Production of a 4.4-MeV γ ray from neutral-current neutrino-oxygen reaction in a water Cherenkov detector for supernova neutrino bursts and the isospin mixing of the 2^- states (12.97 MeV and 12.53 MeV) of ^{16}O.

Makoto Sakuda (Okayama)

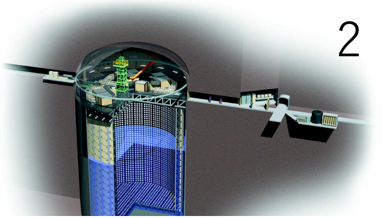
Collaborators: T. Suzuki (Nihon), K.Nakazato (Kyushu), H. Suzuki (Tokyo University of Science), M.Reen (Akal)

- 12.97 MeV(2-) is the first T=1 strong excited state of ^{16}O, as 15.11 MeV (1^+) is the first strong T=1 excited state of ^{12}C. T=1 triplet 2^-(^{16}N,^{16}O,^{16}F) and 1^+(^{12}B,^{12}C,^{12}N). Both states have the isospin mixing.

Outline

1. Introduction: $^{16}O(\nu,\nu')^{16}O(12.97\ \text{MeV},2^-)\rightarrow 4.4\ \text{MeV}\ \gamma$ ray
2. Result: Neutrino-water (H_2O) cross sections at E_ν=0-100 MeV.
3. $^{16}O(e,e')^{16}O^*$(Ex=13 MeV) data
4. Isospin Mixing of two 2- states (12.97 and 12.53 MeV) of ^{16}O
5. (e,e') form factors $F_T(q)^2$ at E_x=13 MeV and the quenching factor of the spin g factor $f_s=g_s^{eff}/g_s$ for 13 MeV, T=1
6. The isospin mixing parameter β between 12.53 MeV and 12.97 MeV of ^{16}O
7. Quenching factor of the axial-vector coupling $f_A=g_A^{eff}/g_A$ for 12.97 MeV, T=1
8. $\mathrm{Br}(\alpha 1) \equiv \mathrm{Br}(12.97\ \text{MeV} \rightarrow \alpha + {}^{12}C(4.4\ \text{MeV}))$
9. Application of this new channel to a detection of SN neutrinos
10. Summary & Outlook

1. Introduction 1: NC γ-ray production in water (H_2O)

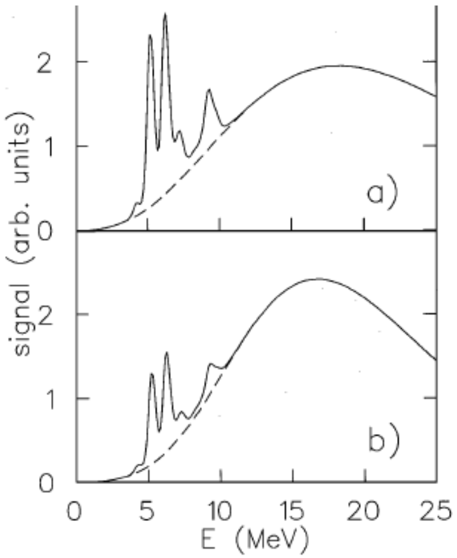


- Langanke et al. (PRL76(1996)) proposed a detection of γ rays ($E\gamma$>5 MeV) from NC ν-$^{16}O(E_x$>16 MeV) from SN neutrinos, just when SK-I started in 1996 (E_{th}>5 MeV).

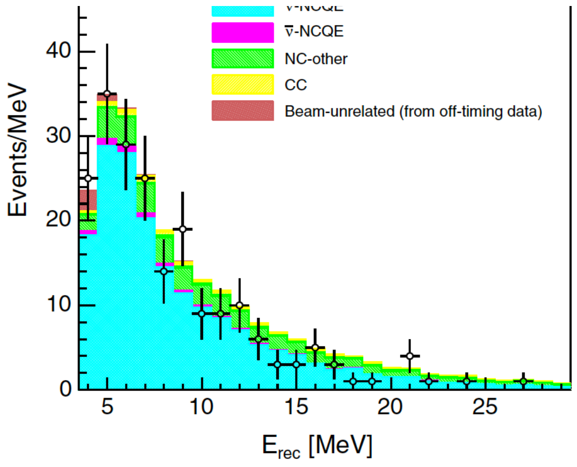
- SK has kept improving the electronics system and water purity and SK-IV (2008-) has reported the solar neutrinos for E_{kin}>3.5 keV (K.Abe(SK-IV), PRD94(2016)).
  - Cf. SK observes 6-MeV γ rays in T2K experiment and 6-MeV γ rays in atmospheric neutrino measurements with neutron tagging.

- We think that it is timely to discuss a new NC reaction ν-$^{16}O(E_x$=12.97 MeV, 2^-) producing a 4.4-MeV γ ray.

Langanke et al., PRL76(1996).



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



	Period	Energy Threshold at SK E_{tot} (E_{kin})
SK-I	1996-2001	5 MeV (4.5 MeV)
SK-II	2002-2005	7 MeV (6.5 MeV)
SK-III	2006-2008	5 MeV (4.5 MeV)
SK-IV	2008Sep.-	4 MeV (3.5 MeV)
SK-Gd	2020, Aug.-	(same)

1. Introduction 2 (Relation to Previous analysis)

☐ Donnelly and Walecka (1972, 1975) analysed the excited states (13 MeV and 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 and 12.53 MeV states was not known.

☐ We re-analysed the (e,e′) data, muon capture rate (some new) and the β decay rate, considering the isospin mixing of the two 2- states. We use Shell Model:T. Suzuki, Otsuka,PRC78, 061301(R) (2008); Yuan et al., PRC85, 064324 (2012).

☐ Then, We applied them to the cross section of NC ^{16}O(ν,ν')^{16}O(E_x=12.97 MeV) and its γ production for the first time.

☐ We also apply the NC cross section to a detection of 4.4 MeV γ rays in SN neutrinos.

☐ Note:If you analyse (e,e′) data without considering the mixing effect (β=0), you will obtain the larger (logically wrong) cross section for 12.97 MeV by about 6-10%(β^2).

- Donnelly and Walecka, Phys.Lett. B41, 275 (1972); Ann.Rev.Nucl.Sci.25, 329 (1975).

