Neutrino-nucleus interactions relevant to atmospheric neutrinos & neutrino oscillation experiments

Makoto Sakuda (Okayama)

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In collaboration with I.Oh, T.Mori, A.Ankowski, and O.Benhar

Outline

0. New Phase After Neutrino 2012 (θ_{13} =9±1° Established)
1. Importance of NC ν-A γ-ray production
2. Process to produce γ-ray production in NC ν-A reactions
3. E<200MeV
4. E>200MeV
5. Proposed experiment to measure the relevant branching ratios (Br(A*→γ))
6. Summary

1. New Phase of ν-A Interactions After Neutrino2012 ($\theta_{13} = 9 \pm 1^\circ$ Established)

- A few % accuracy of the neutrino cross sections is required for the determination of precise value of θ_{13} , MH(mass hierarchy) and CP-phase δ.
- Understanding of the *overlapping region* among Quasi-elastic(QE), Resonance(RES) and Deep-inelastic scattering (DIS) becomes important. In addition, a forward region (low Q^2) in QE,1π and DIS is uncertain, ~20%.
- See Itow, McFarland at Neutrino2012, Okumura@NDM.

1. Importance of γ rays in NC ν-O or ν-C interactions

This process is very important to both Supernova (SN) physics and neutrino oscillation experiments. The x-section is sizable, ~30-40% of that of Elastic (coherent) or QE reaction.

1) SN Detection

- Supernova neutrino bursts in Our Galaxy: The events containing γ rays from NC ν-O (ν-C) interactions comprise 5-10% of the total events. They will give us flux (Temperature), independent of the neutrino oscillations.

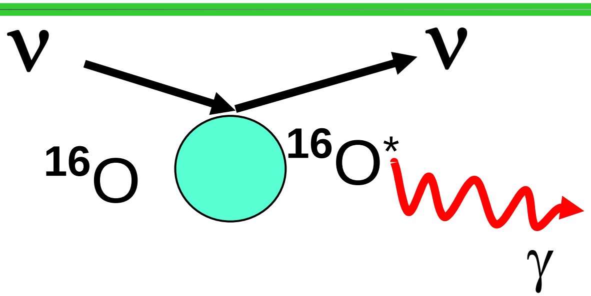
- Supernova Relic Neutrino (SRN) detection: Though we are about to reach the sensitivity to SRN, the γ-rays from Atmospheric NC ν-O (ν-C) interactions at high energy may make serious background in 5-20 MeV region.

2) Neutrino Oscillation Experiments at Beam Dump or LBNE

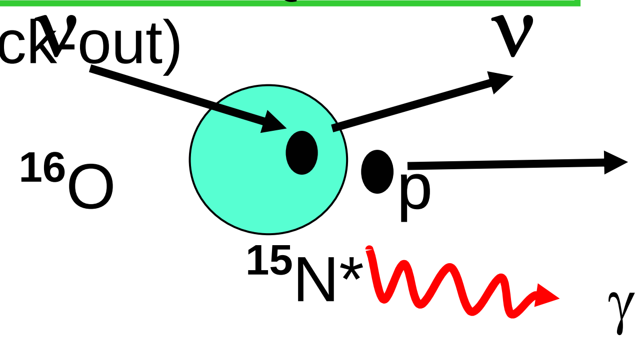
- BD: KARMEN experiment measured the 15.1MeV γ rays from NC ν-C reactions at 29.8MeV. No experiments exist for oxygen at low energy.
- LBNE: The number of γ-ray events from NC ν-A interaction is independent of neutrino oscillations.

Status of γ-ray production study of NC ν-O (-C) reactions

1) E_ν<100MeV: Elastic and Inelastic



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



- Theoretical Calculations
  1) E_ν<100MeV: Langanke et al., *Phys.Rev.Lett.***76**(1996).
     - Inelastic scattering (Giant resonances): $\nu O \rightarrow \nu O^*$, $O^* \rightarrow \gamma$
  2) E_ν>100MeV: Ankowski,Benhar,Mori,Yamaguchi and MS, *Phys.Rev.Lett.***108**(2012)052505
     - Nucleon knockout: $\nu O \rightarrow \nu + p/n + {}^{15}N^*/{}^{15}O^*$ (Excitation of residual nucleus)
- Experiments
  1) E_ν<100MeV: No experiments exists for Oxygen. Karmen for C*(15.1MeV) only → We are preparing the experiment!
  2) E_ν>100MeV: K2K. T2K, RCNP E148 O(p,2pγ)

Feature of the energy dependence

NC Elastic only

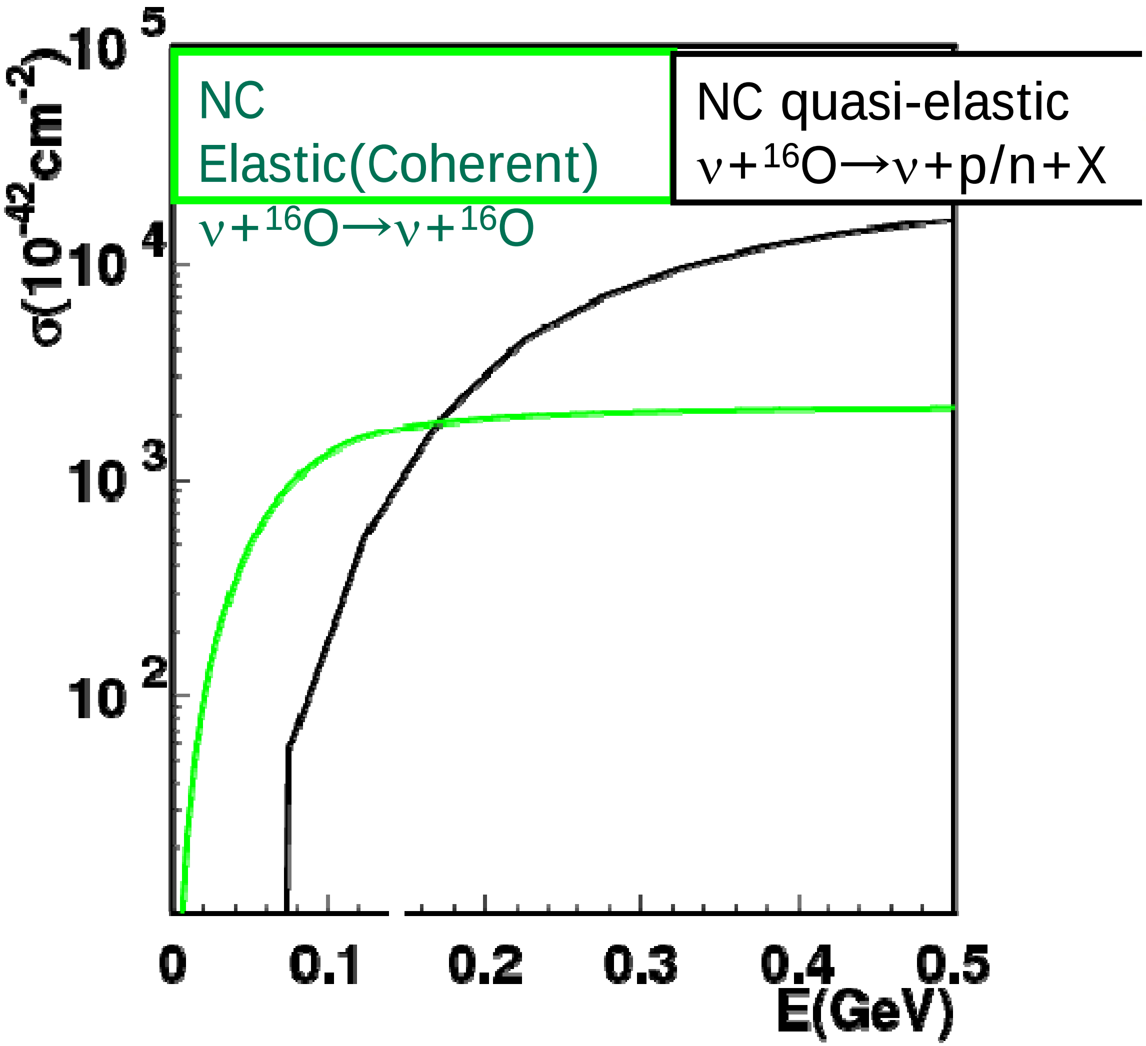
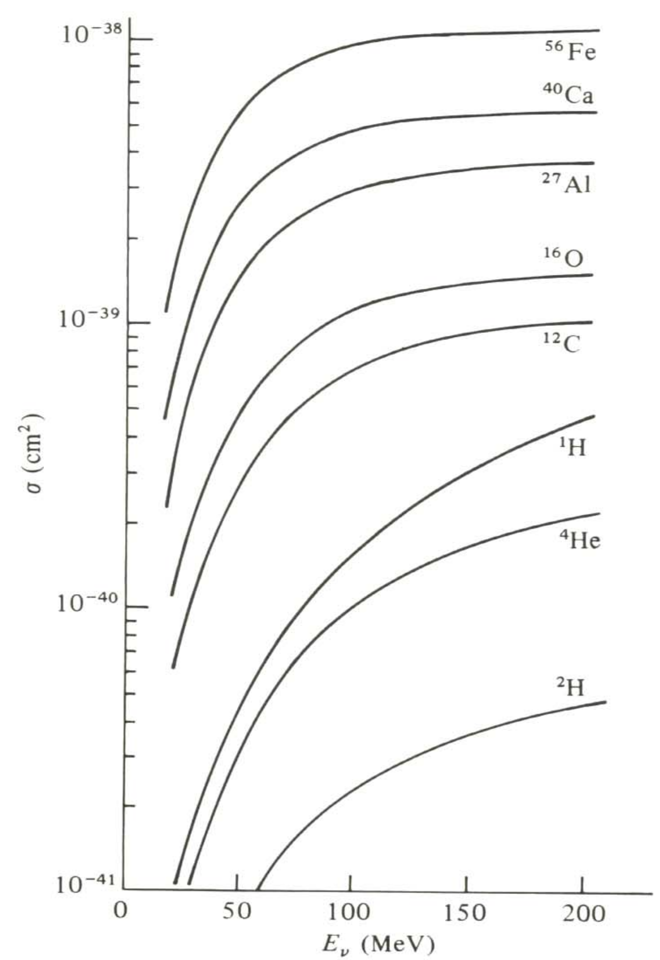


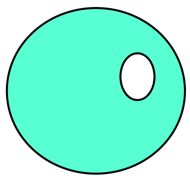
Figure 3.5 Total neutrino elastic scattering cross nuclear targets vs. the incident neutrino energy parameters were used in the calculation.



