Measurement of gamma-rays from neutron-oxygen reaction for neutrino-nucleus interaction

Yosuke ASHIDA (Kyoto University) for the RCNP-E487 Collaboration
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Physics Motivation on “NCQE”

Neutrino neutral current quasielastic interaction is important for several physics searches at **T2K** and **Super-K** (also at **SK-Gd** and **Hyper-K**).

- Supernova relic neutrino
- Sterile neutrino
- Dark matter

![Supernova relic neutrino (IBD)](image1)

![Atmospheric neutrino (NCQE)](image2)
Measurement at T2K Experiment

- **Gamma-ray** emitted from excited nucleus is a signal of NCQE.
- Typical energy of gamma-rays is **5 ~ 10 MeV**, and this is very low energy event at Super-K with large background.
- T2K beam is a powerful tool for measuring the NCQE cross section.
  - Background reduction with timing information
  - Similar neutrino energy to atmospheric neutrino flux peak

\[ {}^{16}\text{O} \rightarrow {}^{15}\text{O}^* / {}^{15}\text{N}^* / \ldots \]

@Super-K
Current Problem

T2K result has large systematics due to poor nuclear reaction model.

ex.) Large gap in reconstructed Cherenkov angle between data and MC

Systematics (K. Huang, Ph.D Thesis, Kyoto University (2016))

<table>
<thead>
<tr>
<th>Systematic error</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>interactions fraction of events</td>
<td>NCQE 68%</td>
<td>NCothers 25%</td>
</tr>
<tr>
<td>Flux</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Cross-section</td>
<td>11%</td>
<td>18%</td>
</tr>
<tr>
<td>Primary $\gamma$ production</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>Secondary $\gamma$ production</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td>Detector response</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Oscillation parameters</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>20%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Gamma-rays from secondary nuclear processes are not well modeled!
Strategy: Nuclear Physics

- No previous measurements on gamma-rays from neutron-oxygen reaction in hundred-MeV region
- Our experiment aims to measure neutron-induced gamma-rays from the secondary process only.
RCNP-E487 Experiment

• RCNP’s wide range neutron beam is suitable for our purpose.
• We carried out the experiment using 80 MeV neutron beam (E487).
• Beam setting:
  • beam time : 24 hours
  • proton energy : 80.6 +/− 0.6 MeV (neutron produced by $^7\text{Li}(p,n)$)
  • Chopping : 1/9 (to separate peak/fast and tail/slow neutron)
Detectors

- **Gamma-ray production**: HPGe detector and LaBr$_3$(Ce) scintillator
  - Upstream to water target & Covered with Pb blocks

- **Neutron flux**: Organic liquid scintillator (BC-501A)
  - On-axis position & without water target

- **Scattered neutron**: CsI(Tl) scintillator
  - Upstream to water target & Covered with Pb blocks
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• Introduction
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• **Observation of strong peaks** \( (6.13 \text{ MeV from } ^{16}\text{O}, 5.27 \text{ MeV from } ^{15}\text{N}) \)

• Observation of other peaks that are from neutron-oxygen reactions (later)

• (We also have time information with \( O(10 \text{ ns}) \) accuracy.)
• Observation of corresponding peaks to ones by HPGe detector
• Resolution is a bit worse than HPGe.
• We have time information (Next)
• Time information is taken well.
• From the 2D distribution (TDC vs. QDC), strong gamma-ray peaks are thought to be by fast neutron reactions.
Neutron Flux: Analysis Flow

- Raw data
  - Time calibration
- Time distribution (all)
- Neutron selection
- Time distribution (neutron)
- Relativity calculation
  \[ \beta = \sqrt{1 - \left( \frac{939.6}{K + 939.6} \right)^2} = \frac{v}{c} \]  (neutron mass = 939.6 MeV/c^2)
- Kinetic energy distribution
- Detection efficiency → SCINFUL-QMD (MC code by JAEA)