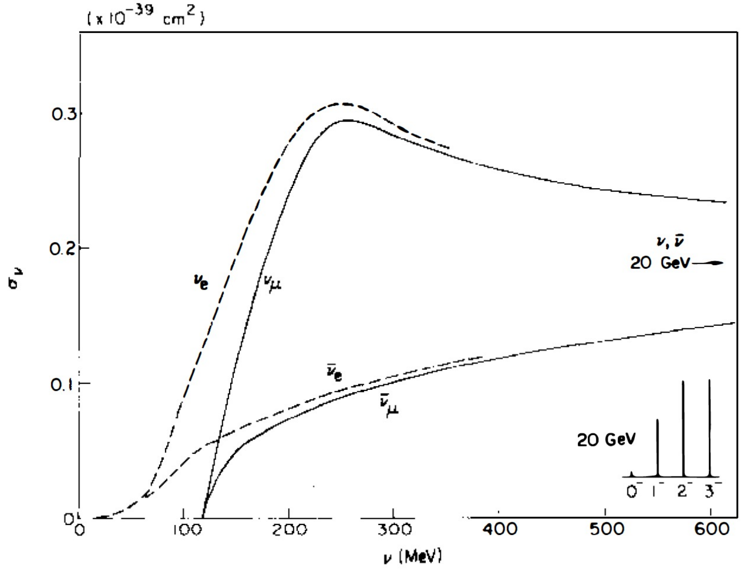


Figure 4.4 Neutrino reaction cross sections for the 13 MeV complex in mass-16 using Set 1 amplitudes from Table 4.2. The arrow indicates the (common) cross section at $\nu = 20$ GeV and the inset shows the relative contributions at this energy (139).

1. SK Supernova detection channels for Online Monitor System

(SNwatch, E>3 MeV) by SK collaboration, Astropart.Phys.81,39(2016).

☐ SK uses the following reaction channels for SN neutrino (Online) detection.

IBD($\bar{\nu}_e p \rightarrow e^+ n$) [H] Ref. Strumia-Vissani, PLB564, 42-54(2003).

${}^{16}_{8}O(\nu_e, e^-){}^{16}_{9}F$
${}^{16}_{8}O(\bar{\nu}_e, e^+){}^{16}_{7}N$ Ref. Haxton,PRD36,2283(1987);Kolbe et al,PRD66,013007(2002);Nakazato,Suzuki,MS,PTEP2018,123E02.

$\nu_e e^-$scattering (ES)
$\bar{\nu}_e e^-$ scattering (ES)
$\nu_x e^-$, $\bar{\nu}_x e^-$ scattering (ES)

☐ The γ ray production from ^{16}O(ν,ν′)^{16}O(E_x> 16 MeV) was calculated by Langanke et al.. Ref. Langanke et al.,PRL76(1996); Beacom-Vogel,PRD58,053010(1998); Kolbe et al,PRD66,013007(2002).

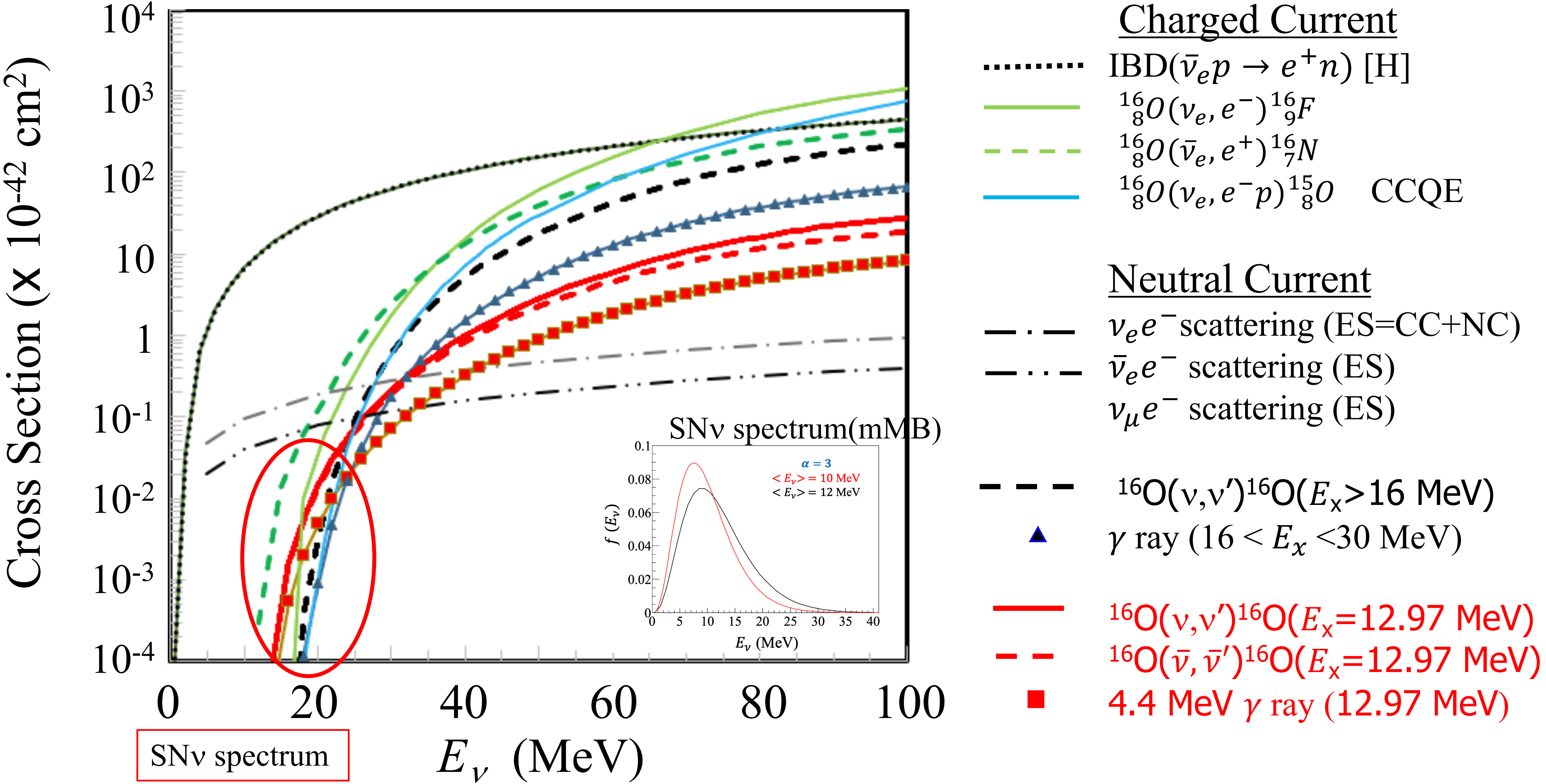
☐ We present the NC cross section of the 4.4 MeV γ ray production from ^{16}O(ν,ν′)^{16}O(E_x=12.97 MeV) and^{16}O($\bar{\nu}, \bar{\nu}'$)^{16}O(E_x=12.97 MeV).

- Since the neutrino spectrum from SN explosion was only measured for $\bar{\nu}_e$ at SN1987A and 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. The NC cross section (or the detected number) is independent of the neutrino oscillations.

2. Neutrino-^{16}O (and H) interactions at E_ν=2-100 MeV

*This talk(red color):^{16}O(ν,ν′)^{16}O(E_x=12.97 MeV) and its γ-ray production are new.

