Electroweak Interactions with ^{16}O below 100 MeV

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@2023- Lepton Interactions with Nucleons and Nuclei, 3-8 Sept, 2023)

Ref. [1] NC^{16}O(12.97/12.53MeV)→4.4MeV γ: MS,T.Suzuki,M.Reen,K.Nakazato,H. Suzuki, PTEP2023, 013D02 (2023)

[2] CC$^{18}O(\nu_e,e^-)^{18}F$: T.Suzuki, K.Nakazato, MS, Nucl.Phys.A1038, 122719(2023).

+Ongoing work on NC^{16}O(12.97/12.53MeV)→2γ cascade totaling 12.97/12.53MeV) and CC CC$^{16}O(\nu_e,e^-)^{16}N$(g.s.,2-)

Outline

1.Introduction : Previous work, Requirements for the reaction channels for SNν , and LS case

2. Neutrino water interactions below 100 MeV

3. Two 2- states (12.97 and 12.53 MeV) of ^{16}O and Isospin mixing

4. $^{16}O(e,e')$ data

5. Isospin structure of the hadronic electroweak current and measurements

6. (e,e') form factors $F_T(q)^2$ at E_x=13 MeV and the determination of the spin g factor $f_s=g_s^{eff}/g_s$ for 13 MeV, T=1

-Determination of the isospin mixing parameter β between 12.53 MeV and 12.97 MeV of ^{16}O

-Determination of the axial-vector coupling $f_A=g_A^{eff}/g_A$

7. (Results) Neutrino-water(H_2O) cross sections at E_ν=2-100 MeV

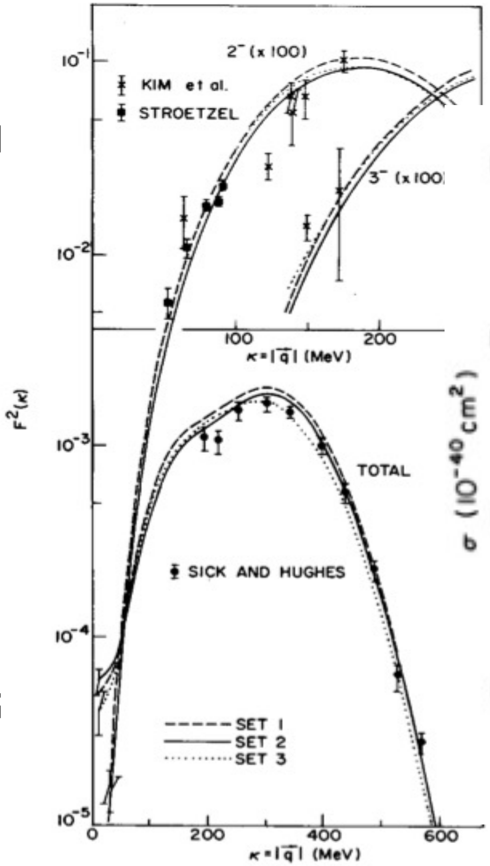
8. Summary & Outlook

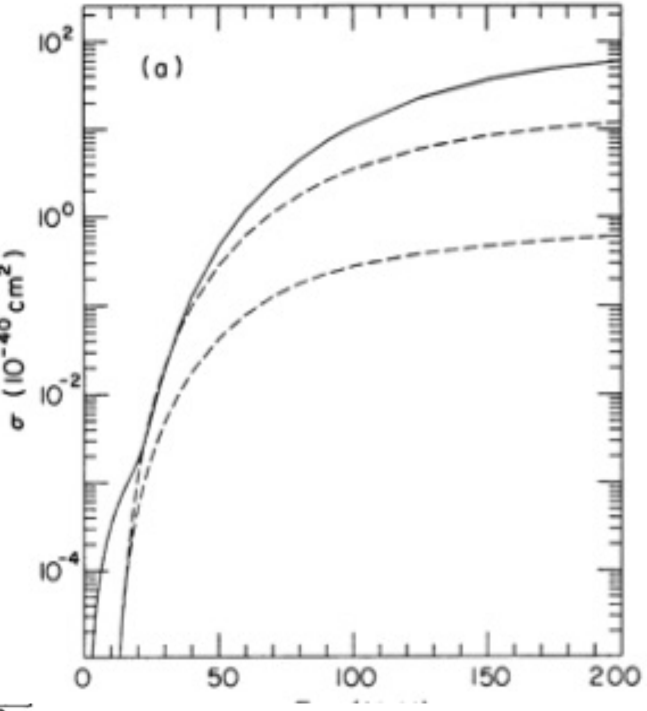
1. Introduction 1: Previous work on electroweak interaction with ^{16}O and this work

- Donnelly and Walecka (1972,1975) analysed the excited states (13-19 MeV) of ^{16}O using (e,e') data for the first time, analysed the muon capture and the β decay rate and obtained the (CC) ν-^{16}O cross sections with accuracy of 15-20%. In those days, the isospin mixing of 12.97 MeV/12.53 MeV states was not known.
- Haxton (1987, PRD36) calculated the electron spectra of CC ν-^{16}O reactions, using Donnelly's quenching factors for negative parity states. He also commented on $\mathrm{CC}\,{}^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)\,{}^{16}_{7}\mathrm{N}(gs, 2^-)$ & γ ray (${}^{16}_{7}\mathrm{N}(gs)$ β decay to ^{16}O(gs)).
- We re-analysed the (e,e') data, muon capture rate (some new) and the β decay rate, considering the isospin mixing β=0.25±05 of the two 2- states, and estimated $f_s=g_s^{eff}/g_s$=0.65+-0.05 and $f_A=g_A^{eff}/g_A$=0.68+-0.05.
- Then, we calculate NC ^{16}O(ν,ν')^{16}O(E_x=12.97&12.53 MeV) and its γ production, and $\mathrm{CC}\,{}^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)\,{}^{16}_{7}\mathrm{N}(gs, 2^-)$ & e^- from ${}^{16}_{7}N(gs)$ β decay. Note:If you analyse (e,e') data without the mixing effect (β=0), you will obtain the larger (logically wrong) ν cross section for 12.97MeV of ^{16}O and ^{16}N(gs) by about 6-10%(β^2).

(Left fig) Form Factors: Donnelly and Walecka, Phys.Lett. B41, 275 (1972).

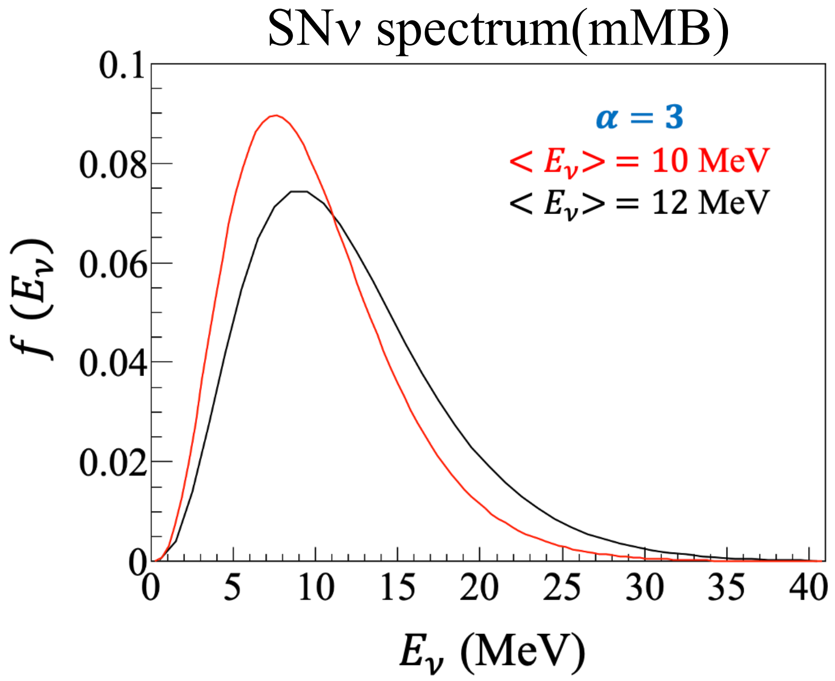
(Right fig) CCν^{16}O and^{18}O: Haxton,PRD36,2283(1987).





1. Introduction 2

- The study of neutrino water (or CH) interactions below 100 MeV is useful for the detection of the supernova neutrino bursts. The neutrino spectrum peaks at ~10 MeV and extends to 50-100 MeV.
- In 1987A, only about 20 events (possibly $\bar{\nu}_e$) were observed by Kamiokande, IMB and Baksan. The neutrino spectra for other neutrino favors are not known. It is important to estimate and measure as many NC and CC reactions with good accuracy for the better understanding of core-collapse SN explosion.



1. Requirements for the reaction channels for SNν (My view) and LS detector case

A) A signal of the reaction must be either (1) a monoenergetic and big one (E_{vis}>10 MeV), or (2) it has a tag (coincidence), so that the number of events can be estimated reliably. [SN bursts should give the T=0 (tag), but it may not be good enough.]

B) The cross section of the reaction must be measured/evaluated accurately, say <10-20%, so that we can consider neutrino oscillations.

□ KamLAND and JUNO experiments (LS detector) uses the next standard reaction channels ①′-⑥′. They are either simple (①′-③′) or measured by LSND/KARMEN(④′-⑤′) at 10-15%. Simple reactions ①′-③′ can be calculated at ~<5%. Reactions ④′-⑤′ satisfy A) and they are measured.

①' IBD($\bar{\nu}_e + p \rightarrow e^+ + n$) & 2.2 MeV γ ($n + p \rightarrow d + \gamma$)

②' νe^- scattering

③' NC $\nu_x + p \rightarrow \nu_x + p$

④' NC ${}^{12}_{6}$C(ν,ν′)^{12}C(15.1MeV, 1^+), ^{12}C(15.1MeV, 1^+) → 15.1 MeV γ ray.

⑤' CC ${}^{12}_{6}\mathrm{C}(\nu_e, e^-){}^{12}_{7}\mathrm{N}(gs, 1^+)$ & e^+ from β decay ${}^{12}_{7}N(gs, 1^+) \rightarrow {}^{12}_{6}\mathrm{C}(gs) + e^+ + \nu_e$ ($T_{e,max}$=16.84 MeV, $T_{1/2}$=11.0 ms)

⑤' CC ${}^{12}_{6}\mathrm{C}(\bar{\nu}_e, e^+){}^{12}_{5}\mathrm{B}(gs, 1^+)$ & e^- from β decay ${}^{12}_{7}\mathrm{B}(gs, 1^+) \rightarrow {}^{12}_{6}\mathrm{C}(gs) + e^- + \bar{\nu}_e$(($T_{e,max}$=13.37 MeV, $T_{1/2}$=20.2 ms)

⑥' ν_eCC, NC 13C(1.1%Abundance)

□ Reactions in water are not measured experimentally except IBD. (Beginning at nuSNS?).

2. Neutrino water interactions below 100 MeV

- SK considers the following reaction channels for SN neutrino detection. Cf. SK collaboration, Astropart.Phys.81,39(2016).

①IBD($\bar{\nu}_e p \rightarrow e^+ n$)

② $\nu_e e^-$scattering (CC+NC)

③ CC ${}^{16}_{8}\mathrm{O}(\nu_e, e^-){}^{16}_{9}\mathrm{F}$

③ CC ${}^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+){}^{16}_{7}\mathrm{N}$

Ref. ③ Haxton,PRD36,2283(1987);Kolbe etal,PRD66,013007(2002);Nakazato,Suzuki,MS,PTEP2018,123E02.

④NC ${}^{16}\mathrm{O}(\nu,\nu'){}^{16}\mathrm{O}(E_x$>16 MeV) & γ ray (E_γ >5 MeV)

Ref. ④Langanke et al.,PRL76(1996); Beacom-Vogel,PRD58,053010(1998); Kolbe et al,PRD66,013007(2002).

- I will talk on our recent publications:

⑤NC ${}^{16}\mathrm{O}(\nu,\nu'){}^{16}\mathrm{O}$(12.97/12.53MeV & γ ray (4.4 MeV) Ref. MS, T.Suzuki, M.Reen, K.Nakazato, H.Suzuki, PTEP2023, 013D02.

⑧ CC ${}^{18}_{8}O(\nu_e, e^-){}^{18}_{9}F$ (^{18}O(0.205% Abundance) Ref.T.Suzuki, K.Nakazato, MS, NPA 1038, 122719 (2023).

and our preliminary work:

⑥ NC ${}^{16}\mathrm{O}(\nu,\nu'){}^{16}\mathrm{O}$(12.97 MeV) & 2-3$\gamma$ rays (Sum 12.97 MeV)

⑥ NC ${}^{16}\mathrm{O}(\nu,\nu'){}^{16}\mathrm{O}$(12.53 MeV) &2-3$\gamma$ rays (Sum 12.53 MeV)

⑦ CC${}^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+){}^{16}_{7}\mathrm{N}(gs, 2^-)$ & e^- from β decay ${}^{16}_{7}N(gs, 2^-) \rightarrow {}^{16}_{8}O(E_x) + e^- + \bar{\nu}_e$ ($T_{e,max}$=10.42 MeV-E_x, $T_{1/2}$=7.13 s)

- Isospin mixing effect must be considered to calculate the reactions ⑤ ⑥ ⑦ correctly.

