# Measurement of γ rays from giant resonances of $^{12}C/^{16}O(p,p')$ and its application to γ production in NC νC/O reactions (p1

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@ SN Workshop, 2018.01.09

Outline

1. Purpose of E398 C,O(p,p′) and Results (須藤)
2. Feature of γ production in NC νC/O reaction
3. Evaluation of SN events
4. Summary

Support from RCNP and JSPS Grant-In-Aid:
*(B) [2012-2014] ″Study of γ-rays from p-O interaction for ν-O reaction experiment″
*Innovative Areas (A Planned Research) [2014-2018]
"History of star formation through observations of Supernova Relic Neutrinos"

# Neutrino Bursts from SN explosion@10kpc (p3

■ The number of events observed in the detectors

□ Super Kamiokande ($H_2O$)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ ~8000 events

$$NC : \nu_x + {}^{16}O \rightarrow \nu_x + X + \gamma \; (\nu_x = \nu_\mu, \nu_\tau)$$ ~700 ? events

□ KamLAND ($CH_2$) 1kton [Inoue@RCNP]

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ ~300

$$NC : \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \; (15.1 MeV)$$ ~60

$$NC : \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \; (E_X > 16 MeV の巨大共鳴)$$ ~60 ?

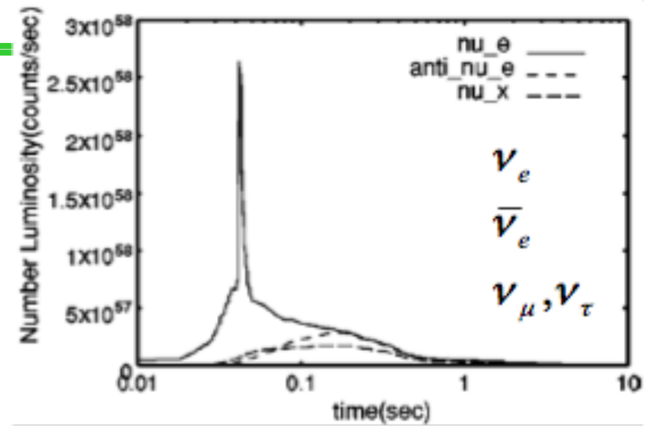
NC: ν+p→ν+p (Inoue@RCNP) ~300

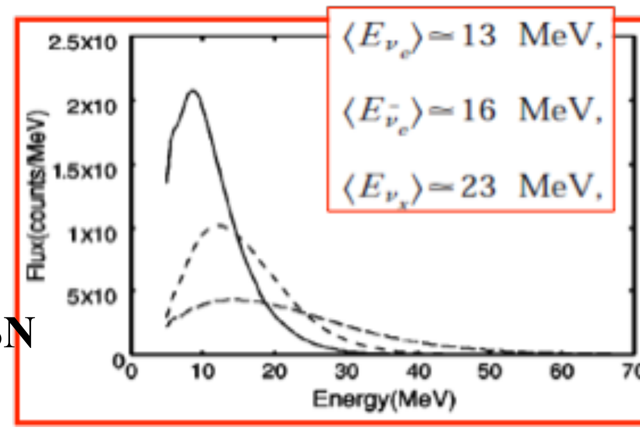
■ **Importance of NC events**

✓ **The 2nd larget reaction and no one has measured them in SN bursts**

✓ **μ,τ –type neutrino-induced events dominate NC reactions since energy (Temperature) is higher than e-type.**

✓ **Independent of neutrino oscillations**




□ It is important to measure both CC signals and NC γ events.

We Do need to Measure Br(C*,O*→γ) = Γγ/Γ ($E_x$). --- Purpose of RCNP E398.

# Neutrino bursts from SN explosion at 10kpc, expected for $H_2O$ detector (22.5kton)

- NC $\gamma$-ray Calculations by Langanke,Vogel,Kolbe,PRL76,2629,'96; Beacom-Vogel,PRD58,053010,'98.

- M.Ikeda et al (SK collab), APJ669,619('07): Evis>18MeV.
- NC $\gamma$ 500 ev?

$$NC\gamma : \nu_x + O \rightarrow \nu_x + X + \gamma \ (\nu_x = \nu_\mu, \nu_\tau) \quad (5\%/6\%) \quad (7)$$

CC:

$$\overline{\nu}_e + p \rightarrow n + e^+ \quad (88\%/89\%), \quad (1)$$

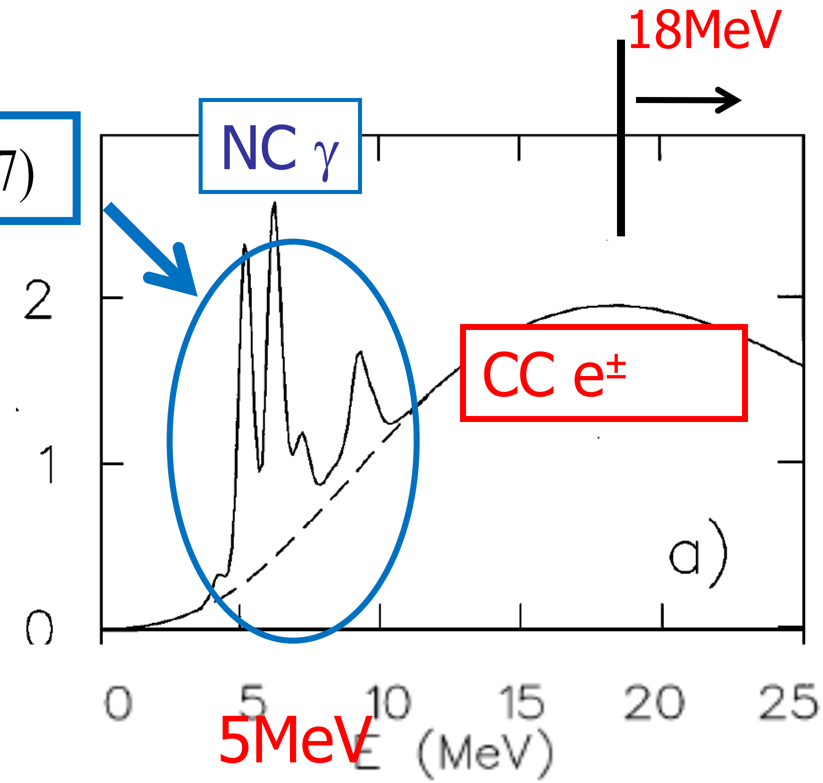
$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (1.5\%/1.5\%), \quad (2)$$

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^- \quad (<1\%/<1\%), \quad (3)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (1\%/1\%), \quad (4)$$

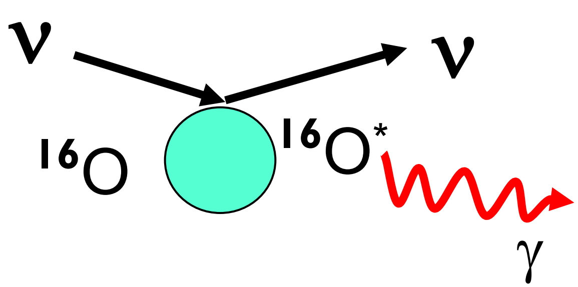
$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F \quad (2.5\%/<1\%), \quad (5)$$

$$\overline{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N \quad (1.5\%/1\%), \quad (6)$$

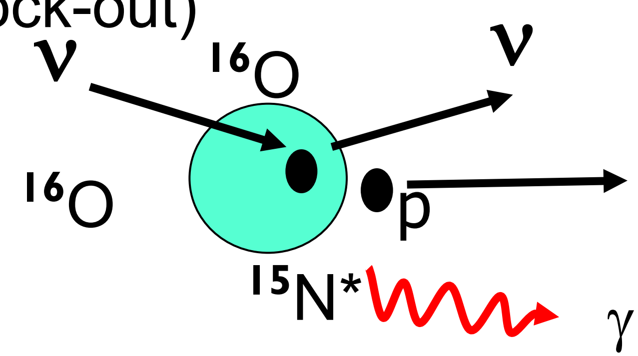


# Feature of $\gamma$-ray production of NC $\nu$-O (-C) reactions (p4

1) $E_\nu$<100MeV: Elastic and Inelastic




2) $E_\nu$>100MeV: Quasi-elastic (1N knock-out)




1)$E_\nu$<100MeV: Inelastic scattering (Giant resonances) +Elastic [CEvNS,not shown]

- $\nu$C,O→$\nu$C*,O*→$\gamma$ : Langanke et al., *Phys.Rev.Lett.*76(1996).
  - They calculate $\nu$O,C→$\nu$C*(15.1MeV) and O*→$\gamma$(>5MeV).
- We (RCNP E398) measure Br(C*,O*→ $\gamma$(>1.5MeV) and reevaluate SN rate.

