ν-nucleus reactions and scatterings for ν detection

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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

detection of SNν

ν-oscillation effects: dependence of charged-current reaction cross sections on ν mass hierarchy

MSW oscillations in SNe

ν- ^{13}C reactions
Suzuki, Balantekin, Kajino, and Chiba
J. Phys. G 46, 075103 (2019)

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)

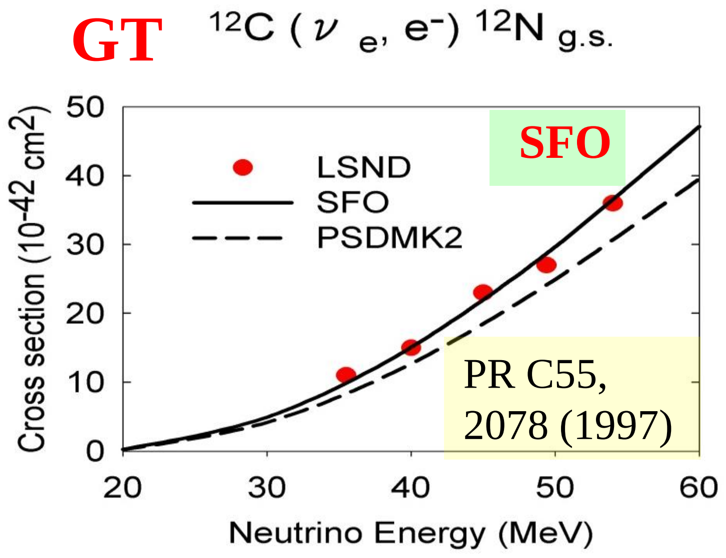
* important roles of tensor force → proper shell evolutions and change of magic numbers toward drip-lines

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

- Spin responses of nuclei are quite well described.
  Gt strength in ^{12}C, ^{14}C; $O = g_A \sigma t_-$
  Mag. mom. of p-shell nuclei; $\mu = g_s s + g_\ell \ell$

▪ν-nucleus reactions
p-shell: SFO

ν-^{12}C

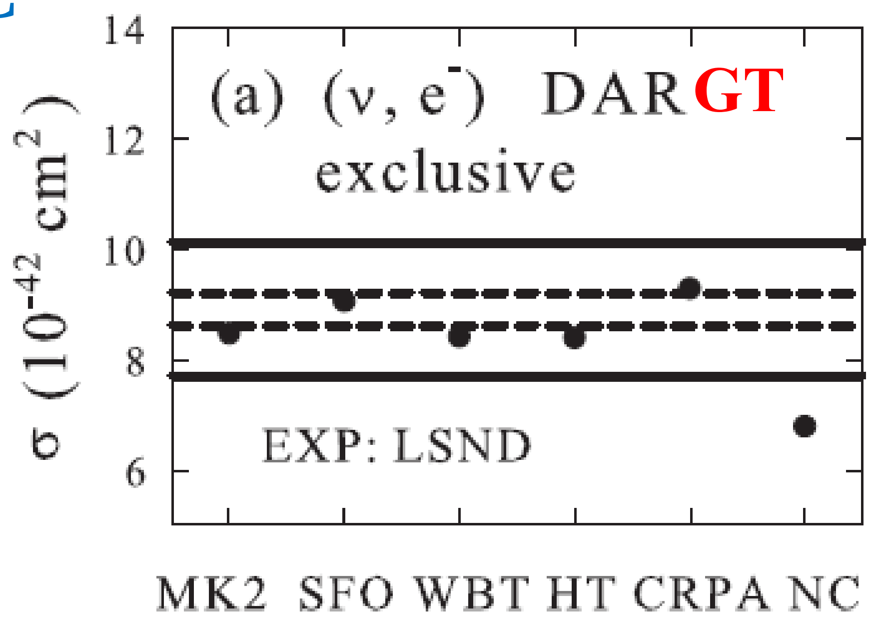


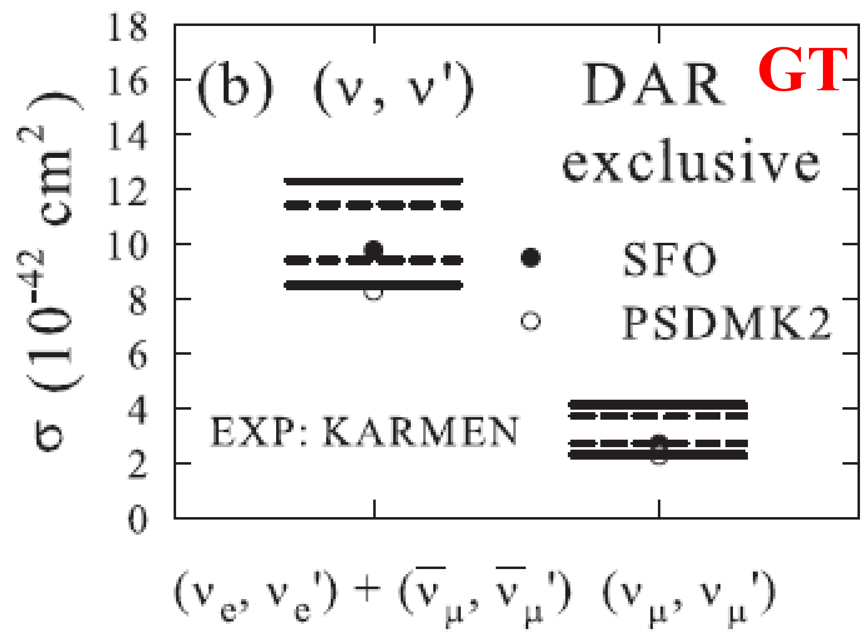
Suzuki, Chiba, Yoshida, Kajino, Otsuka, PR C74, 034307, (2006).

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

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

$$O = g_A\, j_0(qr)\sigma\, t_-$$



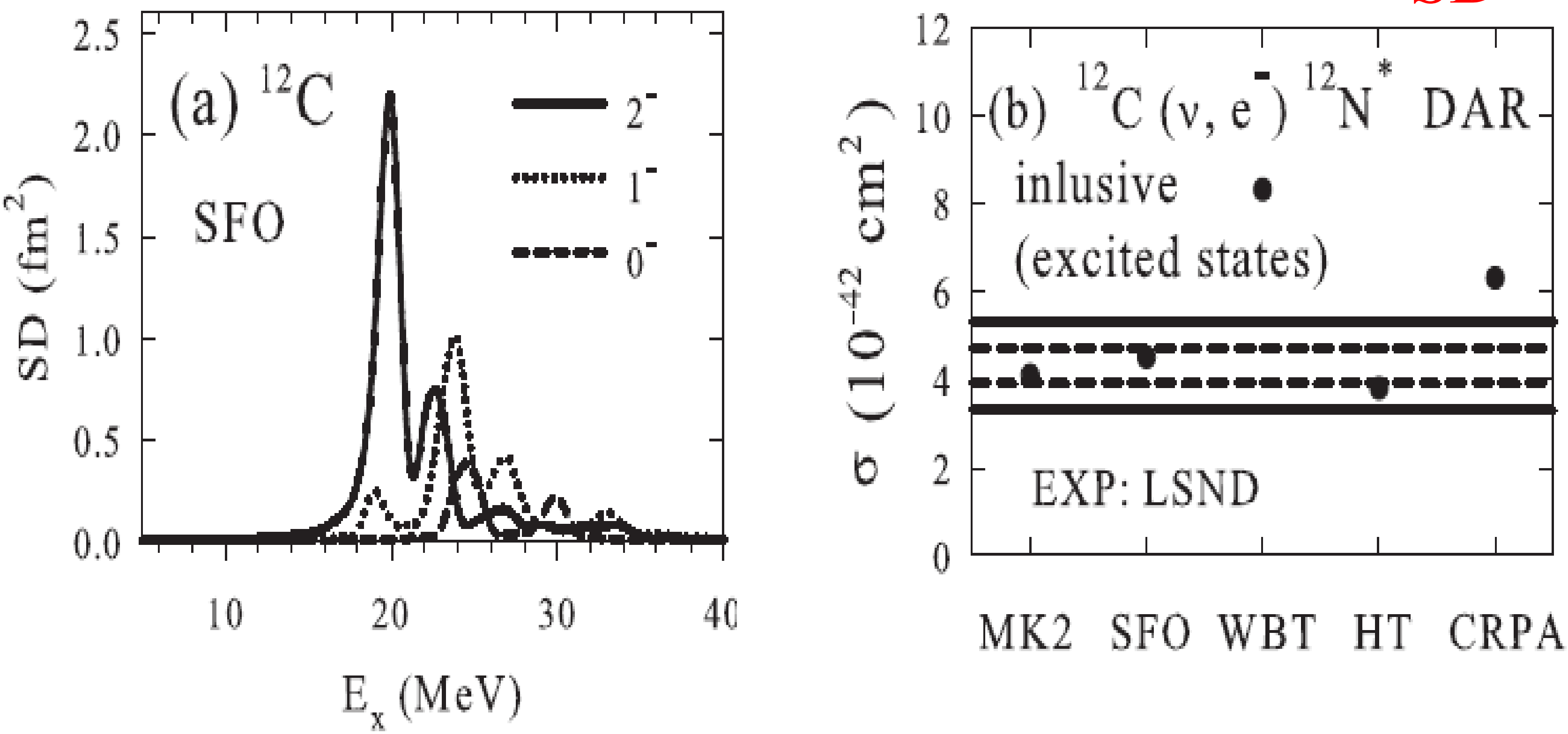


ν-^{12}C

Spin-dipole transitions

$O^J = [\sigma \times r]^J$ J=0$^-$, 1$^-$, 2$^-$

SD



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

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

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 $H = \frac{p^2}{2m}$

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

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

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

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

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

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

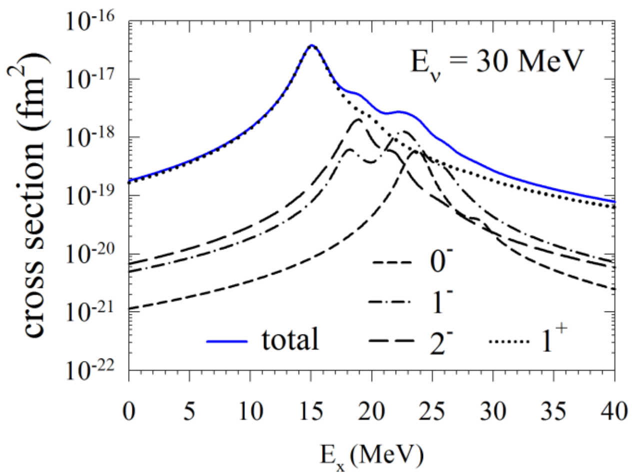
EWS-	0^-	1^-	2^-		
K+LS	48.0	116.6	117.2	MeV・fm^2	[$n(p_{3/2})=6$, $n(p_{1/2})=2$]
SFO	45.61	108.48	154.49		[$n(p_{3/2})=6.42$, $n(p_{1/2})=1.44$]
		(/3 =36.16)	(/5=30.90)		
$E_{av}=EWS_-/S_-$					
K+LS	26.39	22.01	14.13	MeV	
SFO	25.71	25.22	21.50		

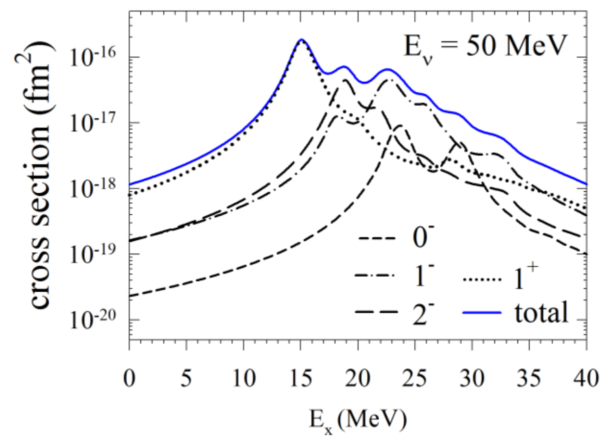
Hauser-Feshbach statistical model

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, ...

