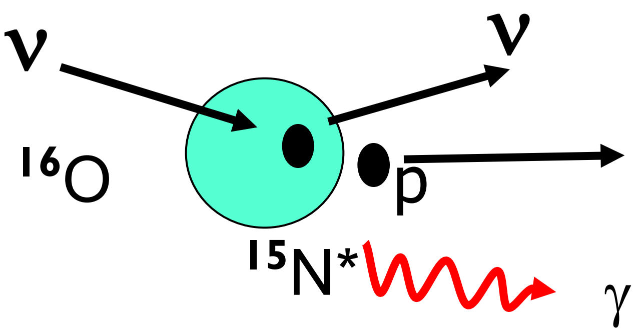
Gamma production from neutral-current neutrino-carbon and -oxygen interactions

Makoto Sakuda (Okayama) @ JPARC, 2017.11.19

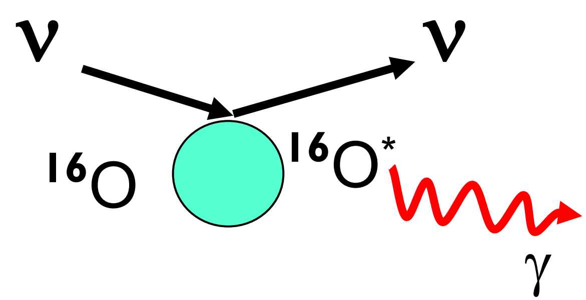
1. Feature of NC γ Production
2. NC QE γ Production (a la Ankowski et al., PRL108,'12)
3. NC Inelastic γ Production (RCNP E398 Result, New)
4. Summary

1. Feature of γ-ray production of NC ν-O (-C) reactions (p4

1) E_ν>100MeV: Quasi-elastic (1N knock-out)



2) E_ν<100MeV:Inelastic



1) E_ν>100MeV: Nucleon knockout (Excitation of residual nucleus).

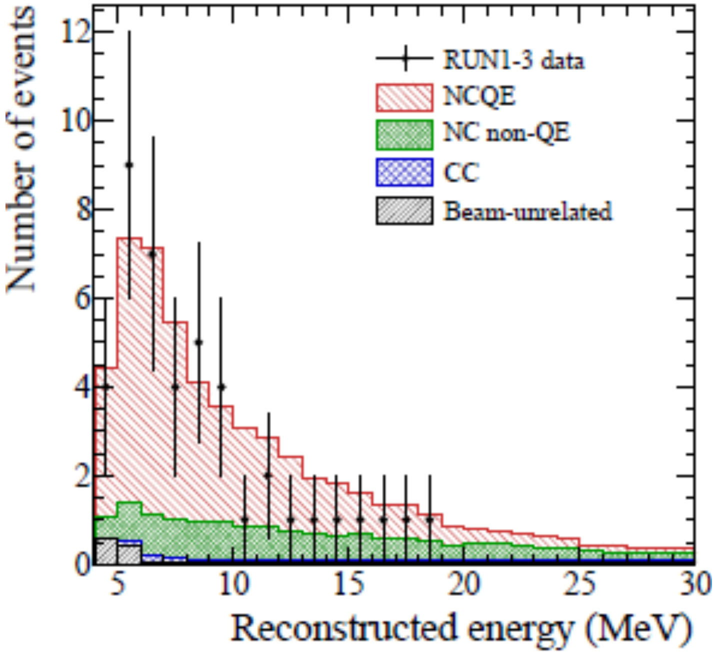
- νO→ν+p/n+$^{15}N^*$/$^{15}O^*$ Ankowski,Benhar,MS et al. *Phys.Rev.Lett.* **108**(2012)052505
- νC→ν+p/n+$^{11}B^*$/$^{11}C^*$: I comment How different C is from O? ←This talk (1)

2) E_ν<100MeV: Inelastic scattering (Giant resonances)

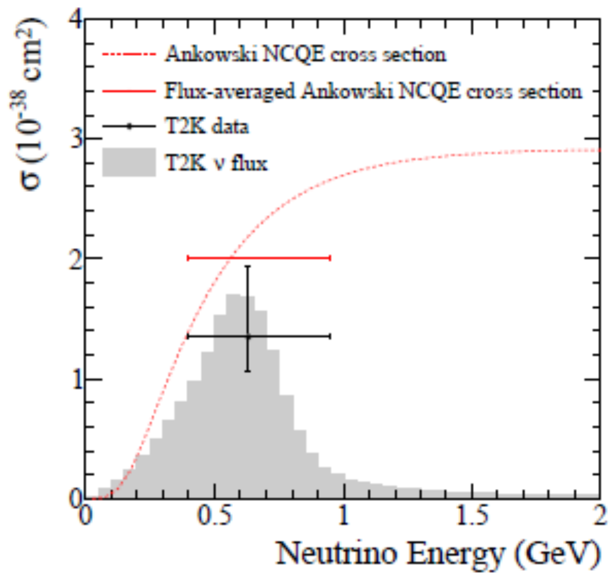
- νC,O→νC*,O*→γ : Langanke et al., *Phys.Rev.Lett.* **76**(1996).
- They calculate νO,C→νC*(15.1MeV) and O*→γ(>5MeV).
- We (RCNP E398) measure Br(C*,O*→ γ(>1.5MeV) and reevaluate SN rate. ←This talk (2)

T2K NC γ production and Karmen NC γ production

T2K 6MeV γ from $^{15}N/^{15}O$



T2K and Ankowski et al, PRL108

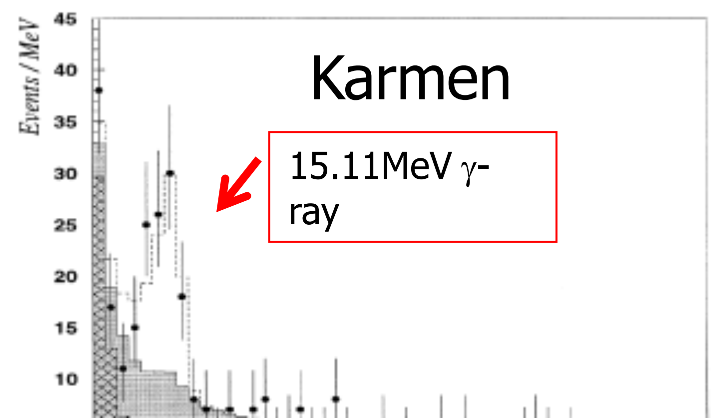


- T2K data is consistent with Ankowski et al.
- KARMEN @E_ν=29.8MeV

$(3.2\pm0.5\pm0.4)\times10^{-42}cm^2$

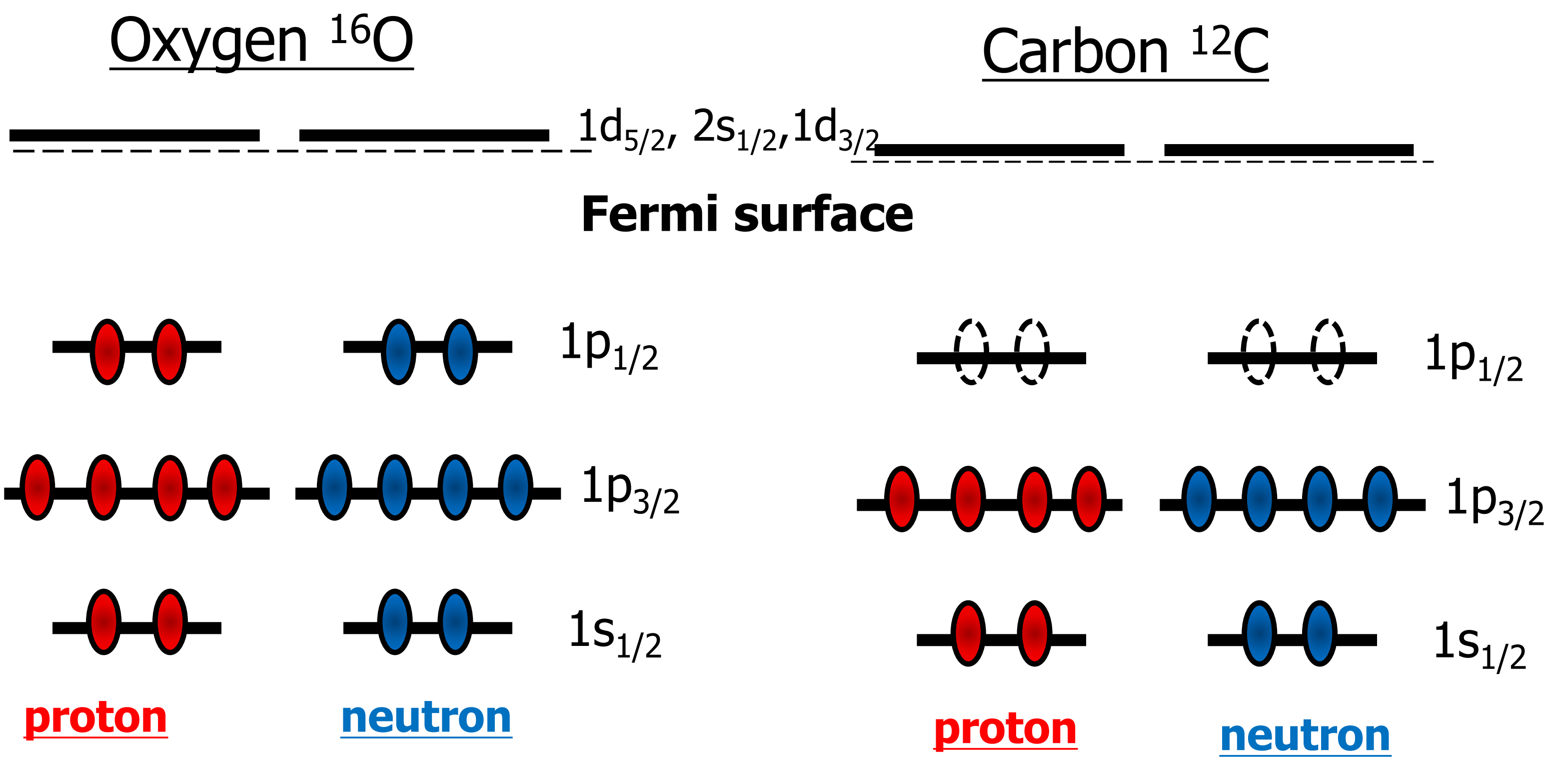
In good agreement with the calculation,

$2.8\times10^{-42}cm^2$.



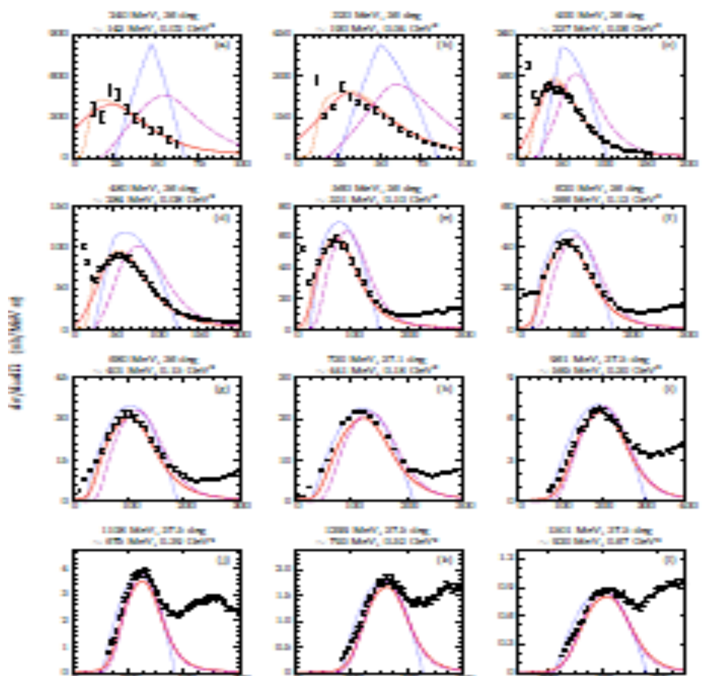
Oxygen and Carbon (Shell Structure)

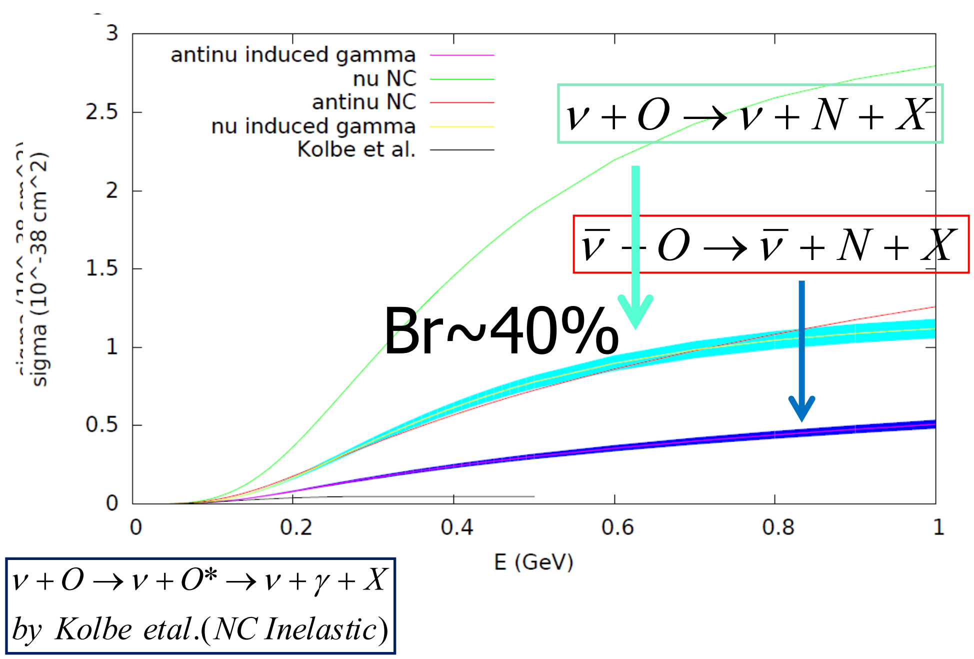
- You learn a shell model in nuclear physics.
- Naïve Shell structure of ^{16}O and ^{12}C.



(1) NC QE γ Production (νO→ν+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 γ-rays (>5MeV) in NC QE is significant (Br~ 40% for O). Ankowski,MS et al, PRL 108,052505('12)
- Note:6MeVγ happens in CCQE or even Delta. 1N knockout is the point.



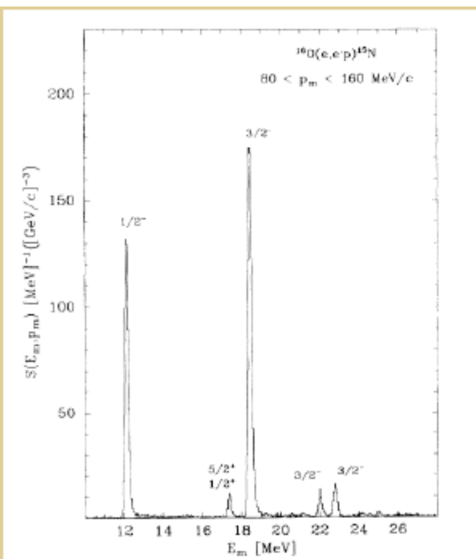


Qualitative Estimate (For Quantitative Estimate, refer to AnkowskiPRL)

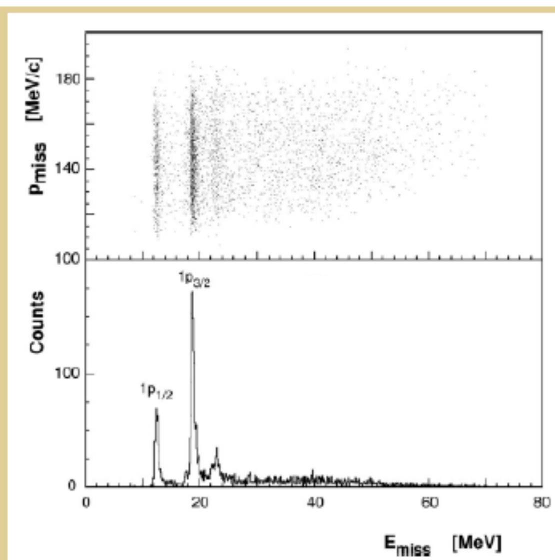
- $p_{3/2}$ knockout gives 6-MeV γ, which contributes mainly to γ production.
- Rough Estimate: Br=0.7x($p_{3/2}$ 4/8*1.0+$s_{1/2}$ 2/8*0.15)=0.38.

$\sigma(\text{NC } \nu\text{O } \gamma) \sim \sigma_{NCQE}$*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.*,

P(p,E) for ^{16}O, O.Benhar et al., PRD72,053005,2005,

O(e,e'p)

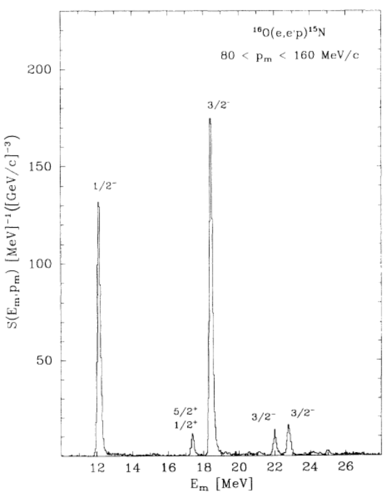


FIG. 1. ^{16}O$(e,e'p)^{15}$N missing energy spectrum for the kinematics centered about $p_m = 120$ MeV/c.

