Coherent Neutrino-Nucleus Scattering Using the DAEdALUS Cyclotron(s) and a CLEAR-like Detector

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DAEdALUS Workshop 2/4/2010
Outline

• What is coherent neutrino-nucleus scattering?
• Why is it important?
• How do you detect this process?
  • An introduction to the CLEAR concept
• Physics reach
• Why is the DAEdALUS/DUSEL combination good for this measurement?
An unobserved process with a large cross section

\[ \nu A \to \nu A \]

The total scattering amplitude can be approximated by taking the sum of the scattering amplitudes of the neutrino with the individual nucleons when the momentum transfer is small.

\[ F(k', k) \propto Af(k', k) \]

where \( f(k', k) \) is the scattering amplitude of the neutrino on a single nucleon.

\[
\left( \frac{d\sigma}{dE} \right)_{\nu A} = \frac{G_F^2}{2\pi} \frac{Q_w^2}{4} F^2(2ME)M[2 - \frac{ME}{k^2}] 
\]

where \( k \) is the incident neutrino energy, \( E \) is the nuclear recoil energy, \( M \) is the nuclear mass, \( F \) is the ground state elastic form factor, \( Q_w \) is the weak nuclear charge, and \( G_F \) is the Fermi constant.

This leaves a cross section dependence of \( A^2 \).

Coherence requires that \( Q < \frac{1}{R} \), where \( R \) is the nuclear radius. For medium \( A \) nuclei, this condition is usually satisfied for neutrino energies up to \( \sim 50 \text{ MeV} \).

A process well-predicted by the SM with small form factor uncertainties (\( \sim 5\% \)). Any deviation from the SM could be new physics.
An unobserved process with a large cross section...and a tiny signature

Flavor blind!

\[ \nu A \rightarrow \nu A \]

In the few-50 MeV range:
- Coherent $\nu$-A elastic $\sigma \sim 10^{-39}$ cm$^2$
- $\nu$-A charged current $\sigma \sim 10^{-40}$ cm$^2$
- $\nu$-p charged current $\sigma \sim 10^{-41}$ cm$^2$
- $\nu$-e elastic $\sigma \sim 10^{-43}$ cm$^2$

Very low energy (WIMP-like) recoils

Recoil energies for stopped-pion neutrino source on Ar

hep-ex:0910.1989
Low energy detection techniques

Recoil energies from 0-100 keV are going to be difficult to detect with the kton-scale, ~5 m drift, charge-detection-only LArTPC(s) planned for DUSEL 4850. Considering only signal-to-noise in a conventional LArTPC, 150 keV is the absolute minimum energy threshold (without charge amplification).

WIMP detectors are sensitive to keV-scale recoils

XENON (3 keV)  CDMS-II (7 keV)  COUPP (5-10 keV)
The CLEAR concept
Coherent Low Energy A Recoils = CLEAR

- CLEAR is on the surface, 46 meters from the stopped-pion neutrino source at SNS.
- Active LAr (LNe) volume = 456 (391) kg
- 60 cm in diameter, 44 cm tall.
- 38 immersed PMTs divided into two arrays.
- Scintillation wavelength in LAr (LNe) = 125 (80) nm, re-emitted at 440 nm.
Why is coherent neutrino-nucleus scattering interesting?

- This process has never been detected.
- Differences from Standard-Model prediction could be a sign of new physics.
- Supernova process.
- Supernova neutrino detection.
- Weak mixing angle.
- Non-standard neutrino interactions.
Core-collapse Supernova

Neutrinos carry energy (10^{53} \text{ ergs}, 99\% of total) out of the star before anything else.

Supernova evolution: Coherent neutrino scattering (\sigma \sim A^2) may push heavy elements to the outer shell of the star (Rev. Nucl. Part. Sci 27 167, 1977).

Supernova neutrino detection: \sim 10 neutrino-nucleus coherent events on Ar in a 10 second window per ton for a galactic supernova at 10 kpc. Important info about numu and nutau that is out of reach for Water Cerenkov.

Oscillation physics, mass hierarchy, absolute neutrino mass... All 6 flavors for coherent neutrino-nucleus!
The weak mixing angle

\[
\left( \frac{d\sigma}{dE} \right)_{\nu A} = \frac{G_F^2}{2\pi} \frac{Q_w^2}{4} F^2 (2ME) M \left[ 2 - \frac{ME}{k^2} \right]
\]

where \( Q_w = N - (1 - 4\sin^2\theta_W)Z \)

where \( Z \) is the number of protons, \( N \) is the number of neutrons, and \( \theta_W \) is the weak mixing angle.

The weak mixing angle can be found by measuring the absolute cross-section. A cross section measurement with \( \sim 10\% \) uncertainty gives a \( \sin^2\theta_W \) uncertainty of \( \sim 5\% \) at a typical \( Q \) value of 0.04 GeV/c.

A first generation experiment may not be competitive with precision APV and e-e scattering experiments. However, there are no other neutrino measurements near \( Q \sim 0.04 \) GeV/c.
Non-Standard Neutrino Interactions

Just like for the weak mixing angle, planned and existing precision experiments are not sensitive to new physics specific to neutrino-nucleon interactions.

