Searching for dark matter with CEvNS detectors at the SNS

Dan Pershey (Duke University)
for the COHERENT Collaboration
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A premier neutron accelerator complex which produces an incredibly intense flux of low-energy neutrinos with exciting physics agenda complementary to its neutron studies.

In early stages of upgrade to double accelerator power and increase beam energy.

The Proton Power Upgrade (coming few years):
- Beam energy: 1.0 GeV → 1.3 GeV
- Beam power: 1.4 MW → 2.8 MW
- Pulse duration (FWHM): 350 ns
Along with upgrade to accelerator power, the complex will construct the Second Target Station (STS) with expected completion $\approx 2030$ which will run simultaneously with the First Target Station (FTS).

After completion, both targets will operate with beam pulses delivered at 45 Hz (15 Hz) for the FTS (STS).

Facilitates significant expansion of neutrino program at ORNL.

Collaborating with lab to design specialized detector hall large enough to fit 10t-scale detectors with sufficient shielding from bright neutron flux.
Neutrino flux at the SNS

- Low energy pions are a natural by-product of SNS running
  - $\pi^+$ will stop and decay at rest
    
    $\pi^+ \rightarrow \mu^+ + \nu_\mu$ : $\tau = 26$ ns
    $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ : $\tau = 2200$ ns
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature

- Flux shape is very well known in both time and energy with very small contribution from decay in flight

Timing distribution at SNS

Energy distribution at SNS
Measuring CEvNS at the SNS with COHERENT

- COHERENT formed to search for coherent elastic neutrino-nucleus scattering (CEvNS)
- Only visible signature is low-energy nuclear recoil
  - Need low-threshold detectors similar to dark matter direct detection
- Made first measurements of CEvNS on CsI (2017/21) and Ar (2020)
  - More data on Ge, NaI, Ar, CsI in the near future, all at the FTS
- Currently transitioning from first-light results to precision measurements and searches for BSM physics

Dark matter in our universe

- First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)
- In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter
- Continuing understanding distribution of dark matter from weak gravitational lensing data
- 100 years since postulation, and we still haven’t found the particle nature of DM despite many attempts – new physics we know exists, we just need to find a new place to look
Origin of weakly-interacting dark matter

Assuming that DM is a particle that interacts weakly with standard-model (SM) matter, in the very early universe, DM was in thermal equilibrium with SM fermions

- As the universe cools, DM production is no longer kinematically allowed, and the DM concentration falls exponentially
- Later, as the universe continued expanding, the DM concentration became so low that DM annihilation stopped since DM particles could no longer find partners to annihilate with

At this point, the universe “freeze-out” of DM occurred, with the DM concentration fixed to the modern observed value

Freeze-out concentration depends on DM cross section – higher cross section implies DM can annihilate even when less dense so that concentration is lower

- Modern relic abundance tells us what the cross section is (as a function of DM mass)
Low-mass DM phenomenology

- For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force.
- The DM scattering cross section is \( \sigma \sim \frac{m^2_\chi}{m^4_Z} \)
  - Lower DM mass \( \rightarrow \) lower cross section \( \rightarrow \) higher DM abundance
  - If \( m_\chi < 2 \text{ GeV/c}^2 \), predicted relic abundance would be so large it would overclose the universe, preventing modern the universe.
Low-mass DM phenomenology

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- The DM scattering cross section is $\sigma \sim m_\chi^2/m_Z^4$
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  - If $m_\chi < 2 \text{ GeV}/c^2$, predicted relic abundance would be so large it would overclose the universe, preventing modern the universe.

- No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, $V$
- In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales.

