The Scintillating Bubble Chamber Experiment

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Abstract

The Scintillating Bubble Chamber (SBC) collaboration is combining the well-established liquid argon and bubble chamber technologies to search for low-mass, GeV-scale dark matter. Liquid-noble bubble chambers benefit from the excellent electron-recoil insensitivity inherent in bubble chambers with the addition of energy reconstruction provided from the scintillation signal for background rejection. The projected sensitivity with a quasi-background-free 10-kg-year exposure at a 100 eV nuclear recoil threshold is approximately 10^{-43} cm^2 for a 1 GeV/c^2 dark matter mass.

1 Introduction

Particle dark matter with GeV-scale masses are favored in asymmetric dark matter models [1] which take the $\mathcal{O}(1)$ difference in the observed baryonic matter and dark matter abundances to be not a coincidence but a consequence of matter/anti-matter asymmetry in the light and dark sectors. Future success for direct-detection searches of GeV-scale dark matter will require low thresholds and technologies that are easily scalable while maintaining particle identification down to nuclear recoil thresholds below 1 keV.

The SBC collaboration is building two functionally-identical detectors (SBC-LAr10 at Fermilab and SBC-SNOLAB at SNOLAB) combining the bubble chamber technology (successful in low mass spin-dependent searches) with energy reconstruction in liquid scintillators (dominant in high mass spin-independent searches). Liquid-noble bubble chambers promise to be an enabling technology in the search for GeV-scale dark matter and additionally in reactor-based coherent elastic neutrino-nucleus scattering (CEνNS) measurements [2].

2 Liquid-noble bubble chambers

Bubble chambers maintain a target fluid (liquid argon (LAr) for SBC) in a superheated state. A localized energy deposition from incident radiation can create a heterogeneous nucleation resulting in the formation of a bubble and a correlated acoustic emission. Bubble chambers are threshold detectors where bubbles are nucleated when sufficient energy is deposited above threshold. With a liquid-noble target fluid, the incident radiation also creates scintillation light providing energy reconstruction missing with Freon-based fluids. Furthermore, without molecular degrees of freedom, nucleation by electron recoils in atomic fluids like LAr are highly suppressed. Liquid-noble bubble chambers, therefore, offer a low-threshold, scalable technology with better electron-recoil rejection than Freon-based bubble chambers.

A 30-g proof-of-principle detector was operated with liquid xenon [3]. A successful record of a nucleation event requires stitching together information over a wide time range ($\mathcal{O}$(ns) for scintillation, $\mathcal{O}$(μs) for bubble formation and acoustic emission). Simultaneous measurement of the bubble position (with cameras), acoustic emission (with a piezoelectric transducer), and scintillation light (with a photomultiplier tube) was achieved and is shown for a nuclear-recoil event in the left of Figure 1.

3 SBC-LAr10 construction

A solid model of the SBC-LAr10 detector is shown in the right of Figure 1. The 10-kg LAr volume is contained within a set of nested, fused silica vessels. A bellows connects the flanges of the vessels and permits vertical movement to reduce the differential pressure across the fused silica from the inner LAr volume to the outer hydraulic fluid. Carbon tetrafluoride, CF_4, is used as the hydraulic fluid which is liquid at 90 K and also scintillates providing a veto region. The LAr will be doped with $\mathcal{O}$(10) ppm Xe to act as a wavelength shifter. The Xe scintillation light is recorded by an array of 32 inward-facing silicon photomultipliers (SiPMs) mounted to copper panels surrounding the vessels. A high-density polyethylene castle acts as thermal insulation and also provides neutron shielding. These components are housed in a pressure vessel cooled with liquid nitrogen thermosyphons connected to a cryocooler.

