Snowmass2021 - Letter of Interest

Neutrino Physics with Noble Liquid Bubble Chambers

NF Topical Groups: (check all that apply □/■)
□ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
■ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

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Collaboration: Scintillating Bubble Chamber (SBC)

Related Snowmass2021 LOIs:
Reaching the solar CEνNS floor with noble liquid bubble chambers (CF1)
Enabling the next generation of bubble-chamber experiments for dark matter and neutrino physics (IF8)

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Abstract: The SBC collaboration is developing scintillating liquid noble bubble chambers for CEνNS and dark matter physics. With a nuclear recoil threshold goal of 100 eV, the CEνNS neutrino energy threshold could be as low as 1.4 MeV. Physics targets include searches for new physics with reactor neutrinos and studies of solar, supernova and pre-supernova neutrinos. Potential applications include reactor monitoring.

I. INTRODUCTION TO SCINTILLATING NOBLE LIQUID BUBBLE CHAMBERS (NF10)

The Scintillating Bubble Chamber (SBC) collaboration is developing noble liquid bubble chambers as low threshold nuclear recoil detectors for dark matter searches and neutrino detection via coherent elastic neutrino nucleus scattering (CEνNS). Previous results from the PICO experiment and others have demonstrated the sensitivity and scalability of freon-filled superheated liquid detectors for dark matter searches [1–4], achieving rejection of electron recoil backgrounds at better than the 10^{-10} level while retaining sensitivity to few keV nuclear recoils [5]. Multiple-scattering neutron events are identified optically and acoustically, leaving single-scatter neutrons as the dominant remaining background in the most recent PICO results [1]. At present the maximum size possible is a few-hundred liters, limited by the fabrication of fused silica target vessels.

A small prototype liquid xenon bubble chamber operated at Northwestern has also achieved sensitivity to few-keV nuclear recoils [6]. A preliminary analysis of additional data from the xenon chamber finds no evidence for bubble nucleation by electron recoils, even at high degrees of superheat corresponding to a calculated nuclear recoil threshold of 0.5 keV, a level at which freon bubble chambers are overwhelmed by electron recoil backgrounds. The relative insensitivity of the noble liquid to electron recoils is believed to be due to the absence of molecular transitions to efficiently convert ionization energy into localized heat, necessary to initial boiling. Noble liquid scintillation, by providing event-by-event energy information, offers an additional channel to reject most single-scatter neutron backgrounds. This combination of low nuclear recoil threshold, insensitivity to electron recoils in the bubble nucleation channel, and scalability to the ton-scale, is unmatched by any current technology.

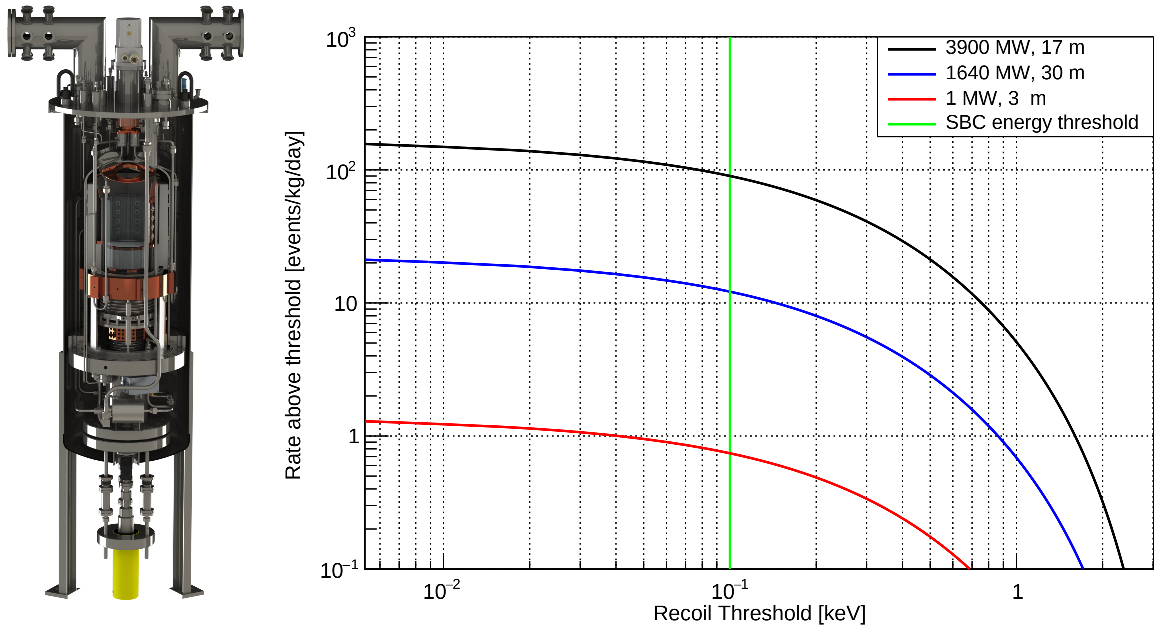
The SBC collaboration is currently constructing a 10-kg liquid argon bubble chamber at Fermilab (Fig. 1) to further explore electron recoil insensitivity in the sub-keV nuclear recoil threshold region, down to the limit of spontaneous thermal bubble nucleation, estimated to be approximately 40 eV. At an assumed threshold of 100 eV, the technology has the potential to both search for scattering of GeV scale dark matter and detect neutrinos via CEνNS with a 1.4 MeV neutrino threshold. Reactor, solar, supernova and pre-supernova neutrinos can all be detected with this threshold. The ultimate neutrino threshold achievable has yet to be determined; sub-MeV neutrino detection may be possible with nuclear recoil thresholds below 100 eV and/or with lighter nuclei in the target. A roadmap for SBC physics is presented in Table I.

