Detecting reactor antineutrinos with a LAr scintillating bubble chamber

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Detecting reactor antineutrinos with a LAr scintillating bubble chamber

Outline:
- CEvNS at nuclear reactors
- LAr Scintillating Bubble Chamber
- Physics reach
- Final Remarks
Coherent Elastic Neutrino-Nucleus Scattering

\[ E_\nu \leq 50 \text{ MeV} \]

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

Maximum NR energy: \( T_{\text{max}} = \frac{2E_\nu^2}{M_N} \)

COHERENT Collaboration, Science 357,1123 (2017)
Coherent Elastic Neutrino-Nucleus Scattering

\[ E_\nu \leq 50 \text{ MeV} \]

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

Ingredients for CEvNS:
- Intense neutrino flux
- Low-threshold detectors
- Great background discrimination

Maximum NR energy: \[ T_{\text{max}} = \frac{2E_\nu^2}{M_N} \]
Two measurements by COHERENT SNS

~134 events

~159 events

CEvNS with nuclear reactors?

✓ Intense antineutrino flux
✓ Completely coherent scattering \( (E_\nu \leq 10\ \text{MeV}) \)
✓ Only \( \bar{\nu}_e \)
✓ Different channel than SNS: \( \pi^+ \rightarrow \mu^+ + \nu_\mu \)

\[ e^+ + \nu_e + \bar{\nu}_\mu \]
CEvNS with nuclear reactors?

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✓ Completely coherent scattering ($E_{\nu} \leq 10$ MeV)
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\[
e^+ + \nu_e + \bar{\nu}_\mu
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nuclear Reactor</th>
<th>Power [GW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEXONO [41]</td>
<td>Kuo-Sheng Nuclear Power Station</td>
<td>2.9</td>
</tr>
<tr>
<td>CONUS [37]</td>
<td>Brokdorf</td>
<td>3.9</td>
</tr>
<tr>
<td>$\nu$GeN [72]</td>
<td>Kalinin Nuclear Power Plant</td>
<td>$\sim$ 1</td>
</tr>
<tr>
<td>MINER [36]</td>
<td>TRIGA 1</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$\nu$CLEUS [38]</td>
<td>FRM2</td>
<td>4</td>
</tr>
<tr>
<td>Ricochet [39]</td>
<td>Chooz Nuclear Power Plant</td>
<td>8.54</td>
</tr>
<tr>
<td>RED-100 [40]</td>
<td>Kalinin Nuclear Power Plant</td>
<td>$\sim$ 1</td>
</tr>
<tr>
<td>SBC [73]</td>
<td>ININ (or Laguna Verde)</td>
<td>$10^{-3}$ (2)</td>
</tr>
<tr>
<td>CONNIE [74]</td>
<td>Angra 2</td>
<td>3.8</td>
</tr>
<tr>
<td>vIOLETA [75]</td>
<td>Atucha II</td>
<td>2</td>
</tr>
<tr>
<td>SoLid [76]</td>
<td>BR2</td>
<td>$(0.4, 1) \times 10^{-1}$</td>
</tr>
<tr>
<td>NEON [77]</td>
<td>Hanbit Nuclear Power Plant</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Taken from D. Aristizabal-Sierra, V. De Romeri, LJF, D.K. Papoulias, JHEP 03 (2021) 294
LAr scintillating bubble chamber

Combines features of scintillation detectors and bubble chambers

❖ Insensitive to electron recoils
❖ Sub-keV thresholds (~100 eV)
❖ Single bubble created from nuclear recoils
❖ Energy resolution for backgrounds above ~5 keV

Proposed reactor locations

- Laguna Verde Nuclear Power Plant
Proposed reactor locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Power</th>
<th>Baseline</th>
<th>Target mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laguna Verde</td>
<td>1 MWth</td>
<td>3 - 10 m</td>
<td>10 kg</td>
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<tr>
<td>Power Baseline</td>
<td>2 GWth</td>
<td>30 m</td>
<td>100 kg</td>
</tr>
</tbody>
</table>
Experimental setups

Water pool
1.6 m
Reactor core

Borated concrete

Experimental hall

Pb (30 cm)
Water (25 cm)

Pb (20 cm)

HDPE Base

3 m

HDPE 50 cm

SBC

Water 3 m

HDPE Base

Laguna Verde Nuclear Power Plant
Expected detection rates
Expected detection rates

