Gamma-ray production in neutral-current interactions

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Outline

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- Could nuclear deexcitation provide an additional signature?

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- Nuclear structure and deexcitation scheme
- Estimate of the cross section

❸ Summary
Introduction
Neutral current vs. charged current

Structure of the NC and CC is the same,

\[
\langle N'(p') | \hat{J}^\mu | N(p) \rangle = \langle N'(p') | \gamma^\mu (F_1 + F_2) - \frac{(p + p')^\mu}{2M} F_2 \nonumber \\
+ \gamma^\mu \gamma_5 F_A + \gamma_5 \frac{q^\mu}{M} F_P | N(p) \rangle
\]

Both \( n \)'s and \( p \)'s may undergo NCE scattering
Neutral current elastic scattering

Structure of the NC and CC is the same, but

\[ F_{i}^{z,(p)} = -\frac{1}{2} \left( F_{i}^{(n)} + F_{i}^{s} \right) + \left( \frac{1}{2} - 2 \sin^2 \theta_W \right) F_{i}^{(p)}, \]

\[ F_{A}^{z,(p)} = \frac{1}{2} \left( F_{A} + F_{A}^{s} \right), \]

\[ F_{i}^{z,(n)} = -\frac{1}{2} \left( F_{i}^{(p)} + F_{i}^{s} \right) + \left( \frac{1}{2} - 2 \sin^2 \theta_W \right) F_{i}^{(n)}, \]

\[ F_{A}^{z,(n)} = -\frac{1}{2} \left( F_{A} - F_{A}^{s} \right), \]

Neutral current elastic scattering

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\[
F_{A}^{z,(p)} = \frac{1}{2} \left( F_{A} + F_{A}^{s} \right),
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\[
F_{i}^{z,(n)} = -\frac{1}{2} \left( F_{i}^{(p)} + F_{i}^{s} \right) + \left( \frac{1}{2} - 2 \sin^{2} \theta_{W} \right) F_{i}^{(n)},
\]

\[
F_{A}^{z,(n)} = -\frac{1}{2} \left( F_{A} - F_{A}^{s} \right),
\]

\( F_{i}^{s} \) are vanishing, see e.g. D. Androić et al., PRL 104, 012001 (2010); Z. Ahmed et al., arXiv:1107.0913
Neutral current elastic scattering

Structure of the NC and CC is the same, but

\[ F_i^{z,(p)} = -\frac{1}{2} F_i^{(n)} + \left( \frac{1}{2} - 2 \sin^2 \theta_W \right) F_i^{(p)}, \]

\[ F_A^{z,(p)} = \frac{1}{2} (F_A + F_A^s), \]

\[ F_i^{z,(n)} = -\frac{1}{2} F_i^{(p)} + \left( \frac{1}{2} - 2 \sin^2 \theta_W \right) F_i^{(n)}, \]

\[ F_A^{z,(n)} = -\frac{1}{2} (F_A - F_A^s), \]

\[ F_A^s = \frac{\Delta s}{(1 + \frac{Q^2}{M_A^2})^2} \]

\[ \Delta s = -0.08 \pm 0.26, \text{ MiniBooNE} \]

\[ \Delta s = -0.12 \pm 0.09, \text{ BNL E734} \]
Neutron contribution to the NC $^{16}$O cross section

\[ \Delta s = -0.08 \]

\[ \Delta s = -0.19 \]

$n$'s yield $\sim$ half of the x-section
Neutral current elastic scattering

- The total NC x-section of a symmetric nucleus is largely independent of $\Delta s$:

  When $\Delta s = 0.0$ is used instead of $\Delta s = -0.08$, the cross section changes by less than 0.3% for $0.2 < E < 5$ GeV.

- In the following $\Delta s = 0.0$. 
Detection

- Neutrons (~50% of NC events) do not emit Cherenkov light.

- In water Cherenkov detectors, the threshold momentum for observation of proton is 1.07 GeV/c.