Reaction channels for the SNν detection (LS and Water)

LS(Liquid Scintillator) Detector

①' IBD($\bar{\nu}_e + p \rightarrow e^+ + n$)

& 2.2 MeV γ ($n + p \rightarrow d + \gamma$)

②' νe^- scattering

③' NC $\nu_x + p \rightarrow \nu_x + p$

④' NC $^{12}_{6}$C(ν,ν')^{12}C(15.1MeV, 1^+)

& γ ray (15.1 MeV)

⑤' CC $^{12}_{6}\mathrm{C}(\nu_e, e^-)^{12}_{7}\mathrm{N}(gs, 1^+)$

& e^+ ($^{12}_{7}\mathrm{N}(gs, 1^+)$ β decay)

⑤' CC $^{12}_{6}\mathrm{C}(\bar{\nu}_e, e^+)^{12}_{5}\mathrm{B}(gs, 1^+)$

& e^- ($^{12}_{7}\mathrm{B}(gs, 1^+)$ β decay)

⑥' ν_e CC, NC 13C(1.1%Abundance)

Water Detector

---- Known reactions (Previous work) ----

① IBD($\bar{\nu}_e p \rightarrow e^+ n$)

② νe^- scattering (CC+NC)

③ CC $^{16}_{8}\mathrm{O}(\nu_e, e^-)^{16}_{9}\mathrm{F}$

③ CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}$

④ NC ^{16}O(ν,ν')^{16}O(E_x>16 MeV) & γ ray (E_γ >5 MeV)

---- Our recent work ----

⑤ NC ^{16}O(ν,ν')^{16}O(12.97/12.53MeV) & γ ray (4.4 MeV)

⑧ CC $^{18}_{8}O(\nu_e, e^-)^{18}_{9}F$, ^{18}O(0.205% Abundance)

---- Our ongoing work ----

⑥ NC ^{16}O(ν,ν')^{16}O(12.97 MeV) & γ rays (Sum 12.97 MeV)

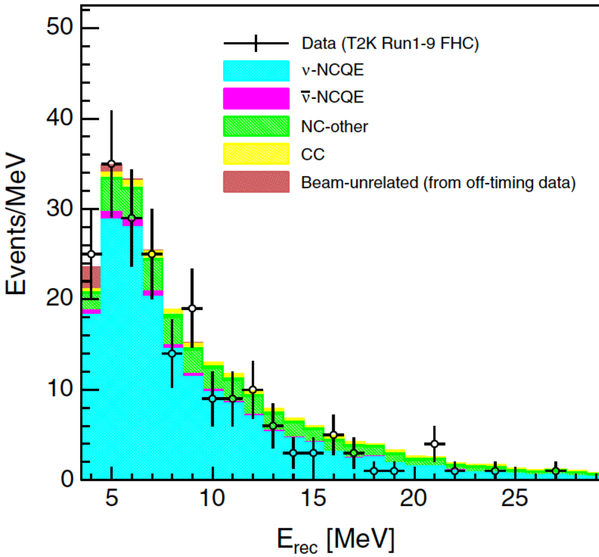
⑥ NC ^{16}O(ν,ν')^{16}O(12.53 MeV) & γ rays (Sum 12.53 MeV)

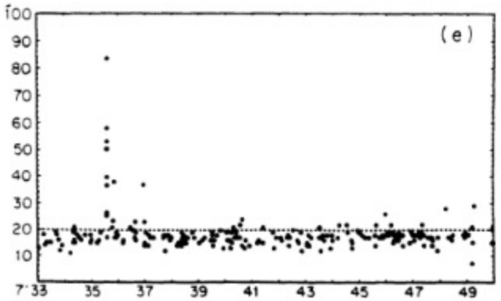
⑦ CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}(g.s., 2^-)$ & γ ray+e^- ($^{16}_{7}\mathrm{N}(gs)$ β decay)

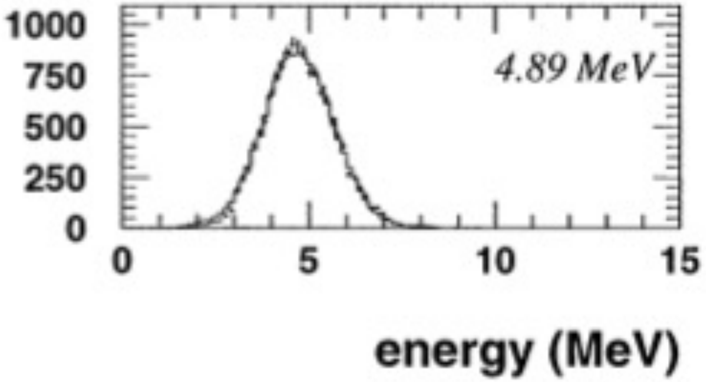
Fact: SK (water Cherenkov) can detect low-energy electrons & γ rays

- SK has kept improving the electronics system and water purity and SK-IV (2008-) has reported the solar neutrinos for E_{kin}>3.5 keV (K.Abe(SK-IV), PRD94(2016)).
- SK can detect a signal of e & γ ray above 4 MeV, if there are no background or the signal has a tag (coincidence).
- In fact, SK observes NCQE 6-MeV γ rays in T2K experiment (GPS coincidence) [right Fig]and 6-MeV γ rays in atmospheric neutrino measurements with neutron tagging (with 2.2-MeV γ ray).
- Linac 4.89 MeV electron (below) and 6-7 MeV γ ray from ^{16}N(gs) β decay (right), measured during the calibration.
- Neutrinos from Supernova (SNν) will give Time=0 tag (Arrival time) in the burst to the detector.

T2K 6-MeV γ rays in $^{16}O(\nu,\nu)$, PRD100, 112009(2019).







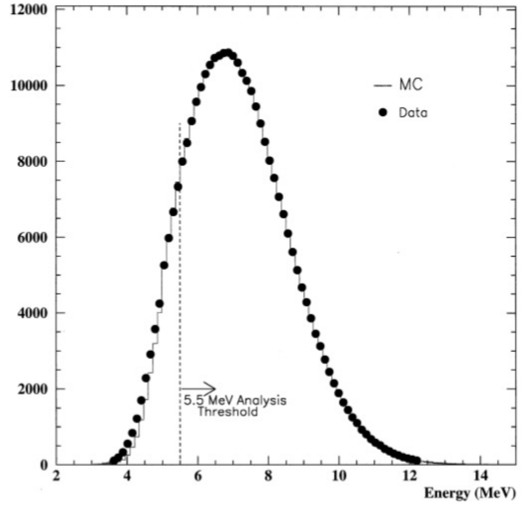
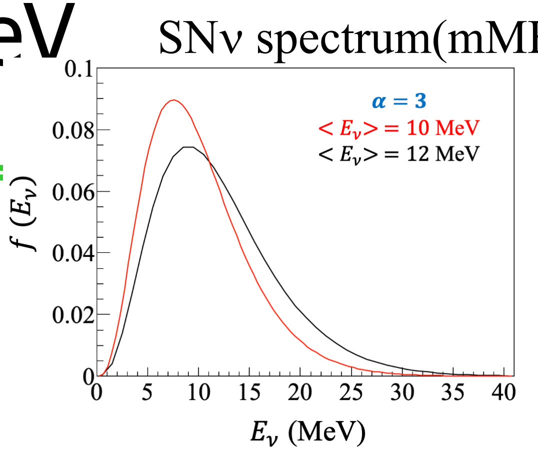
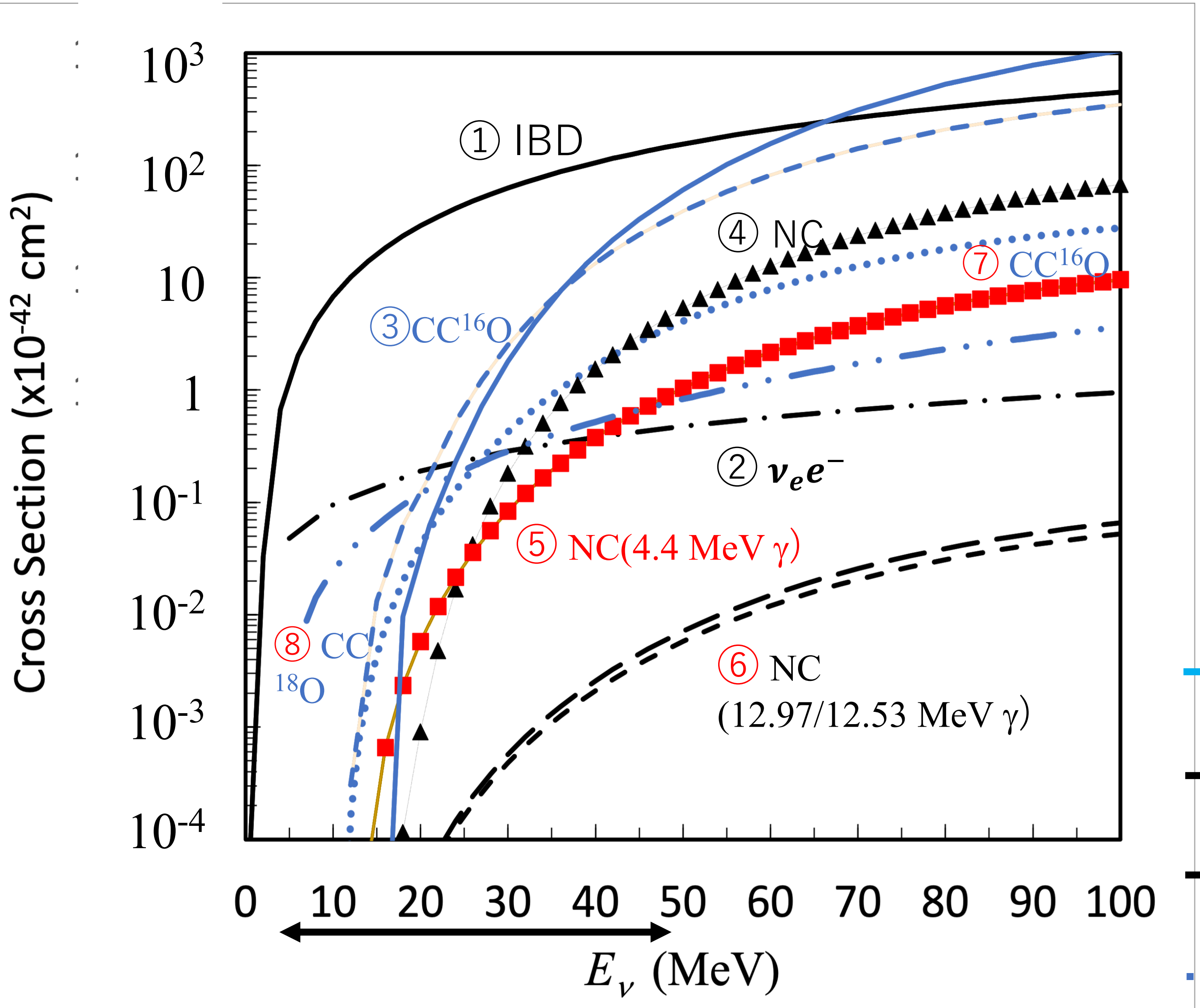


Fig. 5. The position-weighted average energy spectrum for data (points) and MC (line).

2. Neutrino-water(H_2O) interactions at E_ν=2-100 MeV





----Previous work---

① IBD($\bar{\nu}_e p \rightarrow e^+ n$)

② $\nu_e e^-$ scattering (CC+NC)

③ CC $^{16}_{8}O(\nu_e, e^-)^{16}_{9}F$

③ CC $^{16}_{8}O(\bar{\nu}_e, e^+)^{16}_{7}N$

④ NC $^{16}O(\nu,\nu')^{16}O(E_x>16$ MeV) & γ ray (E_γ >5 MeV)

---- Our recent publications ---

⑤ NC $^{16}O(\nu,\nu')^{16}O$(12.97/12.53MeV) & γ ray (4.4 MeV)

⑧ CC $^{18}_{8}O(\nu_e, e^-)^{18}_{9}F$

---- Our ongoing work ----

⑥ NC $^{16}O(\nu,\nu')^{16}O$(12.97 MeV) & γ ray (Sum 12.97 MeV)

