Forbidden transitions in nuclear weak processes relevant to neutrino detection, nucleosynthesis and evolution of stars

Toshio Suzuki
Nihon University,
NAOJ, Tokyo

NIHON UNIVERSITY
COLLEGE OF
HUMANITIES AND SCIENCES

国立天文台
NAOJ

NSD2019

Venezia

May 16, 2019

GT transitions in nuclear weak rates at stellar environments
e-capture and β-decay rates in sd- and pf-shell nuclei are updated
Nuclear URCA process in O-Ne-Mg core and cooling of stars
Synthesis of iron-group elements in Type Ia SNe
ν-nucleus reaction cross sections updated for ^{12}C, ^{13}C, ^{40}Ar, ^{56}Fe, ^{56}Ni; updated
ν-process nucleosynthesis, ν detection
FF (first-forbidden) transitions in β-decay half-lives in N=126 isotones
r-process nucleosynthesis in CCSNe and binary NSM (neutron star mergers)

1. Spin-dipole strength in ^{16}O and ν-induced reactions on ^{16}O

- Spin-dipole strengths in ^{16}O and ν-^{16}O reaction cross sections with new shell-model Hamiltonians
- Synthesis of light elements in SNe based on the cross sections
- Supernova ν detection by ν-^{16}O reactions
- MSW ν-oscillation effects

Dependence of ν-^{16}O cross sections on ν mass hierarchy

Suzuki, Chiba, Yoshida, Takahashi, and Umeda, Phys. Rev. C98, 034613 (2018)
Nakazato, Suzuki, and Sakuda, PTEP 2018, 123E02 (2018)

2. Electron-capture and β-decay rates of sd-shell nuclei

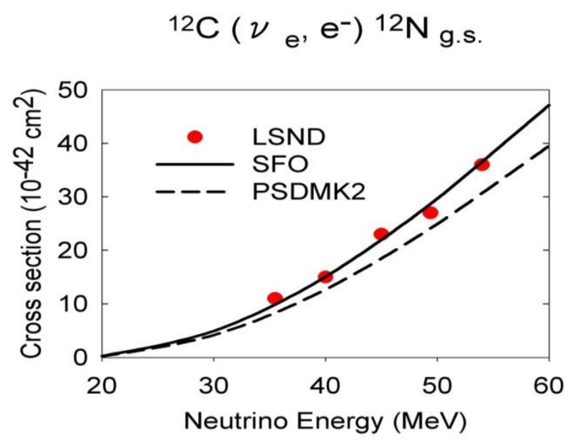
Electron-capture rates for a **2nd-forbidden transition** in ^{20}Ne

- **ν-induced reactions on ^{16}O**

SFO: p-sd shell

CK(p)+MK(p-sd)+G(sd)

Monopole ($p_{1/2}$-$p_{3/2}$; T=0) enhanced



g_A^{eff}/g_A=0.95

B(GT: 12C)_cal = experiment

Magnetic moments Of p-shell nuclei are well reproduced

^{12}C (ν, ν'), (ν_e, e^-) GT+ SD
SFO reproduces exclusive and inclusive DAR cross sections

- **Modification of SFO → SFO-tls**

Full inclusion of tensor force

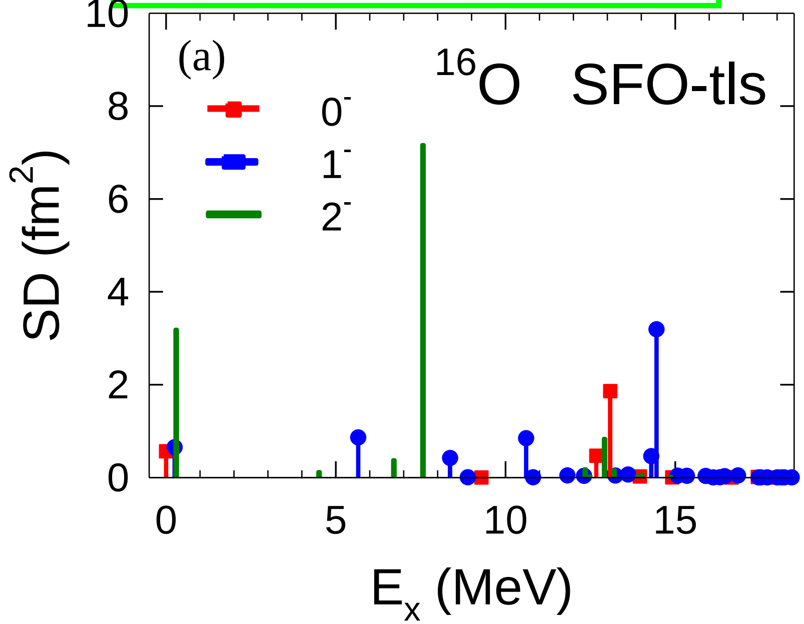
p-sd: tensor-> π+ρ

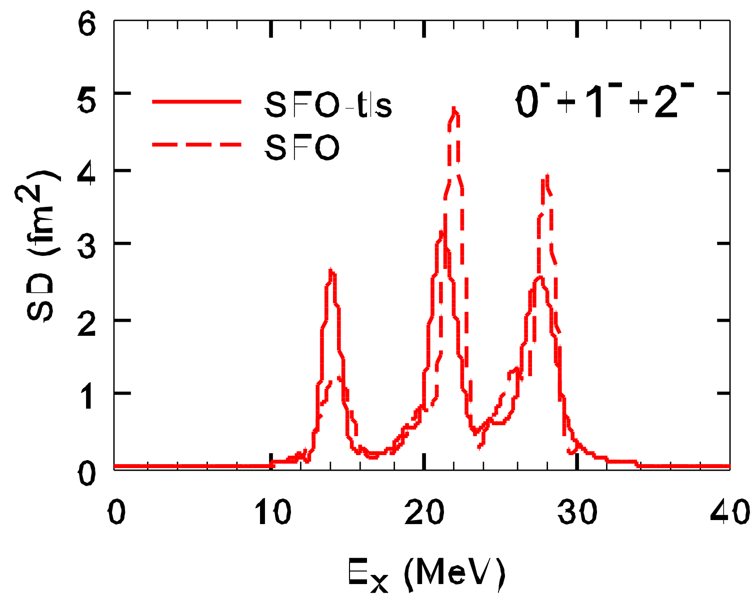
LS -> σ+ρ+ω

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

Spin-dipole strength in ^{16}O

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





Spin-dipole sum

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

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

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

For ^{16}O; N=Z

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

p → sd

$\propto 2\lambda+1$

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 $V_{LS} = -\xi \sum_i \vec{\ell}_i \cdot \vec{\sigma}_i$,

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

$g_\lambda = 1$ 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_-^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)	