γ-production in nucleon decay
Ejiri,PRC48,1442(1993)

- SUSY Golden Mode $P \rightarrow K^{+}\nu$

^{16}O

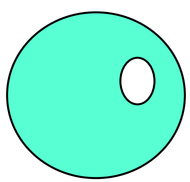


$P \rightarrow K^{+}\nu$

^{15}N

- Residual ^{15}N sometimes emits γ–rays.

^{16}O



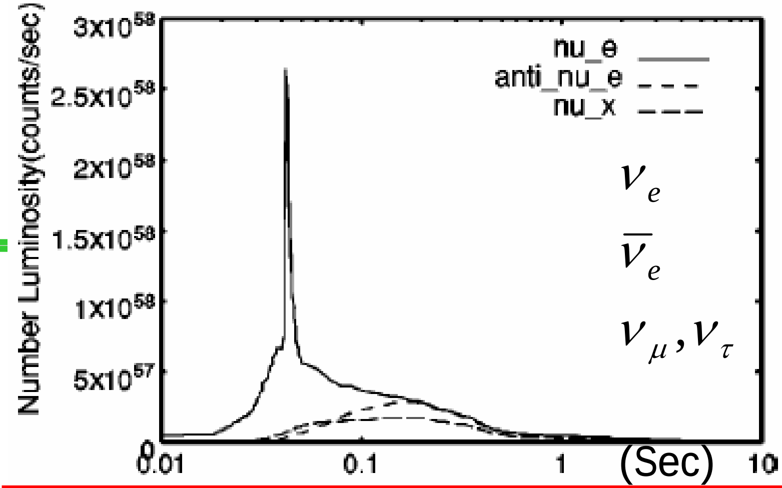
$P \rightarrow K^{+}\nu$, $^{15}N^{*} \rightarrow {}^{15}N+\gamma$

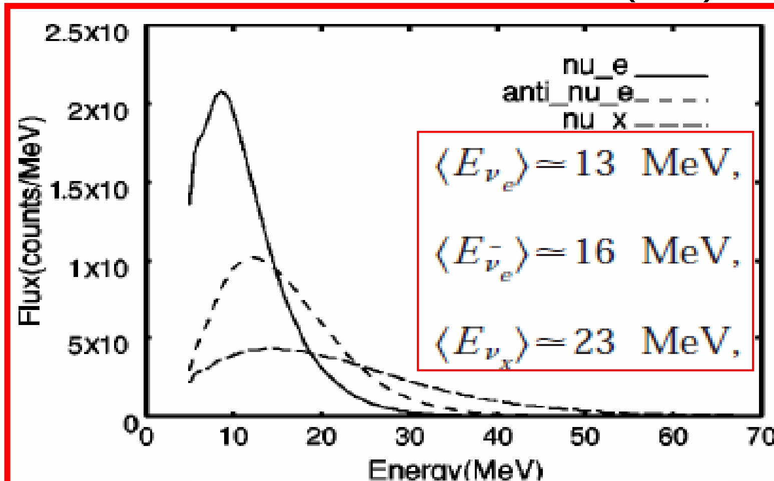
- All we need is the spectroscopic factors Sp($p_{1/2}$,$p_{3/2}$,$s_{1/2}$,,,,)

1) Supernova Physics

- SN bursts from SN explosion@10kpc
  - With about 8000 events, we expect to clarify the Supernova explosion mechanism every msec over 10 seconds
  - NC events (oscillation indep.) are very important. We may solve θ_{13} and Mass Hierarchy. –Kajino@NDM12

(SN1987a:Only 12 events (→Nobel Prize))



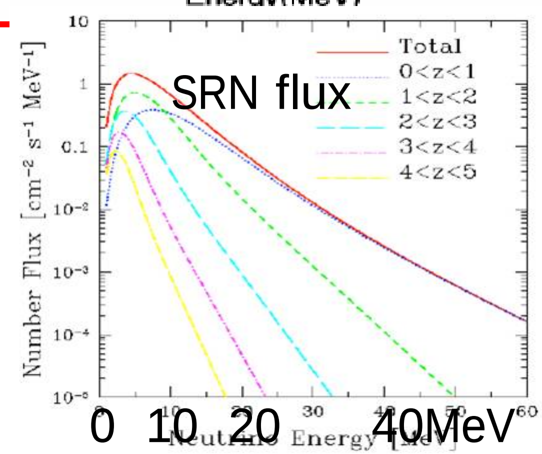


- Supernova Relic Neutrinos(SRN, or DSNB): SN flux from the past (z).

K.Bays et al.(SK),PRD85,052007(2012) has the best sensitivity to SRN.

$$Flux < 2.9\ \bar{\nu}_e/(cm^2 \cdot \mathrm{sec})\ @90\%CL\quad (E_\nu > 17.3MeV)$$

$$while\ 1.7\ \bar{\nu}_e/(cm^2 \cdot \mathrm{sec})\ is\ predicted$$



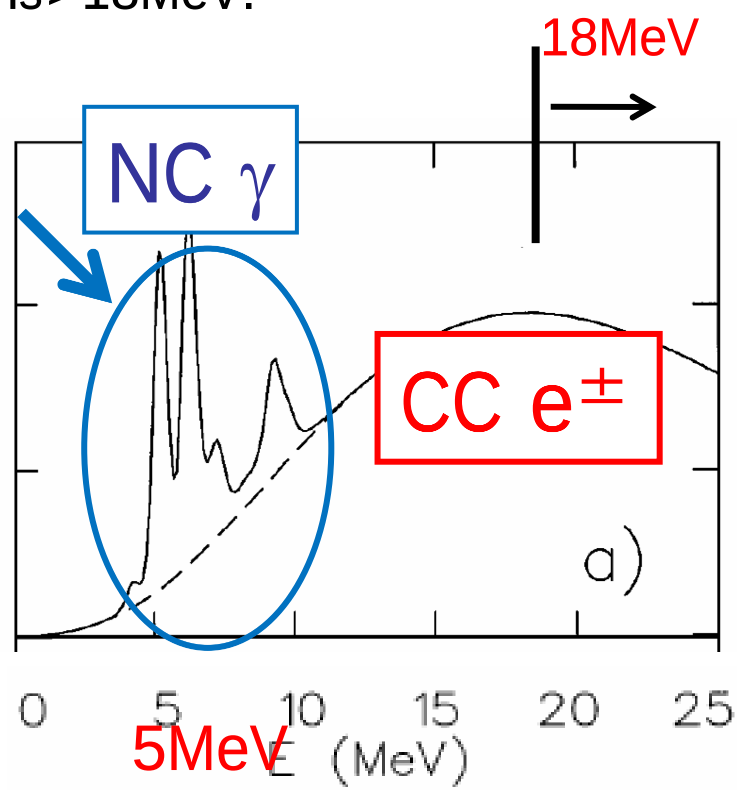
1) Neutrino bursts from SN explosion at 10kpc, expected for H_2O detector (22.5kton)

- 400 γ-ray events (5%) out of total 8000 events (H_2O) above E>5 MeV.
  - NC γ-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.

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

CC:

$$\bar{\nu}_e + p \to n + e^+ \quad (88\%/89\%), \quad (1)$$
$$\nu_e + e^- \to \nu_e + e^- \quad (1.5\%/1.5\%), \quad (2)$$
$$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^- \quad (<1\%/<1\%), \quad (3)$$
$$\nu_x + e^- \to \nu_x + e^- \quad (1\%/1\%), \quad (4)$$
$$\nu_e + {}^{16}\mathrm{O} \to e^- + {}^{16}\mathrm{F} \quad (2.5\%/<1\%), \quad (5)$$
$$\bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + {}^{16}\mathrm{N} \quad (1.5\%/1\%), \quad (6)$$



Neutrino bursts from SN at 10kpc with Liq.scint (KamLAND)

■1000-ton Liq.Scinti.Detector (C+H) observes ~60 NC 15.1MeV γ-ray events.

- P.Vogel :http://sn1987a-20th.physics.uci.edu/, Feb.2007, Hawaii, - KamLAND.US.Proposal(March,1999

■ν_e-bar+p→e^++n : ～300 events

■ν_e+^{12}C→e+^{12}N(^{12}B): ～30 events

■ν+e^-→ ν+e^- : ～20 events

■ NC ν+^{12}C→ν+^{12}C+γ (15.1MeV): ～60 events

■ν+p→ ν+p: ～300 events

2) NC $\nu+A \rightarrow \nu+\gamma+X$ in neutrino oscillation experiment at Short- and Long-baseline (E_ν=30MeV or >200 MeV)

-independent of ν-oscillations-

- KARMEN at Short Baseline
  $\nu+{}^{12}C \rightarrow \nu+{}^{12}C+\gamma$(15.11MeV)
  → Detailed Fig Later.