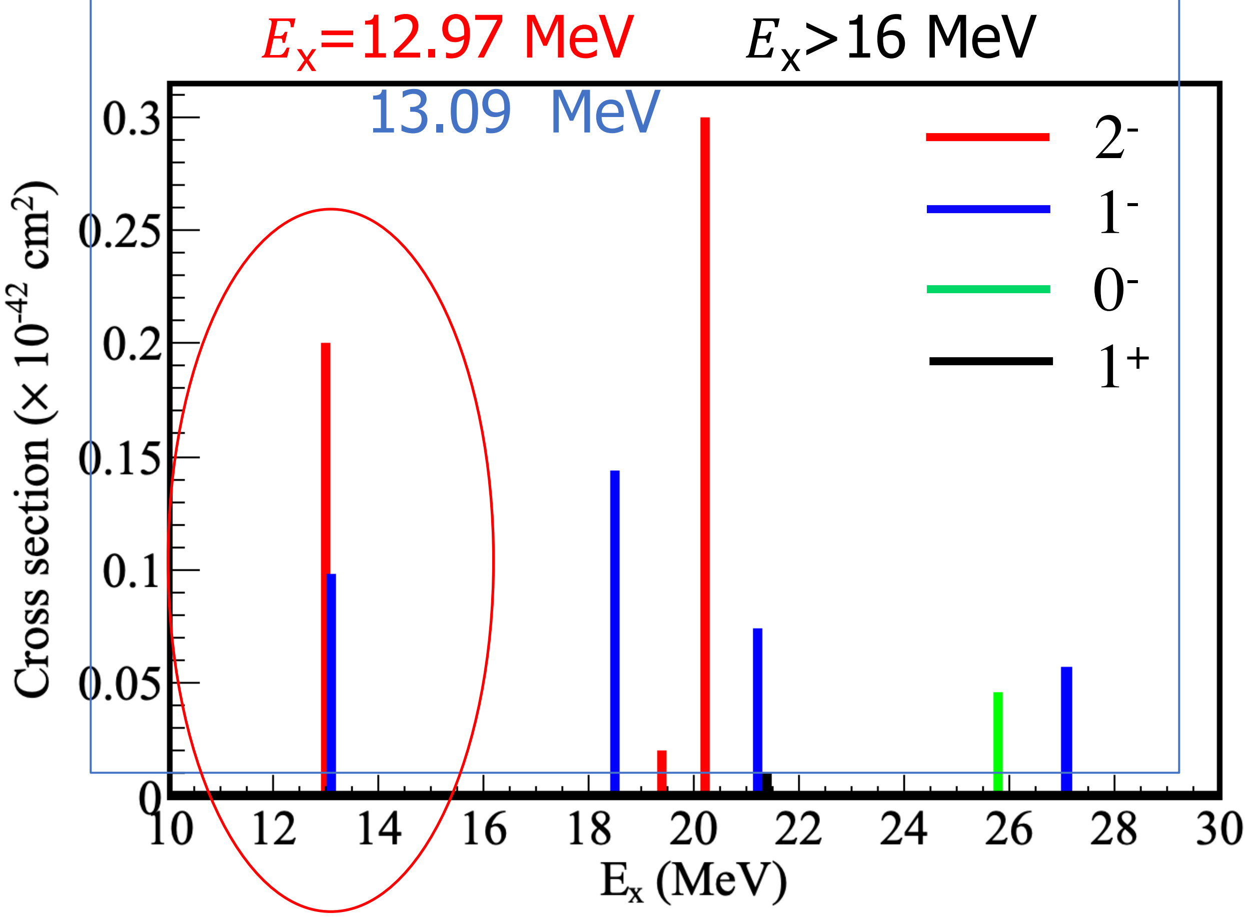
⑥ NC $^{16}O(\nu,\nu')^{16}O$(12.53 MeV) & γ ray (Sum 12.53 MeV)

⑦ CC$^{16}_{8}O(\bar{\nu}_e, e^+)^{16}_{7}N(g.s., 2^-)$

Features of ⑤⑥NC(12.97MeV) and ⑦CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}(g.s., 2^-)$ cross section

- 13 MeV complex: 12.79 MeV, 0-, 12.97 MeV, 2-, 13.09 MeV, 1-.
- Cross section 2- > 1- >0-. The transition from the p-shell to the sd-shell are important, Since the transition strength is proportional to (2J + 1). 1^+ contribution is small.
- CC⑦cross section increase rapidly above 11.44MeV and NC cross section⑤ increases rapidly from 12.97 MeV until 100 MeV. The energy threshold of the NC cross section of Ex > 16 MeV producing a 5.3-MeV, 6.3-MeV and 7.3 MeV γ ray is about 18 MeV.

- $d\sigma/dE_x$ at E_ν=30 MeV.

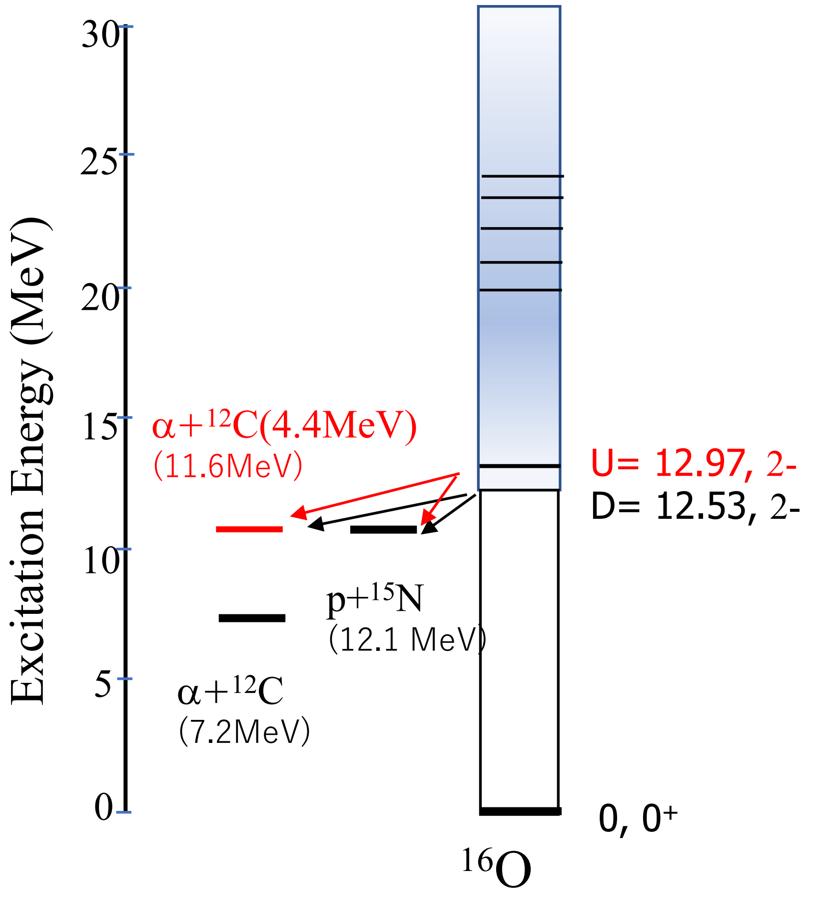


3. Two 2- states (12.97 and 12.53 MeV) of ^{16}O and Isospin mixing

- Isospin mixing is known to be caused for example by Coulomb interaction between the two states through protons, which can violate the isospin symmetry. The origin is still an open question.
- The 12.97-MeV state not only decays to p+^{15}N, but also decays to the T=0 state (α+^{12}C(4.4 MeV)). So, the isospin mixing should exist.
- The physical two 2- states (Up |U> and Down [D>) are written in terms of the pure isospin states (|U,T=0,1> and |D,T=0,1>) with β being the isospin mixing parameter:

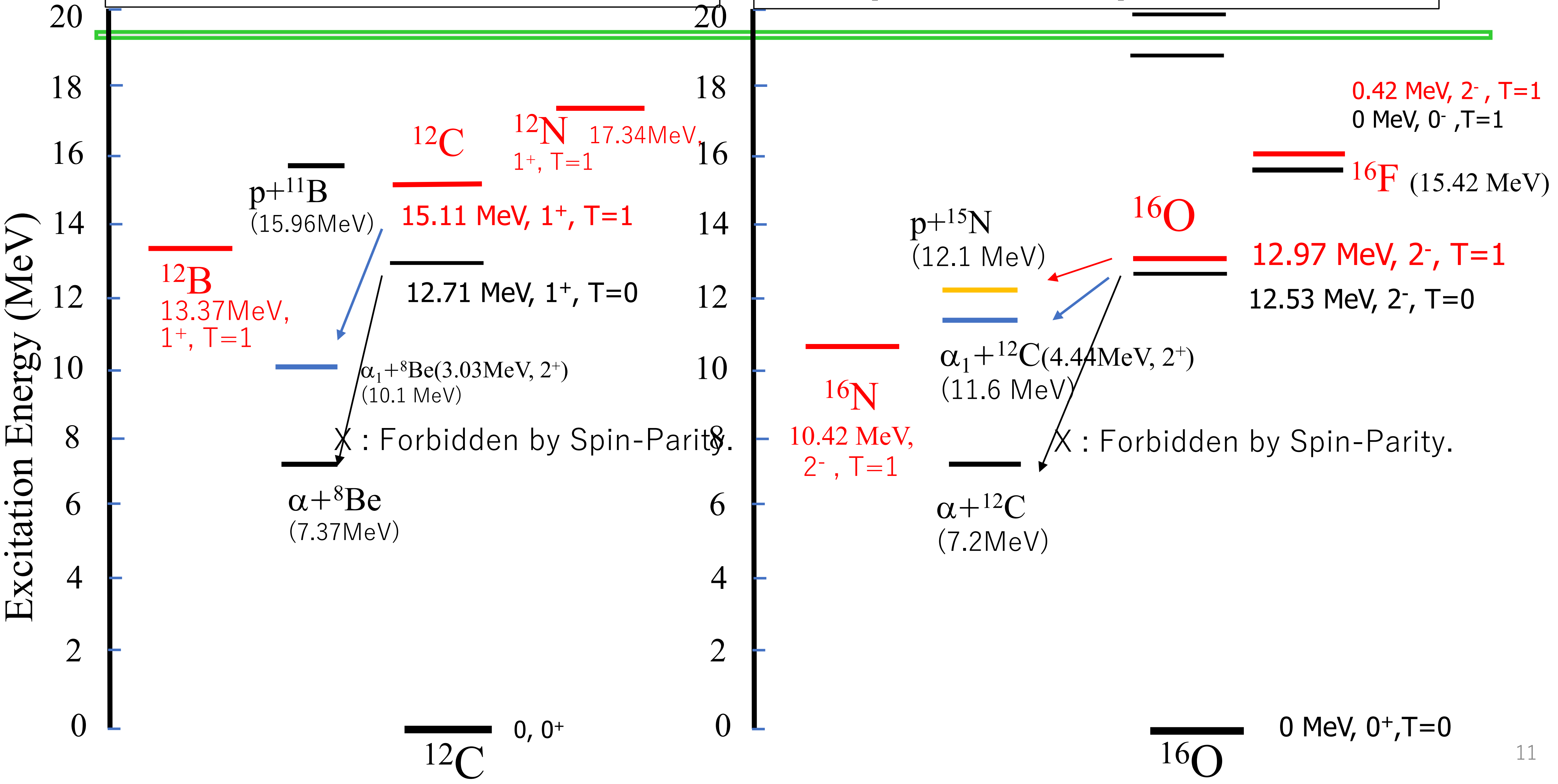
$$|U\rangle = \sqrt{1-\beta^2}\,|U,T=1\rangle - \beta\,|U,T=0\rangle,$$
$$|D\rangle = \sqrt{1-\beta^2}\,|D,T=0\rangle + \beta\,|D,T=1\rangle$$

- Cf. A well-known example of the isospin mixing is the two states, 12.71 MeV (1^+, T = 0) and 15.11 MeV (1^+, T = 1), of ^{12}C. β=0.0491(34) by Neumann-Cosel, NPA669,3(2000).

