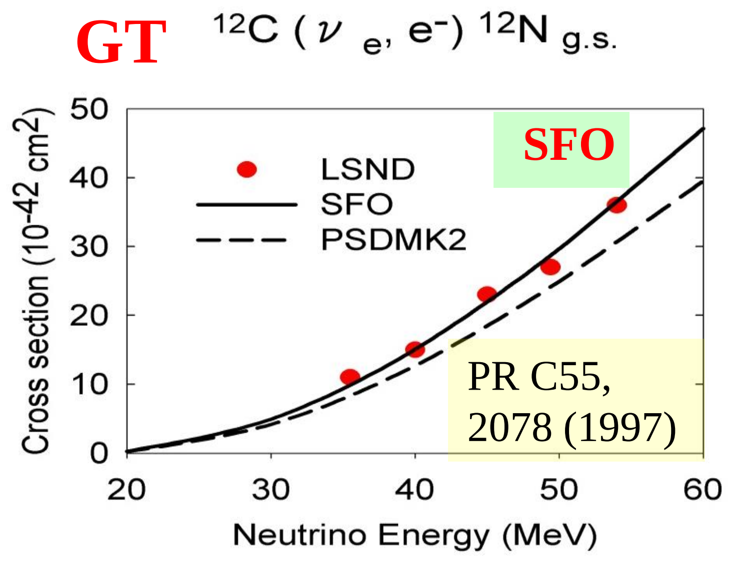
attraction
$\pi p_{3/2}$-$\nu p_{1/2}$
decreases
toward drip-lines

- **ν-nucleus reactions**

p-shell: SFO

pf-shell: GXPF1J (Honma et al.)

cf. KB3 Caurier et al.



GT

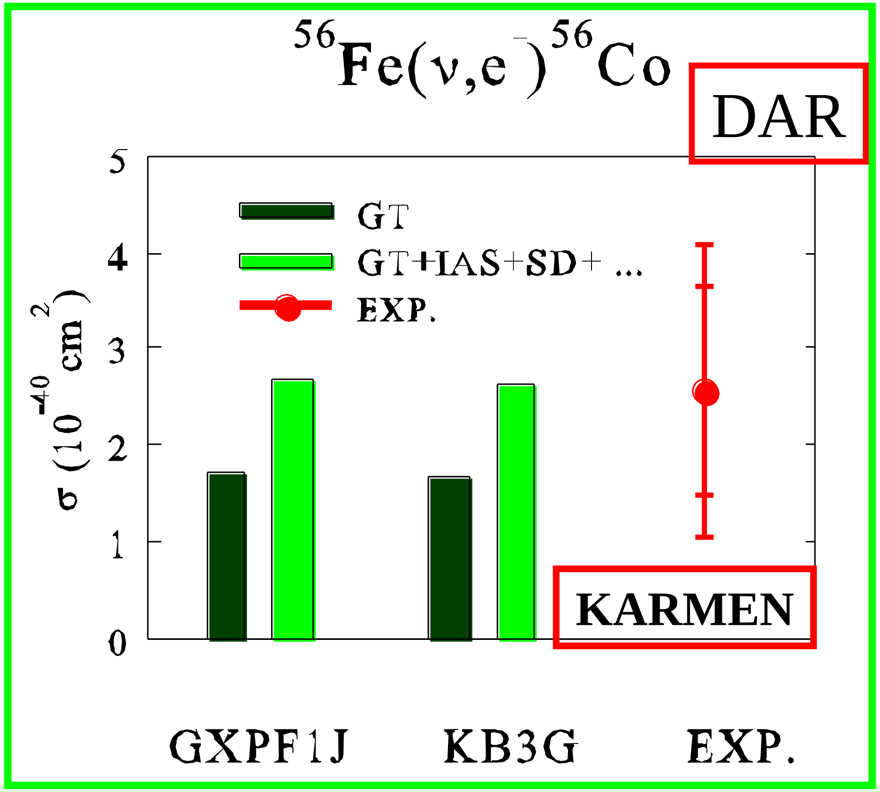
SFO

PR C55, 2078 (1997)

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

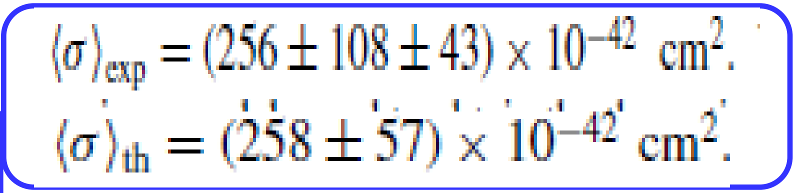


DAR

KARMEN

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

SD + … : RPA (SGII)

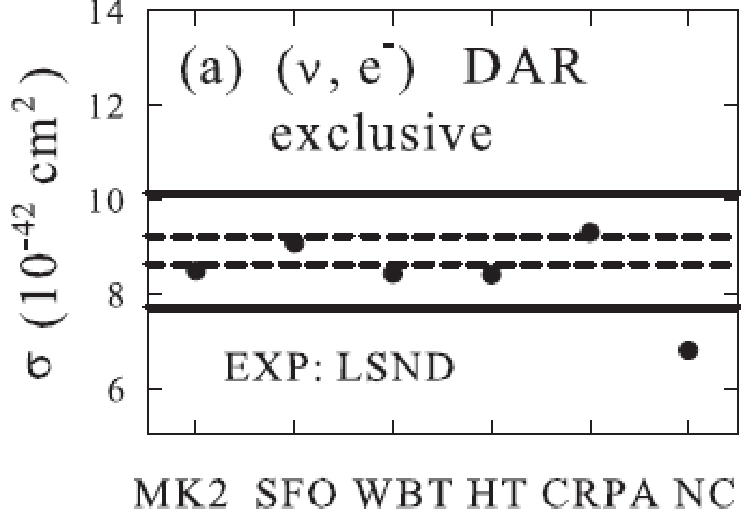


$$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}\ \mathrm{cm}^2.$$
$$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42}\ \mathrm{cm}^2.$$

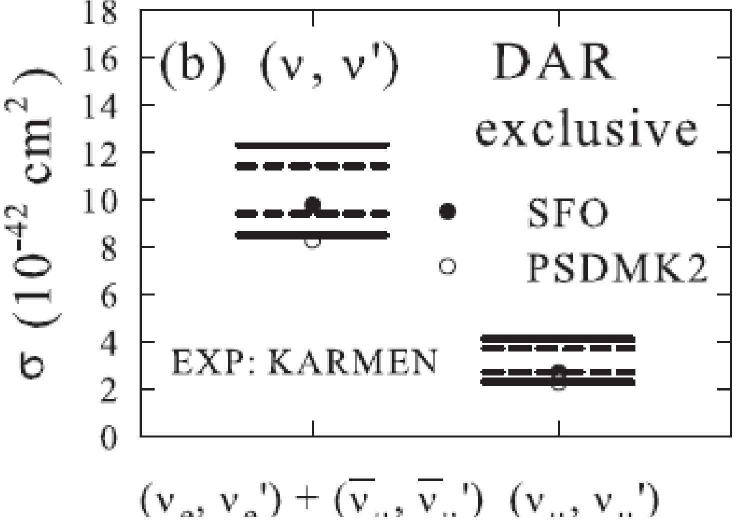
SM(GXPF1J)+RPA(SGII)	259 x10 $^{-42}$cm^2
RHB+RQRPA(DD-ME2)	263
RPA(Landau-Migdal force)	240

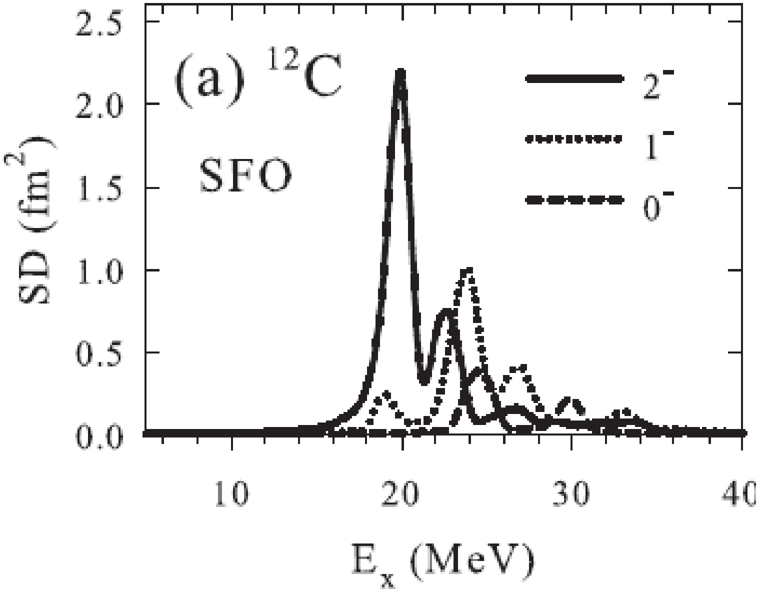
- ν-^{12}C

GT

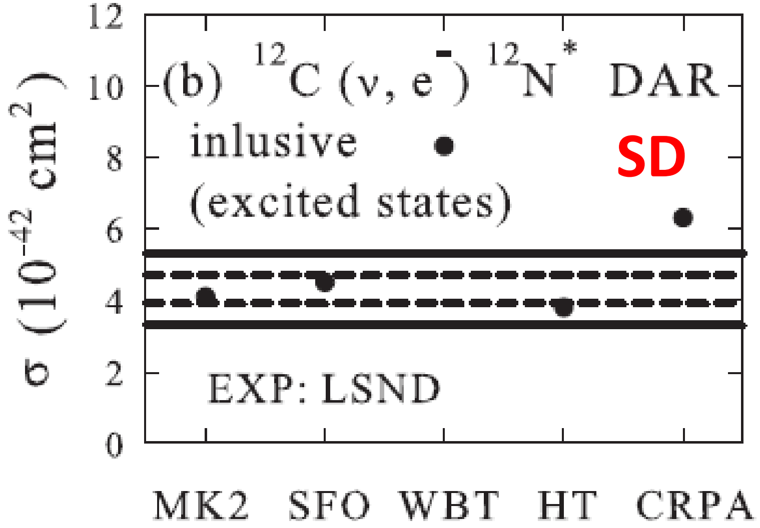


GT





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

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

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

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

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

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

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

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

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

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

$g_\lambda = 1$ 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]

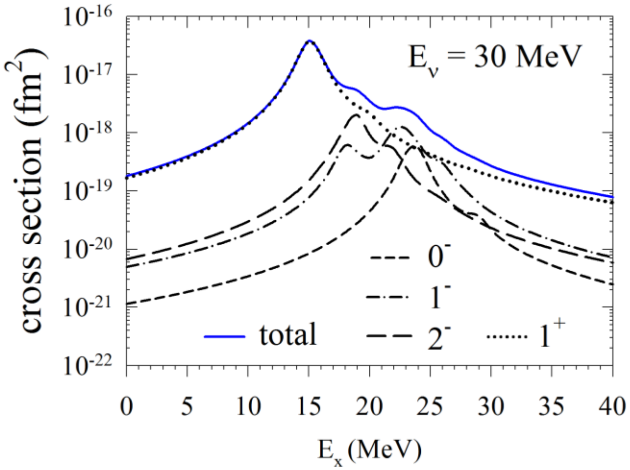
$E_{av}=EWS_-/S_-$				
K+LS	26.39	22.01	14.13	MeV
SFO	25.71	25.22	21.50	

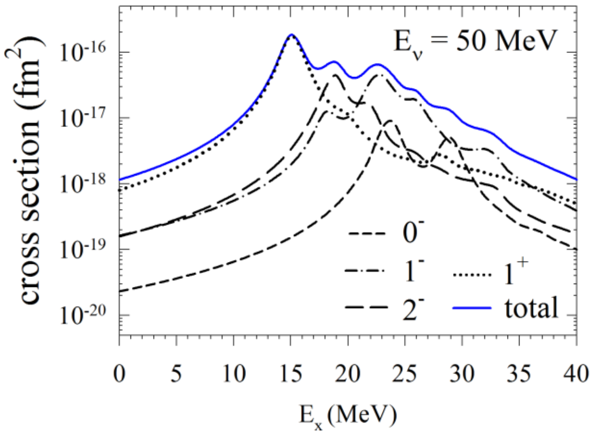
Hauser-Feshbach statistical model

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, ...

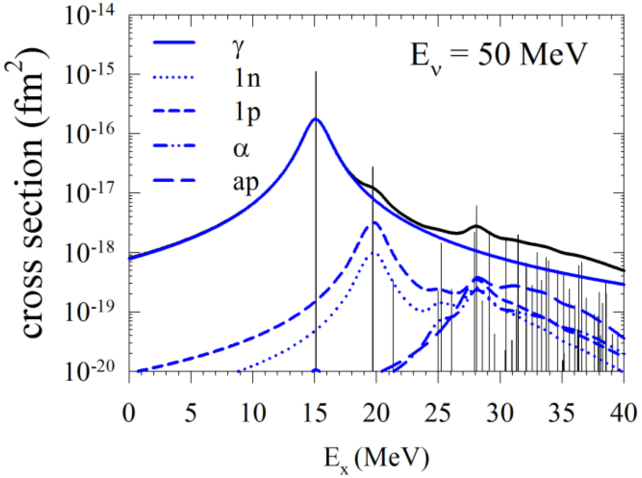
Isospin conservation is taken into account (S. Chiba)