$\bar{E}_\lambda = EWS_-^\lambda / NEWS_-^\lambda$,

	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^-

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

The muon capture rate for $^{16}O\ (\mu, \nu_\mu)\ ^{16}N$ from the 1s Bohr atomic orbit

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

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

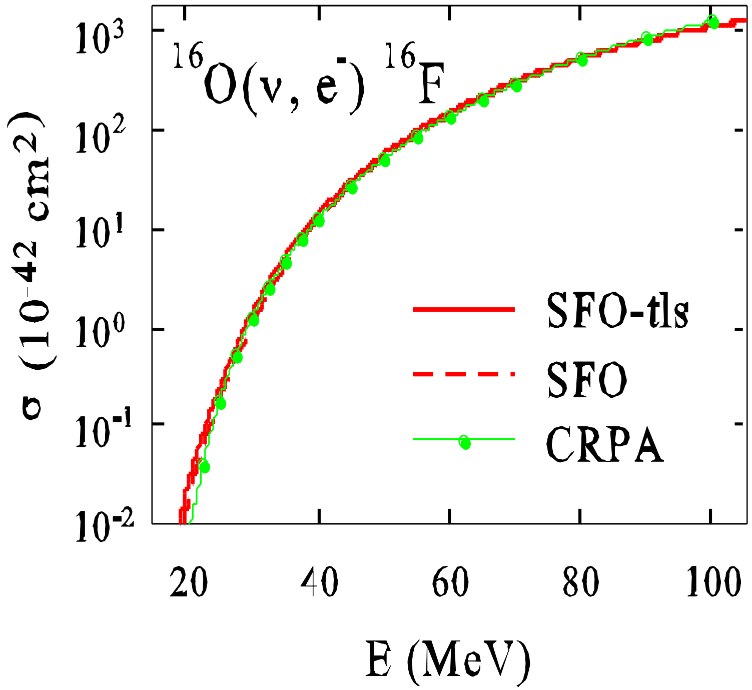
Induced pseudo-scalar current $F_P(q_\mu^2) = \frac{2M_N}{q_\mu^2 + m_\pi^2} F_A(q_\mu^2)$