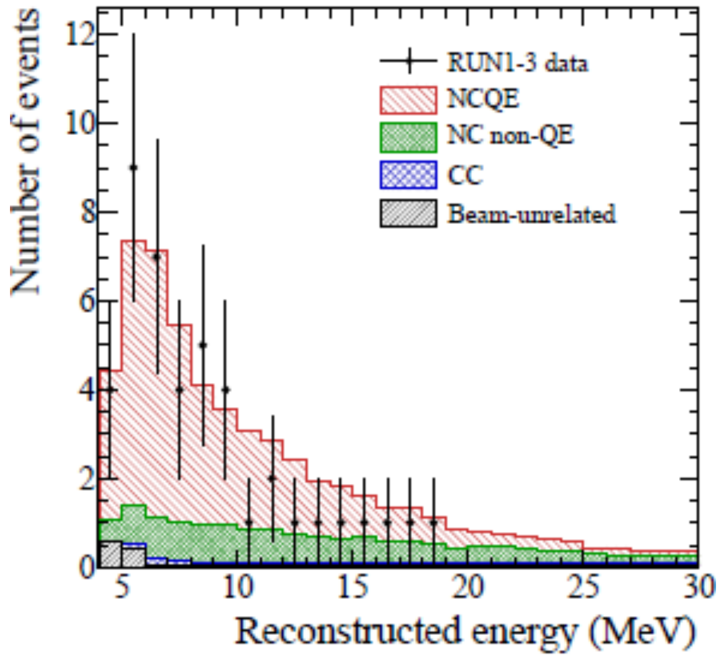
2) $E_\nu$>100MeV: Nucleon knockout(Excitation of residual nucleus).

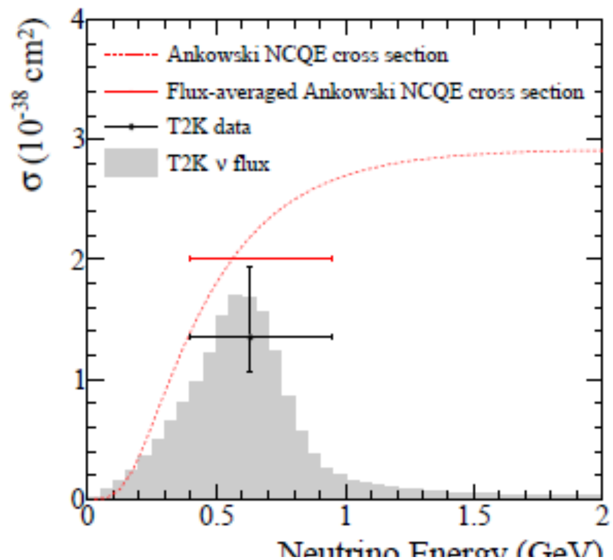
- $\nu$O→$\nu$+p/n+$^{15}$N$^*$/$^{15}$O$^*$ Ankowski,Benhar,MS et al.*Phys.Rev.Lett.***108**(2012)052505
- $\nu$C→$\nu$+p/n+$^{11}$B$^*$/$^{11}$C$^*$: I comment How different C is from O?
- Experiments:T2K, RCNP E148 O(p,2p$\gamma$)

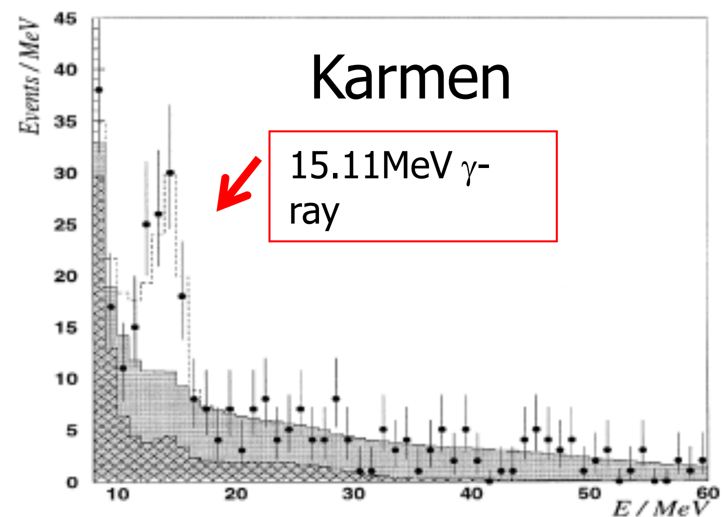
# Experiments: T2K NC $\gamma$ production and Karmen NC $\gamma$ production +CEvNS (Scholberg's talk, not shown here)

