Snowmass2021 - Letter of Interest

Reaching the solar CEνNS floor with noble liquid bubble chambers

Thematic Areas: (check all that apply □/■)
■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Collaboration: Scintillating Bubble Chamber (SBC) Collaboration

Related Snowmass2021 LOIs:
Neutrino physics with noble liquid bubble chambers (NF3)
Enabling the next generation of bubble-chamber experiments for dark matter and neutrino physics (IF8)

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Abstract: Noble liquid bubble chambers are a promising candidate for a post-G2 dark matter search with sensitivity reaching the solar neutrino floor for dark matter particle masses as low as 700 MeV/c^2. Current technologies searching for GeV-scale dark matter suffer from low-energy electron-recoil (ER) backgrounds orders of magnitude higher than the ^{8}B neutrino coherent scattering (CEνNS) rate. The noble liquid bubble chamber eliminates these backgrounds by extending the field-leading ER rejection of freon bubble chambers to sub-keV thresholds, while also adding a scintillation channel to provide event-by-event energy information, eliminating higher energy backgrounds that freon bubble chambers are susceptible to. Construction of a 10-kg demonstrator that will validate the low-threshold capability of this technique is underway. Assuming the success of the 10-kg device, noble liquid bubble chambers will present a scalable, affordable, and background-free method to search for GeV-mass dark matter to the ^{8}B CEνNS floor.

I. MOTIVATION AND CHALLENGES FOR GEV-SCALE DIRECT DETECTION EXPERIMENTS

Thermal-relic dark matter particles in the 1–10 GeV mass range can be produced in supersymmetric extensions to the SM and hidden sector models that evade constraints from the LHC [1–4]. This mass range is particularly motivated for the case of Asymmetric Dark Matter (ADM) [5], where the matter-antimatter asymmetry observed in our universe is produced via interactions with the dark sector, naturally placing the dark matter particle mass near the proton mass. These models are difficult to probe by methods outside direct detection: ADM models produce no indirect detection signal, and beam dump experiments lose sensitivity above 1 GeV. Direct detection constraints, on the other hand, are currently $\sim$4 orders of magnitude above the coherent neutrino scattering (CEνNS) floor from ^{8}B solar neutrinos, and will still have more than an order of magnitude left to explore after the projected reach of the Generation-2 program.

Reaching the ^{8}B CEνNS floor at $\sim$1 GeV requires ton-year exposures and sensitivity to $\sim$100-eV nuclear recoils. Existing detectors explore this region by measuring ionization from these low energy recoils, amplified via gas gain [6], secondary scintillation [7, 8], and Luke-Neganov phonons [9], but all of these techniques are limited by electron recoil backgrounds orders of magnitude above the ^{8}B CEνNS rate [10, 11]. The background fighting tools that enable ton-scale heavy WIMP searches, namely electron/nuclear recoil discrimination and fiducialization in a monolithic target with robust 3-D position reconstruction, are unavailable at the low energies required for GeV-mass dark matter detection. **The noble liquid bubble chamber is the first technique with the potential to apply both of these background-fighting measures to a search for sub-keV nuclear recoils produced by GeV-mass dark matter.**

II. CURRENT STATUS OF THE NOBLE LIQUID BUBBLE CHAMBER TECHNIQUE

Like the freon bubble chambers employed by PICO [20], liquid noble bubble chambers operate by superheating the target fluid to a point where the localized energy deposition from a nuclear recoil creates a single bubble in the chamber, but the more diffuse energy depositions from electron recoils do not. Once created, bubbles grow to macroscopic sizes where standard machine vision techniques allow robust, mm-precision position reconstruction.

A noble liquid target brings two distinct advantages to a bubble chamber. First, particle interactions in the noble liquid generate scintillation light, which can be measured to provide an event-by-event energy scale absent in freon bubble chambers. Simultaneous bubble nucleation and scintillation by nuclear recoils has been demonstrated in a small (30-gram) xenon bubble chamber [21], and advances in both SiPM technology [22] and xenon doping [23] open