Detection efficiency calculation

- inputs to simulator
  - detector position & size → well known
  - light attenuation length → well known
  - threshold → need energy calibration
Neutron Flux: Results

- Reconstruct kinetic energy by using time information ($t_0$ by gamma-ray).
- Neutron selection is done by Pulse Shape Discrimination (PSD).
- Detection efficiency by MC

Detection Efficiency by SCINFUL-QMD*

*D. Satoh et al., JAEA-DATA/CODE 2006-023 (2006)
# Neutron Flux: Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
<td>+/- 0.8 ~ 2.2 %</td>
</tr>
<tr>
<td>Systematic (kinetic energy)</td>
<td></td>
</tr>
<tr>
<td>PSD cut failure</td>
<td>&lt; 0.1 % (can be ignored)</td>
</tr>
<tr>
<td>high energy deposit γ-ray</td>
<td>- 0.8 %</td>
</tr>
<tr>
<td>environmental γ-rays</td>
<td>- 0.3 %</td>
</tr>
<tr>
<td>former bunch neutrons</td>
<td></td>
</tr>
<tr>
<td>scattered neutrons</td>
<td></td>
</tr>
<tr>
<td>charged particles</td>
<td>&lt; 0.1 % (can be ignored)</td>
</tr>
<tr>
<td>Systematic (detection efficiency)</td>
<td></td>
</tr>
<tr>
<td>SCINFUL-QMD model (&lt; 100 MeV)</td>
<td>+/- 6 %</td>
</tr>
<tr>
<td>input threshold (energy calibration)</td>
<td>&lt; 0.1 % (can be ignored)</td>
</tr>
<tr>
<td>input light attenuation factor</td>
<td>&lt; 0.1 % (can be ignored)</td>
</tr>
<tr>
<td>input light output function</td>
<td>&lt; 0.1 % (can be ignored)</td>
</tr>
<tr>
<td>MC statistic</td>
<td>+/- 0.3 %</td>
</tr>
<tr>
<td>kinetic energy reconstruction</td>
<td>+/- 2 %</td>
</tr>
<tr>
<td>Total</td>
<td>+/- 6.5 %</td>
</tr>
</tbody>
</table>
Scattered Neutron

- Measure the neutron-induced background at the gamma-ray detector position using CsI(Tl) PSD.
- Neutron background in signal region for peak neutron energy is estimated to be less than 2 % (small enough).
- Density of CsI is close to that of Ge and LaBr, so it is useful for background estimation.
Cross Section Estimation

- Detection efficiencies for peak gamma-rays are calculated using MC.
- Production cross section for 6.13 MeV
  - $\sigma \sim 5$ mb (Very preliminary!)
  - Background estimation, systematic estimation works remain.

LaBr$_3$(Ce) detection efficiency (by Geant4 simulation)
Reminder: Observed Peaks

- $^{13}\text{C} (5/2^+)$ [3.68 MeV]
- $^{12}\text{C} (2^+)$ [4.44 MeV]
- $^{15}\text{N} (5/2^+)$ [5.27 MeV]
- $^{17}\text{O} (5/2^–)$ [3.84 MeV]
- $^{16}\text{O} (3–)$ [6.13 MeV]

Normalized Counts [$\mu$/C]

Energy [MeV]

- w/ water (39073 sec)
- w/o water (24033 sec)
Clues for Process Identification

- Peak width from light nucleus is larger (Doppler effect):
  - 4.44 MeV and 3.68 MeV peaks are from excited carbons.

