R&D for Measuring Coherent Elastic Neutrino Nucleus Scattering at Fermilab

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LLNL
Coherent Elastic Neutrino Nucleus Scattering

Coherent Elastic (Neutral Current) Neutrino Nucleus Scattering: CENNS
first prediction by D.Z. Freedman (1974)

\[ \mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu \]

Cross section for zero-momentum transfer limit

\[ \sigma_{\nu N} \approx \frac{4}{\pi} E_{\nu}^2 [Z\omega_p + (A - Z)\omega_n]^2 \]

\[ g(Z_0u) = \frac{1}{4} - \frac{2}{3} \sin^2 \theta_W, \quad g(Z_0d) = -\frac{1}{4} + \frac{1}{3} \sin^2 \theta_W \]

\[ \omega_p = \frac{G_F}{4} (4 \sin^2 \theta_W - 1), \quad \omega_n = \frac{G_F}{4} \]

Differential cross section for finite momentum transfer

\[ \frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} [(1 - 4 \sin^2 \theta_W) Z - (A - Z)]^2 M \left( 1 - \frac{ME}{2E_{\nu}^2} \right) F(Q^2)^2 \]
Requirements of the CENNS

For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of

\[ E_\nu < \frac{1}{R_N} \approx 50 \text{ MeV} \]

\[ E_{max} \approx \frac{2E_\nu^2}{M} \approx \mathcal{O}(100) \text{ keV} \]

Requires a ton-scale detector with \( \sim 10 \text{ keV} \) energy threshold

\[ R \approx \mathcal{O}(10^3) \left( \frac{\sigma}{10^{-39} \text{cm}^2} \right) \times \left( \frac{\Phi}{10^{13} \nu/\text{year/cm}^2} \right) \times \left( \frac{M}{\text{ton}} \right) \text{ events/year} \]
• It’s never been observed

• Test Standard Model weak mixing angle ($\sin \theta_W$): K.Scholberg, PRD73 (2006)

• Non-standard interaction of neutrinos: J.Barranco et al, hep-ph/0702175

• Neutrino magnetic moment:
  - Conclusive measurement requires intensive neutrino flux (Project-X era)

• Neutron form factor from coherent scattering of neutrinos: P.S.Amanik et al, hep-ph/0707.4191

• Important input to understand supernova explosion

• Oscillations to sterile neutrinos, $Z'$, ....

• Irreducible backgrounds of direct detection of Dark Matter experiment

→ **Neutrinos always provided us with**
  the physics beyond the *then-Standard Model*!
Dark Matter Search

\[ \sigma_{\chi N} \simeq \frac{4}{\pi} \mu^2 [Z f_p + (A - Z) f_n]^2 \]

\[ \frac{dR}{dE} = \frac{\sigma_0 A^2}{m_\chi 2 \mu_n^2} F_A^2(E) \times \rho_0 \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{f(v)}{v} dv \]
Irreducible Backgrounds

Neutrinos from astrophysical origin

![Graph showing neutrino flux vs. energy for various processes including pp, 7Be, 8B, 12N, 15O, 17F, hep, and atm.]
Irreducible Backgrounds

- Coherent scattering of atmospheric neutrino is an irreducible background in future $O(10 \text{ ton})$ scale dark matter experiments (see Strigari, arXiv:0903.3630)

- What about the inelastic interaction tail by high energy neutrinos?

Sensitivity of dark matter detectors will be saturated out by irreducible neutrino backgrounds
Reactor Neutrinos

$E_{\text{max}} \approx \frac{2E^2}{M} < \text{keV}$

$\Phi = 10^{20} \bar{\nu}_e / \text{sec/4}\pi R^2$ \hspace{1cm} (\(\Phi = 10^{12} \bar{\nu}_e / \text{sec/cm}^2@ \text{20 m}\))

- Ultra-clean, kg-size, ~10 eV threshold detector
- Need to overcome steady state backgrounds and detector noise
- Reactor off-time can be used for background subtraction
- Detector development is challenging for a realistic experiment
• vSNS at Oak Ridge National Lab
• See CLEAR proposal: K. Scholberg et al., hep-ex:0910.1989

