Studying Reactor CEvNS with the Scintillating Bubble Chamber (SBC) Experiment

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Overview

1. Concept
2. Experiment Design
3. Physics Program
4. Reactor Neutrinos Feasibility
5. Conclusions
1. Concept
Bubble Chamber Technique

Bring liquid into superheated state by slowly decompressing.

Energy deposition from particles interacting in the fluid can lead to nucleation.
(need sufficient localized heat)

Tunable energy threshold, via pressure control.
Energy Loss in Liquid Nobles

Energy Deposition In Liquid Noble Gas

- Ionization
  - Escape
  - Recombination
- Excitation
  - De-excitation
  - Penning Quenching
- Atomic Motion
- Scintillation
- Heat
  - Heat Transfer
Scintillating Bubble Chamber

30g of LXe, 30% Overall Light Collection Efficiency
Energy Threshold In LAr

- ER’s can lose \( \sim 10\% \) energy to heat. Consistent with historic results from LAr bubble chamber, with tracks at \( O(10) \) eV in threshold.

- Thermal Fluctuations must be considered at \( O(10) \) eV in threshold.

- Target threshold of 100 eV (LAr) with controlled background levels
2. Experiment Design
SBC Experiment Design

O(10 kg) LAr contained within two fused silica jars, inner and outer jars.
SBC Experiment Design

Hydraulic Piston Controls The Inner Jar Position
Compressing/Decompressing The Target Fluid
SBC Experiment Design

Liquid CF4 Cryogenic Hydraulic Fluid. Contained Within a Stainless-Steel Pressure Vessel
SBC Experiment Design

The Full Inner Assembly Is Placed Inside a Stainless-Steel Vacuum Jacket Vessel
Readout Systems

Three Raspberry-Pi Controlled Camera System,
With Three LED Rings To Provide Illumination.
Readout Systems

32 Hamamatsu VUV4 Quads To Measure Scintillation Light In The Target Fluid.
Readout Systems

Eight Piezo Acoustic Sensors To Monitor The Nucleation Process
3. Physics Program
Dark Matter & Reactor CEvNS

Perform competitive **Low-Mass WIMP** search
(0.7-7 GeV/c²)

Precision study of **reactor CEvNS** interactions for
Argon and Xenon

DOI: https://doi.org/10.22323/1.390.0632
Dark Matter & Reactor CEvNS

SBC-Fermilab - Phase 1

Build and commission the first detector at Fermilab.
Dark Matter & Reactor CEvNS

SBC-Fermilab - Phase 1
Build and commission the first detector at Fermilab.

SBC-SNOLAB - Phase 2
Build and install a second detector at SNOLAB for low-mass dark matter searches.
Dark Matter & Reactor CEvNS

SBC-Fermilab - Phase 1
Build and commission the first detector at Fermilab.

SBC-SNOLAB - Phase 2
Build and install a second detector at SNOLAB for low-mass dark matter searches.

SBC-CEvNS - Phase 3
Upgrade and install detector from (1) at a reactor site for CEvNS studies.
4. Reactor Neutrinos Feasibility
## Considered Setups

<table>
<thead>
<tr>
<th>Setup</th>
<th>LAr Mass [kg]</th>
<th>Power [MW_{th}]</th>
<th>Distance [m]</th>
<th>Anti-v Flux Uncertainty [%]</th>
<th>Threshold Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>2.4</td>
<td>5.0</td>
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<tr>
<td>B</td>
<td>100</td>
<td>2000</td>
<td>30</td>
<td>2.4</td>
<td>5.0</td>
</tr>
<tr>
<td>B(1.5)</td>
<td>100</td>
<td>2000</td>
<td>30</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\[\text{~8 CEvNS/day (100 eV Threshold)}\]

\[\text{~1570 CEvNS/day (100 eV Threshold)}\]

\[\text{Phys. Rev. D 103, L091301}\]
## Considered Setups

**Setup A:**

~8 CEvNS/day @ 100 eV Threshold  
0.25 events/day – reactor backgrounds  
0.85 events/day – cosmogenic backgrounds  
Shielding – 0.3m Pb, 0.25m H\textsubscript{2}O, 0.5m Polyethene, 0.2m Pb