(p5

T2K 6MeV $\gamma$ from $^{15}N/^{15}O$ — T2K and Ankowski et al, PRL108



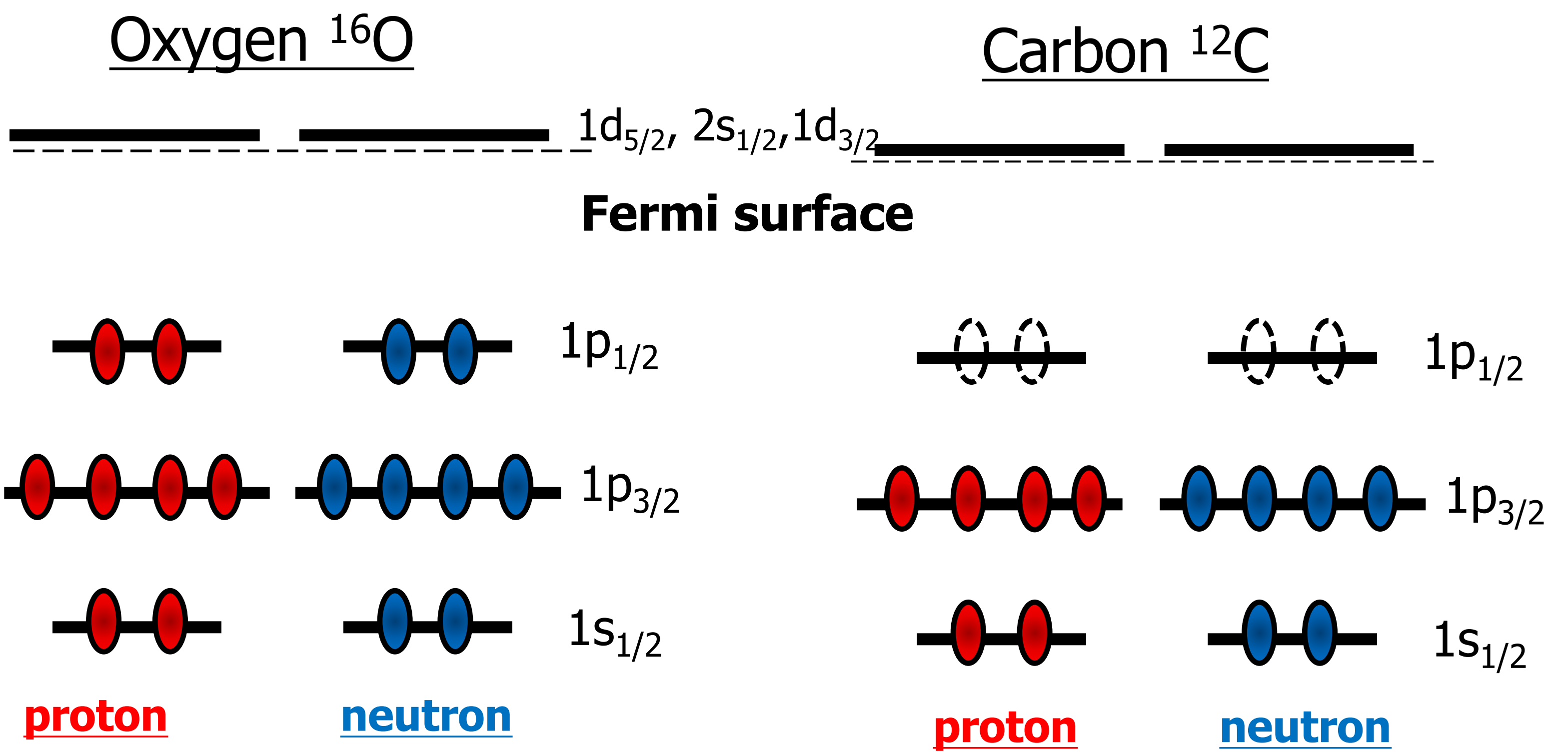

- T2K data is consistent with Ankowski et al.

- KARMEN @$E_\nu$=29.8MeV
- $(3.2\pm0.5\pm0.4)\times10^{-42}cm^2$

In good agreement with the calculation

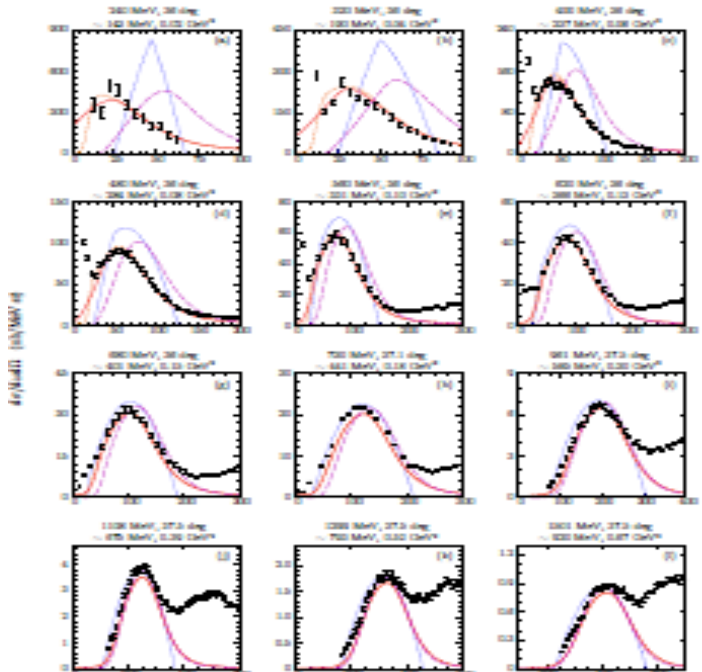
# Oxygen and Carbon (Shell Structure)

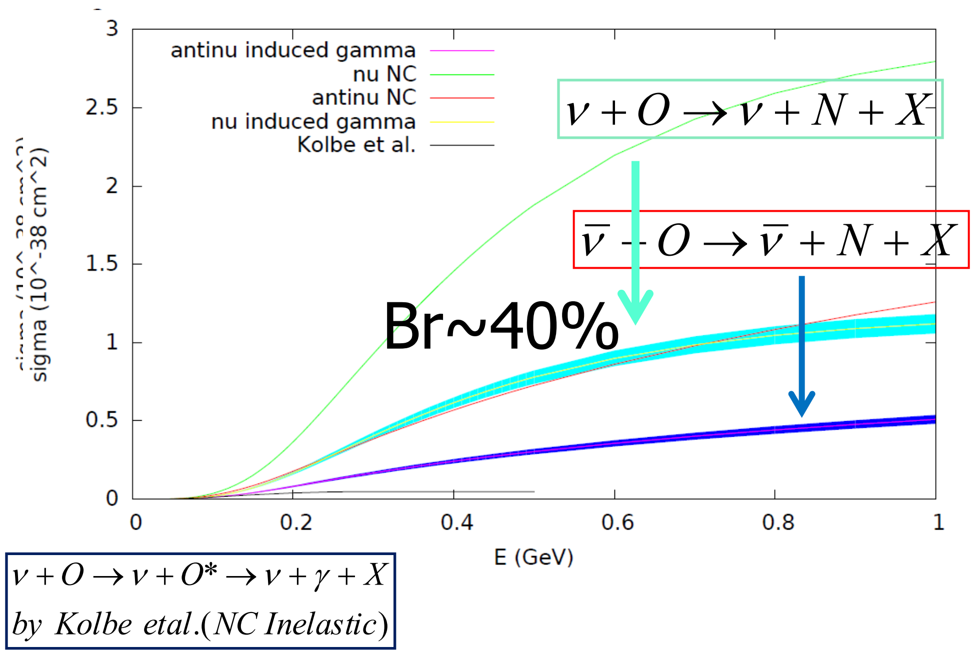
- You learn a single particle model or a shell model in nuclear physics.
- Shell structure of $^{16}O$ and $^{12}C$.



# (1) NC QE $\gamma$ Production ($\nu O \rightarrow \nu + p/n + {}^{15}N^*/{}^{15}O^*$)

- Impulse Approximation with Spectral Function O,C(e,e')
  - Benhar,MS et al., PRD72,053005('05); O(e,e')
    Ankowski,Benhar,MS:PRD91,033005('15). C(e,e')
- Production of $\gamma$-rays (>5MeV) in NC QE is significant (Br~ 40% for O). Ankowski,MS et al, PRL 108,052505('12)
- Note:6MeV$\gamma$ happens in CCQE or even Delta. 1N knockout is the point.



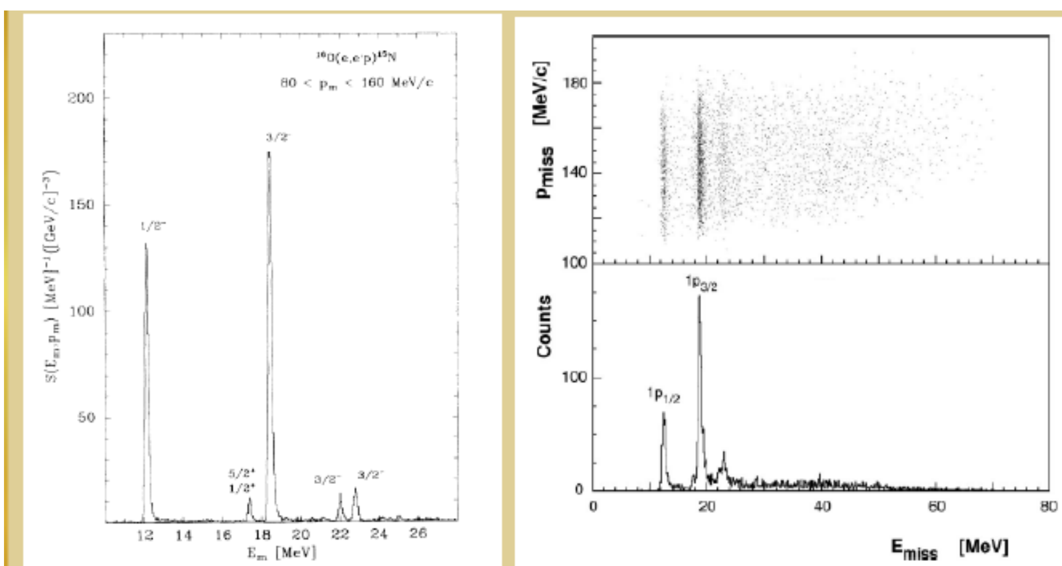


# Qualitative Estimate (For Quantitative Estimate, refer to AnkowskiPRL)

- $p_{3/2}$ knockout gives 6-MeV $\gamma$, which contributes mainly to $\gamma$ production.
- Rough Estimate: Br=0.7x($p_{3/2}$ 4/8*1.0+$s_{1/2}$ 2/8*0.15)=0.38.