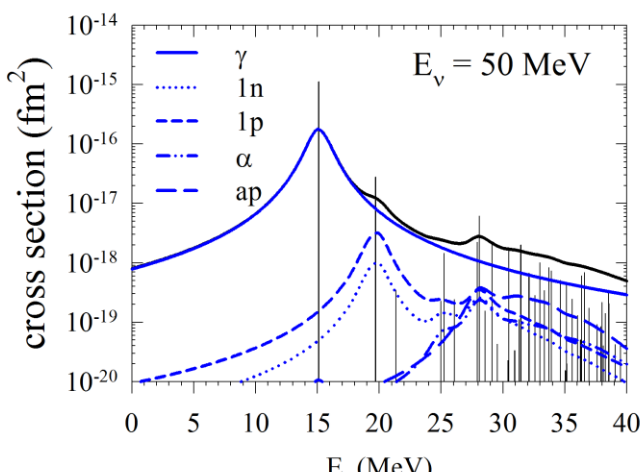
Isospin conservation is taken into account (S. Chiba)

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

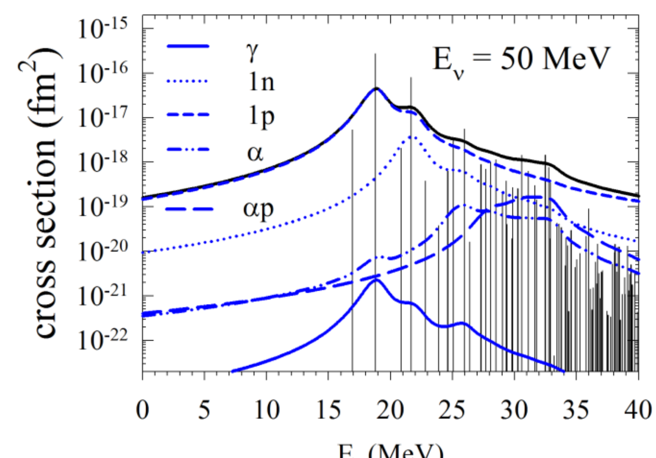




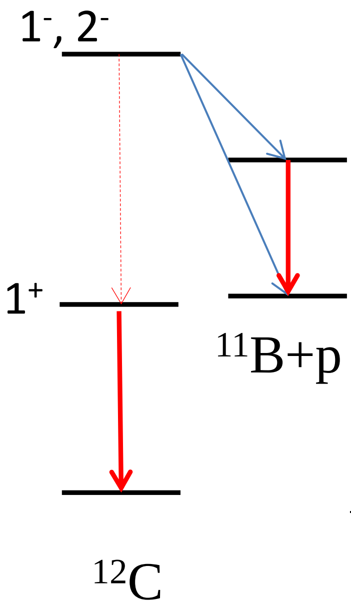
^{12}C 1^{+}

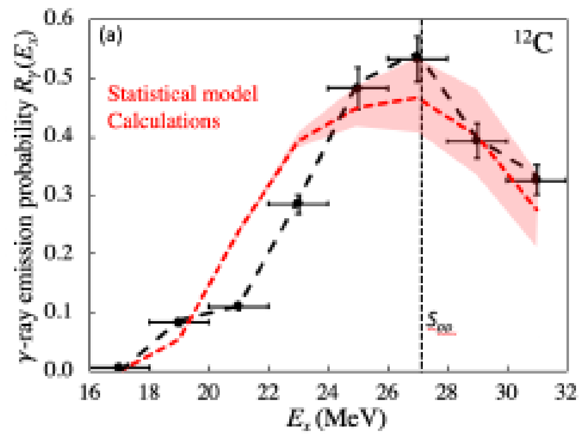


^{12}C 2^{-}



Reen et al., PRC 100, 024615 (2019); Measurement of *γ* rays from giant resonances excited by the 12C(*p, p*) reaction at 392 MeV and 0°





5. Total γ-ray emission probability (R_γ) as a func

$$N_\gamma = \int \sigma(E)\, R(E)\, f(E)\, dE$$

ν flux Model	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)	$E^{tot}_{\nu_e}$ (10^{52} erg)	$E^{tot}_{\bar{\nu}_e}$ (10^{52} erg)	$E^{tot}_{\nu_x}$ (10^{52} erg)
Fermi-Dirac	11.0	16.0	25.0	5.0	5.0	5.0
mMB	12.0	12..0	12.0	5.0	5.0	5.0
Ordinary SN (NK1)	9.32	11.1	11.9	3.30	2.82	3.27
Blackhole (NK2)	17.5	21.7	23.4	9.49	8.10	4.00

Table I. Average energy, $\langle E_\nu \rangle$, and total energy, E^{tot}_ν, of the SN neutrino spectrum for one of neutrinos and antineutrinos (ν_e, $\bar{\nu}_e$ and ν_x ($x = \mu$ and τ)). The neutrino spectra of the ordinary SN (NK1) and the case of a blackhole formation (NK2) are taken from Ref. [14, 26].

Sakuda

Reaction	Present work FD	Present work mMB	Present work NK1	Present work NK2	JUNO Collab. [11] mMB
$p(\bar{\nu}_e, e^+)n$	5378	3959	2194	11681	4300
NC $^{12}C(\nu,\nu')^{12}C^*$(15.1 MeV)	426	147	169	824	150
NC $^{12}C(\nu,\nu')^{12}C^*$(E_X>16 MeV)	180	5	21	222	-

Table II. Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at JUNO(20 kton). For mMB spectra, $\langle E_\nu \rangle$=12 MeV is used for all neutrino flavors.

・ ν-induced reactions on ^{13}C

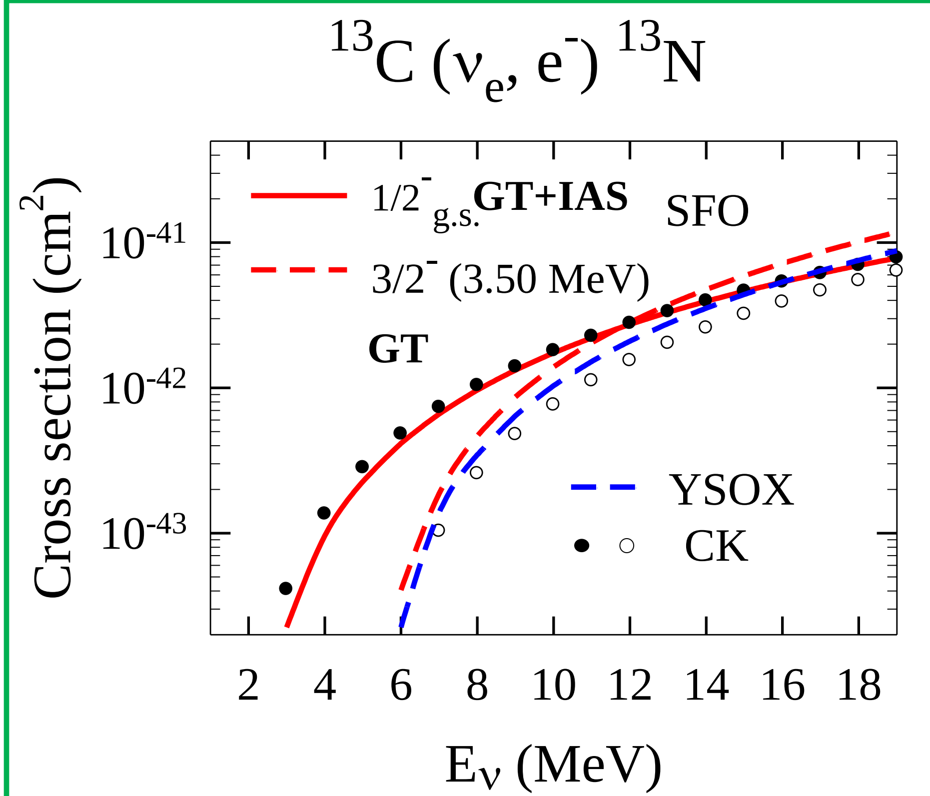
^{13}C: attractive target for very low energy ν