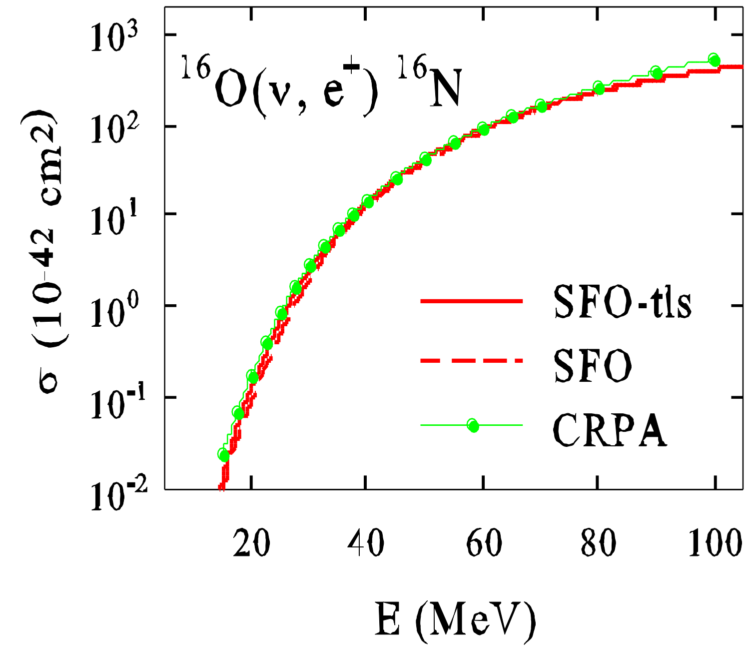
PCAC
Goldberger-Treiman

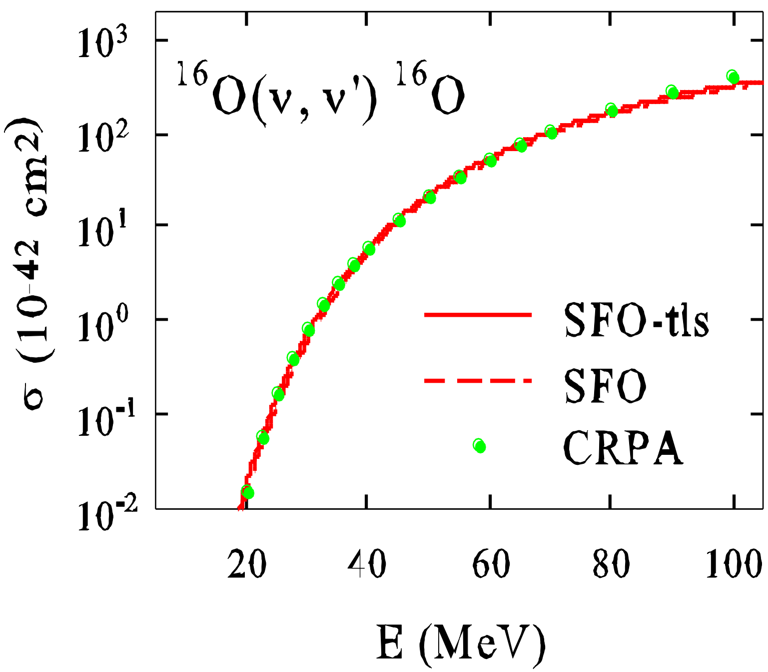
$$-2M_N F_A = \sqrt{2} g_\pi F_\pi$$

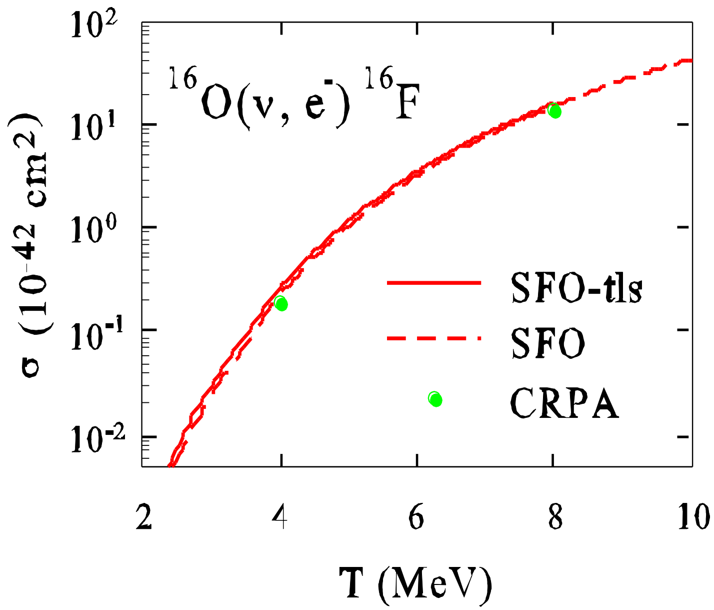
$f = g_A^{eff}/g_A = 0.95$

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









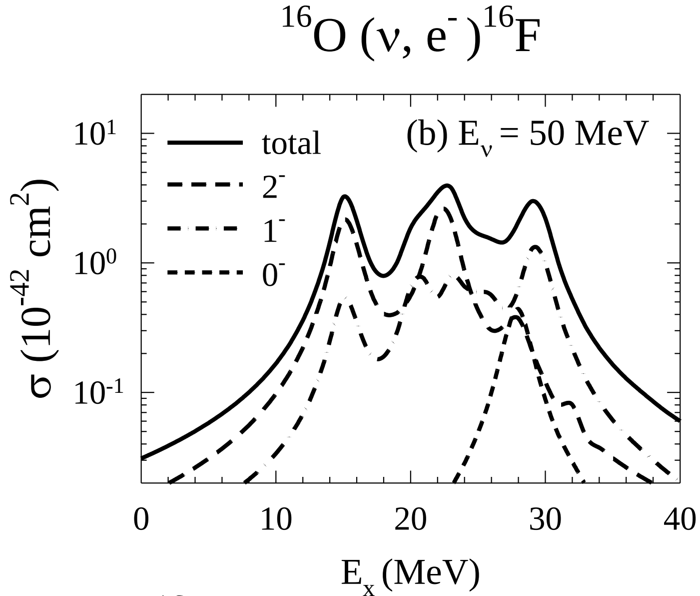
CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

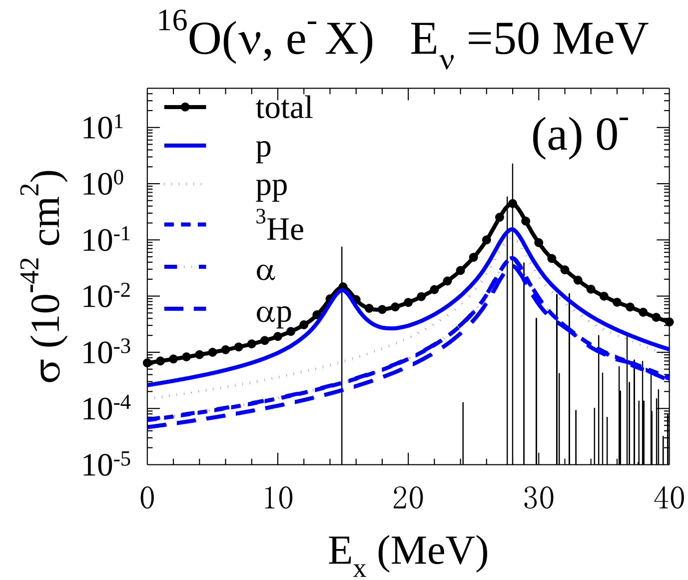
Hauser-Feshbach statistical model

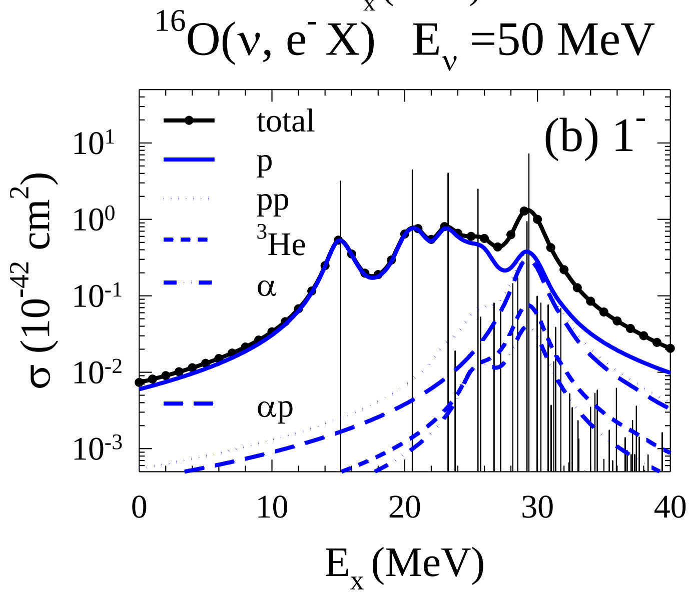
Branching ratios for γ and particle emission channels (with multi-particle emission channels):

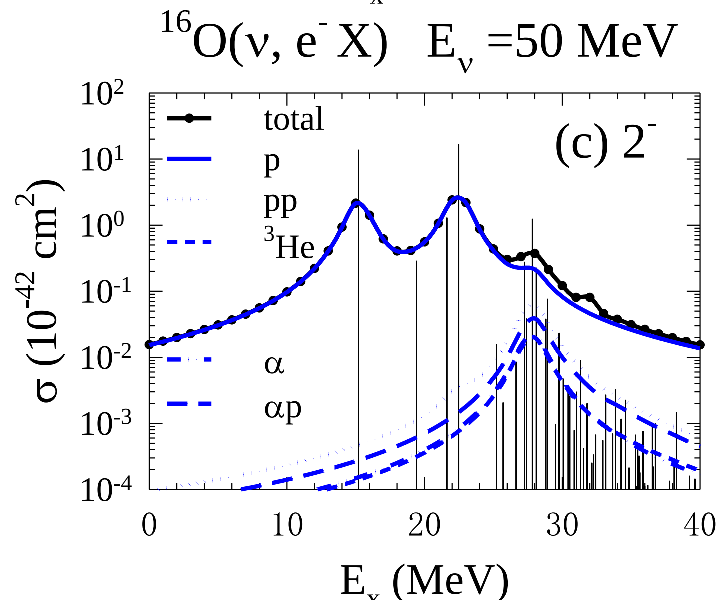
γ, n, p, np (d), nn, pp, ^{3}H (nnp), ^{3}He (npp), α, αp, αn, αnn, αnp, αpp, ...

