NC $\gamma$-ray production in the Supernova energy region (E=10–100MeV)

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A.
1. NC $\gamma$-ray production, Why is it important??
2. E398 $^{16}\text{O},^{12}\text{C}(p,p'\gamma)$ Experiment at RCNP (Just done!)

B. SFIA+FSI (Ankowski, Benhar and MS, arXiv:1404.5687)
   - Importance of FSI to the neutrino energy reconstruction
   - Is the model good at 10-100MeV? If then, does it contribute to the neutrino detection from SN explosion?
1. Status of γ-ray production in NC ν–O (–C) reactions

1) $E_\nu < 100\text{MeV}$: Elastic and Inelastic
   \[ \nu^{16}\text{O} \rightarrow \nu^{16}\text{O}^* \]
   \[ \nu^{16}\text{O}^* \rightarrow \gamma \]

2) $E_\nu > 100\text{MeV}$: Quasi-elastic (1N knock-out)
   \[ \nu^{16}\text{O} \rightarrow \nu + p + ^{15}\text{N}^*/^{15}\text{O}^* \]

● Theoretical Calculations

   ▶ Inelastic scattering (Giant resonances): $\nu^{16}\text{O} \rightarrow \nu^{16}\text{O}^*$, $^{16}\text{O}^* \rightarrow \gamma$

   ▶ Nucleon knockout: $\nu^{16}\text{O} \rightarrow \nu + p/n + ^{15}\text{N}^*/^{15}\text{O}^*$ (Excitation of residual nucleus)

● Experiments

1) $E_\nu < 100\text{MeV}$: No experiments exists for Oxygen. Karmen for C*(15.1MeV) only $\rightarrow$ RCNP E398 (Done last month)

2) $E_\nu > 100\text{MeV}$: T2K $\rightarrow$ K.Abe et al., arXiv:1403.3140 (Mar.’14)
Overall Picture of the $\nu$–A cross section

Elastic (Coherent) $\nu + ^{16}\text{O} \rightarrow \nu + ^{16}\text{O}$

NC quasi-elastic (QE) $\nu + ^{16}\text{O} \rightarrow \nu + p/n + X$
T2K NC $\gamma$ production and Karmen NC $\gamma$ production

T2K 6MeV $\gamma$ from $^{15}$N/$^{15}$O

- T2K data is consistent with Ankowski et al.

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

  In good agreement with the calculation, $2.8\times10^{-42}\text{cm}^2$.

Karmen

- 15.11MeV $\gamma$-ray
NC $\nu$-O $\gamma$-production ($E<100\text{MeV, Inelastic}$)

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

$T=0$ $T=1$

$S_p = 7.296\text{MeV}$

$S_p = 10.02\text{MeV}$

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

Langanke, Vogel, Kolbe, PRL96, '96
Kolbe, Langanke, Vogel, PRD66, '02

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

At $<E> = 25\text{MeV}$, using SMOKER code.
Except for γ-rays from C*(15.11MeV), no measurements exists.
Neutrinos from SN explosion @ 10kpc

The number of events observed in the detectors

- Super Kamiokande (H$_2$O)
  \[
  \bar{\nu}_e + p \rightarrow e^+ + n
  \]
  \[
  NC: \nu_x + ^{16}O \rightarrow \nu_x + X + \gamma \ (\nu_x = \nu_\mu, \nu_\tau)
  \]
  ~8000 events
  ~400~600? events

- KamLAND (CH)
  \[
  \bar{\nu}_e + p \rightarrow e^+ + n
  \]
  ~300
  ~60
  \[
  NC: \nu_x + ^{12}C \rightarrow \nu_x + X + \gamma \ (15.1\text{MeV})
  \]
  \[
  NC: \nu_x + ^{12}C \rightarrow \nu_x + X + \gamma \ (E_X > 16\text{MeV})\text{巨大共鳴} \]
  (~50-60??)

Importance of Neutral-Current events

- The 2$^{nd}$ most reaction and no one has measured them in SN bursts
  *Koshiba-san measured 11 CC events
- $\mu, \tau$ -type neutrino-induced events dominate NC reactions since energy (Temperature) is higher than e-type.
- Independent of neutrino oscillations
  → If Branching fraction of gamma emission is measured accurately, then more quantitative arguments can be done. Ex. SNO solar-$\nu$.
  → We can estimate T by the number of NC events, though we cannot measure the neutrino energy directly.
RCNP E398 experiment
Measurement of $\gamma$-rays from $^{16}$O(p,p$'$) and $^{12}$C(p,p$'$)


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

Definition: the $\gamma$-ray emission probability ($E_\gamma > 5\text{MeV}$) =
(Number of $\gamma$-rays observed for $E_\gamma > 5$ MeV)/(Number of events excited in the range $E_x=15$-30 MeV, each $E_x$ bin) → Fig.