~8 events/day

~1570 events/day
Physics reach

Statistical analysis:

\[ \chi^2 = \min_{\alpha, \beta, \gamma} \left[ \left( \frac{N_{\text{meas}} - (1 + \alpha)N_{\text{th}}(X, \gamma) - (1 + \beta)B_{\text{reac}}}{\sigma_{\text{stat}}} \right)^2 + \left( \frac{\alpha}{\sigma_{\alpha}} \right)^2 + \left( \frac{\beta}{\sigma_{\beta}} \right)^2 + \left( \frac{\gamma}{\sigma_{\gamma}} \right)^2 \right] \]

\[ \sigma_{\text{stat}} = \sqrt{N_{\text{meas}} + (1 + R)B_{\text{cosm}}} \]
Physics reach

\[ \chi^2 = \min_{\alpha, \beta, \gamma} \left( N_{\text{meas}} - (1 + \alpha)N_{\text{th}}(X, \gamma) - (1 + \beta)B_{\text{reac}} \right)^2 \left( \frac{\sigma_{\text{stat}}}{\sigma_{\alpha}} \right)^2 \left( \frac{\beta}{\sigma_{\beta}} \right)^2 \left( \frac{\gamma}{\sigma_{\gamma}} \right)^2 \]

\[ \sigma_{\text{stat}} = \sqrt{N_{\text{meas}} + (1 + R)B_{\cosm}} \]

Fitted variable

Nuisance parameters

- \( \alpha \): flux
- \( \beta \): background
- \( \gamma \): threshold

<table>
<thead>
<tr>
<th>Setup</th>
<th>LAr mass (kg)</th>
<th>Power (MW\text{th})</th>
<th>Distance (m)</th>
<th>Anti-( \nu ) flux uncertainty (%)</th>
<th>Threshold uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ININ</td>
<td>A</td>
<td>10</td>
<td>3</td>
<td>2.4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>100</td>
<td>30</td>
<td>2.4</td>
<td>5</td>
</tr>
<tr>
<td>Laguna Verde</td>
<td>B(1.5)</td>
<td>100</td>
<td>30</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Laguna Verde (best-case scenario)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Physics reach: weak mixing angle

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

\[ Q_w = Z(1/2 - 2\sin^2 \theta_W) + N(-1/2) \]
Physics reach: neutrino magnetic moment

\[
\left( \frac{d\sigma}{dT} \right)_{\text{SM}} + \left( \frac{d\sigma}{dT} \right)_{\mu_e}
\]

\[
\left( \frac{d\sigma}{dT} \right)_{\mu_e} = \pi \frac{\alpha_{\text{EM}} Z^2 \mu_e^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2)
\]
Physics reach: $Z'$ boson

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

\[
Q_w = Z(g_p^V + 2\epsilon_{\alpha\alpha}^u + \epsilon_{\alpha\alpha}^d) + N(g_n^V + \epsilon_{\alpha\alpha}^u + 2\epsilon_{\alpha\alpha}^d)
\]

\[
\epsilon_{\alpha\alpha}^{qV} = \frac{g' x_{\alpha\alpha} x_q}{\sqrt{2} G_F (q^2 + M_{Z'}^2)}
\]
Physics reach: $Z'$ boson as DM mediator

Vector-like fermion $\chi$
Resonance condition: $M_\chi \sim M_{Z'}/2$

Direct translation between planes

$M_{Z'} - g' \leftrightarrow M_\chi - \sigma_{SI}$
Physics reach: Generalized Neutrino Interactions

See talk by Newton Nath
On Thursday
Final Remarks

LAr Scintillating Bubble Chamber offers:

❖ High chance of detecting reactor CEvNS
❖ Opportunity for precision low-energy measurements
❖ More stringent limit to new physics signals, compared with other CEvNS experiments
Thank you for your attention!
In this study, $g_u = g_d = g_x = g'/3$, hence $f_p = f_n \approx \frac{g'^2}{3M_{Z'}^2}$. Therefore, the spin-independent cross-section reduces to

$$\sigma_{SI} \approx \frac{\mu_{\chi n}^2}{\pi} \frac{g'^4}{9M_{Z'}^2}. \quad (11)$$
Bubble chambers

- Superheated fluid
- Energy deposition causes local boiling
  
  Bubble nucleation

- Events detected by cameras, piezo-acoustic sensors, and SiPMs