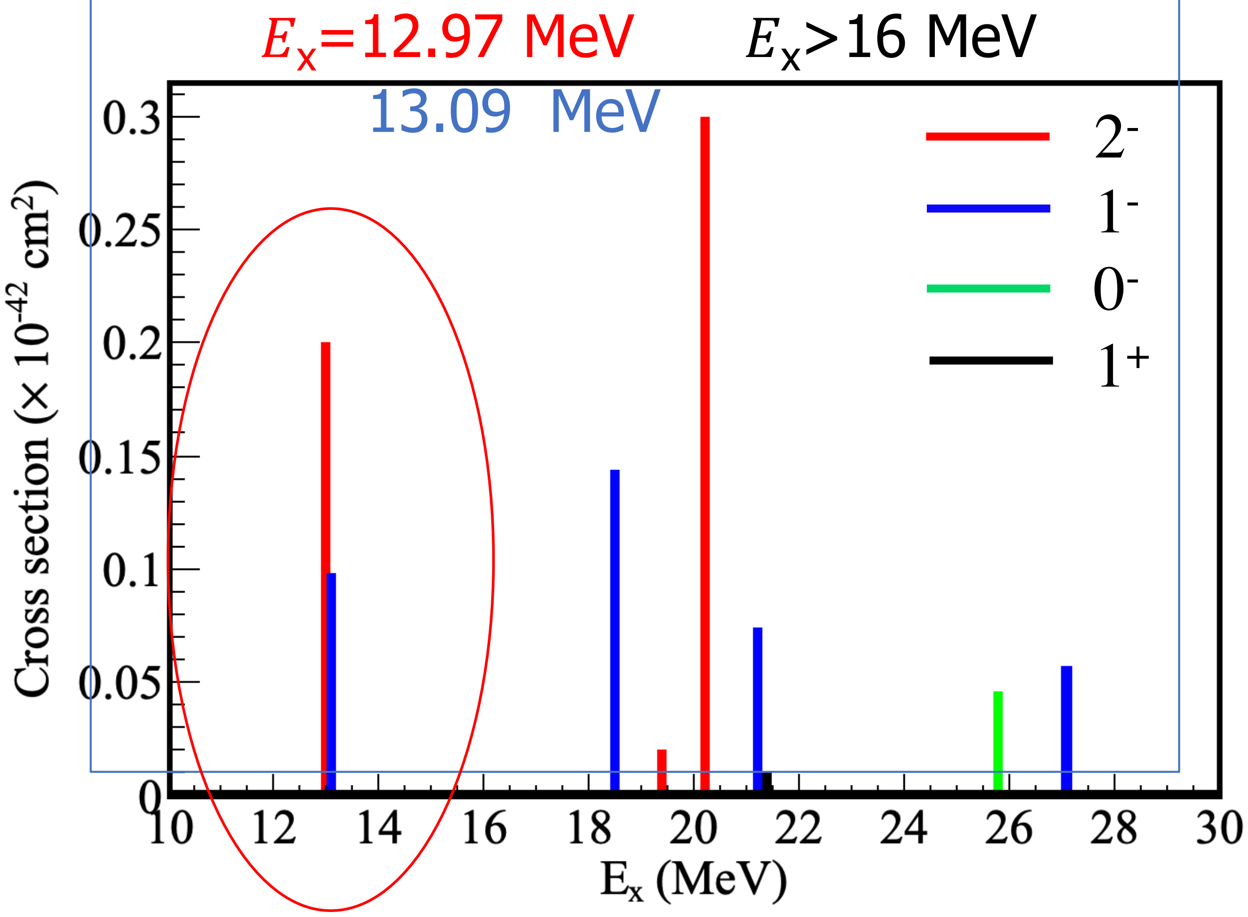
σ_{NC}(E_x=12.97 MeV) is higher than σ_{NC}(E_x>16 MeV) for E_ν<25 MeV.



Features of NC 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.
- The cross section 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. The cross section increases rapidly from 18 MeV until 100 MeV.

- $d\sigma/dE_x$ at E_ν=30 MeV.



E_x=12.97 MeV

E_x>16 MeV

13.09 MeV

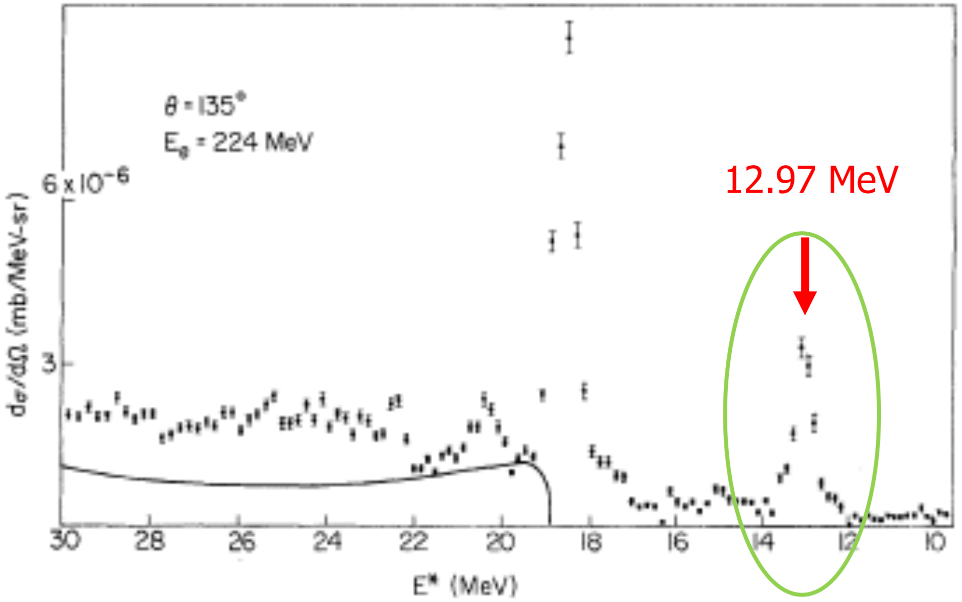
3. $^{16}O(e,e')^{16}O^*(E_x=13\ MeV)$ data

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)