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.

II. REACTOR NEUTRINOS WITH SBC (NF3, NF5, NF2)

The SBC collaboration is exploring reactor sites to deploy a duplicate of the 10-kg Fermilab chamber for a first detection of reactor neutrinos via CEνNS. Figure 1 shows calculated CEvNS events rate for various reactor powers and distances. A site under evaluation is the 1 MW reactor at the National Institute for Nuclear Research (ININ) in Mexico. Simulations of cosmogenic neutron backgrounds in the ININ counting room, with 3 m of concrete overburden, indicate a signal-to-background of better than 10:1 can be achieved with 75 cm of neutron shielding. A liquid scintillator detector deployment has been approved to characterize reactor gamma backgrounds, which will inform shielding design and estimates of background rates due to (γ,n) interactions on detector materials and gamma-nucleus elastic scattering in the liquid argon target [7]. As shown in Figure 1, a larger device at a higher power reactor could detect many hundreds of neutrinos per day to perform a precision measurement of the CEνNS interaction rate. Such a dataset could be used to search for physics beyond the Standard Model including non-standard interactions [8, 9], sterile neutrino oscillations at short-baselines [10, 11] and neutrino magnetic moments [12]. A precision measurement of the weak mixing angle at low momentum transfer is also possible [12, 13].



(a) (b)

FIG. 1: Left: A rendering of the 10-kg SBC detector under construction at Fermilab. Right: CEνNS rates at various sites: close deployment at a 1 MW reactor such as ININ (red), 30 m deployment at a power reactor (blue), and a 17 m deployment at a larger power reactor—the location of CONUS [14] (black).

III. NEUTRINO PHYSICS WITH WITH SBC AT SNOLAB (NF4, NF7)

The SBC collaboration will deploy a low-background 10-kg liquid argon chamber underground at SNOLAB, with a follow-on ton-scale experiment planned. Multi-ton experiments are feasible with modular designs, or with R&D into alternate target vessel materials. A primary physics driver of these devices is to search for GeV-scale dark matter down to the solar neutrino floor. The larger experiments would have sensitivity to neutral current interactions for most of the ^{8}B solar neutrino spectrum, detecting up to 40 events per ton-year. With a few ton-year exposure a precise measurement of the ^{8}B total neutrino flux would be possible, providing constraints on solar metallicity [15]. A handful of neutrinos would be detected per ton for nearby supernova, and for very near supernova all flavors of the softer pre-supernova neutrinos, too low in energy for large Cherenkov detectors, could be observed [16]. This would be complementary to large inverse beta-decay (IBD) experiments sensitive only to $\overline{\nu_e}$. With a 100 eV threshold, sensitivity per ton to pre-supernova neutrinos is many times higher than optimistic projections for other contemplated future dark matter experiments, such as a 300 t argon TPC [17].

IV. OTHER APPLICATIONS (NF7)

The CEνNS detection channel provides an alternative to the traditional IBD channel for detection of reactor neutrinos, and for reactor monitoring for treaty verification purposes [18]. Due to the higher interaction cross section, a noble liquid CEνNS detector could be constructed with a smaller footprint than an IBD detector of comparable sensitivity. A paired arrangement with both an IBD and CEνNS detector can also be contemplated for a simultaneous measurement of the CEνNS and IBD rate to measure $\overline{\nu_e}$ disappearance and infer reactor distance [19]. It is also interesting to consider applications if the neutrino threshold can be lowered further, well into the region inaccessible to IBD experiments (threshold 1.8 MeV). For example, the detection of plutonium breeding blankets in fast reactors might be possible [20].

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