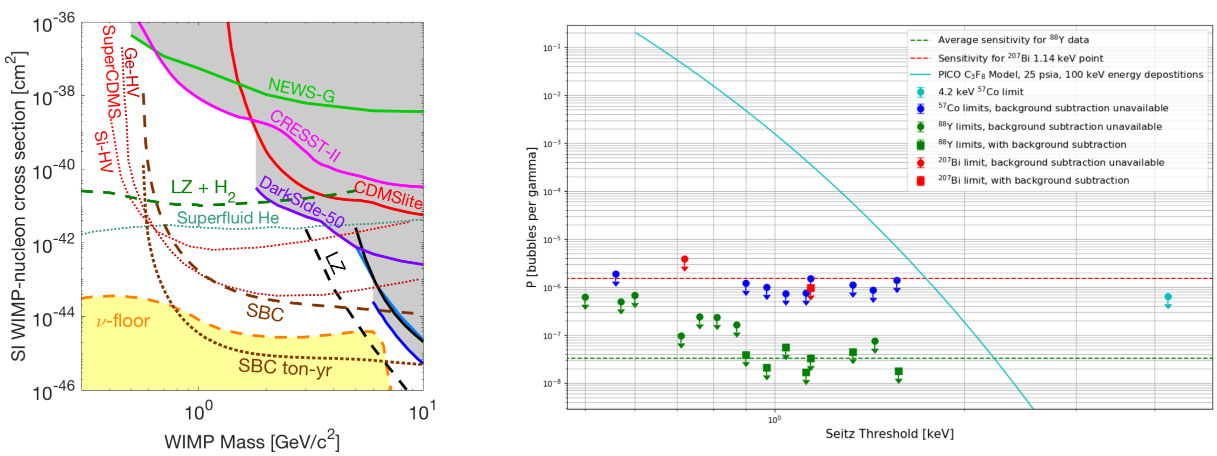

FIG. 1. *Left:* Projected 90% CL limits (in the absence of a dark matter signal) from 10 kg-yr and 1 ton-yr exposures in a liquid argon bubble chamber, assuming sensitivity to 100-eV argon recoils. The 10 kg-yr limit assumes an observed background of one event, without subtraction. The ton-yr limit assumes the CEνNS background only, with background subtraction. Projections for other ongoing/proposed experiments are taken from [11–14]. The gray region indicates parameter space excluded by existing direct detection limits [6, 8, 9, 15–18]. *Right:* Gamma discrimination at low threshold in the prototype xenon bubble chamber. The x-axis shows the thermodynamic threshold, calculated from the pressure and temperature of the xenon. The y-axis shows the average probability of bubble nucleation for electron recoils from external gamma sources. Square (circle) data points are 90% CL upper limits with (without) background subtraction – no background subtraction was attempted at the lowest thresholds. The cyan line shows the expected bubble rate based on electron recoil bubble nucleation thermodynamics in freon-based chambers [19].

the door to efficient scintillation collection in large argon bubble chambers as well. Scintillation yields of 1 photon detected per 5 keV nuclear recoil energy can be achieved with moderate SiPM coverage. In the context of a GeV-scale dark matter search, this scintillation is used as a veto for higher energy recoils generated by fast neutrons. The signal from the scatter of a GeV-mass dark matter particle is a single bubble with *no* coincident scintillation detected.

The second advantage of the noble liquid bubble chamber technique is the ability to remain blind to electron recoils at thresholds far below what is possible in freon bubble chambers — and below the discrimination threshold of any other dark matter detection technique as well. The xenon prototype has shown that superheated xenon remains blind to gamma rays down to thermodynamic thresholds of at least 500 eV (see Fig. 1), far below the onset of bubble nucleation by electron recoils in superheated freons [19]. The qualitative explanation for this difference is that, without molecular degrees of freedom to excite, energetic electrons are unable to directly create the local heat required to nucleate a bubble. Quantitatively, we estimate $\sim$90% of the energy lost by an electron recoil in liquid xenon is radiative (useless for bubble nucleation), with roughly half of that loss appearing as scintillation light. The recombination/scintillation process in argon is less well understood, but similar behavior is expected.

A 10-kg liquid argon bubble chamber now under construction at Fermilab will answer three remaining questions essential to a future noble liquid bubble chamber dark matter detection program:

- **What degree of superheat is possible while remaining blind to electron recoils?**
  The 500-eV thermodynamic threshold (*i.e.*, the threshold calculated from the pressure and temperature of the target fluid) demonstrated in the xenon prototype is still an order of magnitude above the fundamental limit set by statistical mechanics. The Fermilab device will reach temperatures and pressures where thermal fluctuations spontaneously nucleate bubbles at a rate of one event per ton-year, or thresholds of 40 (75) eV in liquid argon (xenon), and will measure any onset of electron-recoil induced bubble nucleation above those thresholds.

- **What is the calibrated nuclear recoil detection threshold of these devices?**
  Nuclear recoil calibrations at keV-scale thresholds in xenon and in freons show the energy threshold for bubble nucleation by nuclear recoils to be within a factor of $\sim$2 of the calculated thermodynamic threshold [20]. Molecular dynamics simulations [24] and simulations of nuclear recoil tracks [25] suggest this will remain true at the 100-eV scale, but this has not yet been verified experimentally. The Fermilab device will use photoneutron sources to calibrate the nuclear recoil bubble nucleation threshold with better than 100-eV resolution.

- **Which target fluids allow low-threhsold operation?**
  Until the calibrations above are complete, it is not known whether xenon or argon will provide greater sensitivity to low-mass dark matter. Superheated liquid nitrogen (molecular, but with the strongest bond in chemistry) may also exhibit good low-threshold performance, adding spin-dependent sensitivity to GeV-scale dark matter at the cost of scintillation. We consider argon the baseline target fluid for a dark matter search, but note the ease of switching between xenon, argon, and nitrogen, should the physics demand it.

III. FEASIBILITY AND PHYSICS REACH OF LARGE-SCALE LIQUID NOBLE BUBBLE CHAMBERS

Table I shows the sequence of chambers planned by the Scintillating Bubble Chamber (SBC) Collaboration for both dark matter and neutrino physics (see also the LOI listed above in NF3). The design of the Fermilab 10-kg chamber can scale to $\sim$300-kg without significant changes. (See the LOI listed above in IF8 for the long-term R&D needed to enable multi-ton chambers.) A noble liquid bubble chamber using current techniques, with a project cost of \$10M, would be sufficient to reach the ^{8}B CEνNS floor.

Active Mass Scale	Location	Timescale	Project Cost	Primary Physics
10 kg	Fermilab	Under construction		Calibration
10 kg	SNOLAB	Near term (<3 years)	\$1M	Dark Matter
10 kg	Research Reactor	Near term (<3 years)	\$1M	Neutrino
100 kg	Power Reactor	Medium term (4–7 years)	\$5M	Neutrino
1 t	Underground	Medium term (4–7 years)	\$10M	Dark Matter/Neutrino
Multi-t	Underground	Long term (>10 years)	>\$10M	Dark Matter/Neutrino

TABLE I. Roadmap for SBC physics with approximate timescales for the start of physics and project costs. No detailed costing has been attempted beyond the 10-kg scale.

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