**Results B:**

~1570 CEvNS/day 100 eV Threshold  
negligible – reactor backgrounds (30m + shielding)  
180 events/day – cosmogenic backgrounds  
Shielding – 3m H\textsubscript{2}O, 0.5m Polyethene

(Reactor Neutrons, \(\gamma\)-n Interactions, \(\gamma\)-n Elastic Thomason Scattering, Cosmogenic Neutrons, \(\gamma\)/\(\beta\) interactions negligible)
CEvNS Physics Reach

Weak-Mixing Angle

\[
\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left( 2 - \frac{M_N T}{E_\nu^2} \right) F^2(q^2),
\]
CEvNS Physics Reach

Weak-Mixing Angle

![Graph showing weak-mixing angle](image1)

\[ \frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left( 2 - \frac{M_N^2}{E^2}\right) F^2(q^2), \]

Dark Mediator Z'

![Graph showing dark mediator Z'](image2)

\[ \mathcal{L}_{\text{eff}} = -\frac{g^2 Q_i Q_q}{q^2 + M_{Z'}^2} \left[ \sum_{\alpha} \bar{p}_\alpha \gamma^\mu P_L \nu_\alpha \right] \left[ \sum_q \bar{q}_\alpha \gamma_\mu q_\alpha \right], \]
CEvNS Physics Reach

Weak-Mixing Angle

\[ \frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_W^2 \left( 2 - \frac{M_N T}{E_\nu^2} \right) F^2(q^2), \]

Dark Mediator \( Z' \)

\[ \mathcal{L}_{\text{eff}} = -\frac{g^2 Q_q Q_u}{q^2 + M_{Z'}^2} \sum_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha \left[ \sum_q \bar{\nu}_q \nu_q \right], \]

Neutrino Magnetic Moment

\[ \frac{d\sigma}{dT} = \frac{\alpha_{\text{EM}}^2 Z^2 \mu_{\nu}^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2), \]
5. Conclusions
Conclusions

• Introduced scintillating bubble chambers technique, with good potential for low threshold \([O(100 \text{ eV})]\) and optimal ER rejection power \([<10^6]\).

• Discuss the SBC design and scientific program with two detectors optimized, respectively, for Dark Matter (SBC-SNOLAB) and neutrino (SBC-CEvNS) studies (SBC-CEvNS).

• Presented the CEvNS feasibility studies, for different reactor configurations, for the weak-mixing angle, dark mediator \(Z’\) and the neutrino magnetic moment.

• Vibrant group, always looking for collaborators.
Thank You, Merci

@SNOLABscience
Backup Slides
HV System
SiPM Testing @ Queen’s U
Xe-doping in LAr
Xe Bubble Chamber at NU

Demonstrated
- Liquid Xenon Bubble Chamber at 900 eV $E_{th}$
- Target Mass = 30 grams
- 0.3% Overall Photon Collection Efficiency

Next Program
- Liquid Argon Bubble Chamber at 40 eV $E_{th}$
- Target Mass = 10 kg
- ER Background of 1 Bubble / Ton-Year
- 2% Overall Photon Collection Efficiency (1-photon ~ 5 keVr)
**Bubble Chamber Physics**

- **Critical Radius:**
  Smallest vapor bubble that will spontaneously grow in a superheated liquid.

- **Seitz Threshold:**
  Minimum amount of energy required to create a vapor bubble with a critical radius.

- **NR/ER Response:**
  NR leads to Nucleation, can ER also induce Nucleation?

\[
E_T = 4\pi r_c^2 \left[ \sigma - T \left( \frac{\partial \sigma}{\partial T} \right)_\mu \right] + \frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l) - \frac{4\pi}{3} r_c^3 (P_b - P_l)
\]

- \(r_c = 23.7\) nm
- \(P_b = 6.2\) bara
- \(P_f = 2.1\) bara, \(T_f = 14^\circ\)C
- \(P_\sigma = 2\sigma/r\)
- \(C_3F_8\)

\[
1.53\ \text{keV} \\
1.81\ \text{keV} \\
-0.15\ \text{keV}
\]