$\sigma$(NC $\nu$O $\gamma$)~$\sigma_{NCQE}$*0.38

- Note: Spectral Function not only gives (p,E) of a nucleon in O, but also gives a spectroscopic factor of $p_{1/2}$, $p_{3/2}$ and $s_{1/2}$ .




M. Leuschner *et al.*,

K.G. Fissum *et al.*,

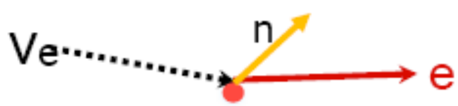
# γ-ray production in NC QE ν-O reactions
# --Important Background to SRN – (Copy from Sekiya)

## BG source: atmospheric neutrino

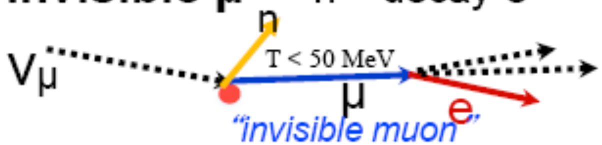
–H.Sekiya@Neutrino2016

- CC

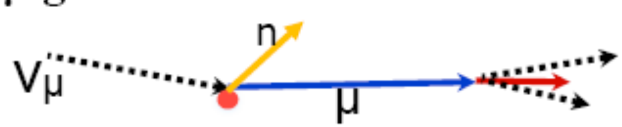
(anti-)$\nu_e$ CC




**Invisible μ** n + decay-e

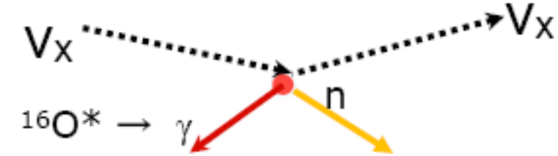


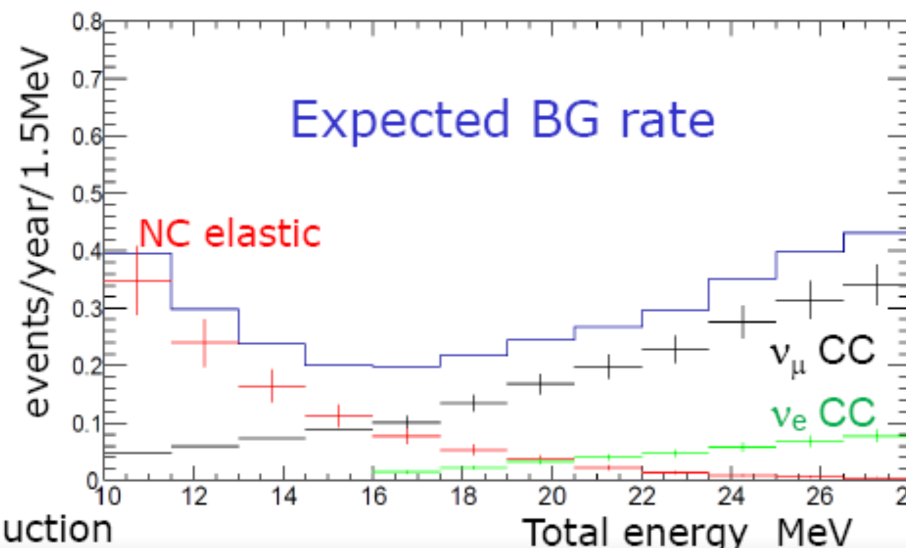

**μ generation**




- NC QE

NC elastic de-excitation γ



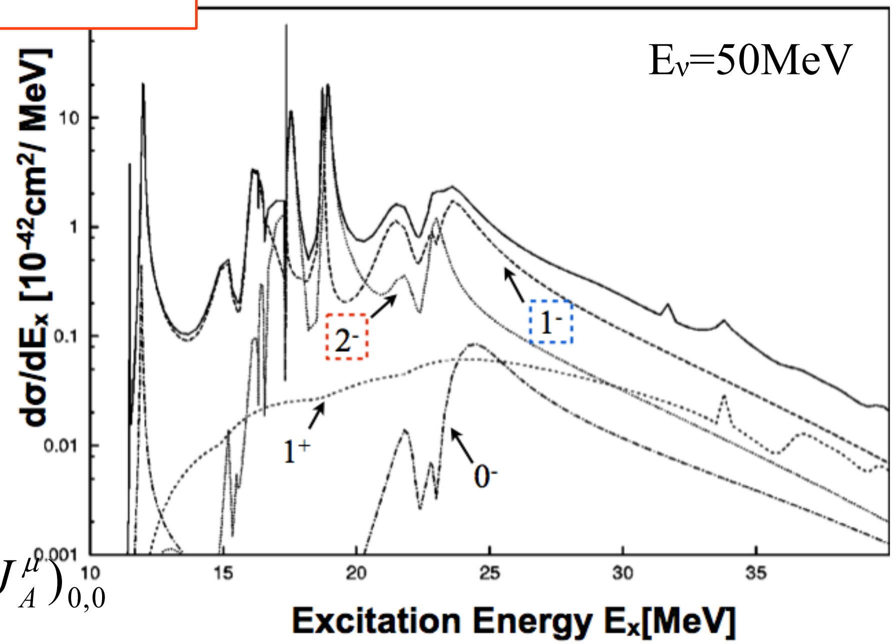

N.B. Vertex information gives further BG reduction

# (2) NC ν-$^{16}$O,$^{12}$C Inelastic reaction
(p6

**Ref.** Langanke et al., *Phys.Rev.Lett.***76**(1996).
**Jachowicz et al .,PRC59( '99), Botrugno, Co', NPA761('05)**

Axial Current Dominant:
Especially, Spin Dipole Resoance : $J^P = 2^-, 1^-$(T=1) Domiant.
( $1^+$,15.1MeV for C)

$^{16}$O(ν,ν' ) Cross Section




✦NC Neutrino-Nucleus Cross Section :

**ν**+A→**ν**+A' : Nuclear Matrix Element

$$J^{\mu}_{em} = (J^{\mu}_{V})_{1,0} + (J^{\mu}_{V})_{0,0}$$

$$J^{\mu}_{CC} = (J^{\mu}_{V})_{1,\pm1} + (J^{\mu}_{A})_{1,\pm1}$$

$$J^{\mu}_{NC} = \beta^1_V (J^{\mu}_{V})_{1,0} + \beta^1_A (J^{\mu}_{A})_{1,0} + \beta^0_V (J^{\mu}_{V})_{0,0} + \beta^0_A (J^{\mu}_{A})_{0,0}$$

$$= (J^{\mu}_{V})_{1,0} + (J^{\mu}_{A})_{1,0} - 2\sin^2\theta_W J^{\mu}_{em} \quad [+(J^{\mu}_{A})_{0,0}]$$

✦GDR ($J^p=1^-$,ΔT=1,ΔS=0,ΔL=1) : $f_1(r)Y_1^m\tau_3$

Spin Dipole R ($J^p=0^-,1^-,2^-$, ΔT=1,ΔS=1,ΔL=1) : $\vec{\sigma} f_1(r)Y_1^m\tau_3$