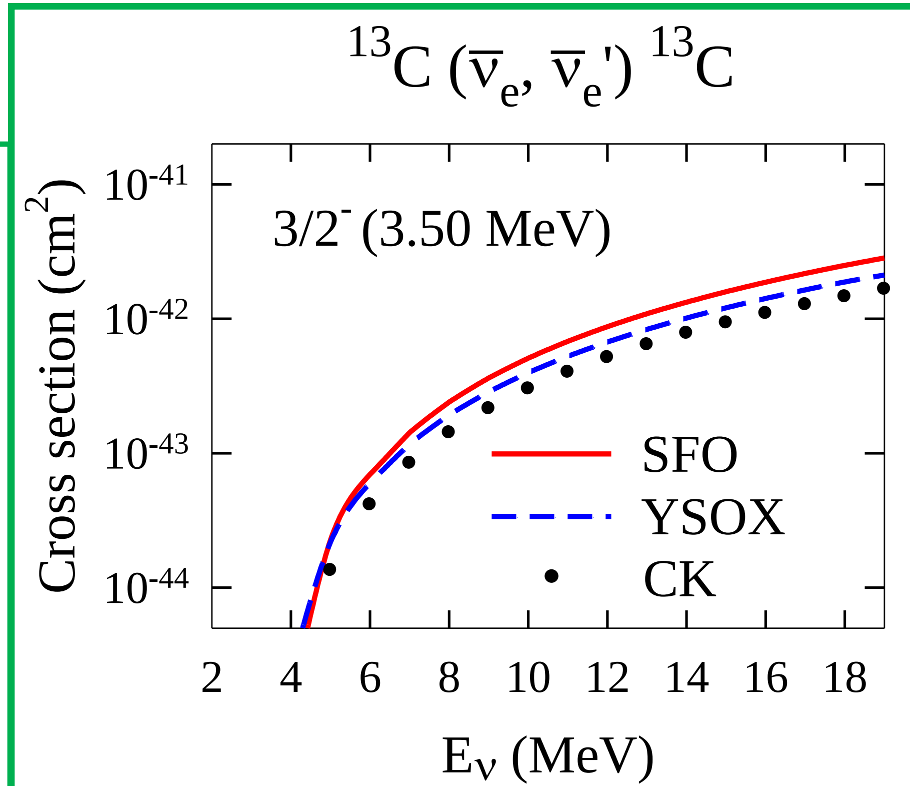
$E_\nu \leq 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\,\mathrm{MeV}$

Natural isotope abundance = 1.07%

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

reactor anti-ν

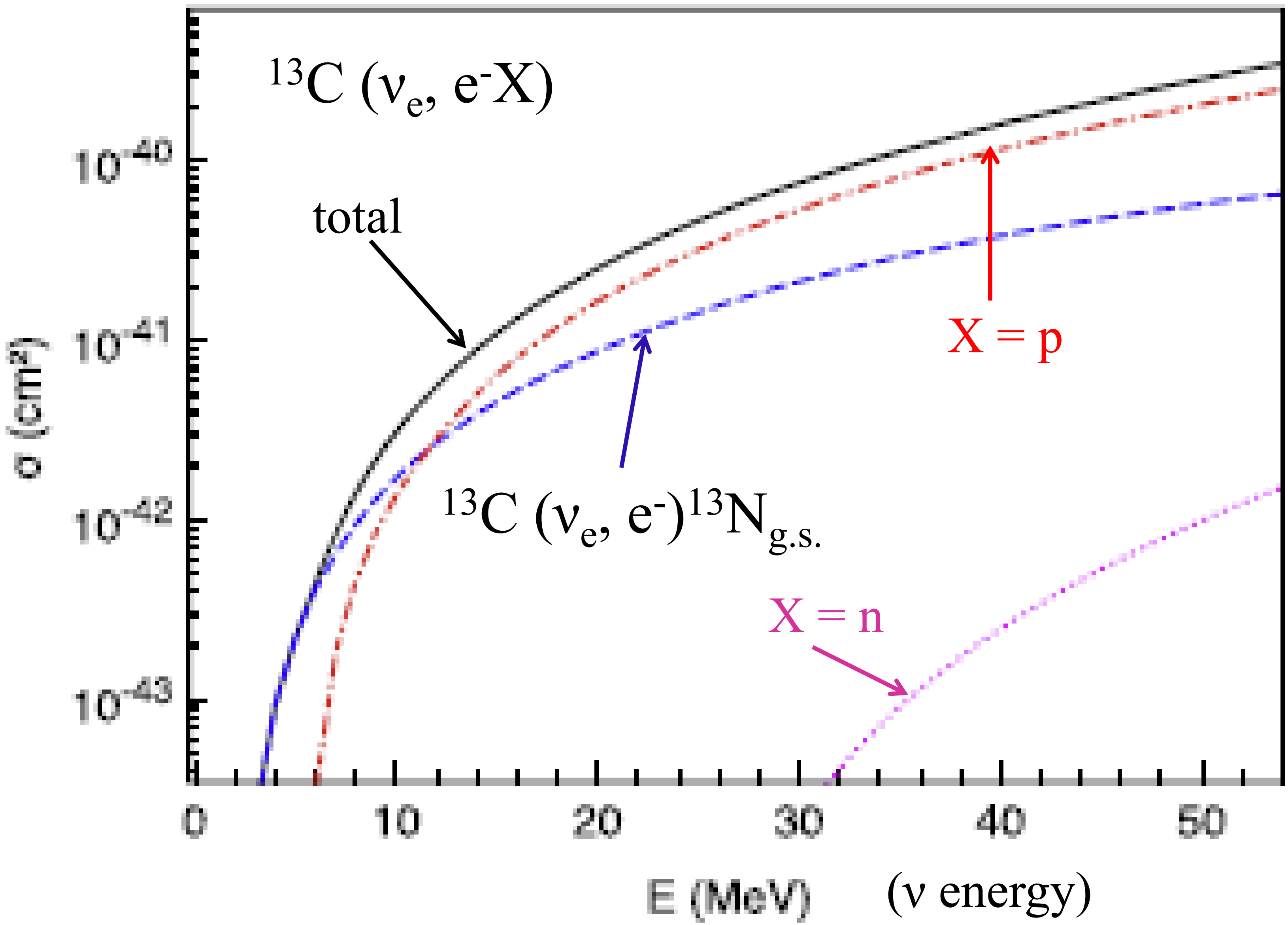




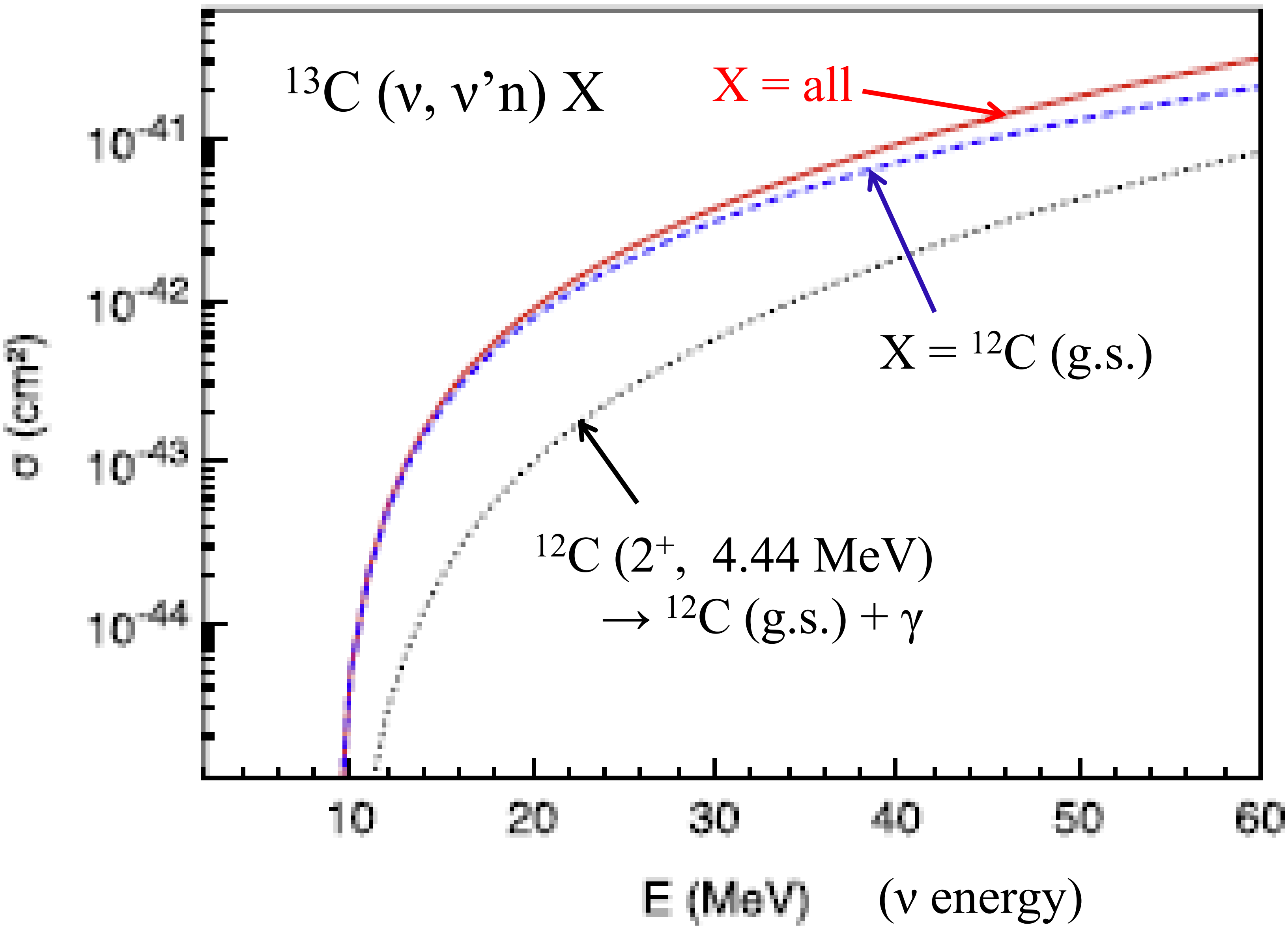
g_A^{eff}/g_A=0.95(SFO),0.85(YSOX)
0.69 (CK)

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

Charged-current cross sections at SN ν energies



Neutral-current neutron-emission cross sections



Particle physics origin of the 5 MeV bump in the reactor antineutrino spectrum?

