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Scintillating Bubble Chambers for Rare Event Searches †

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Abstract: The Scintillating Bubble Chamber (SBC) collaboration is developing liquid-noble bubble chambers for the detection of sub-keV nuclear recoils. These detectors benefit from the electron recoil rejection inherent in moderately-superheated bubble chambers with the addition of energy reconstruction provided from the scintillation signal. The ability to measure low-energy nuclear recoils allows the search for GeV-scale dark matter and the measurement of coherent elastic neutrino-nucleus scattering on argon from MeV-scale reactor antineutrinos. The first physics-scale detector, SBC-LAr10, is in the commissioning phase at Fermilab, where extensive engineering and calibration studies will be performed. In parallel, a functionally identical low-background version, SBC-SNOLAB, is being built for a dark matter search underground at SNOLAB. SBC-SNOLAB, with a 10 kg-yr exposure, will have sensitivity to a dark matter–nucleon cross section of 2×10^{-42} cm^2 at 1 GeV/c^2 dark matter mass, and future detectors could reach the boundary of the argon neutrino fog with a tonne-yr exposure. In addition, the deployment of an SBC detector at a nuclear reactor could enable neutrino physics investigations including measurements of the weak mixing angle and searches for sterile neutrinos, the neutrino magnetic moment, and the light Z′ gauge boson.

Keywords: dark matter; neutrinos; bubble chambers; metastable fluids; liquid argon

1. Introduction

Measurements of the abundance of both baryonic and dark matter, a testament to modern cosmological observations, give rise to two open questions concerning the nature of dark matter and the origins of the matter/anti-matter asymmetry observed in the Universe today. Understanding the nature of dark matter can be achieved through the direct detection of dark matter-nucleon scattering [1] while precision measurements of the coherent elastic neutrino-nucleus scattering (CEνNS) cross section can give hints to a solution to the matter/anti-matter asymmetry [2]. Liquid-noble bubble chambers are an exciting technology capable of measuring the low-energy, sub-keV nuclear recoil signature expected in both direct detection searches and CEνNS measurements [3].

Many dark matter candidates, including Weakly Interacting Massive Particles (WIMPs), populate the 1–10 GeV/c^2 mass range [1] and would therefore generate $\lesssim$1 keV nuclear recoils. This mass range is of particular interest for asymmetric dark matter (ADM) models [4], which naturally favor dark matter particle masses at a few times the proton mass and credit the similarity in dark and baryonic matter abundances not to coincidence but rather as a consequence of a coupled matter/anti-matter asymmetry in the light and dark sectors.

The ability to measure sub-keV nuclear recoils additionally provides the opportunity to measure CEνNS from reactor antineutrinos which are an order of magnitude lower in energy than the neutrinos produced by stopped-pion sources (SNS). This allows for a probe of physics beyond the standard model in a new regime. Furthermore, nuclear reactors are a pure $\bar{\nu}_e$ source, complementing the mixed flavor production in spallation sources, with typical fluxes up to 10^5 times higher than that at SNS providing a high-statistics signal.

The Scintillating Bubble Chamber (SBC) collaboration has designed a 10-kg liquid argon bubble chamber targeting a 100-eV nuclear recoil threshold in preparation for a larger tonne-scale experiment. Liquid-noble bubble chambers are both scalable and quasi-background-free, meaning that the technique is able to discriminate against all backgrounds to the dark matter and CEνNS signals at the level needed to reach <1 background event in the signal region of interest over the lifetime of the experiment.

2. Scintillating Bubble Chambers

The scintillating liquid-noble bubble chamber is an extension of the moderately-superheated, Freon-based bubble chamber technique used by COUPP [5] and PICO [6] to search for dark matter. The great advantage of the bubble chamber for dark matter searches is the intrinsic insensitivity to electron-recoil backgrounds, a direct consequence of the thermodynamics of bubble nucleation. In the simplest models, nucleation requires the formation of a critically-sized proto-bubble to overcome the free energy barrier arising from the surface tension of the bubble before growing to a visible size. A particle interaction can create this critically-sized proto-bubble by locally heating the fluid, as described in the Seitz "Hot-Spike" model [7].[1] PICO has been successful in probing lower-mass spin-dependent WIMP-nucleon cross sections due to this electron-recoil insensitivity and the ability to acoustically discriminate between the remaining alpha background and nuclear recoils.

