Liquid-Noble Bubble Chambers

Prospects for neutrino and WIMP detection

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COFI seminar

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Outline

• Motivation: GeV WIMPs and reactor neutrinos

• The scintillating bubble chamber technique
  – On Paper
  – In Practice

• First Results from a 30-gram xenon prototype
  arXiv:1702.08861 [PRL 118, 231301]

• Lowering thresholds – current status
What could you do with a liquid-noble bubble chamber?

• Discriminating
  – Only sensitive to nuclear recoils (neutrons, neutrinos, and WIMPs)

• Scalable
  – Largest bubble chamber to date: 35 m$^3$ (BEBC)
  – Ton-scale low-background bubble chamber in works (PICO)

• Low threshold?
  – Sub-keV recoil energy threshold is moving from “plausible” to “realistic”
What could you do with an argon bubble chamber?

1 ton-year at 1-keVr threshold
(76 $^8$B neutrino events expected)

(DRAFT of upcoming Cosmic Visions white paper)

Up to an event-per-minute in a m$^3$ target,
Only background is neutrons
Bubble Chambers

- 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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  – CF$_3$I, C$_3$F$_8$, ...

• Particle interactions nucleate bubbles

• Cameras and acoustic sensors capture bubbles

• Chamber recompresses after each event
Scintillating Bubble Chambers

- Superheated Scintillator
  - Xe, Ar, C₆F₆, ...

- Particle interactions nucleate bubbles and produce scintillation

- Cameras and acoustic sensors capture bubbles and photodetectors collect scintillation light

- Chamber recompresses after each event
Bubble Chamber Thermodynamics

- What is a meta-stable state?

![Diagram showing superheated liquid and Gibbs potential vs. density, pressure vs. temperature graphs.]

Superheated Liquid
Bubble Chamber Thermodynamics

• Consider a bubble with
  – \( T_\ell = T_b \) (thermal equilibrium)
  – \( \mu_\ell = \mu_b \) (chemical equilibrium)

• Then \( P_b \) is (approx) the vapor pressure at temperature \( T \)

• \( P_b > P_\ell \), so bubble should grow... *until we consider surface tension*
Bubble Chamber Thermodynamics

• Inward pressure from surface tension!
  \[ P_s = \frac{2\sigma}{r} \]

• Bubble will grow if
  \[ P_b > P_l + P_s \]
  \[ r > r_c = \frac{2\sigma}{(P_b - P_l)} \]

• Bubbles with \( r < r_c \)
collapse and re-condense
Bubble Chamber Thermodynamics

• What does it take to produce critical bubble?

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

\[\text{1.53 keV} \quad \text{1.81 keV} \quad \text{-0.15 keV} \quad \text{= 3.19 keV total}\]

Surface energy, Bulk energy, Reversible Work

\[P_i = 30 \text{ psia}, \quad T_i = 14^\circ \text{C} \]

\[P_b = 89.7 \text{ psia} \quad r_c = 23.7 \text{ nm} \]

\[C_3F_8\]
Bubble Chamber Discrimination

Electron recoil sensitivity in C$_3$F$_8$ and CF$_3$I from various PICO calibration and dark-matter chambers
Nuclear Recoil Threshold

Neutron Calibrations in C\textsubscript{3}F\textsubscript{8} @ \( E_T = 3.2 \) keV

- Carbon Efficiency
- Fluorine Efficiency
- Seitz Threshold

- Observed Rate
- Simulated rate with best-fit efficiency

Systematic uncertainty on neutron flux
Bubble Chamber Backgrounds

- All bubbles look the same!
  - 1-mm diameter bubble has drawn 10 PeV from superheated fluid
  - Nuclear recoil visually indistinguishable from alpha-decay

- ~1-MeV energy resolution in acoustic channel

![Graph showing AP distributions and counts](image-url)

Counts

- 8, 10, 11 events originating within the optical fiducial volume for neutron recoils are expected, based on a measurement of 4 mCi of 222Rn, 218Po (5.5, 6.0 MeV) and 214Po (7.7 MeV).
- 222Rn, 218Po (5.5, 6.0 MeV) and 214Po (7.7 MeV) were observed, similar to Ref. 8.

**V. ANALYSIS**

A set of data quality cuts was applied to remove events from the two peaks at higher AP.

The observed rate of alpha decays is consistent with the theoretical uncertainty attributed to the 1-mm diameter bubble has drawn 10 PeV from superheated fluid.

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**VI. RESULTS**

To search for neutron-induced multiple-bubble events in the WIMP search data, all events for which more than one bubble is reconstructed in one or both of the camera images are removed. The acceptance for single nuclear-recoil events is determined to be 0.9(1.8) single(multiple)-bubble events.

