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# The Scintillation Bubble Chamber (SBC) experiment for dark matter and reactor CE$\nu$NS

**Sumanta Pal***, for the SBC collaboration
*Dept. of Physics, University of Alberta, Edmonton, Alberta T6G 2E1, Canada*
*E-mail:* sumanta@ualberta.ca

The Scintillating Bubble Chamber (SBC) Collaboration is developing a novel detection technique aimed at detecting low-mass (0.7-7 GeV/c$^2$) WIMP interactions and coherent elastic neutrino-nucleus scattering (CE$\nu$NS) of reactor neutrinos. Using a target volume composed of super-heated argon with a tiny amount of dissolved xenon, the nucleation signal from electron recoils (the limiting factor for low-threshold studies in bubble chambers) is suppressed, allowing for the exploration of new parameter space. Particle interactions with the target fluid can lead to the production of heat (bubbles) and scintillation light. By combining these observables, the SBC Collaboration is aiming to reach a threshold of 100 eV for nuclear recoil detection with discrimination and a projected WIMP-sensitivity of $1.73 \times 10^{-43}$cm$^2$, for a WIMP mass of 1 GeV/c$^2$.

In this paper, the design of a 10-kg device and the current activities at Fermilab (FNAL) towards the commissioning and operation of the detector are presented. As part of the detector R&D, ongoing activities at the University of Alberta for different image capture setups are also briefly discussed afterward. Finally, an overview of the collaboration's plans for future operations at FNAL and SNOLAB, including the potential for such a detector to become the leading technology to study CE$\nu$NS are also presented here.

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## 1. Introduction

A bubble chamber detector is a promising technology as a low-energy nuclear recoil (NR) detector studying the nature of dark matter and neutrinos. In this context, the SBC collaboration has planned to use 10-kg liquid argon (LAr) bubble chamber device to pursue a low-mass ($< 10$ GeV/c$^2$) dark matter search focusing on Weakly Interacting Massive Particles (WIMPs) and a precision study of the reactor coherent elastic neutrino-nucleus scattering (CEνNS) in argon and xenon. In brief, the detector consists of a fused silica jar which is surrounded by liquid $CF_4$ ($LCF_4$). The target fluid, LAr mixed with a tiny amount of dissolved xenon, is held inside the jar. $LCF_4$ acts as a thermal bath as well as a hydraulic fluid in the detector. This whole system is enclosed in a vacuum-sealed pressure vessel (PV) which is further thermally isolated by a vacuum jacket from the outside environment. The jars are connected through bellows connection and controlled via a hydraulic system to maintain the fluid pressure. The temperature of the target fluid is maintained using a cold-head and a thermosyphon system. The detector is further equipped with Silicon-Photo-Multipliers (SiPMs) to measure the scintillation light along with cameras to take pictures of the bubbles, and piezo-acoustic sensors to listen to bubble's formation. A schematic concept of the detector is shown in Fig. 1. By slowly lowering the internal pressure in the jar, the target fluid is placed in a super-heated state when it could lead to nucleation of a vapour bubble if the interacting particle deposits enough localized heat energy to overcome the minimal energy threshold called the Seitz threshold [1]. After being imaged with an optical readout, the detector is finally back to its initial state by re-pressurizing the fluid volume which removes all the bubbles in the jar. Whether scintillation light is produced along with bubble nucleation depends on the energy intensity and nature of interactions. The Seitz threshold depends on the pressure of the target fluid. Therefore, the set fluid pressure, and temperature, determine the energy threshold of a bubble chamber. The bubble nucleation is also dependant on the nature of the interaction of the incoming particles with the target fluid. Thus, a nuclear recoil (NR) type interaction is significantly different from an electromagnetic interaction, commonly known as electromagnetic recoil (ER). Using noble liquid as a target adds calorimetry capabilities via the scintillation process and it also allows operating the bubble chamber at energy thresholds of the order of 100 eV, while retaining ER-blindness [2]. A 10-kg device is already under construction at FNAL (SBC-FNAL) to demonstrate a low threshold of 100 eV for nuclear recoil detection and to