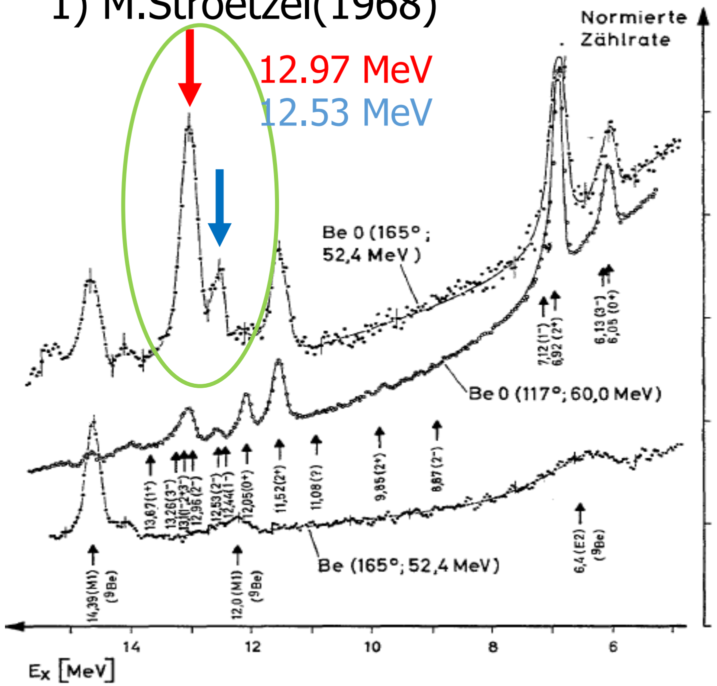
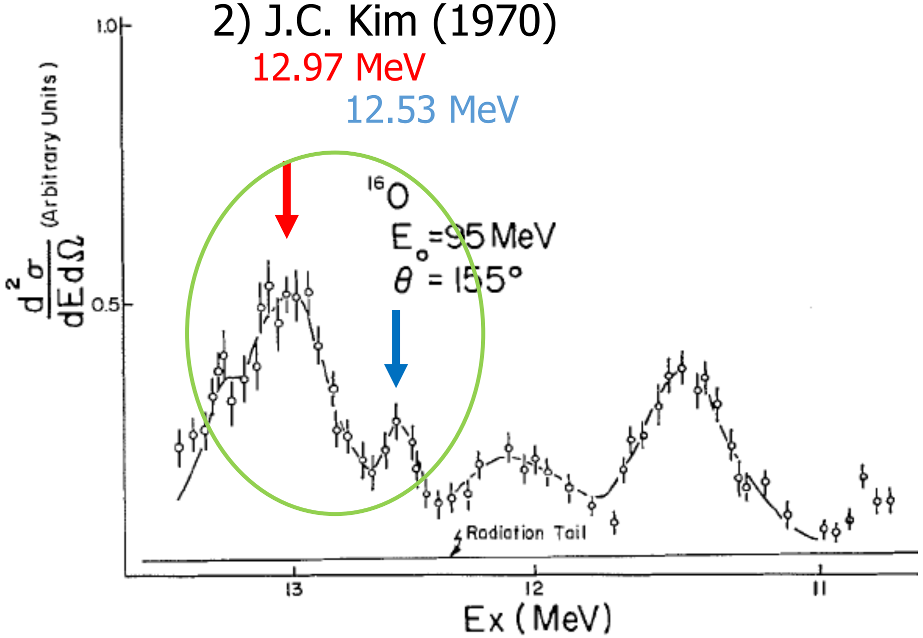


Fig. 1. Unelastische Elektronenstreuung an BeO und Be bei konstanter Impulsüber-

CANADIAN JOURNAL OF PHYSICS. VOL. 48, 1970

2) J.C. Kim (1970)

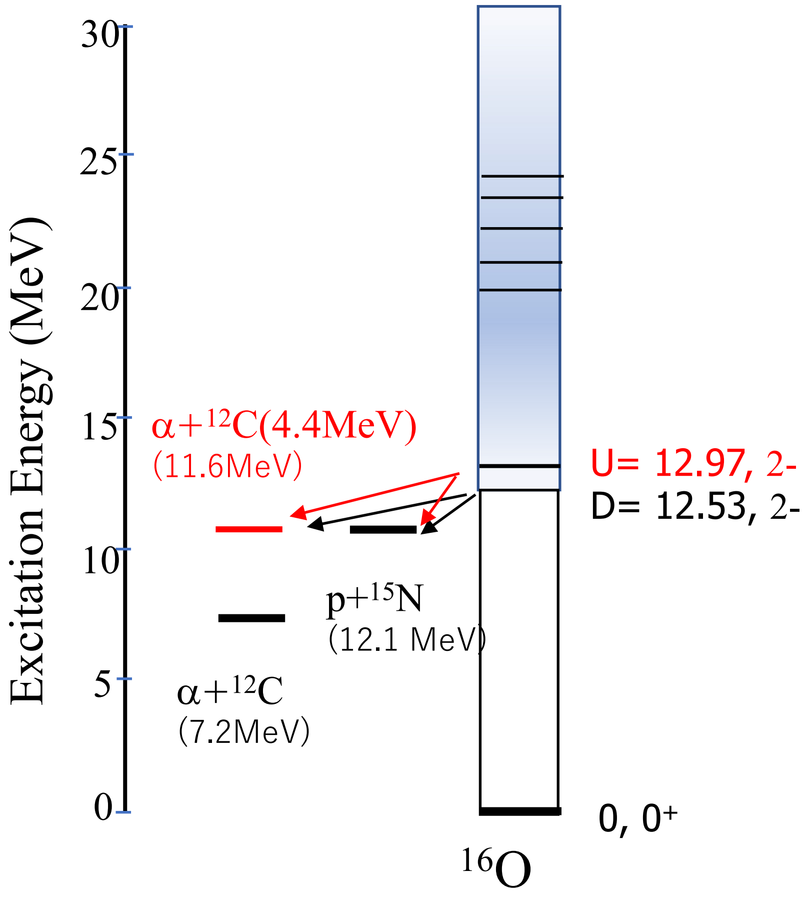


4. Isospin Mixing of two 2- states (12.97 and 12.53 MeV) of ^{16}O

- The isospin mixing is known to be caused for example by the Coulomb interaction between the protons in the nucleus, which can violate the isospin symmetry.
- 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:

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

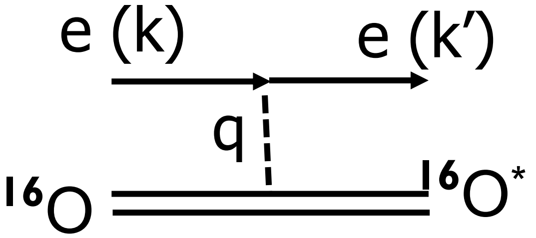
- Cf. A well-known example of the isospin mixing is the two states, 12.71 MeV (1^+, T = 0) and 15.11 MeV (1^+, T = 1), of ^{12}C. β=0.0491(34) by Neumann-Cosel, NPA669,3(2000).