PHYSICAL REVIEW D **99,** 055045 (2019)

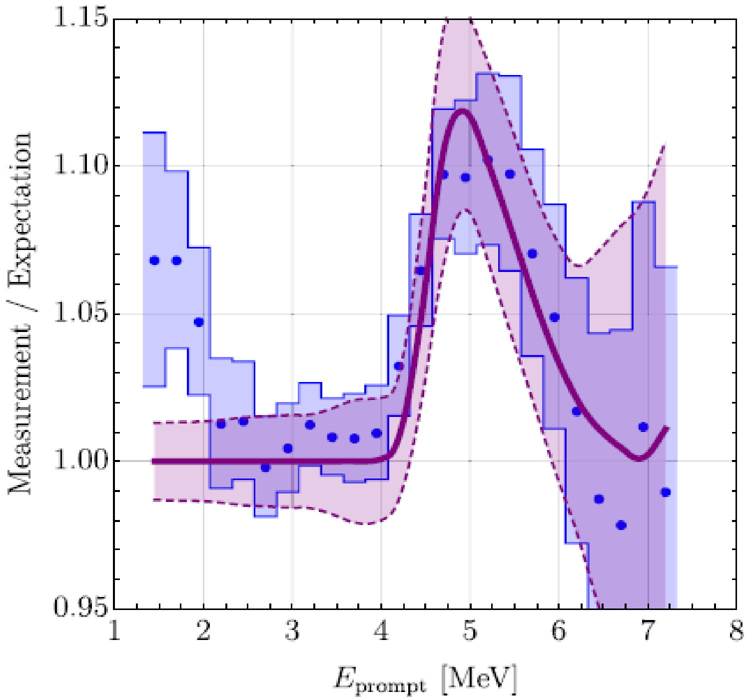
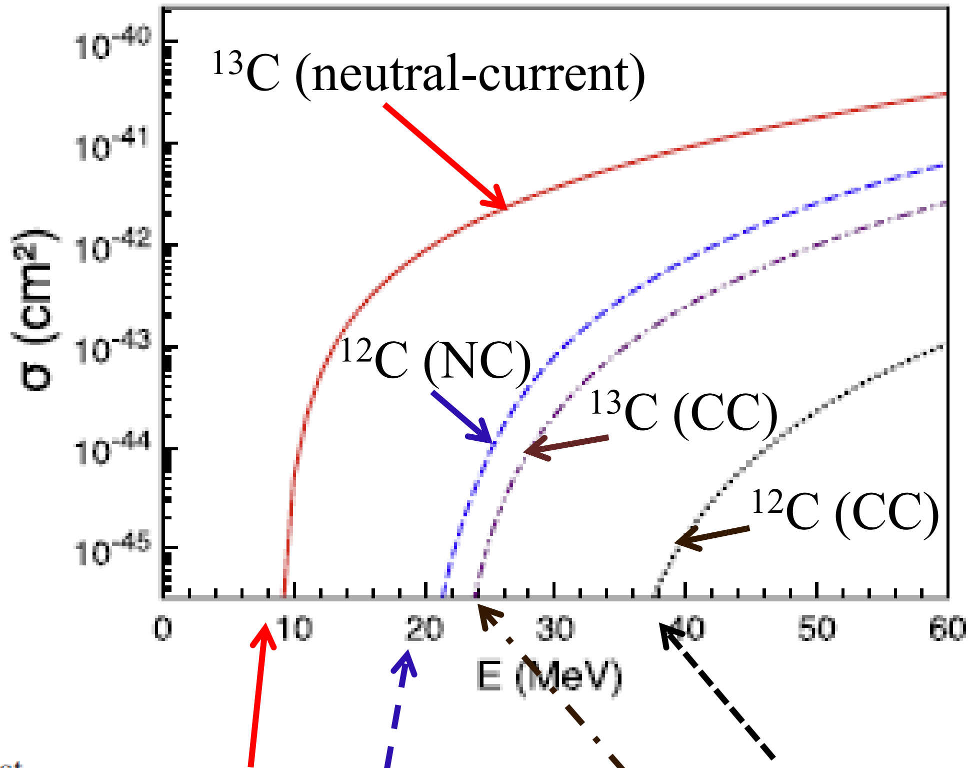


FIG. 1. The prompt energy spectrum corresponding to the best-fit point in Eq. (8). Only transitions to the first excited state of ^{12}C have been included. See text for details.

Neutron-emission cross sections for $\nu_e - {}^{12}C$, ^{13}C reactions



E_{th} = 4.95, 18.72 MeV, 22.28, 32.38 MeV

$$^{13}C\ (\bar{\nu}, \bar{\nu}'n)\ ^{12}C\ (2^+, 4.44\ \text{MeV})$$

$$\rightarrow\ ^{12}C\ (\text{g.s.}) + \gamma$$

E_{th} =9.4 MeV Reactor $\bar{\nu}$ with E $\sim$ 16 MeV Fallot et al, PRL 109 (2012)

Coherent (elastic) scattering on light target

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

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

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

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

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

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

Probe of neutron density distribution

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

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

$T = recoil\ energy$

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

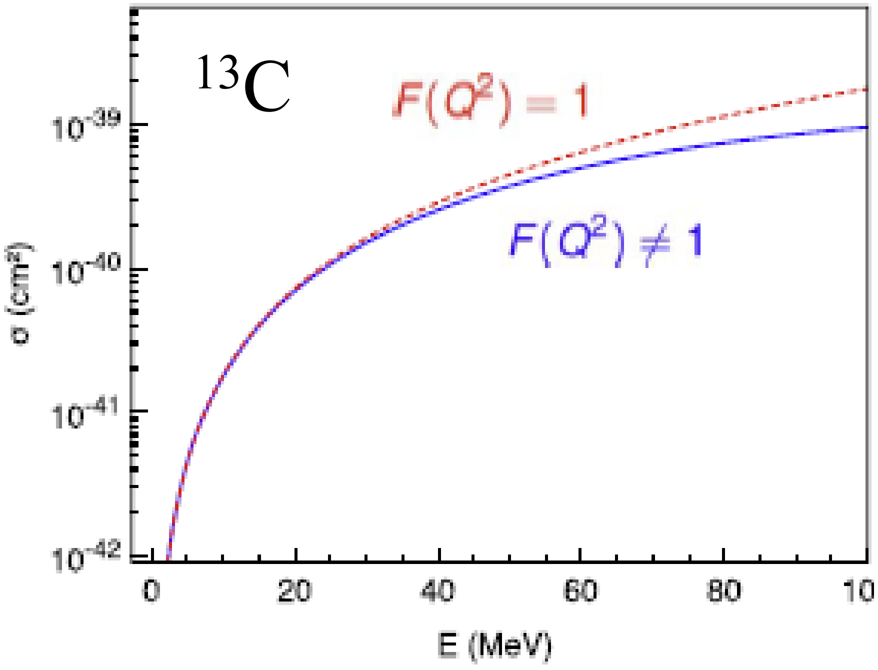
$$F(Q^2) = \{N F_n(Q^2) - (1 - 4\sin^2\theta_W) Z F_p(Q^2)\} / Q_W$$

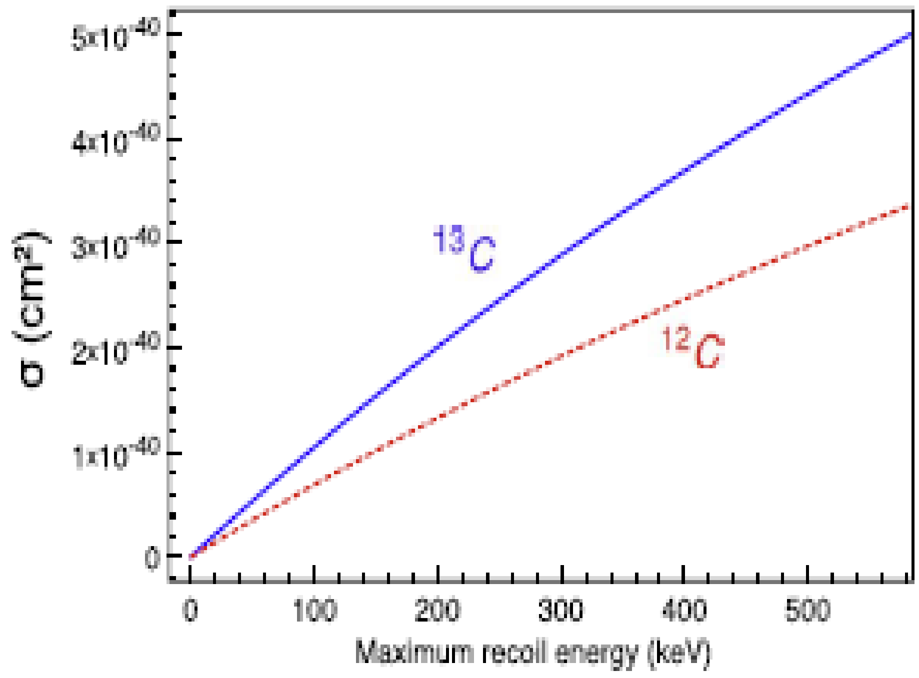
$$Q^2 = 2MT + T^2$$

$$F_{n,p}(Q^2) = \int r^2 j_0(Qr) \rho_{n,p}(r) dr$$

$$\sigma(E) = \int_0^{T_{\max}} dT \frac{d\sigma}{dT}(E,T)$$

Nuclear effects and Isotope dependence in coherent scattering

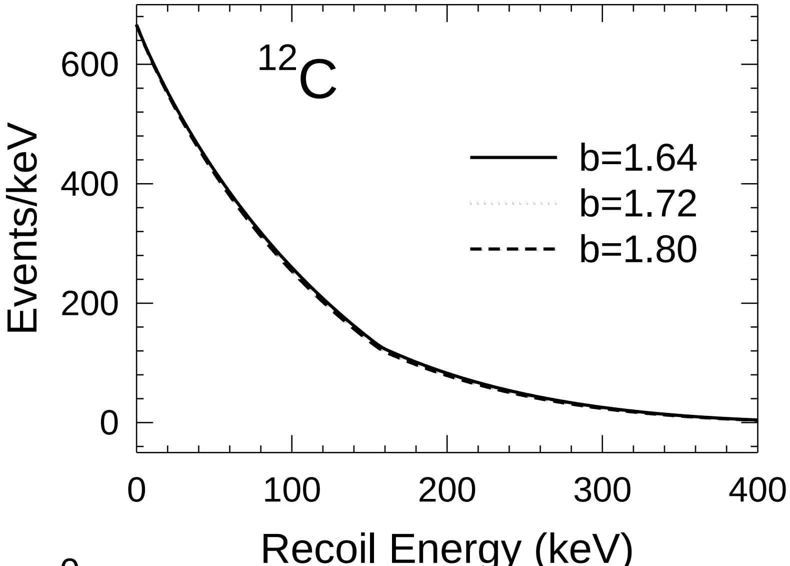


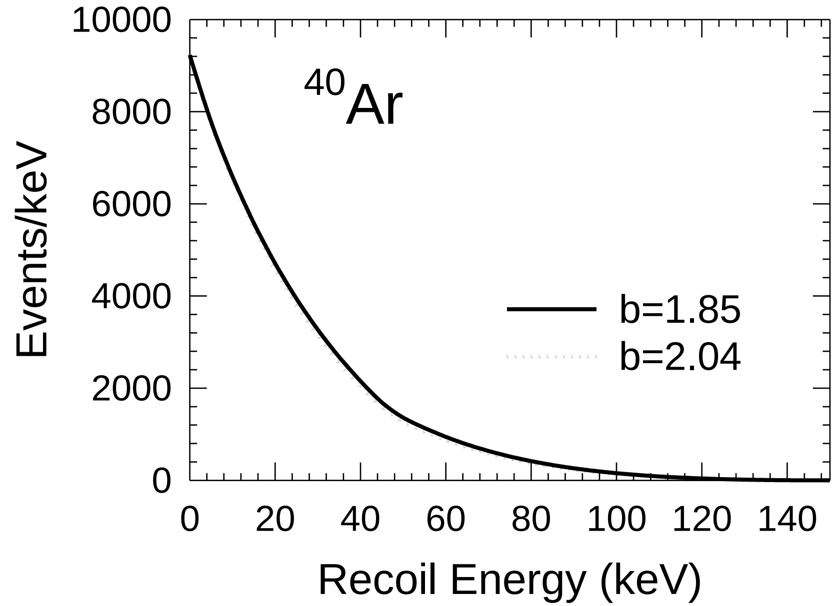


Events/keV - Recoil energy (keV)