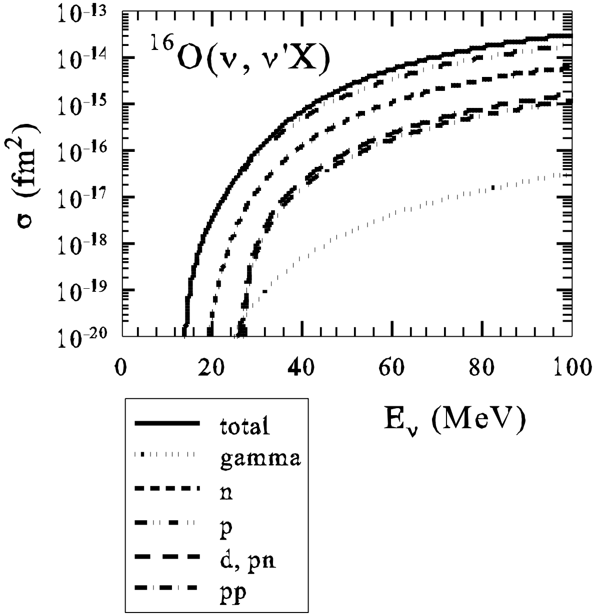
Isospin conservation is taken into account (S. Chiba)

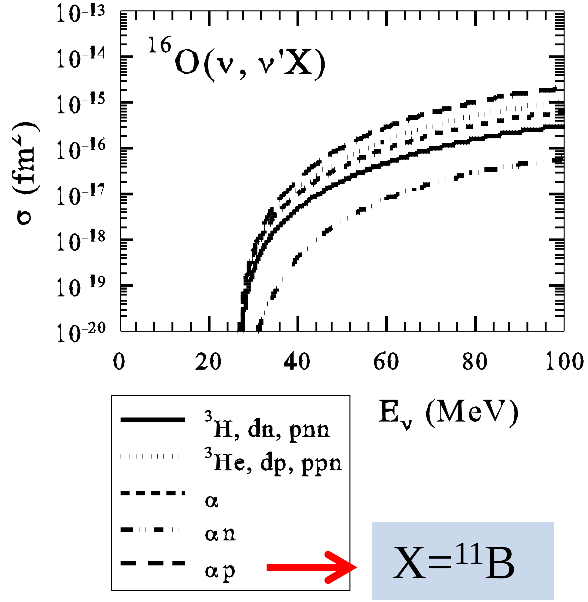


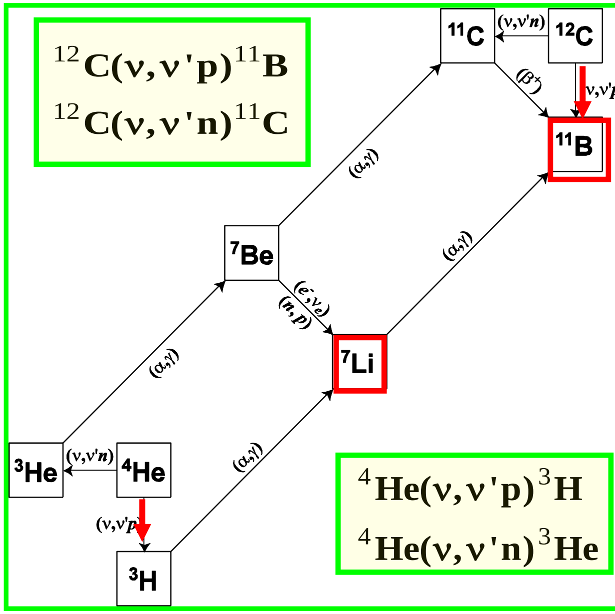












$$\frac{\sigma(^{16}O(\nu,\nu'\alpha p)^{11}B)}{\sigma(^{12}C(\nu,\nu'p)^{11}B)} \approx 10\%$$

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

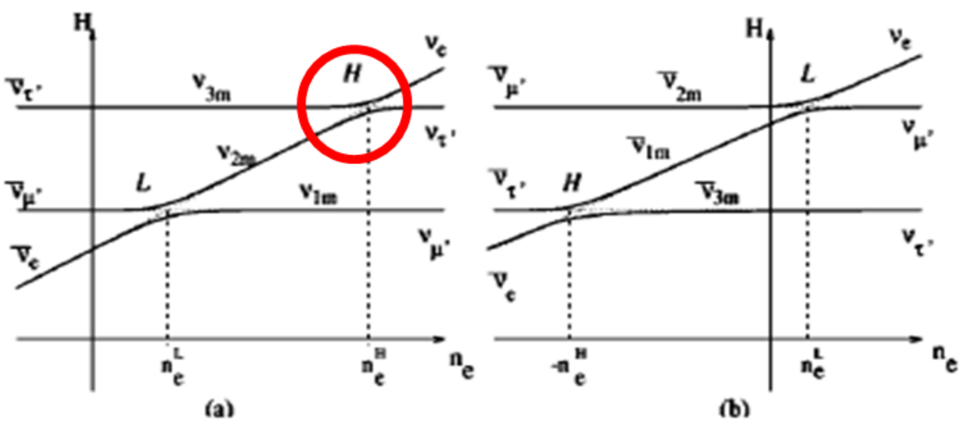
	$15M_\odot$ モデル			$20M_\odot$ モデル		
核種生成量	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$M(^{11}B)$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}C)$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}B+^{11}C)$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

ν oscillation effects → ν mass hierarchy

MSW ν oscillations

Normal hierarchy | Inverted hierarchy



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

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

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

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

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

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

H – resonance: θ_{13}

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

He/C layer

L – resonance: θ_{12}

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

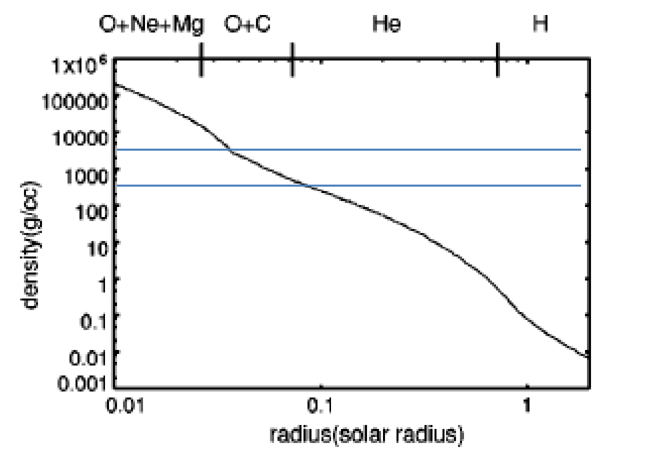
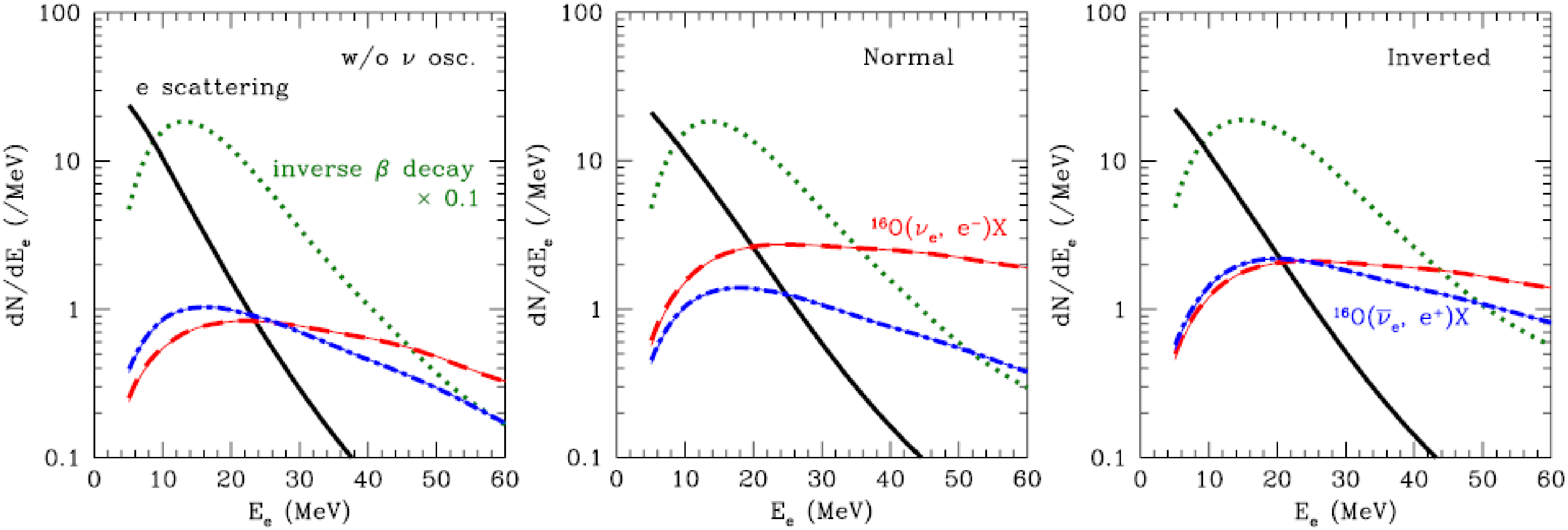