Formula for (1) ^{16}O(e,e’), (2) NC ^{16}O(ν,ν’), (3)CC ^{16}O(ν,e) at E_ν=2-100 MeV

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

1)



$$J_\mu^\gamma = J_\mu^{\gamma(V)} + J_\mu^{\gamma(S)}$$

(1) ^{16}O(e,e’)

$$\left(\frac{d\sigma}{d\Omega}\right)_{e,e'} = 4\pi\sigma_{\rm Mott}F^2(q)/R_{\rm recoil},$$

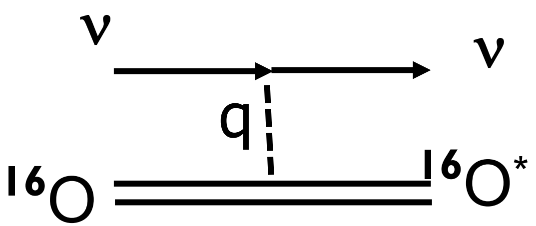
$$\sigma_{\rm Mott} = \left[\frac{\alpha\cos\frac{\theta}{2}}{2E\sin^2\frac{\theta}{2}}\right]^2,$$

$$F^2(q) = \left(\frac{|q_\mu^2|}{q^2}\right)^2 F_L^2(q) + \left(\frac{|q_\mu^2|}{2q^2} + \tan^2\frac{\theta}{2}\right)F_T^2(q),$$

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

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

2)

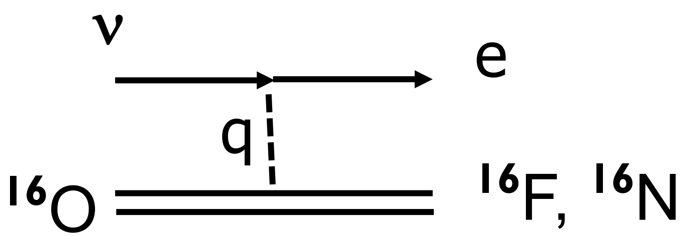


$$J_\mu^{\rm NC} = V_\mu^3 + A_\mu^3 + A_\mu^S - 2\sin^2\theta_W J_\mu^\gamma,$$

(2) NC ^{16}O(ν,ν’),

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

3)



$$J_\mu^{\rm CC} = V_\mu^{\pm1} + A_\mu^{\pm1}$$

(3)CC ^{16}O(ν,e)

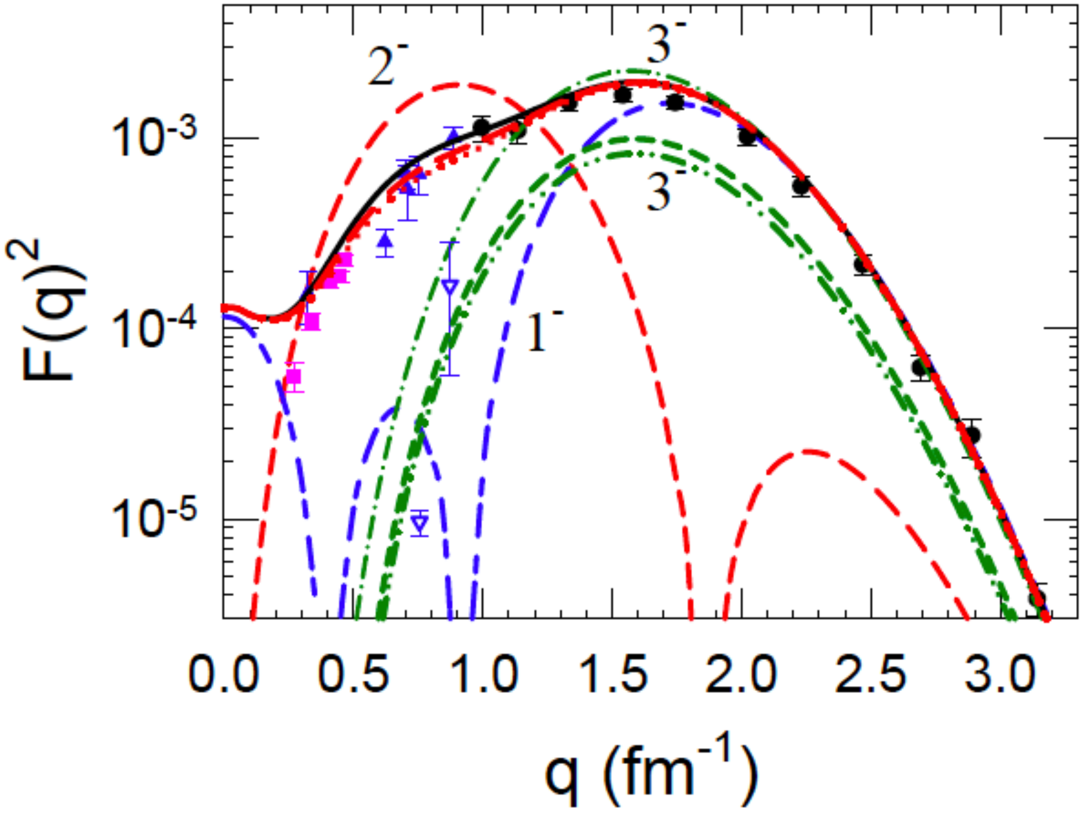
$$\begin{aligned}d\Lambda_{\beta^-} = {} & \frac{G_F^2\cos^2\theta_c}{2\pi^2}k\epsilon(W_0-\epsilon)^2 d\epsilon\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}\frac{4\pi}{2J_i+1}\Bigg\{\sum_{J=0}^{\infty}\left|\langle J_f \parallel \mathcal{M}_J(q) - \mathcal{L}_J(q) \parallel J_i\rangle\right|^2 \\ &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

5. (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(E_x=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. Determination of the isospin mixing parameter β between 12.53 MeV and 12.97 MeV of ^{16}O