- Hence, an additional signature for NC event might be very useful.
Nuclear deexcitation as a prompt signal of NC event

- Nucleon knockout often leaves residual nucleus in an excited state.
- Deexcitation may yield photons above detection threshold.
- Such photons could provide useful signal, especially for water Cherenkov detectors.
NC neutrino-oxygen scattering
Structure of the oxygen nucleus

- p$_{1/2}$: -12.1 MeV
- p$_{3/2}$: -18.4 MeV
- s$_{1/2}$: -42.5 MeV
p1/2 knockout
p1/2 knockout

No $\gamma$ emission
p3/2 knockout
p3/2 knockout

6 MeV as $\gamma$
s1/2 knockout
s1/2 knockout

Many channels

Branching ratio for $E_\gamma > 4$ MeV is $\sim 12\%$, Ejiri, PRC 48, 1442 (1993)
Spectroscopic strengths from the (e,e'p) Saclay data

M. Bernheim et al., NP A375, 381 (1982)
Finite widths

M. Leuschner et al.,
PRC 49, 955 (1994)

K.G. Fissum et al.,
PRC 70, 034606 (2004)
Cross section for $\gamma$ emission accompanying NC event

It is a product of

- NC cross section for the knockout from each shell
- branching ratios for deexcitation by $\gamma$ emission

$B(p_{1/2}) = 0\%, \quad B(p_{3/2}) = 100\%, \quad B(s_{1/2}) \approx 15\%$ for $E_\gamma > 6$ MeV

F. Ajzenberg-Selove, NP A523, 1 (1991);
H. Ejiri, PRC 48, 1442 (1993);
K. Kobayashi et al., arXiv:nucl-ex/0604006
Cross section for $\gamma$ emission accompanying NC event

- The cross sections for each shell and for the whole nucleus are calculated using the spectral function obtained by Omar Benhar.

- Accuracy of the spectral function, accounting for nucleon-nucleon correlations, has been shown against (e,e'p) data.
Our estimate is that

- ~7-MeV photons (from the s1/2 knockout) follow \( \lesssim 3.5\% \) NC events

- 6-MeV photons (from the p3/2 knockout) follow \( \sim 40\% \) NC events
6-MeV $\gamma$ production vs. NC

Ratio weakly dependent on $E$
Ratio largely independent of $M_A$. Band for $M_A$ 1.03 – 1.39 GeV
What features of oxygen are essential?

1. Large contribution to the cross section from a narrow level deexciting into photons

2. Deexcitation with $E_\gamma > 5$ MeV providing clear signal

3. Available spectral function
Summary

1. Deexcitation into photons of $E_\gamma > 5$ MeV following the NC interaction may provide a useful signature for water Cherenkov detectors.

2. The ratio $\sigma(\gamma)/\sigma(\text{NC})$ is largely independent of the axial mass value.

3. In the important for T2K region $E \lesssim 1$ GeV, the ratio is $\sim 40\%$ for the 6-MeV $\gamma$'s from p3/2 knockout. The $E_\gamma > 6$ MeV photons from s1/2 hole are just 2-3\%.
Back-up slides
NC vs. CC for symmetric nuclei

\[ \sigma/N \] of \(^{12}\text{C}\) and \(^{16}\text{O}\) agree to 2.5%
NC vs. CC for symmetric nuclei

For $E > 0.3$ GeV

$\sigma_{\text{NC}} \approx 0.37 \sigma_{\text{CC}}$
NC vs. CC for symmetric nuclei

![Graph showing comparison between NC and CC for symmetric nuclei](image-url)
NC vs. CC for symmetric nuclei

\[ \frac{\sigma_{NC}}{\sigma_{CC}} \]

\[ E_\nu \text{ (GeV)} \]
6-MeV $\gamma$ production x-section vs. NC x-section
6-MeV $\gamma$ production x-section vs. NC x-section

Ratio largely independent of $M_A$.

Band for $M_A$ 1.03 – 1.39 GeV
Structure of the oxygen nucleus

\[ \sim 4 \text{ MeV} \]
Structure of the oxygen nucleus

These differences are not taken into account