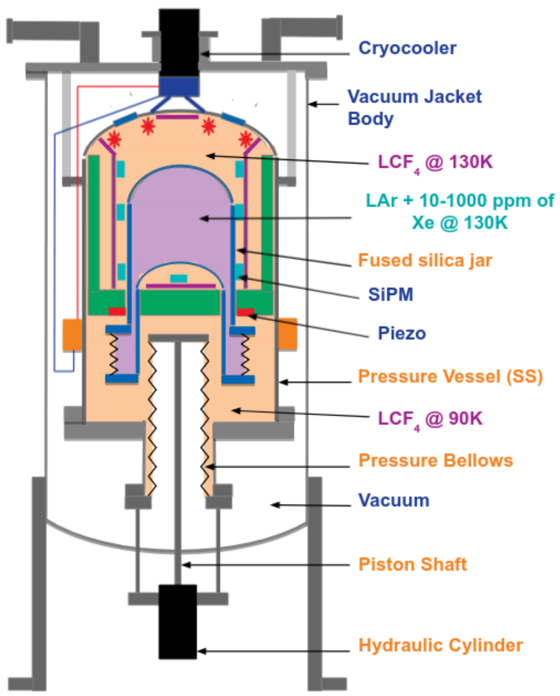


Figure 1: Schematic view of the 10 kg LAr Scintillating Bubble Chamber detector; major components are highlighted here.

understand detector operation as well as to perform its calibration. The process of building a second detector at SNOLAB (SBC-SNOLAB), Canada is also under progress which will be dedicated to search for low WIMP masses.

## 2. ER calibration results from a 30-g xenon test chamber

A 30-g liquid xenon (LXe) bubble chamber was initially built and operated at Northwestern University (NWU), USA in 2016 to demonstrate the principle of the scintillating bubble chamber [2]. For the first time, simultaneous bubble nucleation and scintillation by nuclear recoils were observed in the superheated LXe in this detector. Initial data from 2017 showed no evidence for bubble nucleation by gamma rays, setting a 90% C.L. upper limit of $6.3 \times 10^{-7}$ bubbles per gamma interaction at a 4.2 keV thermodynamic threshold (black dot in Fig. 2). Recent data (all coloured dots in Fig. 2) improved this limit on gamma nucleation lower than $10^{-7}$ at a thermodynamic threshold around 1 keV. This indicates stronger gamma discrimination than in $CF_3I$ or $C_3F_8$ bubble chambers, supporting the hypothesis that scintillation production suppresses bubble nucleation by electron recoils, while nuclear recoils nucleate bubbles as usual. Different neutron sources ($^{252}$Cf, $^{207}$Bi/Be, and $^{88}$Y/Be) are used to calibrate nuclear recoils at a threshold of 0.9 keV and above (Fig. 2). More details about NR/ER calibration results from this test chamber as well as the calibration plan for the 10-kg device at FNAL are discussed in [3].

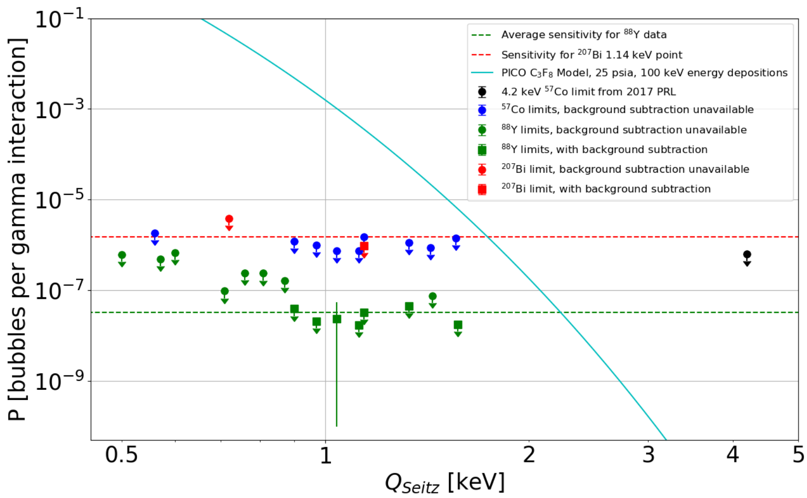


Figure 2: ER calibration using gamma sources.