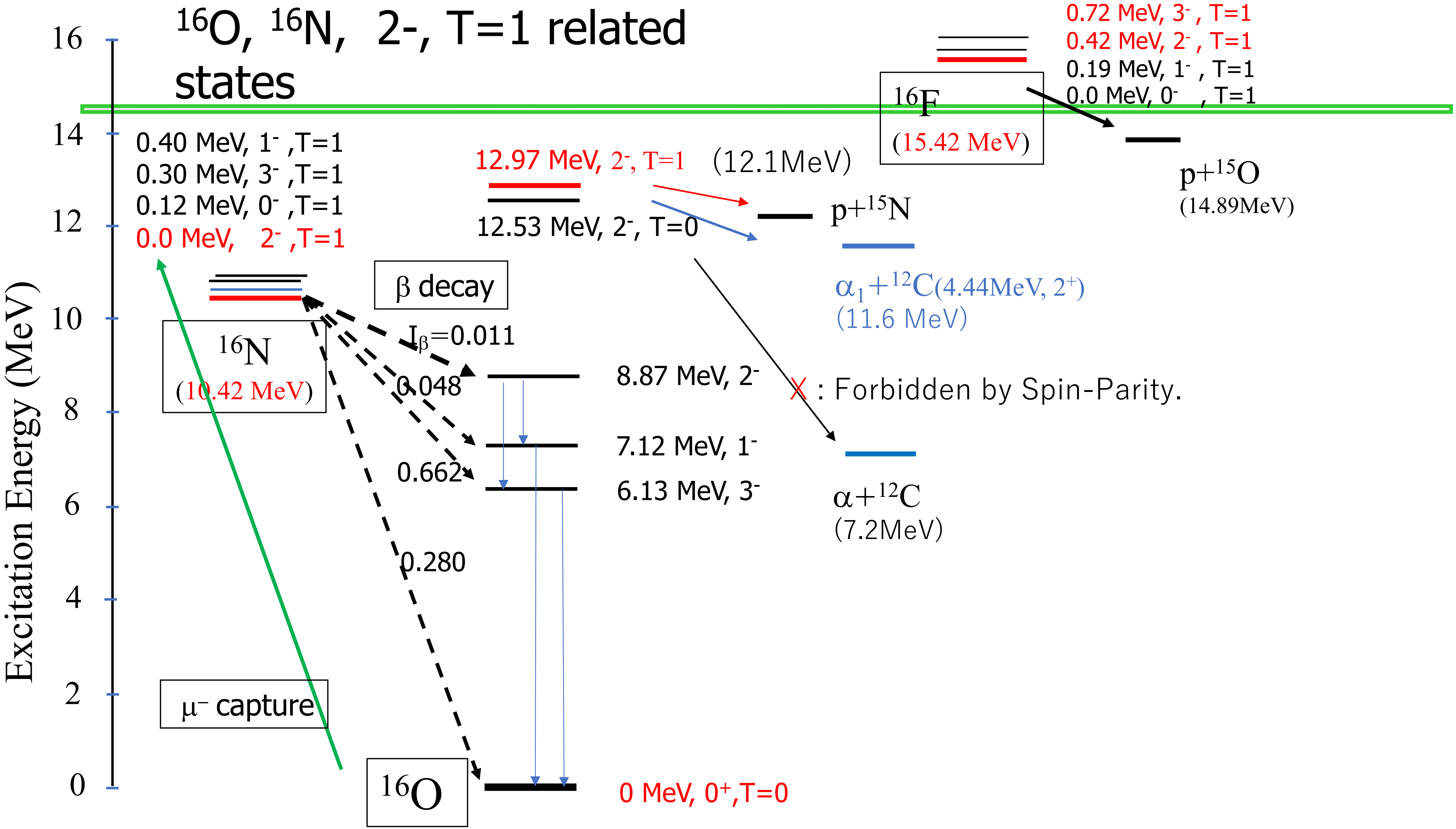


(^{12}B ^{12}C ^{12}N) T=1 Levels

(^{16}N ^{16}O ^{16}F) T=1 Levels



^{16}O, ^{16}N, 2-, T=1 related states



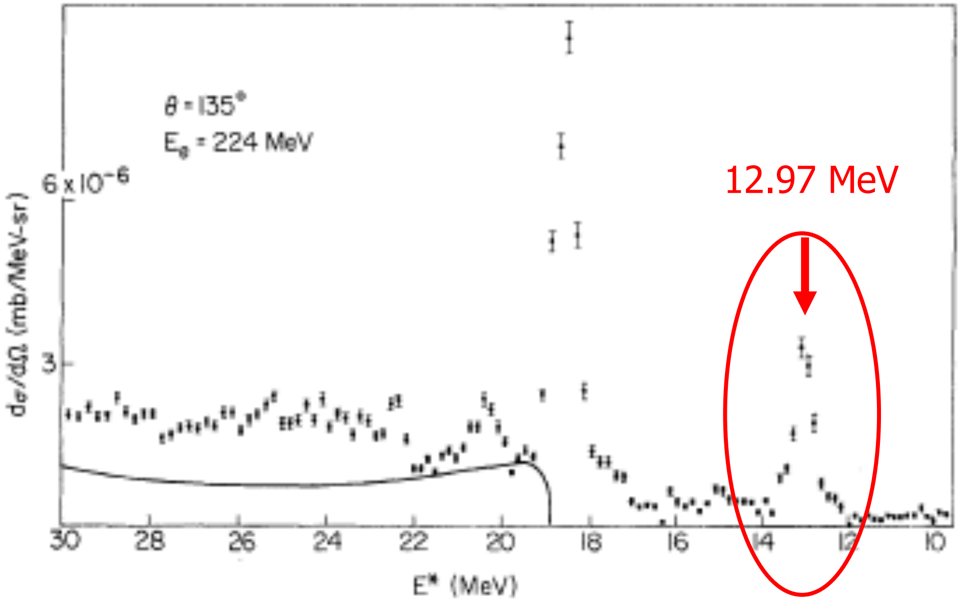
4. $^{16}O(e,e')^{16}O^*(E_x=13\ MeV)$ data

1) M.Stroetzel, Z.f.Physik 214,357(1968). E_e=30-60MeV, θ=105-165deg

2) J.C.Kim et.al., Can.J. Phys.48, 83(1970). E_e=39-104MeV, θ=90-155deg

3) I. Sick et.al., Phys.Rev.Lett.23,1117(1969). E_e=100-400MeV, θ=135-145deg

3) I. Sick (1969)



360 M. STROETZEL:

1) M.Stroetzel(1968)

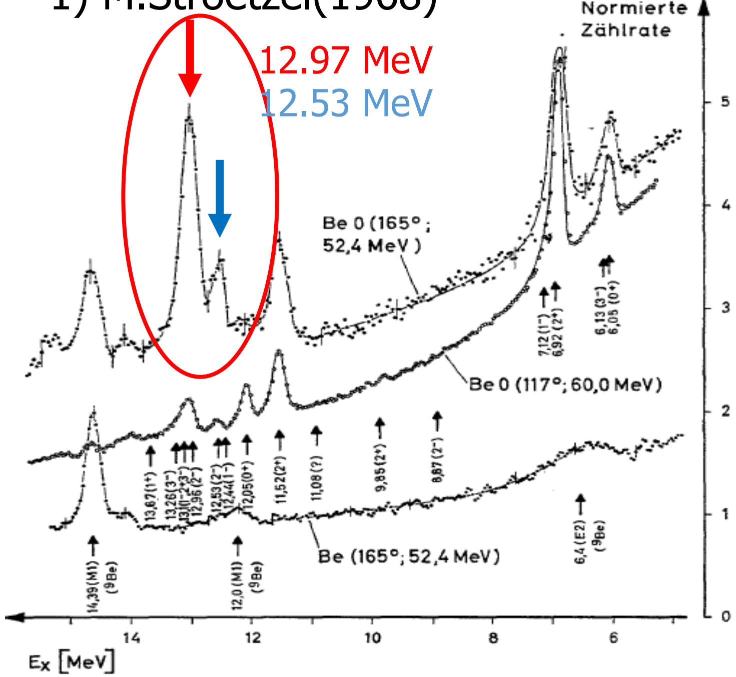
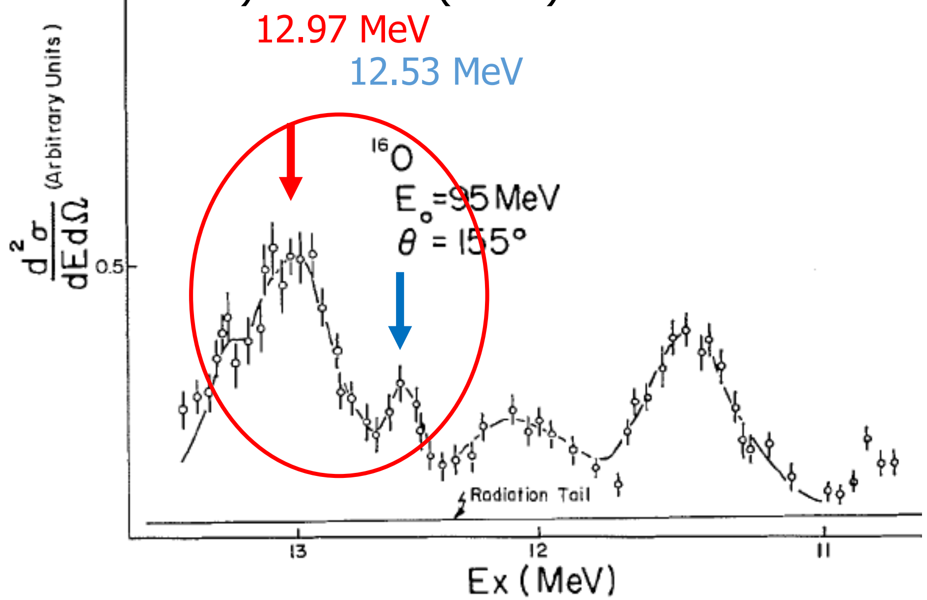


Fig. 1. Unelastische Elektronenstreuung an BeO und Be bei konstanter Impulsüber-

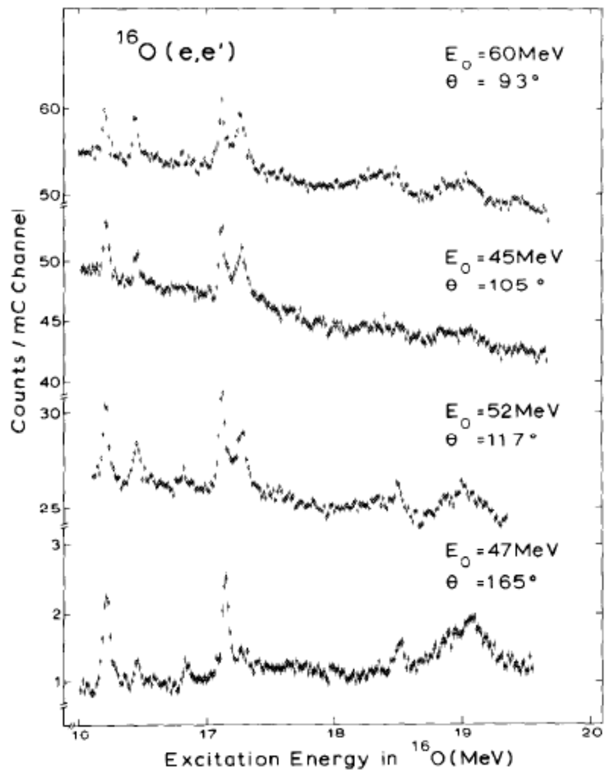
CANADIAN JOURNAL OF PHYSICS. VOL. 48, 1970

2) J.C. Kim (1970)



Data $^{16}O(e,e')^{16}O(Ex>16\ MeV)$

G. Küchler et al. / High-resolution (e, e') (I)



…ctra obtained at several angles and bombarding energies. The distance between points … caption to fig. 5). The spectra at $\theta = 165°$, 117° and 93° correspond to the same moment… $\approx 0.38\ fm^{-1}$) and display the transverse or longitudinal nature of the lines. For example … peak (longitudinal transition) almost disappears at $\theta = 165°$ while the M1 transition … 17.14 MeV is enhanced at backward angles.

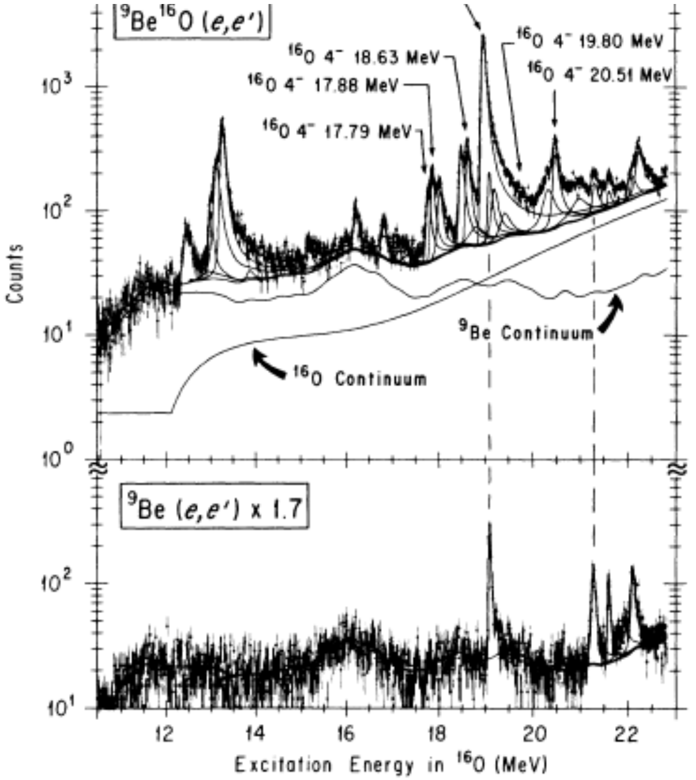


FIG. 1. Fitted $^{9}Be^{16}O(e,e')$ (top) and matching $^{9}Be(e,e')$ (bottom) spectra. The spectra were obtained for $E_1 = 230$ MeV and $\theta = 160°$. The six states in ^{16}O which are the subject of this paper are indicated. See text for explanation of curves. The ^{9}Be data and curves in the bottom figure have been multiplied by 1.7

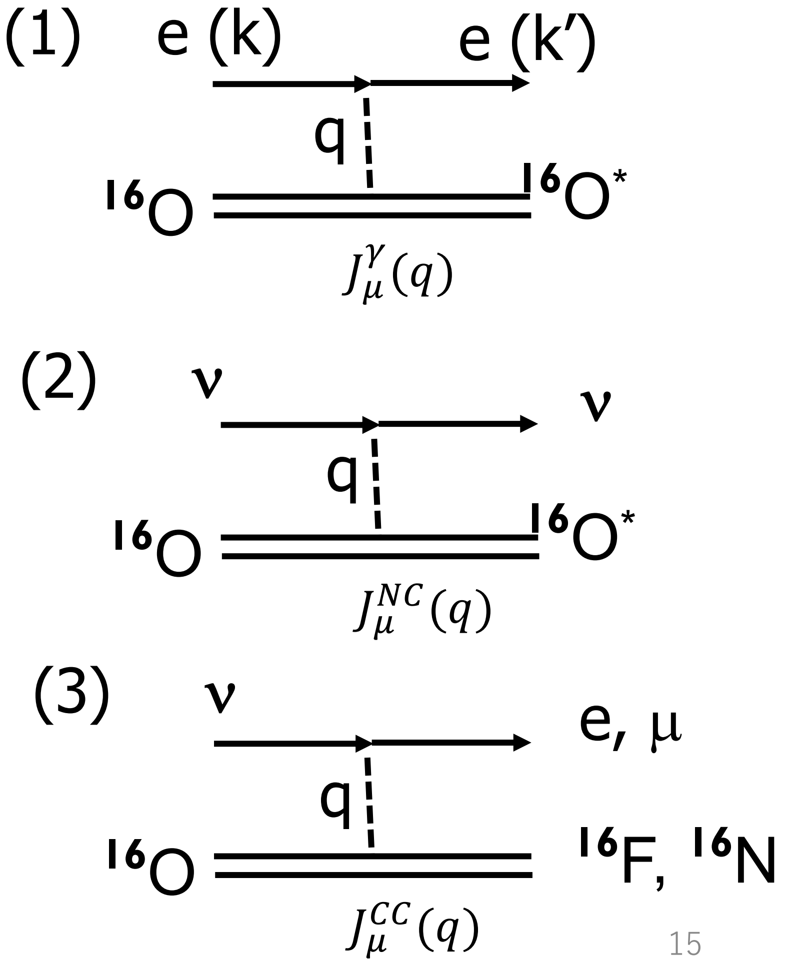
- Kuchler et al., NPA406(1983):
- E_e=30-60MeV, q=105-165deg.
- Hyde-Wright et al.,PRC35(1987): E_e=230MeV, q =90-160deg.
- Hard to resolve resonance states for E_x>18 MeV.