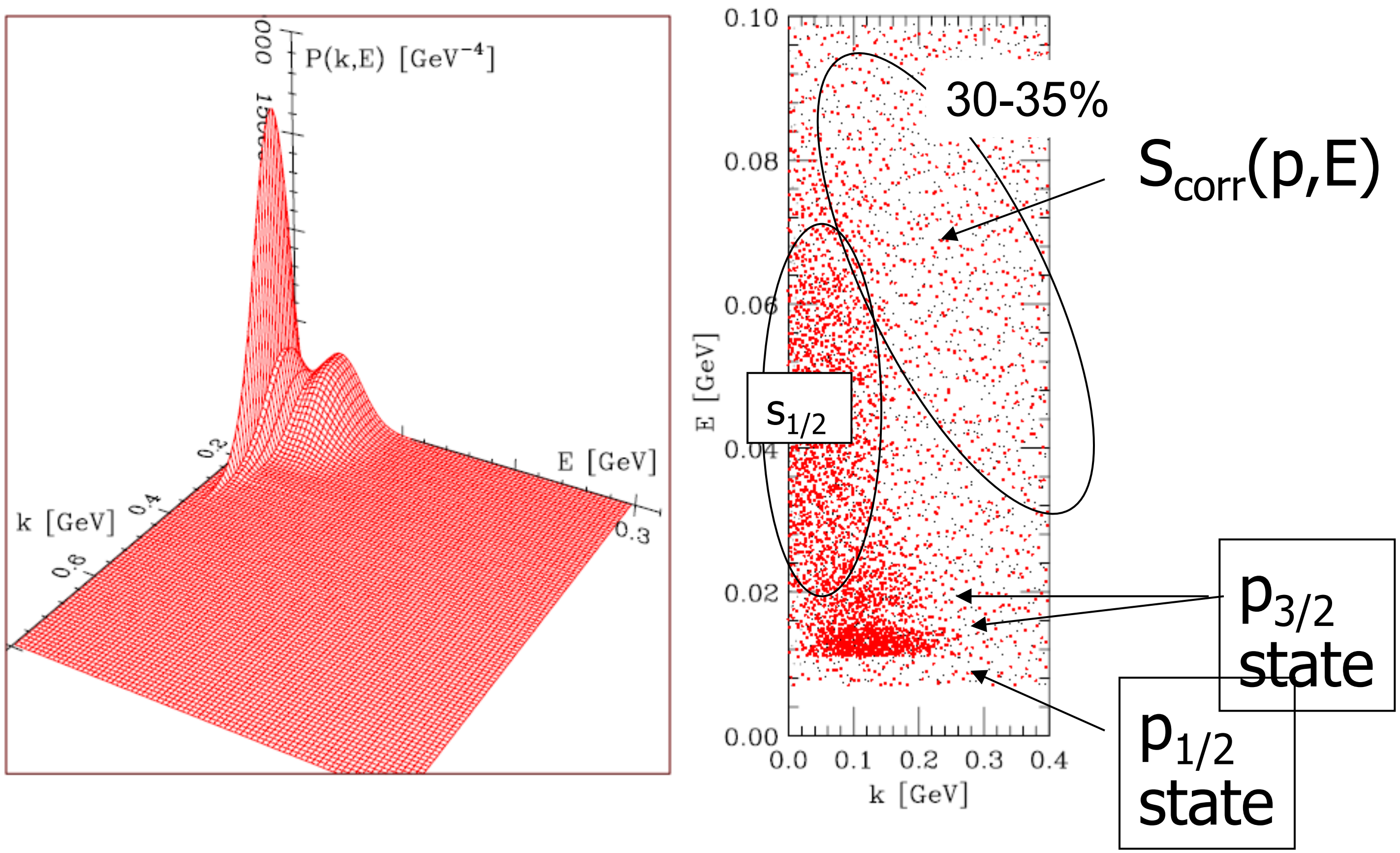
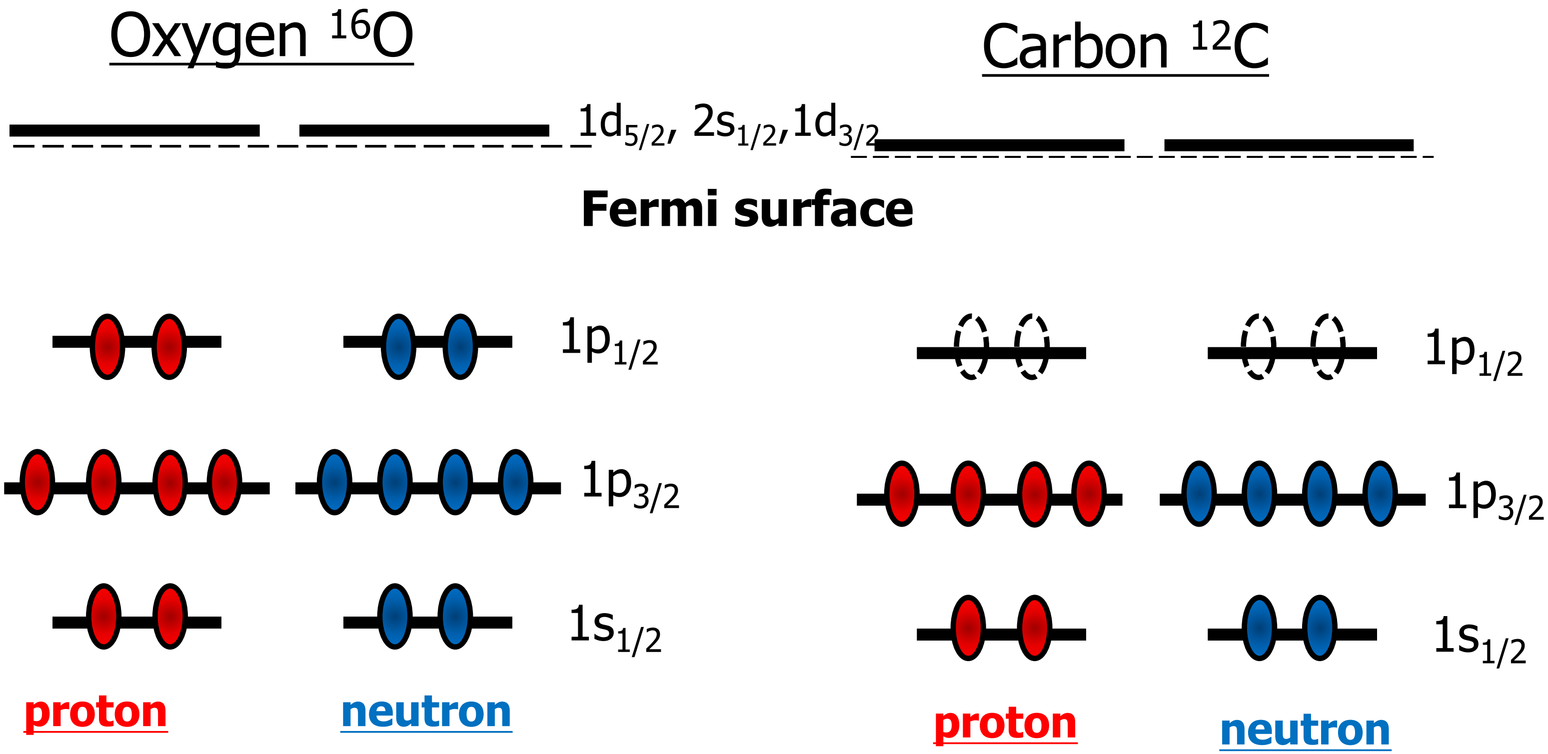


FIG. 2 (color online). Three-dimensional plot (left panel) and scatter plot (right panel) of the oxygen spectral function obtained using the LDA approximation described in the text.

S(p,E) : Probability of removing a nucleon of momentum p from ground state leaving the residual nucleus with excitation energy E.

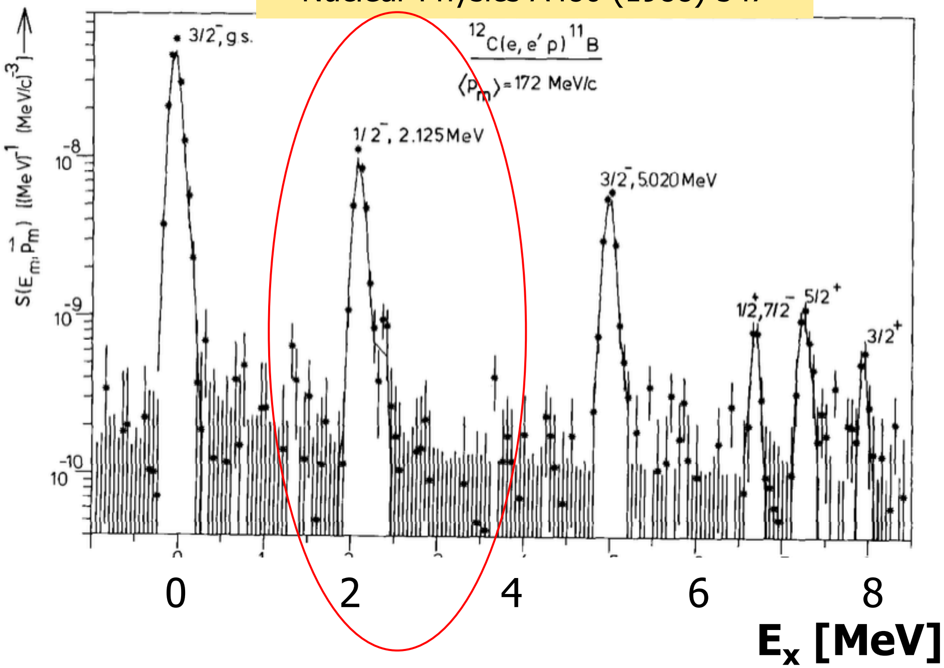
What about Carbon? $\nu C \rightarrow \nu + p/n + {}^{11}B^*/{}^{11}C^*$

- Is $\nu C \rightarrow \nu + p/n + {}^{11}B^*/{}^{1?1}C^*$ similar to $\nu O \rightarrow \nu + p/n + {}^{15}N^*/{}^{15}O^*$?
- From naive picture, few γ rays are produced.

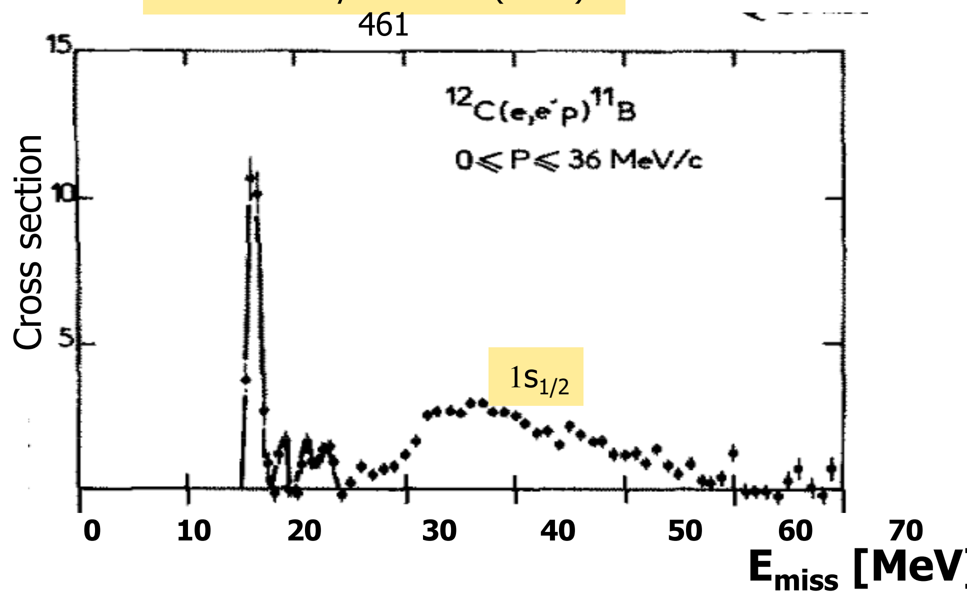


1N knockout for ^{12}C: $^{12}C(e,e'p)^{11}B$ and NC νC γ production

G.Steenhoven et al.
Nuclear Physics A480 (1988) 547



J.Mougey et al.
Nuclear Physics A262 (1976) 461



Y.Kamyshkov et al. Phys.Rev. D 67 076007 (2003)

P3/2 knockout gives 2.1-MeV γ-ray.
Br=0.7*(4/6 x 0.2x1.0+2/6 x 0.7) = 23%

$\sigma(\text{NC } \nu C\ \gamma) \sim \sigma_{NCQE} * 0.23\ (E\gamma > 0)$

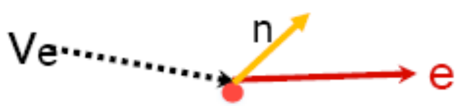
(2) γ-ray production in NC QE ν-O reactions
--Important Background to SRN -- H.Sekiya@neutrino2016

BG source: atmospheric neutrino

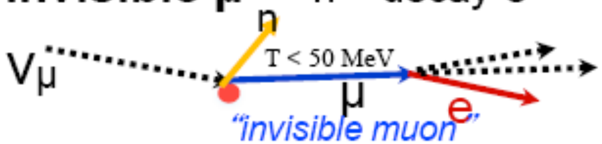
–H.Sekiya@Neutrino2016

- CC

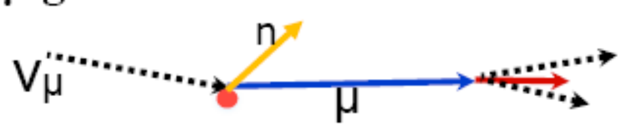
  (anti-) ν_e CC



Invisible μ n + decay-e

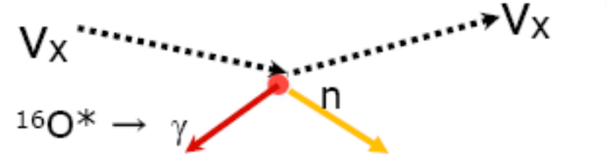


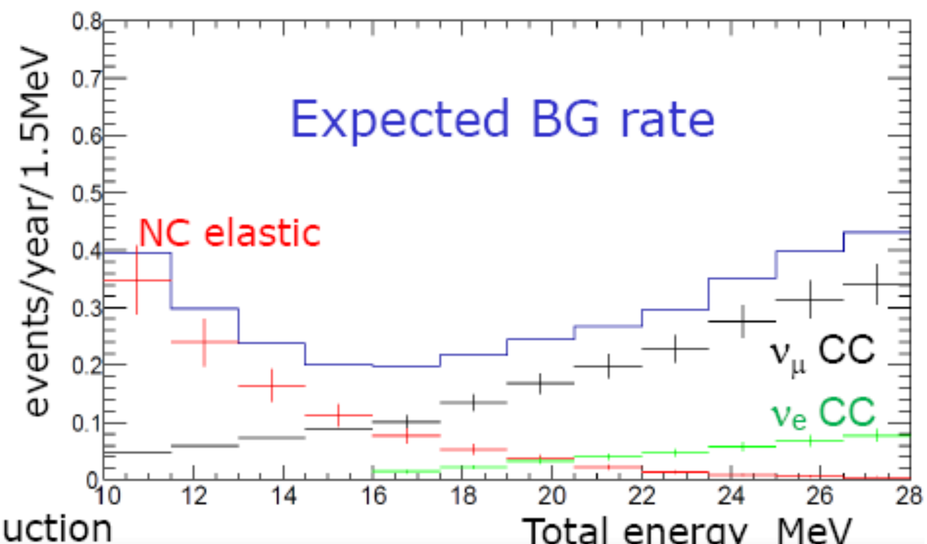
μ generation



- NC QE

  NC elastic de-excitation γ





N.B. Vertex information gives further BG reduction

Measurement of γ rays from giant resonances of ^{12}C and ^{16}O in (p,p') reactions --GR-NaI coincidence experiment-- (p1

Makoto Sakuda (Okayama) @ CAGRA17

For RCNP E398 collaboration:

I.Ou,M.Reen,T.Sudo,R.Dhir,M.Sakuda,Y.Yamada,K.Hagiwara,D.Fukuda,T.Shirahige,Y.Koshio, T.Mori(Okayama),A.Tamii,C.Iwamoto,T.Ito,M.Miura,T.Yamamoto,N.Aoi,E.Ideguchi,T.Suzuki,M.Yosoi (RCNP),T.Kawabata, S.Adachi,T.Furuno,M.Tsumura,M.Murata (Kyoto), H.Akimune (Konan), T.Yano(Kobe),H.Nakada(Chiba)

Outline

1. Purpose of E398 C,O(p,p')
2. Experiment
3. Results
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"

3. Measurement of γ rays from giant resonances of ^{12}C and ^{16}O in (p,p') reactions --GR-NaI coincidence experiment-- p13

Makoto Sakuda (Okayama) @ CAGRA17

For RCNP E398 collaboration:

I.Ou,M.Reen,T.Sudo,R.Dhir,M.Sakuda,Y.Yamada,K.Hagiwara,D.Fukuda,T.Shirahige,Y.Koshio, T.Mori(Okayama),A.Tamii,C.Iwamoto,T.Ito,M.Miura,T.Yamamoto,N.Aoi,E.Ideguchi,T.Suzuki,M.Yosoi (RCNP),T.Kawabata, S.Adachi,T.Furuno,M.Tsumura,M.Murata (Kyoto), H.Akimune (Konan), T.Yano(Kobe),H.Nakada(Chiba)

Support:JSPS Grant-In-Aid:

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*Innovative Areas ("Underground Particle&Nuclear Physics") [2014-2018] "History of star formation through observations of Supernova Relic Neutrinos"

[I do RCNP C,O(p,p') and JPARC-MLF Gd(n,γ) experiments.]