However, the electron recoil insensitivity in moderately-superheated Freons does diminish significantly below $\sim$1 keV, resulting in γ-induced nucleations indistinguishable from nuclear recoils. Furthermore, bubble chambers are threshold detectors, where a bubble is nucleated by any energy deposition above the Seitz threshold. As the amount of energy deposited is unknown, it is impossible to differentiate between high and low energy nuclear recoils. Liquid-noble bubble chambers address both of these issues by using liquid argon (LAr) as a target fluid.

Under ionizing radiation, LAr scintillates in the vacuum-ultraviolet, providing the ability to measure the total energy deposited and allowing for the discrimination between high and low energy nuclear recoils. This energy reconstruction in LAr has a resolution of $\sim$keV; by contrast, the acoustic signal accompanying bubble nucleation measured by PICO gives $\sim$MeV energy resolution [9]. The scintillation signal can be used to reject high energy background events. When superheated, nuclear recoil and alpha events depositing $\gtrsim$10 keV in LAr simultaneously create measurable scintillation light and nucleate a bubble; electron recoils under these conditions will create light only. For a nuclear recoil region of interest $\leq$10 keV, the expected signal is a nucleation without accompanying scintillation.

The key phenomenon driving the SBC program is a fundamental, additional suppression of electron-recoil-induced bubble nucleation in superheated noble liquids, enabling background free operation at nuclear recoil detection thresholds an order of magnitude or more below those achievable in existing Freon-based detectors. The absence of bubble nucleation by electron recoils in superheated noble liquids is likely a consequence of the lack of molecular degrees of freedom for recoiling electrons to excite.[2] Without energy loss to molecular vibrational modes, the only way particle interactions can locally heat the fluid is through the center-of-mass motion of individual atoms [10]. While this is achieved directly by the atom-atom collisions that are the dominant mode of energy loss for nuclear recoils (e.g., the Lindhard effect [11]), the kinematics of elastic electron-atom collisions make this an extremely inefficient means of energy loss for electrons. Instead, electron recoil energy is almost entirely carried away by scintillation light, IR radiation (including bremsstrahlung from electron-atom scattering), and slowly or incompletely recombining ionization.

The first detection of simultaneous scintillation and bubble nucleation by nuclear recoils was made in a 30-gram xenon bubble chamber [12]. A candidate nuclear recoil event from a ^{252}Cf calibration source is shown in Figure 1, with visible bubbles circled in red (top) along with the accompanying acoustic (middle) and scintillation (bottom) signals. This detector was operated stably down to a hardware-limited threshold of 500 eV without evidence of electron recoil-induced nucleations leading to the electron-recoil rejection shown in Figure 2. The same device showed sensitivity to 152-keV neutrons from a ^{88}YBe photo-neutron source (maximum xenon recoil energy of 4.8 keV), confirming that the Seitz model approximately holds for nuclear recoil detection thresholds in noble liquids at thresholds down to at least 1 keV.

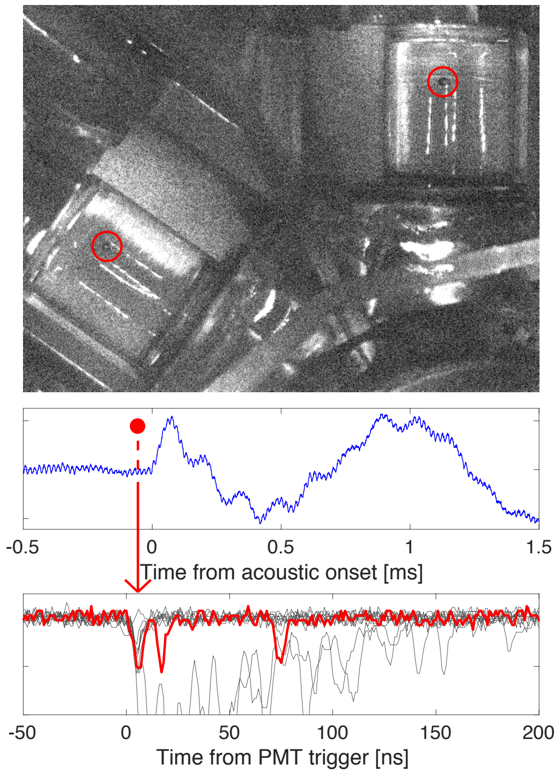

Figure 1. Sample nuclear recoil event from the prototype xenon bubble chamber [12]. (**top**) Stereo image of a single xenon vapor bubble (circled in red). (**middle**) Acoustic record of bubble formation. (**bottom**) PMT waveforms showing xenon scintillation. The bubble-coincident pulse is shown in red, while electron recoils in the same bubble time window generate scintillation pulses without coincident bubble nucleation (gray traces).