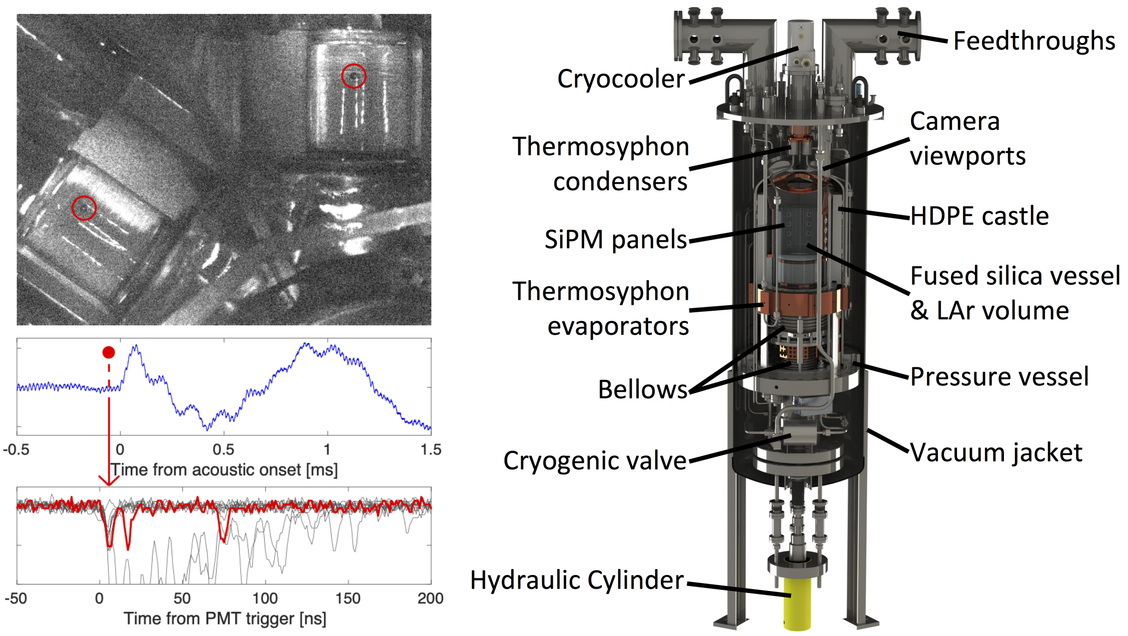

Figure 1: **Left:** Sample nuclear recoil event from the prototype xenon bubble chamber with a stereo image of a single xenon vapor bubble (top) and correlated acoustic trace (middle) and scintillation signal (bottom). Image reproduced from [3]. **Right:** Annotated solid model of the SBC-LAr10 detector.

The pressure vessel is contained within an outer vacuum jacket. This vacuum space reduces the heat load on the pressure vessel and contains the cryogenic valves, cameras, and electrical feedthroughs for the cameras, acoustic sensors, SiPMs, and temperature sensors. A bellows assembly connects from the pressure vessel through the vacuum jacket to a hydraulic cylinder which is used to control the pressure in the LAr volume. During operation, the superheated LAr region will be operated at ~ 130 K with the bellows kept at ~ 90 K to prevent spurious nucleations outside the main LAr volume. During compression the pressure is kept at ~ 200 psia and is lowered to ~ 30 psia to put the LAr volume in a superheated state. Further details of the SBC-LAr10 detector can be found in [4].

4 Expected backgrounds and initial calibration goals

Non-nucleating backgrounds can arise from electron-recoil events (^{39}Ar, Compton scattering) which only produce scintillation light. Nucleating backgrounds can be induced from alpha decays (Po decays on the LAr-wetted surface, (α, n) in the detector components), fast neutrons from the detector components, CEνNS from ^{8}B solar neutrinos, Thomson scattering from MeV-scale γ's, and (γ, n) reactions. Material selection and screening minimize these backgrounds, and further suppression is expected by vetoing high energy events with the LAr and CF_4 scintillation signal.

Stable operation of the bubble chamber in a cryogenic superheated state is the initial goal of operation with the SBC-LAr10 chamber. This includes verification of the thermal model and a homogeneous response (acoustic, pressure, scintillation) across the entire sensitive volume. A measurement of the wall nucleation rate can additionally be made, and if necessary, cleaning and leaching processes can be modified for the low-background SBC-SNOLAB chamber.

SBC is planning an extensive radio-calibration campaign for the SBC-LAr10 detector. A gamma calibration is planned to first confirm the lack of electron recoils seen at keV-scale thresholds in Reference [3]. Further, the electron recoil rejection can be probed at the desired 100 eV threshold and down to the expected thermodynamic limit[1] of 40 eV for argon. The nuclear recoil calibration campaign is vital to affirming the targeted 100 eV threshold. Photoneutron sources (^{124}SbBe) can be used to generate keV-scale ^{40}Ar recoils. Recoils of $\mathcal{O}(100)$ eV can be realized through Thomson scattering (from ^{208}Tl, ^{88}YBe sources). Below 100 eV thermal neutrons can be captured on ^{40}Ar and identified through the subsequent low-energy gamma tag.

5 Physics Potential and Conclusion

The SBC collaboration is currently testing many components and systems (cameras, SiPMs, slow controls, cryogenic seals) that will be used in the SBC-LAr10 and SBC-SNOLAB detectors. The SBC-LAr10 detector is in the commissioning phase at Fermilab and space has been allocated underground for the detector to be run at SNOLAB. The expected sensitivity for the SBC-SNOLAB detector with a quasi-background-free 10-kg-year exposure at a 100 eV nuclear recoil threshold will probe new parameter space below 10 GeV/c^2 dark matter masses down to 10^{-43} cm^2 at 1 GeV/c^2. Projections for SBC-SNOLAB can be found in [4]. A larger experiment with a 1-ton-year exposure will push into the boundary of the Ar neutrino fog.

[1] Here the thermodynamic limit is where random thermal fluctuations in the LAr are expected to create one bubble nucleation per ton-year.

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