## 3. WIMP and CEνNS sensitivity from a 10-kg device

A projected 90% CL limits (in the absence of a dark matter signal) from 10 kg-yr and 1 ton-yr exposures with the SBC detectors at SNOLAB is shown in Fig. 3. The experiment has a projected WIMP-sensitivity of $1.73 \times 10^{-43}$cm$^2$, for a WIMP mass of 1.0 GeV/c$^2$. Limits assume here 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. The neutrino (CEνNS) floor is taken from [4]. Projections from SuperCDMS [5], LZ [6], DAMIC [13], HERALD (superfluid helium) [7], HydroX (H2-doped xenon) [8], NEWS-G [12] and PICO [15] are also shown. The gray region indicates parameter space excluded by existing

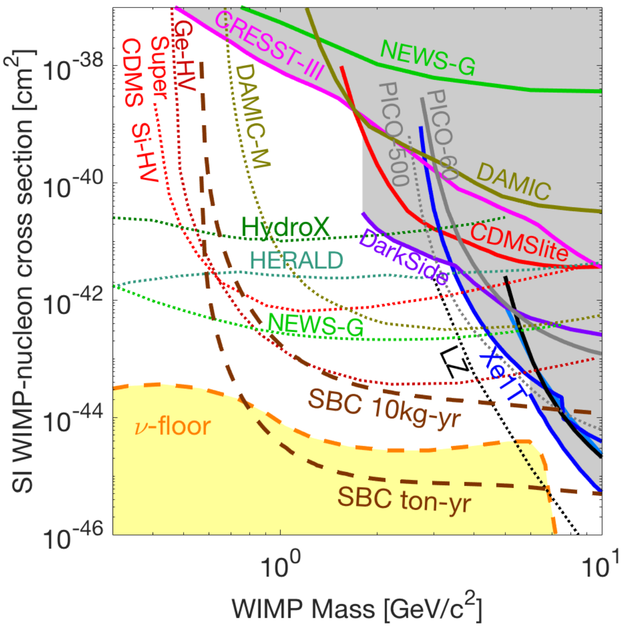


Figure 3: WIMP sensitivity at SBC.

direct detection limits [5], [9]-[15]. An expected start-time of a physics run at SNOLAB with a 10-kg device same as the FNAL setup is still early 2023.

Once the 10-kg device at FNAL is well tested, it will be re-purposed and installed at a reactor site (SBC-CEνNS) for precision studies of CEνNS in LAr. The collaboration is currently investigating the possible reactor sites. Physics reach of the low threshold SBC detector for coherent elastic neutrino-nucleus scattering reactor experiment is studied in detail in the reference [16]. The few-MeV neutrinos produced by nuclear reactors give a continuous rate of sub-keV nuclear recoils. Aiming ~100 eV threshold for nuclear recoil in SBC detector with low backgrounds opens a challenging window to study the fully coherent scattering of low-energy and pure anti-electron neutrino flavor. The authors described in detail the experimental setup at reactors, event rate, non-standard neutrino interactions, etc. in [16]. In this paper, an event rate estimation above neutron background (Fig.4) in the explored sites at National Institute for Nuclear Research (ININ) near Mexico City is highlighted which shows O(0.7) CEνNS events/kg-day at 1 MW reactor in the SBC detector.