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

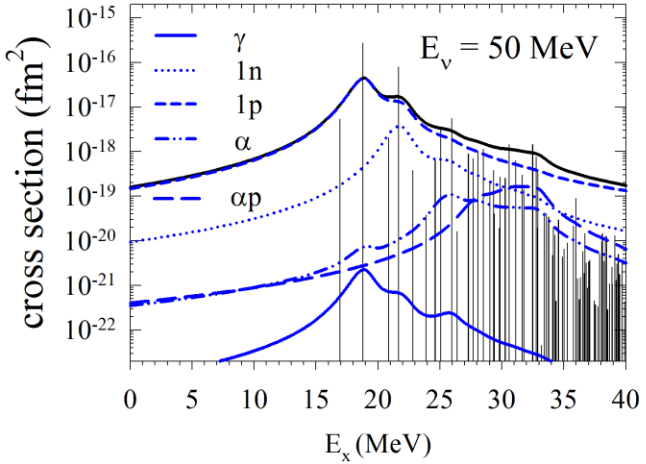




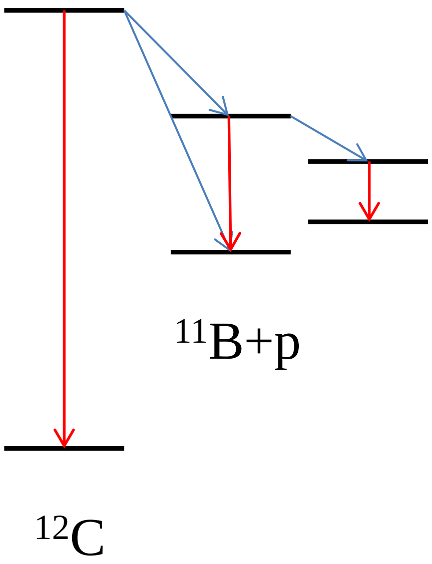
^{12}C 1^+



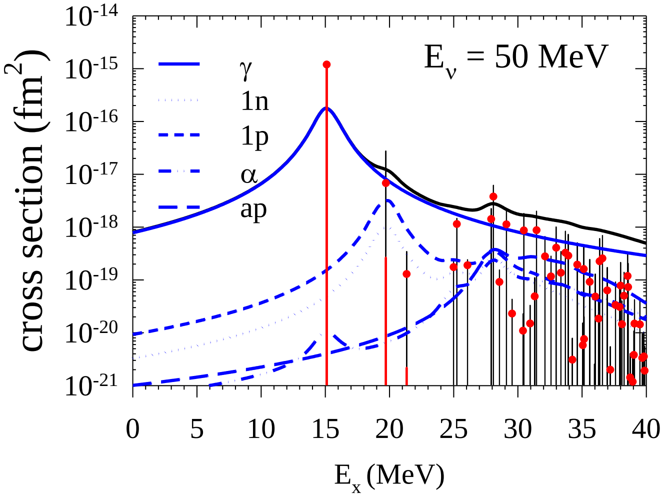
^{12}C 2^-



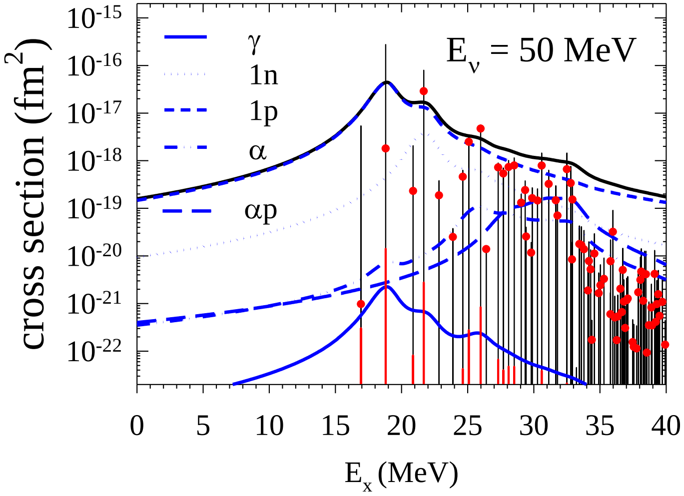
Gamma



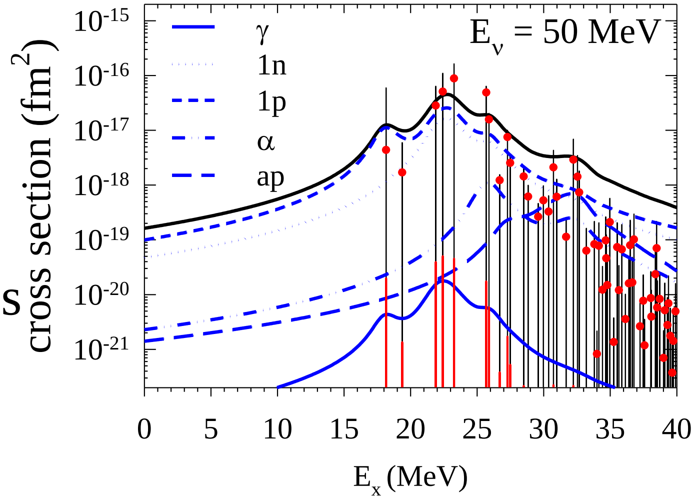
^{12}C 1^{+}



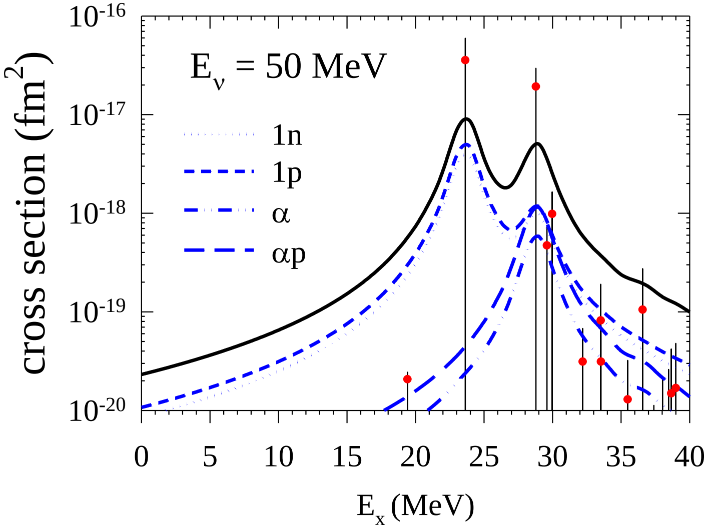
^{12}C 2^{-}



^{12}C 1^{-}



^{12}C 0^{-}



— direct decay

● direct
+ delayed after
particle emissions

▪ν-induced reactions on ^{16}O

- **Modification of SFO → SFO-tls**

  Full inclusion of tensor force

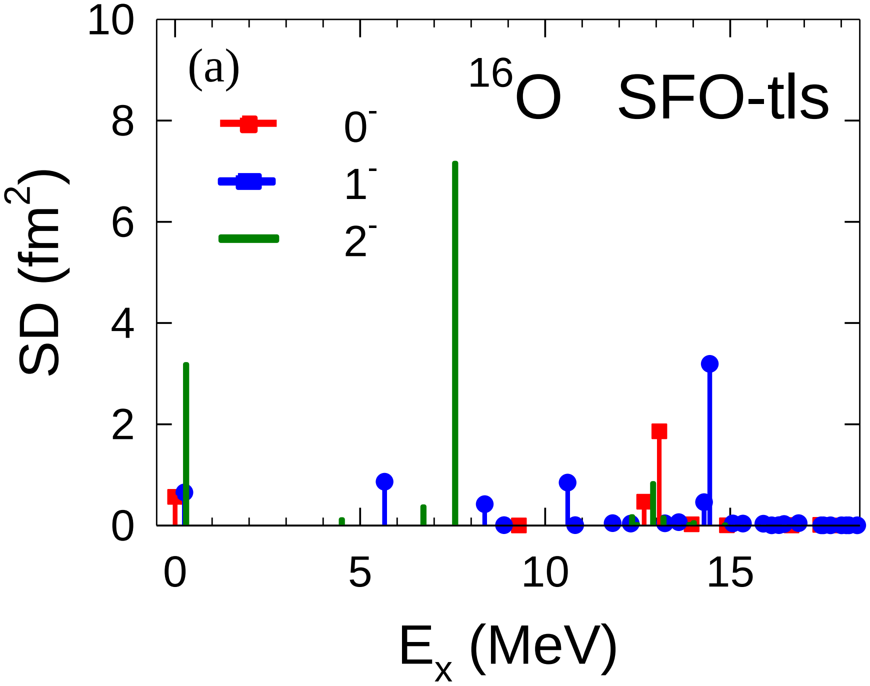
  - **p-sd: tensor-> π+ρ**

    LS -> σ+ρ+ω

$$V = V_C + V_T + V_{LS}$$

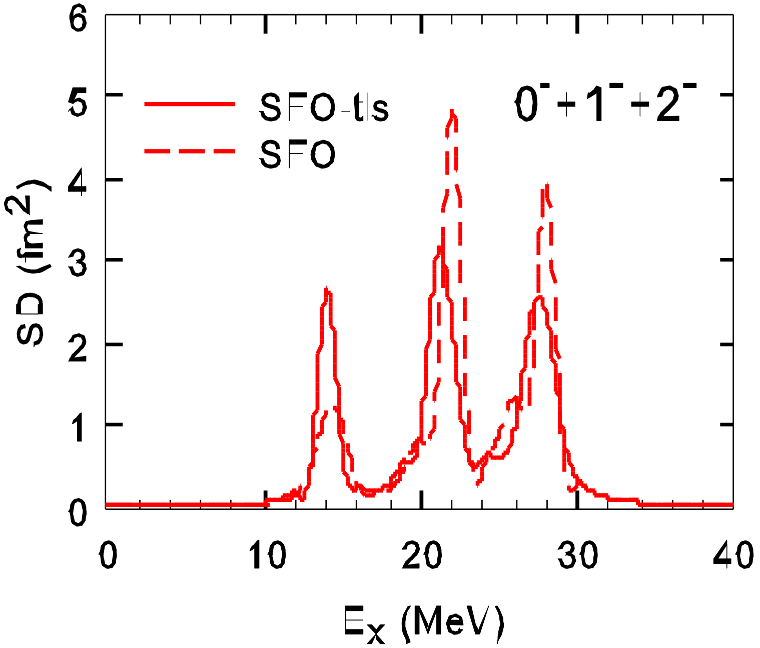
$$V_T = V_\pi + V_\rho$$

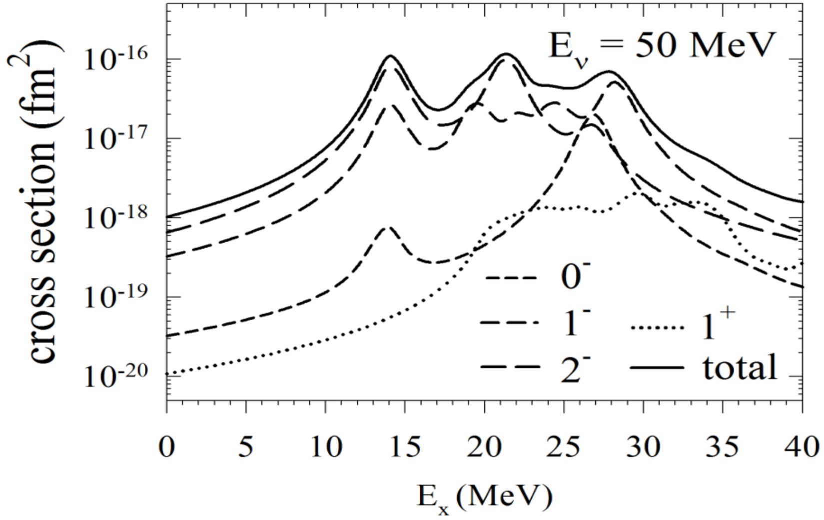
$$V_{LS} = V_{\sigma+\omega+\rho}$$



Spin-dipole strength in ^{16}O

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





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^-

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

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

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

● 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

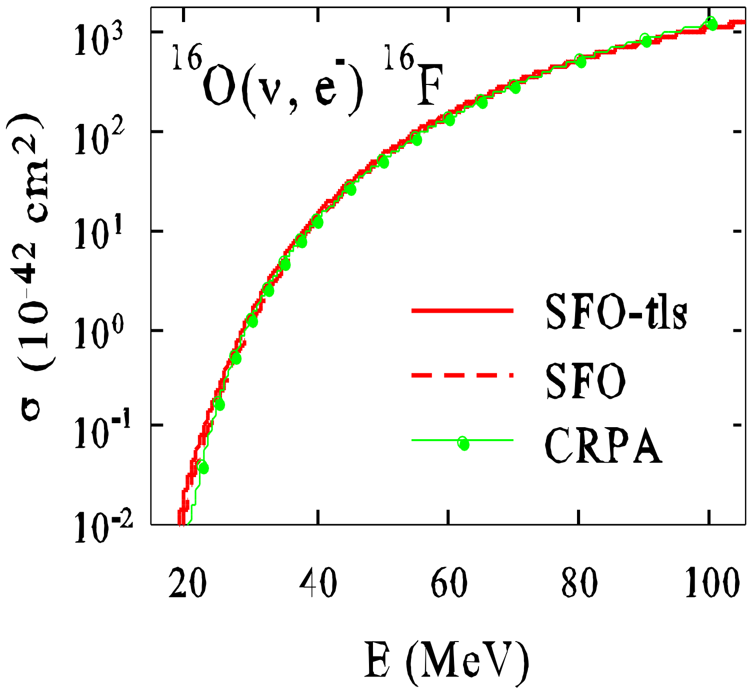
Induced pseudo-scalar current $\quad F_P(q_\mu^2) = \frac{2M_N}{q_\mu^2 + m_\pi^2} F_A(q_\mu^2)$