FIG. 3. Density profile of the presupernova star model used in the paper [20]. The progenitor mass is set to be $15M_\odot$.

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

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 enent numbers

	ordinary supernova			black hole formation		
reaction	no osc.	normal	inverted	no osc.	normal	inverted
^{16}O(ν_e, e^-)X	41	178	134	2482	2352	2393
^{16}O($\bar{\nu}_e, e^+$)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

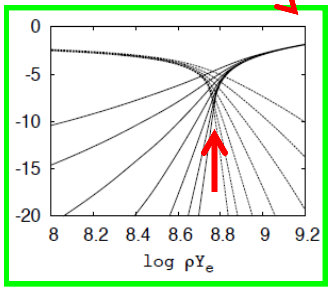
2. Evolution of O-Ne-Mg cores in stars

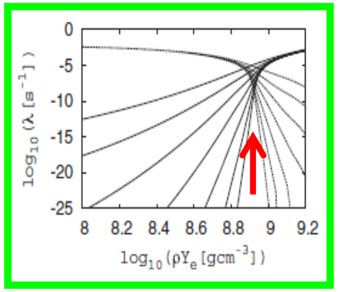
- **Cooling** of O-Ne-Mg core in 8-10 $M_\odot$ stars by nuclear URCA process

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

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

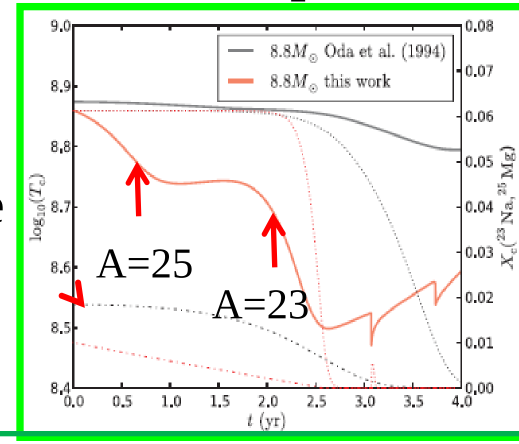
(^{25}Na, ^{25}Mg) & (^{23}Ne, ^{23}Na) pairs → Cooling of O-Ne-Mg core





$\log_{10} T$ = 8 to 9.2 in steps of 0.2

Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)
Jones et al., Astrophys. J. 772, 150 (2013)



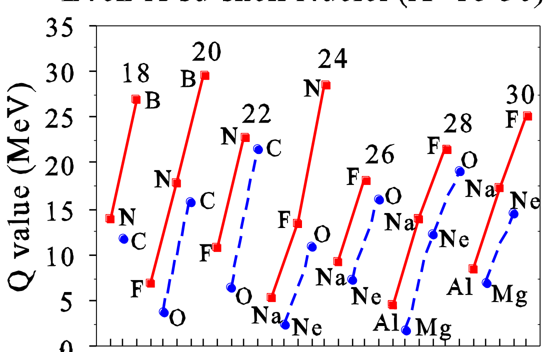
8.8$M_\odot$ star collapses triggered by subsequent e-capture on ^{24}Mg and ^{20}Ne (e-capture SNe)

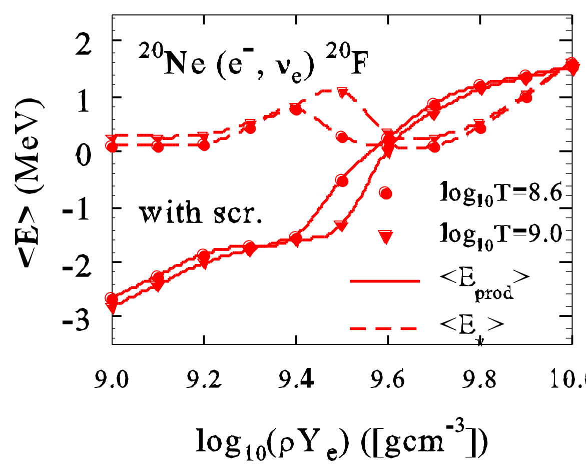
- **Heating of stars:** γ emission after double e-captures on ^{24}Mg and ^{20}Ne

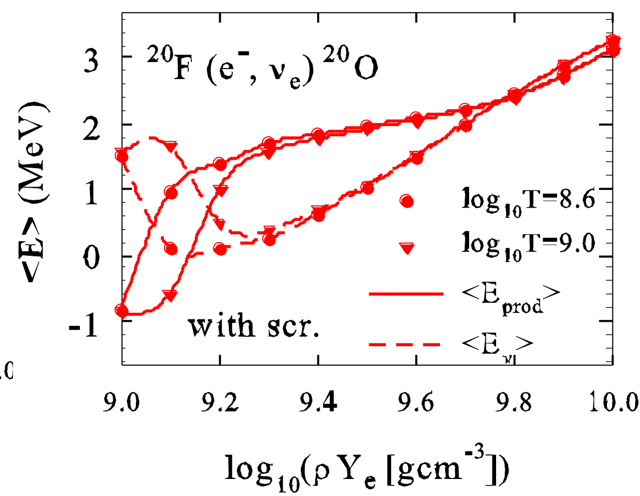
$^{24}Mg(e^-,\nu_e)^{24}Na(e^-,\nu_e)^{24}Ne$