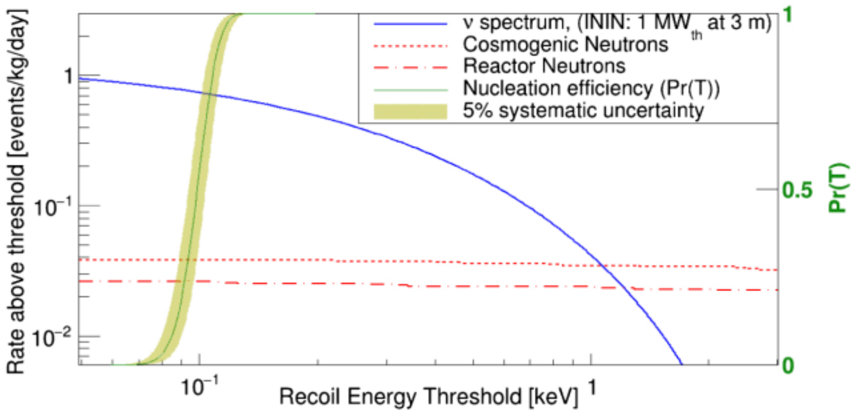


Figure 4: Signal and neutron background rates above the SBC detector threshold at the ININ site. Backgrounds come from the reactor and cosmogenic neutrons.

## 4. Current activities

Fig. 5 shows some of the detector activities for a 10-kg device that is under construction at

FNAL. Other activities, like testing of piezoelectric sensors and SiPMs, are also underway. The primary objectives for the FNAL chambers are to demonstrate the scalability of the techniques, determine the probability of ER-induced nucleation as a function of the Seitz threshold, and measure the nuclear recoil sensitivity of the chamber using mono-energetic neutron sources, like $^{88}$Y/Be, $^{207}$Bi/Be. As of now, assembly of the detector and preliminary tests will be done by early 2022 and the detector will continue to collect physics data until 2024. In parallel to this activity, an R&D for an alternate imaging system is ongoing at the University of Alberta, Canada. The initial plan to connect a Basler camera (acA1300-200$\mu$m) directly to the viewport of the PV shows a higher estimate of backgrounds in the detector. To overcome this problem, the camera system needs to be moved back from the viewport of the pressure vessel (PV), and an appropriate imaging system is required between the viewport and the camera to guide optic rays. Two systems are right now under test in a dedicated optic system in a LAr environment; one of the systems uses a relay lens setup and the other uses a nanoguide (a transparent plastic-type material). Fig. 6 shows different components of the optic system setup. The image is read out by an OV9281 Arducam sensor connected to a RaspberryPi.

Figure 5: Pressure vessel (PV) inside the vacuum jacket for pressure test (left); Jar arrangement with its bellow system (middle); Wiring of various sensors around PV and connections of the cooling lines to the PV (right).

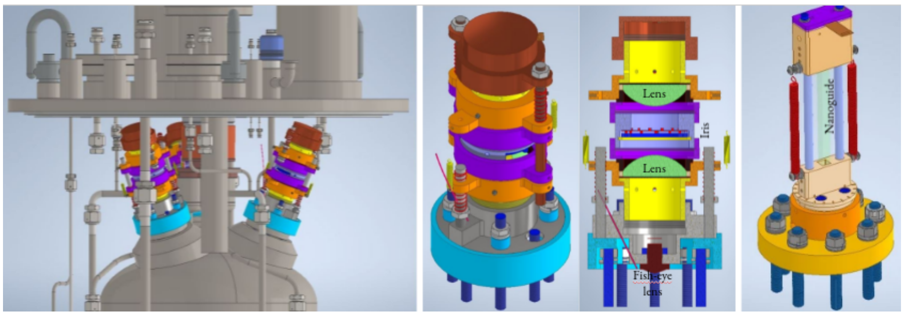


Figure 6: Relay lens housing installed at the viewports of the PV (left); Relay lens setup where lenses, iris and fish-eye lens are highlighted (middle); Nanoguide setup (right).

## 5. Conclusion

The SBC collaboration is developing a novel bubble chamber technique that combines the ER-blindness capability of standard bubble chambers with the calorimetry abilities of liquid noblebased detectors. The 10-kg device at FNAL is already under construction and soon the commissioning will be done by early 2022. SBC-SNOLAB program is also under process and the start date of expected physics runs is still early 2023. The 10 kg-yr exposure of WIMP search looks competitive than other planned or running experiments for the search of low WIMP masses. SBC-CEνNS program looks also challenging to study non-standard neutrino interactions in near future.

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