Reactor CEνNS Detection using Low-threshold Detector Technology Developed for Dark Matter Searches

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\( \chi_0 \)
IBD vs CEνNS: Rate, Threshold, and Background

Prompt $\beta^+$, delayed neutron for full reconstruction. Very good background rejection. Need $E_{\nu}>1.8$ MeV

$E_R \approx m^2 v^2/m_{GeV} \approx 0$-few keV recoil energy
Detected through ionization/phonon/light
Recoil spectra is used to infer the mass/energy

Both Weak Interaction Processes, but
Coherent $\nu$-N Scattering $\Rightarrow A^2$ enhancement

This provides the $\sim 1000x$ higher rate
Also, allows access to sub-IBD $\nu$ spectrum

Determine reactor ON/OFF. Also, fuel type if measured with high statistical significance

Why is Reactor CEνNS not discovered yet?

Kg-scale MINER germanium/silicon cryogenic detector ER/NR discrimination

3000-kg PROSPECT liquid scintillation detector with PSD
The Interplay Between Threshold and Background

MW Reactor at 2m - Scale for Power and $1/r^2$

Exponential background at low energies, especially at surface!

EXCESS workshop June 15-16

The Dark Matter/CEνNS community had a workshop to put all expts. on the same scale to initiate a program to understand background sources.

The biggest remaining hurdle for CEνNS to be used as a practical tool for reactor monitoring and nuclear safeguards is the background.

However, the synergy with DarkMatter is helping us reduce background and improve ER/NR rejection for discovery.
MIνER Experiment - Generic to most expts

Top View

Key Features
1. Low-threshold (<100 eV) with sensitivity to CEνNS
2. Proximity to core (rate enhancement)
3. Once detected, physics program involves precision measurement for new physics – sterile-ν, NSI, etc
4. Moveable Core tests short baseline oscillation

Side View

Precisely Movable Core to Probe m-scale oscillation
MIvER Experiment -
Generic to most expts
CE$\nu$NS Detector Technologies

- Most Dark Matter detectors now in use for CE$\nu$NS – synergy in low threshold and background reduction techniques
- Fundamentally, phonon detectors (with SQUIDs) can access lower recoil thresholds due to lower noise and no Lindhard
- CCDs have shown very low noise and low-threshold too
- Any detector (PPC, CCD) using charge will suffer from Lindhard

<table>
<thead>
<tr>
<th>Light (quenched)</th>
<th>Ionization (quenched)</th>
<th>Phonon (no quenching)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindhard=.1-.2</td>
<td>.15 (Ge), .05 (Si)</td>
<td>No Quenching!</td>
</tr>
<tr>
<td>Req $E_{th}$ =20 eV</td>
<td>30eV(Ge), 10(Si)</td>
<td>200 eV</td>
</tr>
<tr>
<td>Resol. $\sigma$=4 eV</td>
<td>5 eV (Ge), 2 (Si)</td>
<td>40 eV</td>
</tr>
<tr>
<td>CRESST (10 gm)</td>
<td>CDMS(kg), CONNIE(gm)</td>
<td>CRESST, CDMS</td>
</tr>
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Trick to overcome Lindhard: convert ionization to phonon

MINER: ~gm-kg mass with 50 eVnr sensitivity

CONNIE CCD: ~gm mass with eVee sensitivity
gm-kg scale
MINER Detectors

- Ge, Si, Al2O3
- 0V, LV (few V), HV (up to 400V)
- Smallest – 10 gm Si
- Largest – 1.5 kg Ge (SNOLAB)
Detector Technology
Developed for SuperCDMS

iZIP Detector with ionization and phonon sensors for ER/NR discrimination (>keV)

*First SNOLAB Ge iZIP (fabricated at TAMU)*


High Voltage Detector with NTL gain. Give up discrimination in favor of low threshold (~100eV).

*First SNOLAB Si HV (fabricated at TAMU)*
Phonons are collected by superconducting Al fins ($\Delta = \sim \text{meV}$), creating quasi particles that are then trapped by the W Transition Edge Sensors (TES), held in equilibrium between Normal and Super Conducting temp. SQUIDs measure small change in current through sharp $\Delta R/\Delta T$. 

Phonon Sensors
Contact-Free High Voltage Detectors

100-gm single-e sensitive Contact Free Si HV Detector. Signal amplification observed without increase in leakage up to 300 V. Laser calibration done.