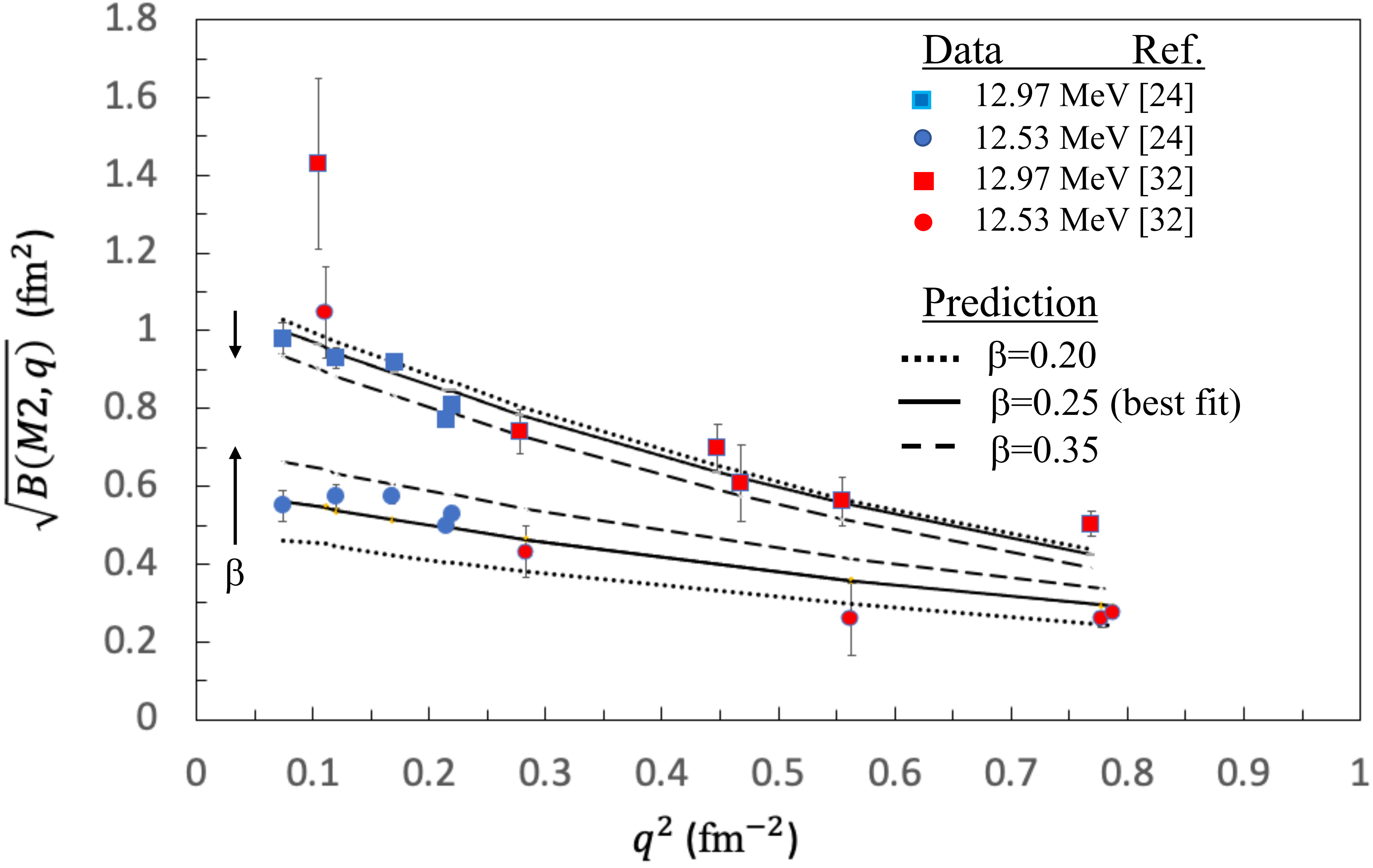
☐ The reduced transition probability $BM_J(q)$ is used instead of the form factor $F_T^2(M_2,q)$, since it is directly related to the magnetic multipole moment which is measured in an experiment.

$J^P=2^-$.

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

☐ 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.



7. Quenching factor 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)

  → $f_A=0.63\pm0.03$.
- ☐ The β decay from ^{16}N(g.s., 2-, T = 1) to ^{16}O(g.s., 0^+)

  → $f_A=0.73\pm0.01$.
- ☐ We take the average between the two values. $f_A=0.68\pm0.05$.
- ☐ Thus, we obtain

  $f_s=0.65\pm0.05$ and $f_A=0.68\pm0.05$.