3. RCNP E398 [Goal]

Measurement of γ-rays ($\Gamma\gamma/\Gamma$) from O(p,p') and C(p,p') (p2

- [Goal]: We measure the γ-decay probability($\Gamma\gamma/\Gamma$) (E_γ>5 MeV) from giant resonances of ^{16}O and ^{12}C, at ±1% stat. accuracy, as the functions of excitation energy (E_x).

  - Definition: The γ-decay probability ($\Gamma\gamma/\Gamma$)(E_γ>1.5MeV)=

  (Number of γ-rays observed for E_γ>1.5 MeV)/(Number of events excited in the range Ex=15-30 MeV, each Ex bin) →Fig.

- [Importance]: Data for νO→νO*→γ and νC→νC*→γ do not exist and they are very important to neutrino physics. Also, understanding the decay mechanism itself is interesting and important for nuclear physics. RCNP Grand-Raiden is the best place for this experiment.

- -Proposal was approved in March, 2013 and Experiment was finished in May, 2014.

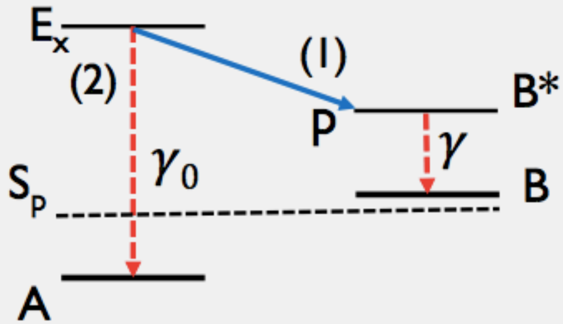
γ production in C,O(p,p') reaction

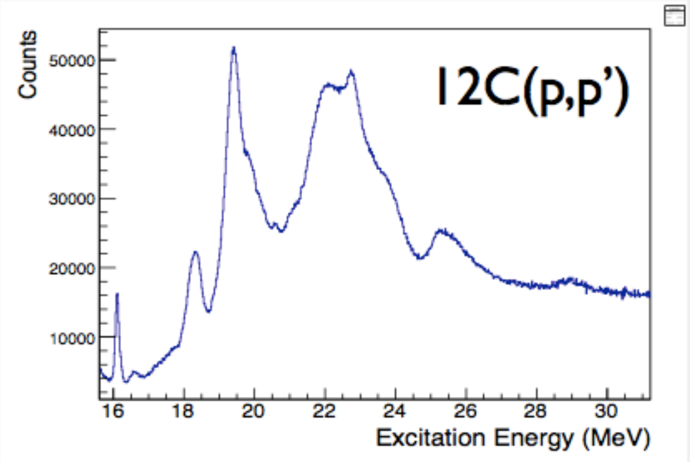
Mandeep' slide

E398 would like to understand the decay mechanism experimentally.

Nucleus is excited to giant resonances by inelastic scattering.

Inelastic Scattering





Giant Resonances

Total Decay width is given as: $\Gamma(E_x)_{tot} = \Gamma_{EM} + \Gamma_{had}$

Gamma decay width: $\Gamma_{\gamma\ tot} = \Gamma_{\gamma\ EM} + \Gamma_{had}(E_x \to B^*)\cdot Br(B^* \to \gamma)$

with $\Gamma_{EM} \approx 10^{-2} - 10^{-4}\, \Gamma^{tot}$

$$Br(E_x \to \gamma) = \frac{\Gamma_{\gamma\ tot}}{\Gamma(E_x)_{tot}} \approx \frac{\Gamma_{had}(Ex \to B^*)\cdot Br(B^* \to \gamma)}{\Gamma_{had}}$$

$Br(B^* \to \gamma)$ is **known**(Table of Isotopes)

Importance to SN Physics: Neutrino Bursts from SN explosion@10kpc

(p16

The number of events observed in the detectors

- Super Kamiokande (H_2**O**)

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

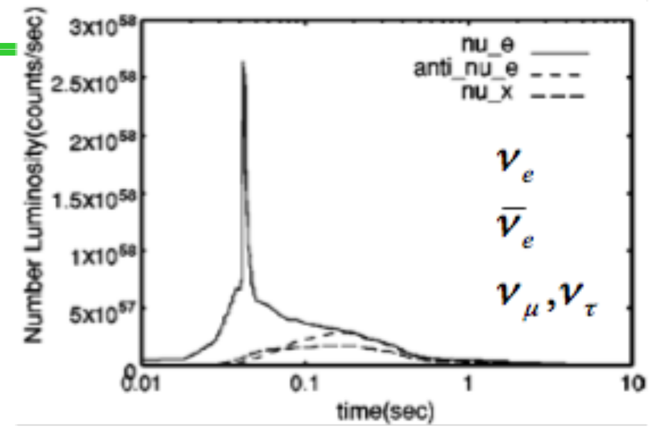
$$NC: \nu_x + {}^{16}O \rightarrow \nu_x + X + \gamma \;(\nu_x = \nu_\mu, \nu_\tau)$$ **400~600? events**

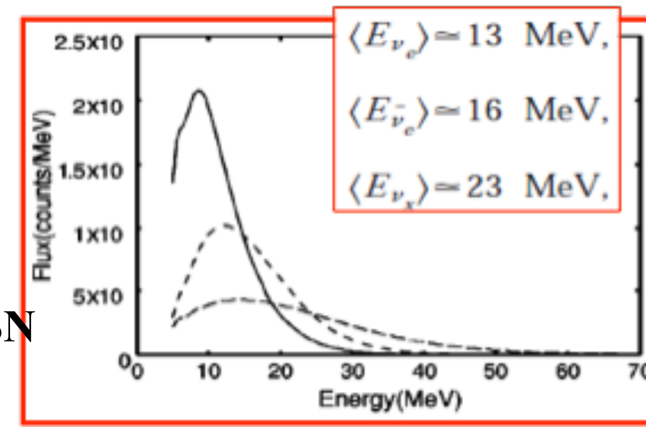
- KamLAND (**C**H_2) 1kton

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

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

$$NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \;(E_X > 16MeV\text{の巨大共鳴})$$ **(~50??)**





Importance of Neutral-Current 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 events.

Note:A.B.McDonald, Nobel Prize 2015 on Solar Neutrino Oscillations)

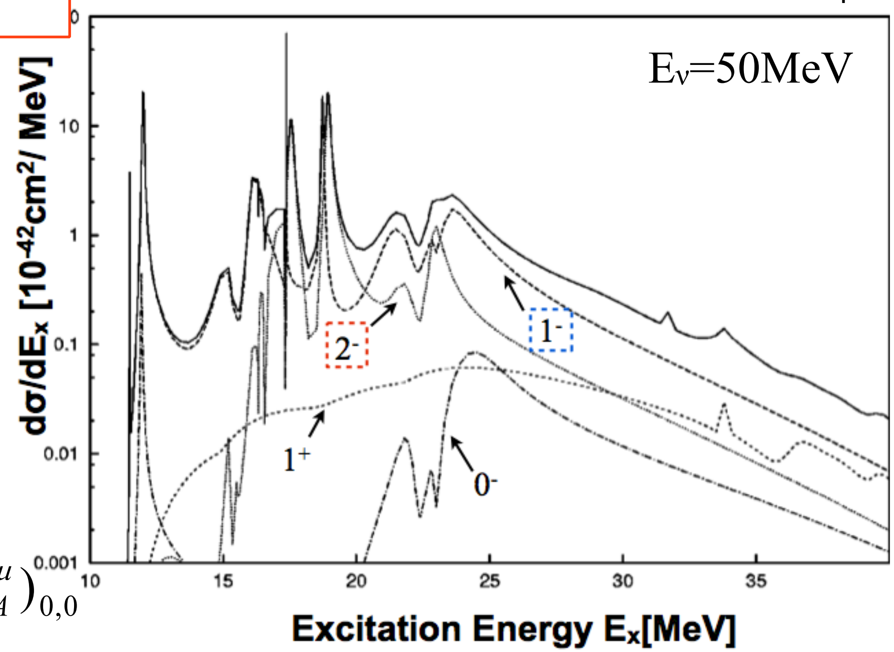
‣We Do need to Measure Br(C*,O*→γ) = Γγ/Γ (**E**$_X$**)**. --- Purpose of RCNP E398.

NC ν-^{16}O,^{12}C reaction

Ref. Langanke et al., PRL, 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) : $f_1(r) Y^m_1 \tau_3$

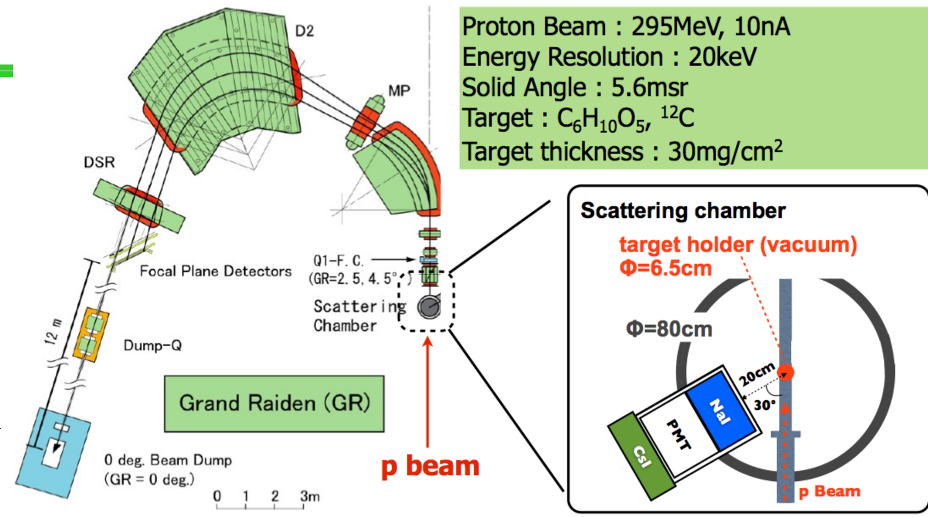
Spin Dipole R ($J^p=0^-,1^-,2^-$, ΔT=1,ΔS=1,ΔL=1) : $\vec{\sigma} f_1(r) Y^m_1 \tau_3$

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

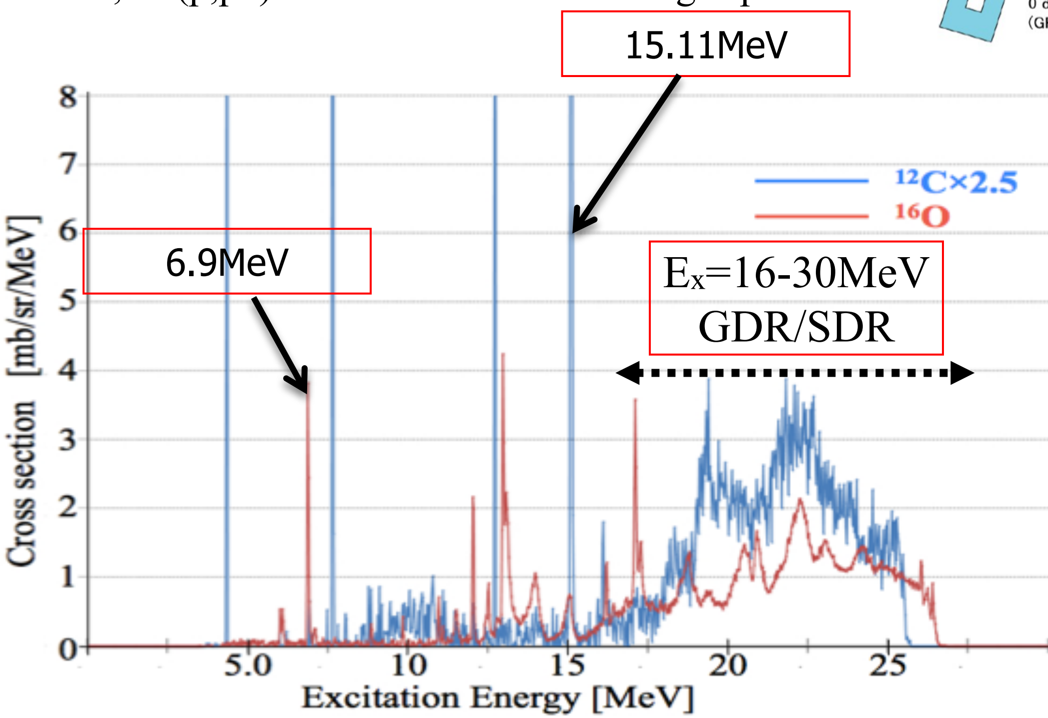
2. RCNP E398 O,C(p,p′) Experiment

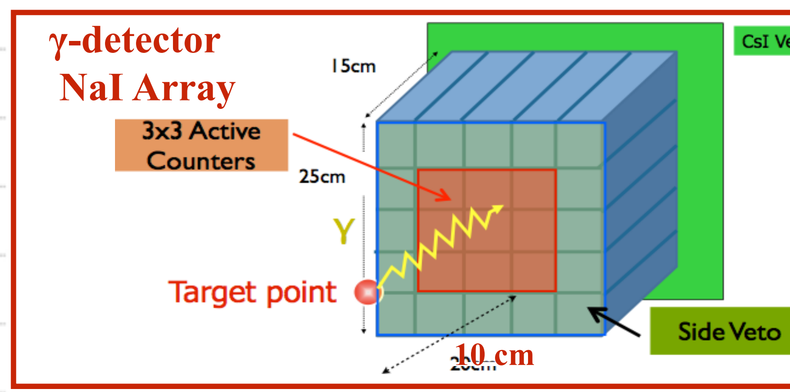
See excellent **Energy Resolution**
$E_x = E_p - E_{p'}$, $\Delta E_x \sim 20$keV

Proton Beam : 295MeV, 10nA
Energy Resolution : 20keV
Solid Angle : 5.6msr
Target : $C_6H_{10}O_5$, ^{12}C
Target thickness : 30mg/cm^2



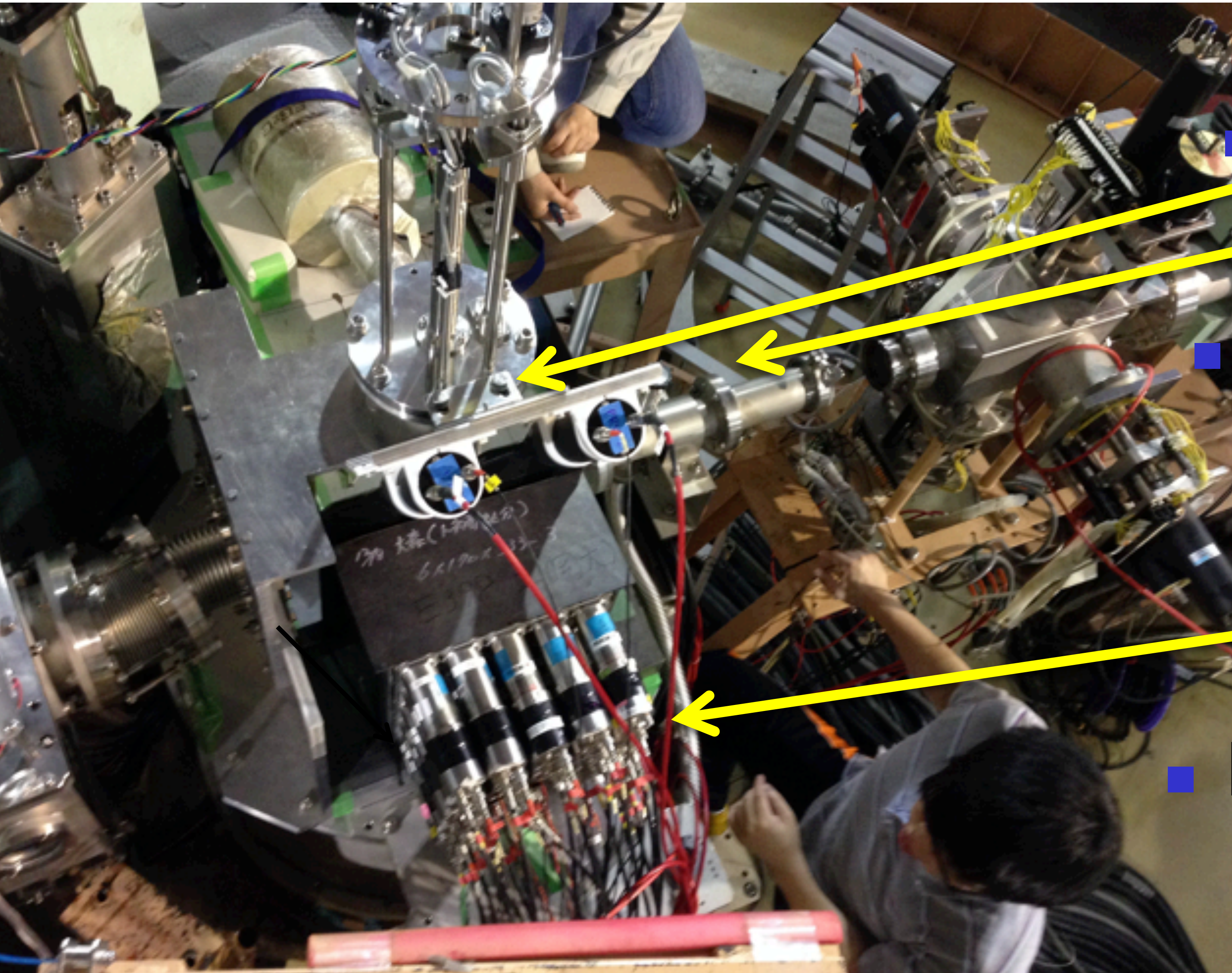
^{16}O,^{12}C(p,p′) cross section at θ=0.4 deg. Ep=295MeV





Ref. A. Tamii, H. Matsubara, et al.RCNP E249 & E299 Collaboration, 5-JAN-2011.