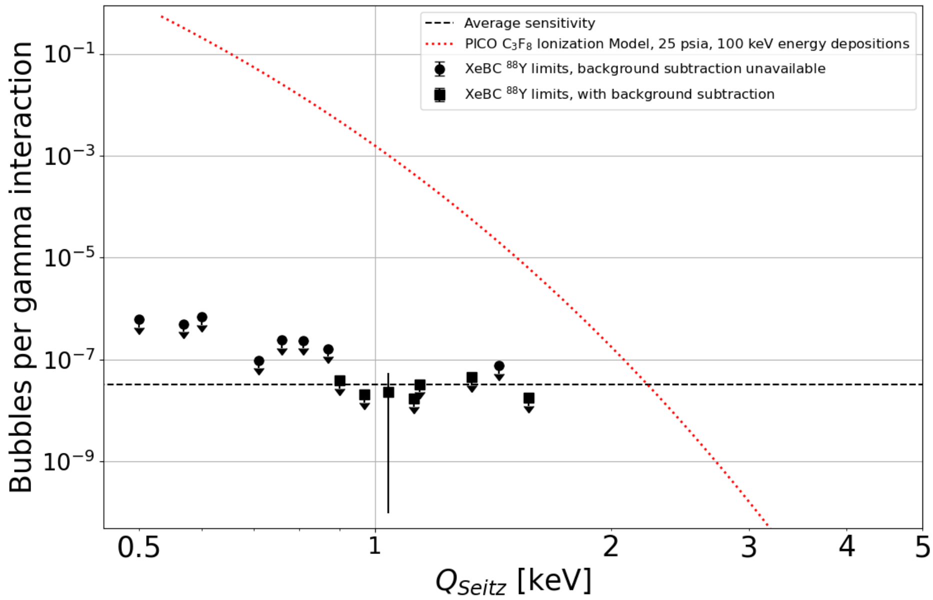

Figure 2. Electron recoil sensitivity of the prototype xenon bubble chamber as a function of superheat (Seitz threshold for bubble nucleation), taken from [13]. No evidence for bubble nucleation by gamma sources is seen, leading to 90% confidence intervals with (square points) and without (round points) ambient nucleating-background subtraction. As reference, the electron recoil rejection in molecular fluids (PICO-60) with the same thermophysical properties as in the xenon chamber is shown in red.

3. SBC-LAr10 Detector Design

Building on the success of the liquid Xe prototype, the SBC collaboration's first physics-scale detector, SBC-LAr10, is currently being commissioned at the Fermi National Accelerator Laboratory. The primary purpose of this device is to characterize the low-threshold performance of the liquid-noble bubble chamber and to undertake an extensive calibration campaign. In parallel, a functionally identical detector, SBC-SNOLAB, is being built with a focus on radiopure construction. This detector will be deployed underground at SNOLAB for the dark matter search. These chambers have been designed to meet the specifications indicated in Table 1.

Table 1. Design specifications for the SBC detectors.

Target fluid	Xe-doped Ar, with options for pure Ar, Xe, N_2, or CF_4
Fiducial volume	10 L (10 kg LAr at 130 K)
Thermodynamic regulation	$\pm$0.5 K, $\pm$0.1 bar ($\pm$5 eV Seitz threshold)
Seitz threshold	Down to 40 eV (LAr at 1.4 bara, 130 K)
Scintillation detection	1 photon per 5 keV NR in Xe-doped argon
Bubble imaging	stereoscopic at 100 fps with mm-resolution
Acoustic reconstruction	Time-of-nucleation reconstructed to $\pm$25 µs resolution