5. Isospin structure of the hadronic electroweak current and measurements

- **The most important relation is the CVC hypothesis: $J_\mu^{\gamma(V)} = V_\mu^3$.**
- V and S denote the isovector (T = 1) and isoscalar (T = 0) component of the hadronic current. Cross sections can be calculated from form factors.

$k^\mu = (E, \vec{k})$ and $k'^\mu = (E', \vec{k}')$

Interaction type	Reactions
(1) (γ) Electromagnetic current $J_\mu^\gamma = J_\mu^{\gamma(V)} + J_\mu^{\gamma(S)}$ Isospin T=1 T=0 (T_3=0)	A(e,e'), A(γ, all), A*→A+γ
(2) (NC) Neutral current $J_\mu^{NC} = V_\mu^3 + A_\mu^3 + A_\mu^S - 2\sin^2\theta_W J_\mu^\gamma$ Isospin T=1 T=1 T=0 T=1,0 (T_3=0)	A(ν,ν')
(3) (CC) Charged current $J_\mu^{CC} = V_\mu^{\pm 1} + A_\mu^{\pm 1}$ Isospin T=1 T=1 (T_3=±1)	A(ν,e), μ capture, β decay



Formula for (1) ^{16}O(e,e'), (2) NC ^{16}O(ν,ν'), (3)CC ^{16}O(ν,e) at E_ν=2-200 MeV

(1) ^{16}O(e,e') $\quad k^\mu=(E,\vec{k})$ and $k'^\mu=(E',\vec{k}')$

$$
\begin{aligned}
(\frac{d\sigma}{d\Omega})_{e,e'} &= 4\pi\sigma_{\rm Mott}F^2(q)/R_{\rm recoil},\\
\sigma_{\rm Mott} &= \left[\frac{\alpha\cos\frac{\theta}{2}}{2E\sin^2\frac{\theta}{2}}\right]^2,\\
F^2(q) &= (\frac{|q_\mu^2|}{q^2})^2F_L^2(q)+(\frac{|q_\mu^2|}{2q^2}+\tan^2\frac{\theta}{2})F_T^2(q),
\end{aligned}
$$

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

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

All cross sections can be calculated electromagnetic from form factors.

(2) NC ^{16}O(ν,ν'),

$$
\begin{aligned}
(\frac{d\sigma}{d\Omega})_{\frac{\nu}{\bar{\nu}'}} = \frac{2G_F^2E_{\nu'}^2}{\pi}\frac{1}{2J_i+1}\cos^2\frac{\theta}{2}\Big\{&\sum_{J=0}^{\infty}|\langle J_f\parallel \mathcal{M}_J(q)-\frac{\omega}{q}\mathcal{L}_J(q)\parallel J_i\rangle|^2\\
&+\left[\frac{|q_\mu^2|}{2q^2}+\tan^2\frac{\theta}{2}\right]\cdot\left[\sum_{J=1}^{\infty}\left(|\langle J_f\parallel \mathcal{T}_J^{\rm el}(q)\parallel J_i\rangle|^2+|\langle J_f\parallel \mathcal{T}_J^{\rm mag}(q)\parallel J_i\rangle|^2\right)\right]\\
&\mp\tan\frac{\theta}{2}\sqrt{\frac{|q_\mu^2|}{q^2}+\tan^2\frac{\theta}{2}}\cdot\\
&\left[\sum_{J=1}^{\infty}2{\rm Re}\langle J_f\parallel \mathcal{T}_J^{\rm mag}(q)\parallel J_i\rangle\langle J_f\parallel \mathcal{T}_J^{\rm el}(q)\parallel J_i\rangle^*\right]\Big\},
\end{aligned}
\tag{A2}
$$

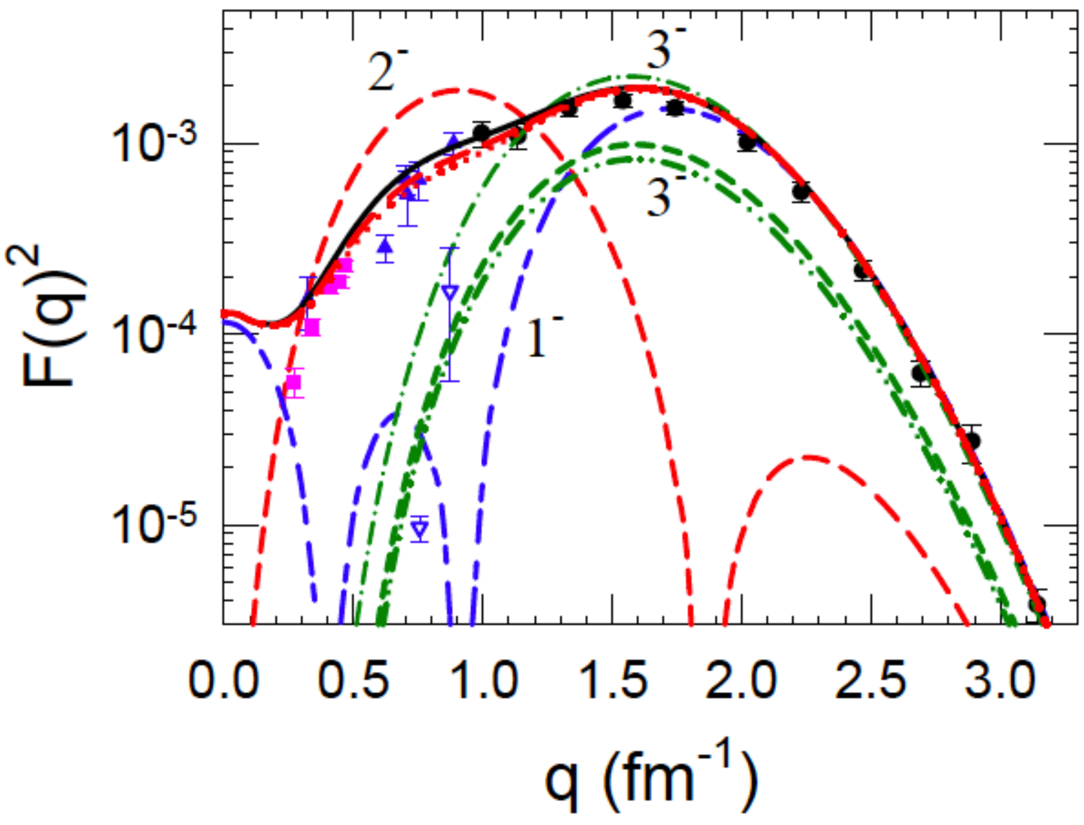
(3)CC ^{16}O(ν,e), β decay
muon capture,

$$
\begin{aligned}
d\Lambda_{\beta^-} = \frac{G_F^2\cos^2\theta_c}{2\pi^2}k\epsilon(W_0-\epsilon)^2d\epsilon\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}\frac{4\pi}{2J_i+1}\Big\{&\sum_{J=0}^{\infty}|\langle J_f\parallel \mathcal{M}_J(q)-\mathcal{L}_J(q)\parallel J_i\rangle|^2\\
&+\left[\sum_{J=1}^{\infty}|\langle J_f\parallel \mathcal{T}_J^{\rm mag}(q)+\mathcal{T}_J^{\rm el}(q)\parallel J_i\rangle|^2\right]\Big\},
\end{aligned}
\tag{A5}
$$

$$
\begin{aligned}
\omega_\mu &= \frac{2G_F^2\cos^2\theta_C}{1+\nu/M_T}|\phi_{1s}|^2\frac{1}{2J_i+1}\\
&\cdot\Big\{\sum_{J=0}^{\infty}|\langle J_f\parallel \mathcal{M}_J(q)-\mathcal{L}_J(q)\parallel J_i\rangle|^2+\sum_{J=1}^{\infty}|\langle J_f\parallel \mathcal{T}_J^{\rm el}(q)-\mathcal{T}_J^{\rm mag}(q)\parallel J_i\rangle|^2\Big\}
\end{aligned}
$$

6-1. (e,e') form factors $F_T(q)^2$ at E_x=13 MeV and the determination of the spin g factor $f_s=g_s^{eff}/g_s$ for 13 MeV, T=1

- The evaluation of the quenching factor f_s must be performed for $^{16}O(E_x$=12-13 MeV, T = 1) using (e, e') cross section.
- Thus, we use the data of ^{16}O(Ex=13.09 MeV, 13.25 MeV, T = 1), but we cannot use those of ^{16}O(12.97 MeV and 12.53 MeV, 2-), since the electromagnetic interaction mixes the iso-vector (T = 1) and iso-scalar (T = 0) states.
- Thus, we obtain f_s = 0.65±05.



- Definition of the spin g factor and $f_s=g_s^{eff}/g_s$: Nuclear magnetic moment $\mu = g_s \mu_N I$, I: nuclear spin.
  - We use $\mu^{eff}=f_s\,\mu= g_s^{eff}\mu_N I$ instead of μ.

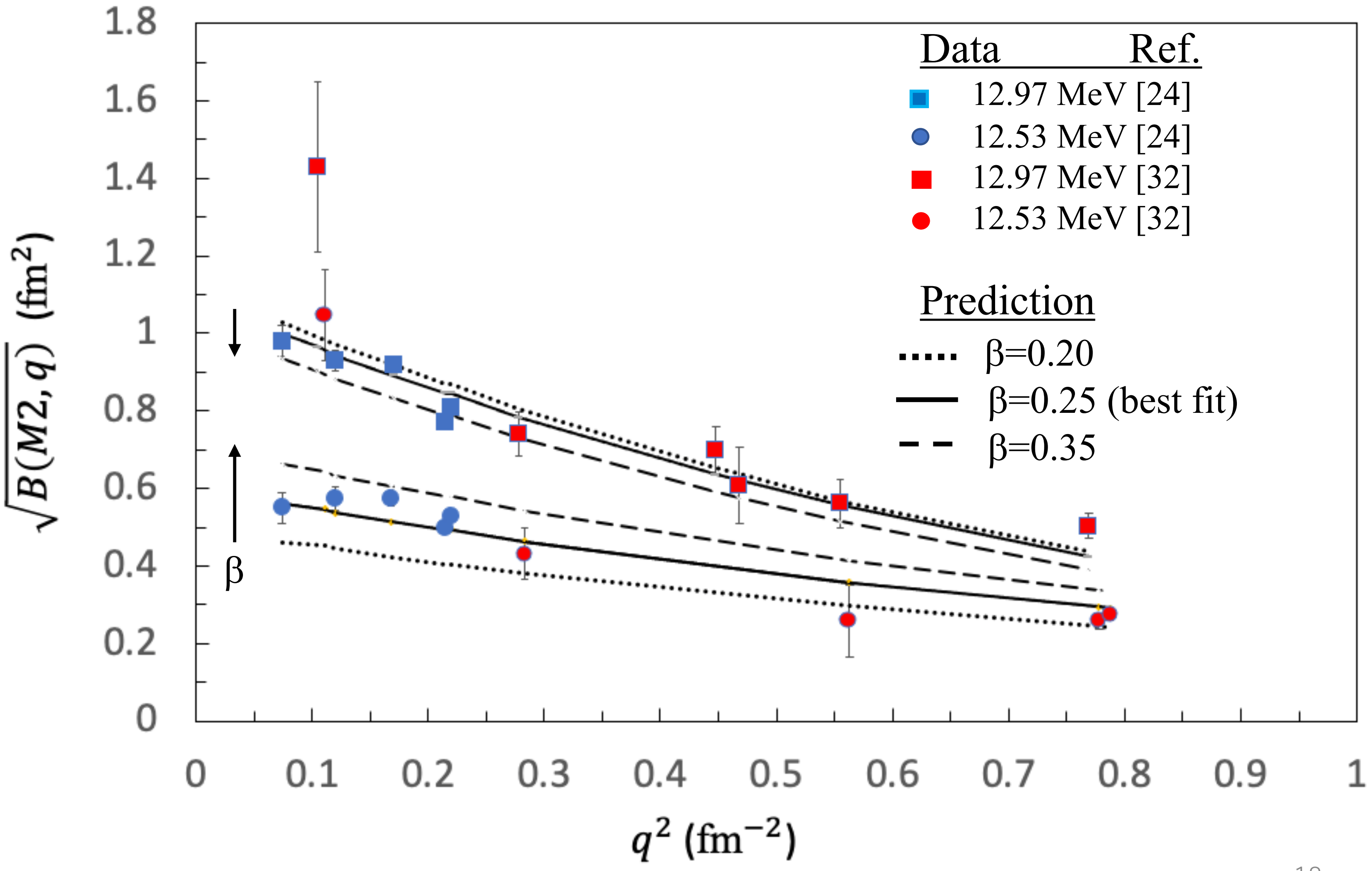
6-2. Determination of the isospin mixing parameter β between 12.53 MeV and 12.97 MeV of ^{16}O

- The reduced transition probability $BM_J(q)$ is used instead of the form factor $F_T^2(M_2,q)$, since it is directly related to the magnetic multipole moment which is measured in an experiment.