[Importance]: Data for $\nu$O→$\nu$O$^*$→$\gamma$ and $\nu$C→$\nu$C$^*$→$\gamma$ do not exist and they are very important to neutrino physics. RCNP Grand-Raiden is the best place for this experiment.

-Proposal was approved in March, 2013 and Experiment was done in May, 2014.
RCNP Grand-Raiden Spectrometer  O,C(p,p’)

See excellent Energy Resolution
Ex=Ep-Ep’,  ΔEx~20keV

$^{16}$O, $^{12}$C(p,p’) cross section at $\theta=0.4$ deg. Ep=295MeV

15.11MeV

6.9MeV

$E_x=16-30$MeV
GDR/SDR

NC $\nu^{-16}O, {^{12}C}$ reaction

Axial Current Dominant:
Especially, Spin Dipole Resoance : $J^p = 2^-, 1^-$ (T=1) Dominant

($1^+, 15.1$ MeV for C)

✦ NC Neutrino-Nucleus Cross Section:
$\nu + A \rightarrow \nu + A'$: Nuclear Matrix Element

$A' | J^\mu_W | A > = < A' | (J^\mu_V - J^\mu_A) \tau_3 | A > = (M^\mu_W \tau_3)_{fi}$

$M^0_W = F^V_1 + F_A \frac{\vec{P} \cdot \vec{\sigma}}{M}$

$M^r_W = F^V_1 \frac{\vec{P}}{M} - i \frac{\vec{\sigma} \times \vec{q}}{2M} (F^V_1 + \kappa F^V_2) + F_A \vec{\sigma}$

✦ GDR ($J^p = 1^-, \Delta T = 1, \Delta S = 0, \Delta L = 1$):
Spin Dipole $R$ ($J^p = 0^-, 1^-, 2^-, \Delta T = 1, \Delta S = 1, \Delta L = 1$):

$\vec{\sigma} f_1(r) Y^{m}_1 \tau_3$

$\vec{\sigma} f_0(r) \tau_3$

$\vec{\sigma} f_1(r) Y^{m}_1 \tau_3$

Ref. Jachowicz et al., PRC59('99), Botrugno, Co', NPA761('05)
Idea of E398: Measure GDR (0deg) and SDR (4deg). $O(\nu,\nu')$ at $E_\nu$=50MeV and $O(p,p')$ at $\theta_{lab}$=0–4deg.

✓ $O(\nu,\nu')$: SDR(2-,1-) contributes. $C(\nu,\nu')$: SDR and $1^+(15.11\text{MeV})$ contributes.

✓ For $O,C(p,p')$, 1-,2- of SDR show up at $\theta_{lab}$=3-5 degrees. ->Kawabata et al. (RCNP)
Spin Flip cross sections $C(p,p')$ at $E=318\text{MeV}$ in $(E_x,\theta)$

Ref. F. T. Baker et al., PRC 48('93)
Form Factors for Giant Resonances $^{12}$C

Fig. 8. Form factors per MeV at excitation energy $E_x$ and $\theta = 155^\circ$ as a function of the momentum transfer.
E398 (May 16–27, 2014)

Target(C,O)
Proton Beam 390MeV
Nal 5x5 array
Online Plots: Ex for 12C (GR spectrometer only)

![Graph showing data with ID 23, 583148 entries, mean 51.11, and RMS 215.1. The x-axis ranges from -500 to 500, and the y-axis from 0 to 2500.](image)
Ex (GR) * NaI Coincidence: Signal (Black), Background (Red)

$C(15.1\text{MeV}), O(6.9\text{MeV})$—calibration lines.

GR Signals (Ex=16-30MeV)
Energy (ADC) in NaI, tagged by $\text{Ex}=15.1\text{MeV}$ (GR).

15.1 MeV clearly observed. Signal(Black), BG(Red). MC (geant4) prediction shown as reference.
• Experiment has just been finished. Data analysis starts now.
• $\gamma$-rays (15.1 MeV, $^{12}$C) are seen and will be used to check the acceptance of NaI and the energy scale.
• We hope to present the first results at the Hawai joint JPS/APS meeting (October, 2014).
• Hope to obtain the first Br(C,O, Ex=16-30MeV GDR,SDR$\rightarrow\gamma$) measurements at a few%-10% stat. errors.
• Need to calculate NC $\nu$+O,C (1-,2-,1+) and combine Br(1-, 2-,1+$\rightarrow\gamma$), and finally obtain NC $\gamma$ production cross section in the SN region.