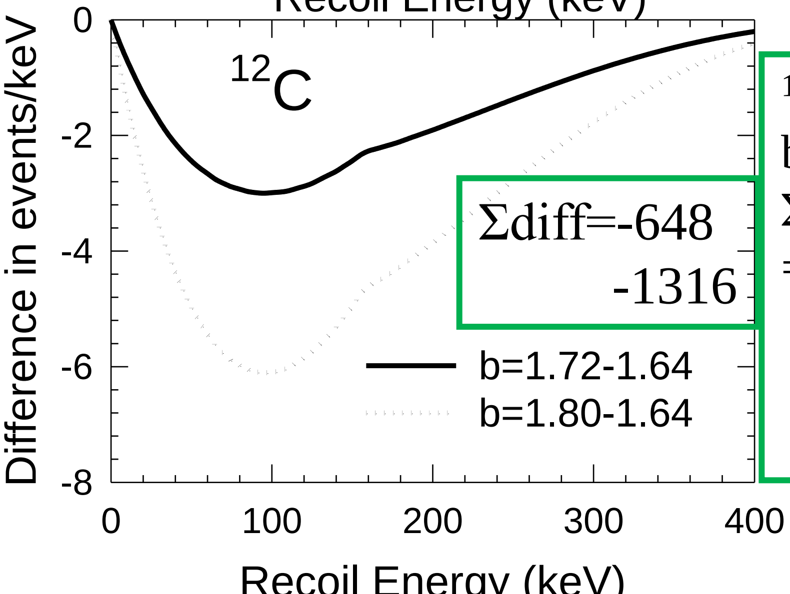
DAR ν (3-flavors)

Φ= 3x10^7 /cm^2/s, 1year, target=1 ton



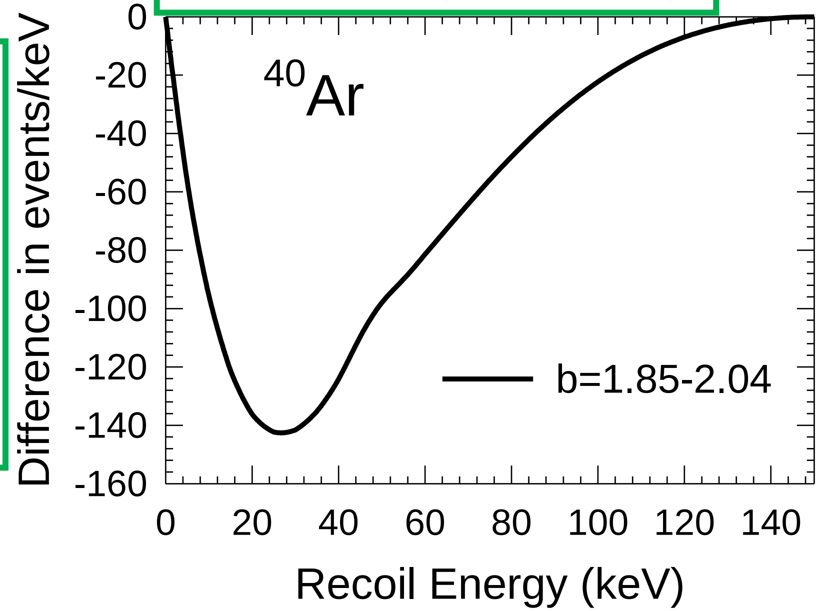


Σdiff=-8770
-2970 (T>50 keV)
-287 (T>100 keV)



Σdiff=-648
-1316

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



▪ν-induced reactions on ^{16}O

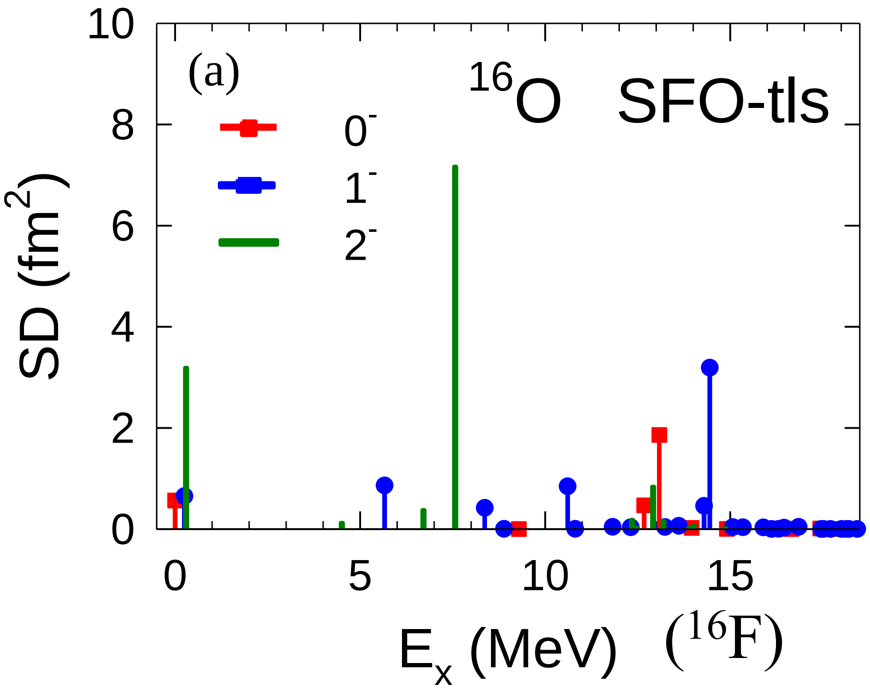
▪Modification of SFO → SFO-tls

Full inclusion of tensor force

▪p-sd: tensor-> π+ρ

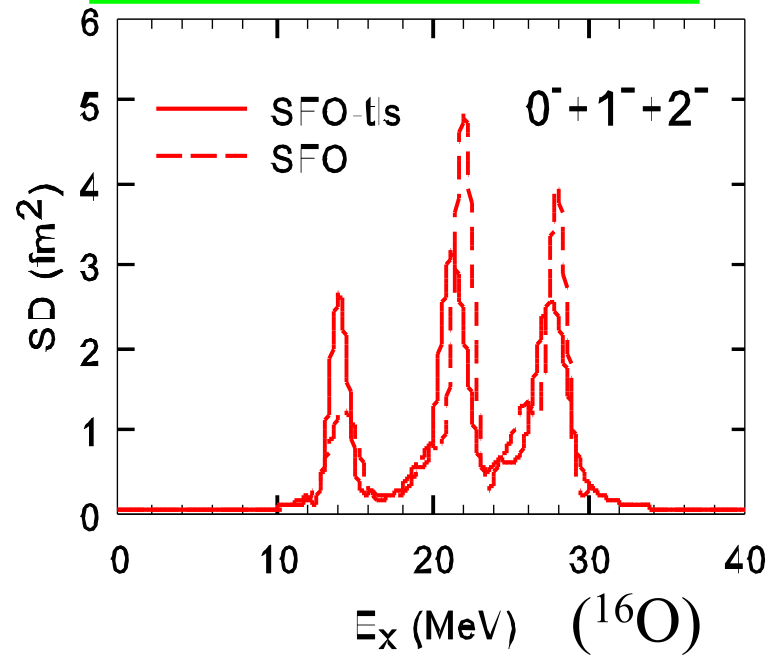
LS -> σ+ρ+ω

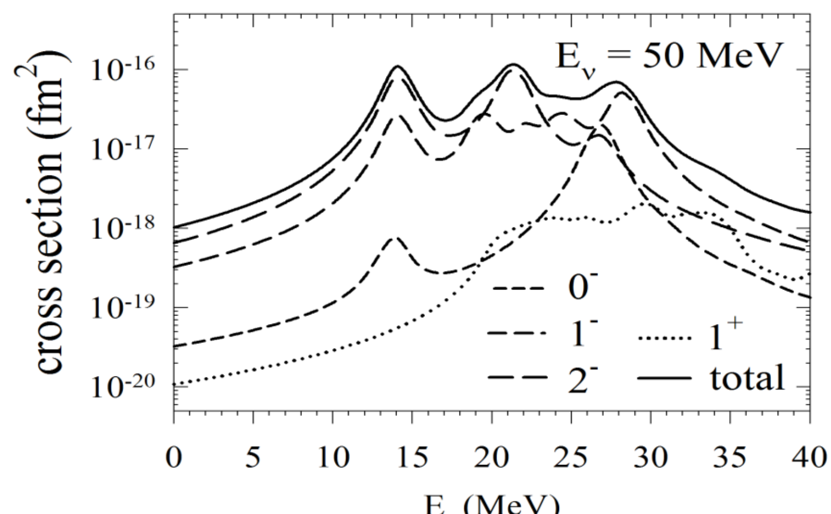
$$V = V_C + V_T + V_{LS}$$
$$V_T = V_\pi + V_\rho$$
$$V_{LS} = V_{\sigma+\omega+\rho}$$



Spin-dipole strength in ^{16}O

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





Spin-dipole sum

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

$p \to sd$

$\propto 2\lambda+1$

$EW\,S^\lambda_-$	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)	

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

Splitting of the strength comes from one-body LS term and two-body tensor interaction

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

$$V_T(r) = F(r)\{[\sigma_1 \times \sigma_2]^{(2)} \times [r^2 Y_2(\hat{r})]^{(2)}\}^{(0)},$$

$$V_T(r) = F(r) \sum_\lambda \frac{\sqrt{4\pi}}{6} \left(\frac{10}{3}\right)^{1/2} \begin{Bmatrix} -2\sqrt{5} \\ \sqrt{15} \\ -1 \end{Bmatrix} \times \{r_1[\sigma_1 \times Y_1(\hat{r}_1)]^{(\lambda)}$$

$$\times r_2[\sigma_2 \times Y_1(\hat{r}_2)]^{(\lambda)}\}^{(0)}, \qquad \text{for } \lambda = \begin{Bmatrix} 0^- \\ 1^- \\ 2^- \end{Bmatrix}.$$