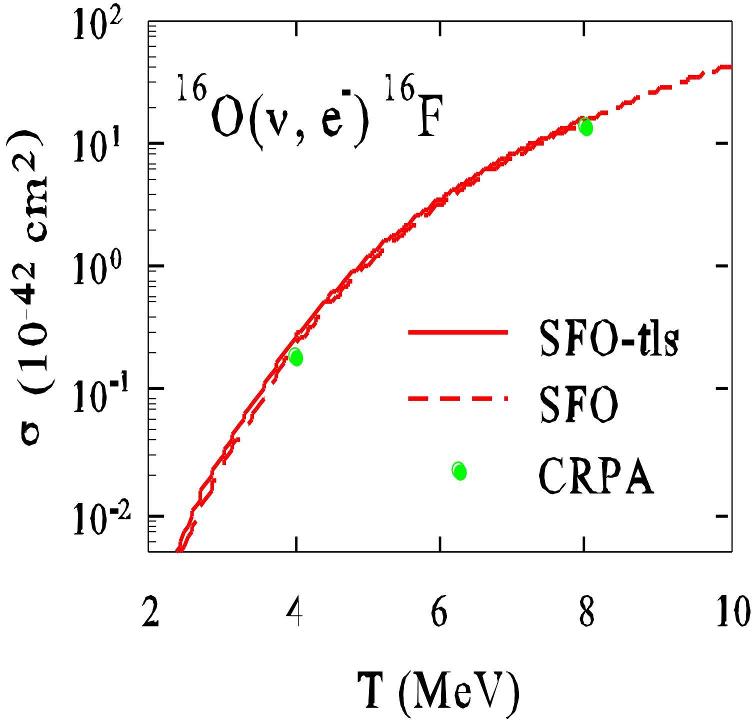
Goldberger-Treiman

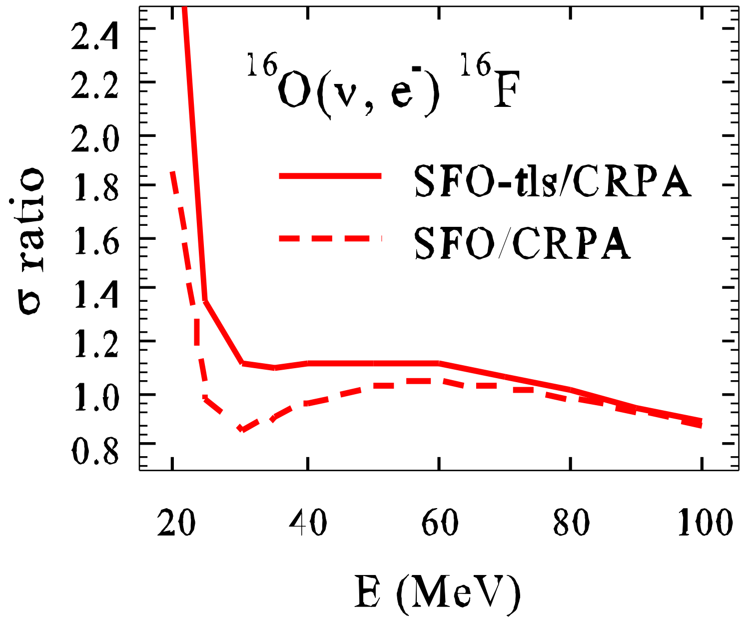
$$-2M_N F_A = \sqrt{2} g_\pi F_\pi$$

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

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}	







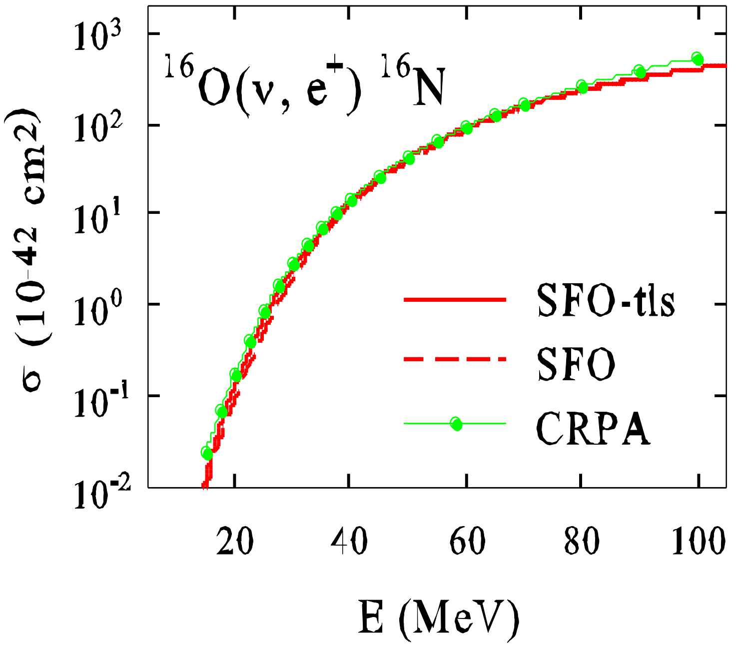
T= temperature of supernova ν

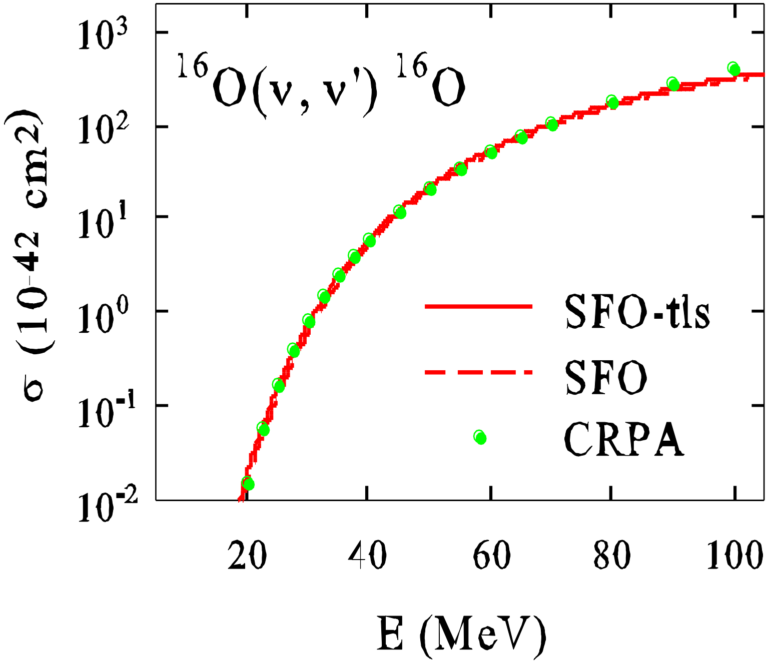
T	σ(SFO-tls)/σ(CRPA):
4	1.41
8	1.17

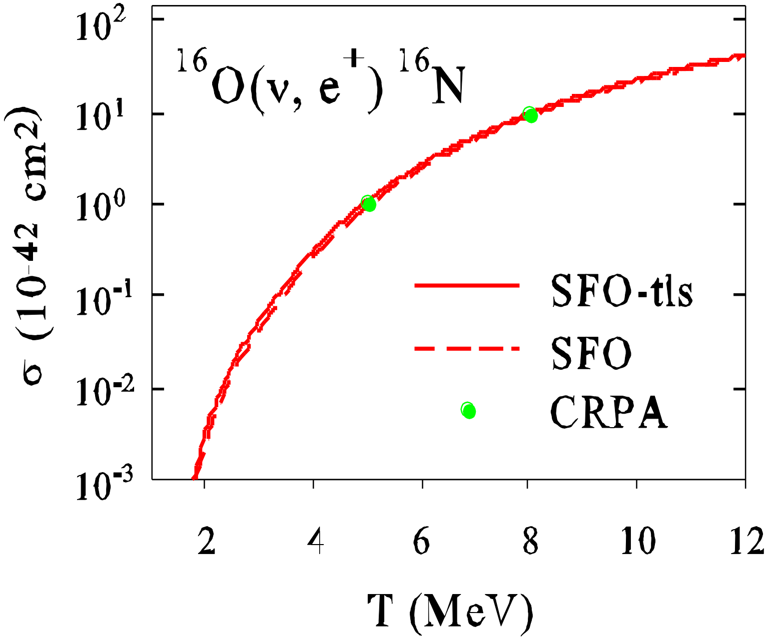
g_A^{eff}/g_A=0.95

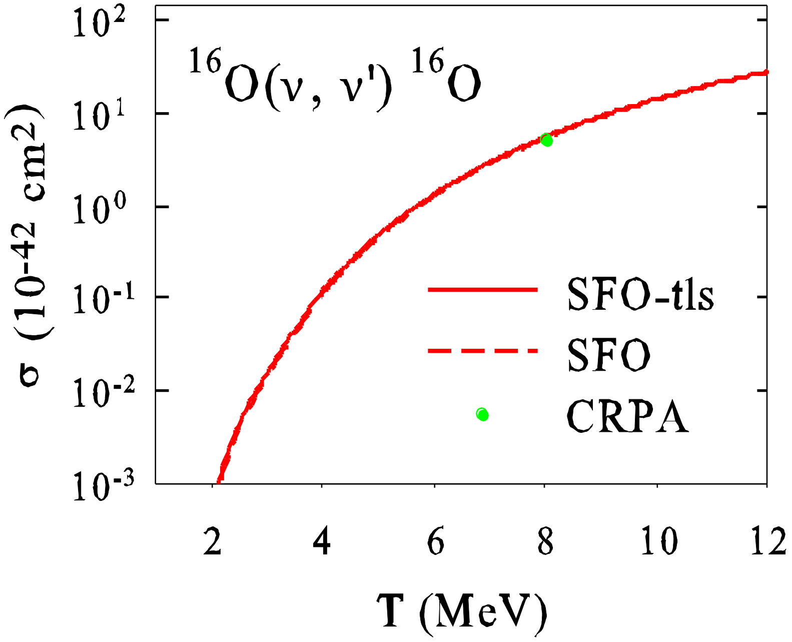
CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

cf. CRPA: Jachowicz et al., PR C65 (2002)
RPA/QRPA: Lazauskas and Volpe, NP A792 (2007)



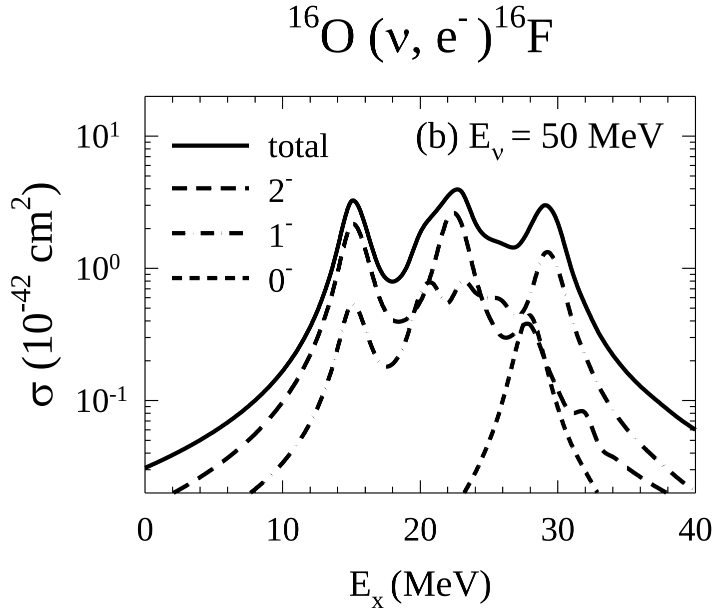


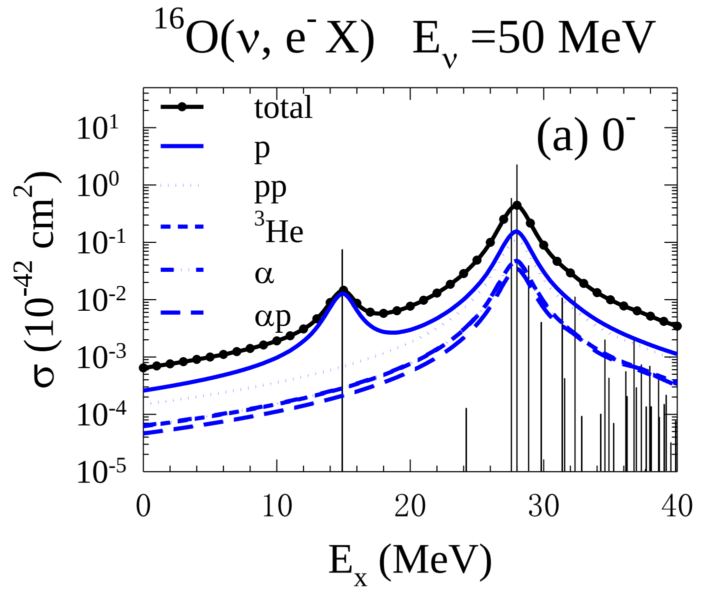


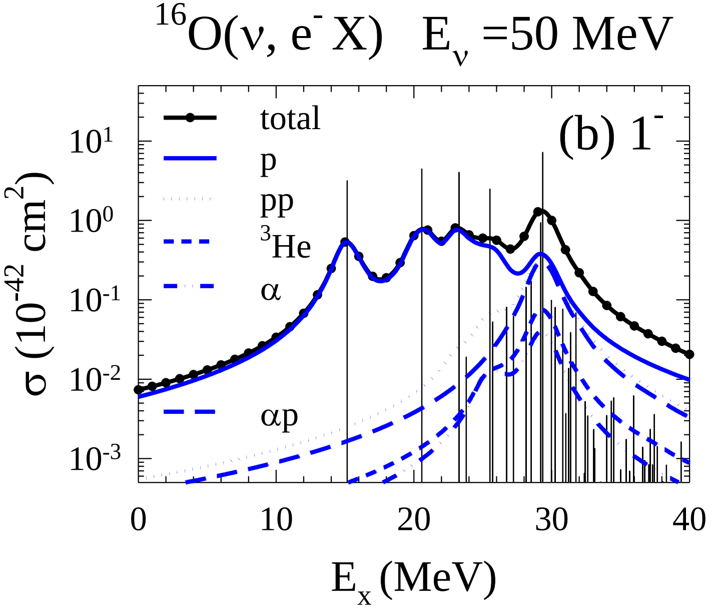


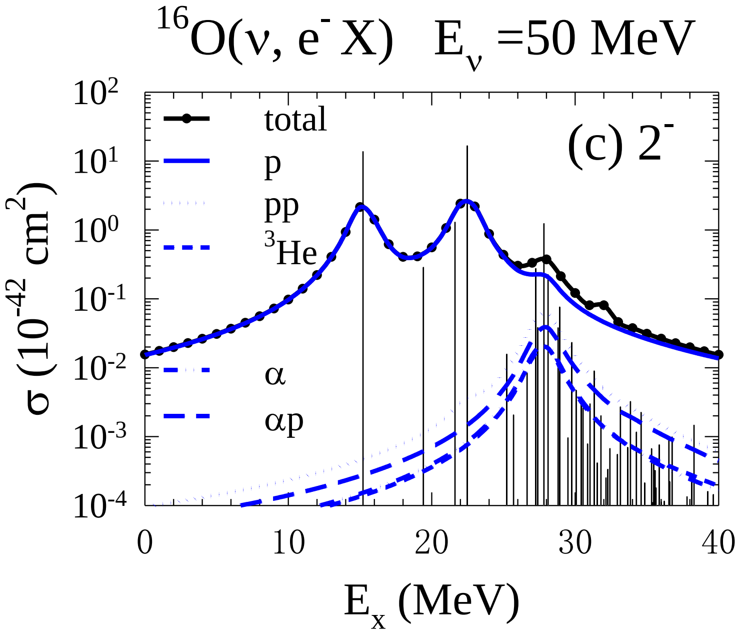
T= temperature of supernova ν

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

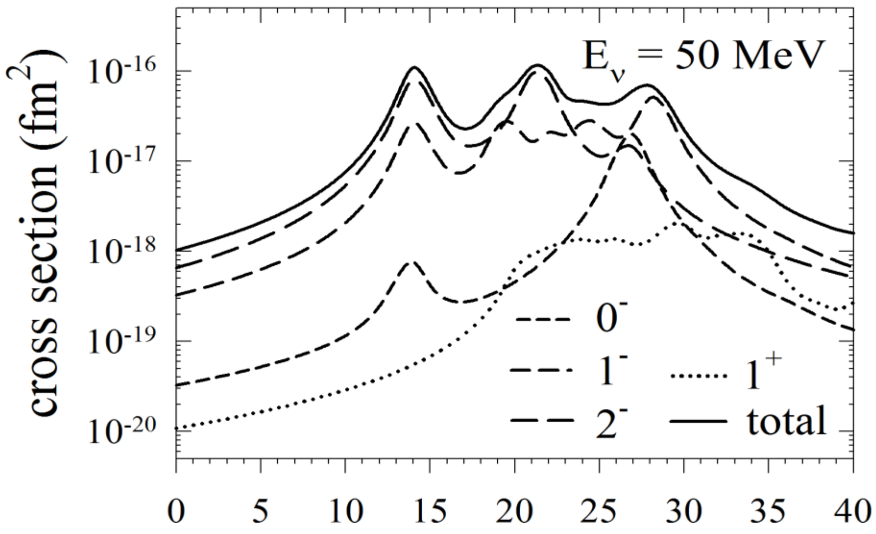

^{16}O (ν, e$^-$)^{16}F
(b) E$_ν$ = 50 MeV
total
2$^-$
1$^-$
0$^-$
σ (10^{-42} cm^2)
10^1
10^0
10^{-1}
0
10
20
30
40
E$_x$ (MeV)


^{16}O(ν, e$^-$ X) E$_ν$ =50 MeV
(a) 0$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
E$_x$ (MeV)

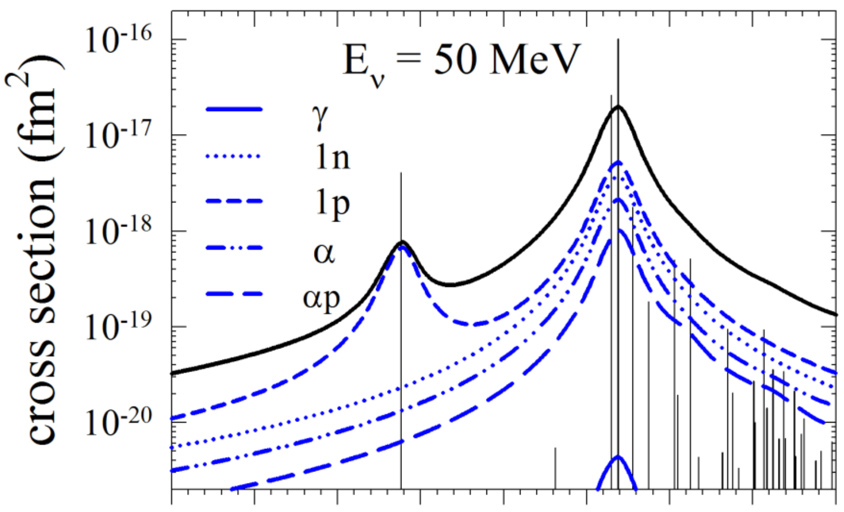

^{16}O(ν, e$^-$ X) E$_ν$ =50 MeV
(b) 1$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
E$_x$ (MeV)