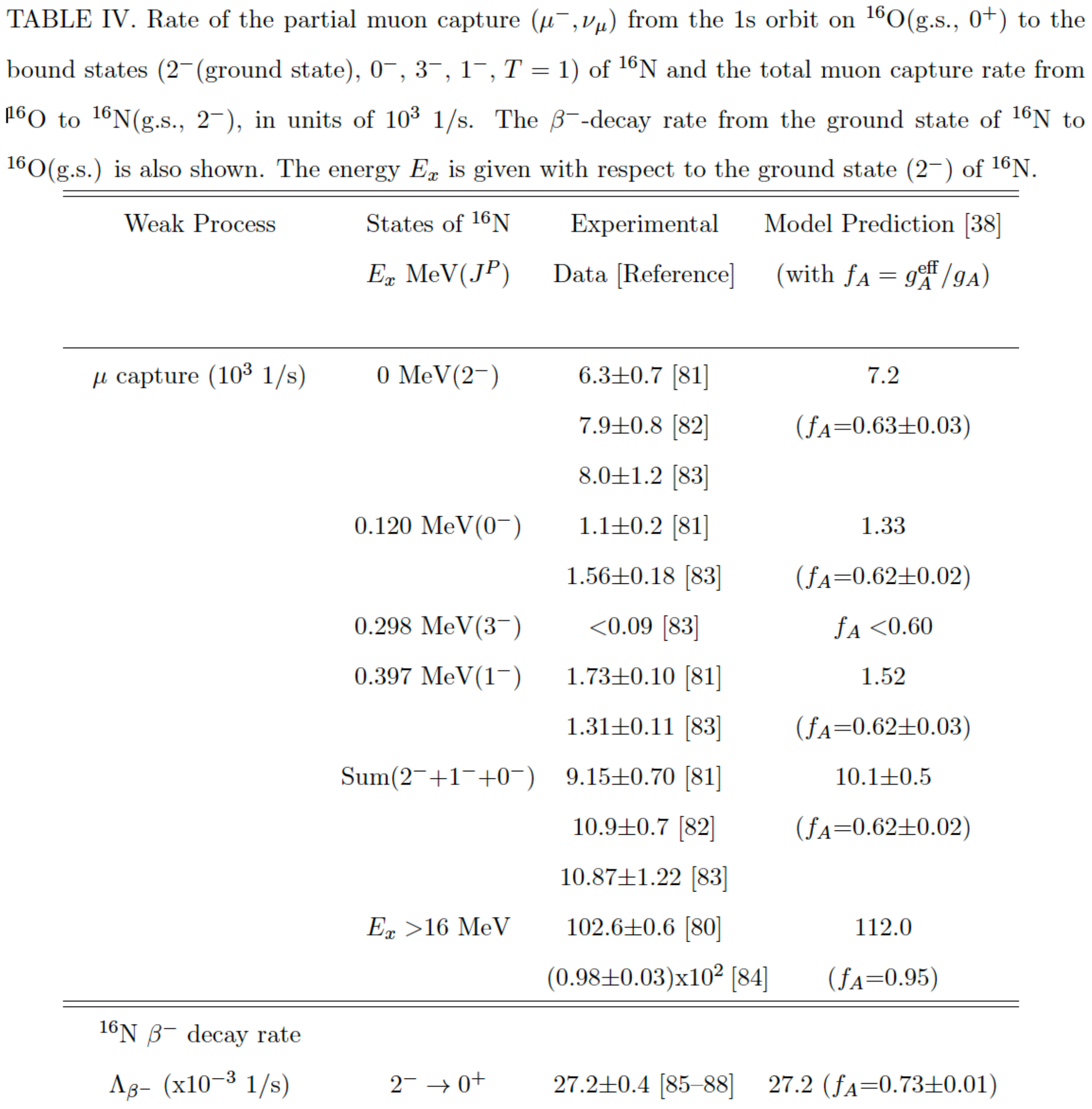


TABLE IV. Rate of the partial muon capture (μ^-,ν_μ) from the 1s orbit on ^{16}O(g.s., 0^+) to the bound states (2^-(ground state), 0^-, 3^-, 1^-, $T=1$) of ^{16}N and the total muon capture rate from ^{16}O to ^{16}N(g.s., 2^-), in units of 10^3 1/s. The β^--decay rate from the ground state of ^{16}N 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 [Reference]	Model Prediction [38] (with $f_A = g_A^{\rm eff}/g_A$)
μ capture (10^3 1/s)	0 MeV(2^-)	6.3±0.7 [81]	7.2
		7.9±0.8 [82]	(f_A=0.63±0.03)
		8.0±1.2 [83]	
	0.120 MeV(0^-)	1.1±0.2 [81]	1.33
		1.56±0.18 [83]	(f_A=0.62±0.02)
	0.298 MeV(3^-)	<0.09 [83]	f_A <0.60
	0.397 MeV(1^-)	1.73±0.10 [81]	1.52
		1.31±0.11 [83]	(f_A=0.62±0.03)
	Sum(2^-+1^-+0^-)	9.15±0.70 [81]	10.1±0.5
		10.9±0.7 [82]	(f_A=0.62±0.02)
		10.87±1.22 [83]	
	E_x >16 MeV	102.6±0.6 [80]	112.0
		(0.98±0.03)x10^2 [84]	(f_A=0.95)
^{16}N β^- decay rate			
Λ_{β^-} (x10^{-3} 1/s)	$2^- \to 0^+$	27.2±0.4 [85–88]	27.2 (f_A=0.73±0.01)

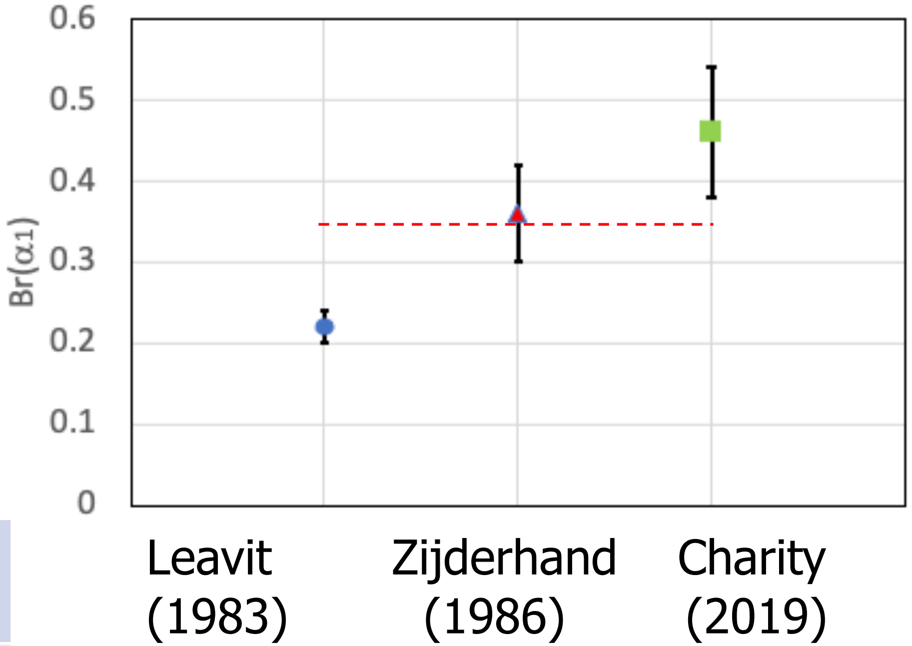
8. $\mathrm{Br}(\alpha 1) \equiv$ Br(12.97 MeV →α+^{12}C(4.4 MeV))

☐Three groups reported the values of the branching ratio
$\mathrm{Br}(\alpha 1) \equiv$ Br(12.97 MeV →α+^{12}C(4.4 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 $\mathrm{Br}(\alpha 1)$.

This is the isospin violating decay.

Experiment and analysis	Reaction	β or $\epsilon = \frac{\beta}{\sqrt{1-\beta^2}}$	$\mathrm{Br}(\alpha 1)$
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



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

(Short Summary) Parameters to calculate the NC 4.4-MeV γ ray production from $^{16}O(\nu,\nu')^{16}O(E_x=12.97$ MeV)

☐We have evaluated the following three quantities to calculate precisely the NC 4.4 MeV γ-ray production from $^{16}O(\nu,\nu')^{16}O(E_x=12.97$ MeV).

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

$f_s=0.65\pm0.05$ and $f_A=0.68\pm0.05$.

(2) The isospin mixing parameter $\beta=+0.25\pm05$ between 12.53 and 12.97 MeV.

(3) Mean value from three hadron-beam measurements: $\mathrm{Br}(\alpha 1) \equiv$ Br(12.97 MeV $\rightarrow \alpha+{}^{12}C(4.4$ MeV))=0.35. This is very uncertain (±50%).

☐We presented this cross section already in Pages 5-6.

9. Estimation of the NC 4.4-MeV γ ray production from ^{16}O(ν,ν')^{16}O(E_x=12.97 MeV) induced by Supernova neutrinos

☐We first use the normalized neutrino spectra (called KRJ fit with α and $\langle E_\nu \rangle$) as,

$$f(E_\nu) = \frac{(\alpha+1)^{\alpha+1}}{\Gamma(\alpha+1)\langle E_\nu\rangle^{\alpha+1}} E_\nu^\alpha \exp\left(-\frac{(\alpha+1)E_\nu}{\langle E_\nu\rangle}\right)$$

The parameter α values of 2-4 are recommended by KRJ. We take $\langle E_\nu \rangle$=10-14 MeV.

☐ And we define the Supernova (SN) neutrino spectrum at the SN core as,

$$\frac{dN_\nu}{dE_\nu} = \frac{E_\nu^{\rm tot}}{\langle E_\nu\rangle} f(E_\nu)$$, $E_\nu^{\rm tot}$=5x10^{52} erg. →Fig.

- Peak or <En>~10 MeV. Majority of the spectrum is contained below E_ν<30 MeV.

☐The SN neutrino flux at the SK is given by

$$F(E_\nu) = \frac{1}{4\pi d_{\rm SN}^2} \frac{E_\nu^{\rm tot}}{\langle E_\nu\rangle} f(E_\nu)$$, d=10kpc.

☐We estimate the visible energy for IBD events and the NC γ events for 32 kton water.
→Fig.

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

- ☐Figure shows E_{vis} using the typical SN_{ν} spectrum at SK.
- ☐IBD events ($\bar{\nu}_e p \rightarrow e^+ n$) can be identified and reconstructed unambiguously by the delayed coincidence method in the SK-Gd detector and that the $\bar{\nu}_e$ spectrum can be measured from the visible energy using the relation $E_{\bar{\nu}_e} = E_{vis} + 1.8$ MeV.
- ☐NC γ rays (E_{γ}) produce E_{vis}~Eγ, regardless of E_{ν}.