- K2K 1ktonWC measured
  $\nu_\mu+O \rightarrow \nu_\mu+\gamma$(6MeV)+X.

-Kameda@NuInt05 Proceedings.

-Spectrum shape is consistent with NC 6.3MeV γ-ray production.

K2K: $\nu+H_2O \rightarrow \gamma$ + nothing

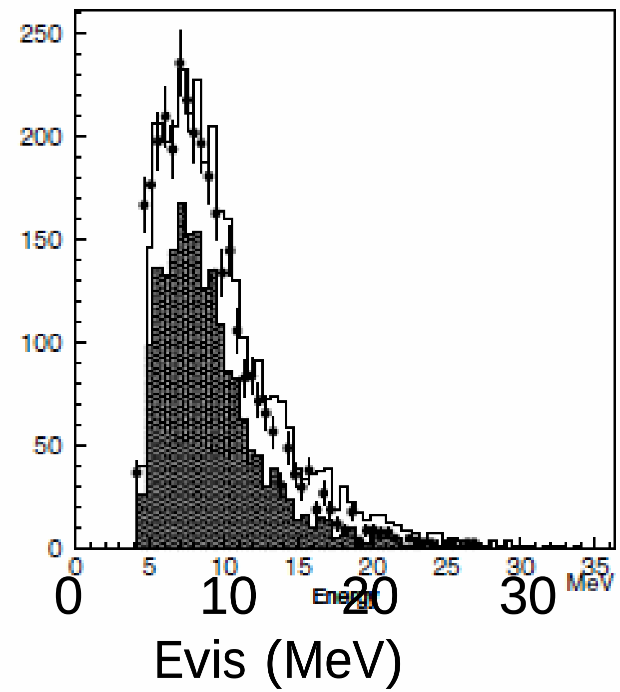
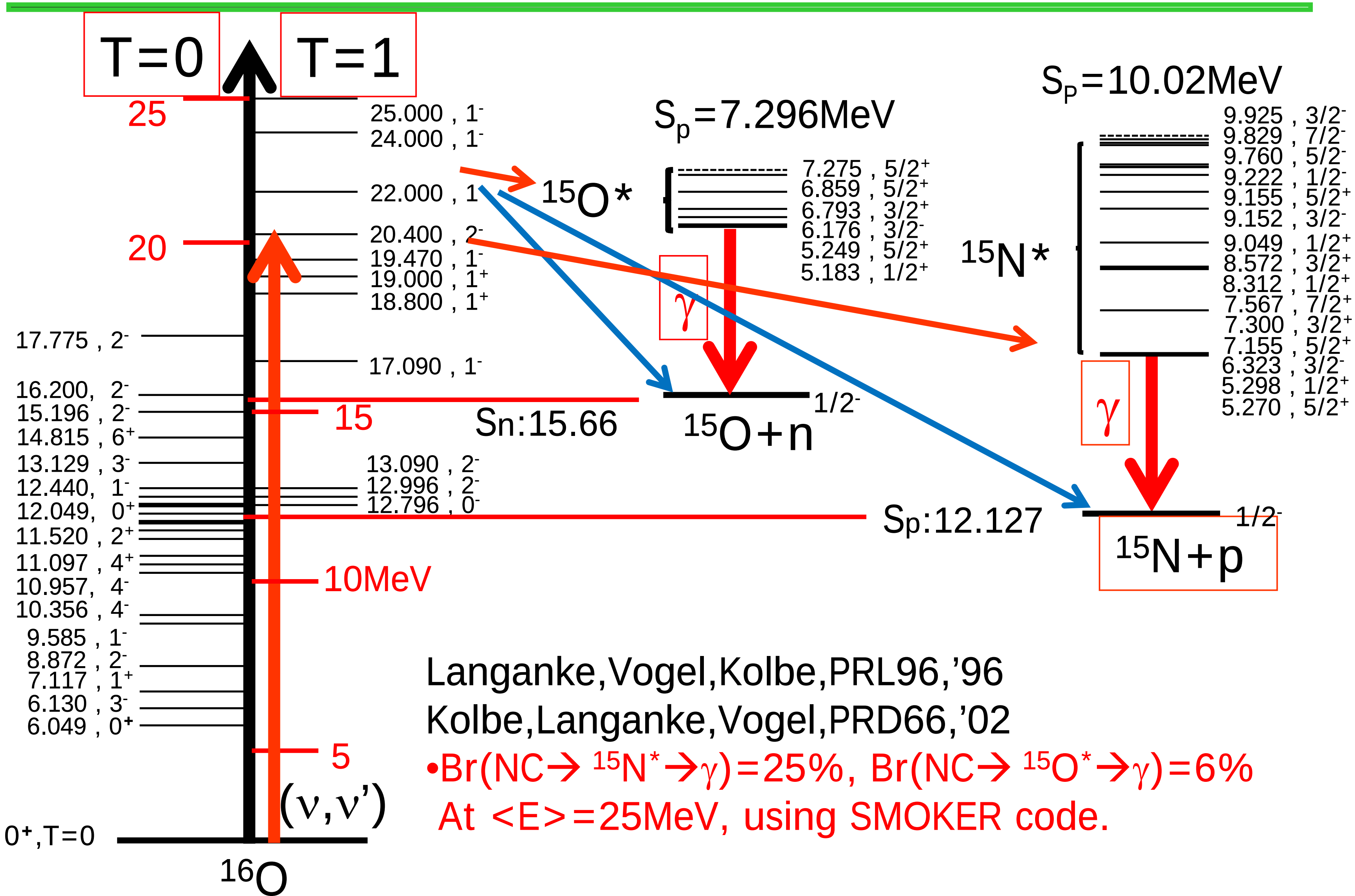


Figure 9. Reconstructed vertex distributions. Dots shows the data, histograms shows the MC normalized by the number of events. Hached histograms shows NC elastic scattering fraction.

3. NC ν-O γ-production (E<100MeV, Inelastic)

$\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^*$; ${}^{16}O^* \rightarrow {}^{15}N^* + p$, ${}^{15}O^* + n$; ${}^{15}N^*$, ${}^{15}O^* \rightarrow \gamma$

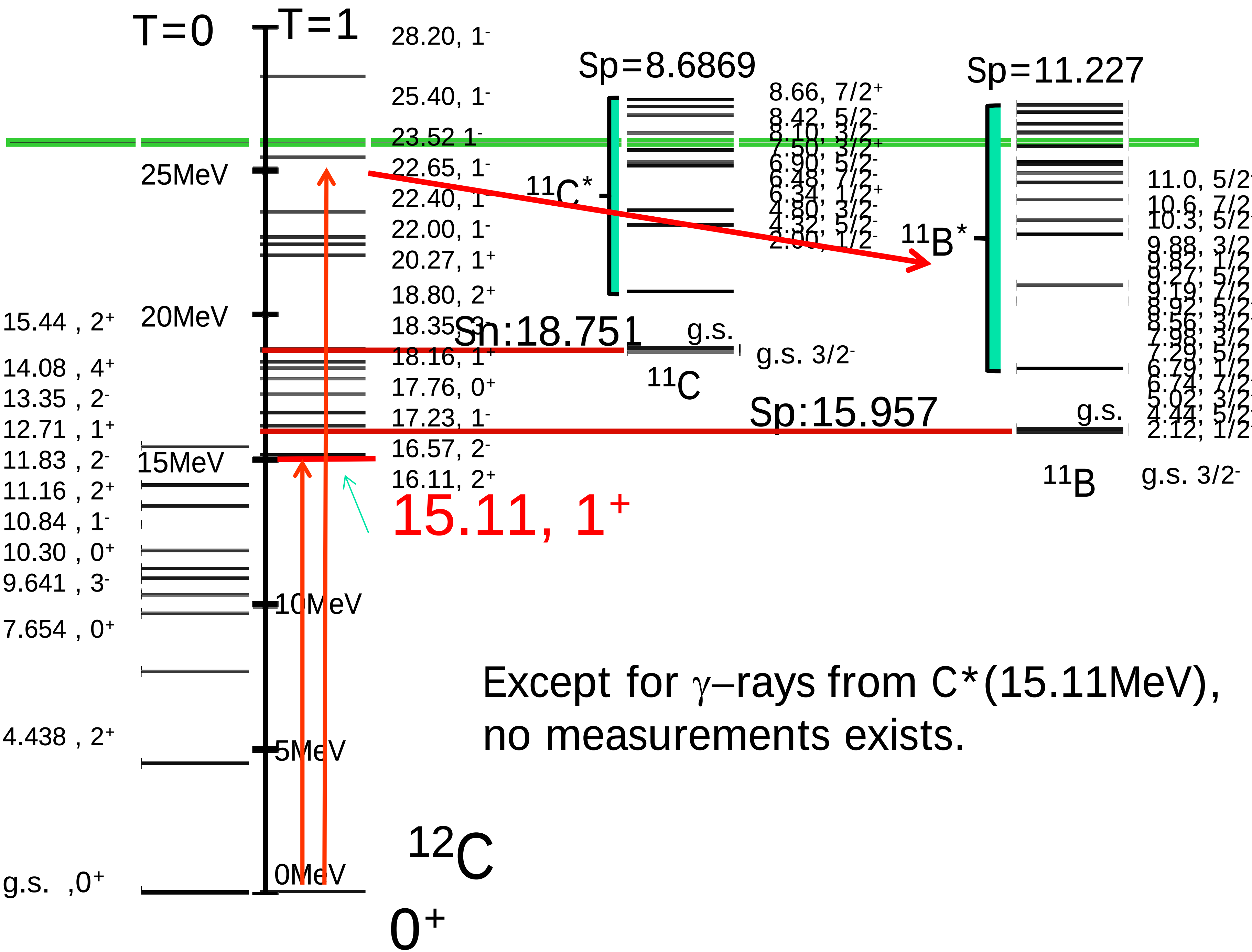


Langanke,Vogel,Kolbe,PRL96,'96

Kolbe,Langanke,Vogel,PRD66,'02

- Br(NC→ ${}^{15}N^* \rightarrow \gamma$)=25%, Br(NC→ ${}^{15}O^* \rightarrow \gamma$)=6%

  At <E>=25MeV, using SMOKER code.