^{16}O(ν, e$^-$ X) E$_ν$ =50 MeV
(c) 2$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
10
20
30
40
E$_x$ (MeV)

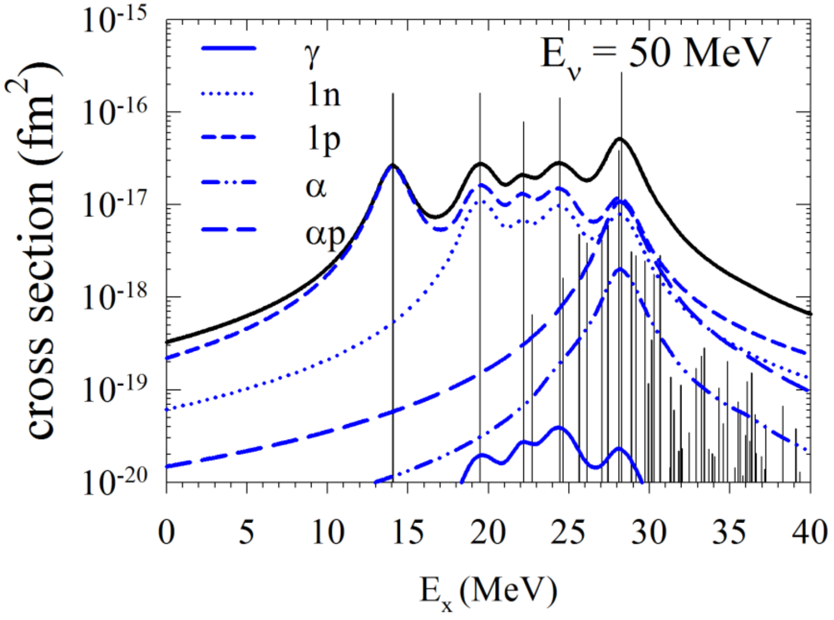
^{16}O Neutral current reactions



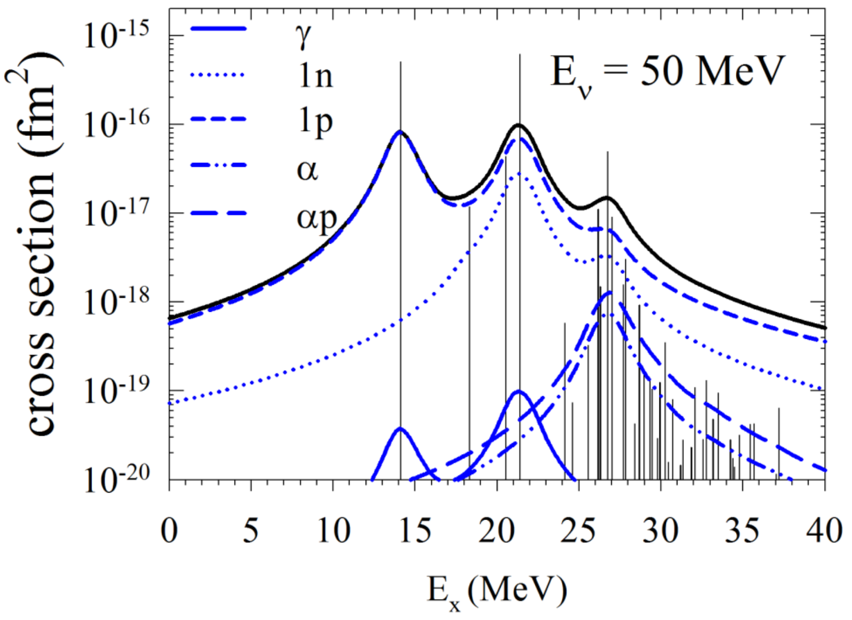
^{16}O 0$^-$



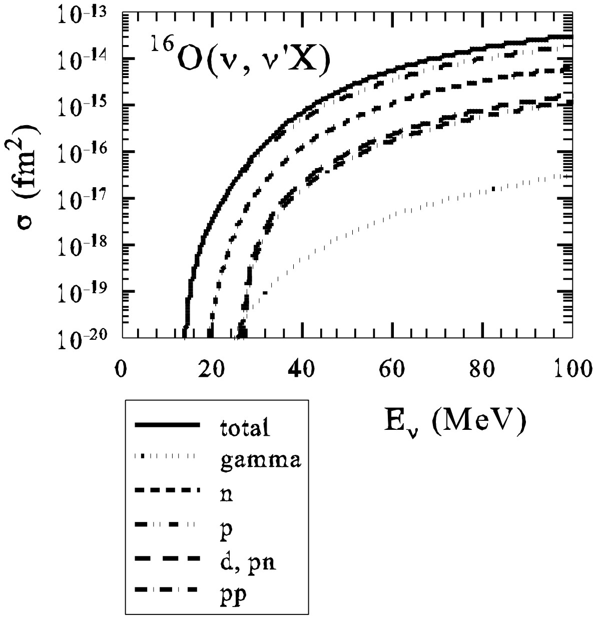
^{16}O 1$^-$

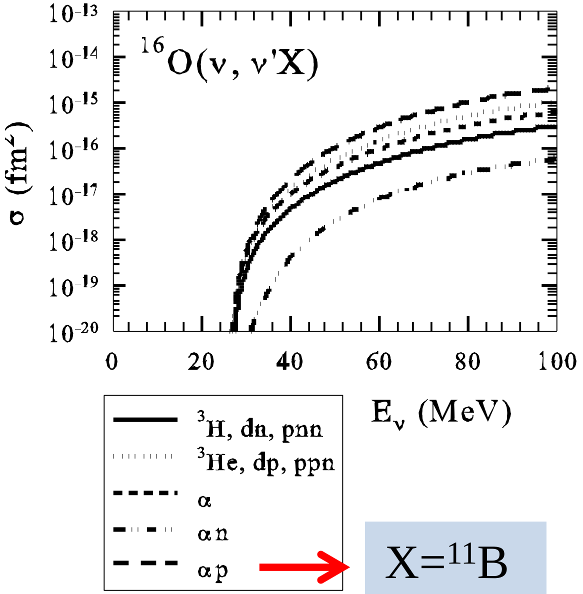


^{16}O 2$^-$

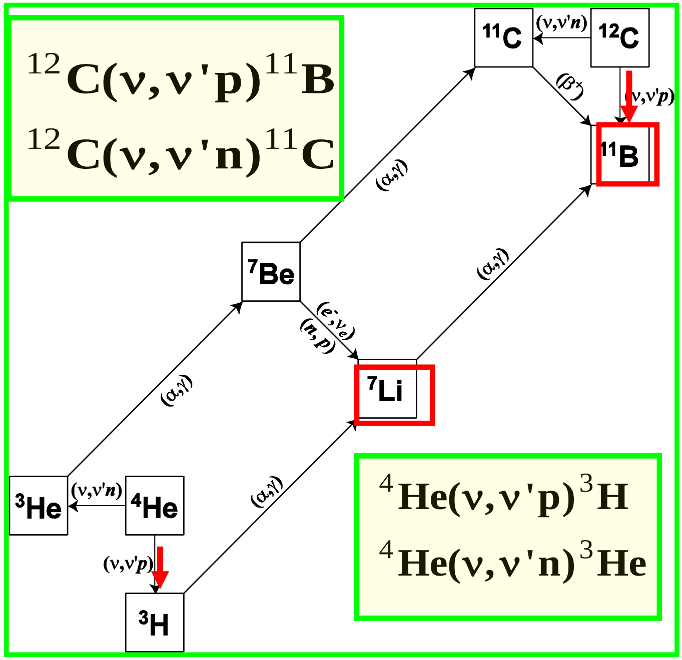


Synthesis of ^{11}B and ^{11}C in SNe





X=^{11}B



^{12}C(ν,ν'p)^{11}B

^{12}C(ν,ν'n)^{11}C

^{4}He(ν,ν'p)^{3}H

^{4}He(ν,ν'n)^{3}He

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

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$_\odot$)

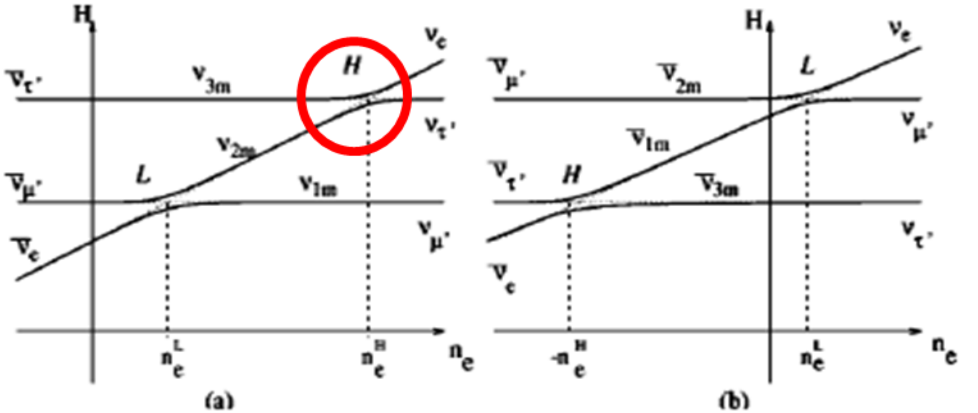
	$15M_\odot$ モデル			$20M_\odot$ モデル		
核種生成量	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}\mathrm{C})$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}\mathrm{B}+^{11}\mathrm{C})$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

ν oscillation effects → 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

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

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

$\text{H}-\text{resonance:}\ \theta_{13}$

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

He/C layer

$\text{L}-\text{resonance:}\ \theta_{12}$

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

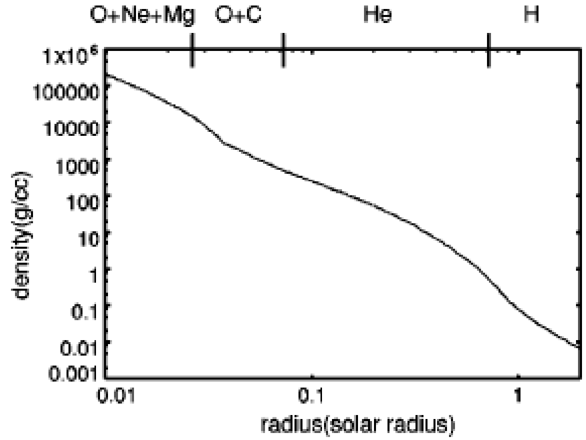
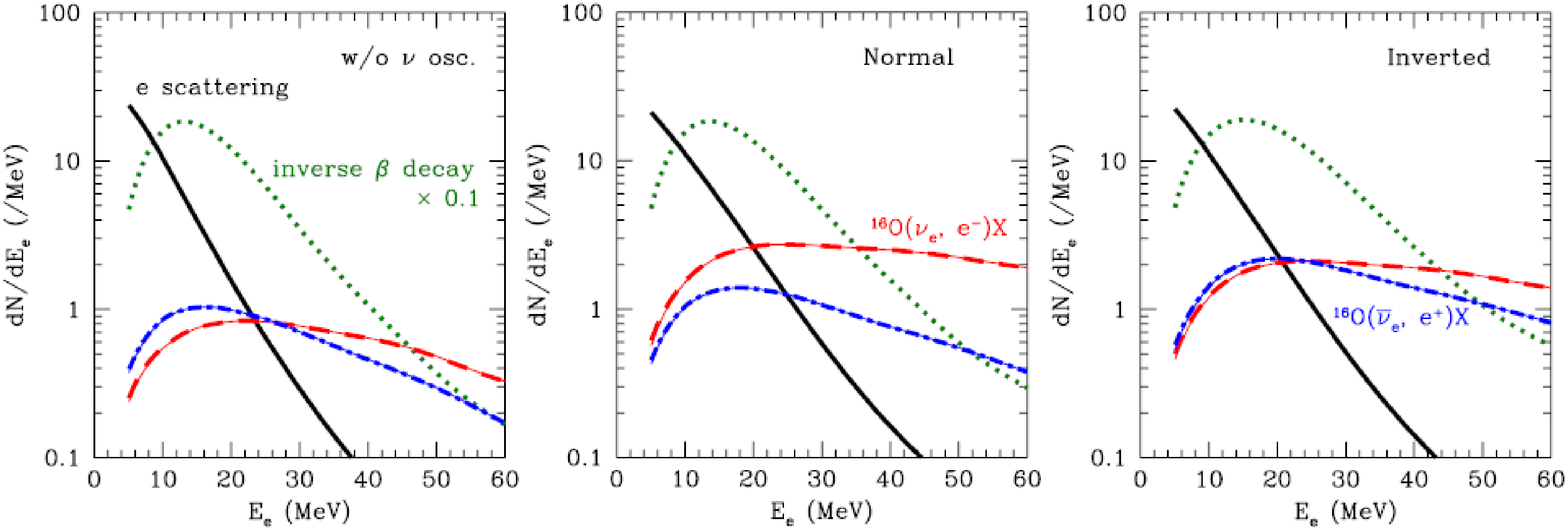


FIG. 3. Density profile of the presupernova star model used in the paper [20]. The progenitor mass is set to be $15M_{\odot}$.