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

- We obtain the isospin mixing parameter β=+0.25±05.

- Cf. Sick data (q^2>0.8 fm^{-2}) contain 3- contribution and cannot be used.



6-3. Determination of the axial-vector coupling $f_A = g_A^{eff}/g_A$

- We use the muon capture rate and β decay rate to determine f_A. In this analysis, we fix f_s=0.65.
- The rate of the muon capture on ^{16}O(g.s.) to ^{16}N(2-, 0-, 1-, T=1)

  → f_A=0.63±0.03.
- The β decay from ^{16}N(g.s., 2-, T = 1) to ^{16}O(g.s., 0^+)

  → f_A=0.73±0.01.
- We take the average between the two values. f_A=0.68±0.05.
- Thus, we obtain

f_s=0.65±0.05 and f_A=0.68±0.05.

Table B1. Rate of the partial muon capture (μ^-, ν_μ) from the 1s orbit on ^{16}O(g.s., 0^+) to the bound states (2^-(g.s.), 0^-, 3^-, 1^-, $T = 1$) of ^{16}N and the total muon capture rate from ^{16}O to ^{16}N(g.s., 2^-), in units of 10^3 1/s. The β^--decay rate from the ground state of ^{16}N to ^{16}O(g.s.) is also shown. The energy E_x is given with respect to the ground state (2^-) of ^{16}N.

Weak process	States of ^{16}N E_x MeV(J^P)	Experimental Data [Ref.]	Model prediction [44] (with $f_A = g_A^{eff}/g_A$)
μ capture (10^3/s)	0 MeV(2^-)	6.3 ± 0.7 [89,90]	7.2
		7.9 ± 0.8 [91]	($f_A = 0.63 \pm 0.03$)
		8.0 ± 1.2 [92]	
	0.120 MeV(0^-)	1.1 ± 0.2 [89,90]	1.33
		1.56 ± 0.18 [92]	($f_A = 0.62 \pm 0.02$)
	0.298 MeV(3^-)	<0.09 [92]	$f_A < 0.60$
	0.397 MeV(1^-)	1.73 ± 0.10 [89,90]	1.52
		1.31 ± 0.11 [92]	($f_A = 0.62 \pm 0.03$)
	Sum($2^- + 1^- + 0^-$)	9.15 ± 0.70 [89,90]	10.1 ± 0.5
		10.9 ± 0.7 [91]	($f_A = 0.62 \pm 0.02$)
		10.87 ± 1.22 [92]	
	$E_x > 5$ MeV	102.6 ± 0.6 [88]	112.0
		$(0.98 \pm 0.03) \times 10^2$ [93]	($f_A = 0.95$)
^{16}N β^- decay rate Λ_{β^-} ($\times 10^{-3}$/s)	$2^- \to 0^+$	27.2 ± 0.4 [94–97]	27.2 ($f_A = 0.73 \pm 0.01$)

7. Neutrino-water(H_2O) interactions at E_ν=2-100 MeV

□We set NC, CC cross section as σ^U_{NC} , σ^D_{NC} and σ^U_{CC} , σ^D_{CC} . The cross section for the reactions ⑤⑥⑦ can be calculated by the equation:

⑤ Total $\sigma_{NC}(4.4\text{-MeV } \gamma) = \sigma^U_{NC} * Br^U(\alpha_1) + \sigma^D_{NC} * Br^D(\alpha_1)$

⑥ $\sigma_{NC}(\text{Total12.97-MeV } \gamma) = \sigma^U_{NC} * \mathrm{Br}(U \rightarrow \gamma\ rays)$

⑥ $\sigma_{NC}(\text{Total12.53-MeV } \gamma) = \sigma^D_{NC} * \mathrm{Br}(D \nleftrightarrow \gamma\ rays)$

⑦ $\sigma_{CC}({}^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+){}^{16}_{7}\mathrm{N}(g.s., 2^-)) = \sigma^U_{CC} + \sigma^D_{CC}$. (No efficiency for the coincidence is considered now. Efficiency=1.)

7.⑦ CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}(g.s., 2^-)$ & γ ray+e$^-$ ($^{16}_{7}\mathrm{N}(gs)$ β decay)

- CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}(g.s., 2^-)$:The neutrino energy E_ν can be calculated from the positron energy T_e as $E_\nu = T_e + 11.44$ MeV. (E_{th}=11.44 MeV)
- β decay $^{16}_{7}N(gs, 2^-) \rightarrow {}^{16}_{8}O(E_x) + e^- + \bar{\nu}_e$ ($T_{\beta,max}$=10.42 MeV-E_x, $T_{1/2}$=7.13 s): The relation between the electron energy T_β and the excited state $^{16}_{8}O(E_x)$ is,

  T_β=10.42MeV -E_x-T_ν. $T_\beta + E_x$= 10.42MeV $-T_\nu$.
- β decay : Sum of the visible energy T_β(e)+E_x(γ) = 10.42MeV $-T_\nu$. Half of the events may be detected.
- We take a delayed coincidence between the positron signal (e^+) from the primary interaction and the delayed signal (T_β(e)+E_x(γ)) at the same vertex.

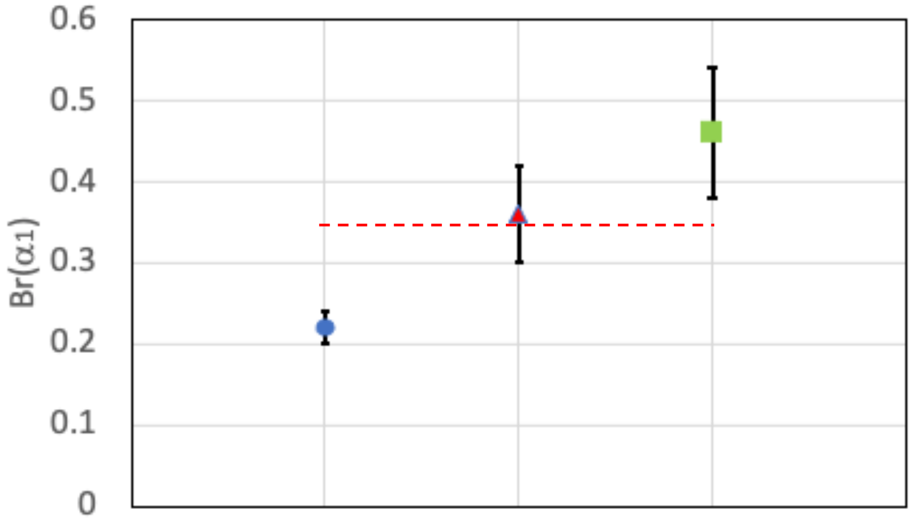
7. ⑤ $\mathrm{Br^U}(\alpha 1) \equiv \mathrm{Br^U}(12.97 \text{ MeV} \rightarrow \alpha + {}^{12}\mathrm{C}(4.4 \text{ MeV}))$

- Three groups reported the values of the branching ratio
  $\mathrm{Br^U}(\alpha 1) \equiv \mathrm{Br^U}(12.97 \text{ MeV} \rightarrow \alpha + {}^{12}\mathrm{C}(4.4 \text{ MeV}))$,

  where the 12.97 MeV state decays to the first excited state of ^{12}C, producing a 4.4 MeV γ ray. We call it $\mathrm{Br^U}(\alpha 1)$.

This is the isospin violating decay.

Experiment and analysis	Reaction	β or $\epsilon = \frac{\beta}{\sqrt{1-\beta^2}}$	$\mathrm{Br^U}(\alpha 1)$
This analysis	Re-analysis of Stroetzel (e,e′) data	$\beta = +0.25 \pm 0.05$	
Stroetzel (1968)	$\sqrt{BM2(q)}$ in (e,e′)	Hinted the mixing~0.25.	
G.Wagner (1977)	^{17}O(d,^{3}He)^{16}N, ^{17}O(d,^{3}t)^{16}O and ^{17}O(^{3}He,α)^{16}O	$\epsilon^2 \geq 0.17 \pm 0.07$	
Leavit (1983)	^{15}N(p,γ)^{16}O	$\epsilon^2 = 0.278 \pm 0.052$	0.37 ± 0.05
Zijderhand (1986)	^{15}N(p,γ)^{16}O		0.22 ± 0.04
Charity (2019)	^{15}O(d,n)^{16}O		0.46 ± 0.05



Leavit (1983) Zijderhand (1986) Charity (2019)

- A simple mean of the three values is $\mathrm{Br}(\alpha 1) = 0.35$ (± 0.17).

7.⑥ $\mathrm{Br}(U \to \gamma\ rays)$ and $\mathrm{Br}(D \to \gamma\ rays)$

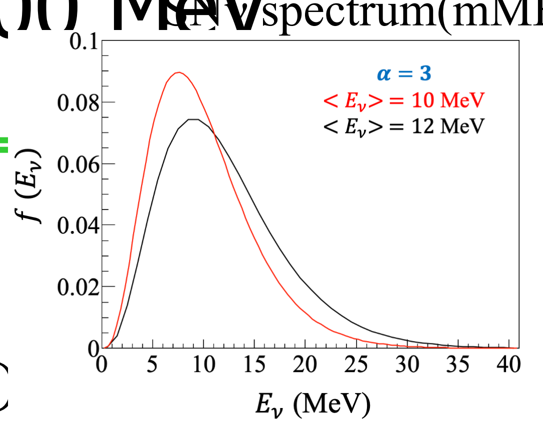
- The branching ratio can be calculated from the nuclear data sheets.

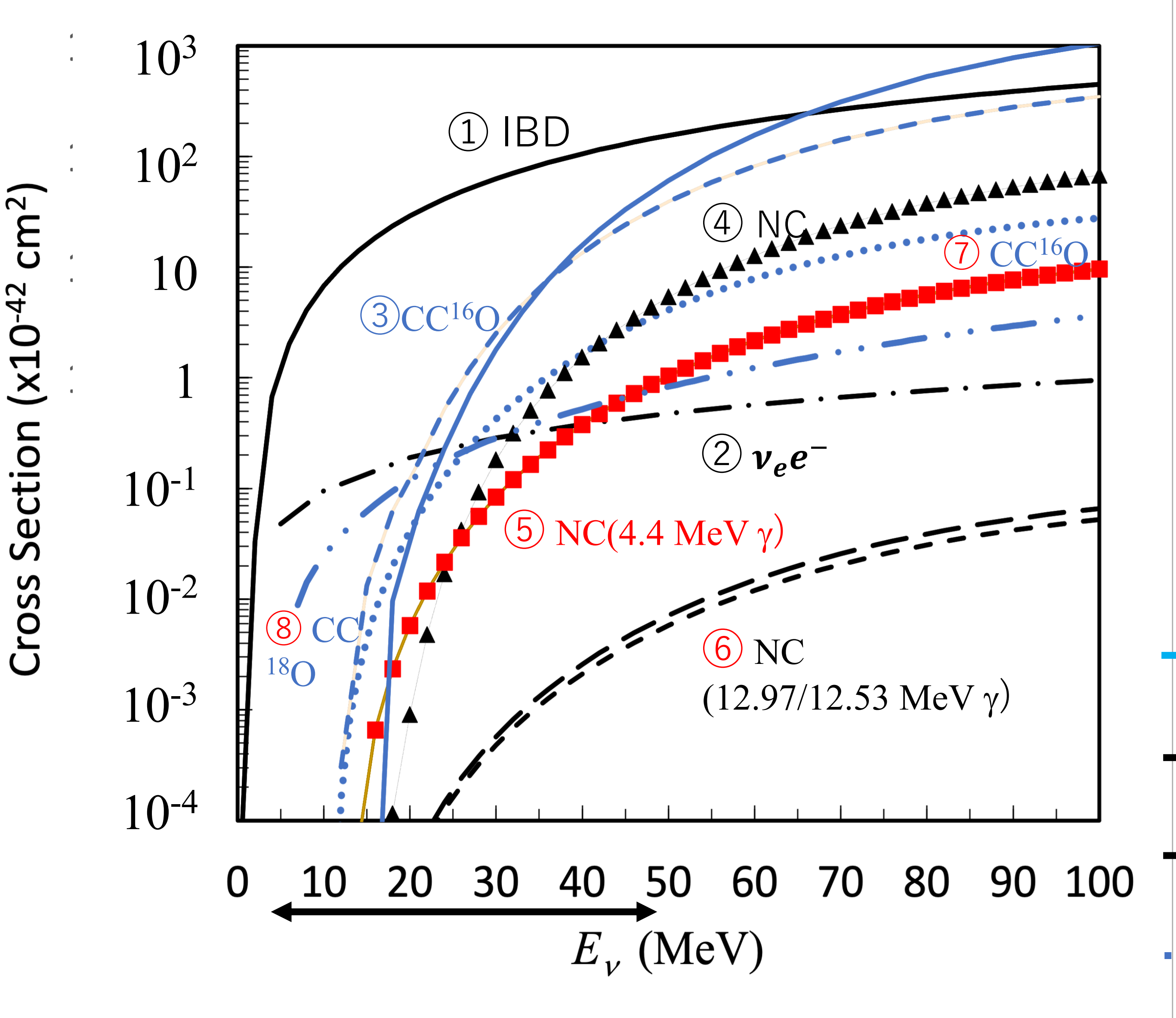
  $\mathrm{Br}(\mathrm{U,\ D} \to \gamma\ \mathrm{rays}) = \Gamma_\gamma/\Gamma = 3.1 \pm 0.04\%$ and $0.27 \pm 0.02\%$, respectively.