• Flux $\sim 2 \times 10^6$/sec/cm$^2$ at 46m from the target
• Steady state background rejection factor $\sim 10^{-4}$
• Expected event rate in a single-phase 500kg LAr detector: $\sim 400$ events/year of detection ($E_{th} > 30$ keVnr)
Neutrinos at Fermilab

to Soudan

MINOS Near Detector

MiniBooNE

BNB Target Building

Wilson Hall

NuMI Target
MI-12 Target Building Area

- 20m
- 30m
- 40m

8 GeV proton
Far-Off-aXis (FOX) Neutrinos at BNB

Beam MC Configuration
- Use standard Booster Beam MC
  - release stopping pion cuts in the original MC
- 8 GeV, 5Hz 5x10^{12} Protons on Beryllium target
  - 32 kW max power
- 173 kA horn current neutrino mode

From Booster Beam MC (S.Brice)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Lifetime (ns)</th>
<th>Decay mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ )</td>
<td>26.03</td>
<td>( \mu^+ + \nu_\mu )</td>
<td>99.9877</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( e^+ + \nu_e )</td>
<td>0.0123</td>
</tr>
<tr>
<td>( K^+ )</td>
<td>12.385</td>
<td>( \mu^+ + \nu_\mu )</td>
<td>63.44</td>
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<tr>
<td></td>
<td></td>
<td>( \pi^0 + e^+ + \nu_e )</td>
<td>4.98</td>
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<tr>
<td></td>
<td></td>
<td>( \pi^0 + \mu^+ + \nu_\mu )</td>
<td>3.32</td>
</tr>
<tr>
<td>( K_L^0 )</td>
<td>51.6</td>
<td>( \pi^- + e^+ + \nu_e )</td>
<td>20.333</td>
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<tr>
<td></td>
<td></td>
<td>( \pi^- + \mu^+ + \nu_\mu )</td>
<td>13.551</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \pi^- + \mu^- + \bar{\nu}_\mu )</td>
<td>13.469</td>
</tr>
<tr>
<td>( \mu^+ )</td>
<td>2197.03</td>
<td>( e^+ + \nu_e + \bar{\nu}_\mu )</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Dominant neutrino production process at the Far-Off-aXis is pion decay at rest
Far-Off-aXis (FOX) Neutrinos at BNB

- $\phi \approx 5 \times 10^5 \text{ v/cm}^2/\text{s} @20\text{m} (\cos\theta<0.5)$ (cf. $\phi(\text{SNS}) \approx 10^7\text{ v/cm}^2/\text{s}@20\text{m}$, $1 \times 10^6\text{ v/cm}^2/\text{s} @60\text{m}$)
- Systematic uncertainties of the neutrino flux estimation should be checked in detail
A ton-scale single phase LAr detector may perform the first ever observation of the CENNS at Fermilab.

- Well known detector technology (DEAP/CLEAN)
- Use pulse shape discrimination of nuclear recoil (fast) and electron recoil (slow) signal in LAr (see Boulay and Hime: astro-ph/0411358)
- Long live ($\tau = 269\text{yr}$) $^{39}\text{Ar}$ beta decay (1kBq/ton) wouldn’t be a serious issue due to duty factor of pulsed beam & Pulse Shape Discrimination (PSD)
Expected CENNS Event Rates at FOX

- 20m from the target ($\phi \approx 5 \times 10^5 \text{ } \nu/\text{cm}^2/\text{s}$)
- Steady state background rejection factor $\sim 10^{-5}$ (Total exposure: $\sim 300$ sec/year)
- Expected event rate in a single-phase 1-ton LAr detector: $\sim 200 \text{evt/year (E}_{\text{th}}> 30 \text{ keV @32kW)}$
- **Beam-induced neutron backgrounds**?
BNB Target Radiation Shielding