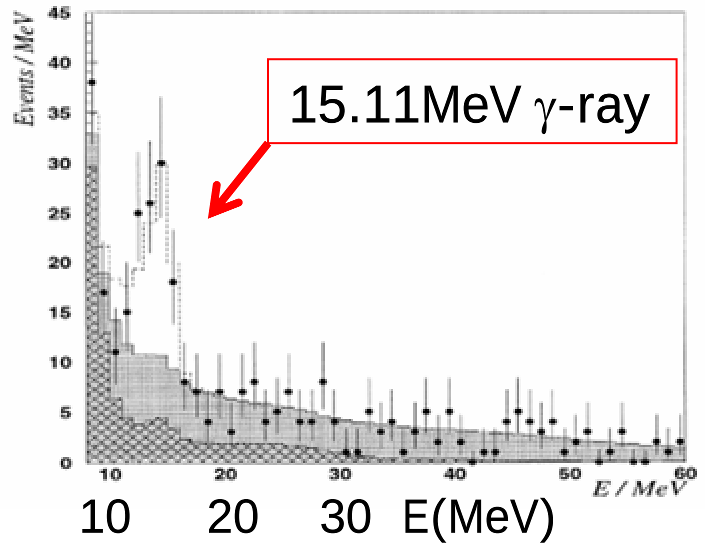
Except for γ–rays from C*(15.11MeV), no measurements exists.

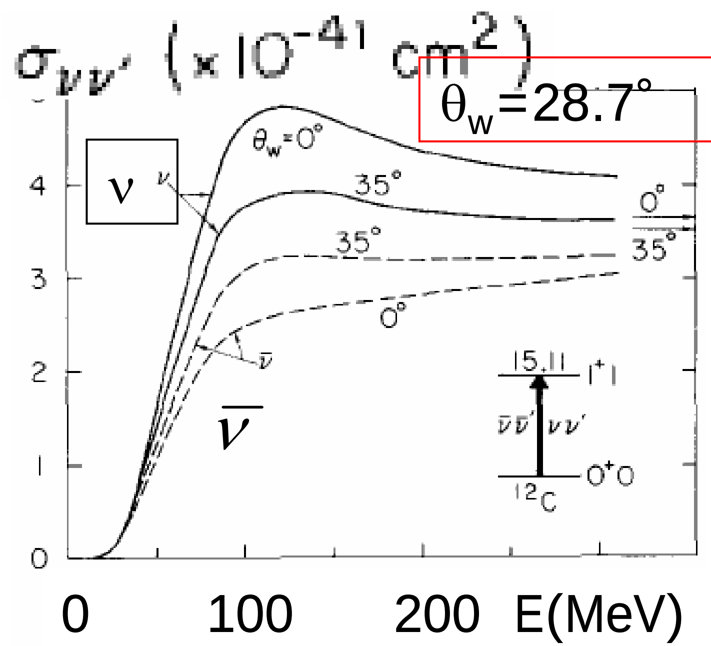
E<200MeV: $\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma(15.11MeV)$ Karmen

Donnelly-Pecci,Phys.Rep.50,1,'79.

- 15.11MeV ($J^P=1^+$, T=1 Giant M1 Resonance) of ^{12}C exists below proton separation energy (S_p=15.96MeV) and it decays to the ground state, emitting a single 15.11MeV γ-ray (Br~80%) and other cascade γ-rays.

- KARMEN measurement @E_ν=29.8MeV $(3.2\pm0.5\pm0.4)\times10^{-42}cm^2$
In good agreement with the calculation, $2.8\times10^{-42}cm^2$.
- Cross section saturates above 100MeV.





Total and partial NC ν-O/-C cross sections calculated for a Fermi-Dirac ν-spectrum (T=8MeV, μ=0MeV)

-Kolbe et al.,NPA540,599,'92;PRD66,013007,'02

- T=8MeV, μ=0→ $\langle E_\nu \rangle$=24MeV.
- For oxygen, $^{16}O(\nu_x, \nu_x p\gamma)^{15}N$ is dominant.

ν_x-^{16}O ($\nu_x=\nu_\mu$, ν_τ)	$\sigma(10^{-42}cm^2)$
$^{16}O(\nu_x, \nu_x)X$	5.19
$^{16}O(\nu_x, \nu_x p\gamma)^{15}N$	1.29
$^{16}O(\nu_x, \nu_x n\gamma)^{15}O$	0.35

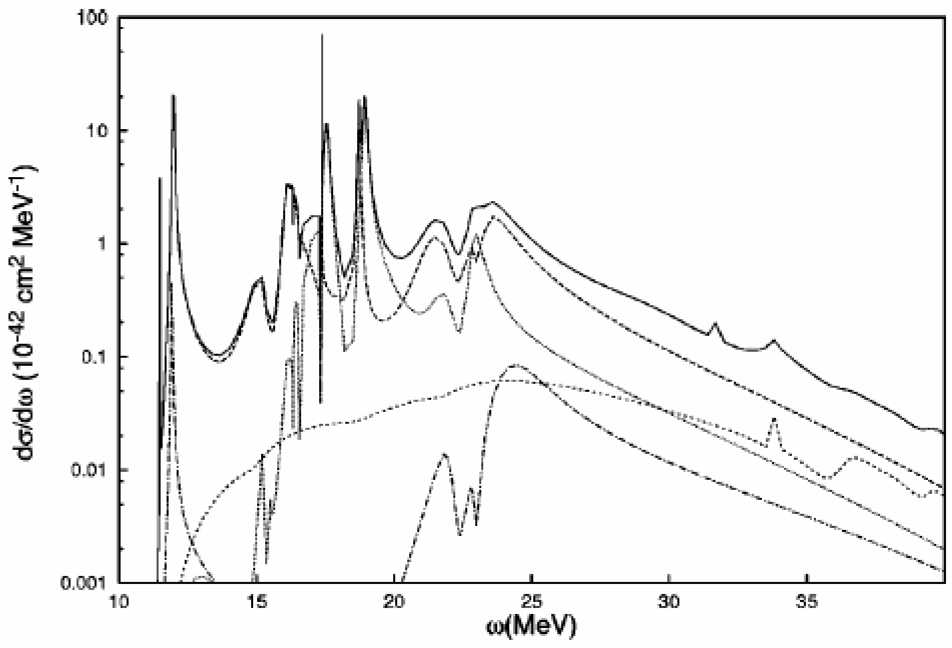
Br~32%

- For Carbon target, the γ production is dominated by 15.11 MeV γ emission. But, how dominant is not shown in the paper.

ν-^{12}C (averaged over all flavors)	$\sigma(10^{-42}cm^2)$
$^{12}C(\nu, \nu')$	6.84
$^{12}C(\nu, \nu'\gamma)$ (including 15.11MeV γ)	3.0

Axial vector dominant

- $J^P = 1^-, 2^-$ dominant, $0^-, 1^+$ small.
- Langanke1996,2002, Janowitz03
- Contribution of vector current –smaller by 2 orders



4. E>200MeV(QE)

$$\sigma_{NC}\left(\nu+{}^{16}O \rightarrow \nu+p/n+X+\gamma\right)$$
$$=\sigma_{NC}\left(\nu+{}^{16}O \rightarrow \nu+p/n+X^{*}\right)\times Br\left(X^{*} \rightarrow X+\gamma\right)$$

- $\sigma_{NC}\left(\nu+{}^{16}O \rightarrow \nu+p/n+X\right)$ can be calculated using the spectral function for O.
- $\sigma_{NC}\left(\nu+N(p,n) \rightarrow \nu+N+X\right)$ can be calculated as follows:

$$\mathrm{H}_{NC} = \frac{G}{\sqrt{2}} j_{\mu} J^{\mu} \qquad \left(\mathrm{H}_{CC} = \frac{G}{\sqrt{2}}\left(j_{\mu}^{(+)} J^{(-)\mu} + j_{\mu}^{(-)} J^{(+)\mu}\right)\right)$$

Leptonic current: $j_{\mu} = \bar{\nu}_e \gamma_{\mu}(1+\gamma_{\mu})\nu_e + \bar{\nu}_{\mu}\gamma_{\mu}(1+\gamma_{\mu})\nu_{\mu} + \bar{\nu}_{\tau}\gamma_{\mu}(1+\gamma_{\mu})\nu_{\tau}$

Hadronic current: $J_{\mu} = J_{\mu}^{V;3} - 2\sin^2\theta_W J_{\mu}^{em}$

Electromagnetic current: $J_{\mu}^{em} = J_{\mu,V3}^{em} + J_{\mu,S}^{em}$ $\qquad J_{\mu}^{\pm} = J_{\mu}^{V_1} \pm i J_{\mu}^{V_2}$

NC Form factor:

$$\left(F_1^V\right)^{NC;N} = \frac{1}{2}F_1^V - 2\sin^2\theta_W F_1^N \qquad F_A^{NC} = \pm\frac{1}{2}F_A \qquad M_A = 1.1 GeV/c^2$$