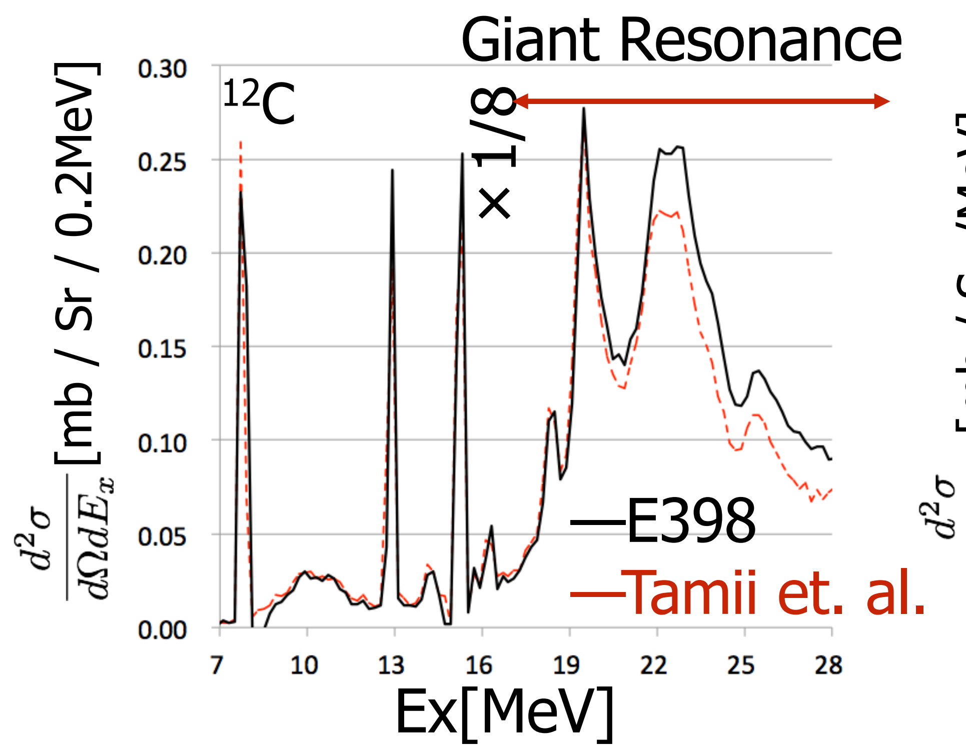
E398 (May 16-27, 2014)



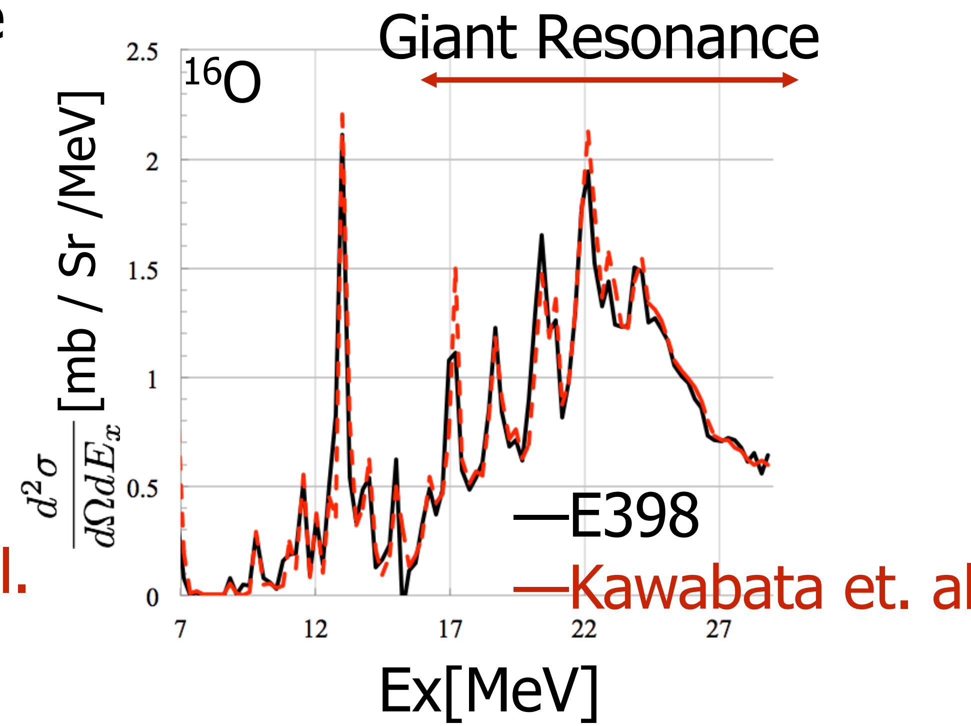
- Target(C,O
- Proton Beam
  - 392MeV
- NaI 5x5 array

3. Our Cross Sections measured with GR p20

- Fair agreement with previous measurements



Ref. A. Tamii et al.:Phys. Lett. B459 (1999).

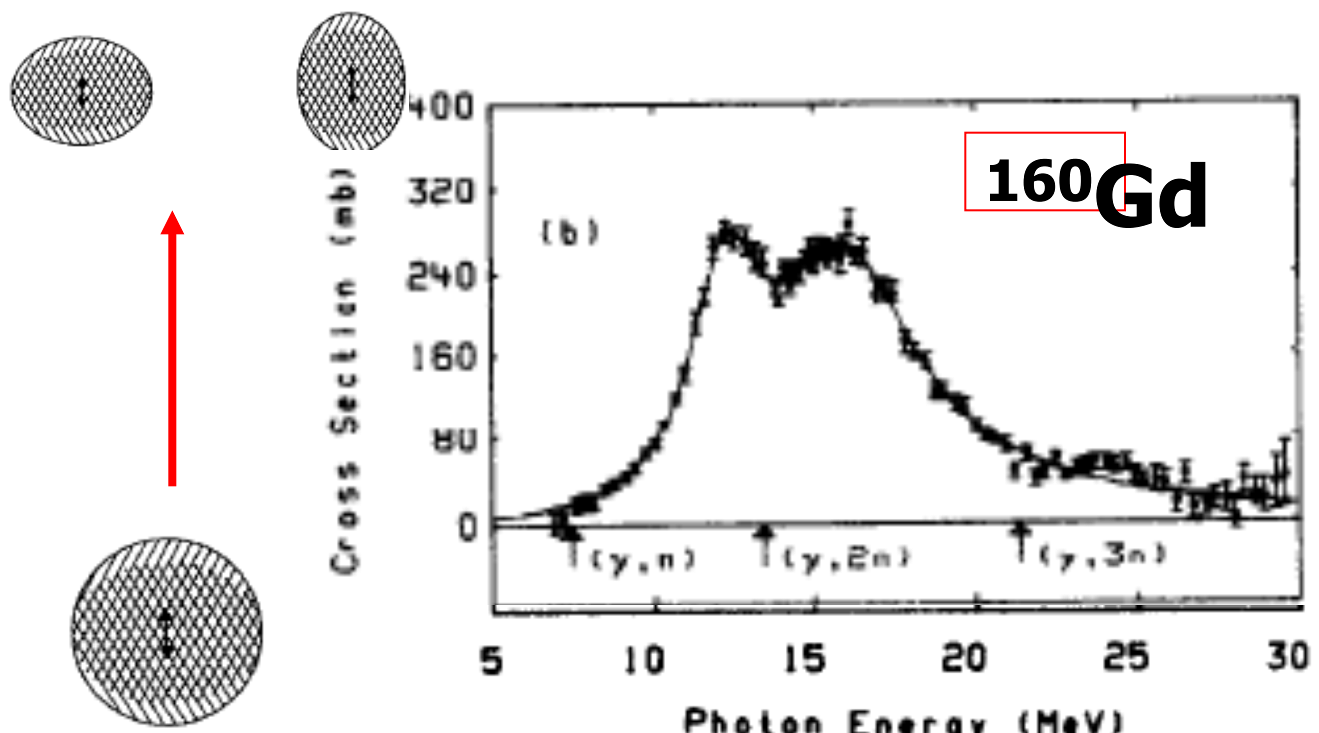


Ref. Kawabata et al.,PRC65('02)064316

Cf. SK-Gd: Gd(n,γ) is the decay from Giant Resonance 2^-

See Photoneutron cross section= γ+Gd→n+Gd

- Total photoneutron cross sections sometimes show 2 Giant Dipole Resonances (GDR), typical of the deformed nuclei, Gd.
- Gd(n,γ) is the inverse reaction.



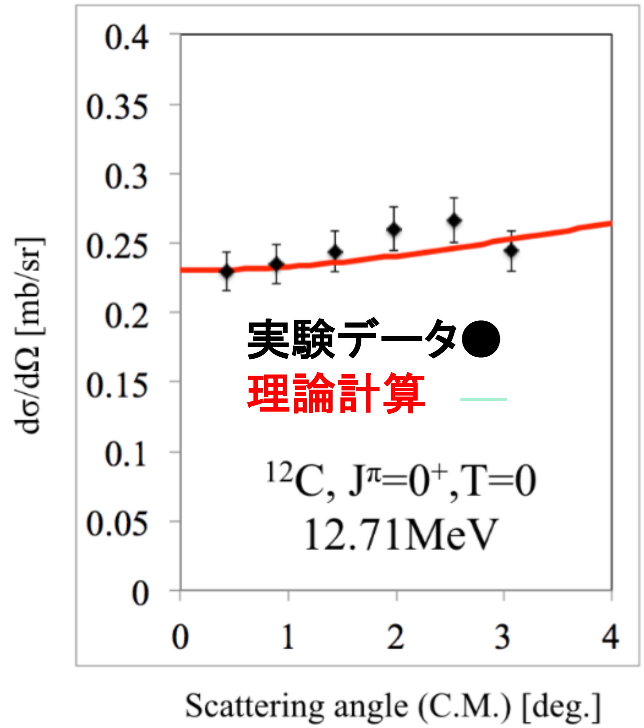
Cross Section dσ/dΩ (^{12}C, 1^+, 15.11MeV, T=1)

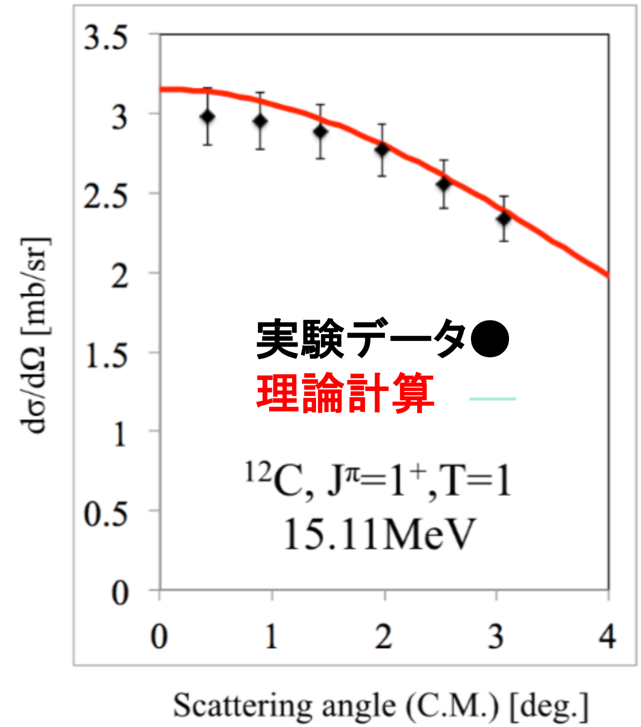
(^{12}C, 1^+, 15.11MeV) cross section data agree with DWBA07.

歪曲波(大局的光学模型) + 1p shellの波動関数* + 自由核子相互作用

*Ref. Cohen S., Kurath D.: Nucl. Phys.73 (1965) 1.

*



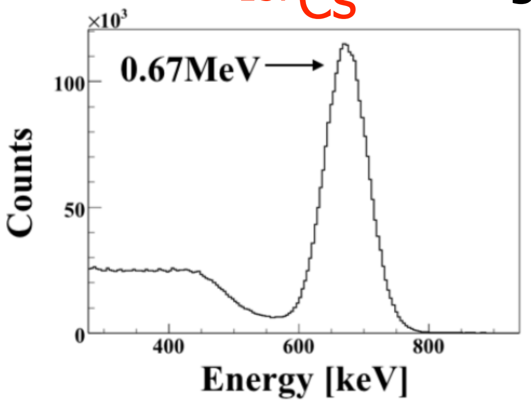


3. NaI Energy Response before experiment (p13

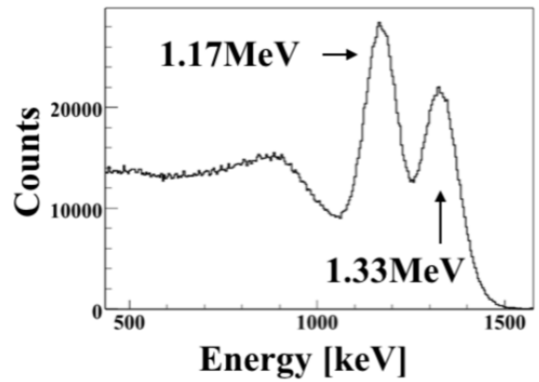
Energy Response has been checked by radioactive sources (^{137}Cs ^{60}Co ^{241}Am ^{252}Cf)

