CEvNS Detection with Ricochet

Joe Johnston

MIT

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Outline

1. Ricochet
   - Superconducting Bolometers
   - Temperature Readout
   - Experimental Site
   - Current Status

2. BSM Searches at Reactors
   - Neutrino Magnetic Moment
   - NSI Couplings
   - Massive Mediators

3. Summary
Ricochet

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- $\approx N^2$ scaling gives large cross section
- Requires low energy recoil detection (hundreds of eV)

Ricochet will achieve this via:

- Zn (superconducting) and Ge bolometers
- Phase 1: 100 eV threshold, 1 kg
- Phase 2: 10 eV threshold, 10 kg
Bolometric Detectors

Heat capacity dominated by lattice contributions at ultra-low temperatures

Used in direct detection of dark matter
Superconducting Bolometers

- Energy deposited via quasiparticles or phonons
- EM events will create more quasiparticles
- Quasiparticles have long recombination times

Simulation of three years of Ricochet data

Figure from J Billard
Multiplexing TES Readouts

- Thermalize a transition edge sensor (TES) to each detector
- RF SQUID inductance depends on external flux
- Each detector readout is tuned to a specific frequency
- GHz input allows scanning over frequencies
Ricochet will likely be at the Chooz Reactor Complex

- Two cores
- 8.5 GW power combined
- Both cores on 60% of the time, one core 40%
- Near Site (NS): 400 m from cores, 120 m.w.e
- Very Near Site (VNS): 80 m from cores, \( \approx 10 \text{ m.w.e expected} \)
Near Site Backgrounds

- Neutron rate from simulation
- Internal backgrounds from EDELWEISS
- 1.5 evts/kg/day background, 0.5 evts/kg/day signal (0.1-1 keV ROI)
• Currently have several Zn crystals
• Initial calibration pulses taken at IPNL Lyon
• Future crystals will be cubes for easier polishing
Ricochet

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Summary

• Reactor detection probes lower energy neutrinos (3 vs 30 MeV)

Assumptions:
• Isotopes Si, Ge, Zn, CaWO₄, and Al₂O₃ (Sapphire).

<table>
<thead>
<tr>
<th>Target</th>
<th>Phase 1</th>
<th>Phase 2</th>
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<tbody>
<tr>
<td></td>
<td>(E_{\text{th}}) [eV]</td>
<td>Mass [g]</td>
</tr>
<tr>
<td>Zn</td>
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<td>500</td>
</tr>
<tr>
<td>Ge</td>
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<tr>
<td>Si</td>
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<tr>
<td>CaWO₄</td>
<td>20</td>
<td>6.84</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>20</td>
<td>4.41</td>
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</tbody>
</table>

Backgrounds:
• Compton: \(10^{-3}\) discrimination power
• Neutrons: 0.1 discrimination power in CaWO₄ and Al₂O₃
Neutrino Magnetic Moment

- Minimal SM extensions allow up to $\mu_\nu \approx 10^{-15}\mu_B$
- A Majorana Neutrino could allow $\mu_\nu \approx 10^{-12}\mu_B$ or higher

$$\frac{d\sigma_{\nu-N}^{\text{Coherent}}}{dE_R} = \frac{d\sigma_{\nu-N}^{\text{SM CEvNS}}}{dE_R} + \frac{d\sigma_{\nu-N}^{\text{mag.}}}{dE_R}$$

$$\frac{d\sigma_{\nu-N}^{\text{mag.}}}{dE_R} = \frac{\pi\alpha^2\mu_\nu^2Z^2}{m_e^2} \left( \frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2} \right) F^2(E_R)$$

[Graph showing Recoil energy vs. dR_{\nuN}/dE_R]
Competitive with terrestrial bounds around several years
Focus on vector couplings to quarks, $\epsilon^{qV}_{ee} = \epsilon^{qL}_{ee} + \epsilon^{qR}_{ee}$, $q = u, d$:

$$Q^2_W \rightarrow Q^2_{\text{NSI}} = 4[N \left(-\frac{1}{2} + \epsilon^{uV}_{ee} + 2\epsilon^{dV}_{ee}\right) + Z \left(\frac{1}{2} - 2\sin^2 \theta_W + 2\epsilon^{uV}_{ee} + \epsilon^{dV}_{ee}\right)^2]$$

- $\epsilon^{uV}_{e\mu}$ constrained by $\mu \rightarrow e$ conversion in nuclei
- $\epsilon^{uV}_{\alpha\beta} / \epsilon^{dV}_{\alpha\beta}$ degeneracy broken by combining different N/Z ratios

Breaking $\epsilon^{uV}_{\alpha\beta} / \epsilon^{dV}_{\alpha\beta}$ degeneracy is important for DUNE

(P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))
Focus on vector couplings to quarks, $\epsilon_{qV}^{\ell\ell} = \epsilon_{qL}^{\ell\ell} + \epsilon_{qR}^{\ell\ell}$, $q = u, d$:

\[
Q_W^2 \rightarrow Q_{NSI}^2 = 4\left[N \left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z \left(\frac{1}{2} - 2\sin^2 \theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2
+ 4 \left[N(\epsilon_{e\mu}^{uV} + 2\epsilon_{e\tau}^{dV}) + Z(2\epsilon_{e\mu}^{uV} + \epsilon_{e\tau}^{dV})\right]^2
\]

- $\epsilon_{e\mu}^{uV}$ constrained by $\mu \rightarrow e$ conversion in nuclei
- $\epsilon_{\alpha\beta}^{uV} / \epsilon_{\alpha\beta}^{dV}$ degeneracy broken by combining different N/Z ratios
- Breaking $\epsilon_{\alpha\beta}^{uV} / \epsilon_{\alpha\beta}^{dV}$ degeneracy is important for DUNE

