ν-Nucleus Reactions induced by Supernova ν

Toshio Suzuki
Nihon Univesity

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Erice

1. Detection of SN neutrinos with water Cherenkov detectors

- Neutral-current reactions on ^{16}O

  Detection of 4.4 MeV γ from ^{12}C (4.4 MeV, 1^+, T=0) induced by

  $^{16}O\ (\nu, \nu')\ ^{16}O$ (12.97 MeV, 2^-) $\rightarrow$ ^{12}C (4.4 MeV, 2^+, T=0) + α

  Isospin mixing in (2^-, T=1, 12.97 MeV) and (2^-, T=0, 12.53 MeV) states in ^{16}O

- Isotopic abundance of ^{18}O = 0.204%

  Effects of the contributions from ν-^{18}O reactions on SN ν detection by charged-current reactions on ^{16}O in water are examined

2. ν-^{20}Ne reactions for nucleosynthesis of ^{19}F

Cross sections for $^{20}Ne\ (\nu, \nu' p)\ ^{19}F$, $^{20}Ne\ (\bar{\nu}_e, e^+ n)\ ^{19}F$ induced by SNν

1. Detection of SN neutrinos with water Cherenkov detectors

Langanke, Vogel and Kolbe, PRL 76, 2629 (1996)
Super Kamiokande (SK-I, II, III): $E_\gamma > 5$ MeV

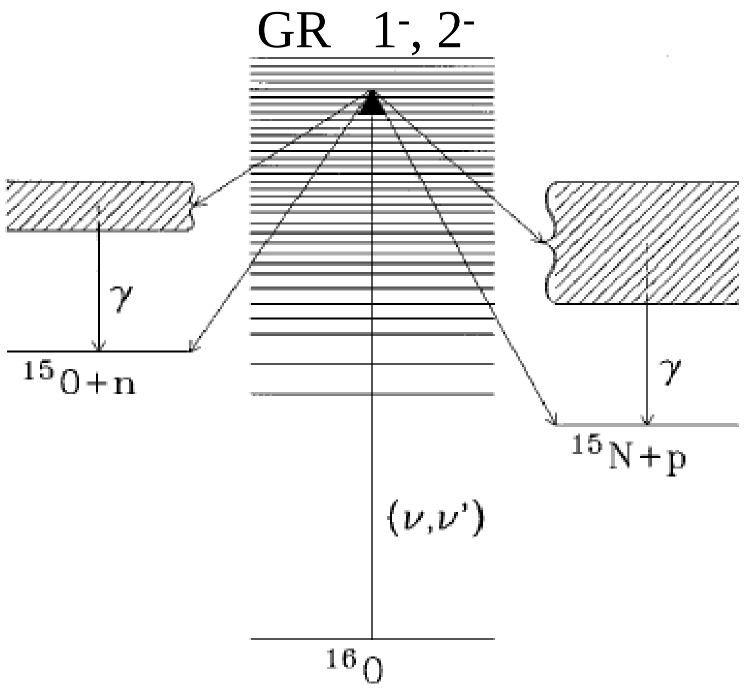


FIG. 1. Schematic illustration of the detection scheme for supernova ν_μ and ν_τ neutrinos in water Čerenkov detectors.

γ spectrum in a water Cherenkov detector

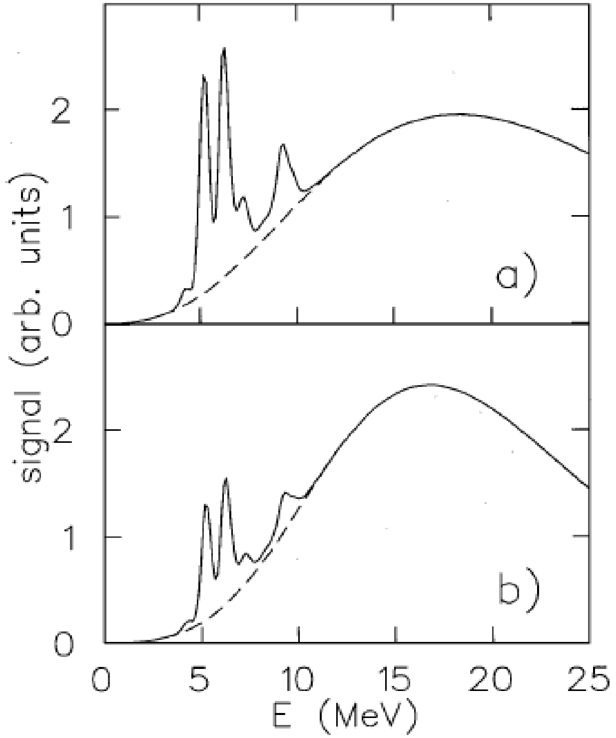


FIG. 2. Signal expected from supernova neutrinos in a water Čerenkov detector. The solid line is the sum of the γ spectrum, generated by ν_x and $\bar{\nu}_x$ reactions on ^{16}O, and of the positron spectrum (dashed line) from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. The upper part (a) has been calculated assuming Fermi-Dirac neutrino distributions with ($T = 8$ MeV, $\mu = 0$) and ($T = 5$ MeV, $\mu = 0$) for ν_x and $\bar{\nu}_e$ neutrinos, respectively. In the lower part (b) Fermi-Dirac neutrino distributions with ($T = 6.26$ MeV, $\mu = 3T$) and ($T = 4$ MeV, $\mu = 3T$) have been assumed for ν_x and $\bar{\nu}_e$ neutrinos. The energy E refers to the photon or positron energy, respectively. The spectra are in arbitrary units.

・SK-IV: E_γ > 3.5 MeV
→ Detection of 4.4 MeV γ from ^{16}O (ν, ν') ^{16}O (12.97 MeV, 2^-) M. Sakuda

^{16}O (12.53 MeV, 2^-, T=0) → ^{12}C (4.4 MeV, 2^+, T=0) + α
└→ ^{12}C(g.s. 0^+) + γ (4.4 MeV)
^{16}O (12.97 MeV, 2^-, T=1) ↛ ^{12}C (4.4 MeV, 2^+, T=0) + α

$\Gamma_{\alpha 1}/\Gamma$ = Br (12.97 MeV → ^{12}C (4.4 MeV) + α)
= 0.37 ± 0.06 Leavitt et al., Nucl. Phys. A 410, 93 (1983)
= 0.22 ± 0.04 NNDC (Zijderhand and van der Leun, Nucl. Phys. A 460, 181 (1986).)
= 0.46 ± 0.06 Charity et al., Phys. Rev. C 99, 044304 (2019)
Averaged value = 0.35

・Isospin mixing

|U> = $\sqrt{1-\beta^2}$ |U, T=1> - β |D, T=0> |U> = | 12.97 MeV, 2^- >
|D> = $\sqrt{1-\beta^2}$ |D, T=0> + β |U, T=1> |D> = | 12.53 MeV, 2^- >

$\beta = \frac{\varepsilon}{\sqrt{1+\varepsilon^2}}$, β^2= <T=0 |H_c| T=1>/ΔE

$\varepsilon^2 = \frac{P_{\alpha D}}{P_{\alpha U}} \frac{\Gamma_{\alpha U}}{\Gamma_{\alpha D}}$ P_α = α penetrability, Γ_α= α-width

We need P_α to derive ε or β

e.g. in Leavitt et al. $\frac{P_{\alpha D}}{P_{\alpha U}}$ is estimated to be ≈0.033 → ε^2=0.28 → $\beta = 0.45 \pm 0.04$