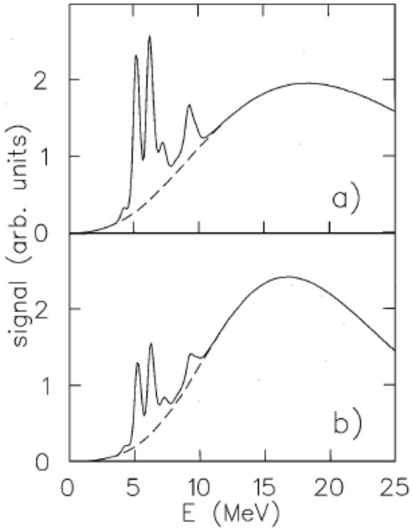
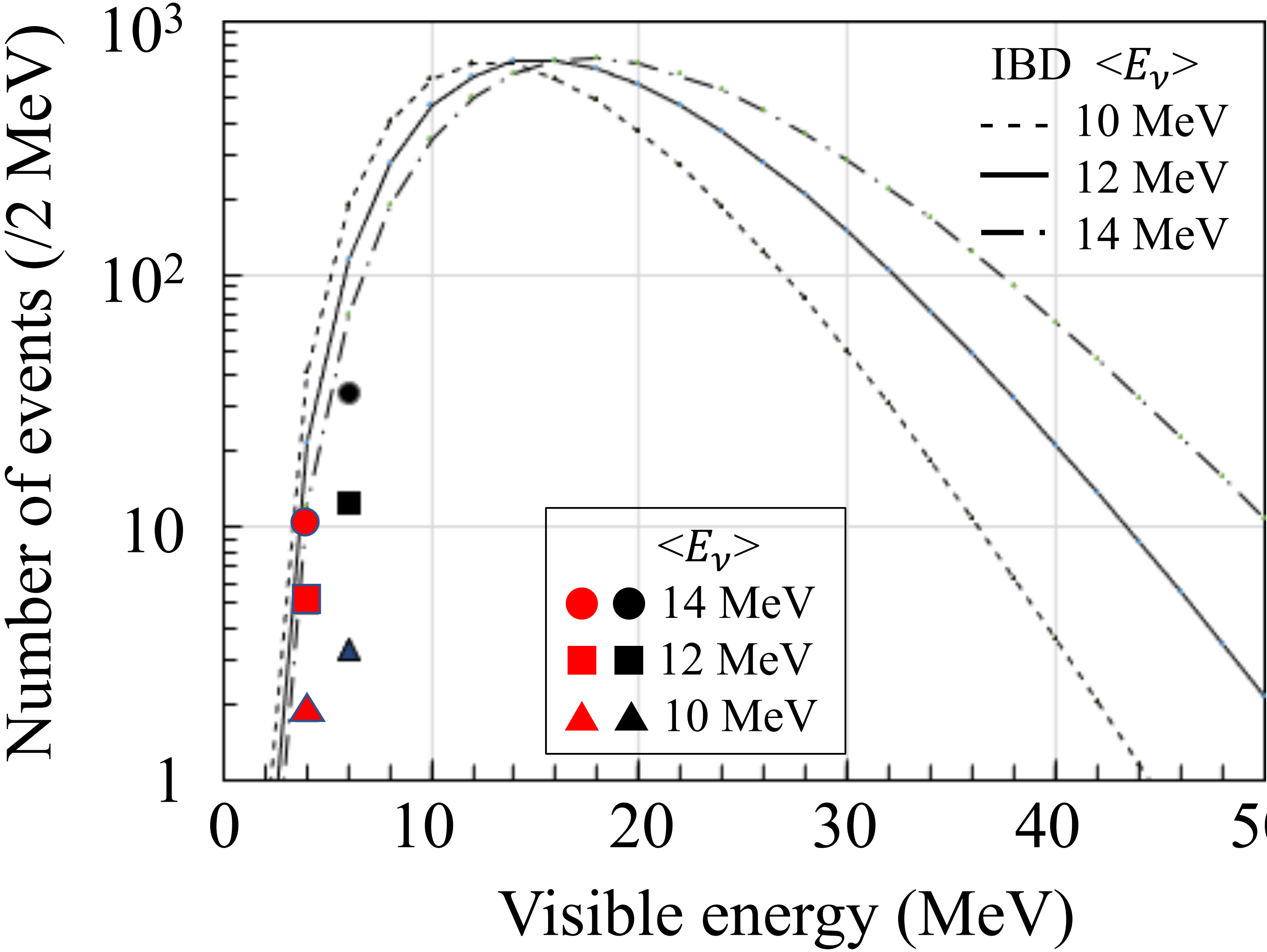


FIG. 2. Signal expected from supernova neutrinos in a water



10. Summary

☐ We have evaluated the following three quantities to calculate precisely the NC 4.4 MeV γ-ray production from $^{16}O(\nu,\nu')^{16}O(E_x=12.97$ MeV).

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

$f_s=0.65\pm0.05$ and $f_A=0.68\pm0.05$.

(2) The isospin mixing parameter $\beta=+0.25\pm05$ between 12.53 and 12.97 MeV.

(3) Mean of the three measurements: $\mathrm{Br}(\alpha 1) \equiv$ Br(12.97 MeV →$\alpha+^{12}C$(4.4 MeV))=0.35. This is very uncertain (±50%).

☐ We then discussed a new NC reaction channel from ^{16}O(12.97 MeV, 2-).

- The cross section is more robust since the form factor is more accurate than those for Ex>16 MeV. ±20%.
- The cross section is even larger at the low energy (E < 25 MeV) than the NC cross section for Ex > 16 MeV, though the 4.4-MeV γ-ray emission probability of ^{16}O(12.97 MeV, J=2-) is still uncertain. ±50%.

☐ We point out a possible detection of 4.4-MeV γ rays produced in the neutrino NC reaction $^{16}O(\nu,\nu')^{16}O(E_x=12.97$ MeV) with a water Cherenkov detector in the SN neutrino bursts.

☐ We hope that new measurements of the cross section of $^{16}O(e,e')^{16}O$ (12.53 MeV, 12.97 MeV, 2-) and the branching ratios of ^{16}O(12.53 MeV, 12.97 MeV,2-) decaying to p and α channels will be performed with better accuracy in the near future at the low-energy electron accelerators (E_e=30-80 MeV). It will resolve the conflicting measurements of $\mathrm{Br}(\alpha 1) \equiv$ Br(12.97 MeV →$\alpha+^{12}C$(4.4 MeV)) in the hadron beam experiments.

Outlook

- Yesterday: Outlook by N.Steinberg (e&ν, CLAS) for T2K and DUNE.

“Electrons For Neutrinos – The Next Generation”.

→Similarly: Outlook For Low-Energy Neutrino Interactions:

☐ We do need the low-energy electron beams & experiments (E_e<100 MeV) to measure (e,e’) inelastic scattering data of ^{16}O (^{12}C and Ar) precisely. If we combine them with new ν data 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 projects:

- ● 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)