Energy Spectrum

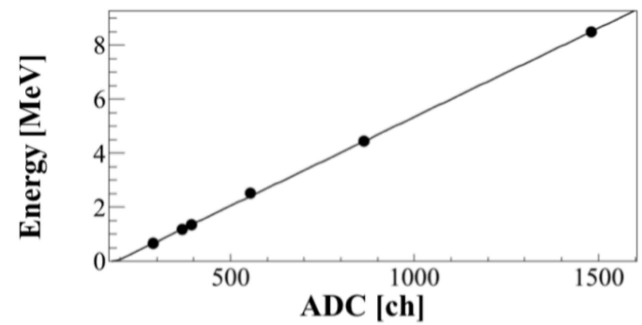
^{137}Cs



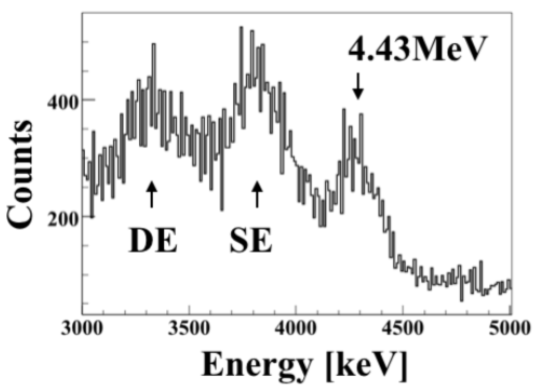
^{60}Co



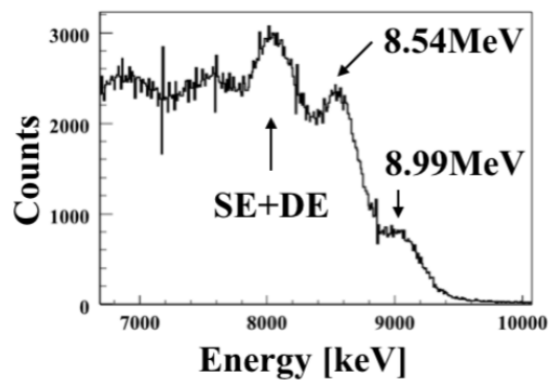
Pulse-height Linearity



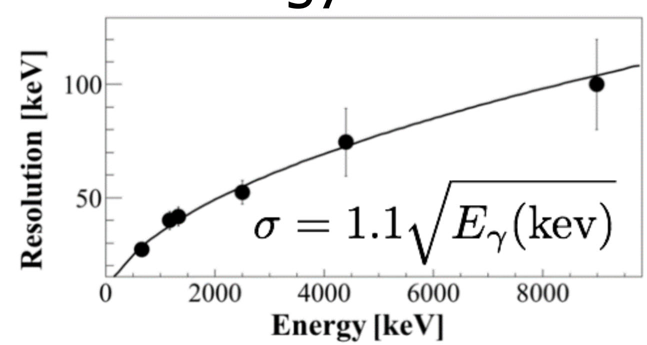
^{241}Am



^{252}Cf



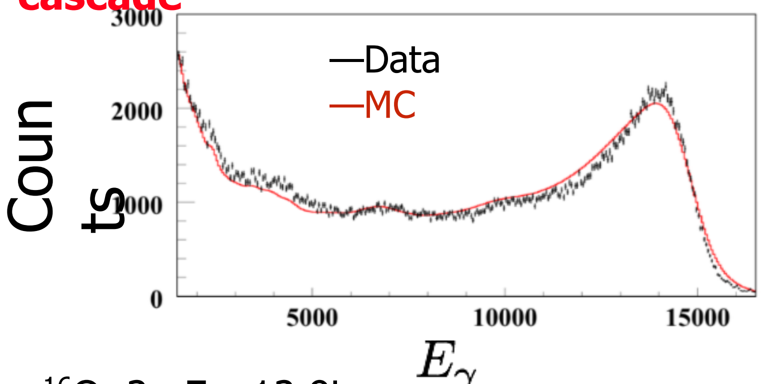
Energy Resolution (σ



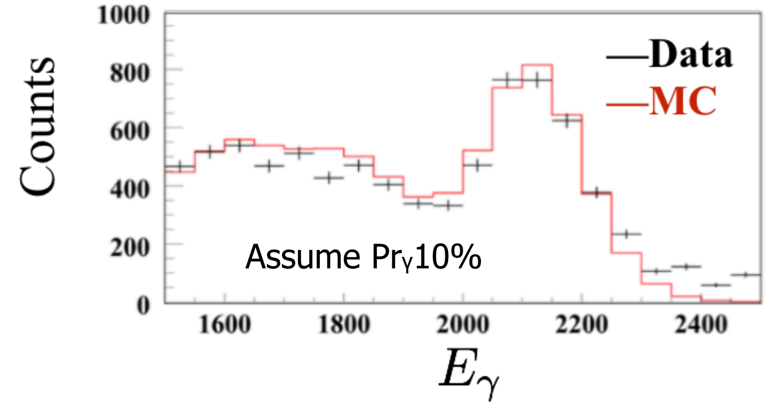
Result of Response Functions (Data/MC)

MC Response Functions reproduce data (±5%) over the entire γ-ray energy (2-15MeV throughout the experiment.

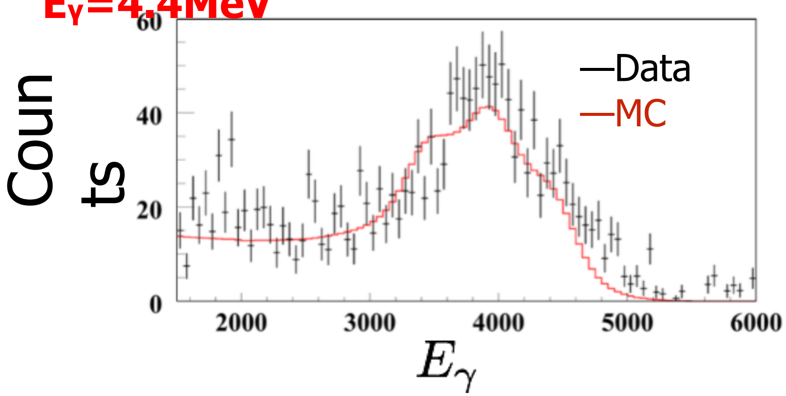
^{12}C, 1^+, E_x=15.1MeV, **E_γ=15.1MeV and cascade**



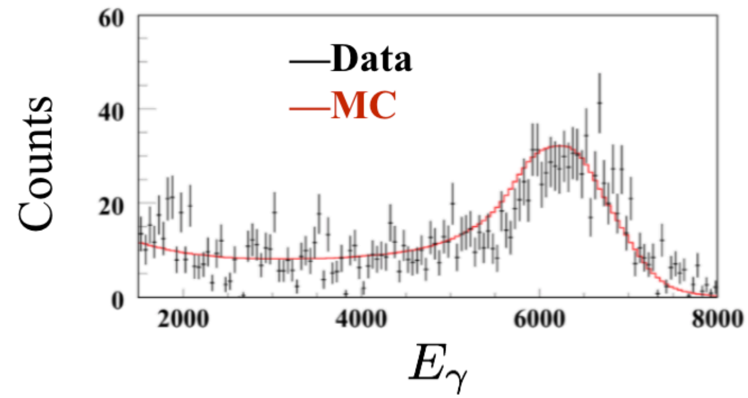
^{12}C, 2^-, E_x=18-20.4 MeV, p-decay, **E_γ=2.12MeV**



^{16}O, 2^-, E_x=12.97MeV,α-decay, **E_γ=4.4MeV**



^{16}O, 2^+, E_x=6.9MeV, **E_γ=6.9MeV**



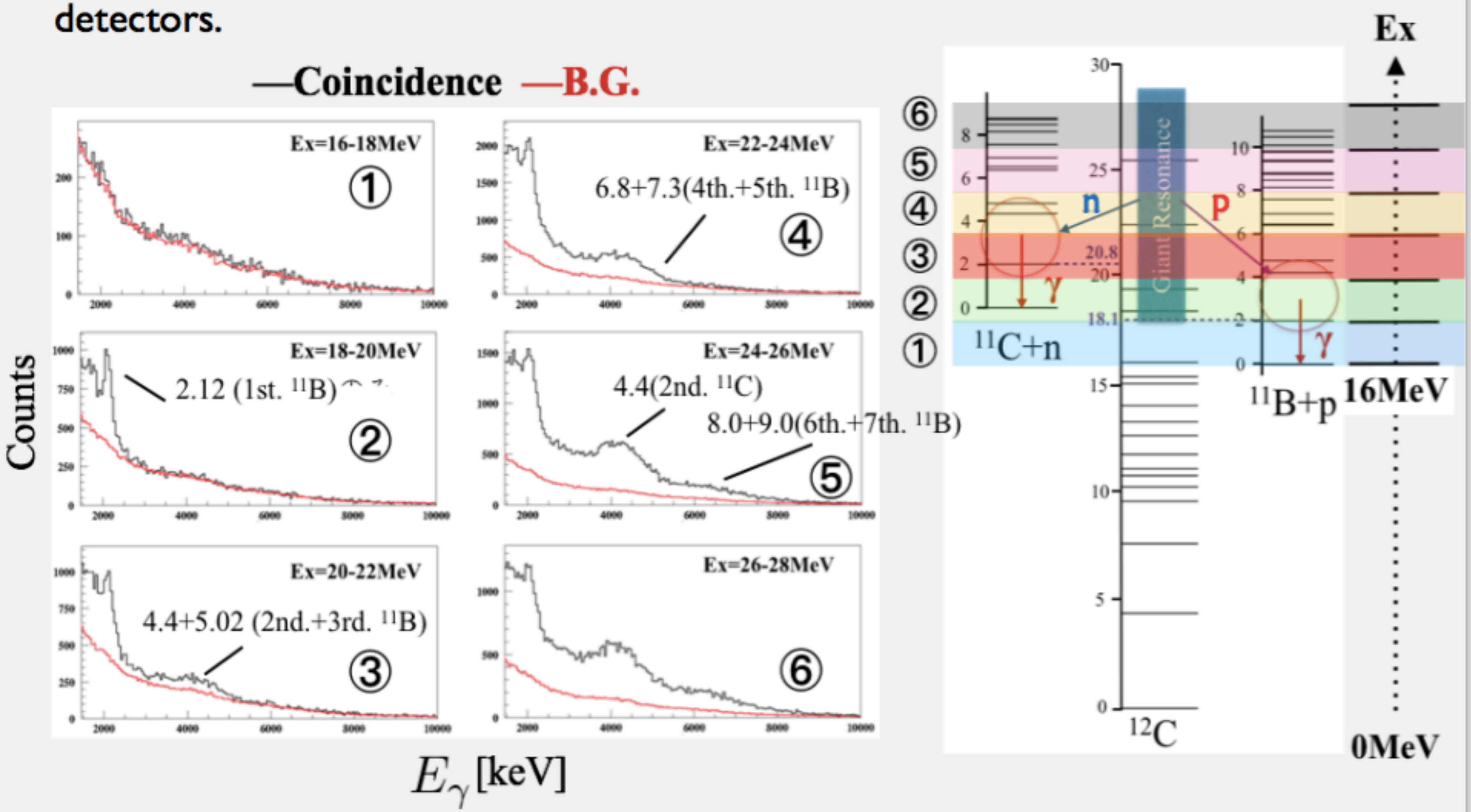
(Ref. Table of Isotopes, 8th ed.)

(3-1) Results on Particle Decay:

$^{12}C^* \rightarrow p/n + {}^{11}B/{}^{11}C$ p10

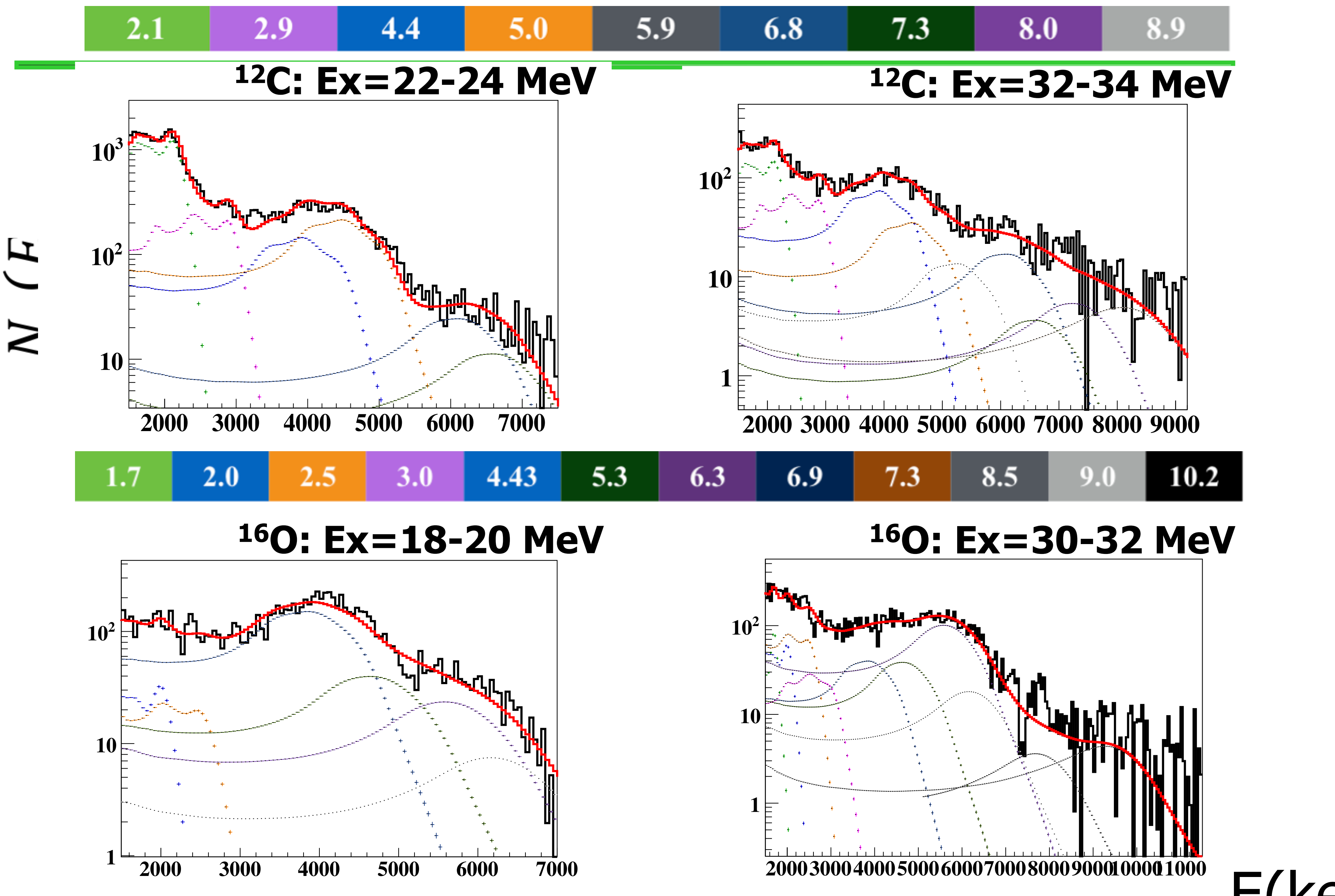
γ-RAYS FROM ^{12}C

γ-rays were measured in coincidence with scattered protons using an array of NaI detectors.



γ-ray energy spectra clearly show that γ-rays are emitted from the excited states of daughter nuclei.

γ-RAYS FROM ^{12}C AND ^{16}O



How to obtain Branching ratios for possible levels from response functions -Mandeep's slide p28

γ-RAYS FROM ^{12}C

Response functions $P(E_\gamma,E)$ were generated for all the possible γ-rays (from daughter nuclei) using GEANT4 and were fitted to data.

$P(E_\gamma,E)$ = Energy deposited(E) when a γ-ray (E_γ) is irradiated uniformly at 10 cm from NaI

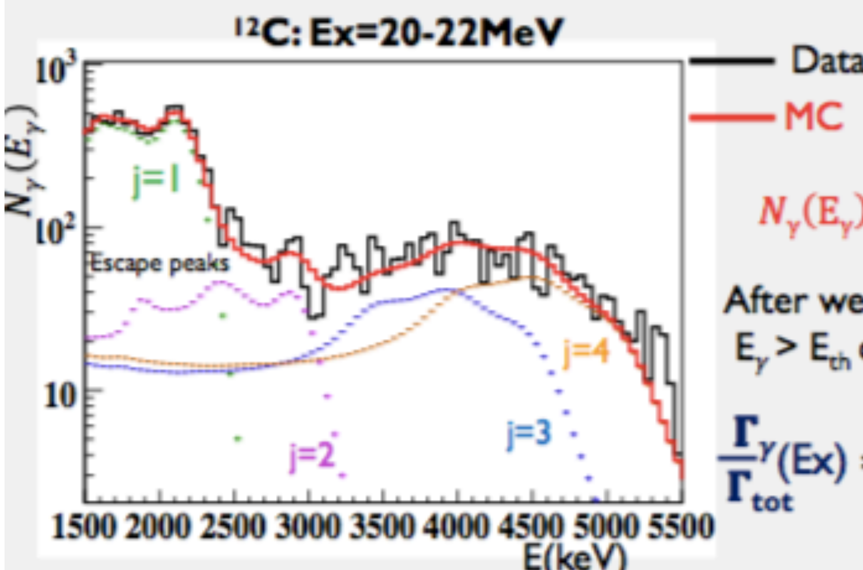
$$\int_{E_{th}=0.5\ \mathrm{MeV}}^{E_{max}} P(E_\gamma,E)dE = \eta\varepsilon^o(E_\gamma)$$