● 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

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

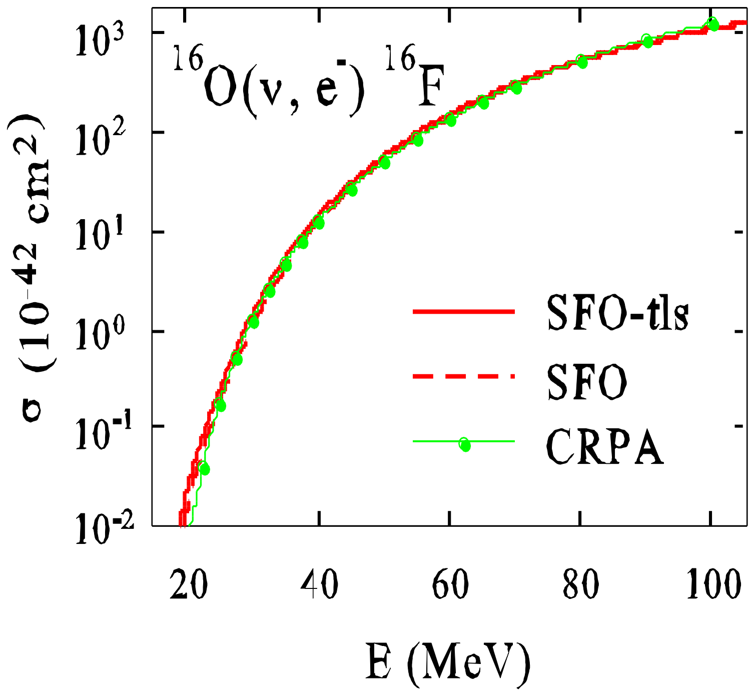
$$\mid \phi_{1s} \mid^2 = \frac{R}{\pi}\left(\frac{m_\mu M_T}{m_\mu + M_T} Z\alpha\right)^3 \qquad R = 0.79$$

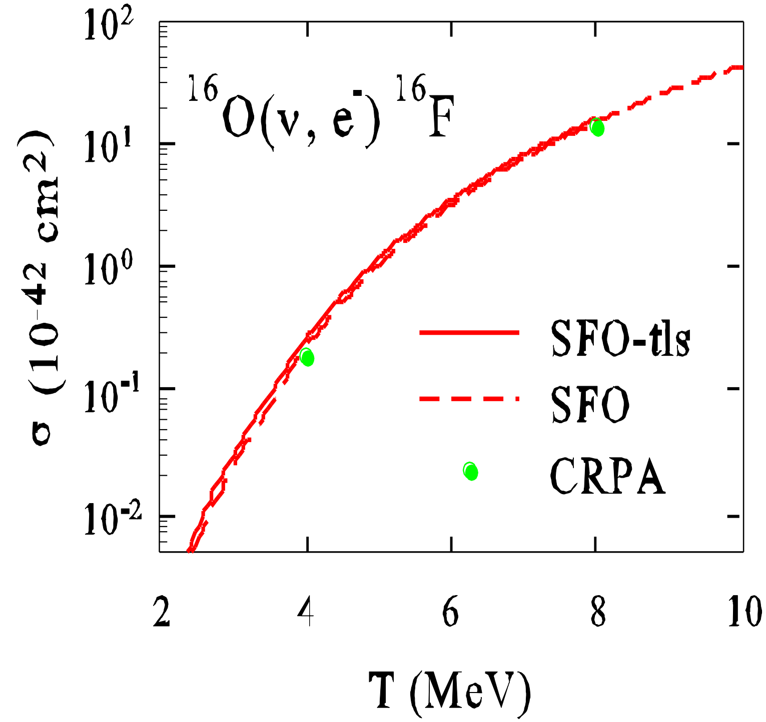
Induced pseudo-scalar current $F_P(q_\mu^2) = \frac{2M_N}{q_\mu^2 + m_\pi^2} F_A(q_\mu^2)$ Goldberger-Treiman

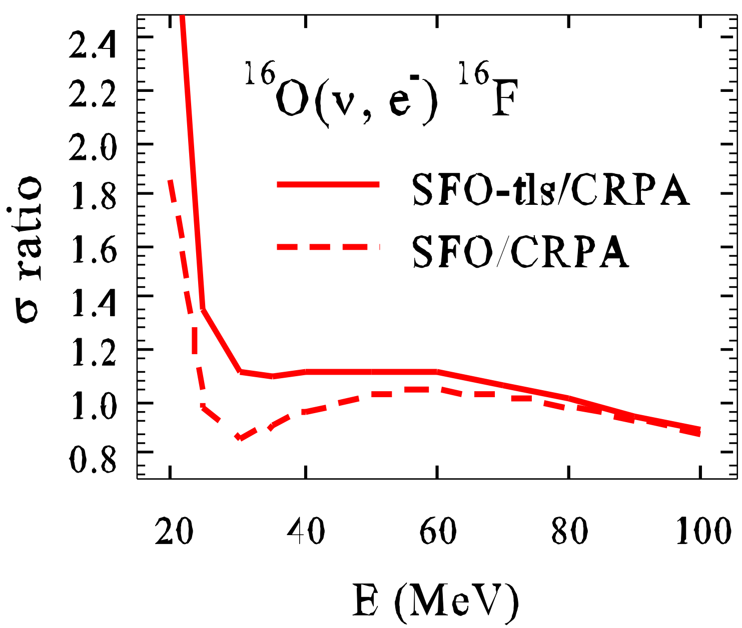
$$-2M_N F_A = \sqrt{2} g_\pi F_\pi$$

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

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}	







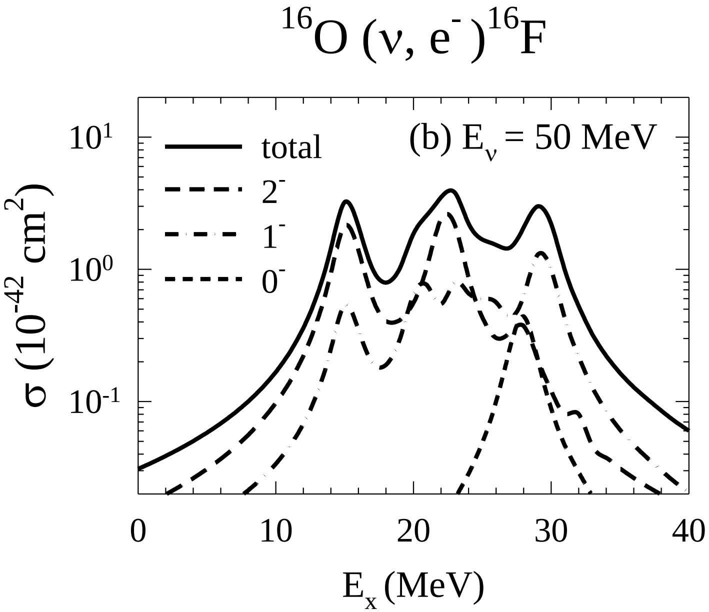
T= temperature of supernova ν

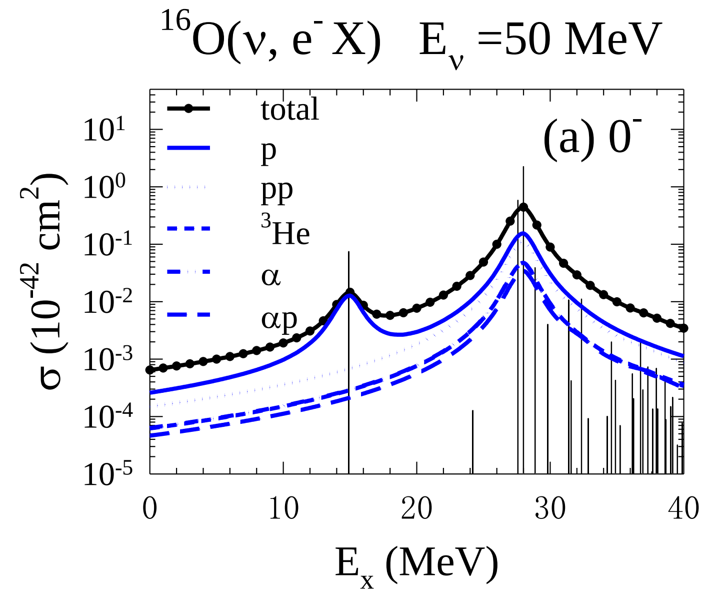
T	σ(SFO-tls)/σ(CRPA):
4	1.41
8	1.17

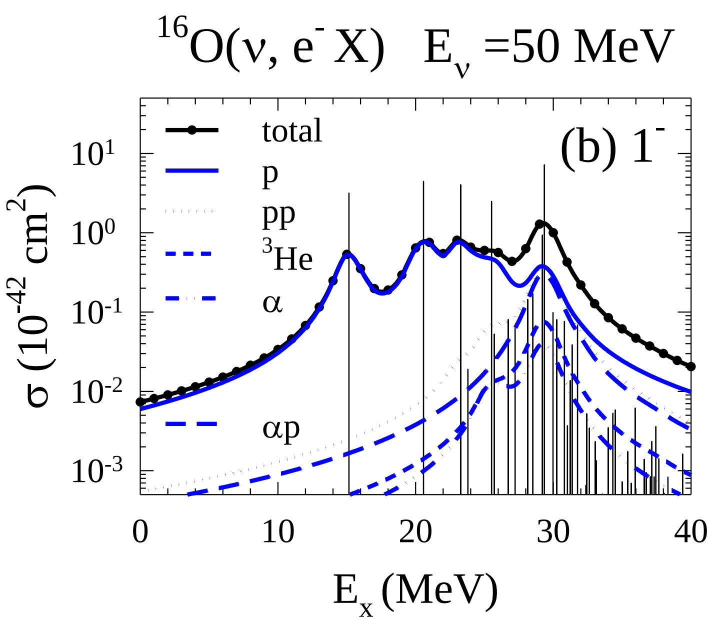
g_A^{eff}/g_A=0.95

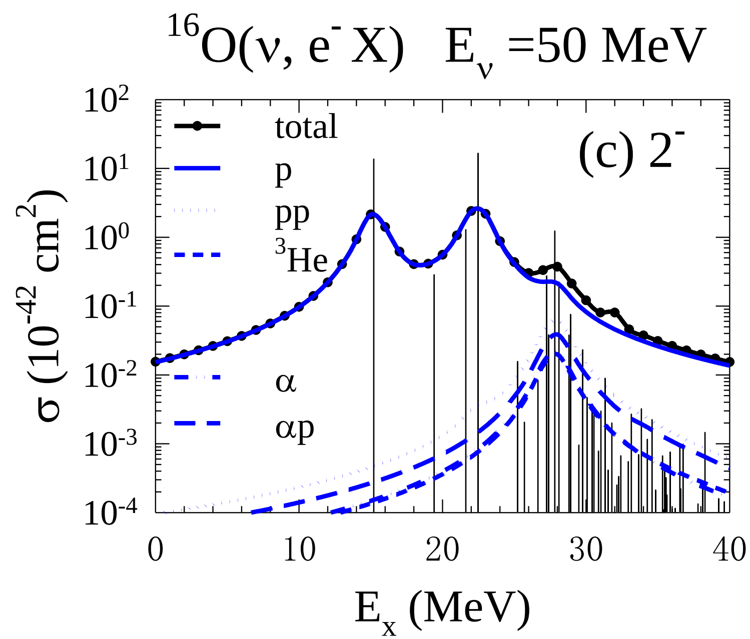
CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