- Simple, general model assumes a vector mediator that kinematically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2} \epsilon^2 F_{\mu\nu} V^{\mu\nu}$

- Model parameters
  - DM and mediator masses: $m_\chi$ and $m_V$
  - SM-mediator and DM-mediator couplings: $\epsilon$ and $\alpha_D$

- Relic abundance given in terms of $Y = \epsilon^2 \alpha_D (m_\chi/m_V)^4$

Classical WIMP mass regime:
- Early sub-GeV DM phenomenology:
- Coherent DM scattering / DM at the SNS:
Any hidden sector particles with masses below \( \approx 220 \text{ MeV/c}^2 \) could be produced in the many proton-Hg interactions within the SNS target.

- This may include mediator particles between SM and DM particles:
  - Dominant production from \( \pi^0/\eta^0 \to V\gamma \)

- Mediator decays to a pair of DM particles, sending a flux out of the SNS:
  - Suitable detector placed in this flux can directly detect DM particles scattering within the detector.
Advantages of low-recoil detectors: cross section

- We’re dealing with low enough $Q^2$ that the deBroglie wavelength is large compared to nuclear radius
- All nucleons within nucleus recoil coherently from neutrino or DM scattering
- Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

This coherency gives a $Z^2$ enhancement in the cross section

Game-changing – small investment in a 14-kg CEvNS detector competes with multi-ton detectors

Potential for $10^3 \times$ exposure increase at STS compared to first light CEvNS detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Mass (t)</th>
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<tbody>
<tr>
<td>LSND</td>
<td>167</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>450</td>
</tr>
<tr>
<td>COHERENT CsI</td>
<td>0.0146</td>
</tr>
<tr>
<td>Argon at STS</td>
<td>10</td>
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</table>

Current CEvNS
Future CEvNS
Advantages of accelerator searches: higher recoil energies

- Galactic DM is slow, thermal with $\beta$ around 0.001 $\rightarrow$ struck nuclei get very soft kick
  - Maximum recoil energy $2p_X^2/m_{\text{Nuc}} \approx 0.01$ eV
  - Much less than scintillation / ionization thresholds
  - About 1 kT for liquid Xe or liquid Ar detectors
  - Coherent DM-nucleus scattering unobservable

- DM produced at accelerators would be relativistic
  - Maximum recoil energy $2p_X^2/m_{\text{Nuc}} \approx 100$ keV $\rightarrow$ $10^7 \times$ higher recoil energies compared to galactic DM

Detecting coherent DM-nucleus scattering easily within reach of CEvNS detectors with modest thresholds between 1 and 20 keV$_{nr}$
Advantages of accelerator searches: less model dependent

- Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM
- But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed, $\beta \approx 0.001$
- Predictions span 20 orders of magnitude
Advantages of accelerator searches: less model dependent

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- Predictions span 20 orders of magnitude

- At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- COHERENT gets the best of both worlds
  - Independent of DM particle nature like accelerator methods
  - Large coherent cross section like astroparticle methods
Advantages of spallation sources: constraining uncertainties

- CEvNS is the principal beam-related background for DM search
  - SM cross section precisely calculated, but uncertainties in detector response unique to each detector
- Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\nu_e/\bar{\nu}_\mu$ flux
- The delayed time window gives us a control sample – can constrain systematic uncertainties in situ and use to refine background estimates in the DM timing ROI
- Ensures DM search never systematics limited – syst uncertainty shrinks as fast as stat
Current data – constraining dark matter with COHERENT CsI[Na]

- Current data from COHERENT CsI[Na] is consistent with predictions for the standard-model backgrounds within expected errors – no DM signal yet observed, must extend sensitivity with future searches.