$^{20}Ne(e^-,\nu_e)^{20}F(e^-,\nu_e)^{20}O$

Even-A sd-shell Nuclei (A=18-30)

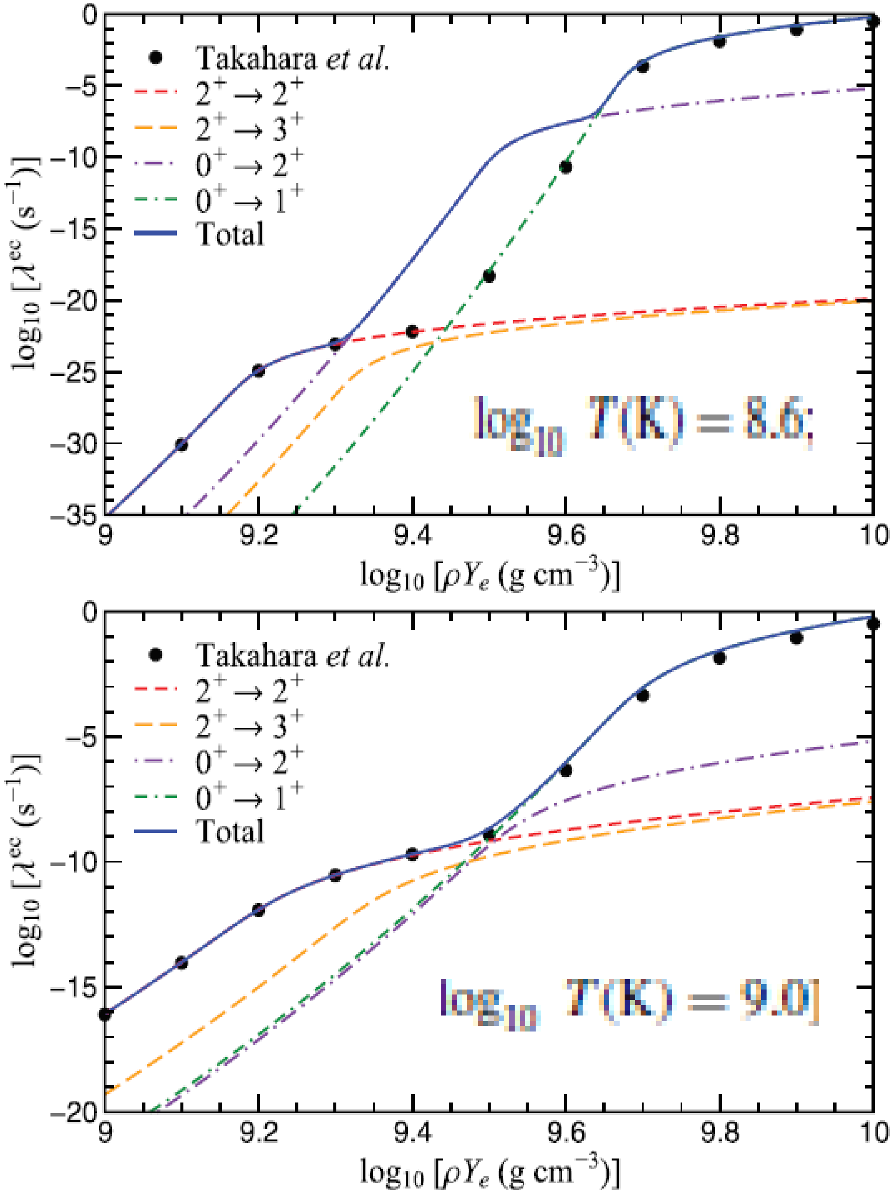




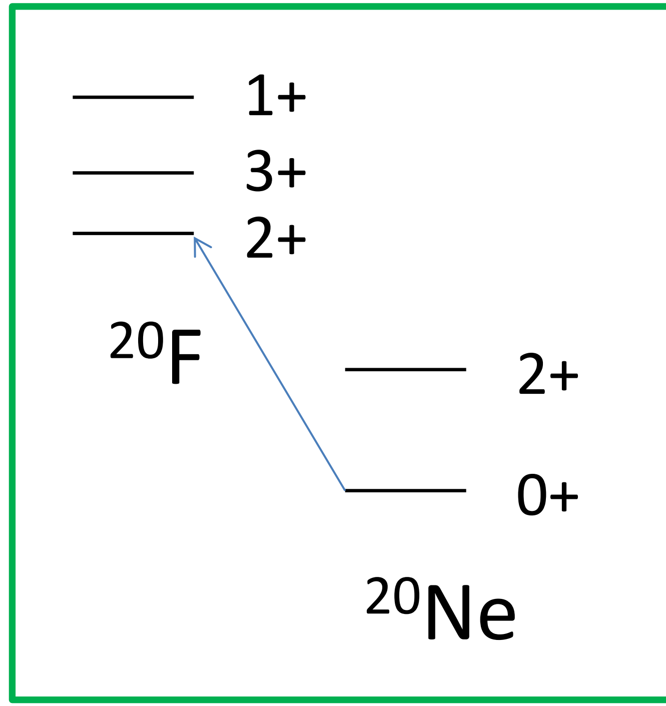


Suzuki, Toki and Nomoto, ApJ. 817 (2016)

^{20}Ne (e$^-$, ν) ^{20}F



Martinez-Pinedo et al., PR C89, 045806 (2014)



0+ -> 2+: 2nd-forbidden transition

Kirsebom et al., arXiv:1805.08149

β-decay exp. -> log ft = 10.47(11)

cf. NNDC : log ft > 10.5

$$ft = \frac{6147}{B(GT)} \qquad B(GT) = g_A \vec{\sigma} \tau_-$$

e-capture rate

$$\lambda^{ec}(T)\,[\mathrm{s}^{-1}] = \frac{g_V^2\, c}{\pi^2(\hbar c)^3} \int_{E_{\min}}^{\infty} \sigma(E_e, T)\, E_e\, p_e c\, f_e(E_e)\, dE_e, \qquad f_\alpha = \frac{1}{1+e^{\frac{\alpha-\mu}{k_B T}}},$$