- In the decay with particle emission, it is more probable to decay to the state with large energy gap from the original excited state or with large angular momentum:
  - In $^{16}\text{O}(3^-; 6.13 \text{ MeV}) \rightarrow ^{12}\text{C} + \alpha$, $^{12}\text{C}(2+; 4.44 \text{ MeV})$ is dominant.
  - In $^{16}\text{O}(3^-; 6.13 \text{ MeV}) \rightarrow ^{15}\text{N} + p$, $^{15}\text{N}(5/2+; 5.27 \text{ MeV})$ is dominant.
  - In $^{16}\text{O}(3^-; 6.13 \text{ MeV}) \rightarrow ^{15}\text{O} + n$, $^{15}\text{O}(5/2+; 5.24 \text{ MeV})$ is dominant.
  - $\alpha$-threshold (7.16) < p-threshold (12.13) < n-threshold (15.66) [MeV]
  - When $^{16}\text{O}(3^-; 6.13 \text{ MeV})$ is created, $^{15}\text{O}$ is unlikely to be produced compared to $^{12}\text{C}$ and $^{15}\text{N}$. 
Physics Process

(a) 6.13 MeV from $^{16}\text{O}(3-)$:

$^{16}\text{O}(n,n')^{16}\text{O}^*$, then $^{16}\text{O}^* \rightarrow ^{16}\text{O} + \gamma$

(b) 5.27 MeV from $^{15}\text{N}(5/2^+)$: (*)

$^{16}\text{O}(n,n')^{16}\text{O}^*$, then $^{16}\text{O}^* \rightarrow ^{15}\text{N}^* + p$, then $^{15}\text{N}^* \rightarrow ^{15}\text{N} + \gamma$ (p-emission)

(c) 4.44 MeV from $^{12}\text{C}(2^+)$:

$^{16}\text{O}(n,n')^{16}\text{O}^*$, then $^{16}\text{O}^* \rightarrow ^{12}\text{C}^* + a$, then $^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma$ (a-emission)

(d) 3.84 MeV from $^{17}\text{O}(5/2^-)$:

$^{17}\text{O}$ creation (neutron capture by $^{16}\text{O}$ or inelastic scattering with $^{17}\text{O}$?), then $^{17}\text{O}^* \rightarrow ^{17}\text{O} + \gamma$

(e) 3.68 MeV from $^{13}\text{C}(5/2^+)$:

$^{16}\text{O}(n,a)^{13}\text{C}^*$, then $^{13}\text{C}^* \rightarrow ^{13}\text{C} + \gamma$

(*) In $(n,np)$ reaction, 6.32 MeV from $^{15}\text{N}(5/2^+)$ is dominant: $(e,e'p)$, $(p,2p)$ experiments
Consideration on T2K Results

- Main contribution to secondary processes are made by neutrons, because protons or alphas would stop very soon due to ionization (and they have kinetic energy smaller than Cherenkov threshold).
- Our results show no additional neutrons are emitted in any processes.
- E487 is with 80 MeV, and at lower energy inelastic cross section is expected to become larger, therefore the case may be more clear.

MC says many secondary-γs are emitted.
Summary

- Precise knowledge of neutrino NCQE interaction is important for several physics searches at T2K and SK.
- Largest source of systematics comes from poor nuclear physics model.
- We study the nuclear process with measurement and aim to improve the model.
- At RCNP, we made a gamma-ray measurement with 80 MeV neutron;
  - **Observed gamma-rays from neutron-oxygen reactions**
  - Measured items necessary to obtain neutron flux
  - Measured scattered neutron backgrounds
  - Estimated very preliminary cross section (analysis is on-going.)
- Physics processes behind the E487 results seem to be consistent with T2K data.
Next Plan

Additional measurements

- We are planning similar experiments to E487 with different energies.
  - 30 MeV: Flux peak, physics boundary near Fermi surface
  - 246 MeV: higher energy, below pion production threshold

T2K analysis

- Using results, we will constrain T2K model.
- Neutron-tagging method can be used for cross check (comparison of data with MC).
- Use all data taken so far (both for nu/anti-nu).
Backup Slides
1. Overflow suppression
   • CAEN V792 doesn't store data if charge integration is larger than maximum of dynamic range.
   • Even if overflow suppression is invoked, TDC stores data well.
   • PSD cannot used for these suppressed samples.