• Forward beamline has been improved. It accepts scattered protons at larger angles $>4$deg.
• After showing the first results, we plan to submit an extension of the experiment to RCNP.
GRFBL (Grand-Raiden Forward Beam Line, RCNP, Osaka)
- Almost complete; operational this Spring-

-A. Tamii (GRFBL workshop, Nov. 28-29, 2013)
Clover (Ge) Array (RCNP)  
-N.Aoi (RCNP) @ GRFBL workshop (Nov.28-29,2013)-

CAGRA (Clover Array)の模式図

全体で16台

ビーム軸に対して
45°に4台
90°に8台
135°に4台
ターゲット中心→Ge：14cm

GEMINI-IIに対して
（BGO付きGe16台のアレイ）
- 光電ピーク検出効率が5倍
- 伽ロの満度が100倍

CAGRA project
E. Ideguchi, T. Koike, M. Carpenter, V. Werner et al.
N. Aoi

米国Doeで承認 (M. Carpenter et al.)
- 輸送費
- 信号読み出し用デジタル回路系
- 被素補給器

RCNP Project (Ideguchi et al.)
全国共同利用実験で使用するための整備
+ アレイ構築に必要なR&D
B. Spectral Function(IA)+FSI Model
(Benhar et al.,PRD72,2005 + Ankowski,Benhar,MS,arXiv:1404.5687)

- At NuInt12 and NuInt14, we mainly discussed about the contribution of 2p-2h/MEC to Quai-Elastic (QE) interactions, while the effect of Spectral Function $S(p,E)$ to QE is agreed on, which is mainly 1p-1h (with initial SRC being taken into account). Now, almost all $\nu$-exp’s (SK, MINOS, Mirerva etc) use SF.

  In addition to a problem of 1p-1h/1p-2h/MEC, FSI is a key question.

- How quantitatively do we understand C,O(e,e’) QE data with any models?? There are 2 important questions relevant to neutrino experiments:

1) How well we predict the peak of the QE cross section $d\sigma/dE_\mu d(\cos \theta)$?? Equivalently, How well can we reconstruct the neutrino energy $E_\nu$ from $(E_\mu, \cos \theta_\mu)$ in $\nu$-experiments??

   - Ankowski1404.5687 (FSI) shows that the models without FSI cannot tell the peak, ie $E_\nu$, within 10-15 MeV.

2) How good is the SFIA/FSI QE model at low energy, ie $E<100$MeV??
   - Is the model valid at $E_\nu <100$ MeV??
   - Does the CC or NC QE process contributes to the SN neutrino detection, while it is considered as un-important at $E_\nu=20-50$ MeV before??

   - Ankowski1404.5687 (FSI) suggests YES!
\[ \frac{\Delta m^2 L}{4 E_{\nu}} = \frac{\pi}{2} \]

\[ \frac{\sigma(\Delta m^2)}{\Delta m^2} \sim \frac{\sigma(E_{\nu})}{E_{\nu}} \]

DE/E = 15 MeV/600 MeV = 2.5%
C(p,p’) is well described by the optical potential model.

We included the result of optical potential in C(e,e’).

e+”p”→e+”p”

\[ E_e + M_\epsilon = E_{e'} + (E_{p'} + U_V) \]
C(e,e′) d²σ/dωdΩ for E=240-2000MeV

- SFIA/FSI is dominant at Q<400-500MeV. The model predicts both the peak and the shape. For Q>400-500MeV, other process (2p-2h?) shows up.
E = 240–2000 MeV
Compared approaches


Our calculation, step function

RFG model
\( \varepsilon = 25 \text{ MeV} \)
\( p_F = 221 \text{ MeV} \)

SF calculation without FSI
$Q = 143 - 224 \text{ MeV}$

**Comparisons to C($e,e'$) data**

- 240 MeV, 36 deg, \(~ 143 \text{ MeV, 0.02 GeV}^2\)
- 200 MeV, 60 deg, \(~ 186 \text{ MeV, 0.03 GeV}^2\)
- 240.4 MeV, 60 deg, \(~ 224 \text{ MeV, 0.05 GeV}^2\)

Barreau et al., NPA 402, 515 (1983)
Q = 259–331 MeV : All Good

Comparisons to C(e,e') data

Barreau et al., NPA 402, 515 (1983)
\[ Q = 366 - 450 \text{ MeV}, \]
new process (2p-2h?) appears at \( Q = 450 \text{MeV} \).
2. CC and NC n-O/C QE interactions

- Artur has shown that IA-SF/ED AI-FSI is good over 240 MeV-1 GeV region. Benhar et al., PRD 72(2005): IA-SF/FSI, E>500 MeV.
- Time is ripe to tackle 10-50 MeV region (supernova related energy). To study giant resonances, we need to understand QE well. Below: CRPA: Kolbe et al., 1997.

\[ E_{e} = 98.0 \text{ MeV} \]

Fig. 2. Same as Fig. 1, but for \( E_{e} = 98 \text{ MeV} \).