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] arXiv: 1809.08398



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

$<E\_\nu_e>$ = 9.32 MeV, $<E\_\bar{\nu}_e>$ = 11.1 MeV, $<E\_\nu_x>$ =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

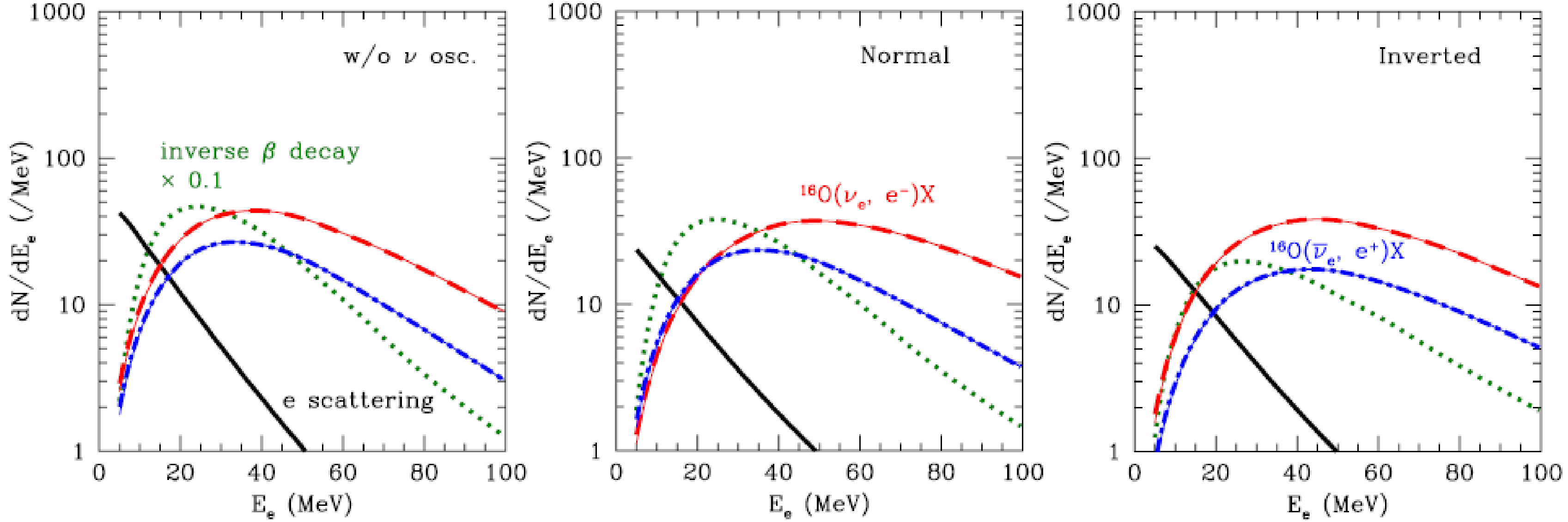
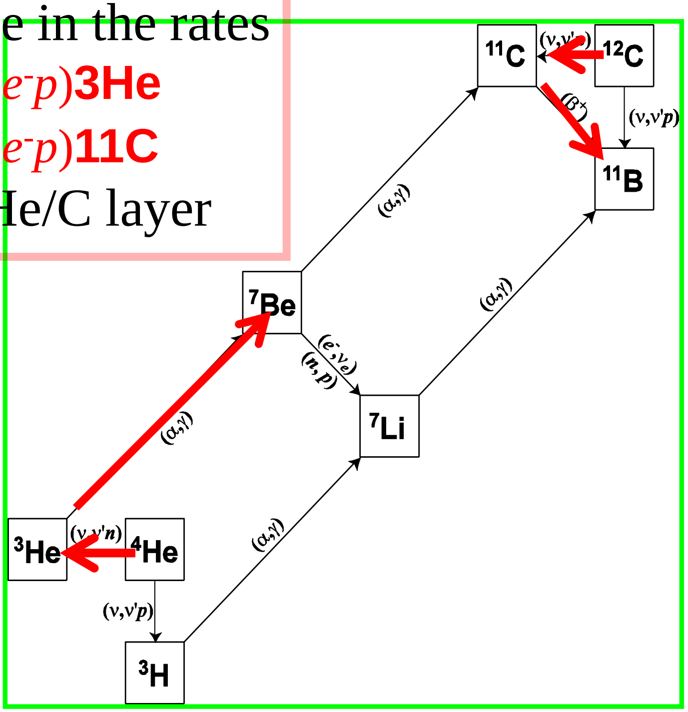


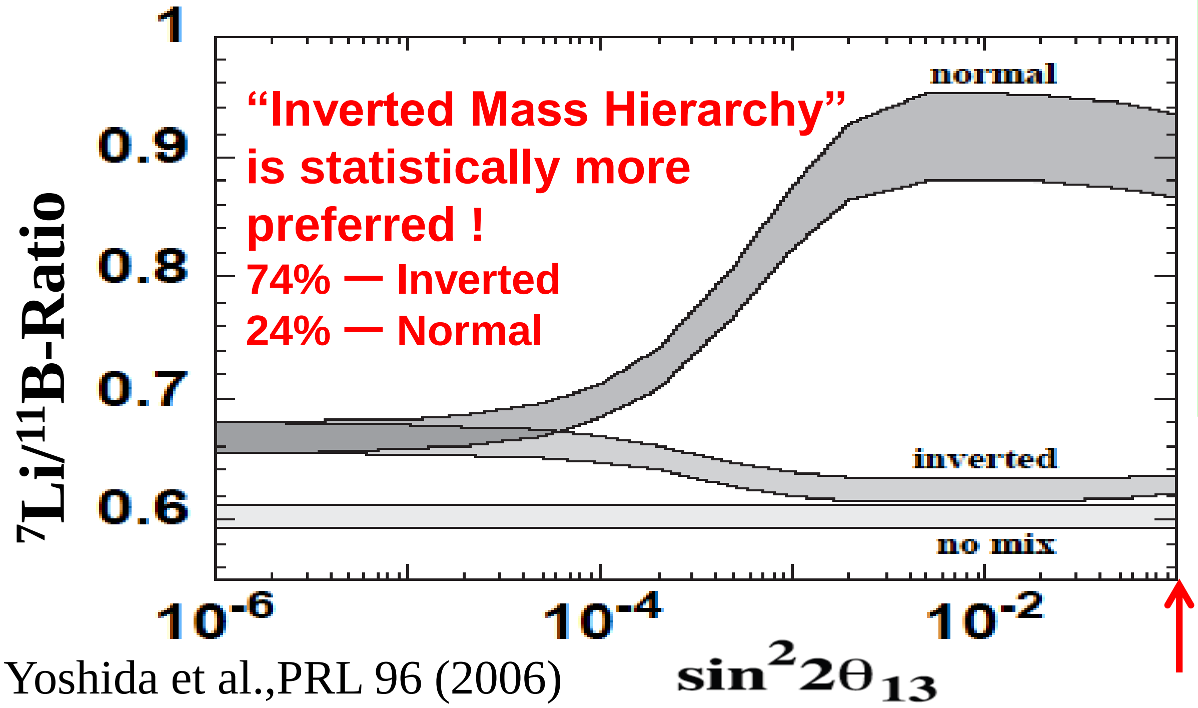
Fig. 5 Same as Fig. 4 but for the model with $(M, Z) = (30M_\odot, 0.004)$, which corresponds to a black-hole-forming collapse.

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





“Inverted Mass Hierarchy” is statistically more preferred !
74% — Inverted
24% — Normal

Yoshida et al.,PRL 96 (2006)

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

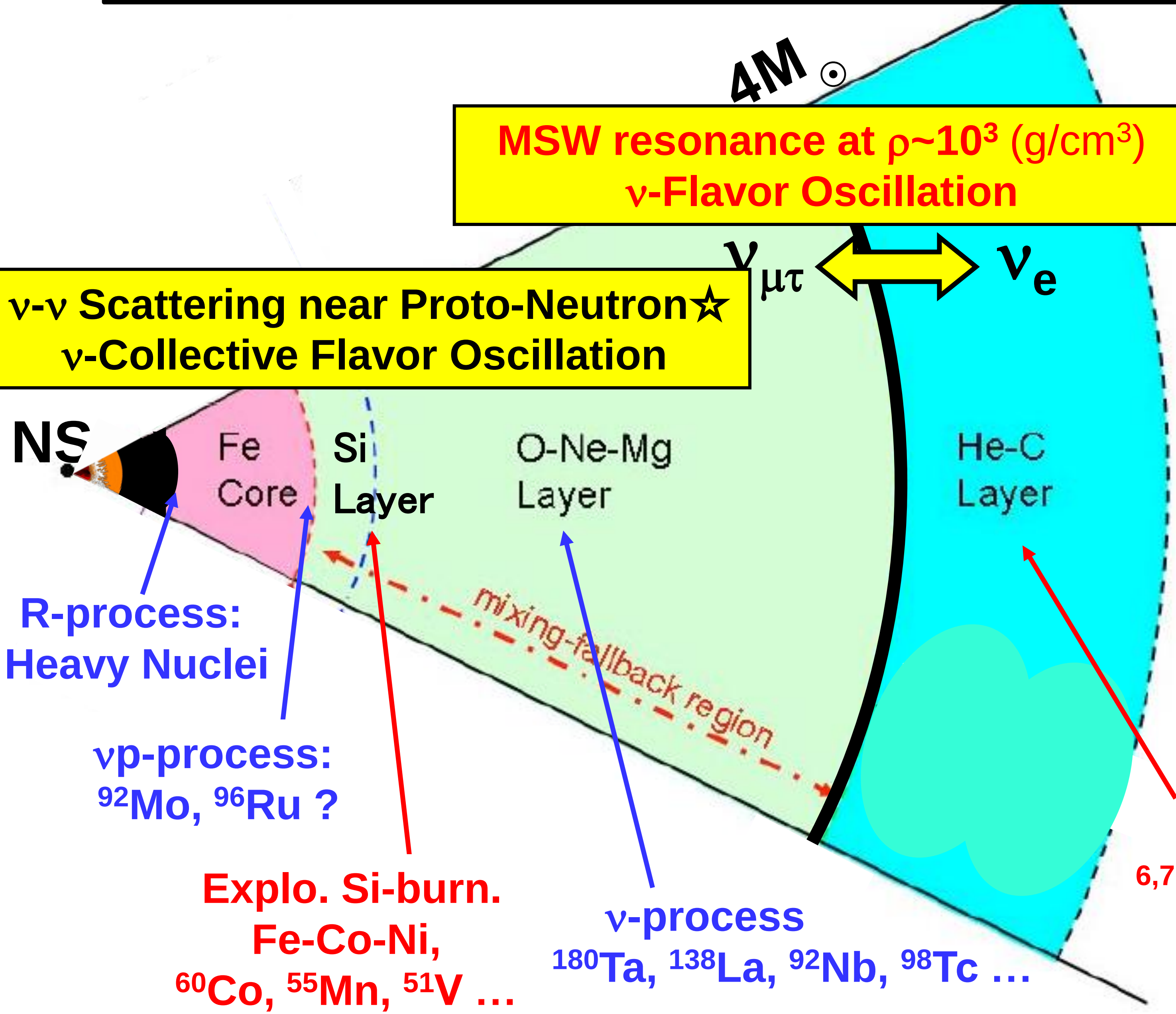
$\sin^2 2\theta_{13} = 0.1$

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

Kajino



MSW resonance at $\rho \sim 10^3$ (g/cm^3)
ν-Flavor Oscillation

ν-ν Scattering near Proto-Neutron☆
ν-Collective Flavor Oscillation

R-process:
Heavy Nuclei

νp-process:
^{92}Mo, ^{96}Ru ?

Explo. Si-burn.
Fe-Co-Ni,
^{60}Co, ^{55}Mn, ^{51}V …

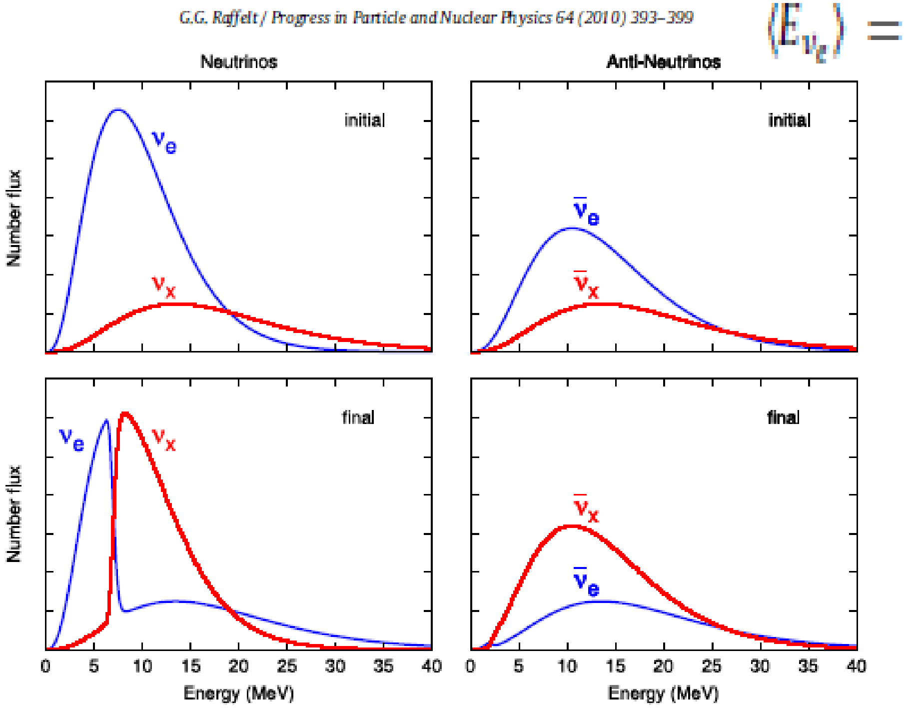
ν-process
^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

ν-process:
^{6,7}Li, ^{9}Be, ^{10,11}B …

Spectrum with ν-oscillations

- With collective oscillation effects

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


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

Normal

Inverted

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

B :

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

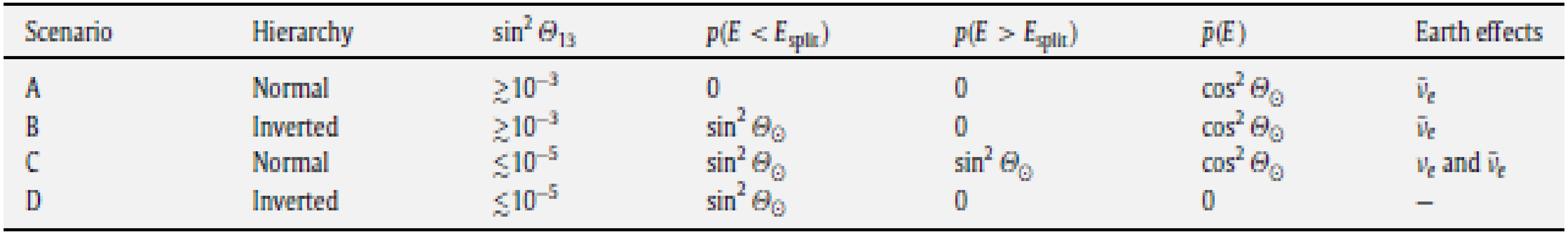
$$+\cos^2\theta_{12}F_{\nu_x}(E)\quad (E < E_{\text{split}})$$

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

- 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	$\sin^2\Theta_{13}$	$p(E < E_{\text{split}})$	$p(E > E_{\text{split}})$	$\bar{p}(E)$	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.

$E_\nu \leq 10\text{MeV} \quad E_\nu^{th}(^{12}\text{C}) \approx 13\text{MeV}$

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 (39.93)
collective +MSW	39.31	39.35 (39.53)

- Target = ^{48}Ca   Q(^{48}Ca-^{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
collective +MSW	302.6	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$^-$αp) ^{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 (ν, e$^+$) X

In case of both MSW+collective oscillation~~s~~

It is not easy to distinguish mass hierarchies on the earth

cf. Sasaki et al., PRD 96, 043013 (2017)

SN νp process -> abundances of p nuclei (Mo, Ru) enhanced

for normal hierarchy; $\bar{\nu}_e + p \rightarrow n + e^+$

cf. Prompt ν_e from core-collapse is free from collective osc.