2. Sliding scale (for reduction of differential non-linearity)
   • Channel 3841 ~ 4095 of CAEN V792 are not correct.
   • PSD cannot used for samples in this region.

[Summary]
   • QDC channel > 3840 : assume all are neutrons (see next page)
   • QDC channel ≤ 3840 : use PSD to extract neutrons
Neutron Flux Analysis

- Most events in higher energy region are thought to be due to neutrons.
  - Proton energy is \( \sim 80 \text{ MeV} \), so there's no pion productions (\( > 140 \text{ MeV} \)).
    \[
    \rightarrow \text{no high energy gamma-rays (main is from excited state } \sim 10 \text{ MeV).}
    \]
- Seeing energy spectra, gamma-ray contribution is getting smaller.
- Gamma-ray contamination is explained later.
• This should affect time reconstruction and then kinetic energy distribution.
• The time walk effect should be corrected.
Neutron Flux Analysis

\[\chi^2 / \text{ndf} = 9.608 \times 10^5 / 7804\]
\[\chi^2 / \text{ndf} = 3.492 \times 10^6 / 20314\]

\[p_0 = 0.04269 \pm 400.4\]
\[p_1 = 0.2618 \pm 13.87\]
\[p_2 = 12.89 \pm 554.6\]

\[p_0 = 0.02303 \pm 326.9\]
\[p_1 = 0.3687 \pm 17.5\]
\[p_2 = 9.191 \pm 536.2\]
Neutron Flux Analysis

3/29 run16 (low-thr)

Entries 430928
Mean 400.2
RMS 13.16
$$\chi^2 / \text{ndf}$$ 69.07 / 51
p0 343.1 ± 5.8
p1 400.6 ± 0.0
p2 1.005 ± 0.018
p3 −0.05091 ± 0.01003
p4 40.9 ± 2.0

3/29 run21 (high-thr)

Entries 371918
Mean 400.5
RMS 11.86
$$\chi^2 / \text{ndf}$$ 66.87 / 51
p0 232.1 ± 4.4
p1 399.9 ± 0.0
p2 1.04 ± 0.02
p3 −0.09185 ± 0.00950
p4 15.53 ± 1.49

3/29 run19 (mid-thr)

Entries 398303
Mean 400.2
RMS 12.71
$$\chi^2 / \text{ndf}$$ 67.6 / 51
p0 278.5 ± 4.9
p1 400.1 ± 0.0
p2 1.054 ± 0.021
p3 −0.09456 ± 0.00935
p4 22.54 ± 1.92

3/29 run22 (high-thr)

Entries 614958
Mean 400.3
RMS 11.85
$$\chi^2 / \text{ndf}$$ 58.86 / 51
p0 382.7 ± 5.9
p1 400 ± 0.0
p2 1.037 ± 0.017
p3 −0.08758 ± 0.00788
p4 28.32 ± 2.01

w/ time-walk correction
Neutron Flux Analysis

3/29 run16 (low-thr)

- Entries: 430928
- Mean: 398.9
- RMS: 13.35
- $\chi^2$/ndf: 249.9 / 131
- $p_0$: 178 ± 2.6
- $p_1$: 398.7 ± 0.1
- $p_2$: 2.413 ± 0.040
- $p_3$: -0.1534 ± 0.0079
- $p_4$: 13.63 ± 0.96

3/29 run19 (mid-thr)

- Entries: 398303
- Mean: 399
- RMS: 12.91
- $\chi^2$/ndf: 174.4 / 131
- $p_0$: 151.6 ± 2.5
- $p_1$: 398.7 ± 0.1
- $p_2$: 2.153 ± 0.039
- $p_3$: -0.1747 ± 0.0080
- $p_4$: 10.55 ± 0.73

3/29 run21 (high-thr)