- Isospin Mixing parameter β from B(M2) values

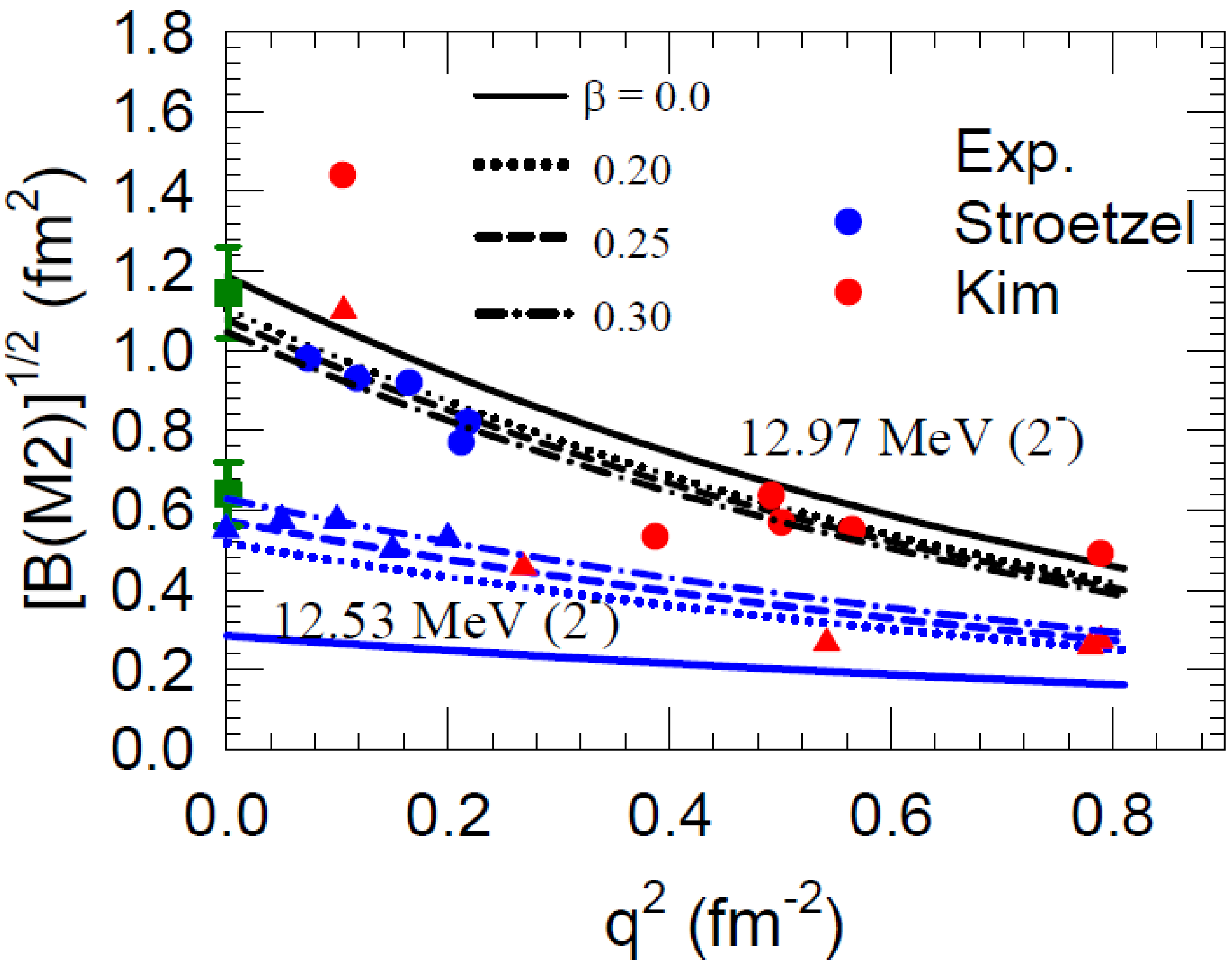
$$B(M_J, q) = \frac{J[(2J+1)!!]^2}{J+1} q^{-2J} F_T^2(M_J, q).$$

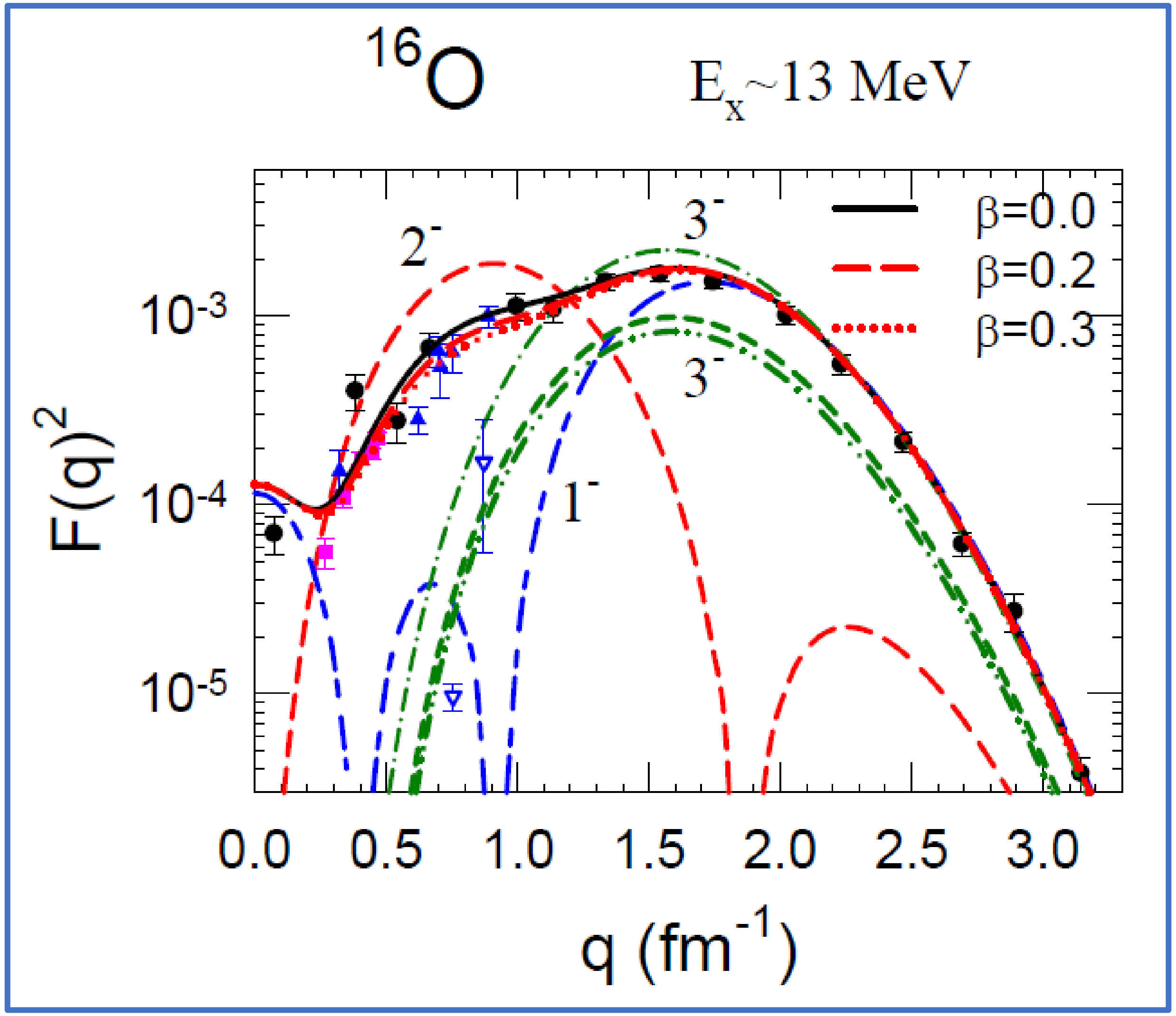
$$F_T^2(q) = \frac{1}{2J_i+1} \sum_{J=1}^{\infty} \{ \left| \langle J \parallel \tilde{T}_J^{\mathrm{el}}(q) \parallel J_i \rangle \right|^2 + \left| \langle J \parallel \tilde{T}_J^{\mathrm{mag}}(q) \parallel J_i \rangle \right|^2 \},$$