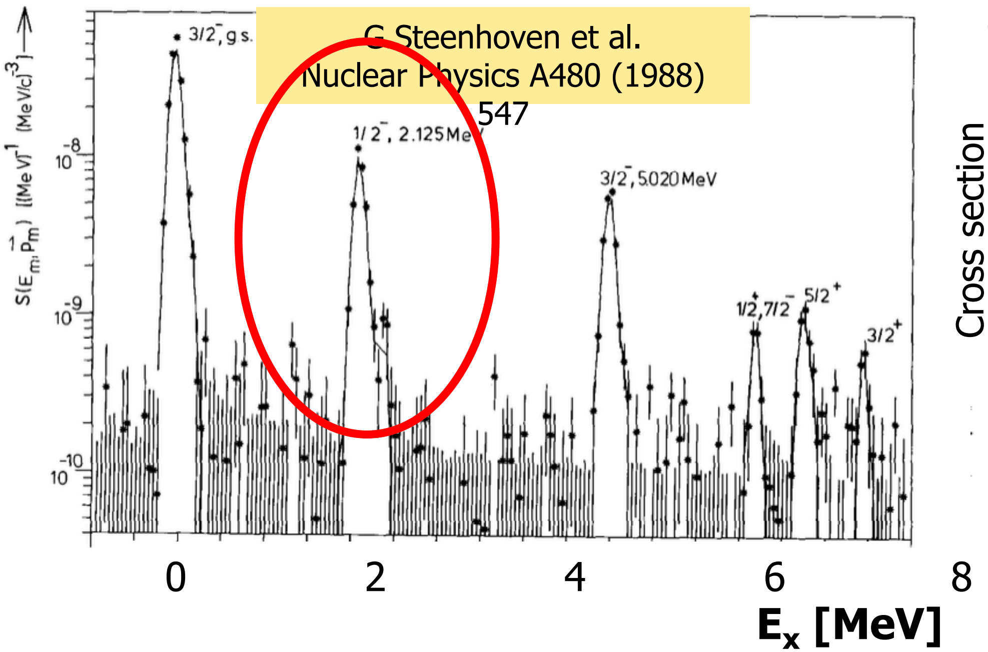
**M1** ($J^p=1^+$,ΔT=1,ΔS=1,ΔL=0) : $\vec{\sigma} f_0(r)\tau_3$

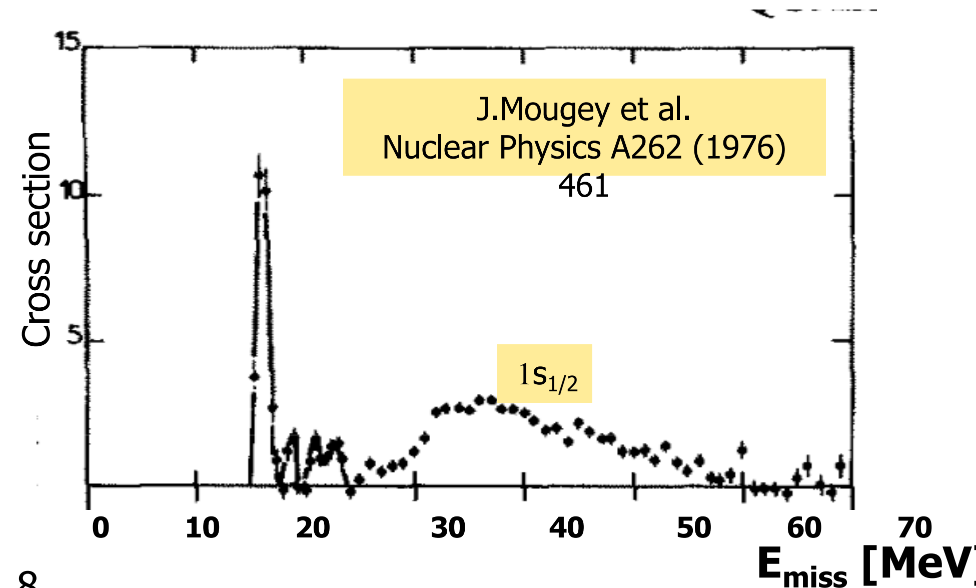
# What about Carbon? $\nu C \rightarrow \nu + p/n + {}^{11}B^*/{}^{11}C^*$

- Is $\nu C \rightarrow \nu + p/n + {}^{11}B^*/{}^{1?1}C^*$ similar to $\nu O \rightarrow \nu + p/n + {}^{15}N^*/{}^{15}O^*$?