A solid model rendering of SBC-LAr10 is shown in Figure 3. The active volume consists of 10 kg of LAr doped with 10–100 ppm of xenon shifting the scintillation wavelength to 175 nm (fiducial volume of dimensions $\sim \varnothing$ 0.23 m $\times$ 0.28 m). The 175 nm light can pass through the fused silica vessel where it will be detected by an array of 32 inward-facing silicon photomultipliers (SiPMs). SBC-LAr10 will use Hamamatsu VUV4 SiPMs while SBC-SNOLAB will use FBK VUV-HD4 which were found to have lower uranium and thorium content. The SiPMs are mounted on copper panels which minimizes the vertical thermal gradient across the active volume. Surrounding the copper panels is a layer of high-density polyethylene (HDPE) for thermal insulation and neutron shielding. The inner detector components are housed in a stainless steel pressure vessel ($\varnothing$ 0.39 m $\times$ 0.8 m) backfilled with liquid carbon tetrafluoride (LCF_4) to act as a hydraulic fluid. Eight lead zirconate titanate piezoelectric transducers are held in contact with the base of the vessel (∼10 cm from the active LAr volume) to record the acoustic emission. Resistive temperature detectors are placed throughout the pressure vessel and HDPE to monitor the temperature, necessary for the thermodynamic regulation given in Table 1.

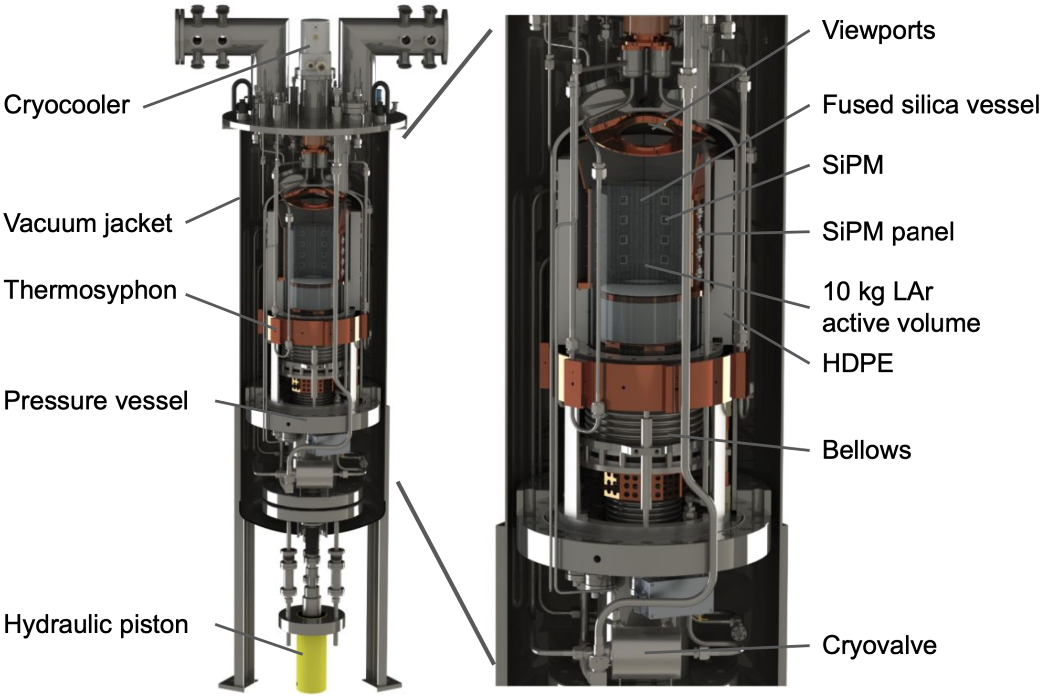

Figure 3. Solid model base design of SBC-LAr10 with main components annotated.

The pressure in the LAr volume is controlled with an externally mounted hydraulic piston which connects through a bellows to the pressure vessel. The pressure vessel is housed in a vacuum jacket (∅ 0.6 m × 2.0 m) and cooled with liquid-nitrogen thermosyphons [14] connected to a Cryomech AL300 cryocooler. The pressure vessel has view ports for cameras (to be mounted in the vacuum space) and feedthroughs for liquid and electrical connections.