Collaborators

S. Chiba[a], T. Yoshida[b], K. Nakazato[c], M. Sakuda[d],
T. Kajino [b,e], T. Otsuka[f], M. Honma[g], B. Balantekin[h],
K. Takahashi[i], H. Umeda[b]

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[b]The University of Tokyo
[c]Kyushu Univ.
[d]Okayama Univ.
[e]National Astronomical Observatory of Japan
[f]RIKEN
[g]University of Aizu
[h]Univ. of Wisconsin
[i]Univ. Bonn

▪ ν-induced reactions on ^{13}C

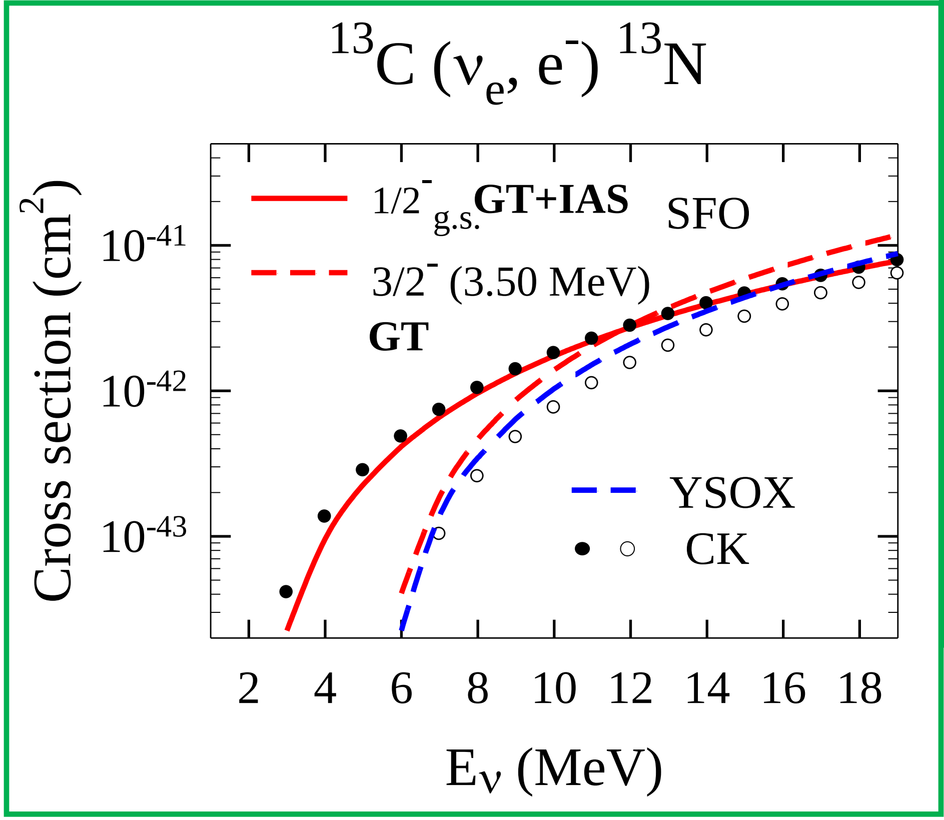
^{13}C: attractive target for very low energy ν

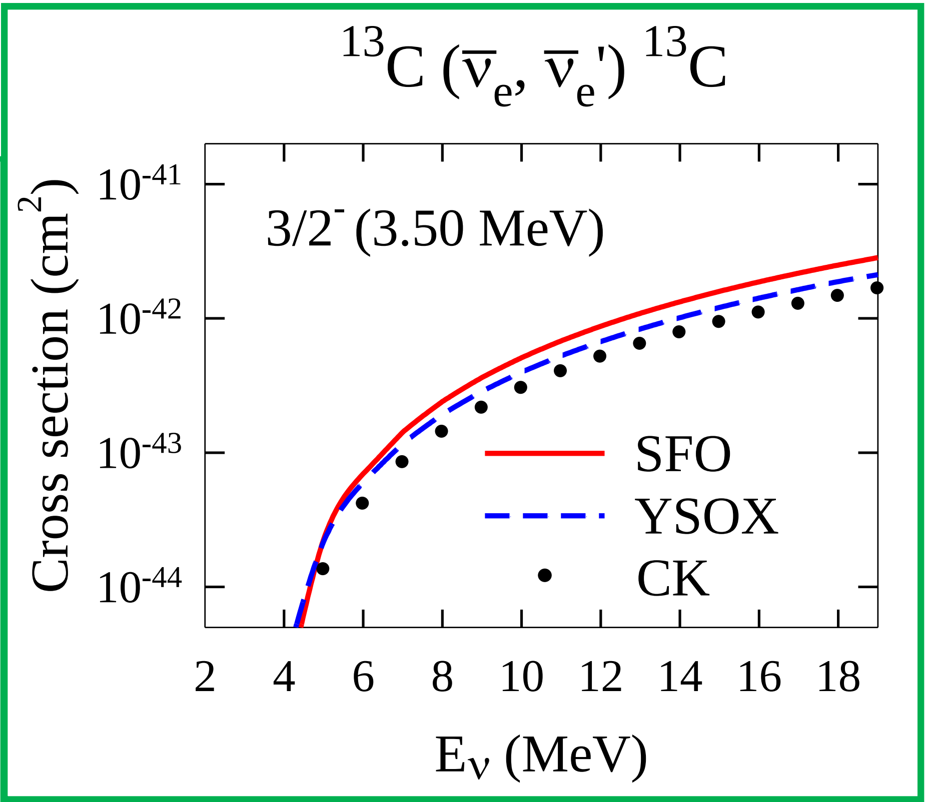
$$E_\nu \le 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}\mathrm{C}) \approx 13\,\mathrm{MeV}$$

$$\mathrm{Natural\ isotope\ abundance} = 1.07\%$$

reactor anti-ν

Detector for solar ν (E<15MeV) and reactor anti-ν (E< 8 MeV)





g_A^{eff}/g_A=0.95(SFO),0.85(YSOX)
0.69 (CK)

Suzuki, Balantekin, Kajino, PR C86, 015502 (2012)

Coherent (elastic) scattering on light target

Neutral current $A_\mu^S = V_\mu^S = 0$

$$J_\mu^{(0)} = A_\mu^3 + V_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$$

Vector part: $V_\mu^{(0)} = V_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$

C0: $(G_E^{IV} - 2\sin^2\theta_W G_E) < g.s. | j_0(qr) Y^{(0)} | g.s. >$

$$<=> \frac{1}{2} G_E^p (1 - 4\sin^2\theta_W)\rho_p(r) - \frac{1}{2} G_E^p \rho_n(r) \qquad (G_E^n \approx 0)$$

$$= -\frac{1}{2} G_E^p \{\rho_n(r) - 0.08\rho_p(r)\} \quad (\sin^2\theta_W = 0.23)$$

Probe of neutron density distribution

Patton, Engel, MacLaghlin, Schunck, PRC 86, 024612 (2012)

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M\{2 - \frac{MT}{E^2}\} \frac{Q_W^2}{4} F^2(Q^2)$$

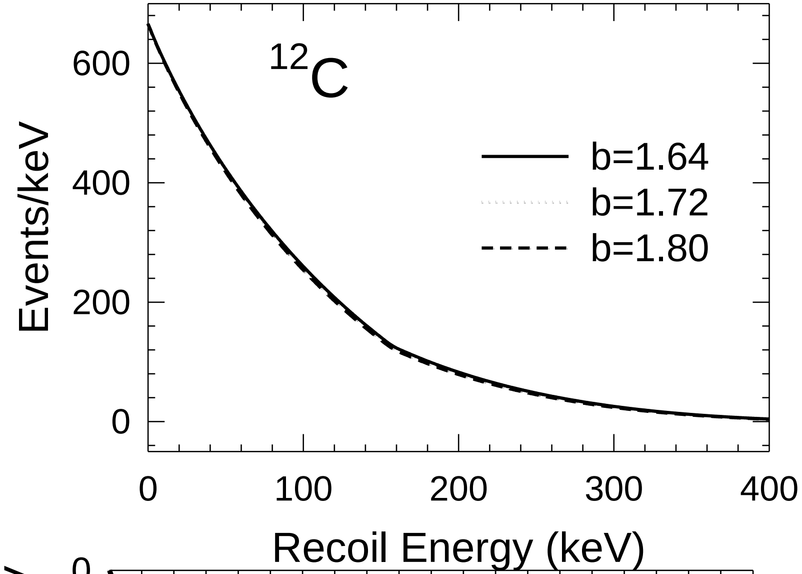
T=recoil energy

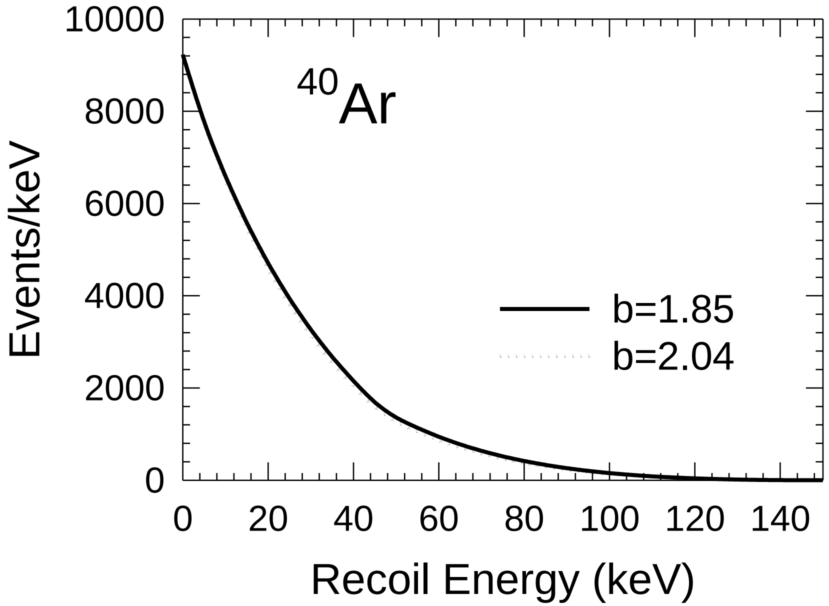
$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$

$$F(Q^2) = \{N F_n(Q^2) - (1 - 4\sin^2\theta_W) Z F_p(Q^2)\} / Q_W$$

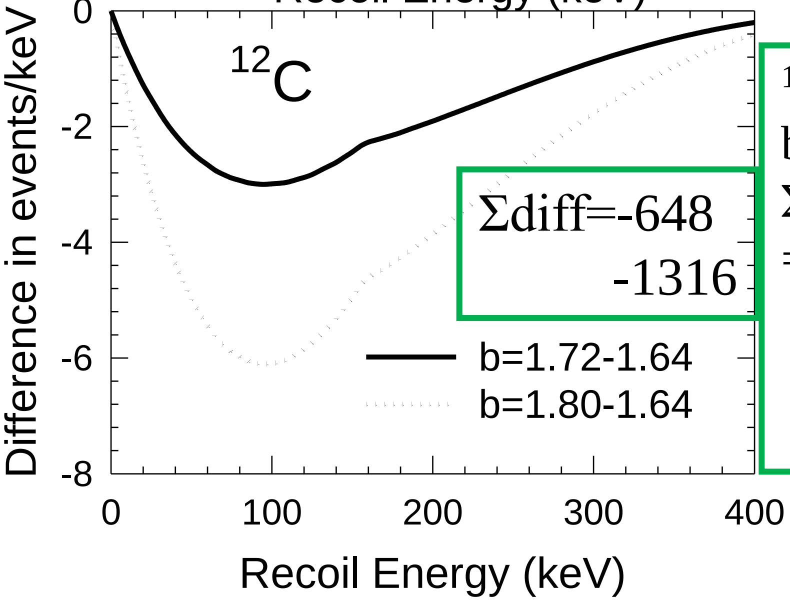
$$Q^2 = 2E^2 TN / (E^2 - ET)$$

Events/keV - Recoil energy (keV)
DAR ν (3-flavors)
$\Phi = 3\times10^7$ /cm^2/s, 1year, target=1 ton



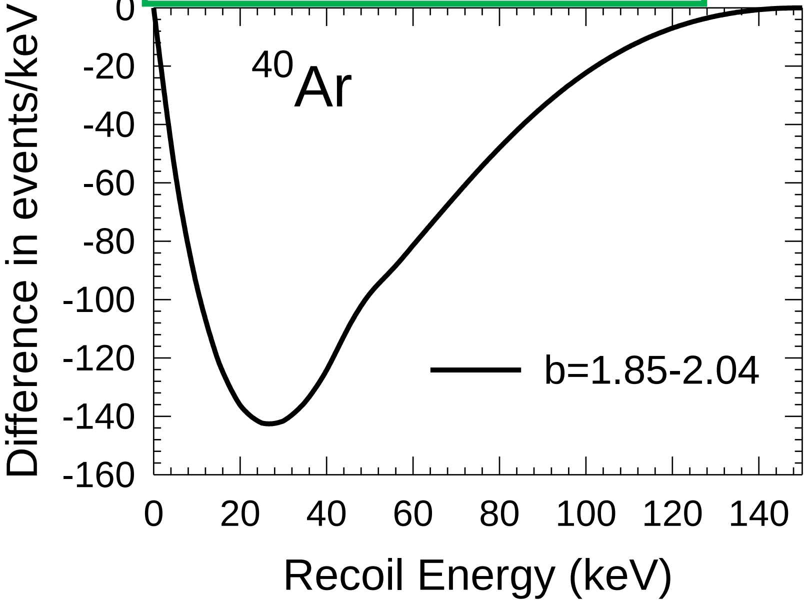


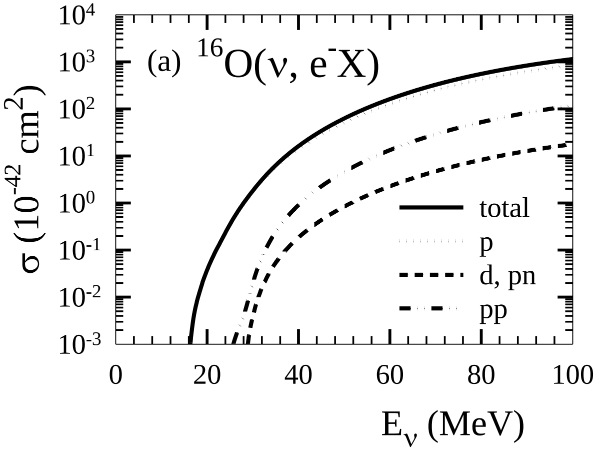
Σdiff=-8770
-2970 (T>50 keV)
-287 (T>100 keV)

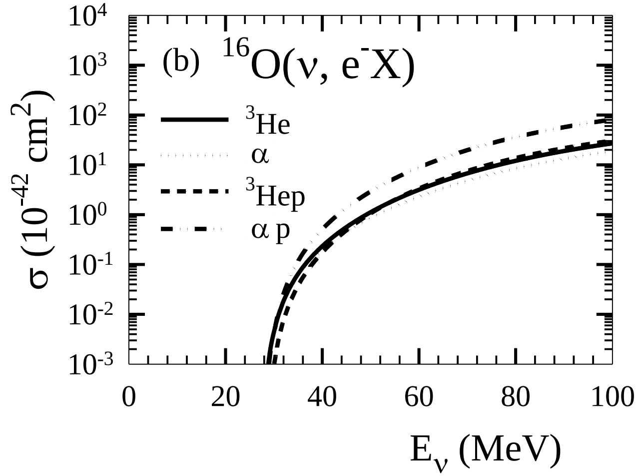


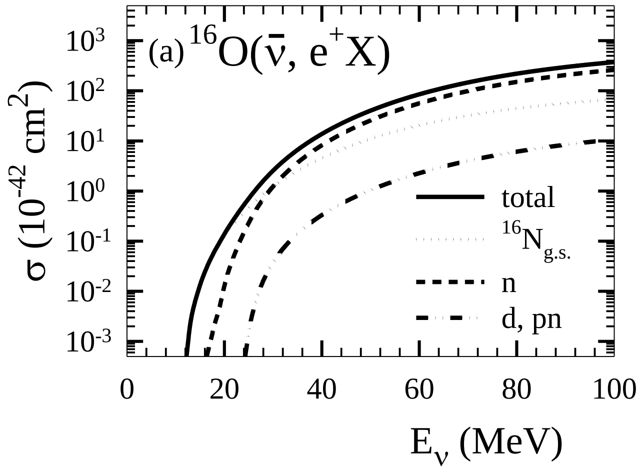
Σdiff=-648
-1316

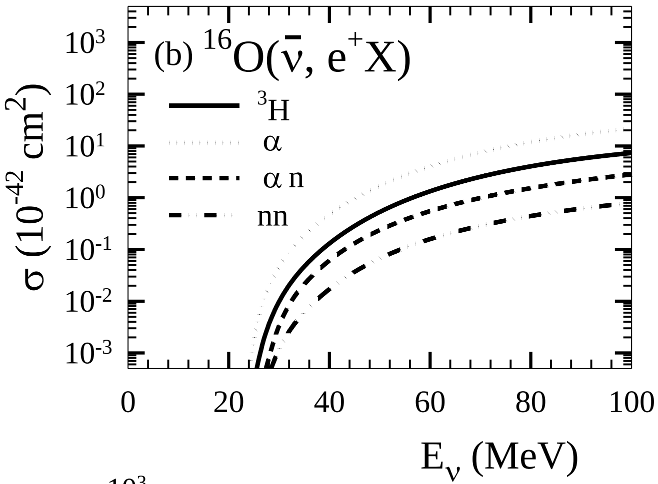
^{12}C:
b=1.80-1.64
Σdiff
=-1158
(T >50 keV)
-867
(T>100 keV)