Efficiency

$$N_\gamma(E_\gamma) = N_{Ex}\sum_j Br_j\, Pj(E_\gamma,E)$$

N_{Ex} = Excitation Counts

Br_j = Branching ratio for j^{th} γ-ray(fit parameter)



j =	1	2	3	4
E_γ (MeV)→	2.12	2.9	4.44	5.0

$$N_\gamma(E_\gamma) = N_{Ex}(Br_1P_1 + Br_2P_2 + Br_3P_3 + Br_4P_4)$$

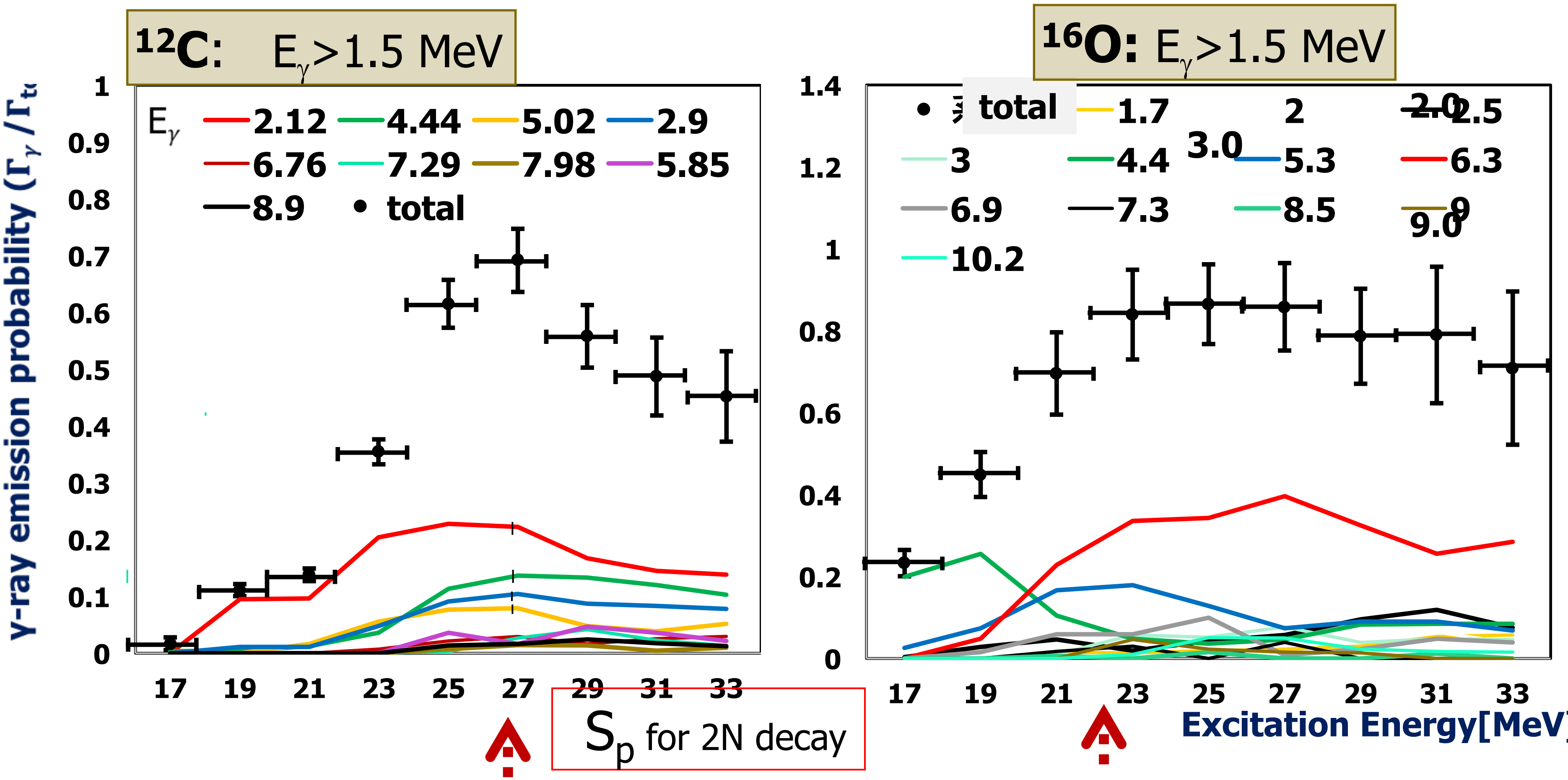
After we have Br_j, γ-ray emission probability for $E_\gamma > E_{th}$ can be obtained as:

$$\frac{\Gamma_\gamma}{\Gamma_{tot}}(Ex) = \frac{N_\gamma}{N_{Ex}}(Ex) = \sum_j Br_j \int_{E_{th}}^{E_{max}} P_j(E_\gamma,E)dE\, /\, \eta\varepsilon^o$$

The same procedure was repeated for all the other Ex bins

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

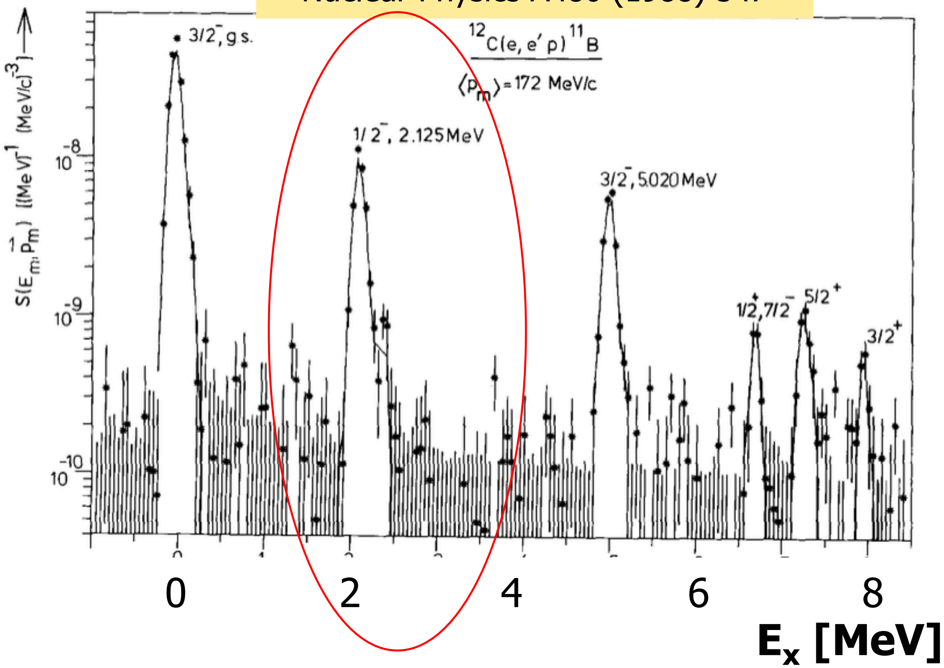
The energy spectrum of γ-rays from giant resonances of ^{12}C and ^{16}O and the emission probability have been measured for the first time as a function of Ex.

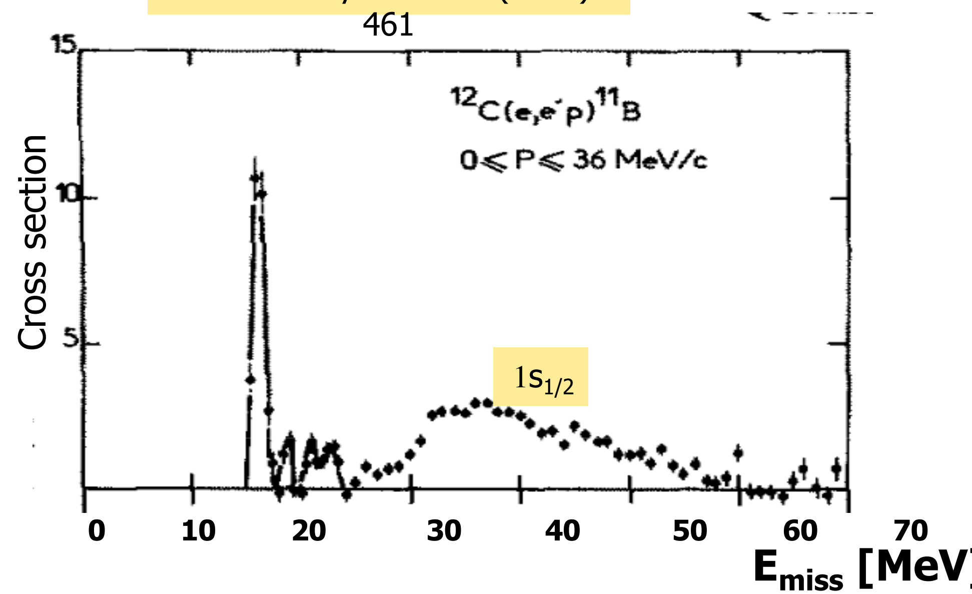


Quasi-free knockout for ^{12}C, ^{12}C(e,e'p)^{11}B

G.Steenhoven et al.
Nuclear Physics A480 (1988) 547

J.Mougey et al.
Nuclear Physics A262 (1976)
461



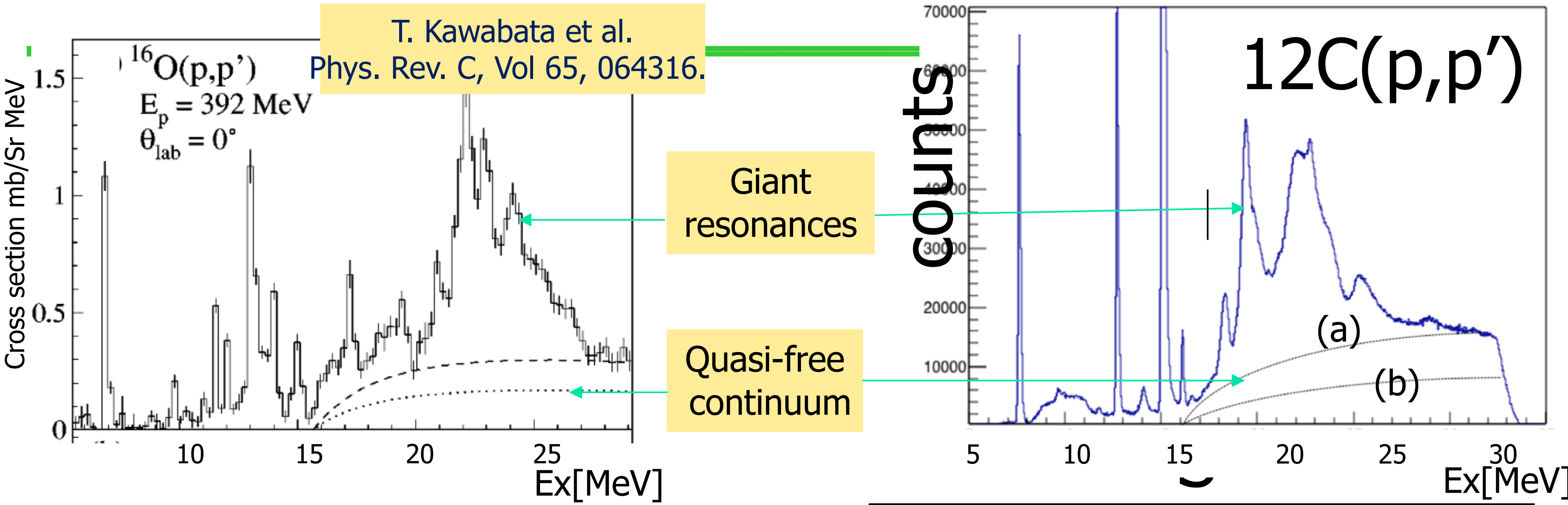


Y.Kamyshkov et al. Phys.Rev. D 67 076007 (2003)

P3/2 knockout gives 2.1-MeV γ-ray.
Br=0.7*(4/6 x 0.2x1.0+2/6 x 0.7) = 23%

Quasi-free knockout for ^{12}C

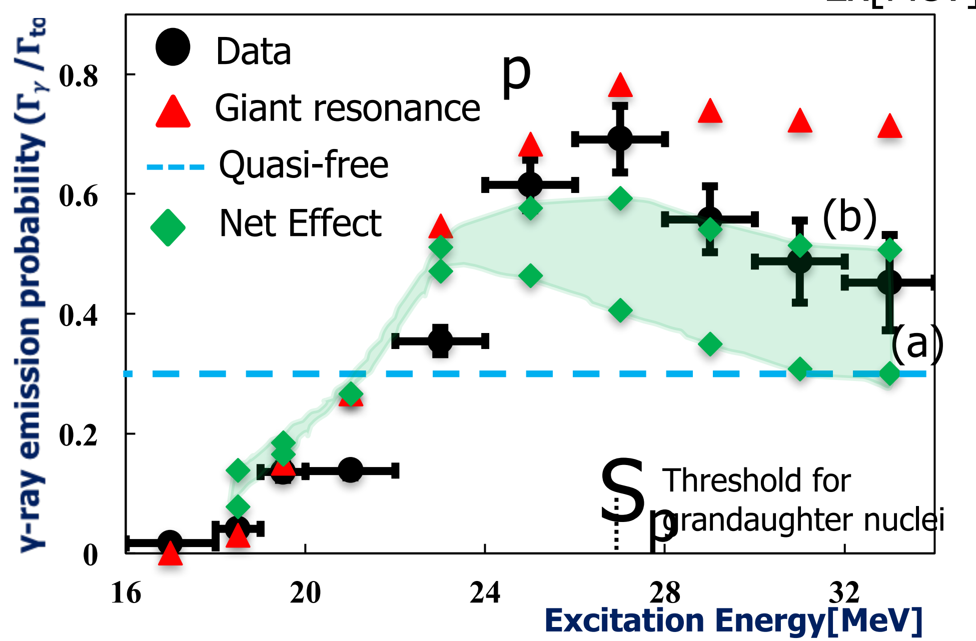
We assume both giant resonances and quasi-free reaction.



We weight the contributions by their respective cross-sections as shown in above figure.

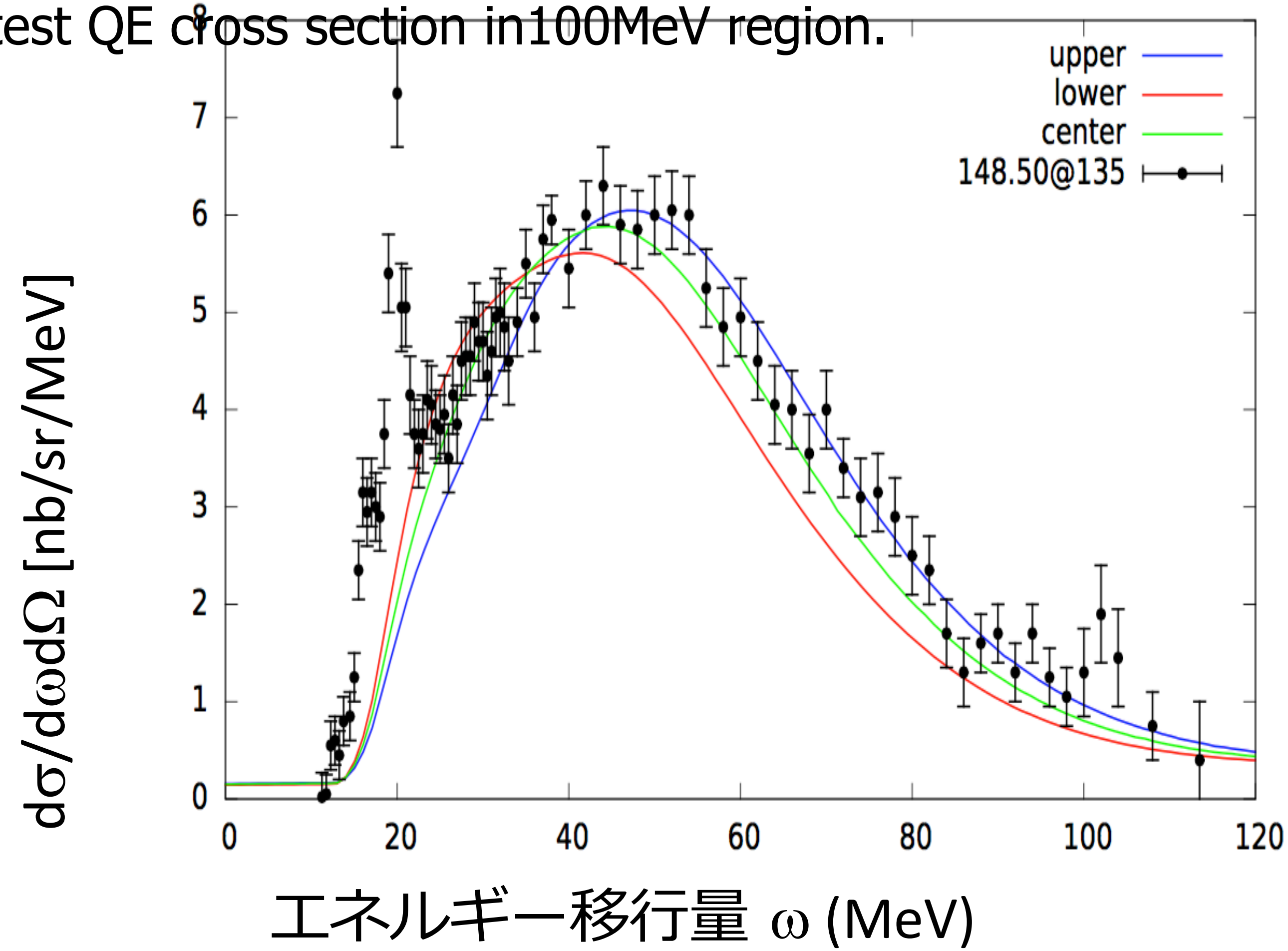
This is the first approximation after considering quasi free knockouts and sequential decays.

We still better understanding of Quasi-free knockout processes.



148.50MeV@135deg

- We show that IA-
- SF/FSI is good over 240 MeV-1GeV region. Benhar et al.,PRD72(2005):IA-SF/FSI, E>500MeV.
- We now test QE cross section in100MeV region.