# Quasi-free knockout for $^{12}C$

$^{12}C(e,e'p)^{11}B$ スペクトル関数

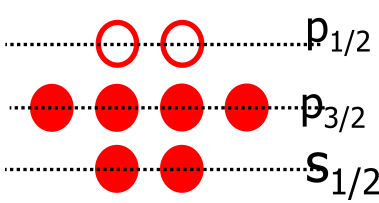



$P_{1/2}$も$p_{3/2}$の20%位混ざっている。従って、γ線が出る。

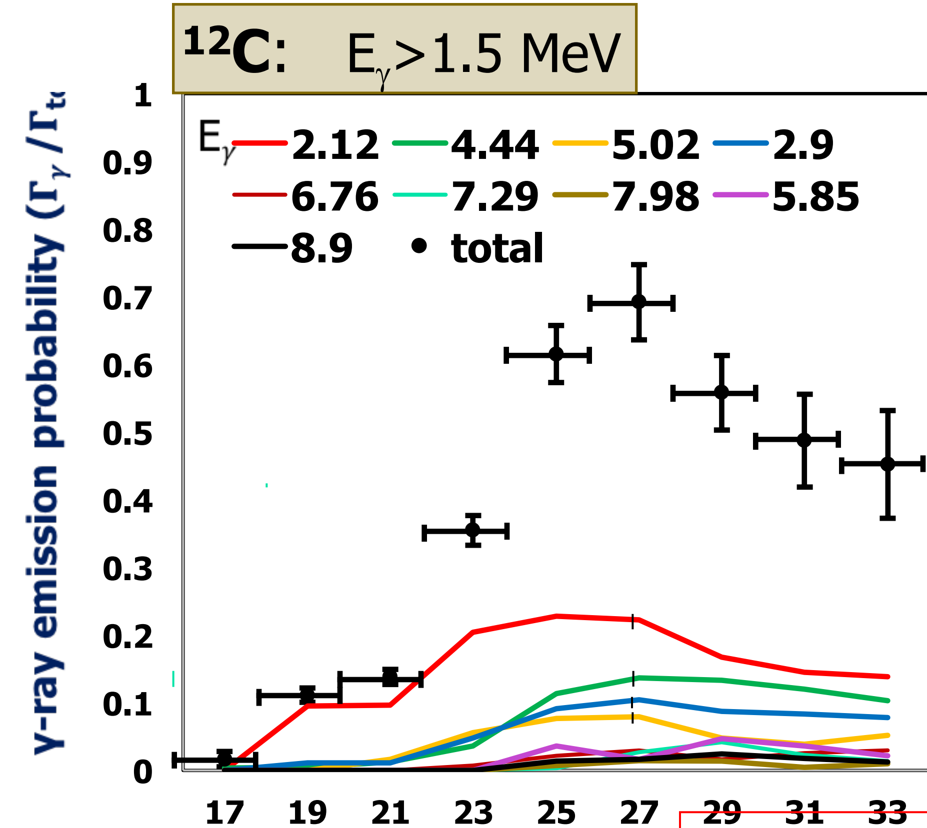
- ✓ 現在、スペクトル関数含め、再評価中。多分QE断面積の10%程。

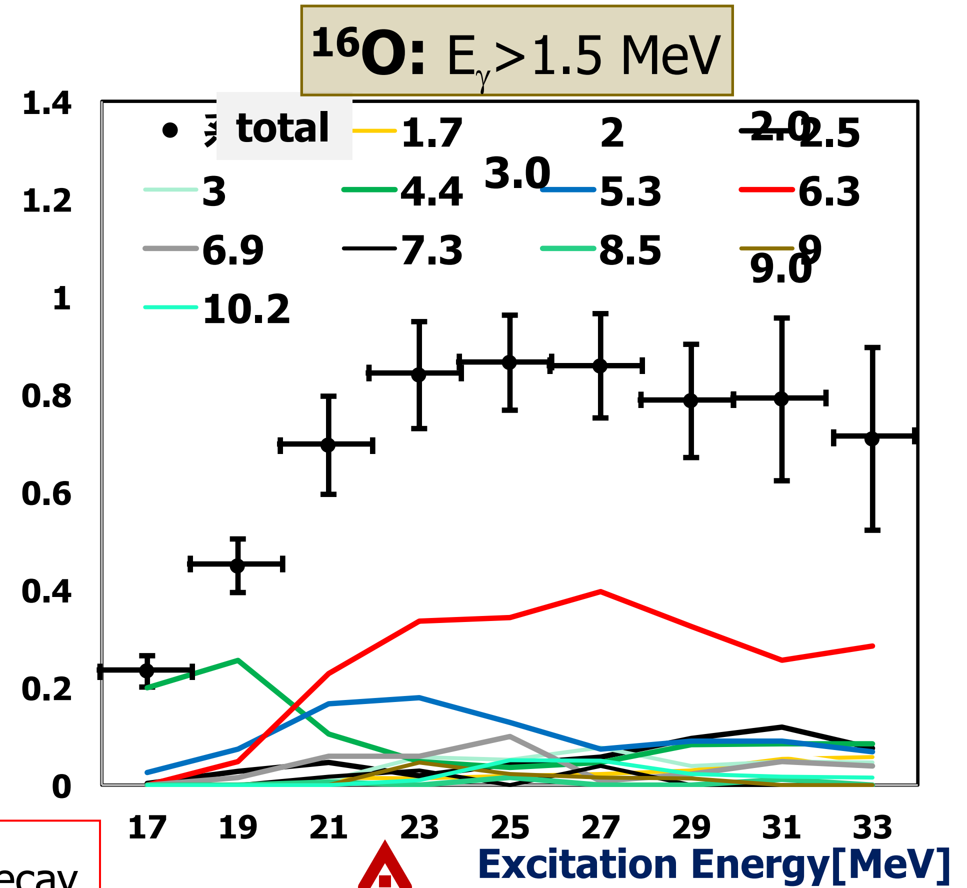
$^{12}C$ shell、簡単でない:



# $\gamma$-ray emission probability ($\Gamma\gamma/\Gamma$ (Ex))

The energy spectrum of $\gamma$-rays from giant resonances of $^{12}C$ and $^{16}O$ and the emission probability have been measured for the first time as a function of Ex.




$S_p$ for 2N decay

# 誤差

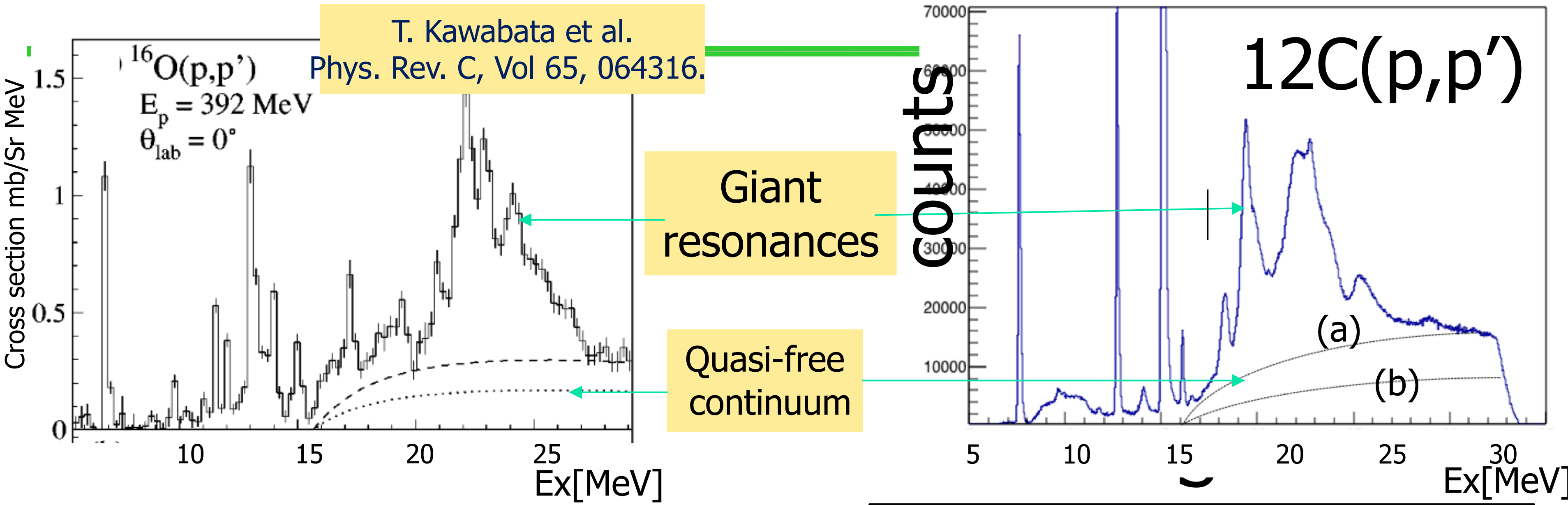
- 統計精度は、2–3%だが、系統誤差は、バックグランド差し引きから：5%–>10%. 鋭意努力中。

$^{12}C$:

| | | | Absolute Err | | Relative | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | range | B.R. | stat err. | Sys err | stat(fit err) | Sys err | sys err(g_BG) | Sys err(eff.) | sys err(Nex) |
| 16 | 18 | 1.67E-02 | 2.81E-03 | 5.34E-03 | 1.68E-01 | 0.319 | 0.303 | 0.05 | 0.086 |
| 18 | 20 | 1.11E-01 | 1.56E-03 | 1.03E-02 | 1.40E-02 | 0.092 | 0.072 | 0.05 | 0.029 |
| 20 | 22 | 1.38E-01 | 2.05E-03 | 1.04E-02 | 1.48E-02 | 0.075 | 0.048 | 0.05 | 0.029 |
| 22 | 24 | 3.55E-01 | 3.27E-03 | 2.06E-02 | 9.22E-03 | 0.058 | 0.017 | 0.05 | 0.024 |
| 24 | 26 | 6.15E-01 | 9.42E-03 | 3.24E-02 | 1.53E-02 | 0.052 | 0.009 | 0.05 | 0.013 |
| 26 | 28 | 6.92E-01 | 1.12E-02 | 4.54E-02 | 1.61E-02 | 0.065 | 0.010 | 0.05 | 0.041 |
| 28 | 30 | 5.58E-01 | 1.27E-02 | 4.17E-02 | 2.27E-02 | 0.074 | 0.023 | 0.05 | 0.050 |
| 30 | 32 | 4.87E-01 | 1.05E-02 | 6.16E-02 | 2.16E-02 | 0.126 | 0.030 | 0.05 | 0.112 |
| 32 | 34 | 4.52E-01 | 1.46E-02 | 6.76E-02 | 3.22E-02 | 0.149 | 0.022 | 0.05 | 0.139 |

# Quasi-free knockout for $^{12}C$

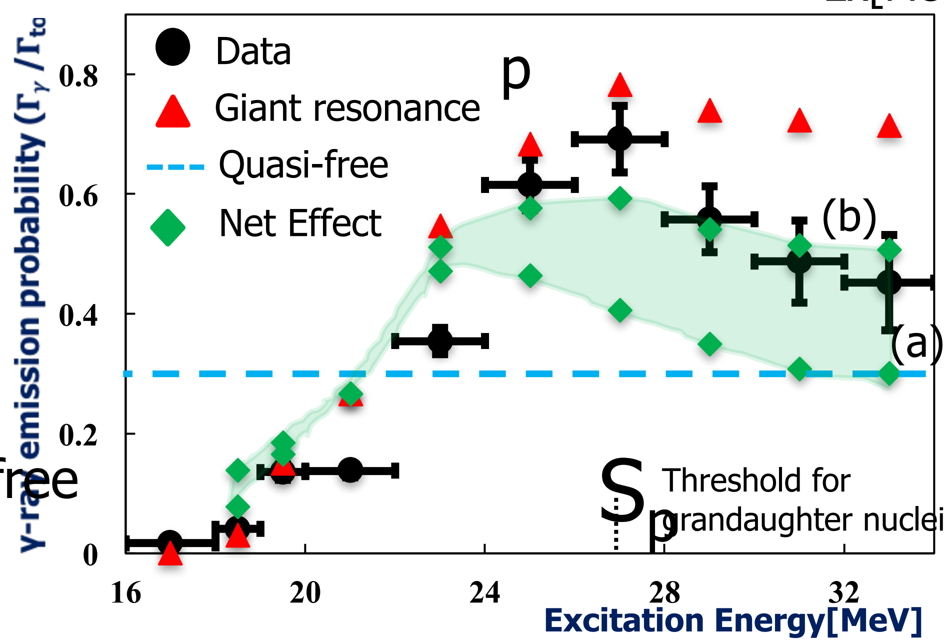





We assume both giant resonances and quasi-free knockout.