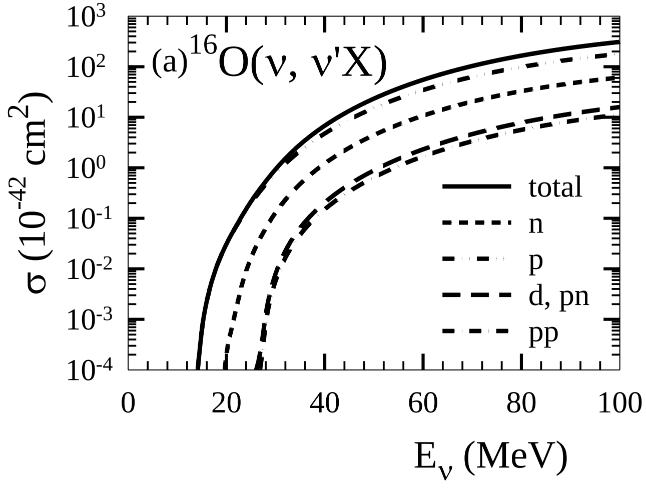


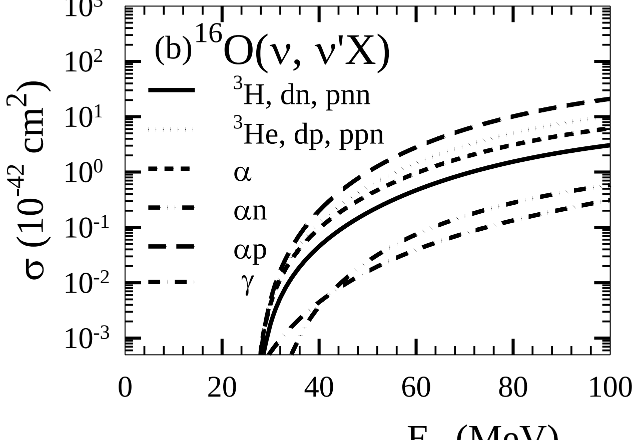

(a) ^{16}O(ν, e$^-$X)
σ (10^{-42} cm^2)
E$_ν$ (MeV)
total
p
d, pn
pp
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100


(b) ^{16}O(ν, e$^-$X)
σ (10^{-42} cm^2)
E$_ν$ (MeV)
^{3}He
α
^{3}Hep
α p
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100

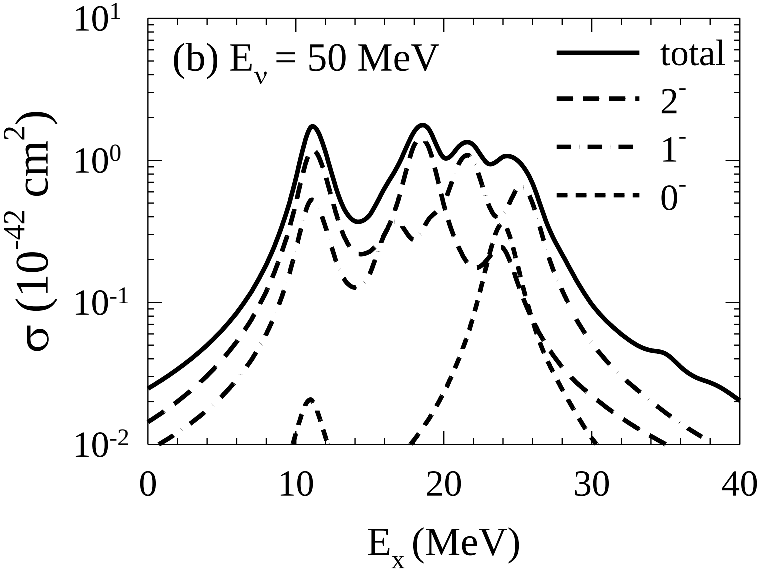

(a) ^{16}O($\bar{ν}$, e$^+$X)
σ (10^{-42} cm^2)
E$_ν$ (MeV)
total
^{16}N$_{g.s.}$
n
d, pn
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100


(b) ^{16}O($\bar{ν}$, e$^+$X)
σ (10^{-42} cm^2)
E$_ν$ (MeV)
^{3}H
α
α n
nn
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100

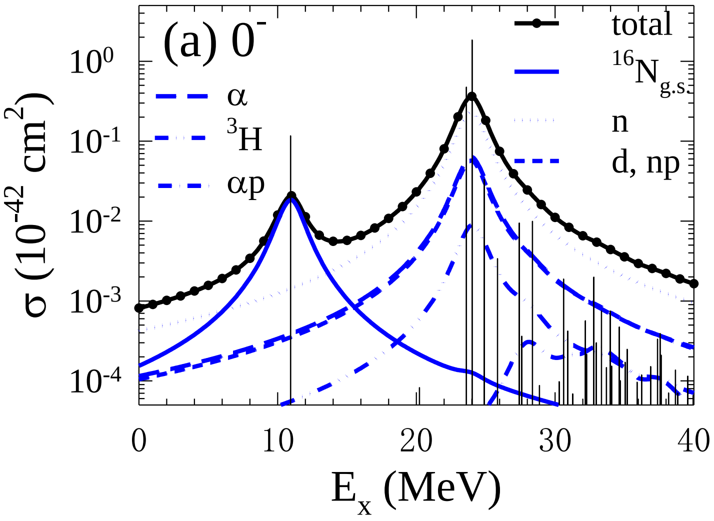

(a) ^{16}O(ν, ν'X)
σ (10^{-42} cm^2)
E$_ν$ (MeV)
total
n
p
d, pn
pp
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100


(b) ^{16}O(ν, ν'X)
σ (10^{-42} cm^2)
^{3}H, dn, pnn
^{3}He, dp, ppn
α
αn
αp
γ
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100

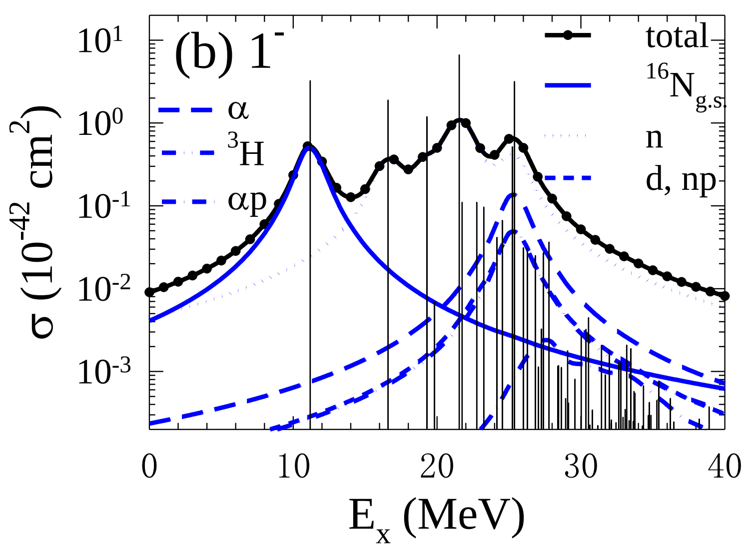
$^{16}O\,(\bar{\nu}, e^{+})^{16}N$



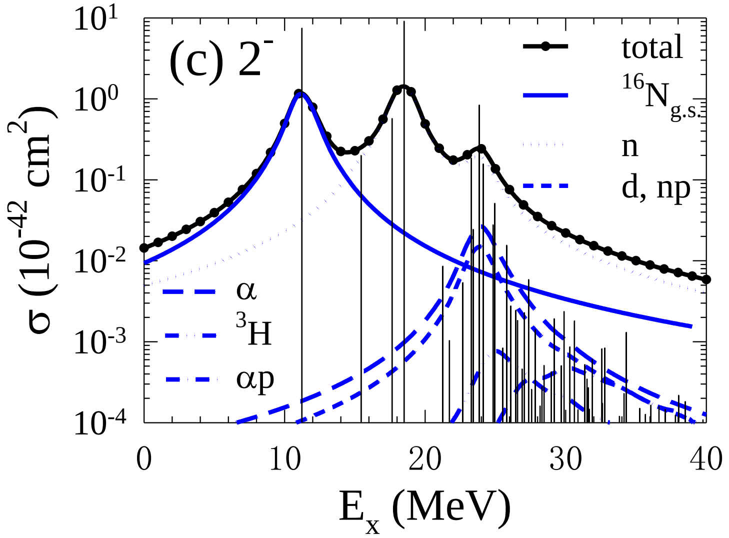
$^{16}O(\bar{\nu}, e^{+} X)\quad E_\nu = 50$ MeV



$^{16}O(\bar{\nu}, e^{+} X)\quad E_\nu = 50$ MeV



$^{16}O(\bar{\nu}, e^{+} X)\quad E_\nu = 50$ MeV



Nucleosynthesis processes of light elements in SNe

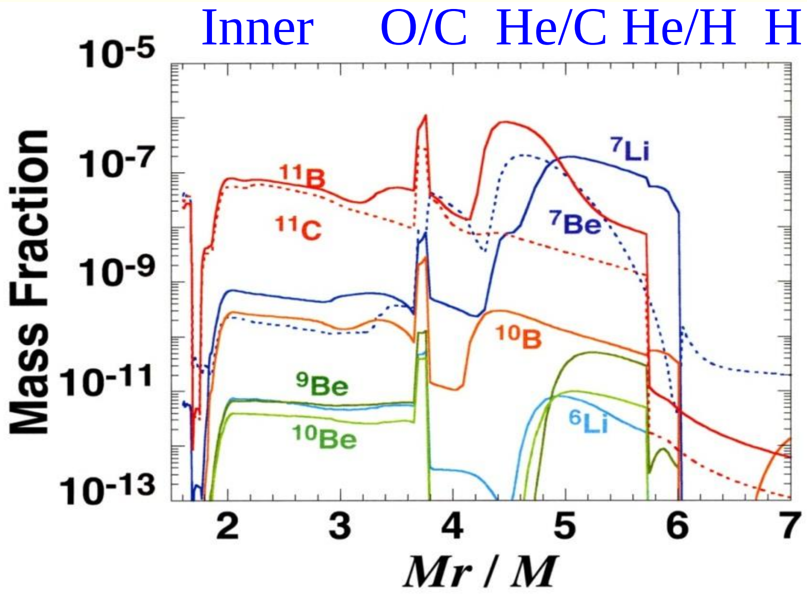
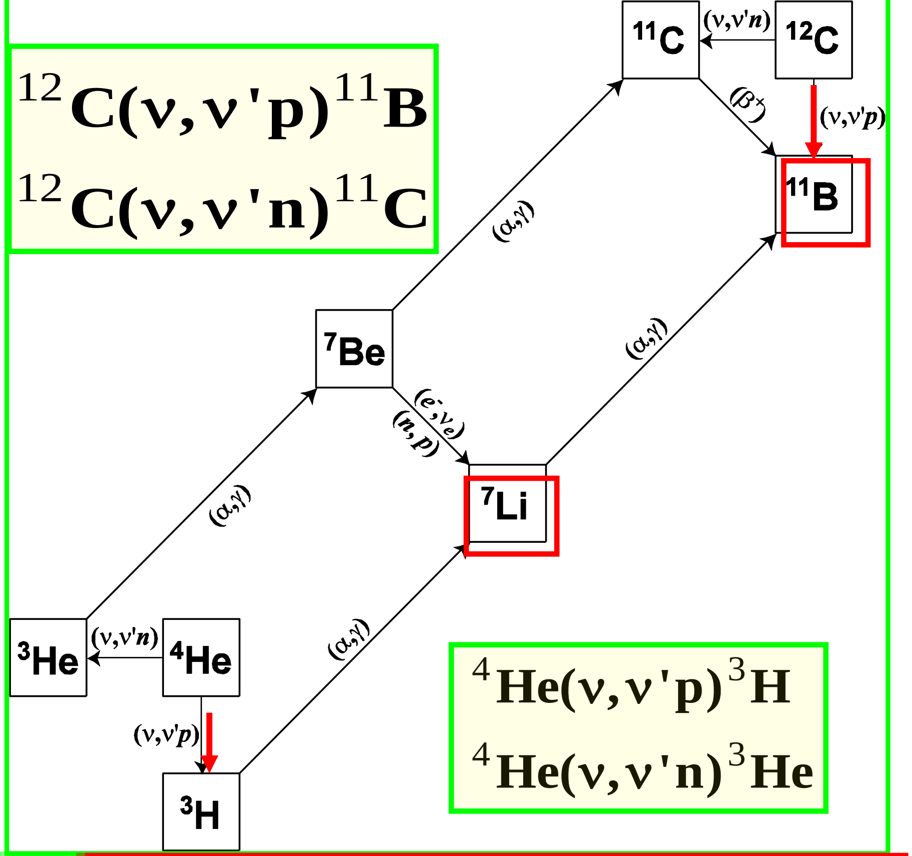


Fig. 4.— Mass fraction distribution of Model 1. The mass fractions of ^{7}Li and ^{7}Be, and ^{11}B and ^{11}C are separated.