$$T_{M2} = \mu_N \frac{q}{\sqrt{6}} \sum_i [\sqrt{\frac{2}{5}} j_1(qr_i) \{ 2g_\ell [Y^{(1)} \times \vec{\ell}]^2 + 3g_s [Y^{(1)} \times \vec{s}]^2 \} + \sqrt{\frac{3}{5}} j_3(qr_i) \{ 2g_\ell [Y^{(3)} \times \vec{\ell}]^2 - 2g_s [Y^{(3)} \times \vec{s}]^2 \}]$$

B(M2) $\beta = 0.25 - 0.30$

^{16}O (e, e') ^{16}O M2 + E1 + M3





$g_s^{eff}/g_s = 0.70$

p-sd shell: SFO-tls Hamiltonian

Suzuki and Otsuka, PRC 78, 061301 (2008)

$f_s = g_s^{eff}/g_s = 0.70\ (2^-),\ 0.65\ (1^-, 3^-)$

μ capture on ^{16}O (10^3/s) ($f_A = g_A^{eff}/g_A$)

^{16}N	Exp.	Calc.
2^- (0.0 MeV):	6.3 ± 0.7,	7.2
	7.9 ± 0.8	($f_A = 0.63 \pm 0.03$)
	8.0 ± 1.2	
0^- (0.120 MeV):	1.1 ± 0.2	1.33
	1.56 ± 0.18	($f_A = 0.62 \pm 0.02$)
1^- (0.397 MeV):	1.73 ± 0.10	1.52
	1.31 ± 0.11	($f_A = 0.62 \pm 0.03$)
$2^-+1^-+0^-$:	9.15 ± 0.70	10.1 ± 0.5
	10.9 ± 0.7	($f_A = 0.62 \pm 0.02$)
	10.87 ± 1.22	
$E_x > 16$ MeV:	102.6 ± 0.6	112.0
	98 ± 3	($f_A = 0.95$)

^{16}N β^- decay rate ($10^{-3}/s$)

$2^- \rightarrow 0^+$:	27.2 ± 0.4	27.2
		($f_A = 0.73 \pm 0.01$)

2^-: $f_A = 0.68 \pm 0.05$

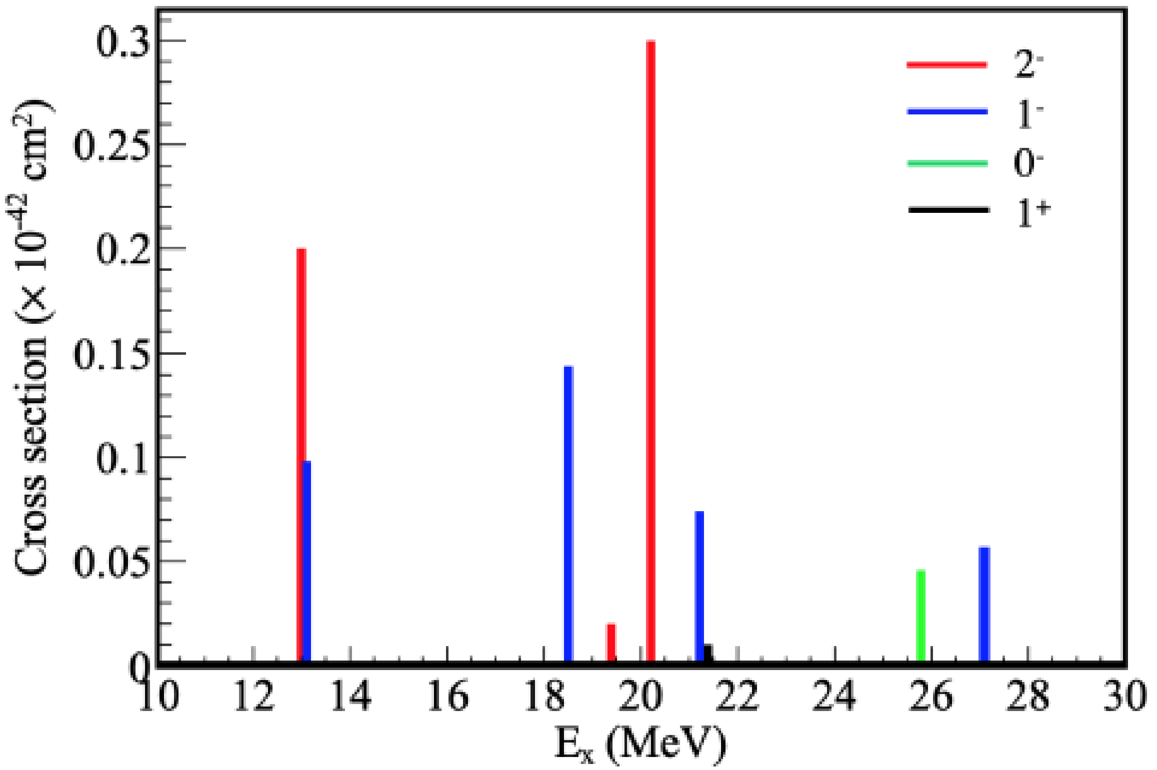
Neutral-current cross sections ^{16}O (ν, ν') ^{16}O*