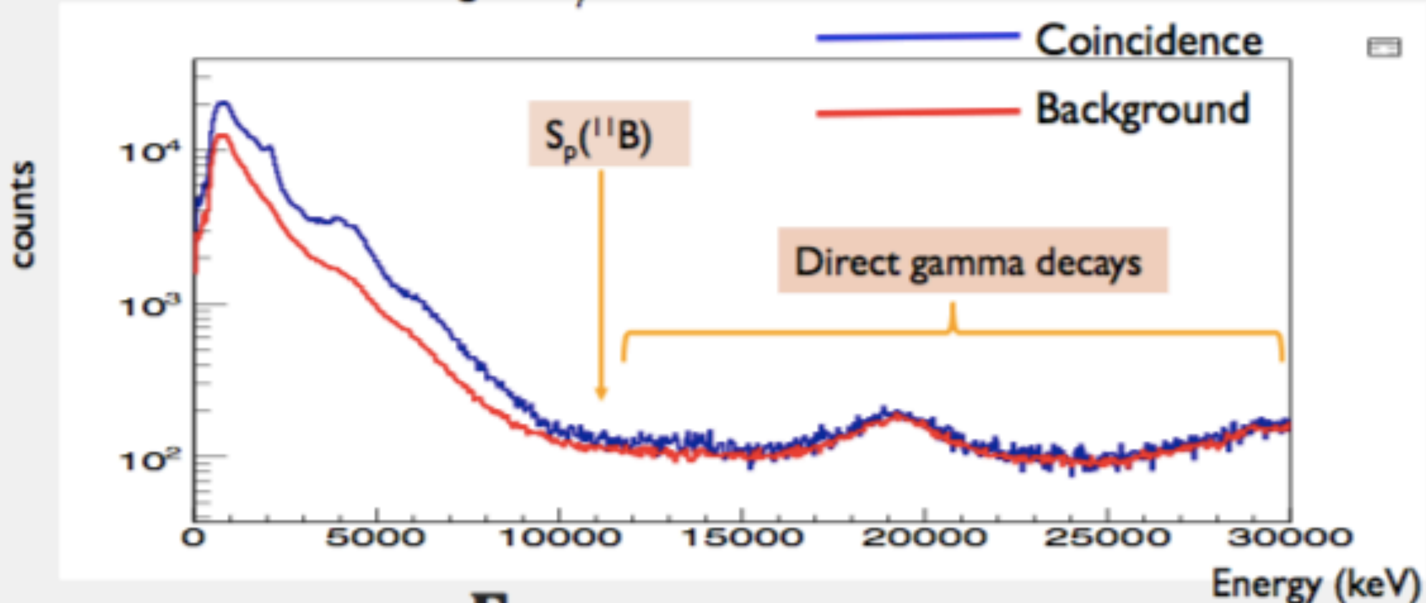


Electromagnetic (Direct) Decay Search

-Eγ>10 MeV- Mandeep's slide p19

BRANCHING RATIO: (ELECTROMAGNETIC DECAY)

No γ-rays(E_γ> 10 MeV) are expected from hadronic mode, so, EM(Direct) decays can be observed in the region E_γ> 10 MeV.



$$Br(E_x \rightarrow \gamma_{direct}) = \frac{\Gamma_\gamma}{\Gamma_{tot}} = \frac{(N_\gamma)\,(E_{NaI} > 10\ MeV)}{N_{Ex}(16\text{–}34\ MeV) * \eta\varepsilon_{MC}}$$

$\eta\varepsilon_{MC} = 0.062$

$$\mathbf{Br(E_x \rightarrow \gamma) = 0.35\% \pm 0.01\%(stat.) \pm 0.3\%(sys.)}$$

At this moment, the value is not significant and we just give the upper limit.

E398:Summary

1. γ-ray energy spectra clearly show that γ-rays are emitted from the excited states of daughter nuclei.

2. We presented the emission probability of γ-rays from giant resonances of ^{12}C and ^{16}O which has been measured for the first time as a function of excitation energy (Ex).

3. We performed decay model calculations for ^{12}C and it fairly agrees with data for Ex< 27 MeV. The reason of decreasing trend could be Quasi-free knockout process.

4. We also presented the upper limit to direct decay branching ratio i.e. **0.35%** $\pm 0.01\%(stat.)$ $\pm$**0.3%(sys.)**.

E398:Applications to Neutrino Physics

Estimation of supernova neutrino Events

E398 results are applied for the estimation of γ N_{NC} for Super-K and KamLAND.

The expected number of events from the core-collapse:

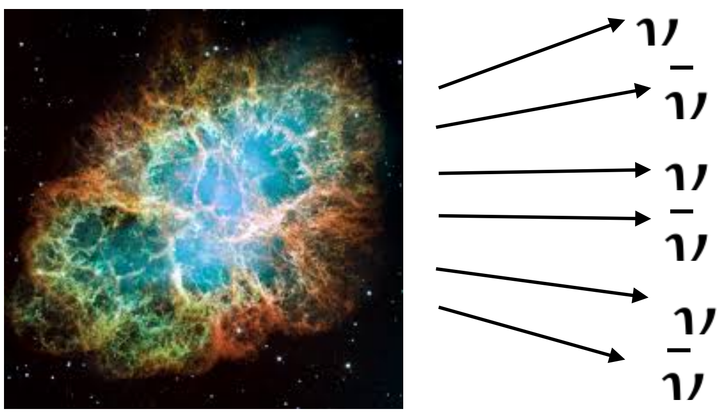
$$N_i = Flux(\nu_j) \times n_{target} \times \sigma_i$$

Where $Flux(\nu_j) = \frac{L_{\nu_j}}{<E_{\nu_j}>} \frac{1}{4\pi D^2}$ and σ_i is the cross section for reactio

D = 10 kpc

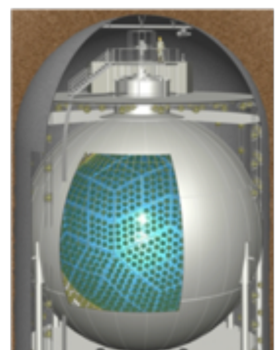
Total Gravitational Energy

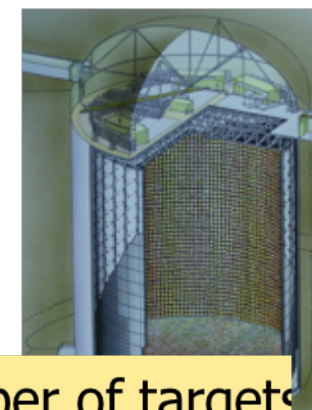
L =3 x 10^{53} ergs



L divided equally $L_{j\nu}$ =

KamLAND (1kton) **SK (32.48kton)**





n_{target} is number of targets

KamLAND (1kton)	SK (32.48kton)
$n_{^{12}C}$:4.30×10^{31}	$n_{^{16}O}$:1.09×10^{33}
n_p :8.60×10^{31}	n_p :2.17×10^{33}

KamLAND collaboration: Phys. Rev. C 84 (2011) 03580

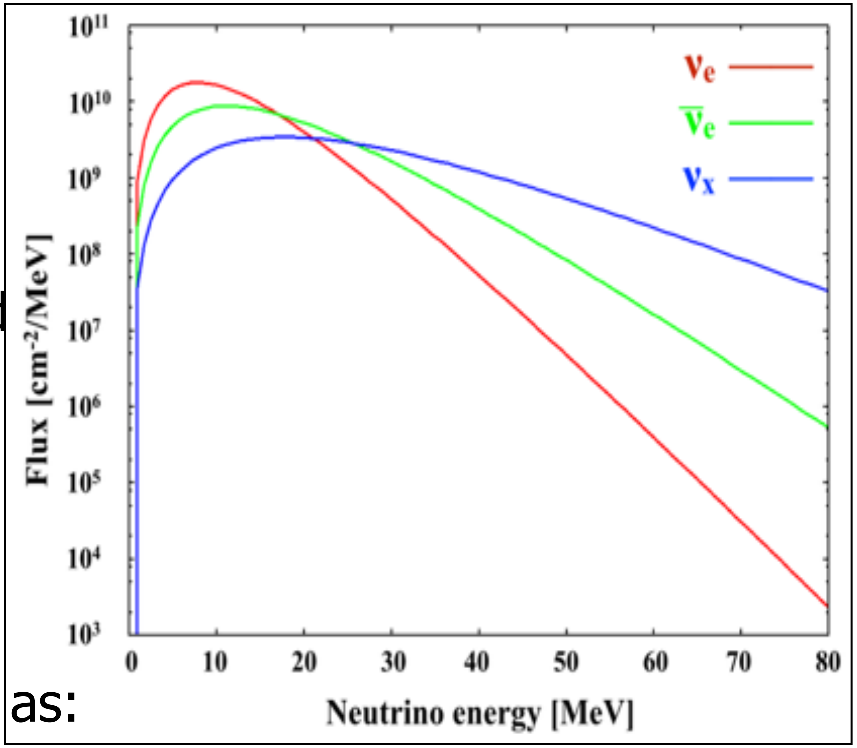
Assumptions

~~The NC events are assumed to be induced by only ν_x (ν_μ, ν_τ and their anti~~

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.

$$FD(E_{\nu_j}, T_{\nu_j}) = \frac{0.553}{T^3_{\nu_j}} \frac{}{1 \cdot}$$

Solving Analytically, we get Average Energy as:

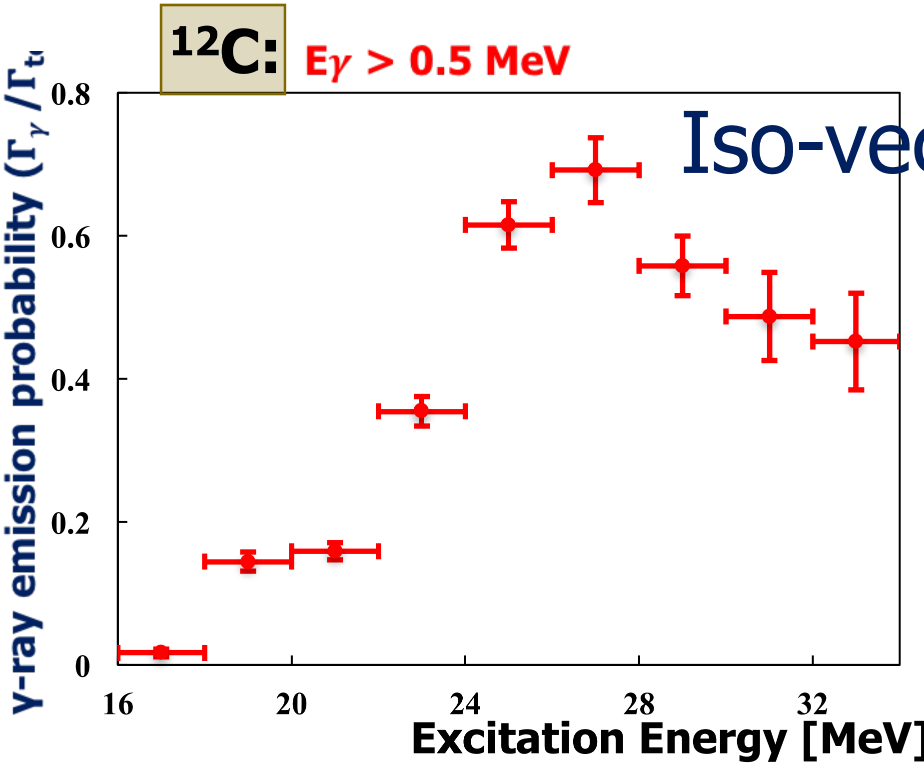
$$< E_{\nu_j} > = 3.15 \times T_{\nu_j}$$

Now, we need cross section information

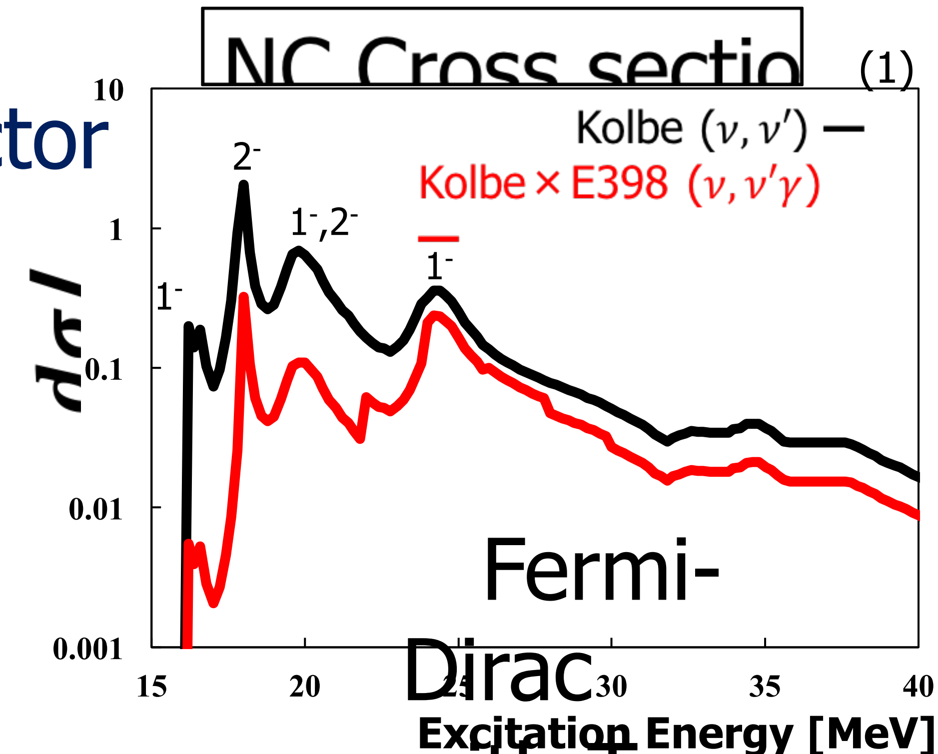
Ref. J. F. Beacom and M. R. Vagins: Phys. Rev. Lett.

Inelastic Scattering Cross section: ^{12}C

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



Iso-vector



Fermi-Dirac with T=

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

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

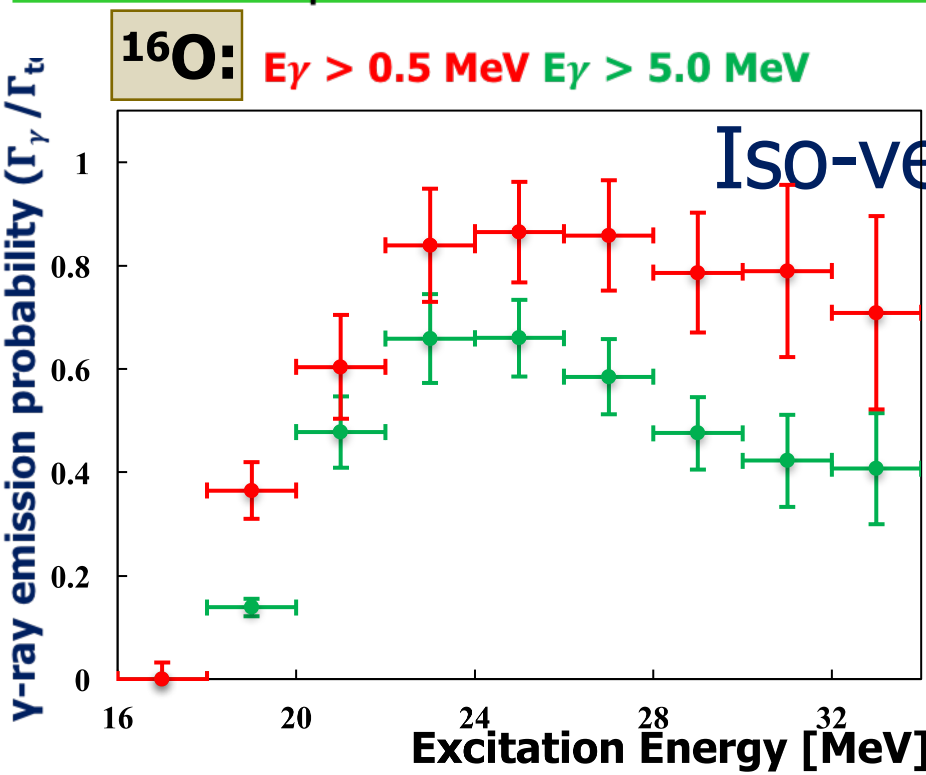
E398

σ_{NC}^{γ} → ^{12}C : **1.10 ± 0.09 x 10^{-42} cm^2**

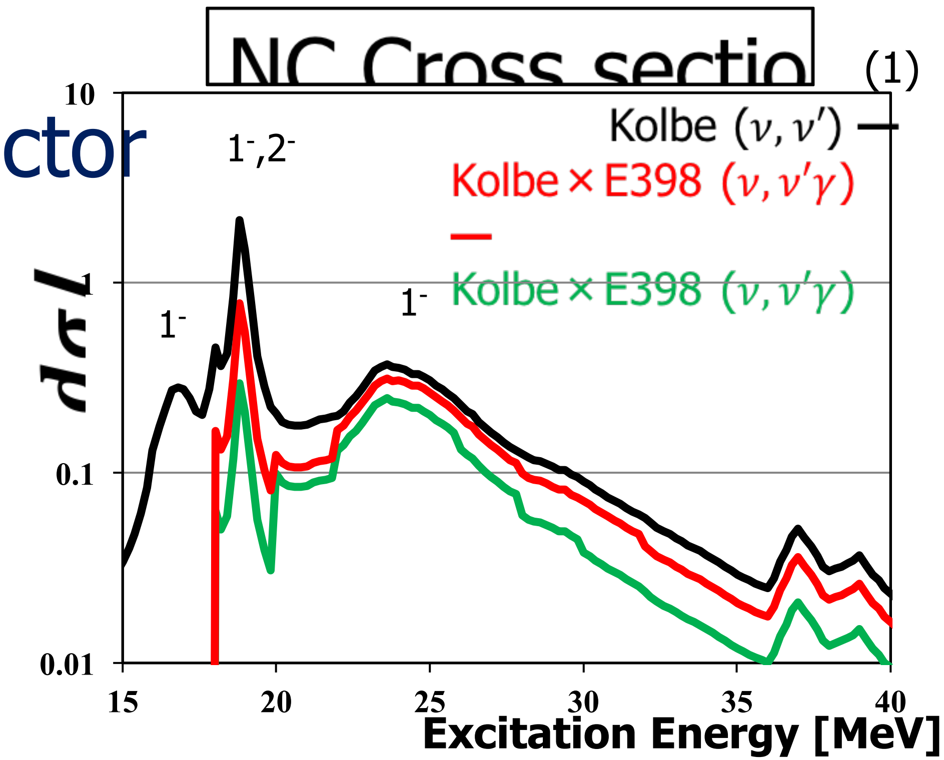
(1) E. Kolbe et al Nucl. Phys. A540 (1992)