<table>
<thead>
<tr>
<th></th>
<th>Prediction</th>
<th>Data</th>
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<tbody>
<tr>
<td>CEvNS</td>
<td>341 ± 41</td>
<td>320 ± 33</td>
</tr>
<tr>
<td>BRN</td>
<td>27.6 ± 6.9</td>
<td>25.8 ± 6.6</td>
</tr>
<tr>
<td>NIN</td>
<td>7.6 ± 2.7</td>
<td>7.4 ± 2.7</td>
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Recoil energy distribution of COHERENT CsI[Na] data

- Data also agrees well with the background-only prediction for the recoil energy distribution
  - $\chi^2 = 103/120$ for background-only 2D fit
- Look for an excess in the DM ROI while controlling backgrounds with delayed events
COHERENT constraint on sub-GeV dark matter

- At 90% confidence, current CsI[Na] data significantly improves on constraints
  - Constraint slightly stronger than our sensitivity due to deficit of events in DM timing ROI
- First to probe beyond the scalar target that matches the DM relic abundance
- Achieved with small 14.6 kg detector – how much further can STS extend these bounds

![Graph showing dark matter annihilation signal versus mass]
Potential for new CEvNS detectors at the STS

- COHERENT already successful with CEvNS detection with argon using a 24kg single-phase, scintillating calorimeter
- At the STS, we are working with ORNL to accommodate a 10t upgrade to this concept at a baseline of 20m
- Threshold and dynamic range designed to allow simultaneous measurement of 10 keV to 50 MeV to measure both CEvNS

- We also plan for an array of cryogenic, undoped CsI scintillating detectors
  - Cooling undoped CsI to 40 K increases the crystal light yield while also eliminating background scintillation within the crystal (afterglow light)
- Can deploy 700 kg of crystal with a threshold of $\approx 0.1$ keV$_{ee}$ due to the favorable light yield
Future COHERENT sensitivity to dark matter

- **Immediate future**: germanium detector currently being commissioned – will fully explore scalar target at lower masses
- **In coming years**: future (funded by Korea) argon and cryogenic CsI detector at the FTS – will be sensitive to a lower DM flux and probe the Majorana fermion target (solid lines)
- **In next decade**: large detectors placed forward at the STS will begin to ambitiously test even the most pessimistic spin scenarios (dashed lines)
Summary

- COHERENT opened a new pathway to direct detection of accelerator-produced dark matter by making the first detection of CEvNS at the SNS at ORNL.

- CEvNS experiments show impressive potential for constraining dark matter at beam dump experiments with several unique advantages.

- First constraint already probes scalar dark matter consistent with the relic abundance with just 14.6 kg of target mass.

- Promising future for CEvNS experiments promising strong probes of dark matter parameter space exploring relic lines for all viable spin scenarios.
Future beam improvements at the SNS

- Two staged improvement to the beam
  1: Proton Power Upgrade
    - Increases the power of neutron beam
      \[1.4 \rightarrow 2.8 \text{ MW}\]
    - Feasibility of a second target station
  2: Second Target Station
    - Implements a second beamline at the accelerator

- Expected completion \(\approx 2030\text{s}\)
- Interest from the lab to design STS to accommodate a specialized detector hall for neutrino measurements capable of fitting a 10-t detector
A hand-held neutrino detector
– Built at U Chicago
– 14.6-kg CsI[Na] crystal
– Manufactured by Amcrys-H
– Single R877-100 PMT

Shielding design
– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to moderate neutrons

<table>
<thead>
<tr>
<th>Layer</th>
<th>HDPE*</th>
<th>Low backg. lead</th>
<th>Lead</th>
<th>Muon veto</th>
<th>Water</th>
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</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>3”</td>
<td>2”</td>
<td>4”</td>
<td>2”</td>
<td>4”</td>
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<tr>
<td>Colour</td>
<td></td>
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</tbody>
</table>

Detector made first detection of CEvNS (2017)
Our expected dark matter flux is produced through three channels

- $\pi^0 \rightarrow V\gamma$ decay: dominant channel where kinematically allowed, $2m_\chi < m_\pi$,
- $\eta^0 \rightarrow V\gamma$ decay: similarly only contributes for $2m_\chi < m_\eta$
- $pN \rightarrow pNV$ bremsstrahlung: only dominant at high energies and rate increases significantly at the $\rho$ resonance, $m_V \approx m_\rho$
Directionality of flux at the SNS