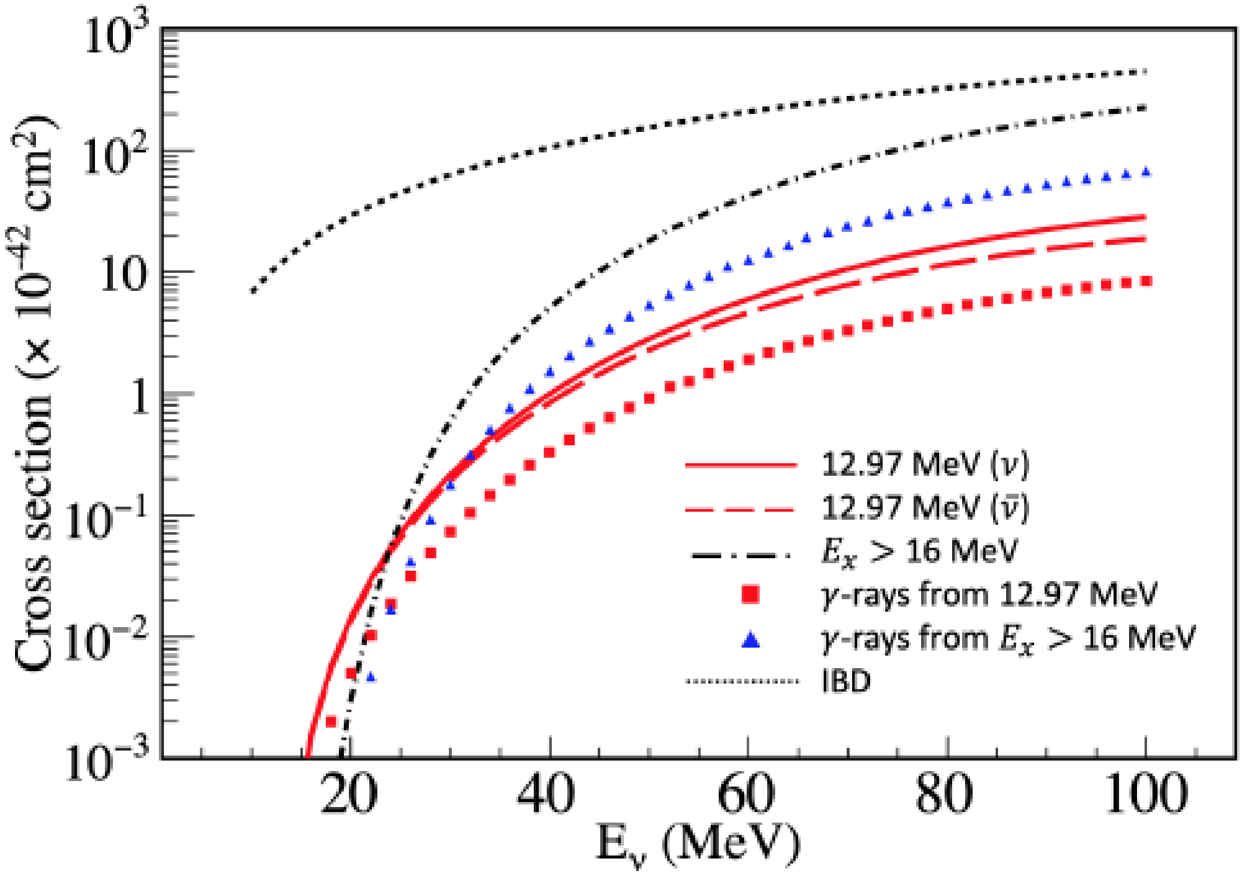
$f_A = 0.68$ for 2^- (12.97 MeV), 1^- (13.09 MeV)

$1 - \beta^2 = 0.94$ ($\beta = 0.25$), $f_A^2 * (1 - \beta^2) = 0.43$

|2-, 12.97 MeV> $\rightarrow \alpha + {}^{12}$C (4.4 MeV)
with $\Gamma_{\alpha 1}/\Gamma = 0.35$

|1^-, 13.09 MeV> $\rightarrow$ p + ^{15}N$_{g.s.}$





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)
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
Fermi-Dirac	11.0	16.0	25.0	5.0	5.0	5.0
Blackhole (NK2)	17.5	21.7	23.4	9.49	8.10	4.00

Reactions	Present work			
	Flux			
	mMB	NK1	FD	NK2
$p(\bar{\nu}_e, e^+)n$	5900	3290	7960	18290
NC $^{16}O(\nu,\nu')^{16}O^*$(12.97MeV), E_γ =4.4 MeV)	0.85	13	89	158
	Other works			
CC $^{16}O(\nu_e, e^-) +^{16} O(\bar{\nu}_e, e^+)(E_e > 5$ MeV) [12]	xx	77	xx	3831
νe elastic scattering [12]	yy	140	yy	514
NC $^{16}O(\nu,\nu')^{16}O^*(E_\gamma$ >5 MeV)[4]	14	62	498	984

Expected number of neutrino events from a core-collapse supernova at 10 kpc Super-K (32kton).

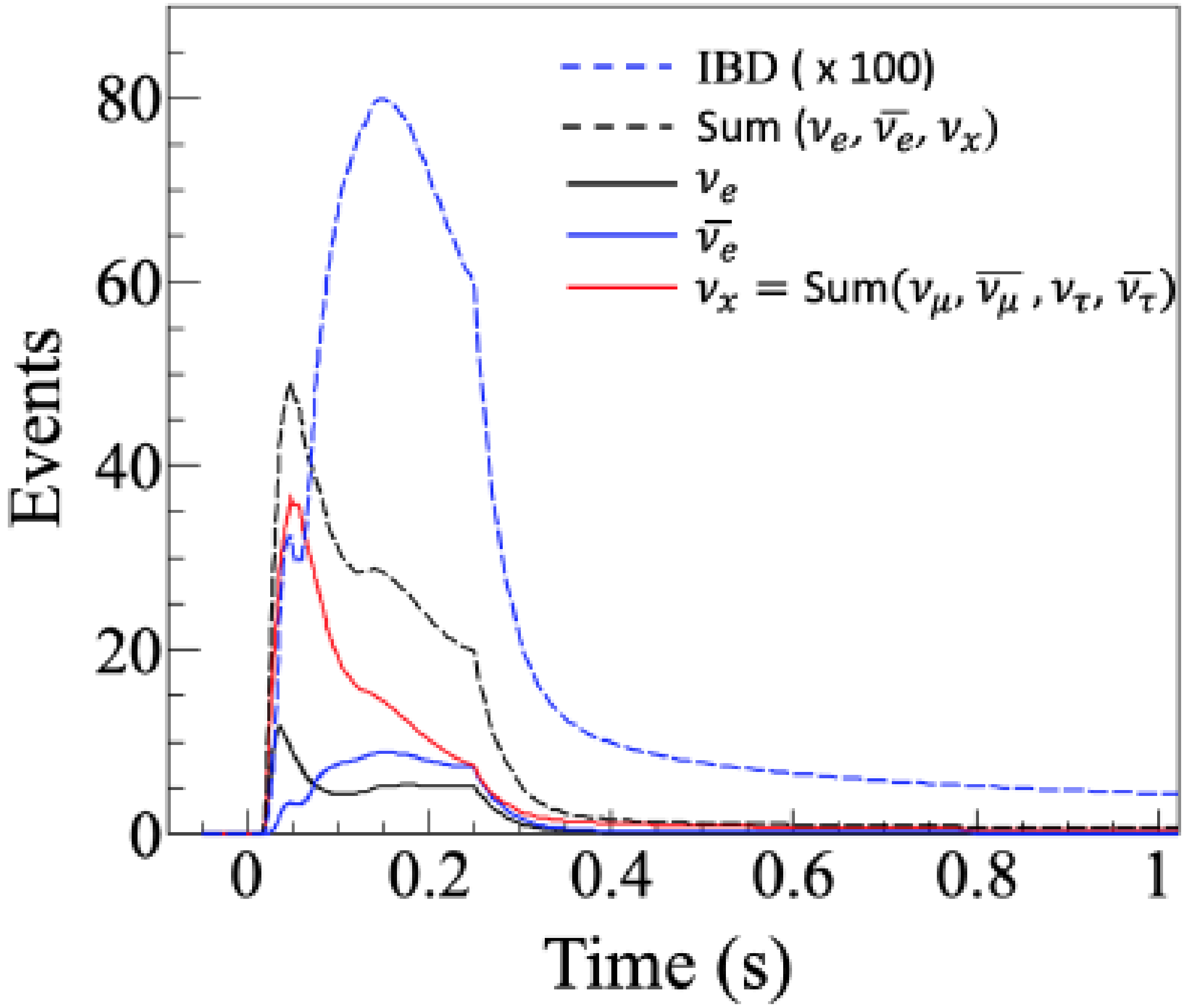
Fermi-Dirac: $$f_{FD}(E_\nu) = 0.555\frac{E_\nu^2}{T^3}\frac{1}{1+\exp(E_\nu/T)}$$