This is the first approximation after considering quasi free knockouts and sequential decays.

We still better understanding of Quasi-free knockout processes.



# Summary (of data analysis)



- We have carried out E398 in 2014 to measure γ rays from giant resonances of $^{12}C$ and $^{16}O$ using Grand Raiden (GR) and an array of NaI(Tl) γ-ray counters.
  - Good control of γ-ray Response Functions using radioactive sources and known γ-ray levels (2.1,4.4,6.9, 15.1MeV) throughout the experiment was critical. →Sudo's talk
- GR-NaI Coincidence results: →Mandeep's talk
  - First measurement of the emission probability (Γγ/Γ(Ex)) as a function of Ex for 16-34 MeV (every 2 MeV).
  - The γ-ray energy spectra clearly show that γ rays are emitted from the excited states of the daughter nuclei after hadronic (p-/n-) decay of $^{12}C$ and $^{16}O$, qualitatively consistent with a prediction by Langanke (1996).
  - The γ-ray emission probability increases as Ex up to Γγ/Γ(Ex)=0.7 for $^{12}C$ at Ex=27 MeV and 0.9 for $^{16}O$ at Ex=23 MeV until the energy threshold for two nucleons decay, and then decreases gradually.

# 3. How to estimate the number of SN $\nu$'s

## ESTIMATION OF SUPERNOVA NEUTRINO EVENTS

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E398 results are applied for the estimation of $N_{NC_\gamma}$ for Super-K and KamLAND.

The expected number of events from the core-collapse:

$$N_i = Flux(\nu_j) \times n_{target} \times \sigma_i$$

Where $Flux(\nu_j) = \dfrac{L_{\nu_j}}{<E_{\nu_j}>} \dfrac{1}{4\pi D^2}$ and $\sigma_i$ is the cross section for reaction $i$

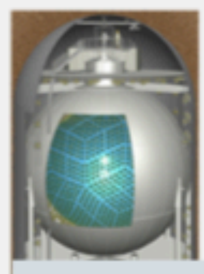
D = 10 kpc

Total Gravitational Energy

$L$ =3 x $10^{53}$ ergs

$\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, $\bar{\nu}_\tau$

$L$ divided equally among all species $L_{\nu_j} = \dfrac{L}{6}$

| KamLAND (1kton) | SK (32.48kton) |
|---|---|
|  |  |

$n_{target}$ is number of targets

| | |
|---|---|
| $n_{^{12}C}$ :$4.30\times10^{31}$ | $n_{^{16}O}$ :$1.09\times10^{33}$ |
| $n_p$ :$8.60\times10^{31}$ | $n_p$ :$2.17\times10^{33}$ |

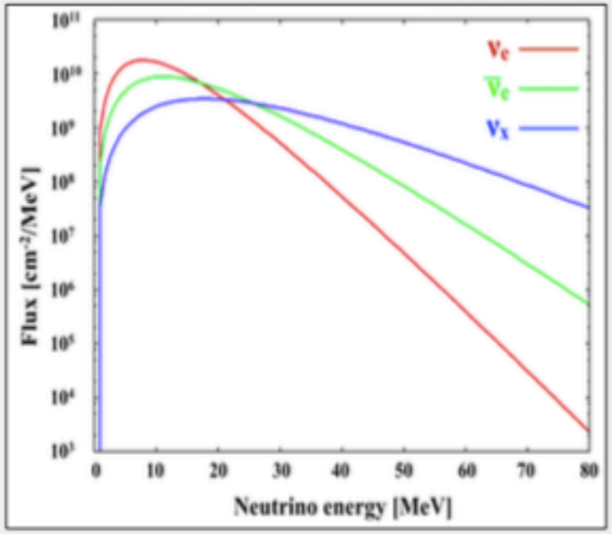
KamLAND collaboration: Phys. Rev. C 84 (2011) 035804.

# ASSUMPTIONS

The NC events are assumed to be induced by only $\nu_x$ ($\nu_\mu, \nu_\tau$ and their anti particles).

Equilibrium Temperature

$T_{\nu_e} = 3.5$ MeV
$T_{\bar{\nu}_e} = 5$ MeV
$T_{\nu_x} = 8$ MeV




Supernova neutrino spectra is approximated by that of Fermi-Dirac distribution.

$$FD\,(E, T_{\nu_j}) = \frac{0.553}{T_{\nu_j}^3} \frac{E^2}{1+\exp E/T_{\nu_j}}$$

Solving Analytically, we get Average Energy as:

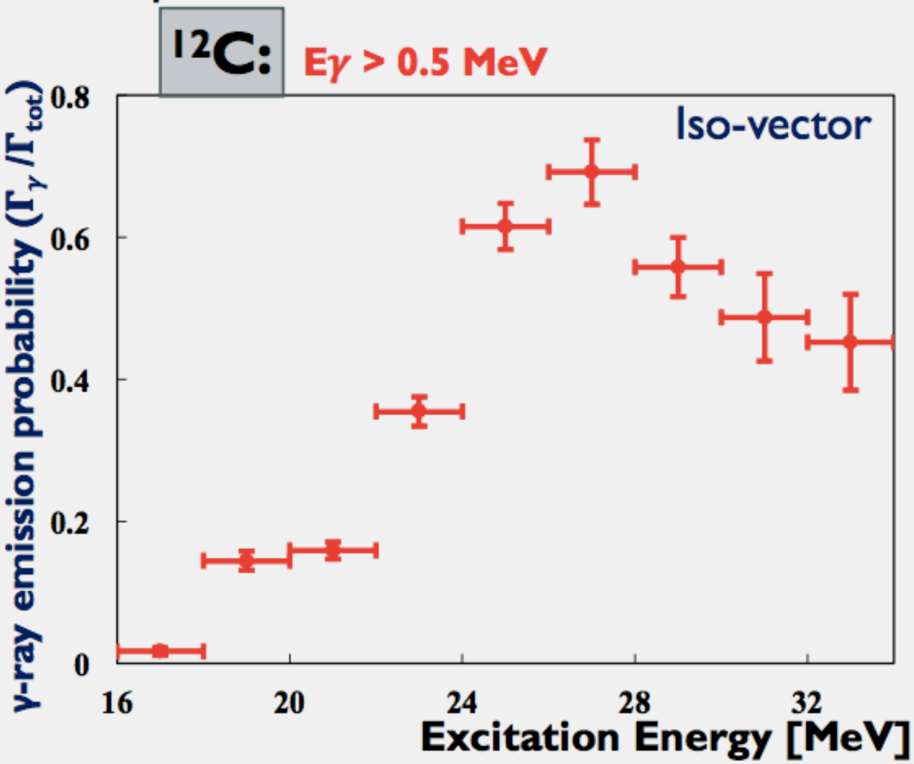
$$< E_{\nu_j} > = 3.15 \times T_{\nu_j}$$