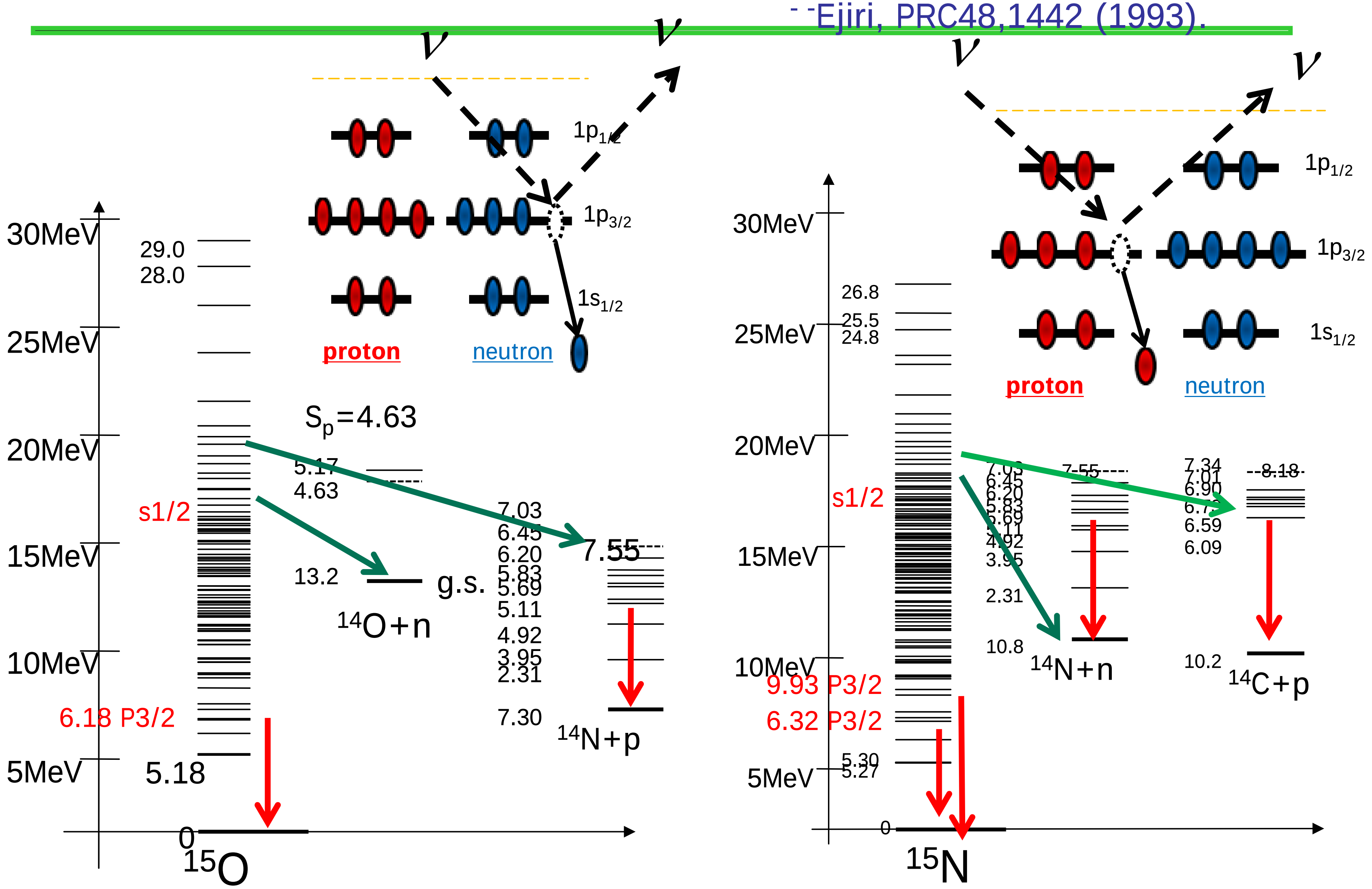
$$\left(F_2^V\right)^{NC;N} = \pm\frac{1}{2}F_2^V - 2\sin^2\theta_W F_2^N \qquad F_{pseudo}^{NC} = 2M^2\frac{F_A^{NC}}{\left(M_{\pi}^2 + Q^2\right)}$$

- $Br\left(X^{*} \rightarrow X+\gamma\right)$ is estimated by using Spectroscopic factors of Oxygen and some data.

E_ν>200MeV: NC QE process producing γ-rays

ν+O→ ν+n+^{15}O*, ν+p+^{15}N*

Ejiri, PRC48,1442 (1993).



S(p,E) for ^{16}O, O.Benhar,MS et al., PRD72,053005,2005, will give a spectroscopic factor for p,s shells (Fig) when a proton or neutron is kicked out by a neutrino.

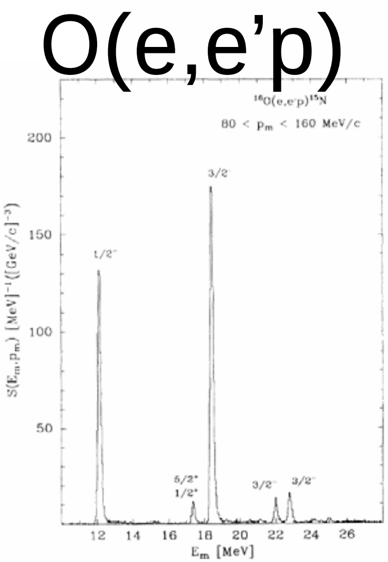


FIG. 1. $^{16}O(e,e'p)^{15}N$ missing energy spectrum for the kinematics centered about $p_m = 120$ MeV/c.

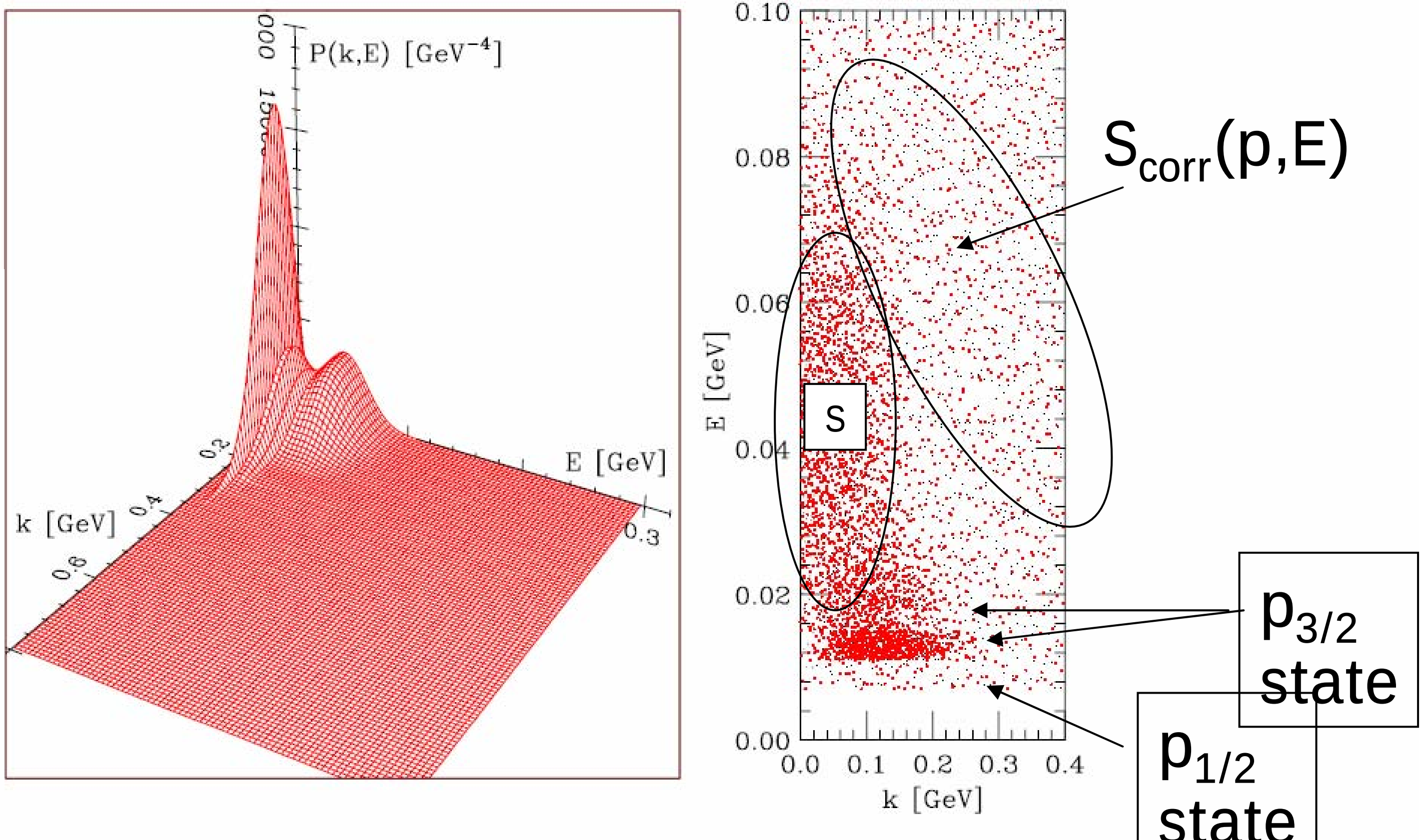
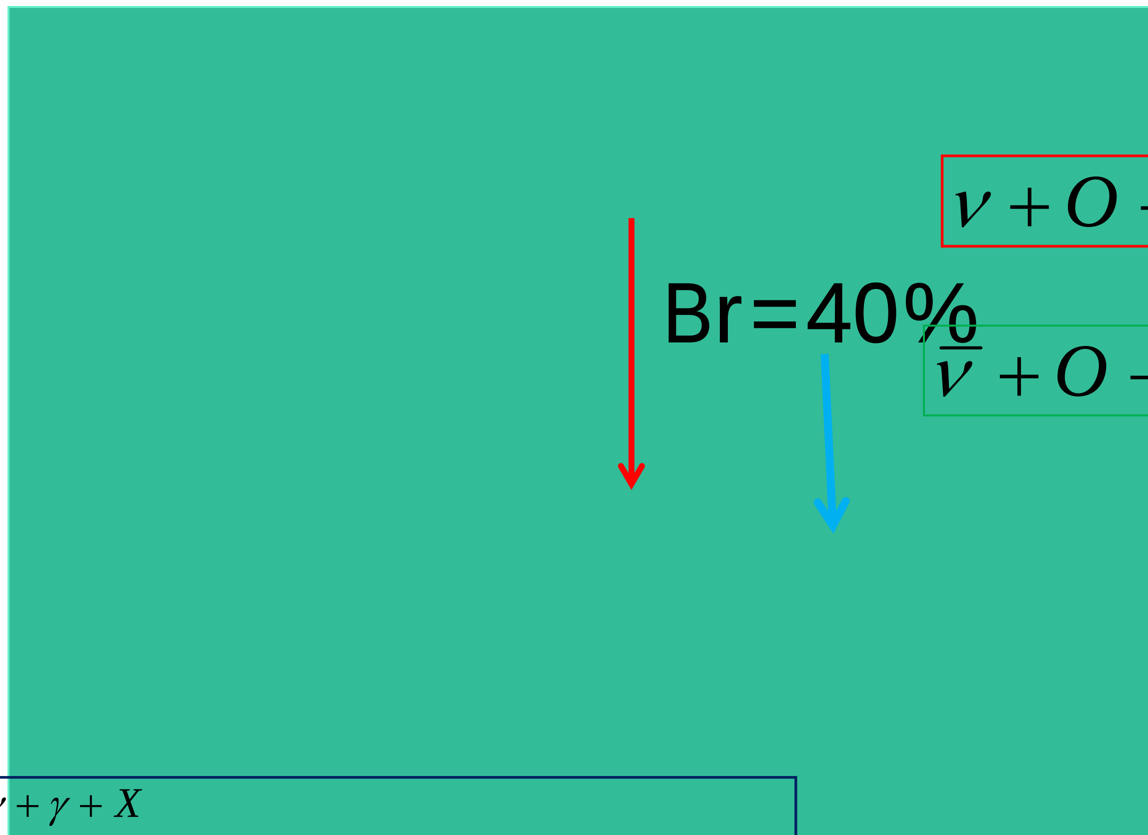