- Entries: 614958
- Mean: 399.1
- RMS: 12.18
- $\chi^2$/ndf: 209.4 / 131
- $p_0$: 221.2 ± 3.2
- $p_1$: 398.5 ± 0.0
- $p_2$: 1.955 ± 0.030
- $p_3$: -0.1662 ± 0.0065
- $p_4$: 12.09 ± 0.69

3/29 run22 (high-thr)

- Entries: 371918
- Mean: 399.3
- RMS: 12.21
- $\chi^2$/ndf: 170.3 / 131
- $p_0$: 398.5 ± 0.1
- $p_1$: 1.952 ± 0.038
- $p_2$: -0.1721 ± 0.0078
- $p_3$: 6.478 ± 0.530
- $p_4$: 10.55 ± 0.73

w/o time-walk correction
Neutron Flux Analysis

1. 3/29 run16 (low-thr)
   - Neutron + γ-ray: Entries 410769, Mean 46.1, RMS 24.97
   - Neutron: Entries 336507, Mean 47.36, RMS 24.57

2. 3/29 run19 (mid-thr)
   - Neutron + γ-ray: Entries 382793, Mean 46.92, RMS 24.93
   - Neutron: Entries 321546, Mean 48.03, RMS 24.6

3. 3/29 run21 (high-thr)
   - Neutron + γ-ray: Entries 360385, Mean 48.28, RMS 25.19
   - Neutron: Entries 309629, Mean 49.32, RMS 24.93

4. 3/29 run22 (high-thr)
   - Neutron + γ-ray: Entries 595935, Mean 48.13, RMS 25.17
   - Neutron: Entries 511522, Mean 49.22, RMS 24.89
Contaminated gamma-rays that are not cut by PSD can be estimated by seeing prompt-gamma peak (background level subtracted).

4.5\% of gamma-rays are detected as neutrons
→ In peak region almost no low energy deposit gamma-ray, so such effect can be ignored.
High energy gamma-rays are not cut by PSD, but contamination is small compared to total neutron events.

linear fit \( p0 = 16.0 \pm 0.5, p1 = -0.0034 \pm 0.0002 \)

→ event number in triangle can be calculated as \( \sim 2784 \), Total neutron number = 346354

→ contamination level is 0.8 %.
Former bunch neutrons can be estimated by seeing just before fastest neutron peak (environmental gamma-rays & former bunch neutrons inclusive).

0.3 % contamination level in peak region
LqS Calibration

Incoming Photon
(Energy $E_{\gamma, \text{in}}$)

$\theta$

$\phi$

BC-501A

Recoil Electron
(Energy $E_{e, \text{recoil}}$)

Scattering Photon
(Energy $E_{\gamma, \text{scatter}}$)

Gamma-ray Detector
LqS Calibration

\[ \chi^2 / \text{ndf} \quad 0.07615 / 6 \]

\[ p_0 \quad -0.3495 \pm 0.0535 \]

\[ p_1 \quad 0.001784 \pm 0.0001154 \]

<table>
<thead>
<tr>
<th>( E_\gamma, \text{in [MeV]} )</th>
<th>( \theta \text{ [deg]} )</th>
<th>( E_e, \text{recoil [MeV]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.275</td>
<td>120</td>
<td>1.006 + 0.046 / −0.030</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>0.910 + 0.237 / −0.103</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.708 + 0.236 / −0.150</td>
</tr>
<tr>
<td>0.511</td>
<td>120</td>
<td>0.307 + 0.026 / −0.018</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>0.256 + 0.097 / −0.055</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.170 + 0.073 / −0.061</td>
</tr>
</tbody>
</table>
• Linearity is achieved within ± 0.7%.
• $\chi^2$/ndf seems not good? (I think some fitting problem in ROOT.)
LaBr Calibration

- Gain shift is < 0.5% during whole beam time.
- This is small enough considering resolution.