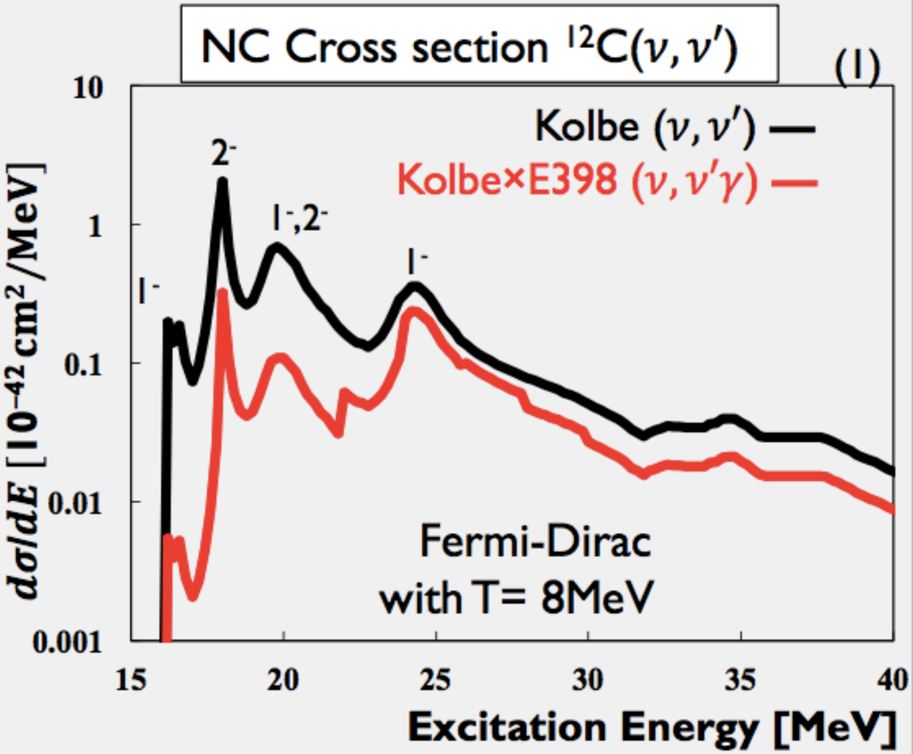
Now, we need cross section information

Ref. J. F. Beacom and M. R. Vagins: Phys. Rev. Lett. 93 (2004)

# INELASTIC SCATTERING CROSS SECTION: $^{12}C$

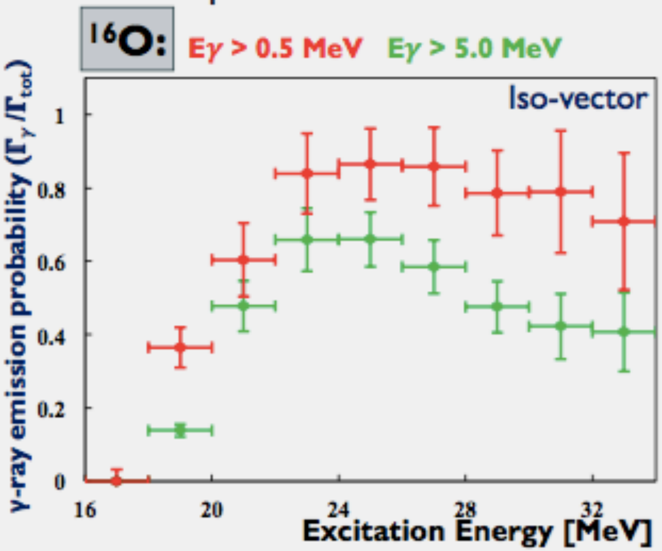
The differential inelastic scattering cross sections for $^{12}C(\nu,\nu')$ were folded by Fermi-Dirac spectrum.

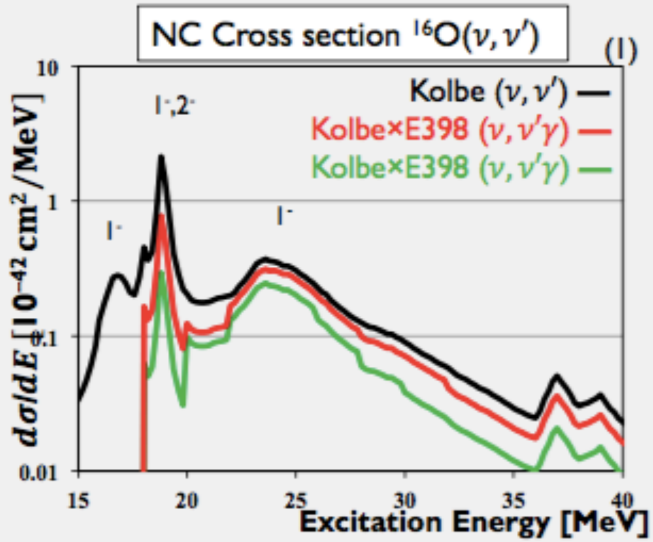


# INELASTIC SCATTERING CROSS SECTION: $^{16}O$

The differential inelastic scattering cross sections for $^{16}O(\nu,\nu')$ were folded by Fermi-Dirac spectrum.




This γ-ray emission probability takes into account γ-rays which are only from Iso-vector de-excitations.

$$\sigma_{NC\gamma} = \int_{S_p}^{70} \frac{d\sigma_{NC}}{dE_x} \times \frac{\Gamma_\gamma}{\Gamma}(E_x) dE_x$$

E398

$\sigma_{NC_\gamma} \rightarrow$ $^{16}O_{(E\gamma>0.5\ MeV)}$: **2.49 ± 0.33 x $10^{-42}$ cm$^2$**

$^{16}O_{(E\gamma>5.0\ MeV)}$: **1.60 ± 0.24 x $10^{-42}$ cm$^2$**

(1) E. Kolbe et al Nucl. Phys. A540 (1992) 599.

# Summary –continued (SN events) →Mandeep's talk p21

- We have applied our measurement to the estimation of NC $\gamma$-ray events with KamLAND and Super-K from supernova explosion.

| Detector | Interaction | Reaction | $N_i$ (E398) | Other Calculations |
|---|---|---|---|---|
| KamLAND (1 kton) $E_\gamma > 1.5$ MeV | CC | $\nu_e + p \rightarrow e^+ + n$ | 320 | 330 |
| | NC | $\nu_x + {}^{12}C \rightarrow \nu_x + \gamma_{15.1} + {}^{12}C$ | 53 | 58 *(1) |
| | NC | $\nu_x + {}^{12}C \rightarrow \nu_x + \gamma + X$ | 20 ± 2 | - |
| Super-K $E_\gamma > 5.0$ MeV | CC | $\nu_e + p \rightarrow e^+ + n$ | 8120 | 8300 |
| | NC | $\nu_x + {}^{16}O \rightarrow \nu_x + \gamma + X$ | 720 ± 170 | 710 *(2) |
| | NC | $\nu_x + {}^{16}O \rightarrow \nu_x + \alpha + {}^{12}C + \gamma_{15.1}$ | 10±3 | |

(1) A. Suzuki: Nucl. Phys. B (Proc.Suppl.) 77 (1999) 171101

(2) J.F. Beacom, P.Vogel: Phys.Rev.D,vol.58,053010

# まとめ:C01の活動の中で何をどうまとめるか。

- RCNP E398 実験:系統誤差の決定を早く決める。(須藤・Mandeep)
  - 炭素・酸素原子核の巨大共鳴の粒子崩壊でのγ線生成率 ーE$\gamma$=2-11MeV, Br=70-80%
  - (予想外の嬉しい信号)炭素・酸素原子核の巨大共鳴の電磁崩壊でのγ線生成率 -E$\gamma$=16-35MeV, Br=0.3%
  - 粒子崩壊と電磁崩壊と組み合わせ、巨大共鳴崩壊の原子核物理としてのより良い理解。
- E398 実験結果を使った応用
  - 超新星爆発でのニュートリノ炭素・酸素中性カレント事象数を出す。
    - 中里/鈴木GrのFlux+鈴木俊夫氏の計算＋E398実験結果で系統的な評価。
  - 巨大共鳴の直接崩壊E$\gamma$=16-35MeVの生成率は、実験屋にとっては2次粒子(n,p,$\gamma$)の相互作用として重要(であると思う)。
- $^{157}$Gd(n,$\gamma$)結果とりまとめ中。(田中君のポスター)
- 現象論的解析:$^{12}$Cのスペクトル関数を決めて、NC QE $\nu$C のγ生成断面積も計算する。(Ankowski,Benhar+岡山)