Theory and Phenomenology of Coherent Elastic Neutrino Nucleus Scattering

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Coherent Elastic Neutrino Nucleus Scattering (CE$\nu$NS)

- neutrino interacts with nucleus through neutral current
- can’t see neutrino afterward, but could see small kick to nucleus

Outline

- introduction
- where CE$\nu$NS is already in use
- future physics from CE$\nu$NS
Basic cross section

Coherent elastic neutrino nucleus scattering cross section

$$\frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[ 2 - 2\frac{T}{E} + \left(\frac{T}{E}\right)^2 - \frac{M T}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2)$$

- $E$: neutrino energy, $T$: nuclear recoil
- $Q^2 = \frac{2E^2 T M}{(E^2 - E T)}$: squared momentum transfer
- $Q_W = N - Z(1 - 4 \sin^2 \theta_W)$: weak charge
- $F(Q^2)$: form factor - largest uncertainty in cross section

Assumes a spin zero nucleus, no non-standard model interactions
Making a theoretical prediction

Fold cross section (previous slide) with incoming neutrino spectrum (e.g. left figure) to find nuclear recoil spectrum (right figure)

$\nu_S$ from $\pi/\mu$ decay at rest

Spectrum of nuclear recoils

Fig. from Scholberg 2006

Fig. from Patton et al 2012
Coherent Elastic Neutrino Nucleus Scattering (CEνNS) appears many places

A few of these

- Opacity source in supernova neutrinos
- Mechanism for detecting supernova neutrinos
- Means for studying active-sterile oscillations
- Background in dark matter detectors
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Supernovae Neutrinos

Schematic picture of neutrino emission from proto-neutron star

Neutrinos are emitted from deep in the center
Coherent elastic neutrino nucleus scattering is an opacity source in supernova

1D Supernova Simulations

Figure from S. Bruenn
Coherent Elastic Neutrino Nucleus Scattering (CEνNS) appears many places

A few of these

- Opacity source in supernova neutrinos
- **Mechanism for detecting supernova neutrinos**
- Means for studying active-sterile oscillations
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Coherent Elastic Neutrino Nucleus Scattering (CEνNS) for detecting supernova neutrinos

Event rates in CLEAN detector, Horowitz et al 2003
Coherent Elastic Neutrino Nucleus Scattering (CEνNS) appears many places

A few of these

- Opacity source in supernova neutrinos
- Mechanism for detecting supernova neutrinos
- Means for studying active-sterile oscillations
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CEνNS proposed as a mechanism for probing sterile neutrino oscillations

(Anderson et al 2012, Formaggio et al 2012)

Since CEνNS measures only neutral current it is insensitive to active flavor transformation, ideal for studying active sterile transformation

Example: sensitivity to sterile oscillations using Ar at Daeδalus
Coherent Elastic Neutrino Nucleus Scattering (CEνNS) appears many places

A few of these

• Opacity source in supernova neutrinos
• Mechanism for detecting supernova neutrinos
• Means for studying active-sterile oscillations
• Background in dark matter detectors
CEνNS background is a limit on future dark matter sensitivity discussed in Snowmass Summary: WIMP Dark Matter Direct Detection
Even though we are counting on this process, it has never been detected!

Why not? Large cross section but need to see the small recoil of the nucleus
Beyond First Detection of CE$\nu$NS

- nonstandard $\nu$ interactions
- form factor
Beyond First Detection of CE$\nu$NS

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Nonstandard interactions

Some nonstandard interactions are currently poorly constrained. Examples are vector couplings for electron neutrinos with up and down quarks, $\epsilon_{ee}^{uV}$ and $\epsilon_{ee}^{dV}$, although there are other couplings that contribute as well. To define the NSI, use eq from Barranco et al 2006,

$$\mathcal{L}_{\nu_{Hadron}}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \sum_{\alpha,\beta=e,\mu,\tau} \left[ \overline{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] *$$

$$\left( \varepsilon_{qL}^{\alpha\beta} \overline{q} \gamma^\mu (1 - \gamma^5) q + \varepsilon_{qR}^{\alpha\beta} \overline{q} \gamma^\mu (1 + \gamma^5) q \right)$$  \hspace{1cm} (1)$$

The vector couplings are the only ones relevant for spin zero nuclei $\epsilon_{\alpha\beta}^{qV} = \epsilon_{\alpha\beta}^{qL} + \epsilon_{\alpha\beta}^{qR}$. Limits are $-1.0 < \epsilon_{ee}^{uV} < 0.6$ and $-0.5 < \epsilon_{ee}^{dV} < 1.2$.
Nonstandard interactions