Minor design modifications are expected for the SBC-SNOLAB detector, based on the experience gained during construction and commissioning of SBC-LAr10. Both detectors, however, must hold the target volume in the desired superheated state with at least ±0.5 K and ±0.1 bar precision (corresponding to a ±5 eV Seitz threshold at the target operating condition), while sensitive to potential bubble nucleations. When bubble nucleation does occur, the chamber will be recompressed quickly to drive the active volume back to an entirely liquid state. Both the precision regulation and fast compression must be achieved without exposing the superheated liquid to rough surfaces that can lead to spurious bubble nucleation. SBC adopts a buffer-free, dual-temperature-zone strategy to achieve this, similar to the strategy used by PICO-40L and PICO-500 [15].

Like all low-background detectors, SBC-LAr10 will require shielding in order to operate; however, these requirements are different for the SBC-SNOLAB detector. The calibration-focused chamber, SBC-LAr10, will be deployed at Fermilab in the MINOS Near Detector Hall tunnel, approximately 100 m underground. This will reduce the cosmic-ray muon rate by an amount sufficient to allow the low-energy calibration without additional shielding. The dark matter search chamber will be deployed at SNOLAB (space has been allocated underground following the successful Gateway 1 review) to achieve a more significant reduction in the muon-induced background rate. External shielding will be required to minimize the environmental neutron rate; shielding studies are in progress for the SBC-SNOLAB detector.

4. Operational Strategies and Expected Backgrounds

A bubble nucleation event in SBC is defined as a full cycle in the state of the chamber, from stable liquid, to superheated liquid, to bubble formation, and back to stable liquid. The recompression of the chamber after bubble formation can be triggered from multiple signals including the pressure rise from bubble formation or the real-time analysis of the camera images looking for changes in pixel density. When not superheated, SiPM-based triggers can be taken to record non-nucleating scintillation events in the LAr volume. For each nucleation trigger, data from the acoustic transducers, SiPMs, and cameras must be saved in real time and stitched together to form a single event.

The first calibration studies will be to confirm the lack of electron-recoil nucleations at the keV scale, as observed in the Xe bubble chamber prototype. Then, the electron-recoil rejection can be investigated at and below 100 eV, down to the thermodynamic limit. For SBC, a thermodynamic limit of 40 eV is defined as the point which would lead to 1 nucleation per tonne-year due to random thermal fluctuations in the LAr volume.

After calibration with a γ source, an extensive neutron calibration campaign is planned across a wide range of nuclear recoil energies. Photoneutron sources (^{124}SbBe) can be used to generate $\mathcal{O}(1)$ keV nuclear recoils. Photon-nucleus scattering (^{208}Tl), the low-energy Compton scattering limit [16], can generate $\mathcal{O}(100)$ eV recoils. Below this, thermal neutron capture on argon can be tagged to isolate $\leq \mathcal{O}(100)$ eV nuclear recoils.

The neutron calibration campaign can be used to constrain the nuclear recoil bubble nucleation efficiency as a function of recoil energy at a fixed thermodynamic condition. The SBC and PICO collaborations have together developed a Markov-Chain Monte-Carlo-based method to combine constraints from diverse calibration sources with appropriate handling of systematic uncertainties [17]. This method better constrains parameters of interest by breaking the degeneracy in nuisance parameters associated with each source measurement. In SBC, this will be used to achieve 20% uncertainty on the nuclear recoil bubble nucleation energy threshold in SBC-LAr10, sufficient to determine the dark matter reach for the LAr bubble chamber technology. Further constraining at the $\sim$5% level is necessary for precision CEνNS measurements.

The nuclear recoil background in the SBC-SNOLAB dark matter search detector is expected to arise from fast neutrons, both environmentally generated and from (α, n) reactions in the detector materials. Bulk α decays in the LAr volume can be vetoed based on their large scintillation signal, and the single-scatter neutron scattering rate can be determined based on the multi-scatter rate (the ratio of neutrons which multi-scatter to single-scatter is greater than 1). Excess γ-rays generate stray light, but are non-nucleating. However, γ-rays greater than $\sim$1.3 MeV can induce nuclear recoils above the 100-eV-threshold. Lastly, the expected rate of CEνNS scattering from ^{8}B solar neutrinos is expected to be $\sim$2 in the nuclear recoil region of interest (100 eV to 10 keV) for SBC-SNOLAB with a 10-kg-year exposure.

5. Current Status and Physics Reach

The SBC-LAr10 detector is currently in the assembly and commissioning phase at Fermilab. Following successful cryogenic systems testing, the inner vessel components are in final assembly and preparation for operation in the MINOS tunnel. All inner vessel components were built in duplicate, meaning the components for SBC-SNOLAB are additionally prepared.