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{G_F^2 \cos^2\theta_c}{2\pi} \frac{F(Z, E_e)}{(2J_i+1)} \\ &\times \Bigg(\sum_{J\geqslant 1} \mathcal{W}(E_\nu)\{(1-(\hat{\boldsymbol{\nu}}\cdot\hat{\boldsymbol{q}})(\boldsymbol{\beta}\cdot\hat{\boldsymbol{q}})) \\ &\times [|\langle J_f\|\hat{\mathcal{T}}_J^{\mathrm{mag}}\|J_i\rangle|^2 + |\langle J_f\|\hat{\mathcal{T}}_J^{\mathrm{el}}\|J_i\rangle|^2] \\ &- 2\hat{\boldsymbol{q}}\cdot(\hat{\boldsymbol{\nu}}-\boldsymbol{\beta})\mathrm{Re}\langle J_f\|\hat{\mathcal{T}}_J^{\mathrm{mag}}\|J_i\rangle\langle J_f\|\hat{\mathcal{T}}_J^{\mathrm{el}}\|J_i\rangle^*\} \\ &+ \sum_{J\geqslant 0} \mathcal{W}(E_\nu)\{(1-\hat{\boldsymbol{\nu}}\cdot\boldsymbol{\beta}) + 2(\hat{\boldsymbol{\nu}}\cdot\hat{\boldsymbol{q}})(\boldsymbol{\beta}\cdot\hat{\boldsymbol{q}}) \\ &\times \langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle|^2 + (1+\hat{\boldsymbol{\nu}}\cdot\boldsymbol{\beta})\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle|^2 \\ &- 2\hat{\boldsymbol{q}}(\hat{\boldsymbol{\nu}}+\boldsymbol{\beta})\mathrm{Re}\langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle^*\} \Bigg),\end{aligned}$$

$$\boldsymbol{q} = \boldsymbol{\nu} - \boldsymbol{k} \qquad \mathcal{W}(E_\nu) = \frac{E_\nu^2}{(1+E_\nu/M_T)},$$

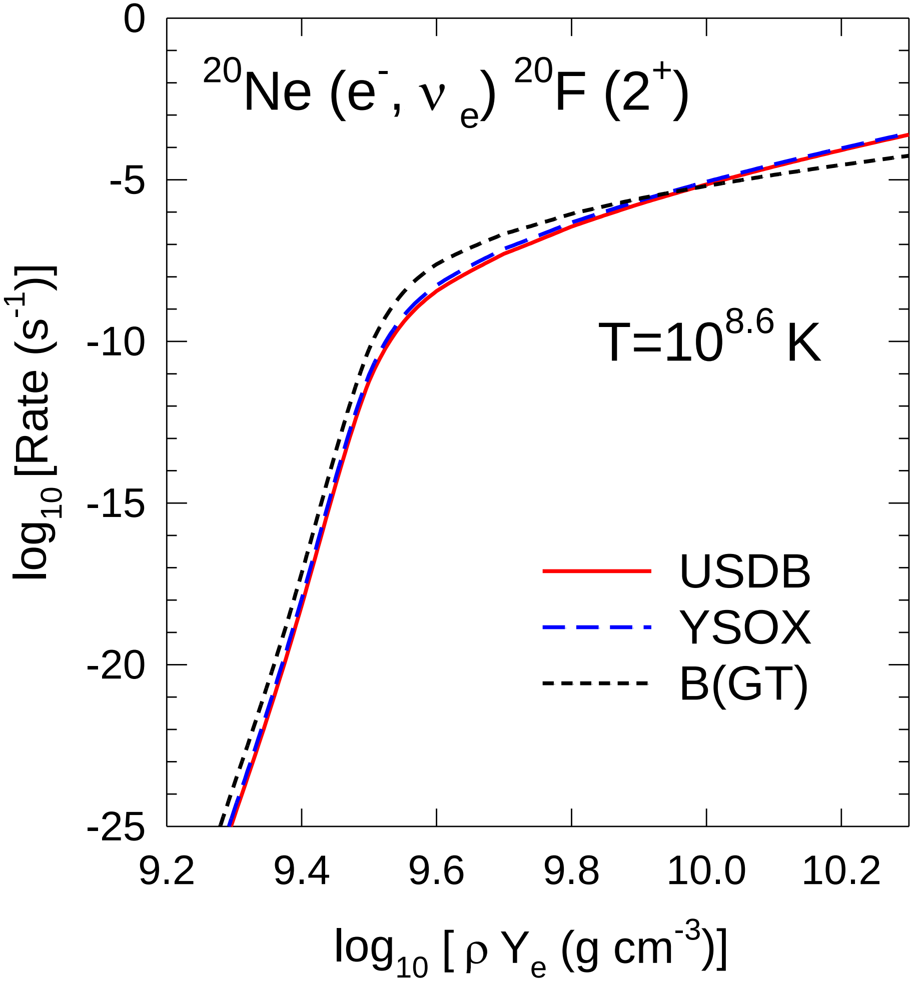
Parr et al., PRC80, 055801 (2009)