- Target is located 6.4m underground from the building surface
  - 2.6m-thick iron shielding blocks
  - 2.5m-thick concrete shielding blocks
- Neutron yield/pulse: \( N_n = (5 \times 10^{12} \text{ pot/pulse}) \times (30 \text{ neutrons/proton}) = 1.5 \times 10^{14} \text{ neutrons/pulse} \)
  \( \phi_n(@\text{surface}; R=640\text{cm w/ iron & concrete shielding}) = \sim 102 \text{ neutrons/pulse/m}^2 \)
  For 5”D×5”H neutron detector: Rate = 1.3 neutron pass/pulse
  → This is far from the accurate estimation
- Best way to figure out the backgrounds at the target building is to measure them
Beam-induced Background Survey (March~April 2012)

EJ-301 (~kg) Commercial Liquid Scintillator (@target building surface)

- No (or rare, if any) beam-induced muons
- Gammas are easy to shield (lead blocks)
- Neutron shielding wasn’t easy
- High flux of neutrons are detected in the target building
SciBath-768 Neutral Particle Detector

**Initial Survey : Feb 2012**
- Commercial 5”D EJ-301 neutron detector
- Establish logistics of data taking procedure at the target building
- Measure beam induced event rate

**SciBath (Indiana University)**
- (45cm)$^3$ volume containing
- 82 liters (70kg) of liquid scintillator:
  - mineral oil, 11% pseudocumene, + PPO
- 3 16x16 grids, in x,y,z (768 total), 2.5cm spacing, 1.5mm wavelength-shifting (WLS) fibers (UV->blue)
- coupled to clear plastic fibers, routed to readout:
- 12 Hamamatsu 64-anode PMTs
- custom-built readout system

**Goal**
- Beam induced neutron background measurement
- Measure energy spectrum of the neutrons
- cosmic-induced fast neutron flux measurement

![Simulation Graph](image)
• Pre-beam, in-beam, off-beam backgrounds measurements

• Data taking: Feb~Apr 2012

• Neutron flux and spectrum measurement (preliminary) \( \Phi_n = \sim 1 \text{ n/pulse/m}^2 \)
Beam Background Simulation

- **Beam Dump**
- **Virtual Detectors**
- **Concrete Shielding**
- **Iron Shielding**
- **Decay pipe**
- **Proton Beam**
- **Water**

**Neutron energy spectrum from MC at MI-12 basement (Preliminary)**

**Fast Neutrons**
- at least ~10m of shielding needed
- often counterintuitive
- need for different layers
  (steel, concrete, water, poly ...)

**Experiment doesn’t have to be zero BG**
- trade offs between neutrino flux, background rate and live time

These fast neutrons are notorious ones
Low Energy Threshold LAr Detector Development

1-kg detector 2012
- Operational experience
- Measure scintillation light efficiency of nuclear recoils in LAr

10-kg detector 2013
- Study beam induced neutron shielding near the beam target
- Characterize the BNB neutron backgrounds in LAr target
- Understand design issues of the ton-scale detector

Ton-scale detector for the CENNS experiment
1-kg LAr Detector

1-kg LAr prototype detector

- SCENE Collaboration: (CENNS+DarkSide) SCintillation Efficiency of Noble Elements
- Goals:
  - Measure scintillation light yield in low-energy (<50 keV) nuclear recoils
  - Can run in single-phase mode or dual phase TPC mode
  - Use pulsed neutron beam at University of Notre Dame
Detector performance is good enough to carry out in-beam measurement.

Date taking at the end of 2012 and early 2013.
1-kg Detector in Neutron Beam

Van de Graaff (Notre Dame)

LAr detector

electrons

turbo

cryocooler

DAQ

8 ft

5 ft

Neutron Beam Data (before cut)

Preliminary

Neutron Beam Data (after cut)

Preliminary

Yoo
10-kg Detector

10-kg prototype detector

- Goals:
  - Neutron background study at BNB area
  - Demonstrate detector capability

- Existing cryostat and gas handling system from 1-kg prototype

- Parts are ordered and/or purchased

- Initial phase will use two R5912-02MOD 8” PMTs (Hamamatsu)

- To be ready in early 2013
Neutron Shielding Test Option

- Not very difficult to make pits: Fermilab FESS
- Safety, environmental issue need to be understood
- Test can start May 2013 -- earliest scenario
Fermilab is welcoming neutrino projects
In case of full power operation of BNB, the neutrino flux can be almost half of the SNS neutrino flux at the practical location of the detector (BNB:20m vs. SNS:60m)
This program is ‘coherent’ with the Project-X campaign
Future of FOX neutrinos?