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

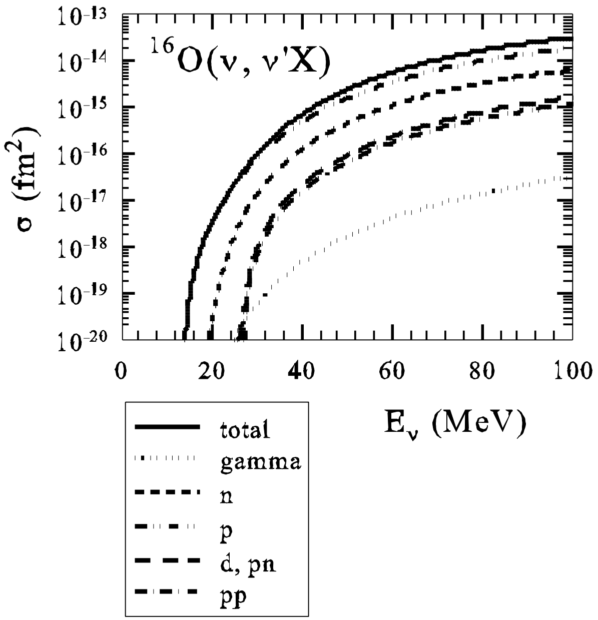

^{16}O (ν, e$^-$)^{16}F
(b) E_ν = 50 MeV
total
2$^-$
1$^-$
0$^-$
σ (10^{-42} cm^2)
E_x (MeV)

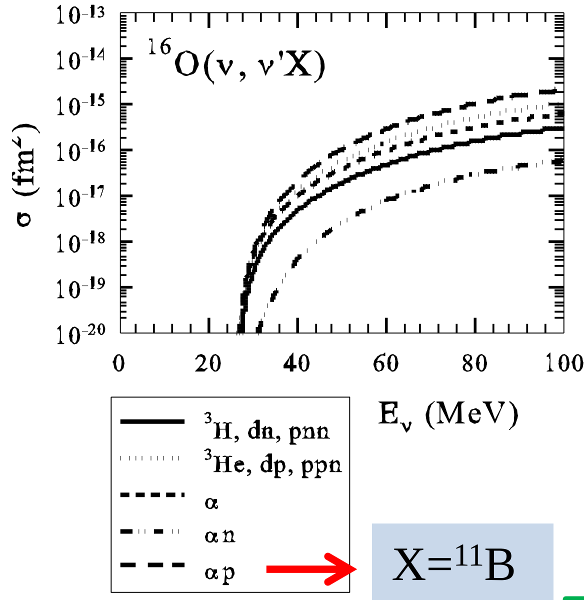

^{16}O(ν, e$^-$ X) E_ν =50 MeV
(a) 0$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
E_x (MeV)


^{16}O(ν, e$^-$ X) E_ν =50 MeV
(b) 1$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
E_x (MeV)

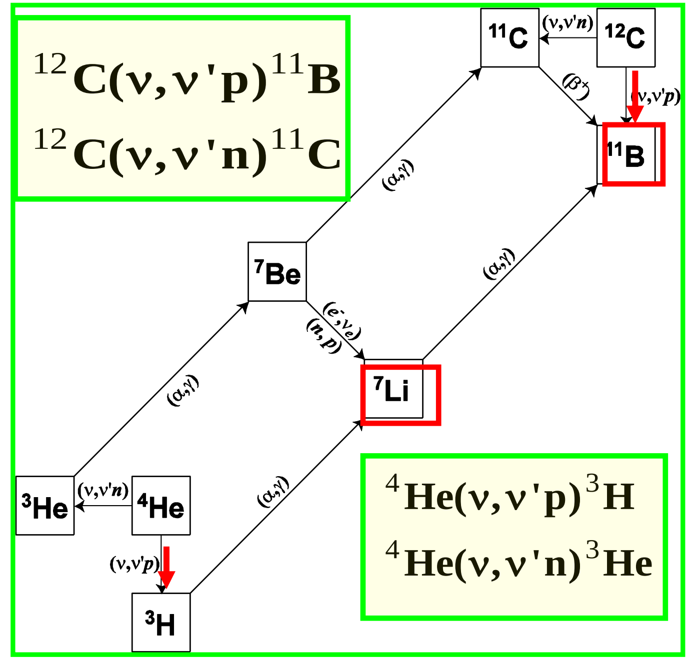

^{16}O(ν, e$^-$ X) E_ν =50 MeV
(c) 2$^-$
total
p
pp
^{3}He
α
αp
σ (10^{-42} cm^2)
E_x (MeV)

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 ($10^{-7} M_\odot$)

yields 核種生成量	$15M_\odot$ モデル			$20M_\odot$ モデル		
	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

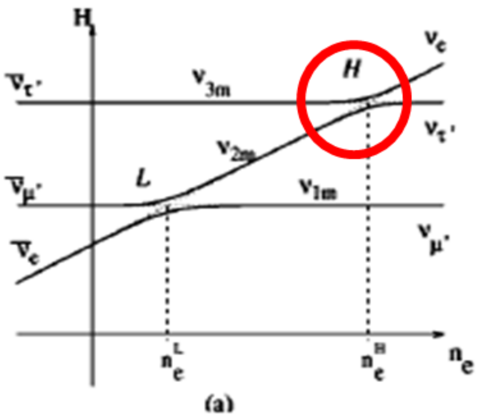
Expected γ-emission neutrino event number from a core-collapse SN at 10 kpc to be detected at Super-K are evaluated for neutral-current reactions on ^{16}O as in the case of ^{12}C.

Sakuda et al., OMEG15 Proceedings, and to be published.

ν oscillation effects → ν mass hierarchy

MSW ν oscillations

Normal hierarchy | Inverted hierarchy



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

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

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

Normal hierarchy: $(P, P') = (0, 0.68)$
Inverted hierarchy: $(P, P') = (0.32, 0)$; $\sin^2\theta_{12} = 0.32$

Dighe and Smirnov, PR D62, 033007 (2000)

Resonance condition

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

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

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

$\rho Y_e = 300 - 3000 \;\; \text{g} \cdot \text{cm}^{-3}$ He/C layer

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

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

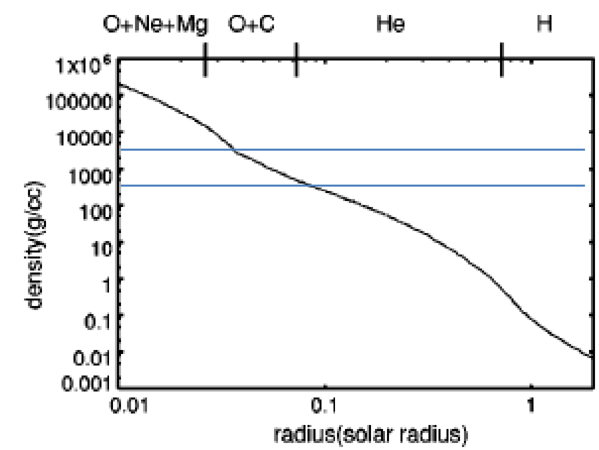
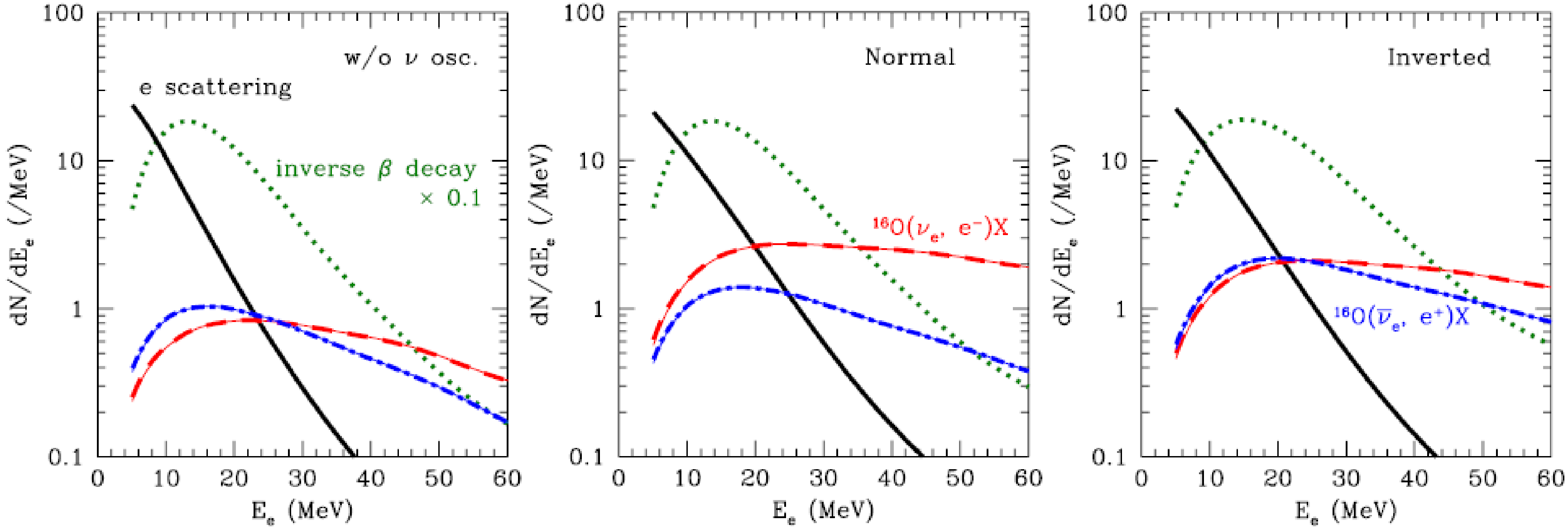


FIG. 3. Density profile of the presupernova star model used in the paper [20]. The progenitor mass is set to be $15 M_\odot$.

