Scintillating Bubble Chambers for Reactor CEvNS

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The Magnificent CEvNS, Nov 2018
The Reactor CEvNS Detector Conundrum

- Low Background
  - Continuous beam, cannot use duty cycle to eliminate backgrounds
  - On–Off subtraction not trivial
  - **Ideal**: Event-by-event discrimination ala WIMP searches
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Low Threshold
- $\nu$'s < 10 MeV
  $\rightarrow$ recoils < ~1 keV
Low Background
- Continuous beam, cannot use duty cycle to eliminate backgrounds
- On - Off subtraction not trivial
- Ideal: Event-by-event discrimination ala WIMP searches

Low Threshold
- $\nu'$s $< 10$ MeV
  $\rightarrow$ recoils $< \sim 1$ keV

Scalable
- High stats for high precision
2.1 Bubble Chamber Overview

The PICO Collaboration, product of the recent merger between COUPP and PICASSO, uses superheated fluids to search for WIMP dark matter. The baseline PICO detector is a bubble chamber filled with a target liquid (C$_3$F$_8$ or CF$_3$I) and run in a moderately superheated state where it is sensitive to the low energy nuclear recoils from WIMP scatters but completely insensitive to recoiling electrons and minimum ionizing particles, eliminating the gamma and beta backgrounds that plague most dark matter direct detection experiments. A WIMP scatter creating a nuclear recoil over the energy threshold set by the temperature and pressure of the chamber creates a single macroscopic bubble.

Figure 2 shows a schematic of the typical COUPP or PICO bubble chamber. The superheated fluid is contained in a synthetic silica bell jar. This jar plus the attached bellows assembly form a clean, sealed inner volume, with a buffer fluid (typically water) filling the space above the superheated target. The inner vessel is immersed in a pressure vessel filled with hydraulic fluid. The bellows on the inner vessel serve to balance the pressure between the inner vessel fluids and the hydraulic fluid, preventing any differential pressure from building across the wall of the silica vessel.

Cameras mounted outside the pressure vessel continuously capture stereo images of the target fluid, providing both the primary trigger on bubble nucleation and the 3-D position of the event. On this trigger acoustic transducers record the ultrasonic emission from the bubble formation, and the chamber rapidly recompresses to a non-superheated state, re-condensing the bubble vapor. Following a ~30 second settling time the chamber re-expands to the superheated state, arming for the next event. Despite this reset period, the currently operating COUPP-60 experiment is live >85% of the time when taking physics data.

Although beta-decays and gamma-interactions will not nucleate bubbles in the superheated fluid, an alpha-decay in the fluid will create a single bubble. This bubble, however, has ~4x greater acoustic emission than a bubble nucleated by a nuclear recoil (see Fig. 3). This effect was first seen by the PICASSO Collaboration in superheated droplets [23], and has since been confirmed in COUPP bubble chambers [24][8]. The discovery of acoustic alpha discrimination has transformed the bubble chamber into a potentially background-free technology for dark matter detection.
• Superheated Target
  – CF$_3$I, C$_3$F$_8$, ...

• Particle interactions nucleate bubbles

• Cameras and acoustic sensors capture bubbles

• Chamber recompresses after each event
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Bubble Chamber Thermodynamics

• What is a metastable state?
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Superheated Liquid
Bubble Chamber Thermodynamics

• What is a metastable state?

![Diagram showing Gibbs potential vs density and pressure vs temperature with labels for Particle Interaction and Superheated Liquid.](Diagram)
Bubble Chamber Thermodynamics

• What does it take to nucleate a bubble?

\[ P_i = 2.1 \text{ bara}, \quad T_i = 14^\circ\text{C} \]

\[ P_b = 6.2 \text{ bara} \]

\[ P_\sigma = 2\sigma/r \]

\[ C_3F_8 \]
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$r_c = 23.7\text{ nm}$

$C_3F_8$

“Critical Radius”
Bubble Chamber Thermodynamics

- What does it take to nucleate a bubble?

\[ E_T = 4\pi r_c^2 \left( \sigma - T \left( \frac{\partial \sigma}{\partial T} \right)_\mu \right) \]

\[ + \frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l) \]

\[ - \frac{4\pi}{3} r_c^3 (P_b - P_l) \]

= 3.19 keV “Thermodynamic Threshold”

\[ P_l = 2.1 \text{ bara, } T_l = 14^\circ\text{C} \]

\[ P_b = 6.2 \text{ bara} \]

\[ r_c = 23.7 \text{ nm} \]

\[ C_3F_8 \]

1.53 keV

1.81 keV

-0.15 keV

“Critical Radius”
Electron Recoil Discrimination

• Extreme discrimination against $\beta$, $\gamma$ backgrounds

• $\beta$, $\gamma$ sensitivity sets threshold for NR detection

(Dan Baxter, Conference on Science at SURF, May 14, 2017)
Nuclear Recoil Response

Multiple neutron sources used to constrain recoil detection efficiency

Calculated thermodynamic threshold

Calibrated fluorine recoil detection efficiency
• Superheated Target
  – $\text{CF}_3\text{I}$, $\text{C}_3\text{F}_8$, ...

• Particle interactions nucleate bubbles

• Cameras and acoustic sensors capture bubbles

• Chamber recompresses after each event
Scintillating Bubble Chambers

- Superheated Scintillator
  - Xe, Ar, C$_6$F$_6$, ...