With a 10 kg-yr exposure, SBC-SNOLAB will have sensitivity to the dark matter-nucleon cross sections of 10^{-42} cm^2 at 1 GeV/c^2, shown in Figure 4. At $\mathcal{O}(1)$ tonne-year exposures we expect quasi-background-free operation to be achievable in a low-background (underground and well-shielded) environment, noting that at these exposures the solar neutrino CEνNS and potential dark matter signals become backgrounds to each other, forming the so-called neutrino fog [18]. Therefore, at a tonne-year exposure the SBC program shifts from performing a dark matter search to exploring solar neutrino physics through the CEνNS channel.

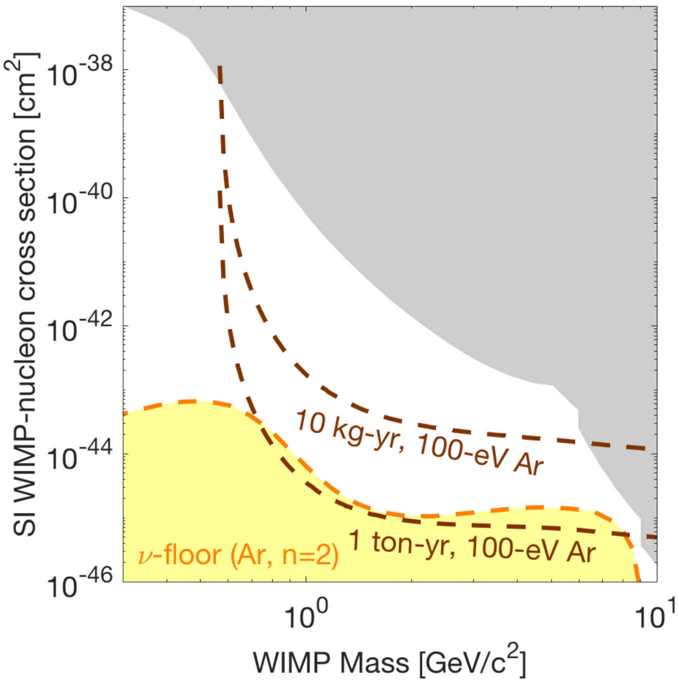

Figure 4. Spin-independent dark matter-nucleon cross section sensitivity for the SBC-SNOLAB detector (dashed brown) with a 10 kg-yr and 1 tonne-yr exposure and a 100 eV threshold along with the currently-excluded parameter space in grey from DarkSide-50 [19,20] below 5 GeV/c^2 and Xenon1T [21,22] above. These projections assume zero background except from the CEνNS signal, which is taken to have zero rate uncertainty. The boundary of the "n = 2" neutrino fog, as defined in [18], is also shown for reference.

The SBC-LAr10 chamber, at 100-eV threshold, is additionally capable of detecting dozens (hundreds) of CEνNS events per day at a typical research (power) reactor site. The challenge is to locate a site with sufficient overburden and shielding (or space to build shielding) to suppress the rate of cosmic- and reactor-induced neutron events to below the CEνNS signal rate. The neutron environment at the Instituto Nacional de Investigaciones Nucleares (ININ) TRIGA Mark III reactor near Mexico City [23] is being characterized as a potential site along with Laguna Verde. The ININ site has a 1 MW_{th} reactor with a movable core allowing as little as a 3 m baseline to an exposure room, with 3 m overburden to shield cosmic rays. The physics potential for SBC-LAr10 of measuring the weak mixing angle, neutrino magnetic moment, and searches for Z' light gauge bosons and sterile neutrinos is investigated in [24,25].

The liquid-noble bubble chamber technology being developed by the SBC collaboration will provide a promising opportunity to measure sub-keV nuclear recoils. SBC-SNOLAB will probe dark matter parameter space in an interesting mass range, complementing searches in the sub-GeV dark matter mass parameter space [26] on a different target nucleus with a unique detection technology that is highly effective at background suppression. With high-statistics CEνNS scattering realizable, the neutrino physics potential is equally promising.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Notes

1. A modern review of radiation-induced nucleation in bubble chambers is given in [8].
2. One goal of the SBC-LAr10 detector is to confirm this hypothesis.

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