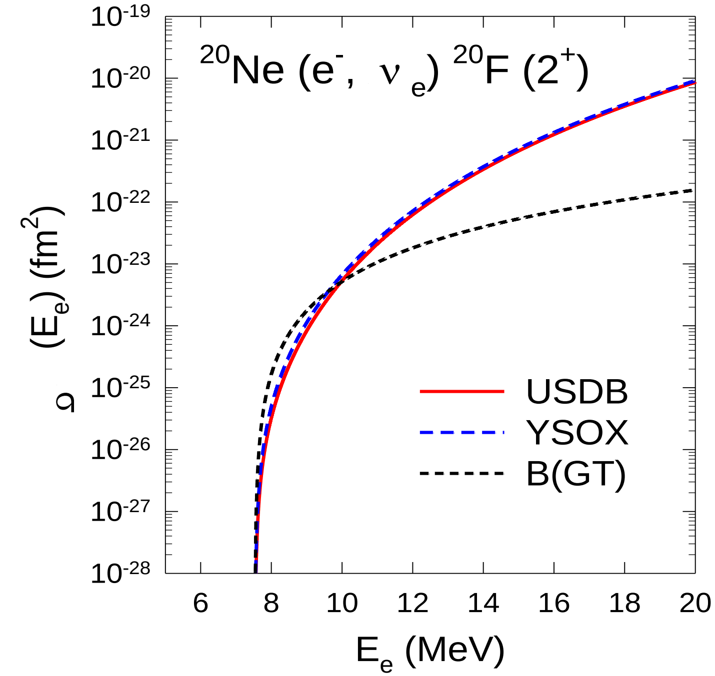
$J=2^+$

$$C2 + L2: \quad F_1^V \frac{q_\mu^2}{q^2} j_2(qr) Y^2$$

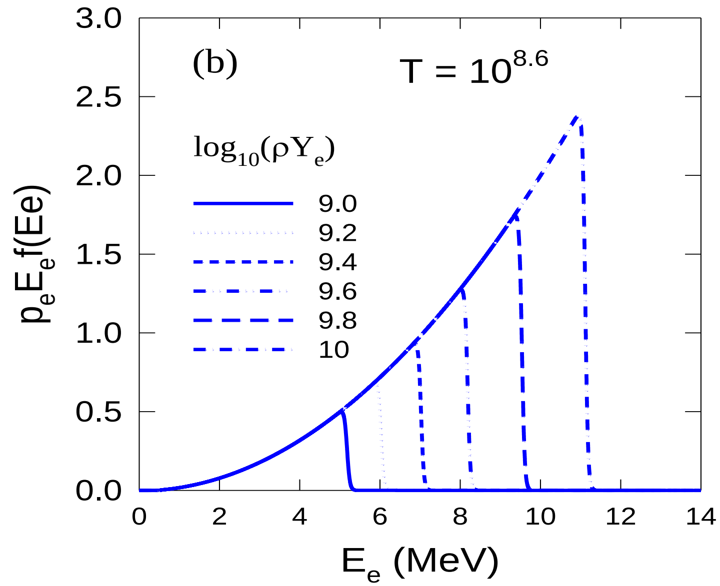
$$E2: \quad \frac{q}{M}[F_1^V(\sqrt{\frac{3}{5}} j_1(qr)[Y^1 \times \frac{\nabla}{q}]^2 - \sqrt{\frac{2}{5}} j_3(qr)[Y^3 \times \frac{\nabla}{q}]^2) + \frac{1}{2}\mu_V j_2(qr)[Y^2 \times \sigma]^2$$

$$M2_5: \quad F_A j_2(qr)[Y^2 \times \sigma]^2$$





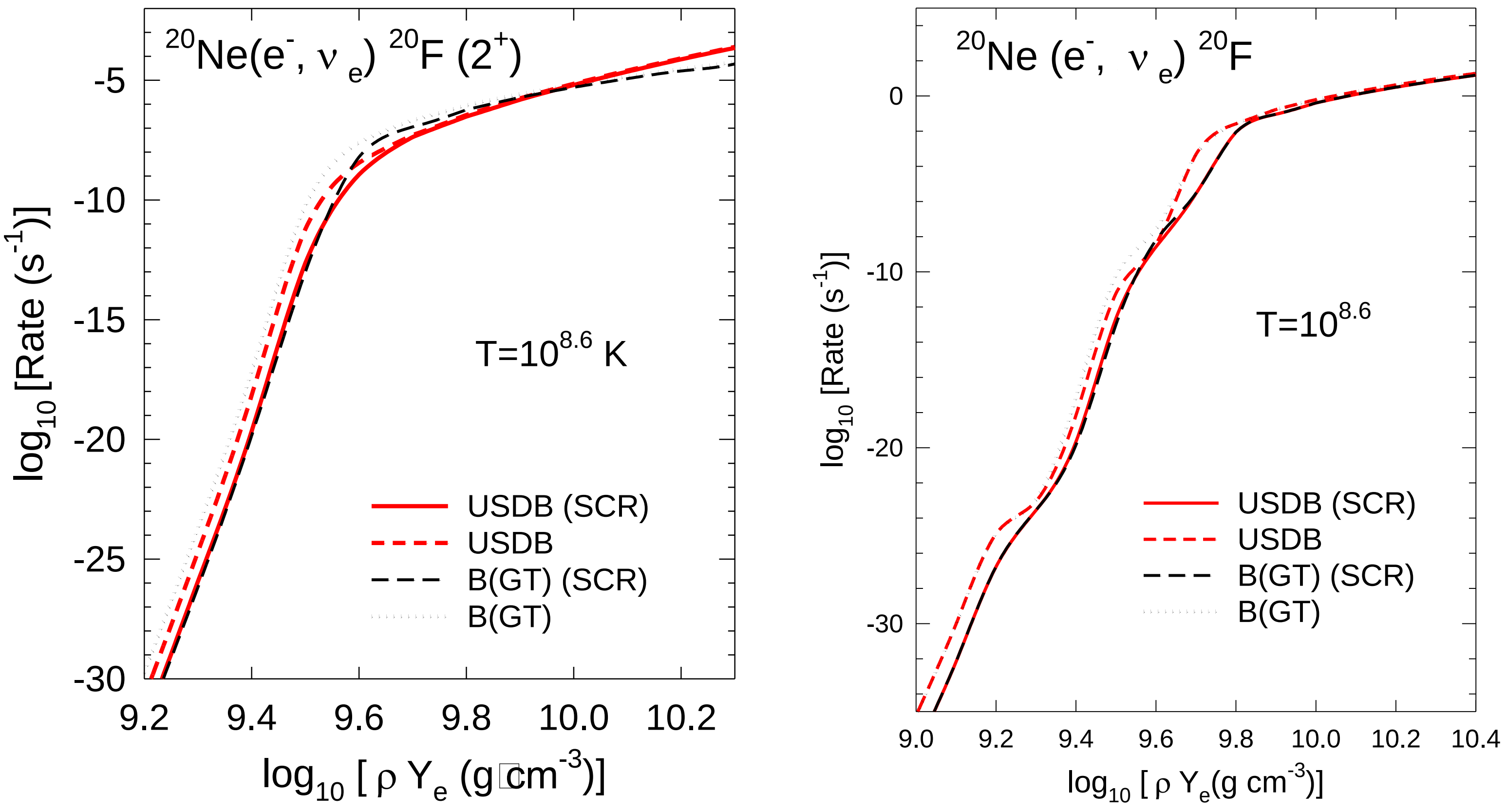
×



USDB: sd

YSOX: p-sd

Coulomb effects



Summary

1. ν-^{16}O reactions and ν detection

・Spin-dipole strengths in ^{16}O and ν-^{16}O reaction cross sections are evaluated with a shell-model Hamiltonian, SFO-tls. Partial cross sections for γ emission, single- and multi-particle emission channels are obtained by Hauser-Feshbach method with isospin conservation.

・Syntheses of light elements ^{11}B and ^{11}C in SNe are studied with full inclusion of the multi-particle emission processes.

・Charged-current reactions on ^{16}O induced by SNν are studied. Mass hierarchy dependence of the cross sections is presented; promising for distinguishing mass hierarchies in future SNν detection

2. Evolution of O-Ne-Mg core in stars

・e-capture rates for 2nd-forbidden transition in ^{20}Ne, ^{20}Ne $(0^+) \rightarrow$ ^{20}F (2^+) are evaluated by multipole expansion method with shell-model Hamiltonians; USDB (sd), YSOX (p-sd), and compared with those obtained with a prescription that treats the transition as an allowed GT one. Sizable difference in the rates are noticed between the two methods.

Collaborators

S. Chiba[a], T. Yoshida[b], K. Nakazato[c], M. Sakuda[d],
K. Takahashi[e], H. Umeda[b]
K. Nomoto[f], S.-C. Leung[f], S. Zha[g]

[a]Tokyo Institute of Technology
[b]The University of Tokyo
[c]Kyushu Univ.
[d]Okayama Univ.
[f]IPMU, The Univ. of Tokyo
[e]Univ. Bonn
[g]Univ. Hong Kong