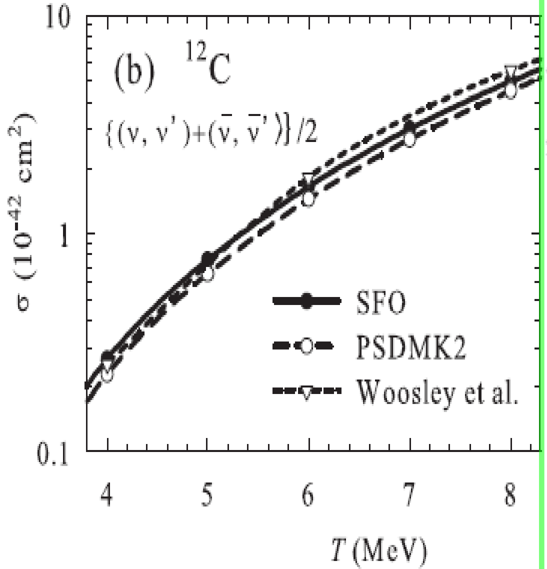


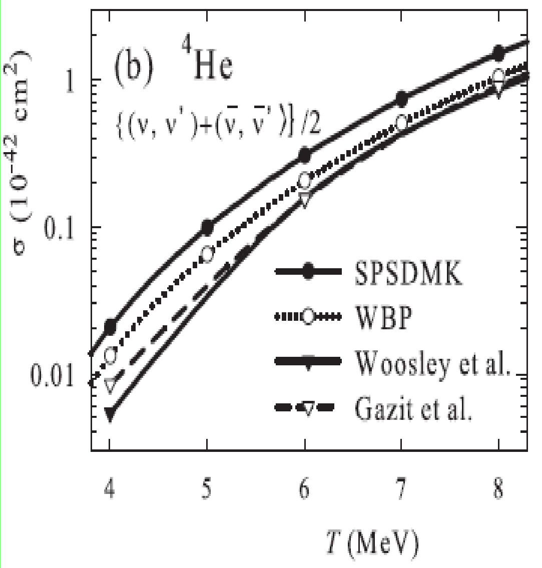
$^{12}C(\nu,\nu'p)^{11}B$

$^{12}C(\nu,\nu'n)^{11}C$

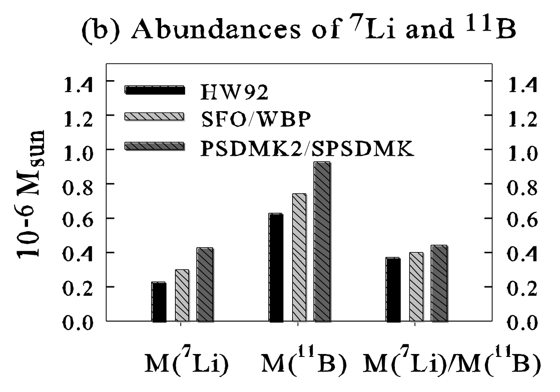
$^{4}He(\nu,\nu'p)^{3}H$

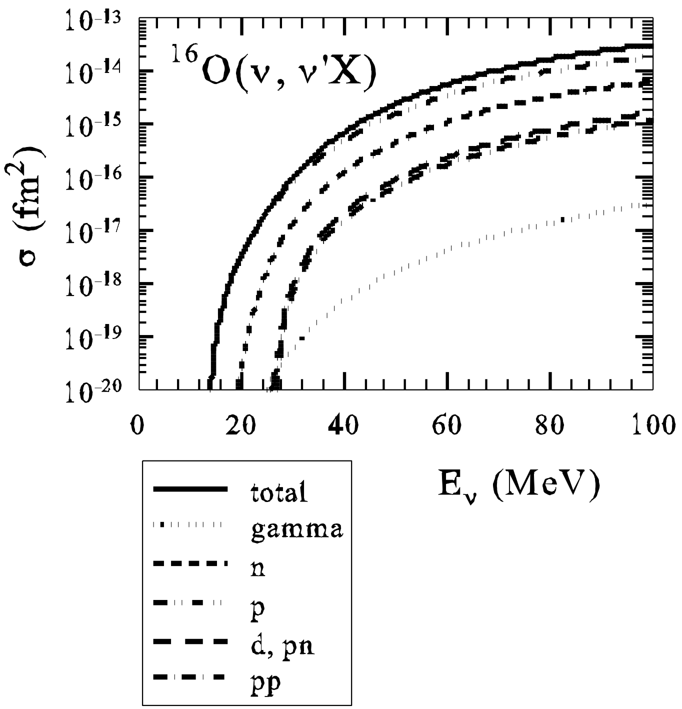
$^{4}He(\nu,\nu'n)^{3}He$

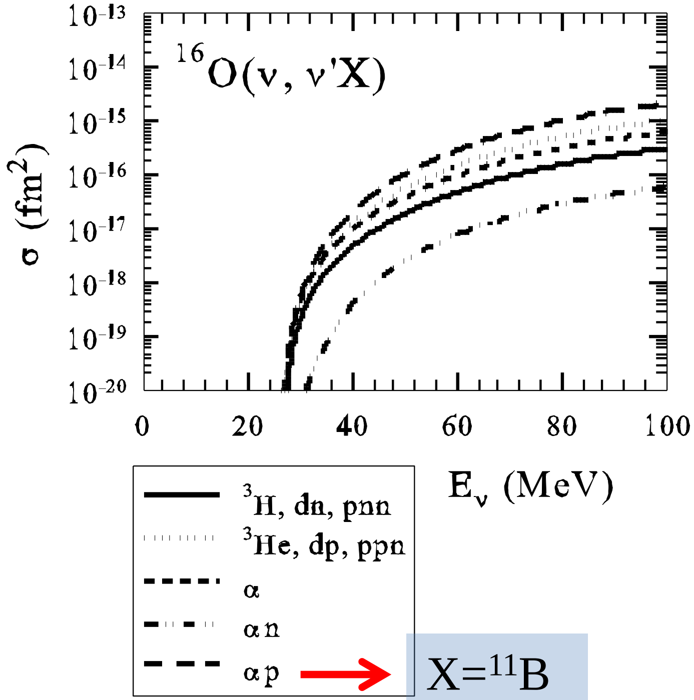




Enhancement of ^{11}B and ^{7}Li abundances in supernova explosions







X=^{11}B

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

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

Case2: previous branches, and new cross sections

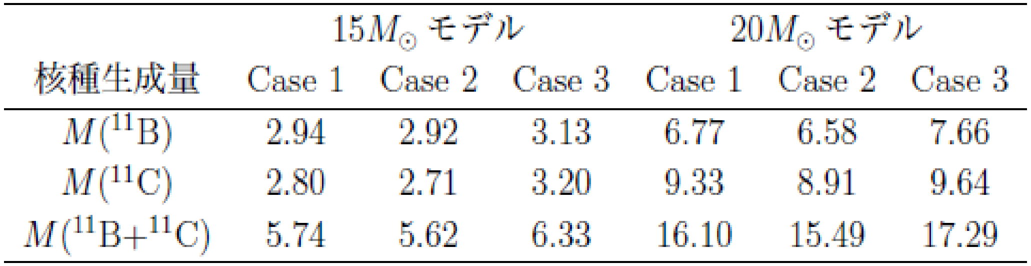
Case3: multi-particle branches and new cross sections

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
$M(^{11}B)$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}C)$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}B+^{11}C)$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

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



核種生成量	$15M_\odot$ モデル Case 1	Case 2	Case 3	$20M_\odot$ モデル Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
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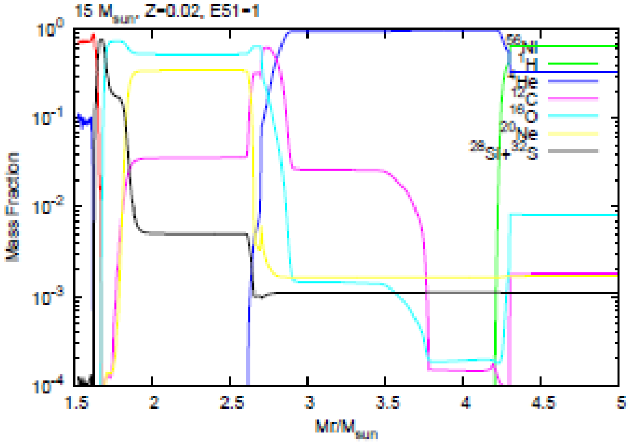
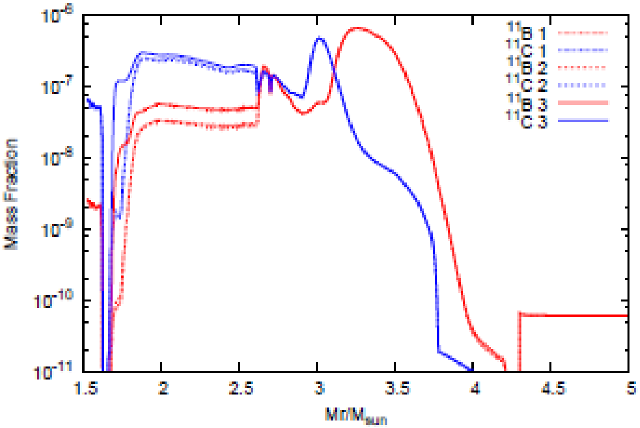
T. Yoshida

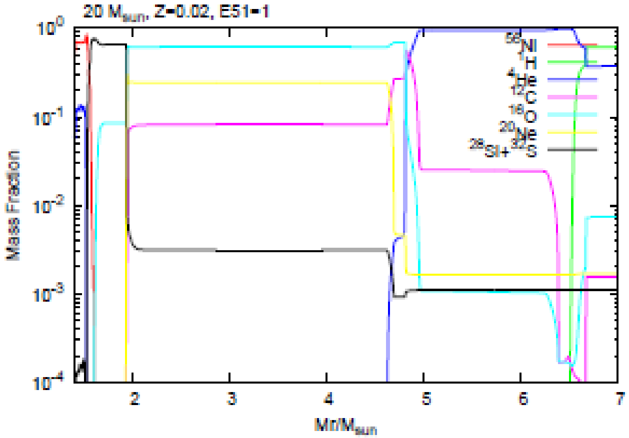
Case1: previous branches used in ^{16}O (γ, n, p, α-emissions) and HW92 cross sections
Case2: previous branches, and new cross sections
Case3: multi-particle branches and new cross sections

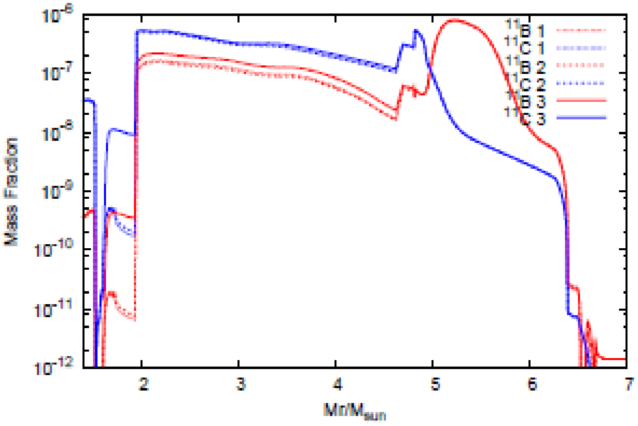
15M$_\odot$





20M$_\odot$

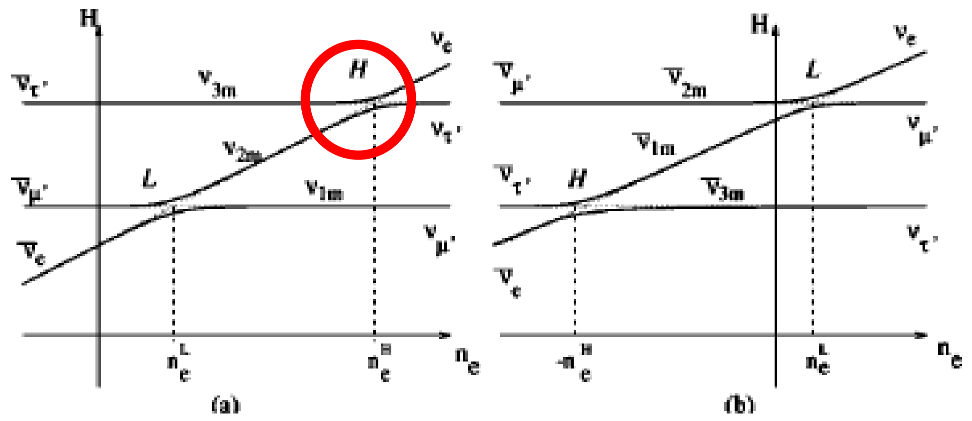




MSW ν oscillations

Normal hierarchy

Inverted hierarchy

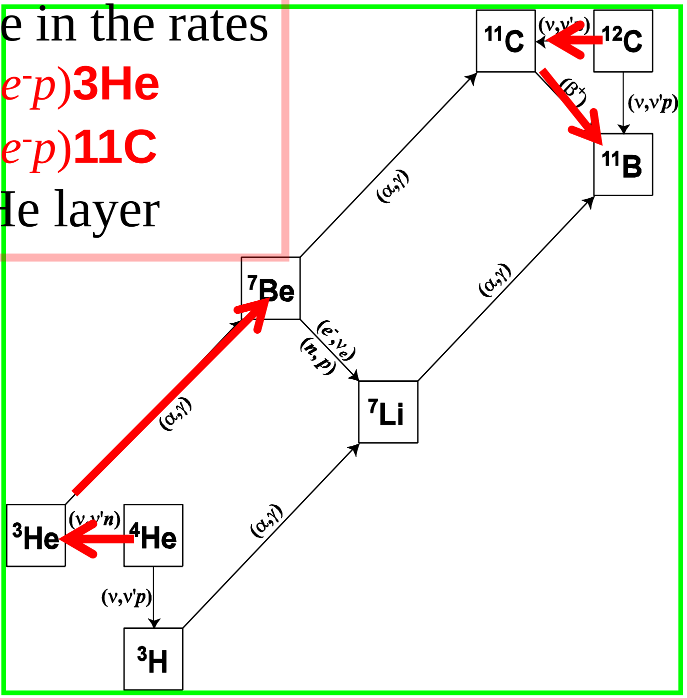


Increase in the rates

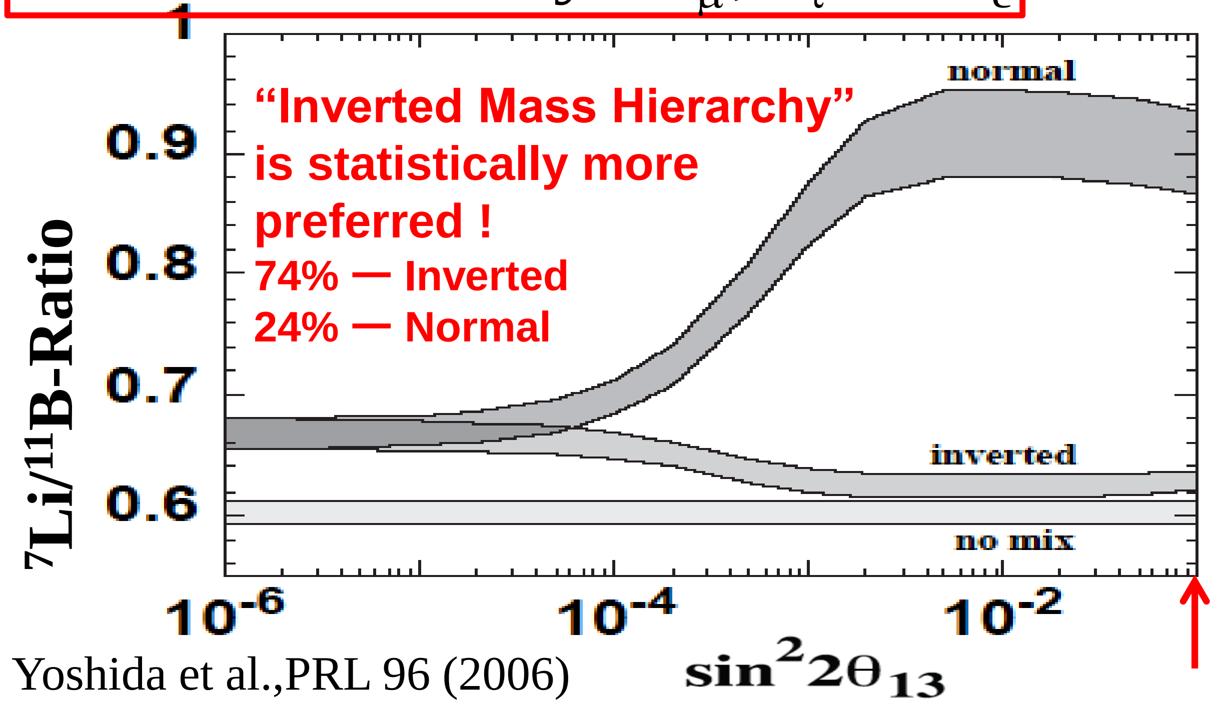
4He(ν_e,e^-p)**3He**

12C(ν_e,e^-p)**11C**

in the He layer



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



"Inverted Mass Hierarchy" is statistically more preferred !

74% — Inverted

24% — Normal

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).