Continue considering example $\epsilon_{ee}^{uV}$ and $\epsilon_{ee}^{dV}$. The zero order effect on CE$\nu$NS is to change the standard model weak charge to an effective weak charge.

$$Q_W = N(1 - 2\epsilon_{ee}^{uV} - 4\epsilon_{ee}^{dV}) + Z(1 - 4\sin^2 \theta_W + 4\epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})$$

Recall:

$$\frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[ 2 - \frac{2T}{E} + \left( \frac{T}{E} \right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2)$$
Nonstandard interactions

Changing the size of $Q_W$ effectively changes overall magnitude of recoil curve. Shows limits which could be achieved after 100 kg/yr at SNS.

Additional non-standard interactions such as the flavor changing neutral currents can be probed. Also, first order effect in changing relative contributions of neutron and proton form factor.

Scholberg 2006
Beyond First Detection of CE$\nu$NS

- nonstandard $\nu$ interactions
- form factor
Form factor

Understanding the structure of the nucleus

Form factor, $F(Q^2)$ is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

$$F(Q^2) = \frac{1}{Q_W} \int [\rho_n(r) - (1 - 4\sin^2 \theta_W)\rho_p(r)] \frac{\sin(Qr)}{Qr} r^2 dr$$

$$\langle R^2 \rangle_{SGII}^{1/2} = 3.405 \text{ fm}$$
$$\langle R^2 \rangle_{G202}^{1/2} = 3.454 \text{ fm}$$
Form factor

Form factor, $F(Q^2)$, is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

$$F(Q^2) = \frac{1}{Q_W} \int \left[ \rho_n(r) - (1 - 4 \sin^2 \theta_W) \rho_p(r) \right] \frac{\sin(Qr)}{Qr} r^2 dr$$

- Proton form factor term is suppressed by $1 - 4 \sin^2 (\theta_W)$
- Neutron form factor is not suppressed

CE$\nu$NS can be used to determine the form factor

Amanik et al 2009
Form factor

\[ F(Q^2) = \frac{1}{Q_W} \int \left[ \rho_n(r) - (1 - 4\sin^2\theta_W)\rho_p(r) \right] \frac{\sin(Qr)}{Qr} r^2 dr \]

- Proton form factor can be measured by electromagnetic probes.
- Neutron form factor is less well known:
- Neutron scattering - many measurements - requires theory to go from cross section to form factor
- Parity violating electron scattering - PREX at Jlab Pb at one \( Q^2 \), extract \( A_{PV} \sim 0.65 \times 10^{-6} \) then determine neutron radius, now also CREX at Jlab on Ca

\( C_\nu NS \) recoil curve can be fit: neutron radius and higher moments
Nuclear-Neutron form factor from CE\(\nu\)NS

Taylor expand the \(\sin(Qr)\) form factor:

\[
F_{n}(Q^2) = \frac{1}{Q_W} \int \rho_n(r) \frac{\sin(Qr)}{Qr} r^2 dr \approx \frac{N}{Q_W} \left( 1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \ldots \right)
\]

Moments of the density distribution, \(\langle R_n^2 \rangle\), \(\langle R_n^4 \rangle\) characterize the form factor. Patton et al 2012, 2013
Liquid argon scenario

3.5 tonnes argon 16m from SNS, 18m from Daeðalus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

Fig. from Patton et al 2012

Band is measurement from neutron scattering. Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.
Xenon is more constraining

300 kg Xenon 16m from SNS, 18m from Daeδalus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

fig. from Patton et al 2012

Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.
Beyond NSIs and the form factor

- Nonstandard $\nu$ interactions
- Form factor
- $\sin^2 \theta_W$
- $\nu$ magnetic moment

$$Q_W = N + Z(1 - 4\sin^2 \theta_W)$$
Beyond NSIs and the form factor

- Nonstandard $\nu$ interactions
- Form factor
- $\sin^2 \theta_W$
- $\nu$ magnetic moment

Look for excess events at low recoil energy using neutrinos from stopped $\pi/\mu$
Summary

- Coherent elastic neutrino nucleus scattering is not yet detected, but in many communities such as supernova simulation, supernova detection, active-sterile oscillations, dark matter detection it is assume to exist as predicted by standard model

- Going beyond a first detection...
  - non-standard interactions
  - form factor

- and beyond these...
  - Weinberg angle
  - neutrino magnetic moment

- overall, a rich physics opportunity from the theory point of view