Short Baseline Neutrinos at Project X

Exploring 3 GeV and 8 GeV programs
This workshop

- 8GeV, 0.3MW pulsed beam will provide intensive high energy (∼GeV) neutrinos at on-axis. Low energy scattering of ∼GeV on-axis neutrinos is very interesting. (study DM backgrounds)

- The same beam will provide very precious byproduct - low energy neutrinos with 4π coverage.

- Characterizing these neutrino sources will be extremely useful for the future short baseline experiments.
## Project-X Stages

### Project X Campaign

<table>
<thead>
<tr>
<th>Program:</th>
<th>Onset of NOvA operations in 2013</th>
<th>Stage-1: 1 GeV CW Linac driving Booster &amp; Muon, n/edm programs</th>
<th>Stage-2: Upgrade to 3 GeV CW Linac</th>
<th>Stage-3: Project X RDR</th>
<th>Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW</th>
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</thead>
<tbody>
<tr>
<td>MI neutrinos</td>
<td>470-700 kW**</td>
<td>515-1200 kW**</td>
<td>1200 kW</td>
<td>2450 kW</td>
<td>2450-4000 kW</td>
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<td>8 GeV Neutrinos</td>
<td>15 kW +0-50kW**</td>
<td>0-42 kW* + 0-90 kW**</td>
<td>0-84 kW*</td>
<td>0-172 kW*</td>
<td>3000 kW</td>
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<td>8 GeV Muon program e.g. (g-2), Mu2e-1</td>
<td>20 kW</td>
<td>0-20 kW*</td>
<td>0-20 kW*</td>
<td>0-172 kW*</td>
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<td>1-3 GeV Muon program, e.g. Mu2e-2</td>
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<td>80 kW</td>
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<td>Kaon Program</td>
<td>0-30 kW** (&lt;30% df from MI)</td>
<td>0-75 kW** (&lt;45% df from MI)</td>
<td>1100 kW</td>
<td>1870 kW</td>
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<td>8</td>
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<tr>
<td>Total max power</td>
<td>735 kW</td>
<td>2222 kW</td>
<td>4284 kW</td>
<td>6492 kW</td>
<td>11870 kW</td>
</tr>
</tbody>
</table>

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.
Road Map to LowE-ν Intensity Frontier

Far-off-axis BNB neutrino source is an extremely valuable resource to study beam background and neutrino flux

**BNB Era**
- Understand beam-induced neutron background at the BNB target area and establish shielding methods (~2013)
- Propose CENNS experiment to Fermilab Physics Advisory Committee (~2014)
- CENNS experiment (2017~2018)
- OscBNB experiment at Fermilab? (2018~)
  - One can imagine putting a full absorption target
  - Target is cheaper if it is not a spallation source

**Project-X Era**
- Neutrino flux and beam background study at BNB will be an important input to design the Project-X target
- BNB target station (MI-12) and detector infrastructure would still be very useful to test different target material
- The Project X stage-1 siting plan includes the option for a compressor ring which could drive a high power target for low energy neutrino experiments.
- A chance to design a detector close to source (4π coverage detector facilities?)
• A lot of interesting physics cases in low energy neutrino interactions
  More details: https://indico.fnal.gov/conferenceDisplay.py?confId=5926

• Coherent scattering of neutrinos is a good first experiment
  which can test the total neutrino flux from the neutrino source
  - Largest interaction cross section (small detector volume)

• Fermilab has a ‘well-defined’ low-energy neutrino source: BNB
  - It is a very valuable asset by two practical reasons
    1. New physics in low energy neutrino study
    2. Beam and target parameter input study for Project-X program

• CENNS Collaboration
  Fermilab, Duke University, Indiana University, University of Florida, North Carolina State University, University of Houston, UCLA, LANL, INFN (Italy)