- Neutrino flux produced at rest – isotropic
- Largest beam-related background for DM searches at the SNS

- DM produced in-flight – is boosted
- A forward-directed detector would optimize DM / background

- After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux
Recent updates to cross section generator (BdNMC)

- DM particles scatter with coherent cross section
  \[ \frac{d\sigma}{dE_r} = 4\pi Z^2 \varepsilon^2 \alpha_{EM} \alpha_D \frac{2m_NE_X^2}{p_X^2(m_p^2 + 2m_NE_r)^2} |F(Q^2)|^2 \]

- This model has changed significantly since our previous sensitivity estimates
  1: A substitution of \( m_p \rightarrow m_N \) for a proper treatment of coherent scattering
     - Overall increases cross section, but spectrum is much softer – detector thresholds much more impactful for DM analyses
     - Degrades (Improves) sensitivity for DM masses below (above) 10 MeV/c^2
  2: A more accurate form factor treatment
     - BdNMC now uses the nuclear form factor accounting for spread of protons within nucleus rather than the proton form factor accounting for spatial spread of charge within each proton
     - Significantly reduces sensitivity at higher masses
  3: Improved configured resolution of DM scattering cross section from 100 MeV to 1 MeV
     - Gives slight reduction in event rate, but is more accurate
High-flux Sources for Low-energy Neutrinos

- Nuclear reactors
  - Very high flux: $\sim 2 \times 10^{20} \bar{\nu}_e / s$
  - Maximum recoil energy for CsI: 1 keV
  - Reactor-off data $\rightarrow$ in-situ background constraint

- Pion decay-at-rest ($\pi$DAR) at accelerators
  - High flux: $\sim 3 \times 10^{14} \nu_\mu / \nu_e / \bar{\nu}_\mu / s$
  - Maximum recoil energy for CsI: 15 keV
  - Pulsed beam $\rightarrow$ in-situ background constraint

Fermilab collaboration
For selecting a source, we want
- High beam power → faster accumulation of signal
- Low duty factor → improved background rejection through beam pulsing

With power upgrades and construction of the STS, the SNS will be the most effective machine for studying CEvNS
- Further SNS timing (350 ns FWHM) is ≪ the muon lifetime allowing separation of neutrino flavors
The COHERENT CsI[Na] detector

A hand-held neutrino detector
– Built at U Chicago
– 14.6-kg CsI[Na] crystal
– Manufactured by Amcrys-H
– Single R877-100 PMT

Shielding design
– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to moderate neutrons

Detector made first detection of CEvNS (2017)
First observation of CEvNS with CsI[Na]

Made first observation of CEvNS
– Established the existence of CEvNS to 6.7σ
– 134 ± 22 CEvNS events
– 173 ± 48 CEvNS predicted

Data released publicly, used to study
– neutrino NSI
– new forces
– neutrino magnetic moment
– $\sin^2 \theta_W$ at low-$Q^2$
– neutrino charge radius
– nuclear weak charge distribution
– + more
Timing of scintillation in CsI[Na]

- CsI has a high light yield and low background, but afterglow photons can be troublesome
  - CsI can scintillate for up to 1 s following a large energy deposit within the crystal
- The afterglow rate in Na-doped CsI is low enough to allow a search for small, few keV nuclear recoils associated with DM and CEvNS scatters

Collar et al., NIM A773 56 (2016)
Only a fraction of the struck nucleus’s kinetic energy, $E_{nr}$, goes into scintillation energy, $E_{ee}$.