Modified Maxwell-Boltzmann: $$f_{mMB}(E_\nu) = \frac{128E_\nu^3}{3\langle E_\nu\rangle^4}\exp\left(-\frac{4E_\nu}{\langle E_\nu\rangle}\right)$$

Sakuda, Suzuki, Reen, Nakazato, and Suzuki, PTEP in press, arXiv:2211.07851

Preliminary:

Time evolution of events



1. Burst
2. Accretion
3. Cooling

K. Nakazato

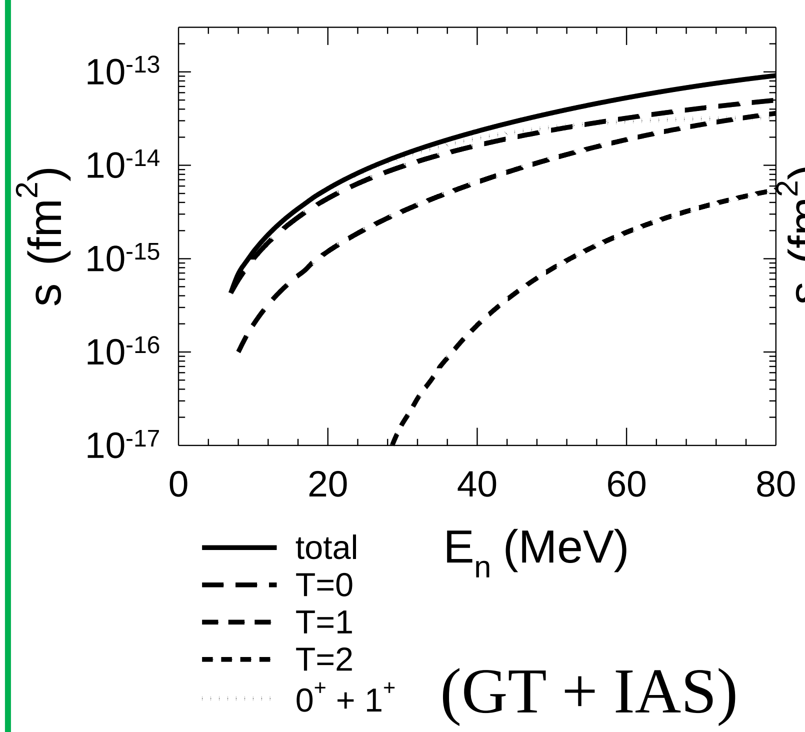
- ν-^{18}O reactions

  ^{18}O 0.204 % of oxygen isotopes

GT strength in ^{18}O

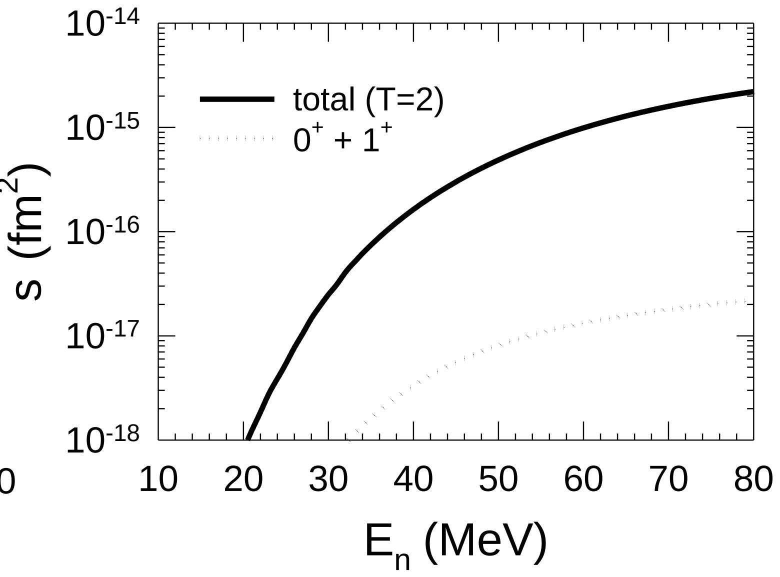
Exp. (^{3}He, t), Fujita et al., PRC 100, 034618 (2019)

^{18}O (n$_e$, e$^-$) ^{18}F



(GT + IAS)