Initial demo with 250 gm Ge with $\sigma=7$ eV
https://doi.org/10.1016/j.nima.2017.02.032

Single-e/h pair 100 gm Si:
https://inspirehep.net/literature/1828158
**Hybrid HV Detector**

**Main idea:** Monolithic detector with a LV and a HV side – LV to measure primary phonons like iZIP and HV to measure NTL phonons. Do it without significant NTL pollution from HV to LV. \( \sim 100 \text{gm} \)

Charge transport from LV region to HV almost 100%

\[
P_{HV} = \alpha \left[ (1 - \eta_{HL}) E_R L V_{HV} / 4 + \eta_{LH} E_R (1 + LV_{LV} / 4) \right]
\]

\[
P_{LV} = \beta \left[ \eta_{HL} E_R L V_{HV} / 4 + (1 - \eta_{LH}) E_R (1 + LV_{LV} / 4) \right]
\]

Discrimination: \( D = \frac{P_{HV}}{P_{LV}} \)

Discrimination improves at low energies. Funded by DOE to push the DM and CE\(\nu\)NS discovery potential – background is key to discovery.

Phonon-mediated High-voltage Detector with Background Rejection for Low-mass Dark Matter and Reactor Coherent Neutrino Scattering Experiments:
https://inspirehep.net/literature/1802528
~100 gm 3" x 4mm sapphire detector

TES sensors will be optimized for the faster timing

~5 times better (A+B+C+D) resolution than Si detector with same mask (~120 eV in Si HV at 0V)
Pulse examples and Copper fluorescence

- Much faster timing from sapphire for position reconstruction and possible ER/NR discrimination
- 8.05 and 8.91 keV copper fluorescence lines for new way of calibrating in-situ
Low-Threshold Ge Detector inside Fully Hermetic Ge Shielding

- 3He + 32Si (β-decay in bulk)
- Ge Activation
- Surface Betas
- Surface 206Pb
- Neutrons
- CNS

12 Ge coin was run. Next runs with~30-75 gm Ge coin run planned.

Inner copper shielding to for additional hermetic shielding being designed. Capable of hosting gm-kg scale detector.
MIvER Background with 4" Pb shielding

5-hour Reactor On
Core On: Raw count (ER+NR) ~3000 DRU. NR band with single-scatter cut <100 DRU above keV.

11-hour Reactor Off
Core Off: Raw count (20-45 keV ER+NR) ~2000 DRU. NR band with single-scatter cut <100 DRU above keV.

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Low Energy Scan using BeGe (77K) detector shows flat Compton background. Raw count (ER+NR) ~85 DRU inside both γ and N shielding

Core On
Counts/s
Time (s)

- Nal (~1kg) Rate v. Time (integrated: 30 keV – 2.1 MeV)
- Raw count (ER+NR) ~40 DRU inside both γ and N shielding

MIvER has breakthroughs in both NDA
Our Non-blind Region Excess

~100 gm 3” x 4mm sapphire detector

All configurations sandwiched between two 3”x1” detectors, except the Ge coin has additional active Ge donut veto

Passive and active inner shielding/veto payoff. Single-scatter events in bulk!

ER/NR discrimination, even if ~500eV, is highly desirable for discovery potential in CEνNS and DM

On MINER, we attempt to use Ge, Si and sapphire detectors of same size in the same configuration to understand BG.
CEvNS for Monitoring – Game Changing Technologies in Hand!

**10-kg 100-ev NR Ge Hybrid**
(discrimination gives 10-DRU)

**10-kg 100-ev NR Si Hybrid**
(discrimination gives 10-DRU)

**10-kg 100-ev NR Si HV**
(without discrim. 100-DRU)

**Exposure in kg-days**

- 1 day for 5-σ detection
- 10 days for 5-σ detection
- 100 days for 5-σ detection

**Safeguards needs quick (<100 days) Detection!**

**10-kg Non-Phonon** (Lindhard) detector
(1000-DRU without discrimination and without background modeling) – Integrate on tails

**Reactor CEvNS experiments** will not only help us understand fundamental new physics, but also fundamentally change how we use the unstoppable neutrinos to detect threat!
Possible Near Field Applications

• Expectations: provide reactor operation/history
  • Reactor power and fuel cycle changes, such as fuel composition U/Pu/Th and fuel burnup
  • Identify covert reactors/Pu diversion

• Compact MIvER setup ideal for deployment
  • Monitor age and cooling time at spent fuel storage
  • Breeding and proliferation activities in the case of advanced and molten salt rectors

Phase-2 at South Texas Project (STP) ~3 GW next year.

MIvER Compact Installation with Bluefors closed-cycle fridge in RF cage and shielding

Beneficial to collaborate at a common site for quicker application of technology

We invite you to bring your technology to STP and collaborate on a common state of art shielding, active veto, analysis, and applications.
Reactor CENNS Program is very active

- Dark Matter detector technologies with stricter threshold and background requirements have allowed CENNS programs to flourish.
- Background at surface (not underground like Dark Matter experiment) still an issue
- Rapid progress in achieving sub-1000 DRU and sub-100eVnr requirements
- Within the next couple of years CENNS will open up new frontiers in fundamental physics research and applied nuclear safeguards