Model-independent Non-Standard Interaction (NSI) Lagrangian

\[ L_{\nu, H}^{\text{NSI}} = -\frac{G_F}{2} \sum_q \sum_{\alpha, \beta} [\bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta] (\epsilon_{\alpha\beta}^{qL} [\bar{q} \gamma_\mu (1 - \gamma^5) q] + \epsilon_{\alpha\beta}^{qR} [\bar{q} \gamma_\mu (1 + \gamma^5) q]) \]

The cross section with NSI vector coupling constants

\[ \left( \frac{d\sigma}{dE} \right)_{\nu A} = \frac{G_F^2 M}{\pi} F^2 (2ME) \times (Z (g_V^p + 2\epsilon_{ee}^u + \epsilon_{ee}^d) + N (g_V^n + \epsilon_{ee}^u + 2\epsilon_{ee}^d))^2 \]

The signature of NSI is a deviation from the expected cross section.

See Barranco, et al. [hep-ph/0702175 (2003)] for specific NSI new physics possibilities from a neutrino-nucleus coherent measurement (extra neutral gauge bosons, leptoquarks, and R-parity breaking interactions)
Constraints on Non-standard interaction parameters

Non-standard interaction parameters are often poorly constrained

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TABLE I: Constraints on NSI parameters, from Ref. [35].

<table>
<thead>
<tr>
<th>NSI Parameter Limit</th>
<th>Source</th>
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<tr>
<td>(-1 &lt; \varepsilon_{ee}^{uL} &lt; 0.3)</td>
<td>CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering</td>
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<tr>
<td>(-0.3 &lt; \varepsilon_{ee}^{dL} &lt; 0.3)</td>
<td>CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering</td>
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<td>(</td>
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Allowed-region at 90% CL for a CLEAR measurement consistent with the SM (w/ 15% systematic uncertainty)

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The flux

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

Delayed (2.2 microsec)

For 1300 MeV protons on Hg (nucl-ex/0309014)

• Homestake DUSEL will develop a major campus at 300 feet below ground, corresponding to shielding exceeding ~150 mwe.

• Free cosmic-ray neutron/gamma passive shielding!

• 300’ of shielding is definitely overkill, especially considering the 1/r^2 dependence of the neutrino flux. Shielding of only a few 10s of meters would be perfect.

• Is there room between 0 and 300’ at DUSEL? Or, can a cyclotron be placed at the drive-in location of DUSEL 300 in order to reduce the baseline of a coherent detector?

• A surface detector would allow for a shorter baseline. Note that CLEAR is on the surface and has a baseline of ~150’.
This plot assumes a 300’ baseline, Ar target, and 4E22/flavor/year of nue, numu, and nuebar and is scaled from CLEAR (hep-ex:0910.1989).

Scaling from CLEAR:
Assuming a nuclear recoil energy window from 20-120 keV (30-160 keV) and a 1000 (857) kg LAr (LNe) target, there will be about 816 (312) events from the muon decay flux, and about 193 (101) events from the prompt numu flux.

Multiply these rates by 20 for a baseline of 65’!
Backgrounds for CLEAR

Intrinsic, steady-state backgrounds are the main worry for CLEAR. Nuclear recoils due to neutrons look like signal.

Note that CR-related backgrounds are not plotted here. They can be measured quite well during the beam dead time. However, the CR rate drove the CLEAR single-phase design (see: dead time for a two-phase). Perhaps a two-phase detector (Ar or Xe) with even better neutron/gamma-like separation and position resolution could be used with 150 mwe shielding?

Background mitigation

- A repetition frequency of 2000 Hz with a 100 microsec window gives a rejection of steady state background of 0.2 and knowledge of the steady-state rate. Fast scintillation signal from individual events can be known to within ~10ns.

Mitigation of backgrounds (see: WIMP-detection):

- **Ar-39 (beta) background:**
  Neon, Xenon, or depleted Argon and Pulse Shape Discrimination (PSD), charge-to-light ratio in time in a dual phase detector.

- **Radon background:**
  Mechanical scrubbing, HEPA filters, and radon-impermeable plastic.

- **Gamma backgrounds (238-U, 232-Th, 40-K):**
  PSD, charge-to-light ratio in time in a dual-phase detector.

- **Beam- and cosmic ray-related:**
  Shielding. Underground, these backgrounds will be much lower as compared to SNS. Expensive shielding/veto is probably not necessary with 150 mwe overhead.
Conclusion

- There is a lot of physics in coherent neutrino-nucleus scattering. The process hasn’t even been observed before!
- First generation experiment reach: observation of process, supernovae, NSI parameter sensitivity.
- A DAEdALUS cyclotron would provide a very intense source of neutrinos—\(4 \times 10^{22}/\text{flavor/year}\) of nue, numu, and numubar. For comparison, SNS will provide \(~2 \times 10^{22}/\text{flavor/year}\).
- There seems to be room at DUSEL above or below ground for a dedicated coherent scattering detector. A baseline of tens of meters would be perfect.
- Backgrounds for coherent scattering are manageable with the use of a two-phase design, shielding/veto, beam timing and dead time measurements, and standard WIMP-detection background mitigation techniques.

The DAEdALUS/DUSEL combination will be great for a coherent measurement!

Thanks to: J. Conrad, T. Wongjirad, K. Scholberg, B. Fleming, M. Soderberg