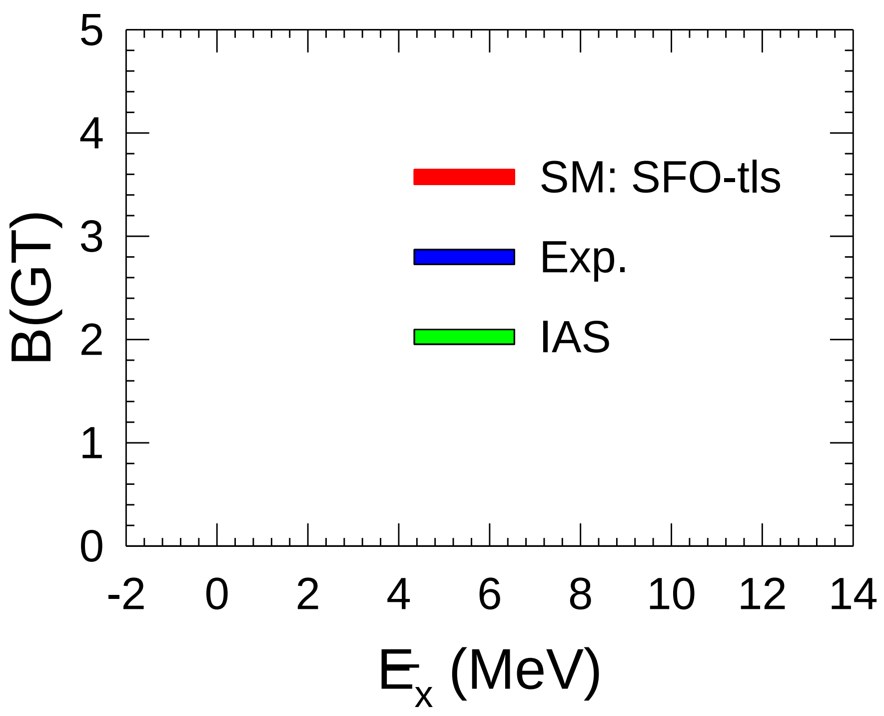
^{18}O ($\overline{n}_e$, e$^+$) ^{18}N



SD dominant

No IAS

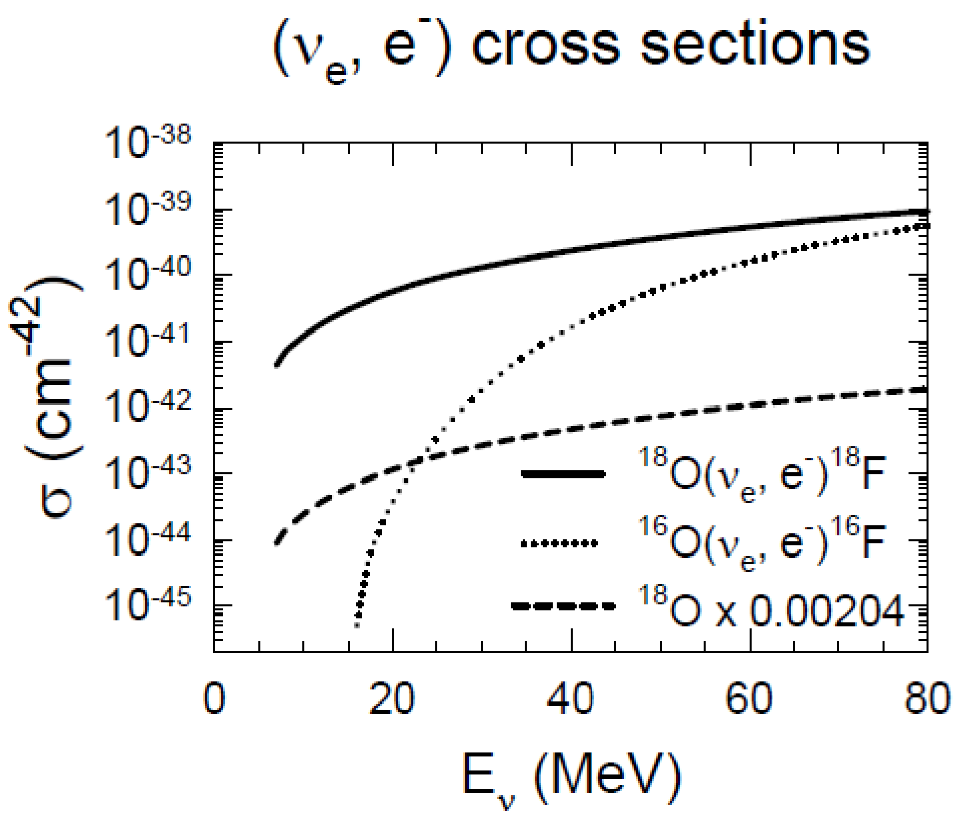
^{18}O -> ^{18}F

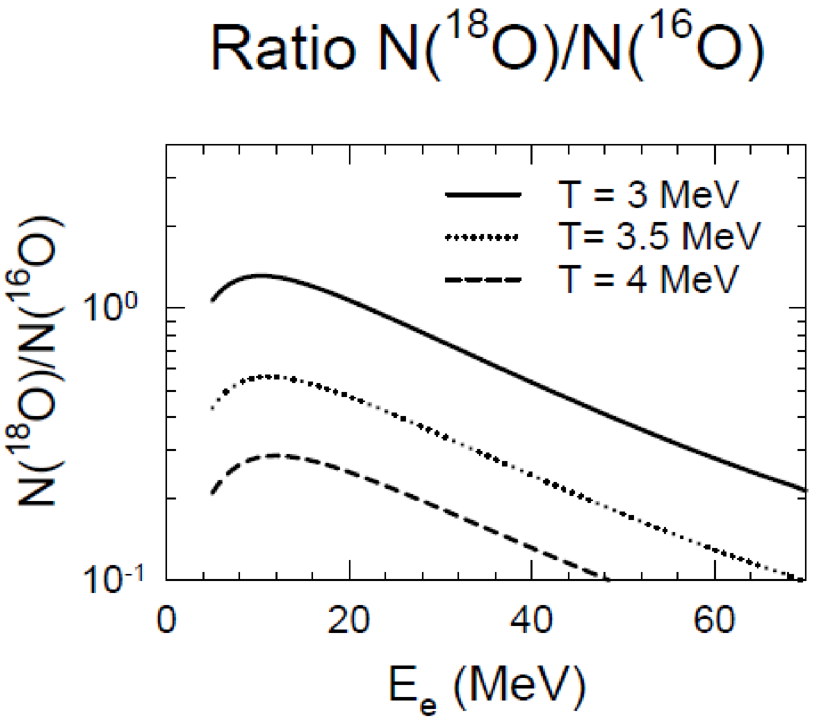


Σ B(GT)$_{exp}$ = 4.06

Σ B(GT)$_{calc}$ = Σ B(GT)$_{exp}$

$f_A = g_A^{eff}/g_A = 0.88$





(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

Expected event numbers Nakazato,Suzuki,Sakuda, PTEP (2018)

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

SK 32Kton
10 kpc
$E_\nu^{tot} \approx$ 3x10^{52} erg / flavor

Ee = 5- 60 MeV:

Ratio = 1.3 - 0.3 T = 3 MeV
0.5 - 0.1 T = 3.5 MeV
0.3 – 0.07 T = 4 MeV

Expected event numbers with $^{18}O(\nu_e, e^-)^{18}F$

(ν_e, e^-)	no osc.	normal	inverted
	41 ->68 (+66%)	178 -> 203 (+14%)	134 -> 172 (+28%)

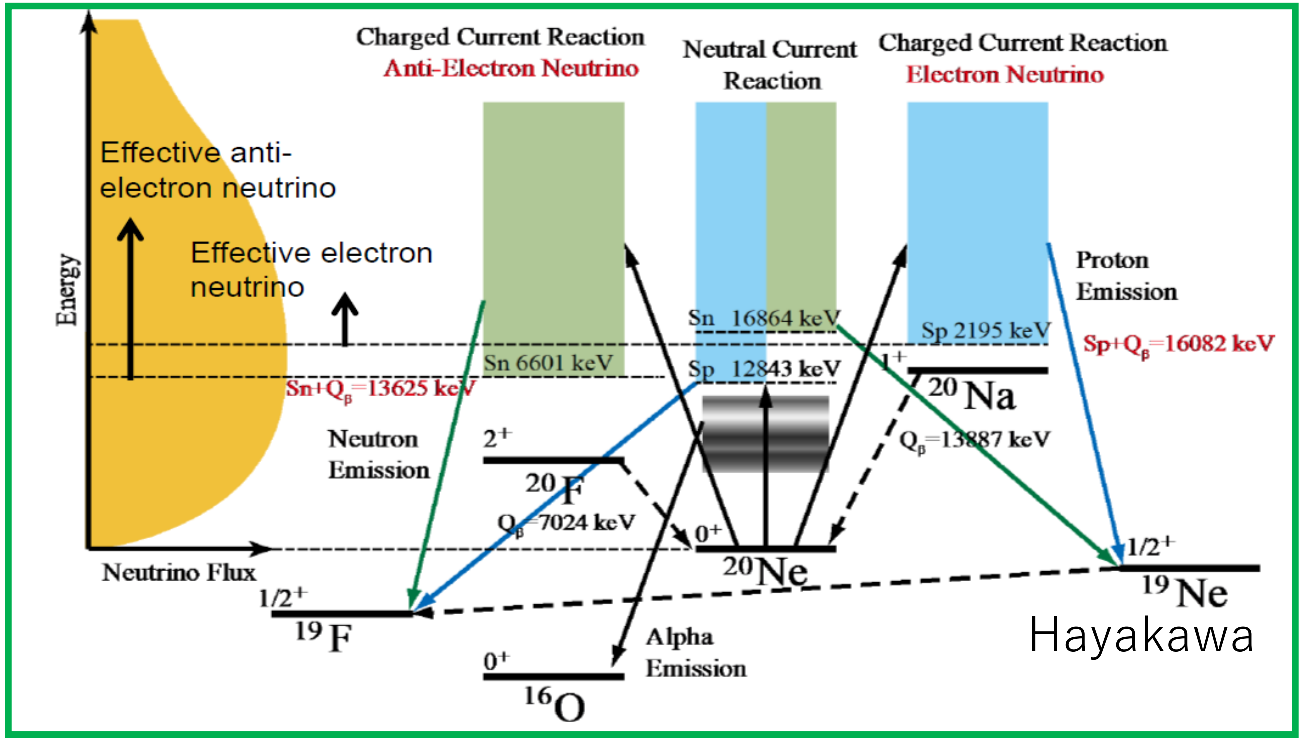
2. Synthesis of ^{19}F by ν process

$\nu - {}^{20}$Ne reactions

^{20}Ne (ν, ν'p) ^{19}F S_P = 12.843 MeV

^{20}Ne ($\bar{\nu}_e$, e^+) ^{20}F Q=7.024 MeV, ^{20}F $\rightarrow$ ^{19}F + n S_n = 6.601 MeV

Q + S_n = 13.625 MeV



cf.