- We use the measurements of Gorodetzky et al for the cascade γ transitions. U and D states produce 2-3 γ rays.

12.53 MeV (2^-, 1)	Γ_γ (eV)	Branching ratio (%)
Transition to the state		
$\to$0 MeV	-	-
$\to$8.83 MeV	0.86±0.10	25±3
$\to$7.12 MeV	0.51±0.10	15±3
$\to$6.13 MeV	2.1±0.2	60±6
$\to$All states	3.4±0.3	100%
Reference	Gorodetzky *et al.* [7]	
12.97 MeV (2^-, 1)	**Γ_γ (eV)**	**Branching ratio (%)**
Transition to the state		
$\to$0 MeV	-	-
$\to$8.83 MeV	0.90±0.10	25±6
$\to$7.12 MeV	0.44±0.10	12±2
$\to$6.13 MeV	2.3±0.3	63±6
$\to$All states	3.6±0.3	100%
Reference	Gorodetzky *et al.* [7]	

7.(=2.) Neutrino-water(H_2O) interactions at E_ν=2-100 MeV





----Previous work---

①IBD($\bar{\nu}_e p \rightarrow e^+ n$)

② $\nu_e e^-$scattering (CC+NC)

③ CC $^{16}_{8}O(\nu_e, e^-)^{16}_{9}F$

③ CC $^{16}_{8}O(\bar{\nu}_e, e^+)^{16}_{7}N$

④NC $^{16}O(\nu,\nu')^{16}O(E_x$>16 MeV)
& γ ray (E_γ >5 MeV)

---- Our recent publications ---

⑤NC $^{16}O(\nu,\nu')^{16}O$(12.97/12.53MeV)
& γ ray (4.4 MeV)

⑧ CC $^{18}_{8}O(\nu_e, e^-)^{18}_{9}F$

---- Our ongoing work ----

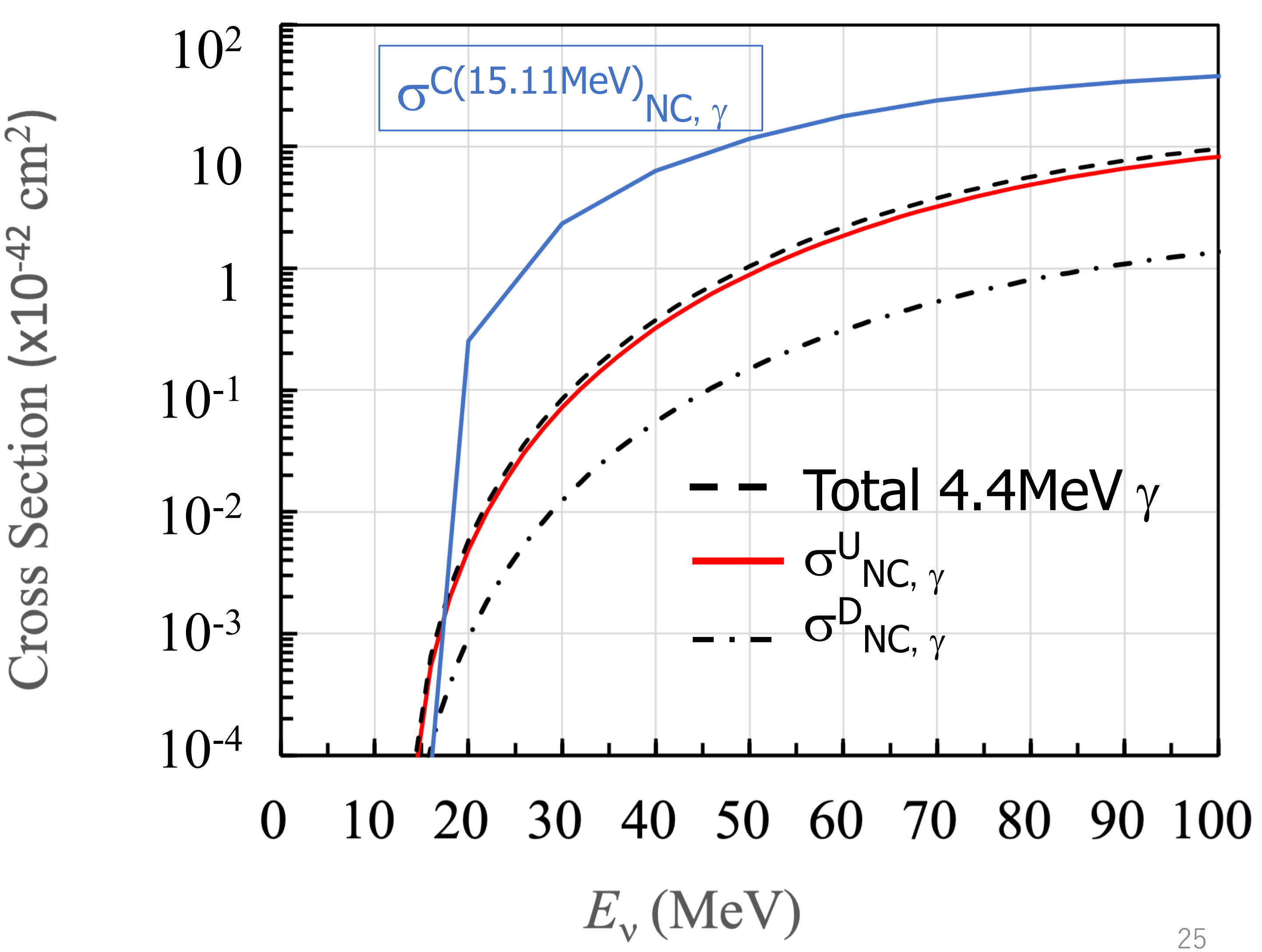
⑥ NC $^{16}O(\nu,\nu')^{16}O$(12.97 MeV)
& γ ray (Sum 12.97 MeV)

⑥ NC $^{16}O(\nu,\nu')^{16}O$(12.53 MeV)
& γ ray (Sum 12.53 MeV)

⑦ CC$^{16}_{8}O(\bar{\nu}_e, e^+)^{16}_{7}N(g.s., 2^-)$

7. NC cross section of the 4.4-MeV γ ray production $\sigma_{NC}(4.4\text{-MeV } \gamma)$ using both U=12.97 MeV and D=12.53 MeV

- We notice that $^{16}O(\nu,\nu')^{16}O$(D=12.53 MeV, 2^-) can produce 4.4-MeV γ ray through isospin mixing and $Br^D(\alpha 1) \equiv Br^D$(12.53 MeV →α+$^{12}C$(4.4 MeV))=0.83±0.03.
- $\sigma^D_{NC,\gamma} = \sigma^D_{NC} * Br^D(\alpha_1) = \frac{\beta^2}{1-\beta^2} \frac{Br^D(\alpha_1)}{Br^U(\alpha_1)} \sigma^U_{NC,\gamma} = 0.16\ \sigma^U_{NC,\gamma}$ at β=0.25.
- Total $\sigma_{NC}(4.4\text{-MeV } \gamma) = \sigma^U_{NC,\gamma} + \sigma^D_{NC,\gamma}$
  - increases rapidly above E_{th}=12.53 MeV
  - Increases as the isospin mixing (β) increases, $\propto 1+2.4\beta^2$, because $Br^D(\alpha_1)$=0.83 is much larger than $Br^U(\alpha_1)$=0.35.
- Cf. $\sigma_{NC}(^{12}C(15.11\text{MeV } \gamma))$ is shown for comparison (blue).



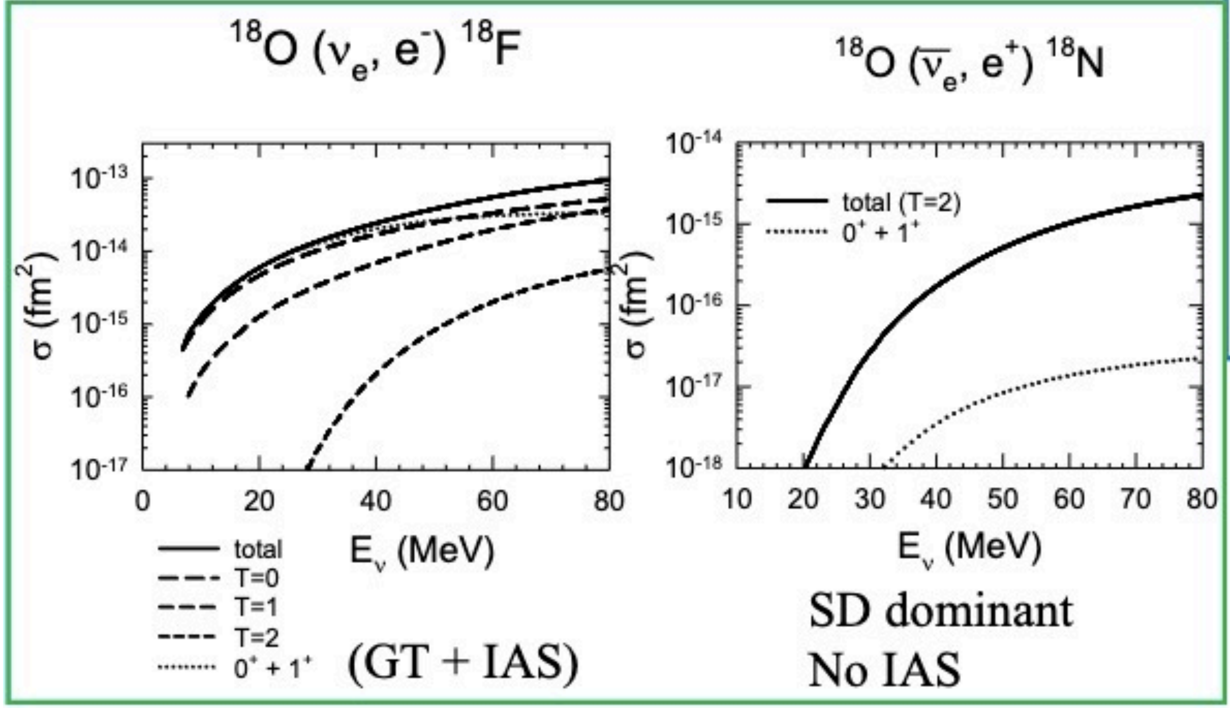
Result of ⑧ CC ${}^{18}_{8}O(\nu_e, e^-){}^{18}_{9}F$ from T.Suzuki (SNS workshop, 2023, March)

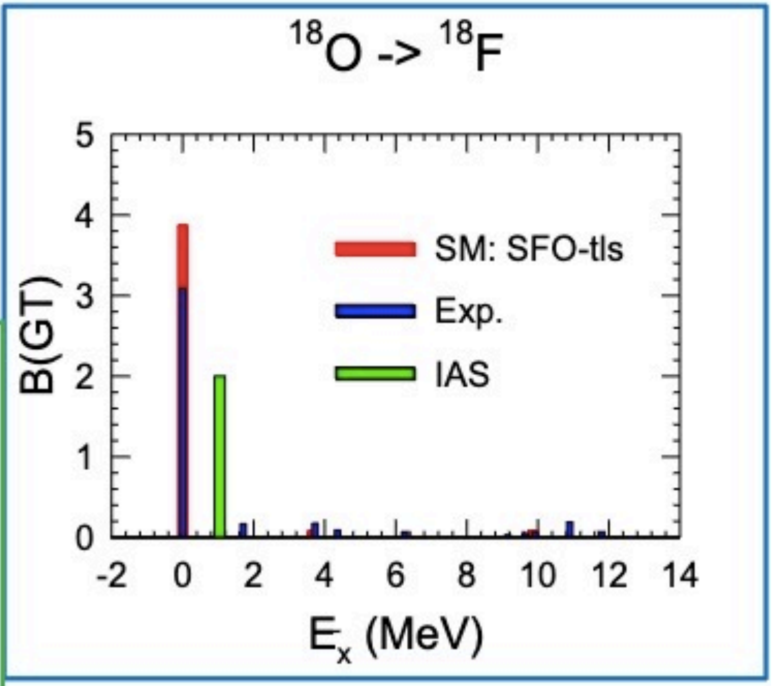
- ν-^{18}O reactions

^{18}O 0.204 % of oxygen isotopes

GT strength in ^{18}O

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





$\Sigma\, B(GT)_{exp} = 4.06$

$\Sigma\, B(GT)_{calc} = \Sigma\, B(GT)_{exp}$

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

8. Summary

- We have studied the electroweak interactions of ^{16}O and ^{16}N: we re-analysed the ^{16}O(e,e′) data, the muon capture rate on ^{16}O(some new) and the ^{16}N β decay rate.
- We have determined the following quantities to calculate the cross section of NC γ-ray production ⑤⑥ from ^{16}O(ν,ν′)^{16}O(E_x=12.97,12.53 MeV, 2-) and ⑦ CC $^{16}_{8}\mathrm{O}(\bar{\nu}_e, e^+)^{16}_{7}\mathrm{N}(g.s., 2^-)$. Results of ⑥⑦ are very preliminary.

(1) Quenching factors for the spin g factor (f_s) and the axial-vector coupling constant (f_A).