There are five separate measurements of the scintillation response using CsI[Na] grown by the same manufacturer used for our detector:

- Empirically model $E_{ee}(E_{nr})$ as a fourth order polynomial with $E_{ee}(0) = 0$ and fit to the global data.
Calibrating the CsI[Na] detector

- Detector calibrated
  - 59.5 keV gamma using $^{241}$Am decay calibration source
  - 57.6 keV $^{127}$I($n,\gamma$) peak using a $^{252}$Cf neutron source

- A 13.35 photon / keV light yield is achieved
  - LY uniformity across crystal shown to be everywhere within 3%

- Single PE charge monitored during data collection using accidental peaks
### Measurement Uncertainties

- Re-assessed all systematic uncertainties
- Huge improvement to QF error from newly available data, better model and fit strategy
- Neutrino flux normalization now dominates our cross section uncertainty
- Overall precision improves 33% → 16%

**Diagram:**

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<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Experimental</th>
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<tbody>
<tr>
<td>(\nu) Flux</td>
<td>![Graph]</td>
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<tr>
<td>BRN Norm.</td>
<td>![Graph]</td>
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<tr>
<td>NIN Norm.</td>
<td>![Graph]</td>
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<tr>
<td>SSBkg Norm.</td>
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<td>QF</td>
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<td>Efficiency</td>
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<tr>
<td>Light Yield</td>
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<tr>
<td>Statistical</td>
<td>![Graph]</td>
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**Legend:**

- **Preliminary**
- COHERENT CsI
- 2017 Result
- 2020 Result

**Uncertainty (%)**

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<tr>
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<th>5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
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</table>
Ran Eljen cell scintillator in CsI shielding to study neutron backgrounds in detector location

- Fit to timing data gives the relative ratio of BRN and NIN events with uncertainties
- MCNP simulation predicts the observed recoil distribution very well in the Eljen cells
- Ran observed neutrino flux through CsI simulation to determine analysis backgrounds
  - Together, only 7% of signal
If there is DM in the SNS beam, it would give an additional population of nuclear recoils at times coincident with the arrival of the beam.

The recoil distributions are also different – though most of our sensitivity comes from CEvNS/DM overlap region.

2D fit to data for these two signals will give an estimate of DM produced at the SNS.
Less conservative scenarios: lowering $\alpha_D$

- Our dark matter model has two couplings: $\varepsilon$ and $\alpha_D$
  - Complicates parameter space since our relic abundance depends on $Y \propto \varepsilon^2 \alpha_D$
- Our contour depends on our assumption of $\alpha_D$ – smaller values give tighter constraints
- $\alpha_D = 0.5$ is the largest, most conservative assumption before perturbative effects important
Future COHERENT dark matter detectors at FTS

- COH-Ge-1: 18 kg of Ge PPC detectors
- Low threshold, $\sim 0.2$ keV$_{ee}$, improves sensitivity at low masses
- Funded with NSF MRI, detector commissioning late 2022

- COH-Ar-750: next-generation argon scintillator
- Large 610-kg fiducial volume
- Preliminary plans for 10-t argon detector at the STS placed forward from beam exploiting DM flux directionality

- COH-CryoCsI-1: future 10-kg, undoped CsI scintillator
- Crystals cooled to 40 K, significantly reducing afterglow scintillation while improving overall light yield
- With low threshold and high $Z$, small detector has very favorable sensitivity

Chernyak et al., Eur. Phys. C80 547 (2020)
Searching for leptophobic dark matter

- Above model assumes a general BSM kinetic mixing between photon and portal particle

- Leptophobic dark matter: it is also possible that light dark matter preferentially interacts with quarks – leptophobic DM: a specific case of general model
  - Interaction Lagrangian: $\mathcal{L} \sim \sqrt{4\pi\alpha_B} V^\mu \sum_q \bar{q} \gamma_\mu q$

- Differences in terminology, $\alpha\alpha_B$ analogous to kinetic mixing parameter, $\varepsilon^2$
- Experiments sensitive to coherent nuclear scattering well suited for searching for this DM
- Lepton scattering experiments unable to probe $V_{qq}$ coupling, COHERENT data more unique
  - E.g.: LDMX, BDX, NA64, electron-recoils in direct detection