^{20}Ne (ν, ν'n) ^{19}Ne

S_n = 16.864 MeV

^{20}Ne (ν_e, e^-) ^{20}Na

Q=13.887 MeV

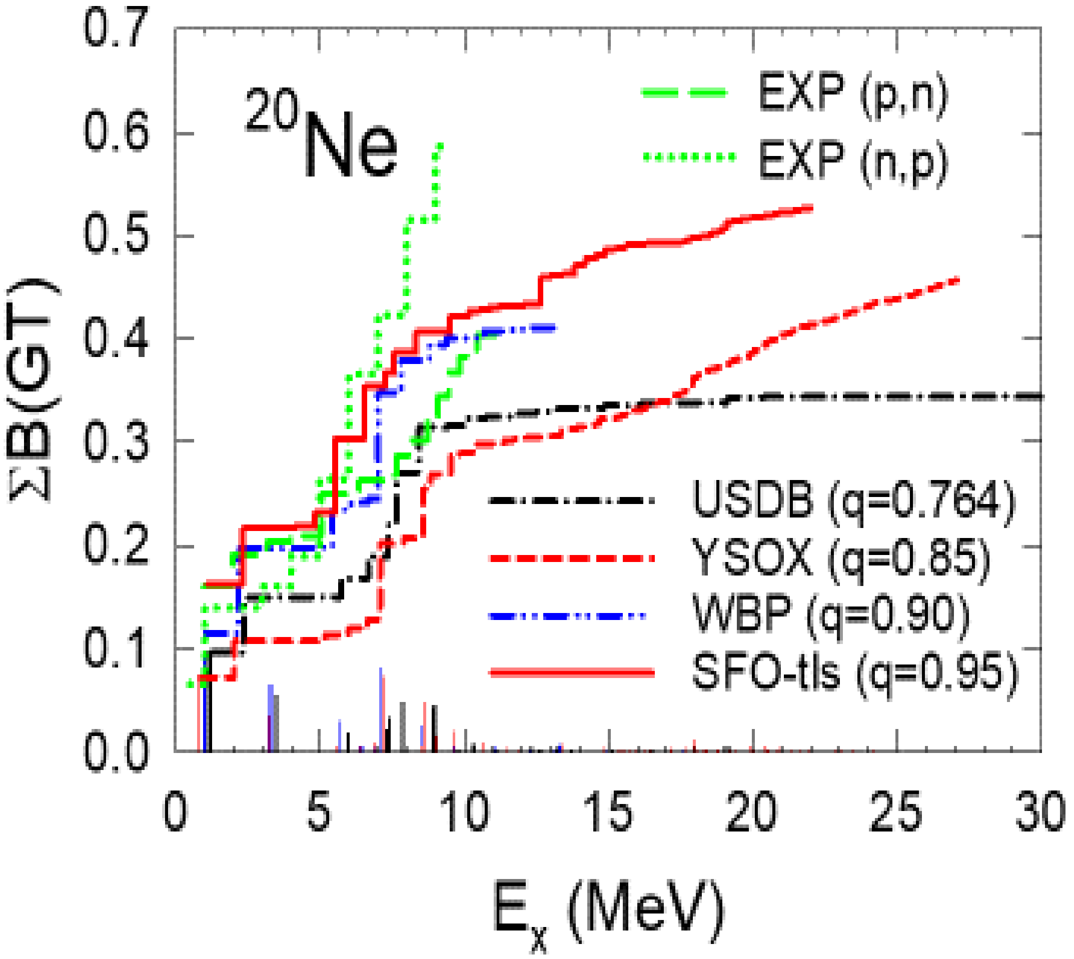
^{20}Na $\rightarrow$ ^{19}Ne + p

S_p = 2.195 MeV

Q + S_p = 16.082 MeV

$T(\nu_e) < T(\bar{\nu}_e) \leqq T(\nu_x)$

GT strength

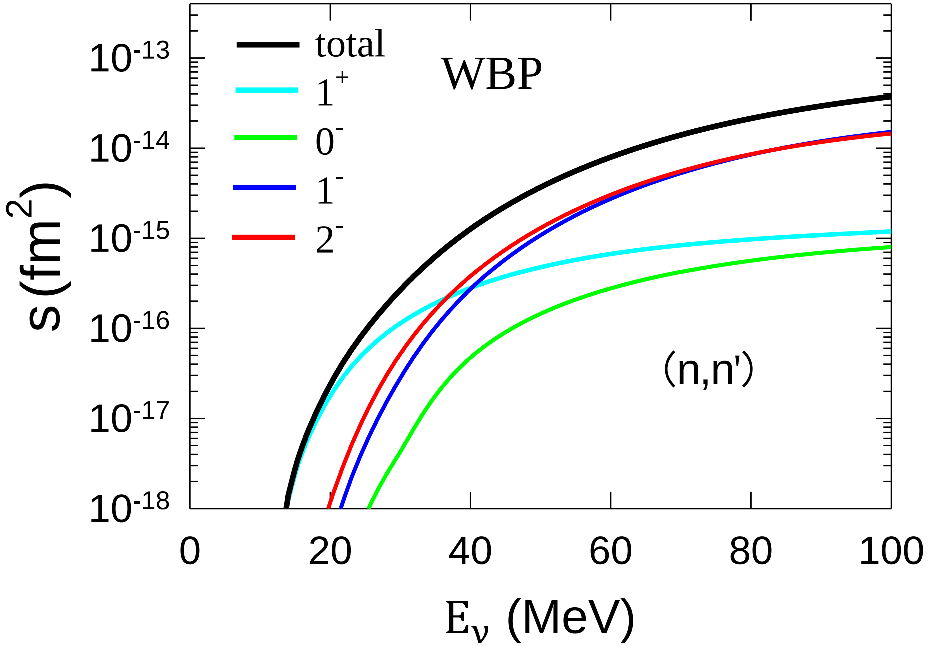


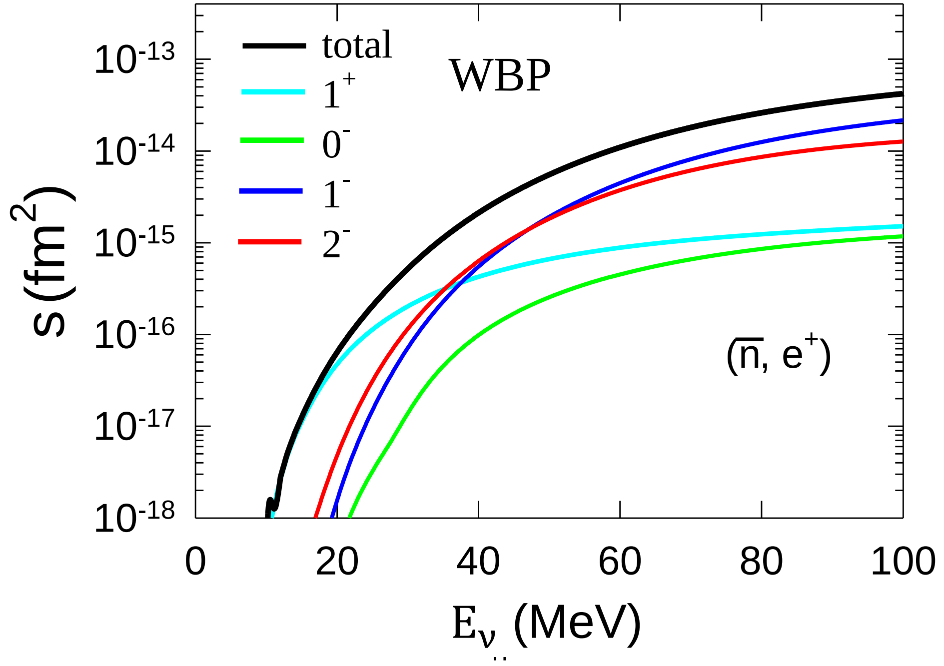
$q = g_A^{eff}/g_A$

SFO-tls: p-sd shell

WBP: p-sd-pf shell

Cross sections

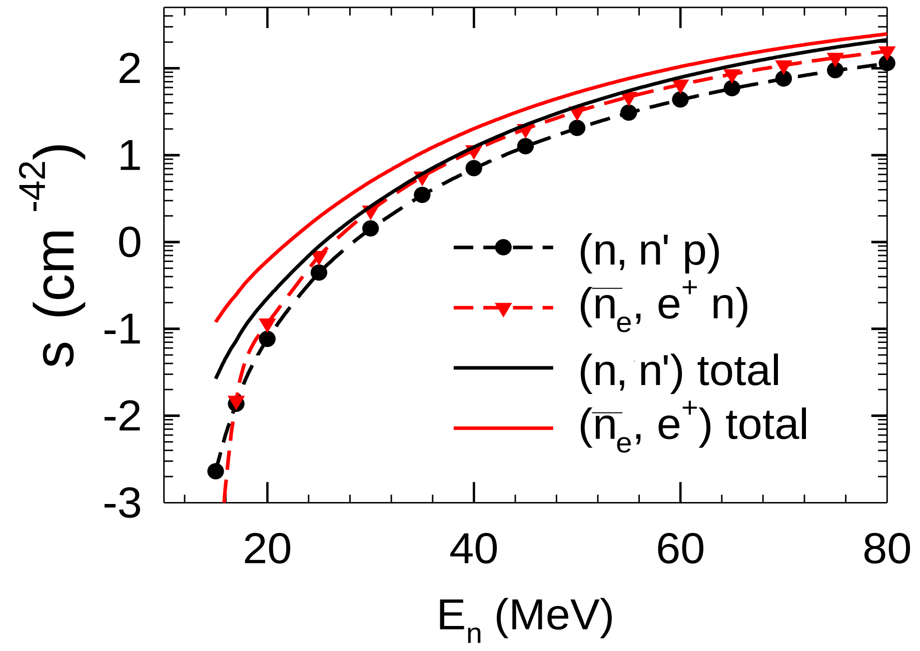




Hauser-Feshbach statistical model

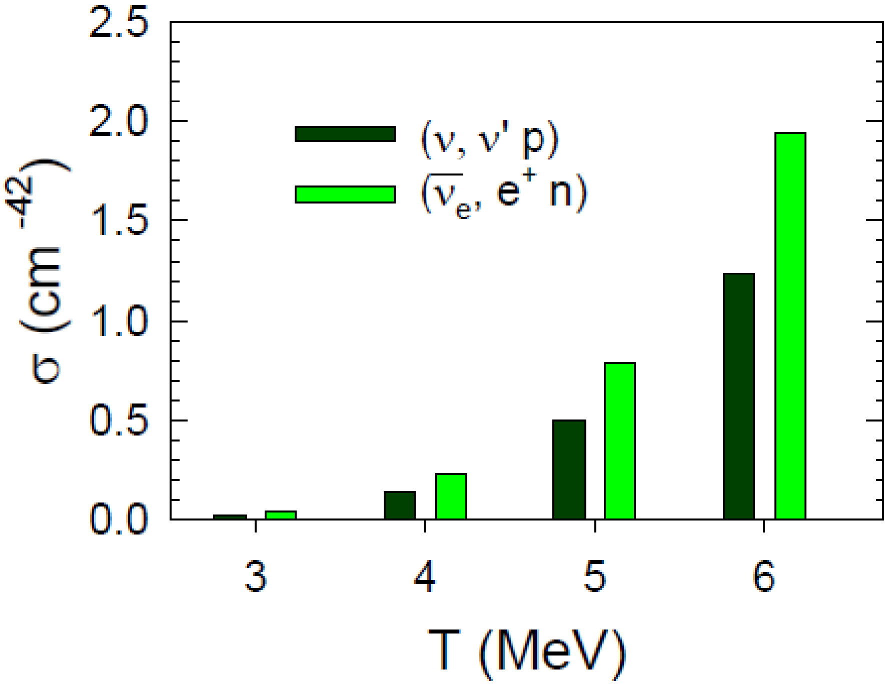
→ BR for γ, p, n, d, ^{3}He, α and multi-particle emissions

^{20}Ne -> ^{19}F



Fermi-Dirac with temperature T

^{20}Ne -> ^{19}F



$(T_{\nu_e}, T_{\bar{\nu}_e}, T_{\nu_x})$ = (3.2, 5, 6) MeV

(a) $(\nu, \nu' p)$ $\sigma = 5.50 \times 10^{-42} cm^2$

(b) $(\bar{\nu}_e, e^+ n)$ $\sigma = 0.79 \times 10^{-42} cm^2$

b/(a+b) = 0.13

$(T_{\nu_e}, T_{\bar{\nu}_e}, T_{\nu_x})$ = (3.2, 4, 4) MeV

(a) $(\nu, \nu' p)$ $\sigma = 0.76 \times 10^{-42} cm^2$

(b) $(\bar{\nu}_e, e^+ n)$ $\sigma = 0.23 \times 10^{-42} cm^2$