(P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))
Flavor Conserving Ge+Si:

N/Z values: Ge=1.27, Zn=1.18, Si=1.01, Al=1.08, O=1.00, W=1.48
Flavor Conserving All:

A multi-target experiment can place very strong bounds
Focus on vector couplings to quarks, $\epsilon^{qV}_{ee} = \epsilon^{qL}_{ee} + \epsilon^{qR}_{ee}$, $q = u, d$:

$$Q^2_{W} \rightarrow Q^2_{\text{NSI}} = 4[N \left( -\frac{1}{2} + \epsilon^{uV}_{ee} + 2\epsilon^{dV}_{ee} \right) + Z \left( \frac{1}{2} - 2 \sin^2 \theta_{W} + 2\epsilon^{uV}_{ee} + \epsilon^{dV}_{ee} \right)]^2$$

$$+ 4 \left[ N(\epsilon^{uV}_{e\tau} + 2\epsilon^{dV}_{e\tau}) + Z(2\epsilon^{uV}_{e\tau} + \epsilon^{dV}_{e\tau}) \right]^2$$

- $\epsilon^{uV}_{e\mu}$ constrained by $\mu \rightarrow e$ conversion in nuclei
- $\epsilon^{uV}_{\alpha\beta} / \epsilon^{dV}_{\alpha\beta}$ degeneracy broken by combining different N/Z ratios
- Breaking $\epsilon^{uV}_{\alpha\beta} / \epsilon^{dV}_{\alpha\beta}$ degeneracy is important for DUNE

(P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))
Flavor Changing Constraints:

![Graph showing 95% CL allowed regions - Very Near Site - Phase 1](image)

- CHARM
- LHC monojet
- COHERENT

95% CL allowed regions - Very Near Site - Phase 1

- Ge
- Zn
- Si
- CaWO$_4$
- Al$_2$O$_3$
- All
A massive scalar mediator adds a term to SM CEvNS

\[
\frac{d\sigma_\phi}{dE_R} = \frac{(g_\nu)^2 Q^2_{\phi}}{4\pi} \frac{E_R m_N^2}{E_\nu^2 (q^2 + m_\phi^2)^2} F^2(E_R)
\]

\[Q_\phi \approx (15.1 Z + 14 N) g_q\]
Lower mediator masses are better probed at low neutrino energies
A vector mediator interferes with SM CEvNS

\[ Q_W \rightarrow Q_{SM+NP} = Q_W - \frac{\sqrt{2}}{G_F} \frac{Q_{Z'}}{q^2 + m_{Z'}^2}, \]

Recoil energy, \( E_R \) [keV]

\[ \frac{dR_{\nu N}}{dE_R} \text{ [events/kg/keV/day]} \]

Phase 2 Phase 1

CEvNS on a CaWO\(_4\) target (Near Site)

BG after rejection
Standard Model CEvNS
+ \( m_{Z'} = 10 \) keV; \( g_{Z'} = 4 \times 10^{-6} \)
+ \( m_{Z'} = 1 \) MeV; \( g_{Z'} = 10^{-5} \)
+ \( m_{Z'} = 100 \) GeV; \( g_{Z'} = 10^{-1} \)

\( m_{Z'} \) [MeV]

Median 90% Upper Limit on \( g_{Z'} \)

COHERENT (2017)

Z'−model, \( g_\nu = g_u = g_d = g_{Z'} \)
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Summary
Ricochet:

- Superconducting Zn bolometers for background rejection
- Multiplexing TES readout will allow necessary scaling
- Experimental site at Chooz reactor complex
- Zn crystals fabricated and in testing

Proposed experiments will be able to place bounds on new physics:

- Probe neutrino magnetic moment
- Multiple targets tightly constrain NSI
- Low energy neutrinos better constrain simple mediator models
$\nu$-cleus

$\nu$-cleus

- Initially 11 g, 110 g at a later phase
- Threshold $O(\leq 10 \text{ eV})$
Background Assumptions

Compton Background:
- 100 events/kg/day in Ge
- Factor $10^{-3}$ discrimination power

Neutron Background:
- 10 times larger at VNS
- Factor of 0.1 discrimination power for CaWO$_4$ and Al$_2$O$_3$
- No reactor correlation

All other backgrounds negligible
- 10% background normalization uncertainty
- 5% CEvNS normalizations uncertainty
Likelihood:

\[ \mathcal{L}(D|\theta, \psi) = \mathcal{L}(\psi) \times \prod_{i}^{N_{\text{bins}}} P\left( N_{\text{obs}}^{(i)} | N_{\text{sig}}^{(i)}(\theta) + N_{\text{bg}}^{(i)}(\psi) \right). \]

- \( \theta \) is our parameter of interest
- \( \gamma \) is nuisance parameters, for example constraining the backgrounds.
- A 10% uncertainty is assumed on all background normalizations
- A 5% uncertainty is assumed on the CEvNS signal
- Use profile likelihood ratio test to determine most bounds
- An asimov data set is used to determine bounds on NSI

Introduce a 4-fermion coupling \((\alpha, \beta = e, \mu, \tau, f = e, u, d, P = L, R)\)

\[
\mathcal{L}^{\text{NSI}} = -\epsilon_{\alpha \beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f} \gamma^\rho P f)
\]
\[ \sin^2(\theta_W) \] and APV constraints

- It is very difficult to place bounds on new physics without assuming some constraint on \( \sin^2(\theta_W) \)
- We fix \( \sin^2(\theta_W) \), but multiply all CEvNS signals by a 5\% envelope to account for all systematic uncertainties