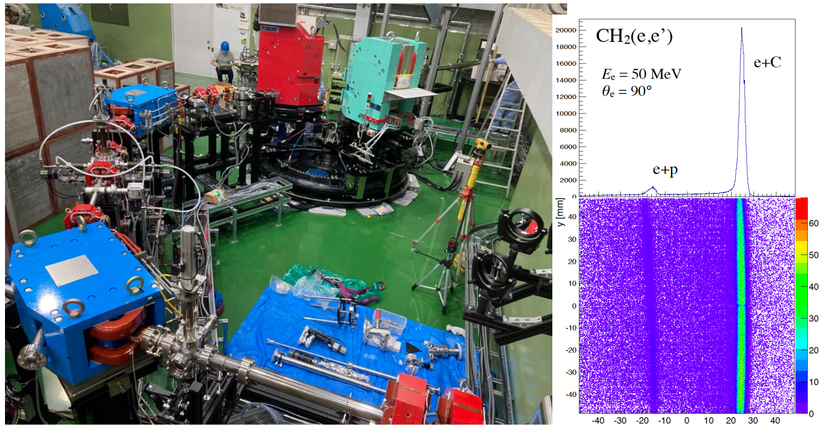
f_s=0.65±0.05 and f_A=0.68±0.05.

(2) The isospin mixing parameter β=+0.25±05 between 12.53 and 12.97 MeV.

Outlook

- We do need the low-energy electron beams & experiments (E_e<100 MeV) to measure (e,e’) inelastic scattering and the branching ratio to the p, α, γ decays of ^{16}O (^{12}C and Ar) precisely. If we combine them with new ν measurements at low energy (ν-SNS?), we can improve the neutrino-^{16}O (^{12}C and ^{40}Ar) cross section at low energy for the precise Supernova (neutrino) physics (Dark Matter, or Astrophysics). There are several low-energy electron beams:
  - S-DALINAC at Darmstadt (E_e=2.5-85 MeV):Peter von Neumann-Cosel (NuInt14), JPS Conf. Proc. 12, 010030 (2016).
  - MAGIX at MAMI and MESA (Mainz, E_e=105 MeV). B.Schimme et al.,NIMA1013(2021).
  - ELPH (Tohoku, Japan, E_e=20-60 MeV) under operation.

    T.Suda, KEKnews, 25Oct., 2021. (Right Figures)

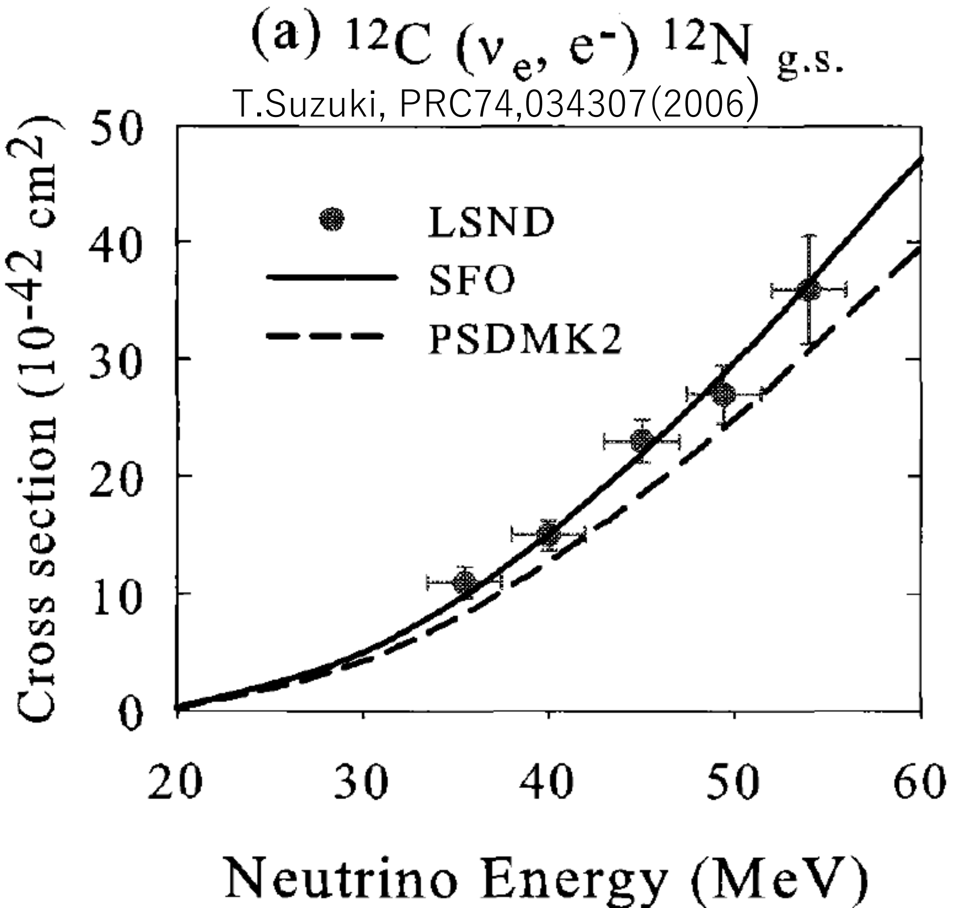


^{12}C cross section

$^{12}C(\nu_e, e^-)^{12}N$ flux averaged cross sections.

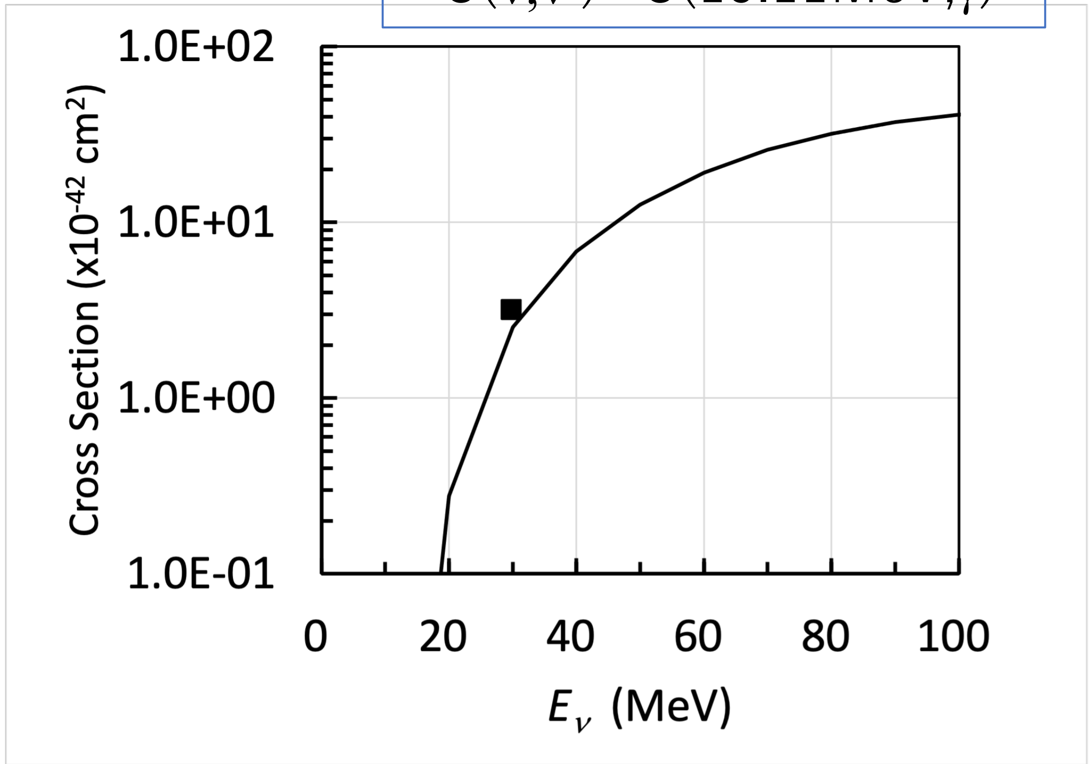
Experiment	$\langle\sigma(^{12}C(\nu_e, e^-)^{12}N_{g.s.})\rangle$ ($cm^2 \times 10^{-42}$)	$\langle\sigma(^{12}C(\nu_e, e^-)^{12}N*)\rangle$ ($cm^2 \times 10^{-42}$)
E225	10.5 ± 1.0 (stat.) ± 1.0 (sys.)[a]	5.4 ± 1.9[d]
KARMEN	9.6 ± 0.3 (stat.) ± 0.7 (sys.)[b]	4.8 ± 0.6 (stat.) $^{+0.4}_{-0.5}$ (sys.)[b]
LSND	8.9 ± 0.3 (stat.) ± 0.9 (sys.)[c]	4.3 ± 0.4 (stat.) ± 0.6 (sys.)[c]

- Only neutrino-^{12}C cross sections are measured at KARMEN and LSND. ^{12}C(e,e') cross sections are also measured.
- We do need the measurements of ^{16}O(e,e') in the electron beam (Ee=30-100 MeV) and neutrino cross sections at En=20-100 MeV.



T.Suzuki, PRC74,034307(2006)

$^{12}C(\nu,\nu')^{12}C(15.11MeV,\gamma)$



Question

- Can QMC calculate this simple matrix element for

(1) 15.11 MeV and 12.71 MeV of ^{12}C, and

(2) 12.97 MeV and 12.53 MeV of 16O??

- Right: Coulomb matrix element $\langle U|H_c|D\rangle$. Isospin mixing of the two 1^+ states (15.11 MeV and 12.71 MeV) of ^{12}C (Cosel, NPA669,3(2000))

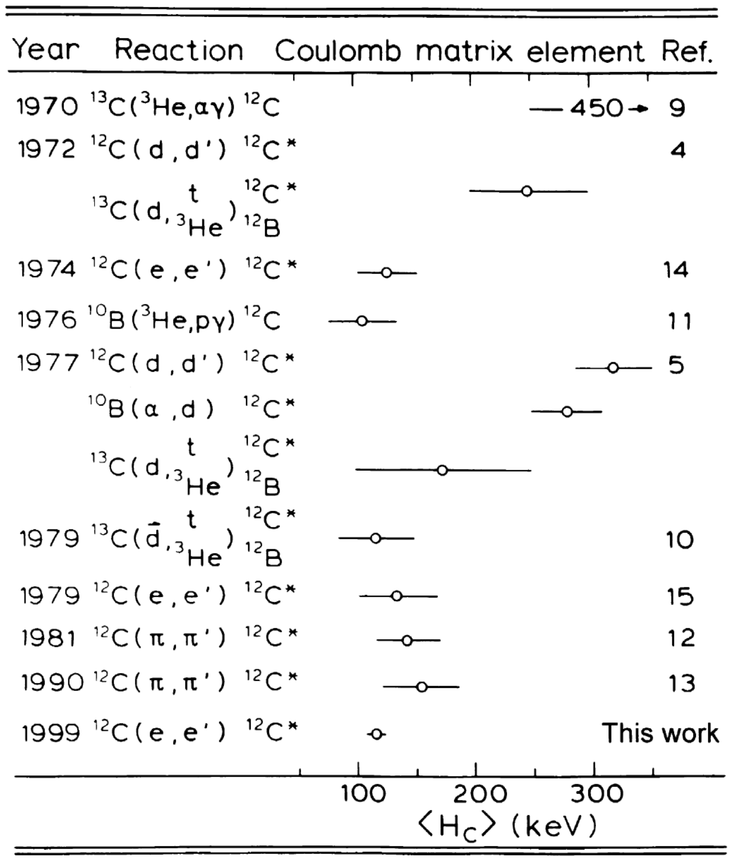


Fig. 1. Summary of isospin mixing matrix elements derived over the last 30 years for the 1^+ doublet in ^{12}C.

- Backups

Supernova Model Discrimination with Hyper-Kamiokande

K.Abe et al.(HyperK), APJ 916:15 (2021)

- Similarly, we do not consider neutral-current interactions on 16O nuclei, a subdominant channel that mainly produces gamma-rays with an energy of 5.2MeV to 6.3 MeV (Langanke et al. 1996). After Compton scattering on an electron or electron-positron pair production, the visible energy from these events would typically be below 5 MeV.

SFO-tls model

an important role. The p-sd shell cross-shell part of SFO is a phenomenological Millener-Kurath interaction [18]. It is important to update the p-sd cross-shell part of the Hamiltonian with proper inclusion of the tensor interaction. Here, we use a modified version of SFO, in which the tensor and two-body spin-orbit components of the p-sd cross-shell matrix elements are replaced by those of $\pi + \rho$ meson exchanges and $\sigma + \omega + \rho$ meson exchanges [19], respectively. The modified

4.4 MeV γ ray (12.97/12.53 MeV ●) and 6 MeV γ ray (Ex>16 MeV ●) at SK from SN neutrinos (10 kpc)

- Figure shows E_{vis} using the typical SN$_\nu$ spectrum at SK.
- IBD events ($\bar{\nu}_e p \rightarrow e^+ n$) can be identified unambiguously in the SK-Gd detector and the $\bar{\nu}_e$spectrum can be measured as

  $E_{\bar{\nu}_e}$ = E_{vis} + 1.8 MeV.
- NC γ rays (E_γ) produce E_{vis}~Eγ, regardless of E_ν. This plot can be seen as NC(ν=6*$\bar{\nu}_e$).
- 右図

KRJ (α , $<E_\nu>$)	(3, 10)	(3, 12)	(3, 14)
IBD	4840	5900	6900
NC 4.4 MeV γ(12.97MeV)	1.9	5.1	10.7
4.4 MeV γ (12.97/12.53MeV	2.2	5.9	12.5
NC Eγ>5 MeV (Ex>16MeV)	3.3	12.5	33.9