FIG. 2 (color online). Three-dimensional plot (left panel) and scatter plot (right panel) of the oxygen spectral function obtained using the LDA approximation described in the text.

NC quasi-elastic cross section and γ-production cross section- Ankowski, MS et al., *PRL.***108**(2012) 052505

$$\sigma_\gamma \equiv \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + \gamma + Y + N) \qquad (1)$$
$$= \sum_\alpha \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + X_\alpha + N)\,\mathrm{Br}(X_\alpha \to \gamma + Y),$$



$$\nu + O \to \nu + N + X$$

$$\bar{\nu} + O \to \bar{\nu} + N + X$$

$$\nu + O \to \nu + O^* \to \nu + \gamma + X$$

by Kolbe etal.(NC Inelastic) – Smaller by 10(15) *at* 0.5(1.0) *GeV*

Branching ratio Br($^{15}N^*$, $^{15}O^* \rightarrow \gamma$, E_γ>5MeV)

- Br~41% dominated by $p_{3/2}$, only Br~2% from $s_{1/2}$
- $s_{1/2}$ cross section, ie Br too, is much suppressed below 200MeV, due to its large binding energy.

$$\sigma_\gamma \equiv \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + \gamma + Y + N) \qquad (1)$$
$$= \sum_\alpha \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + X_\alpha + N)\,\mathrm{Br}(X_\alpha \to \gamma + Y),$$

TABLE I. Spectroscopic strengths of the ${}^{16}_{8}$O hole states and their branching ratios for deexcitation by the $E_\gamma > 6$ MeV photon emission.

α	$p_{1/2}$	$p_{3/2}$	$s_{1/2}$
S_α	0.632	0.703	0.422
$\mathrm{Br}(X_\alpha \to \gamma + Y)$	0%	100%	$16 \pm 1\%$

- We used the following numbers for Br($S_{1/2}$ →g, E>5MeV): ^{15}N Br=15.6% (E148), ^{15}O Br=16% (Kamyshkov et al.,PRD67)
- $s_{1/2}$: Br(^{15}N $s_{1/2}$→γ)=2/8x0.422x0.16=0.02
- $p_{3/2}$:Br(^{15}N p3/2→γ)=4/8x0.703x1.0=0.352
- If the cross sections for $s_{1/2}$ and $p_{3/2}$ are the same, we simply obtain Br=0.352+0.02=0.37.

  Since the binding energy of $s_{1/2}$ is larger, the cross section of $p_{3/2}$ is larger and Br of γ-production is dominated by $p_{3/2}$. We obtain Br~41%.

5. Preparing for O,C(p,p'γ),(He,tγ) at 0 degrees at RCNP

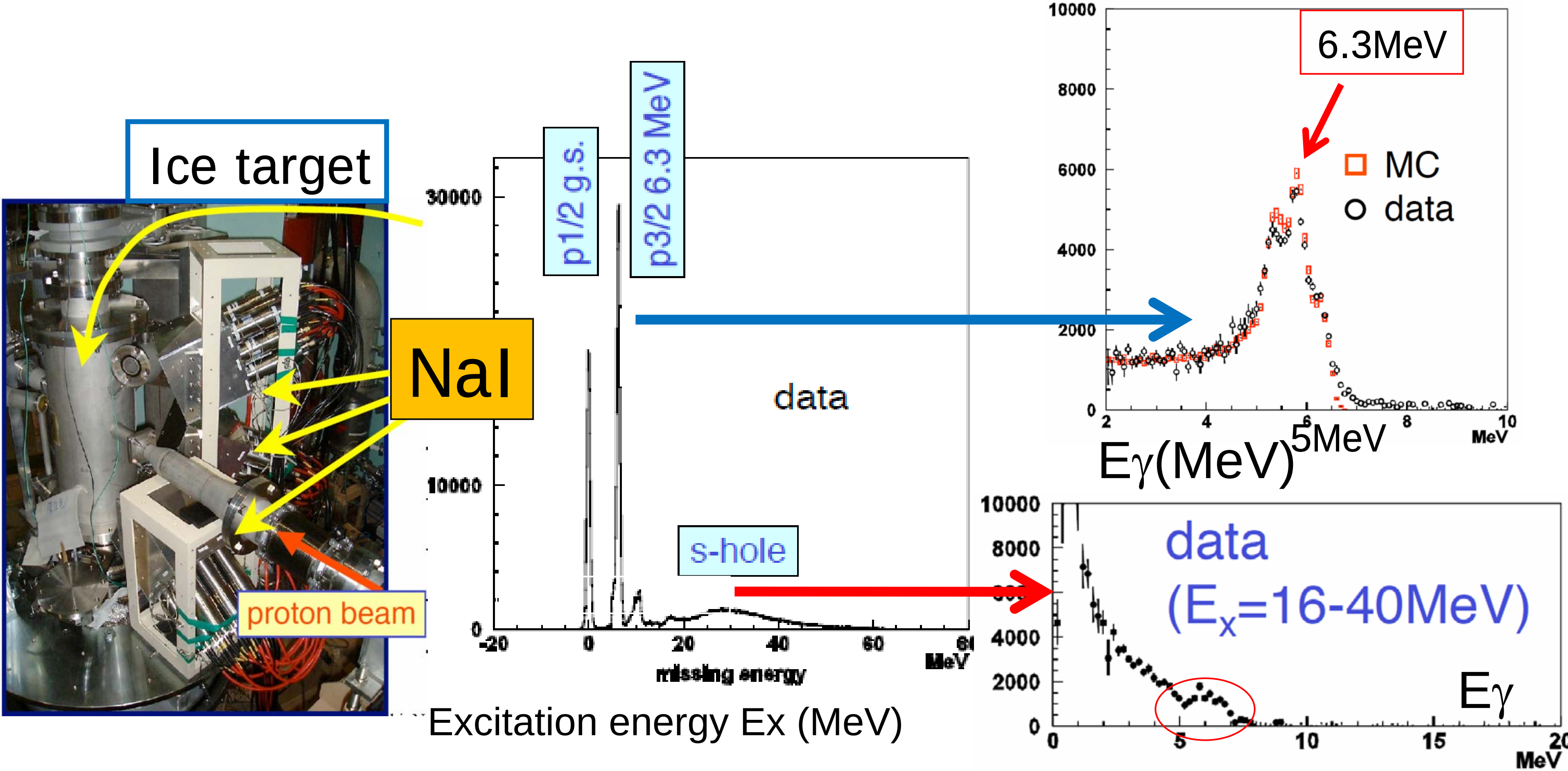
- This proposal is relevant to supernova physics (E<100MeV). We would like to measure γ-rays from excited states including giant resonances in 5<Ex<20MeV.