Inelastic Scattering Cross section: ^{16}O

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



Iso-vector



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

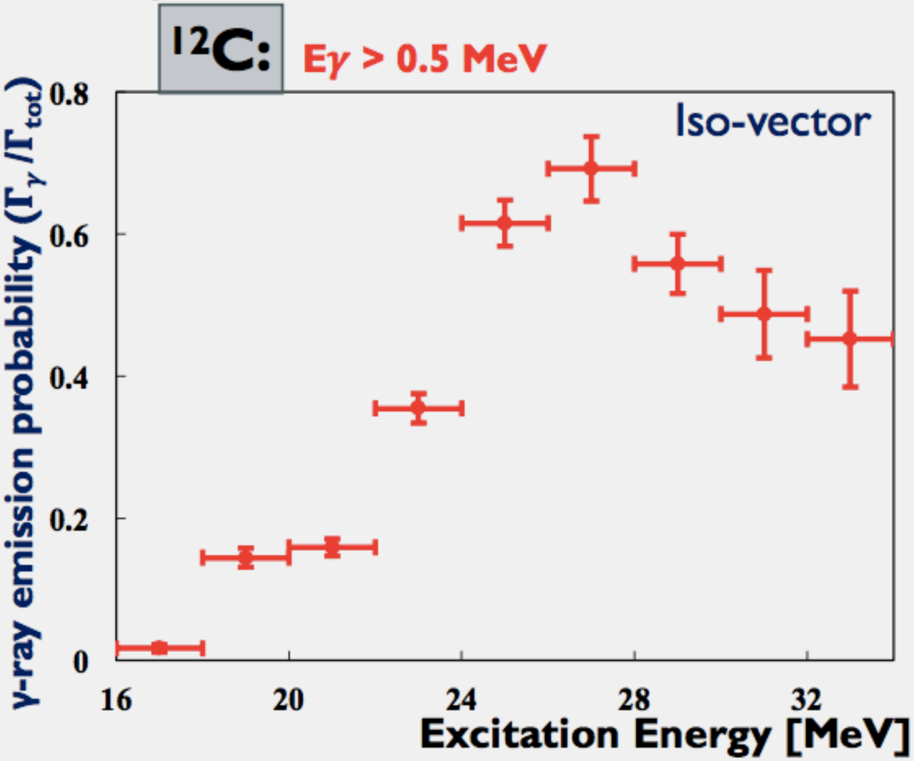
$\sigma_{NC\gamma} \rightarrow {}^{16}O_{(E\gamma>0.5\ MeV)}$: **2.49 ± 0.33 x 10^{-42} cm^2**

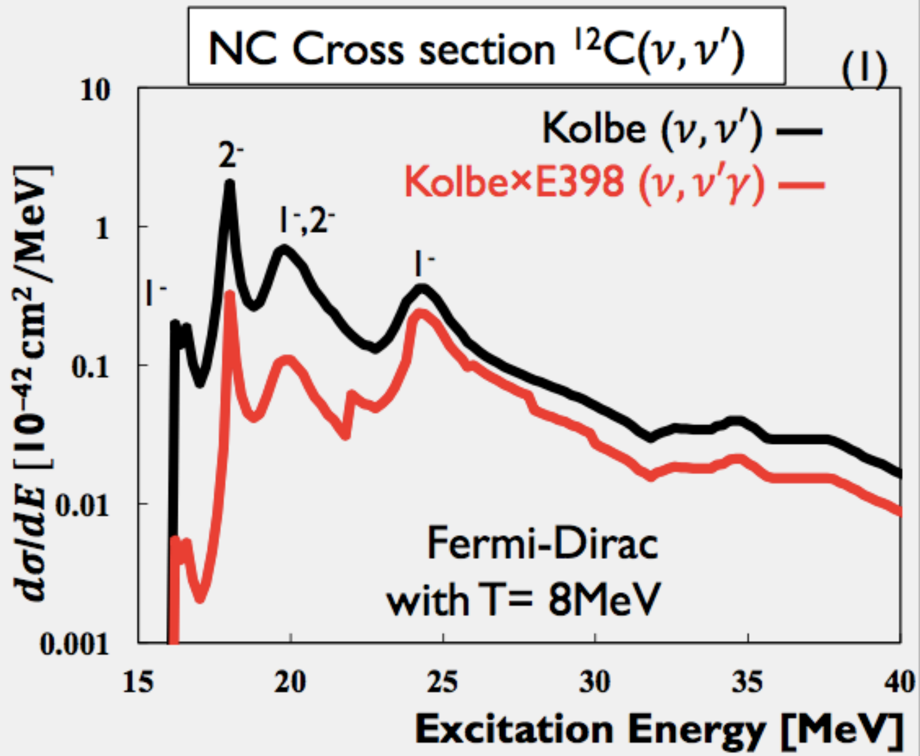
(1) E. Kolbe et al Nucl. Phys. A540 (1992)

How to estimate the number of SN ν's

INELASTIC SCATTERING CROSS SECTION: ^{12}C

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





Supernova Neutrino Events

Using all the information we estimate the neutrino events.

Detector	Interaction	Reaction	N_i (E398)	Other Calculations
KamLAND (1 kton) E_γ > 0.5 MeV	CC	$\bar{\nu}_e + p \rightarrow e^+ + n$	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_γ > 5.0 MeV	CC	$\bar{\nu}_e + p \rightarrow e^+ + n$	8120	8300
	NC	$\nu_x + {}^{16}O \rightarrow \nu_x + \gamma + X$	**720 ± 170**	710 *(2)

- NC events for liquid scintillator type neutrino detectors were estimated for the first time.
- This analysis considers the decay only from iso-vector excitations
- We also give the events for Super-K with γ threshold > 0.5 MeV

(1) A. Suzuki: Nucl. Phys. B (Proc.Suppl.) 77 (1999) 171101 (2) J.F. Beacom, P.Vogel:

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.

Summary –continued (Model Calculation/Future)

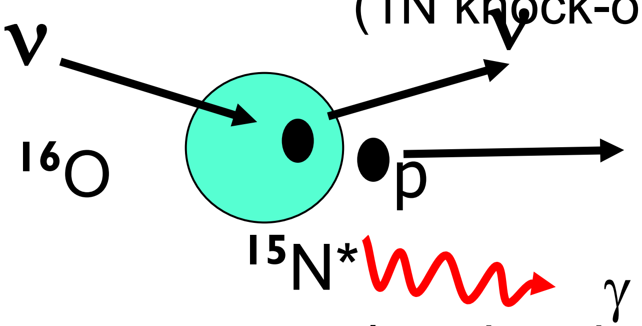
- We performed decay model calculations for ^{12}C considering optical potential and it fairly agrees with data for Ex< 27 MeV.
- We need better theoretical understanding of 1N and 2N decays of giant resonances and a reliable quasi-free calculation. We welcome your suggestions.

- We will be publishing data on the spectrum and the γ emission probability.
- We will continue to work on the search for electromagnetic (direct) decays.

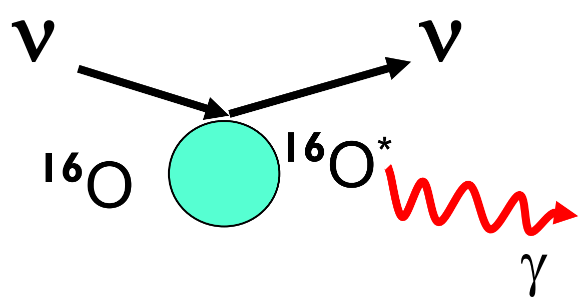
- Experiment: We wish to continue the experiment covering θ_p>3 degrees at GRFBL to understand better on GDR and SDR (hadronic and EM) decays, and quasi-free process. We would like to understand the decay mechanism quantitatively.

SUMMARY: γ-ray production of NC ν-O (-C) reactions (p41

1) E_ν>100MeV: Quasi-elastic (1N knock-out)



2) E_ν<100MeV:Inelastic



1) E_ν>100MeV: Nucleon knockout (Excitation of residual nucleus).

- $\nu O \rightarrow \nu + p/n + {}^{15}N^*/{}^{15}O^*$ Ankowski,Benhar,MS et al. *Phys.Rev.Lett.* **108**(2012)052505
- $\nu C \rightarrow \nu + p/n + {}^{11}B^*/{}^{11}C^*$: I comment How different C is from O? ←This talk (1)

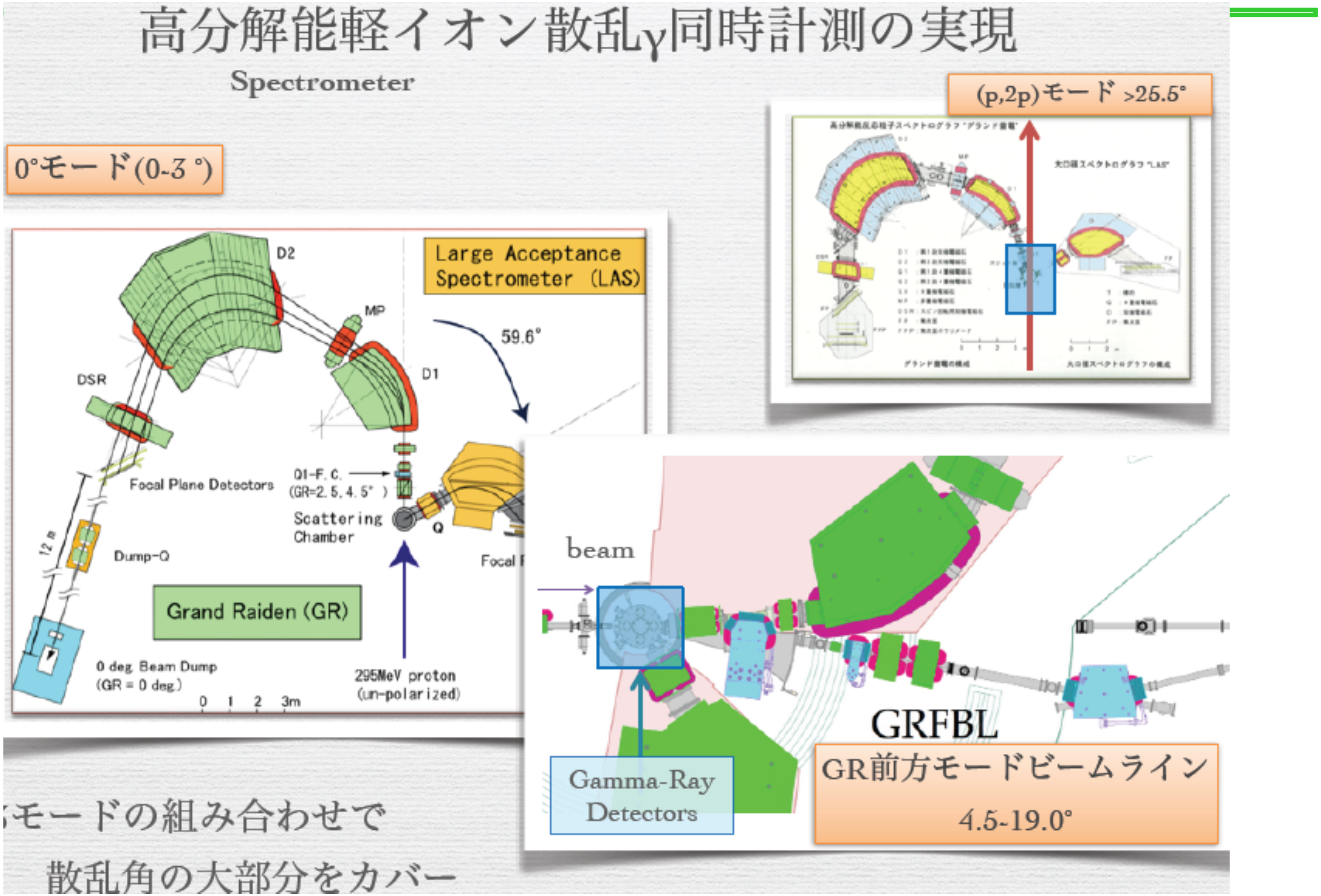
2) E_ν<100MeV: Inelastic scattering (Giant resonances)

- νC,O→νC*,O*→γ : Langanke et al., *Phys.Rev.Lett.* **76**(1996).
- They calculate νO,C→νC*(15.1MeV) and O*→γ(>5MeV).
- We (RCNP E398) measure Br(C*,O*→ γ(>1.5MeV) and reevaluate SN rate. ←This talk (2)

- We would like to address all the questions in a quantitative way experimentally and theoretically.

We will propose an extension of the experiment at GRFBL (Grand-Raiden Forward Beam Line, RCNP)

- -A.Tamii (GRFBL workshop, Nov.28-29,2013)



ー新学術「地下素核研究」第4回超新星ニュートリノ研究会（平成30年1月8-9日、四季の湯強羅静雲荘）の案内ー

- 参加登録は、以下のURLで受け付けております。
  http://www.lowbg.org/ugnd/workshop/groupC/sn20180108/

- 「超新星からのマルチメッセンジャー」固武慶 (福岡大学)
- Kate Scholberg, "Coherent Neutrino Nucleus Scattering"

CAPTAIN@NuInt17

Low-Energy Neutrino Physics Program

Robert L. Cooper
New Mexico State University
on behalf of the CAPTAIN Collaboration

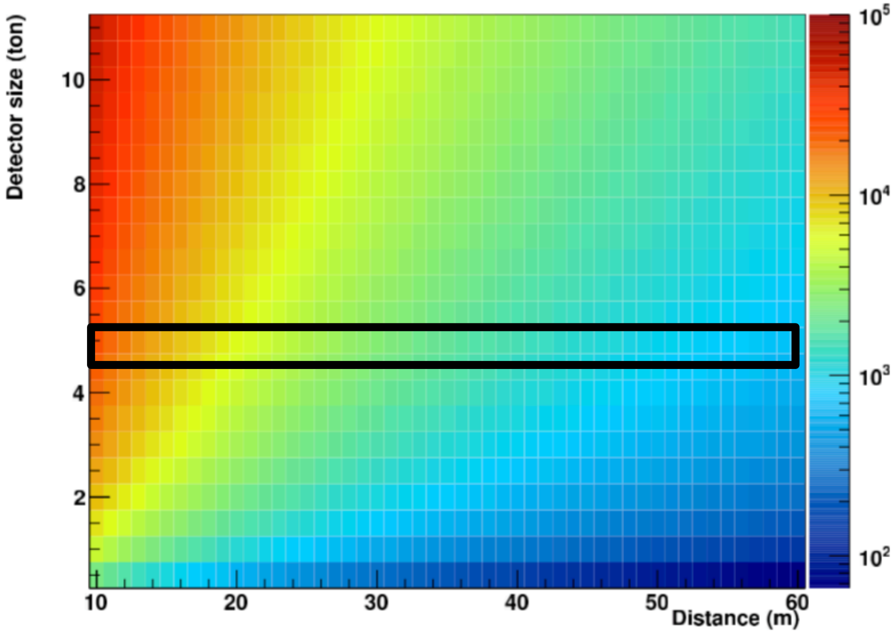
Low-Energy Program

- Study low-energy neutrino interactions in LAr for SN detections in DUNE

$$\nu_e\mathrm{ArCC}: \quad \nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$
$$\bar{\nu}_e\mathrm{ArCC}: \quad \bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$
$$\mathrm{ES}: \quad \nu_x + e^- \rightarrow \nu_x + e^-$$
$$\nu_x\mathrm{ArNC}: \quad \nu_x + {}^{40}Ar \rightarrow {}^{40}Ar^* + \gamma$$

- Dominantly ν_e interactions
- 1000s events anticipated in full-CAPTAIN
- Study de-excitation gamma rays and **neutron emission**

ORNL SNS



A. Bolozdynya et al. arXiv:1211.5199

NaI Array and Veto Counters