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

PTEP 2018, 123E02 82018)

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



(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)

Expected event numbers

	ordinary supernova		
reaction	no osc.	normal	inverted
$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$	41	178	134
$^{16}\mathrm{O}(\bar{\nu}_e, e^+)\mathrm{X}$	36	58	103
electron scattering	140	157	156
inverse β-decay	3199	3534	4242
total	3416	3927	4635

10 kpc, Super-K (32.8 kton)

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

reaction	black hole formation no osc.	normal	inverted
$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$	2482	2352	2393
$^{16}\mathrm{O}(\bar{\nu}_e, e^+)\mathrm{X}$	1349	1255	1055
electron scattering	514	320	351
inverse β-decay	17525	14879	9255
total	21870	18806	13054

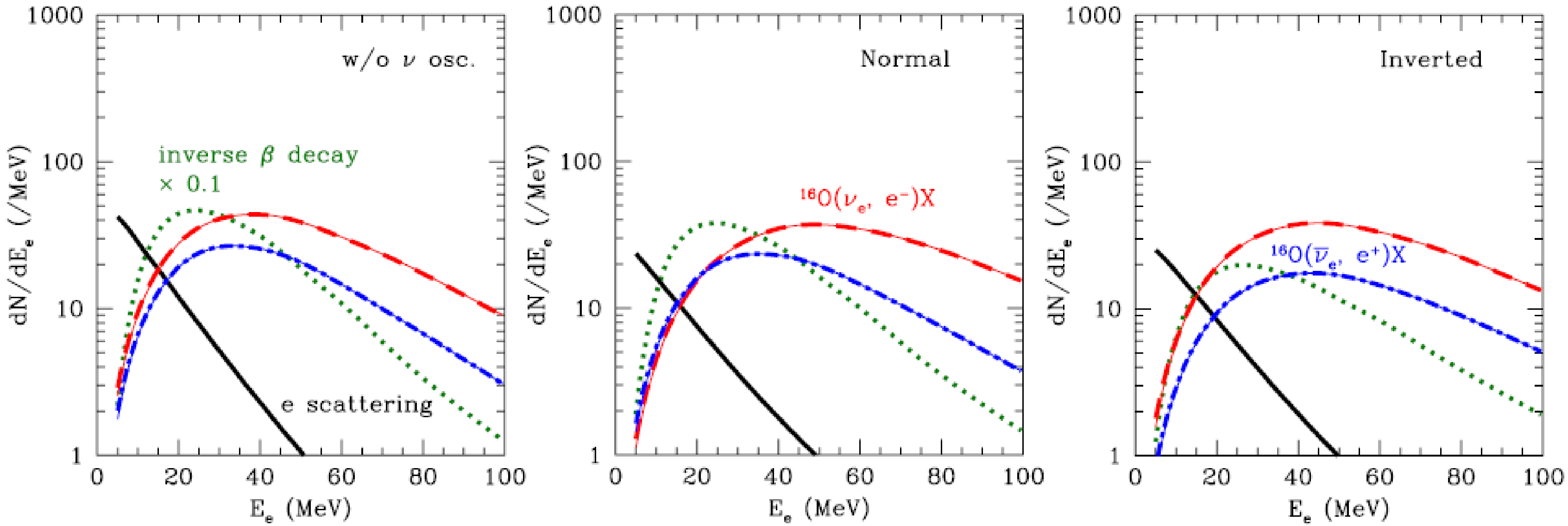
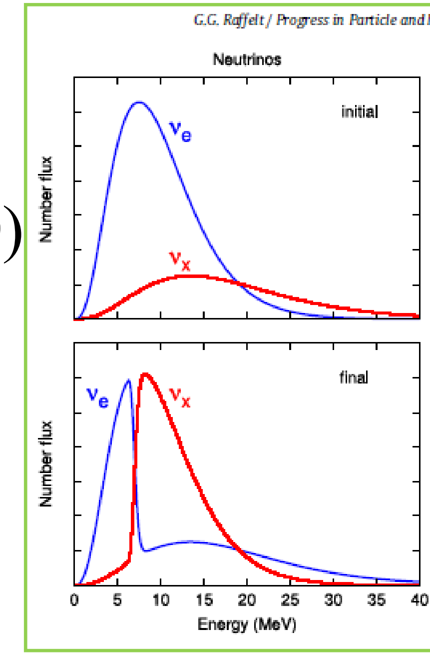


Fig. 5 Same as Fig. 4 but for the model with $(M, Z) = (30M_\odot, 0.004)$, which corresponds to a black-hole-forming collapse.

Effects of collective ν oscillation

▪Splitting (swapping) of ν spectrum occurs for inverted (normal) hierarchy for ν, and for normal (inverted) hierarchy for anti-ν.

Bimodial instability: Raffelt et al., PPNP 64 (2010)



ν:	Collective	MSW	Collect.+MSW
normal	×	○	○
inverted	○	×	○

▪MAA: Multi-azimuthal-angle instability

Splitting also occurs for normal (inverted) hierarchy for ν (anti-ν); $N(\nu_e) > N(\nu_e)$

Raffelt et al., PRL111, 091101 (2011)

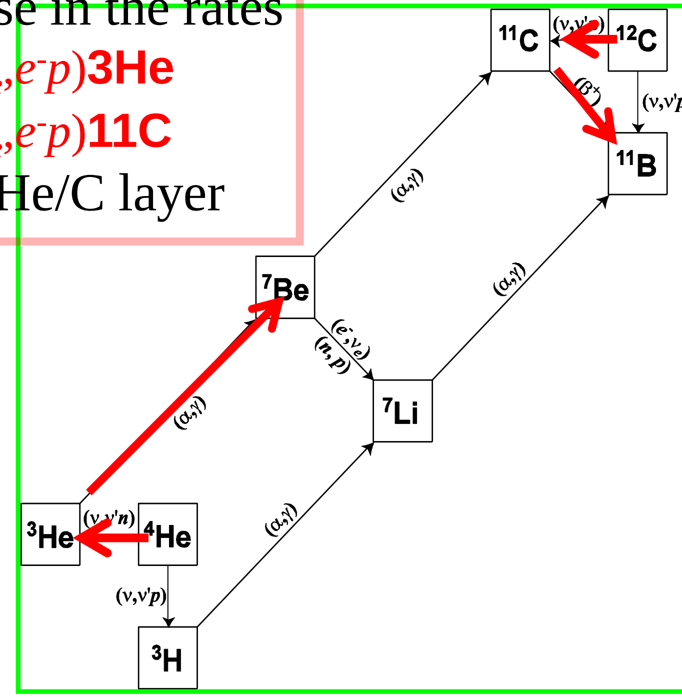
Chakraborty and Mirizzi, PRD 90, 033004 (2014)

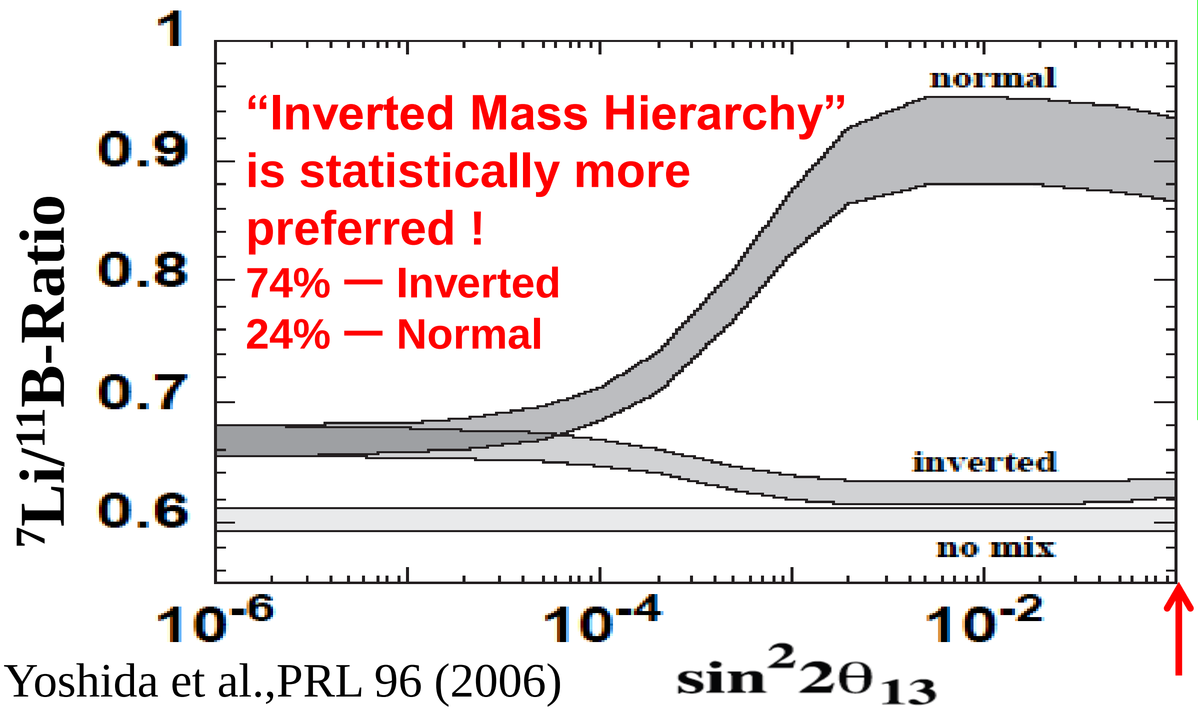
ν:	Collective	MSW	Collect.+MSW
normal	○	○	×
inverted	○	×	○

MSW ν oscillations

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

Increase in the rates
$^4He(\nu_e, e^- p)^3He$
$^{12}C(\nu_e, e^- p)^{11}C$
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 $^7Li/^{11}B$ 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).

For MAA instability case:
$^7Li/^{11}B \rightarrow$ normal hierarchy (?)

Summary

1. ・ν-^{12}C GT + SD shell-model with SFO
   Neutral-current reactions with γ emissions
   Coherent scattering

 ・ν-^{13}C GT + SD, n-emission channel, coherent scatt.

 ・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:
   Cross sections of ^{16}O (ν, e$^-$) X and ^{16}O ($\bar{\nu}$, e$^+$) X induced by SN ν
   (MSW+collective oscillations)

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