- **Particle beam:** p or ^{3}He (max E=400MeV)
- **Target:** ^{16}O and ^{12}C
- **Grand Raiden:** Measure excitation energy
- Ex with scattered p or t
- at ~0 degrees.
- ΔEx=20keV(@Ep=295MeV)
- ***γ*** **-ray detector:** Placed nearby the target

E148 $^{16}O(p,2p)^{15}N^*$ measured $Br(^{15}N^* \rightarrow \gamma)$

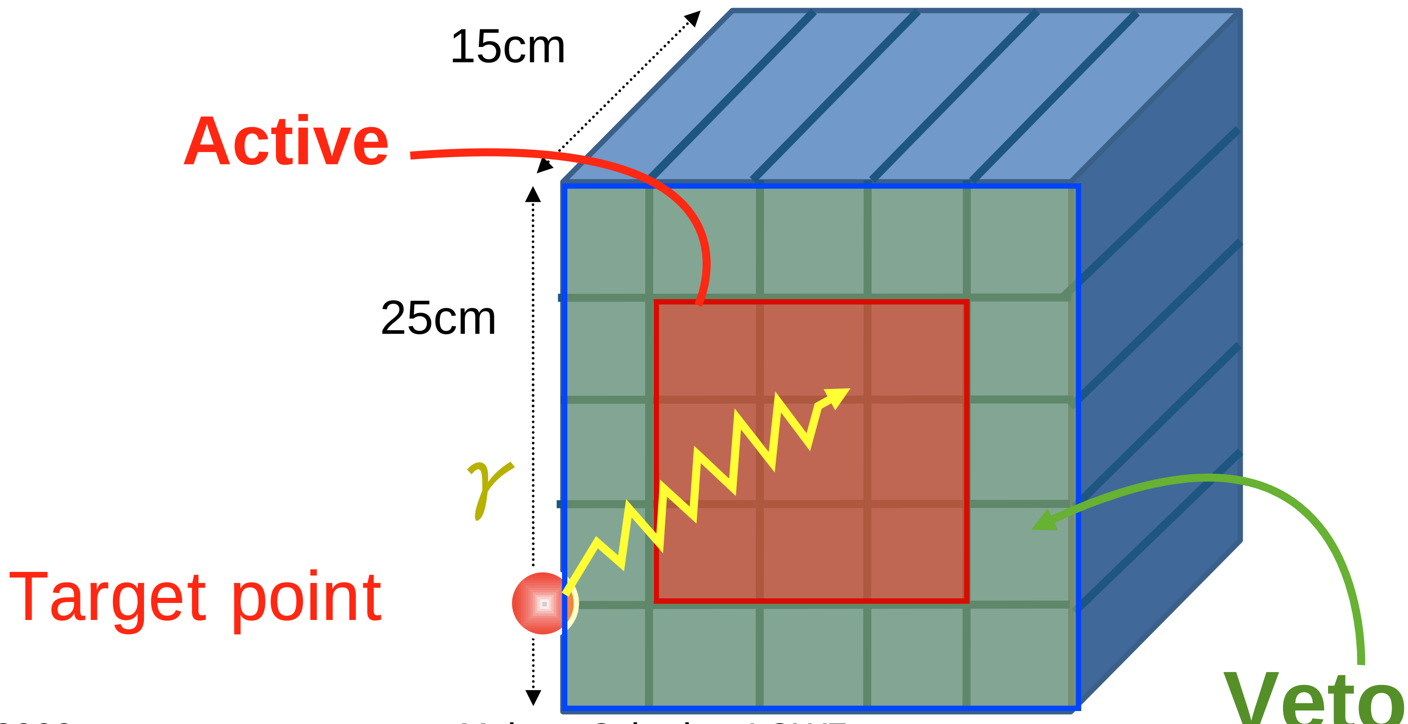
Tag Ex (ΔEx=20KeV) and Eγ. Kobayashi et al.,nucl-ex/0604006 (@NuInt04)

- 6MeV γ rays from $p_{3/2}$ hole are clearly observed.
- $Br(^{15}N^*(s\text{-hole}) \rightarrow {}^{15}N\gamma)$=15.6+-1.3%, E$\gamma$>6MeV.



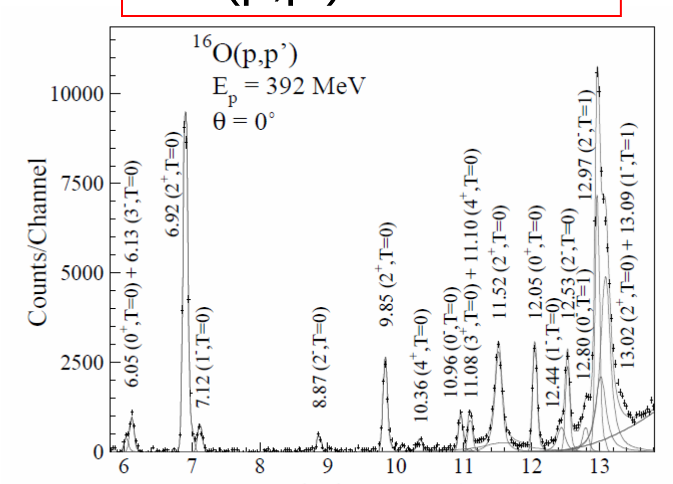
Target and γ detector array (Photo from E148)

We designed one 5x5 NaI(Tl) array (25x25x15cm), using inner 3x3 array as active counters and outer 16 counters as veto (Compton suppression) counters. Downstream Veto counters (CsI) will be installed too. We have 27 NaIs from RCNP E148 O(p,2p)N.



We like to measure O, C(p,p'γ) and O,C(He,tγ) near 0 degrees at RCNP

$^{16}O(p,p')$ T.Kawabata

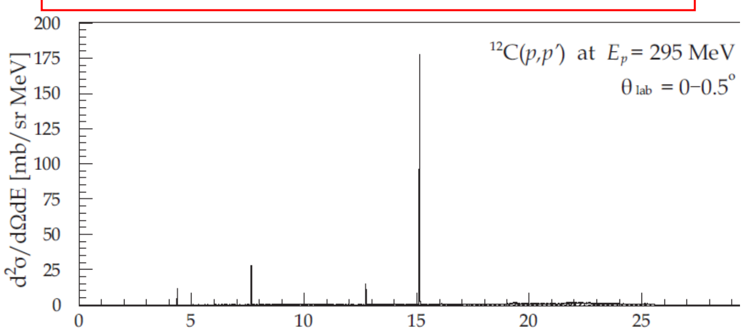


Excitation energy[MeV]

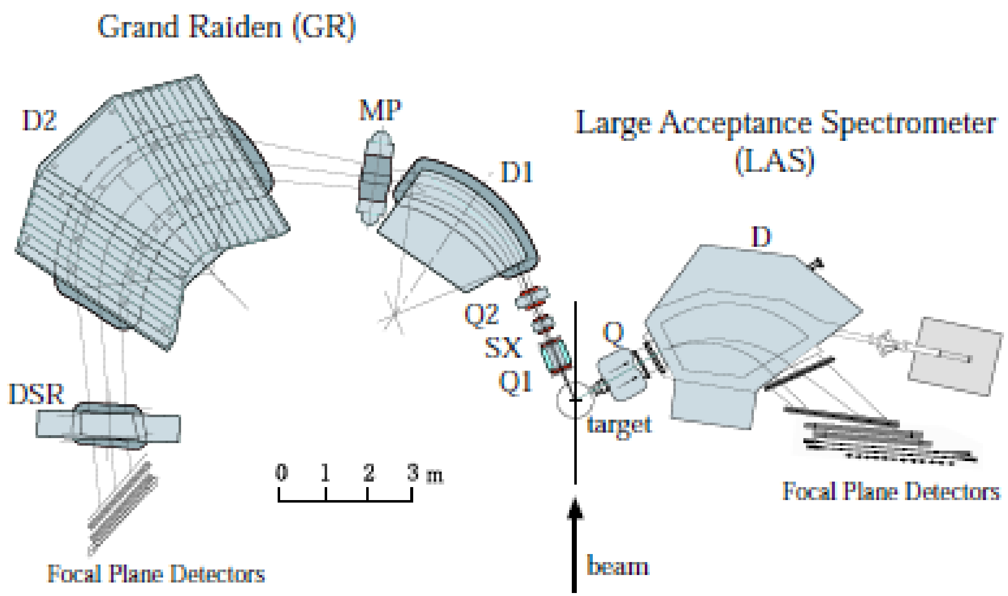
- We like to measure γ-rays in the forward direction of O,C(p,p'). No Systematic study has been done.

- Similar motivation: H.Ejiri et al., Ga(He,tγ)Ge, Phys.Lett.B433,257,1998.