- Particle interactions nucleate bubbles and produce scintillation

- Cameras and acoustic sensors capture bubbles and photo-detectors collect scintillation light

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NU Xenon Bubble Chamber

- 30-gram xenon target
- 25-psi, $-38^\circ C$
  \( E_T = 0.5 \text{ keV} \)
- Single fluid (no buffer)
- IR illumination for cameras
- IR-blind PMT (R6834) for 175nm scintillation
Nuclear Recoil Event

[Graph showing various measurements such as Xenon pressure, LED Gate Image, Acoustic amplitude, log_{10}[PMT pulse area (au)], PMT amp, and Δt (speed of sound)]

PRL 118, 231301 (2017)
Electron Recoil Discrimination

- Xenon predicted to have slightly worse ER discrimination than CF$_3$I
  - no good for CEvNS…
Electron Recoil Discrimination

• Xenon measured to have phenomenal ER discrimination!
  – No observation so far of bubbles nucleated by gamma-rays
  – Explored thresholds down to 900 eV
NR Threshold vs Thermodynamic Threshold

- $^{88}$Y-Be($\gamma$,n): 152 keV neutrons
  - Max 4.7 keV xenon recoil
  - Bubble nucleation by $E_T = 2$ keV

- $^{207}$Bi-Be($\gamma$,n): 94 keV neutrons
  - Max 2.9 keV xenon recoil
  - Bubble nucleation by $E_T = 1$ keV
Electron Recoil Discrimination

- Liquid nobles fundamentally different than molecular fluids!
  - No molecular bonds -> no efficient way to locally turn ER energy into heat
Scintillating Argon Bubble Chamber

- 10-kg Argon target
- Designed to reach $E_T = 40$ eV
  - 1 spontaneous bubble / ton-year
- Collaboration of 7 Institutions in US, Canada, Mexico
Scintillating Argon Bubble Chamber

- Critical parts arriving now
- Construction at FNAL in 2019
- Commissioning and *Calibration* in 2020
Physics with an Argon Bubble Chamber

- WIMP searches to solar $\nu$-floor (1 – 7 GeV)
- $O(10)$ CEvNS events / kg-day @ reactor

Follows Calibration @ FNAL
## Potential SBC Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold (Bubble Nucleation)</td>
<td>100 eV$_r$ (Argon recoil energy)</td>
</tr>
<tr>
<td>Resolution (Bubble Nucleation)</td>
<td>$\sim$100 eV$_r$ (spectrum built by threshold scan)</td>
</tr>
<tr>
<td>“Quenching” (Bubble Nucleation)</td>
<td>$1 - \text{Lindhard} \approx 0.8$</td>
</tr>
<tr>
<td>Threshold (Scintillation*)</td>
<td>5 keV$_r$ (single photon detected)</td>
</tr>
<tr>
<td>Resolution (Scintillation*)</td>
<td>Poisson on # photons detected</td>
</tr>
<tr>
<td>Quenching (Scintillation*)</td>
<td>Lindhard $\approx 0.2$</td>
</tr>
<tr>
<td>Target Mass</td>
<td>10-kg being built now, scalable to 1-ton before $^{39}$Ar becomes concern</td>
</tr>
<tr>
<td>Background concerns</td>
<td>Neutrons only (and no Pb shield -&gt; no NIN’s)</td>
</tr>
<tr>
<td>Other unique features</td>
<td>Event-by-event tagging of inelastic recoils</td>
</tr>
</tbody>
</table>

*Scintillation used primarily as veto and for sideband studies-Most reactor CEvNS events will have zero scintillation signal*
Summary

- Liquid Noble Bubble Chambers
  - Unique potential for background-free reactor CEvNS measurements
  - Stay tuned as story unfolds...

**Funding acknowledgements:**
- Fermilab LDRD 2018-003
- DOE Award DE-SC0012161
Why Liquid-noble Bubble Chambers

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Figure 2: (Left) Schematic of a typical COUPP or PICO bubble chamber showing the target fluid (C\(_3\)F\(_8\) or CF\(_3\)I), buffer fluid (water) and hydraulic fluid volumes. (Right) Stereo images taken from the COUPP–60 data, showing the 18-liter CF\(_3\)I target and a neutron-induced 5-bubble event from an AmBe calibration source.

Event-by-event Energy

10\(^{-10}\) discrimination

Low-threshold (< keV) ER discrimination

Magnificent CEvNS Dahl, 11/3/2018
Scintillating Bubble Chamber History
(Why they might not work...)

- Glaser built a xenon bubble chamber in 1956 and found:
  - **No bubbles** in pure xenon even at \(~1\) keV threshold (with gamma source)
  - Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)

Scintillating Bubble Chamber History (...or why they might work *really* well)

- Scintillation suppresses bubble nucleation?
  - **Electrons** should be even less likely to make bubbles than in freon chambers
  - Greater superheat (lower thresholds) possible

- **Nuclear Recoils should be largely unaffected**, thanks to Lindhard Effect

Acoustic – Scintillation Coincidence

- < 1% accidental coincidence rate in calibration data
- Slope = speed of sound in xenon (to 20%)

\[ \Delta t = 16 \mu s + (z \times 2.4 \mu s/mm) \pm 25 \mu s \]
Scintillation Spectra

- Scintillation unaffected by superheated state
PICO: Dan Baxter (GS), Miaotianzi Jin (GS)

LZ: Dylan Temples (GS)

Scintillating Bubble Chamber: Jianjie Zhang (PD), Jon Chen (UG), Trent Cwiok (UG), Jared Gupta (UG), Ricky Puig (UG), Allison Grimsted (HS), John Gresl (MS), Theo Baker (UG).

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Key Pubs:
— PRL 118, 251301 (2017), arXiv:1702.07666 (PICO-60)
— PRL 118, 231301 (2017), arXiv:1702.08861 (XeBC)