b/(a+b) = 0.23

Summary

1. Detection of 4.4 MeV γ from ^{16}O (ν,ν') ^{16}O (12.97 MeV, 2^-)
   Isospin mixing in (2^-, T=1, 12.97 MeV) and (2^-, T=0, 12.53 MeV)
   Expected event no. of 4.4 MeV γ ~ 1/5 of γ with $E_\gamma > 5$ MeV

2. Effects of the contributions from ν-^{18}O reactions on the SN detection by charged-current reactions on ^{16}O are studied.
   Cross sections for ^{18}O are larger at E_ν < 20 MeV
   Expected event nos. of SNν are enhanced by ~15-30% for the case with the MSW osc. and by ~65 % for the case without the osc.

3. Cross sections for ^{20}Ne (ν, ν'p) ^{19}F, ^{20}Ne (ν_e, e^+n) ^{19}F induced by SNν are evaluated for the study of production of ^{19}F in SN.
   Synthesis of ^{19}F by simulation calculations in SN is under way by Kajino group.

Collaborators

ν-^{16}O

M. Sakuda, Okayama Univ.
K. Nakazato, Kyushu Univ.
H. Suzuki, Tokyo Univ. of Science
M. S. Reen, Akal Univ.

ν-^{20}Ne

S. Chiba, Tokyo Institute of Technology
T. Kajino, Beihan Univ.

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