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ALL of these are easily identifiable with scintillation signal

More information *always* key to background discrimination
Scintillating Bubble Chamber History

• Glaser built a xenon bubble chamber in 1956 and found:
  
  – **No bubbles** in pure xenon even at $\sim 1$ keV threshold (with gamma source)

  – Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)

  [Image of xenon bubble chamber]

  *This work was supported by the U.S. Atomic Energy Commission.*

  [Reference: Phys. Rev. 102, 586 (1956)]
Scintillating Bubble Chamber History

• 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

  **Experimental verification needed!**
NU Xenon Bubble Chamber Schematic
NU Xenon Bubble Chamber Model

• NU Prototype
  – 30-gram xenon target
  – No buffer fluid
  – 30-psia, –50°C superheated state
  – IR illumination for cameras
  – IR-blind PMT (R6834) for 175nm scintillation
NU Xenon Bubble Chamber

- First Bubbles June 2016
Sample Nuclear Recoil Event
NU Xenon Bubble Chamber v 2.0

-65 to -50 °C superheated

-105 °C normal

¼” Sapphire Window (Blackbody absorber)

Minimum $E_T$ decreased from 30 keV to 4 keV
Sample Nuclear Recoil Event

Xenon pressure (psia)

Time from DAQ trigger (s)

Acoustic amplitude (au)

Time from DAQ trigger (ms)

PMT amp (mV)

Time from PMT trigger (ns)

LED Gate

Image shown at left

\[ \log_{10} \text{[PMT pulse area (au)]} \]

\( \Delta t \)
Acoustic – Scintillation Coincidence

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

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

- $^{57}$Co calibration (122-keV photo-peak)
- No bubbles over background rate
- Same signal in normal and superheated states
- Poor resolution due to position dependence
- Average 1 phe per 25 keVr (0.4% photon detection efficiency)
• Without scintillation, xenon would be slightly worse than CF$_3$I.
Nuclear Recoil Efficiency

• Can determine nuclear recoil bubble nucleation threshold from bubble rate and multiplicity as before...
  – $^{252}$Cf not the best source for this
  – Not many multi-bubble events in small chamber

• 2 doubles, 160 singles at $E_T=8.2$ keV
  – Recoil energy threshold $19 \pm 6$ keV

• Check with scintillation channel!
Scintillation Spectrum for Bubble Events

$E_T = 8.2 \text{ – } 8.6 \text{ keV}$

$E_T = 8.6 \text{ – } 15 \text{ keV}$

No $E_T$ dependence observed in other bins

*Simulation assumes 15-keV threshold for bubble nucleation
NU Xenon Bubble Chamber v 3.0

Removed inner jar to eliminate narrow (.5mm) annular region

Minimum $E_T$ decreased from 4 keV to 0.8 keV (and still falling…)

-65°C to -50°C superheated

-65°C to -58°C

-105°C normal

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• Turns out Glaser wasn’t kidding about gammas not making bubbles in xenon...
Nuclear recoil sensitivity

• Threshold analysis ongoing at $E_T=1.0$ keV
  – Much larger $^{252}\text{Cf}$ exposure to work with
    • Determine threshold from bubble multiplicity
    • Position corrections for scintillation signal from 40-keV inelastic scatters -> higher resolution in scintillation channel
  – $^{207}\text{Bi}-^9\text{Be} (\gamma,n)$ source
    • 97 keV neutrons (max 3.0 keV recoil)
    • Source is weak, but may see rate over background (and over bare $^{207}\text{Bi}$ gamma source)
  – Will soon have higher-activity ($\gamma,n$) sources
  – Meanwhile, just began data taking at $E_T=0.8$ keV
Next Steps

• Low-threshold calibrations in xenon (summer/fall)
  – Easy reconfig to get to -40°C ($E_T=0.5$ keV)
  – New gamma-n sources coming
  – Lots of analysis, simulation work coming to nail down recoil threshold

• Switching to argon (fall/winter/spring)
  – New thermal control scheme (same cryostat)
  – Waveshifter deposition on jar (w/o obscuring images)

• R&D for larger detectors (anytime…)
  – Need pressure-resistant photo-detector system compatible with camera illumination and immersion in hydraulic fluid (e.g. CF$_4$)
    (SiPM’s very likely candidate…)
  – Site selection and background sims for future proposals
Our Group

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Summary

- Scintillating bubble chambers work!
  - Confirmed coincident scintillation and bubble nucleation by nuclear recoils
  - Electron discrimination *better* than in freons (still finding out how much better...)
  - Low-threshold performance looking very promising, stay tuned (or jump in!)
"Bright" event
(Muon track with nuclear recoil)

Event at 25.9 psia, –72.9°C
51.8 keV thermodynamic threshold

0.2 phe/keVee, from $^{57}$Co 122-keV gamma calibration
"Medium Bright" Event (alpha-decay candidate)

Event at 19.3 psia, −72.9°C
37.1 keV thermodynamic threshold

0.2 phe/keVee, from $^{57}$Co 122-keV gamma calibration
“Dim” Event (nuclear recoil)

Event at 30.8 psia, −72.9°C
68.2 keV thermodynamic threshold

0.2 phe/keVee, from $^{57}$Co 122-keV gamma calibration
• Without scintillation, we would expect poorer discrimination in xenon than CF$_3$I
Ongoing R&D

• Lower thresholds (higher superheat)
  – Look for gamma sensitivity
  – Precision nuclear recoil calibrations

• Alternate targets
  – Argon
    • Hydraulics -> pneumatics
    • Expect better gamma-discrimination than xenon
  – Organic scintillators
    • Superheated fluid -> supersaturated gas+liquid solution
    • Many light-nuclei available (C, F, H)