$^{12}C(p,p')$ H.Matsubara, 2010



Excitation energy[MeV]



Super-K search for SRN (Zhang@ν2012)

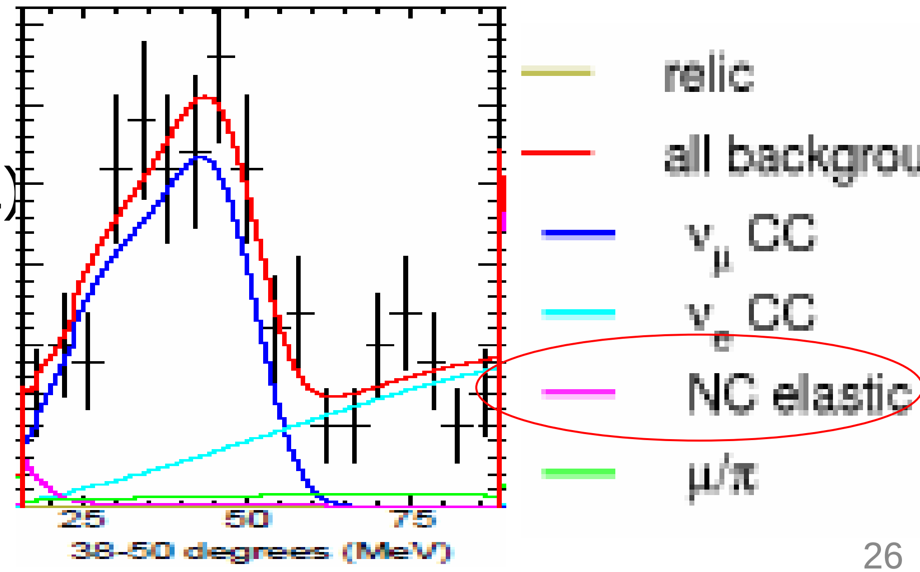
(1) $\bar{\nu}_e + p \to e^+ + n$ Single tag analysis: K.Bays et al.,Phys.Rev.D85 052007,2012) used SK-I,SK-II and SK-III data

SRN Flux< 1.7(LMA Flux) (90%CL) for Ee>16MeV

(2) $\bar{\nu}_e + p \to e^+ + n,$
$n + p \to d + \gamma(2.2MeV)$
Double tag analysis using SK-IV data

SRN Flux< 6.5(LMA Flux) (90%CL) for Ee=12-30 MeV

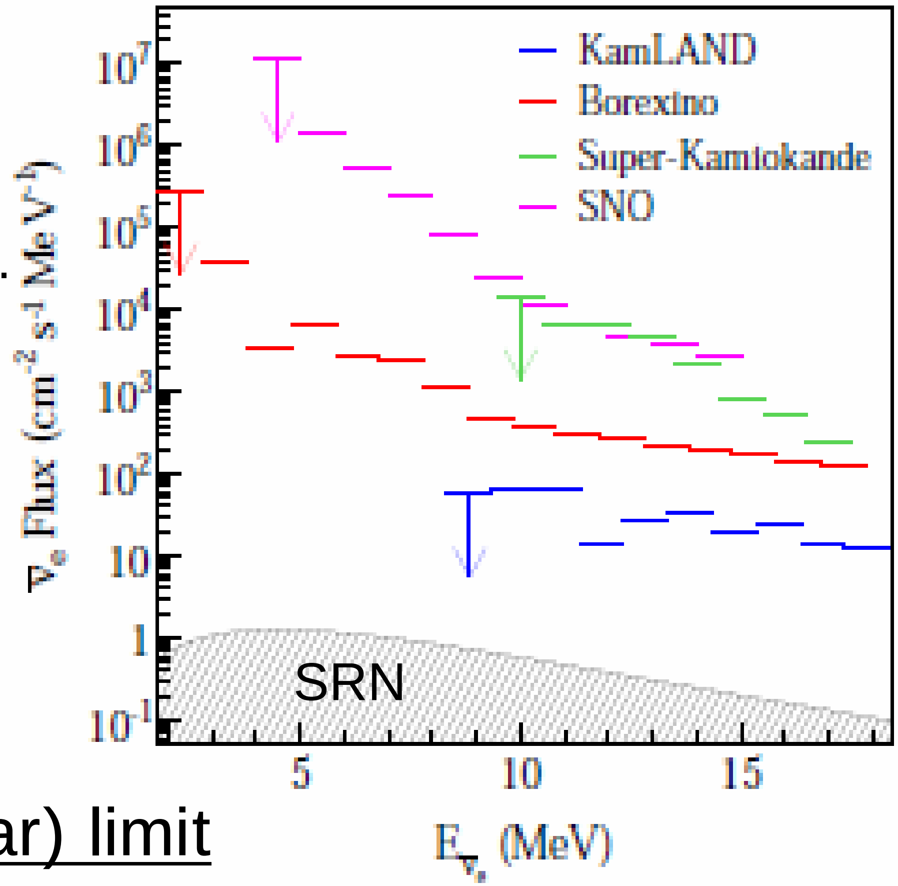
Cf.KamLAND flux <14*LMA flux



Other experimental searches for $\overline{\nu}_e$ (SRN)

-All these liq.scinti detectors have delayed coincidence (double tag) for a signal.

- KamLAND: $\overline{\nu}_e + p \to e^+ + n \ \ (n + p \to d + \gamma)$ (8.3MeV<E_ν<30.8MeV)
  - A.Gando etal.,ApJ745,193(2012)
- SNO: $\overline{\nu}_e + d \to e^+ + n + n \ (n + d \to \gamma(6.25MeV))$
  $(4 < E_{\overline{\nu}} < 14.8 MeV)$
  - Aharmim etal., PRD70,093014(2004).
  $\nu_e \ \ (21 < E_\nu < 35 MeV)$
  - Aharmim etal., APJ653,1545(2006)
- Borexino :
  $\overline{\nu}_e + p \to e^+ + n \ \ (n + p \to d + \gamma)$
  - G.Bellini etal.,PLB696,191(2011)

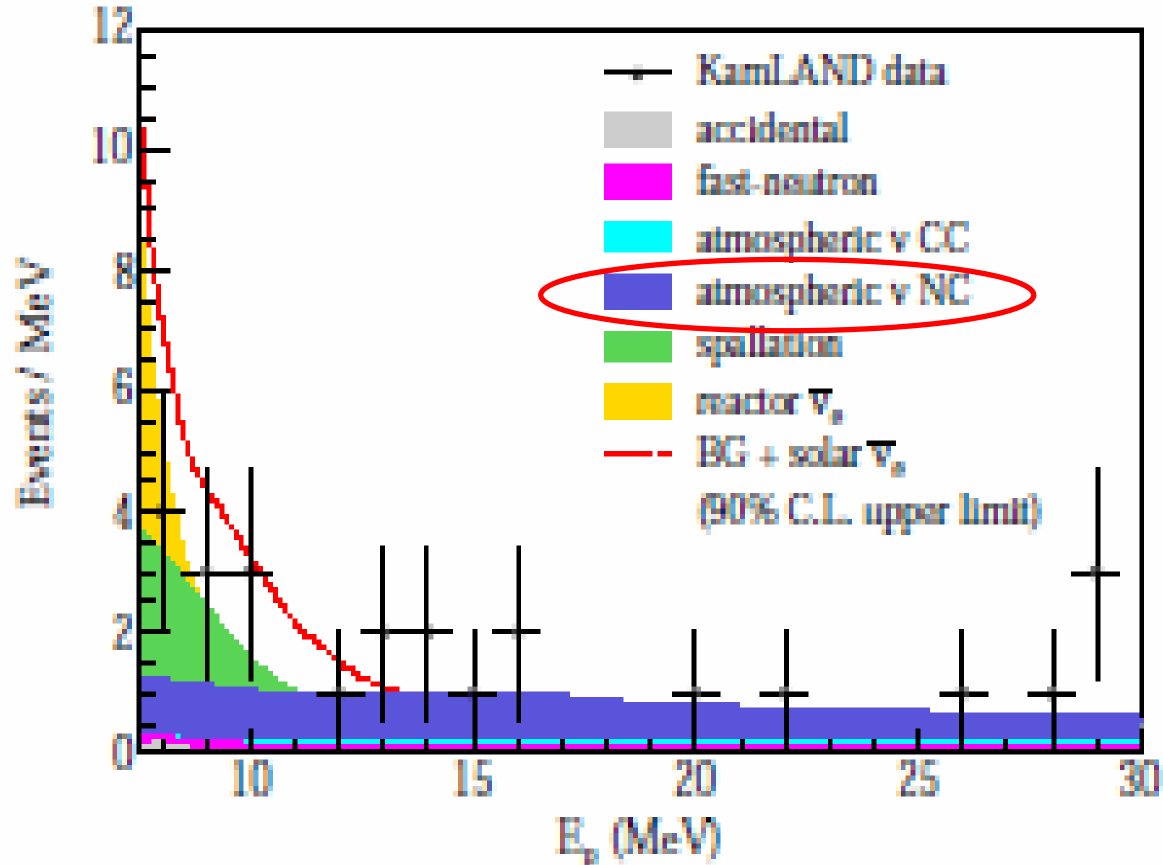


- <u>Even KamLAND (4.53kton year) limit is still 2 orders of magnitude above SRN.</u>

KamLAND 25 $\bar{\nu}_e$ *Candidates* and MC prediction

- They concluded that "Atmospheric ν NC background will be a challenge for future Large Liq.Scintillator detectors". Fig. from KamLAND paper.

A.Gando etal.,ApJ745,193(2012)



Summary

- We reviewed the γ-ray production from excited nuclei in NC ν-O or -C interactions for both E<100MeV and E>200MeV.
  - Neutrinos from SN explosion in our galaxy
  - Supernova Relic Neutrinos (SRN, DSNB)
  - Shrot or Long Baseline ν-oscillation experiments
- We calculated the γ-production from NC QE cross section using the spectral function for the first time. We find that this cross section is larger at E>100MeV than the γ-production based on the excitation of O* which saturates above 200 MeV. This cross section is dominated by $p_{3/2}$ and Br(NC→γ)~40%.
- We plan to measure both the excitation energy (E_x) and the energy of γ-rays ($E\gamma$) in the O,C (p,p'γ) and (He,tγ) experiment at ~0 degrees, and thus we will measure the branching ratios of γ–ray emission as functions of E_x from giant resonances for $E\gamma$>5 MeV. This experiment will provide essential information for γ-ray production in NC ν-O,C reactions

- Backup

Apology: I skip the recent progress in improved shell model calculation (E<100MeV)

- JPS Journal “Buturi” (January 2012).
- SFO model: