Metastable Water: Breakthrough Technology for Dark Matter & Neutrinos

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■ (CF1) Cosmic Frontier: Dark Matter: Particle-like

Neutrino Frontier Topical Groups:

■ (NF04) Neutrino Physics Frontier: Neutrinos from Natural Sources
■ (NF05) Neutrino Physics Frontier: Neutrino Properties
■ (NF06) Neutrino Physics Frontier: Neutrino Interaction Cross-Sections
■ (NF07) Neutrino Physics Frontier: Applications
■ (NF10) Neutrino Physics Frontier: Neutrino Detectors

Intensity Frontier Topical Groups:

■ (IF6) Instrumentation: Calorimetry
■ (IF8) Instrumentation: Noble Elements

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Abstract: We present a discussion of a new detector technology, the “Snowball Chamber,” which is based on the phase transition (of liquid to solid) for metastable fluids. A water-based supercooled detector has the potential to move past the Neutrino Floor, and extend the reach of direct detection dark matter experiments to low-mass WIMP candidates for both spin-dependent (on the proton) and spin-independent interactions. The detector concept also has applications within coherent elastic neutrino-nucleus scattering experiments. Some of the foreseeable, potential pitfalls are presented, as is a brief vision of an R&D program toward the maturation of this technology.

Introduction

The last several decades have seen the successful development of numerous technologies capable of performing direct searches for particle-like dark matter [1, 2]. In general, the marquee experiments are each mature, reliable, and expected to reach their sensitivity goals; however, looking beyond the current generation, the parameter space of dark matter candidates accessible with current technology is limited. Instrumentation thresholds and the kinematics of elastic scattering [3] constrain the lowest mass dark matter candidates that can be studied [4]. The coherent elastic neutrino-nucleus scattering (CEνNS) of solar, atmospheric, and diffuse galactic supernova neutrinos will soon become a background (the neutrino floor) that challenges the reach to lower cross-sections, made even more difficult by the required scale of future experiments. Without a new approach for detection technology, experimental searches will remain blind to important regions of parameter space. A new technology which pushes past the neutrino floor, extends sensitivities to low-mass dark matter candidate particles [5], and is insensitive to the conventional backgrounds could open up these new horizons. The path forward–envisioned here–builds upon the transformative "Snowball Chamber" technology, a proton-rich, supercooled liquid water detector [6, 7]. A host of related measurements within neutrino physics, utilizing the CEνNS interaction [8] on oxygen nuclei, and/or the potential of these detectors to track electron interactions, is likewise open to such a technology.

A pure liquid can be placed into a state of "metastability" by controlling the temperature below the freezing point (without freezing), so long as it is housed within a sufficiently clean and smooth container [9, 10], in order to avoid nucleation sites [11, 12]. Nucleation centers from particle interactions can be formed which instigate the freezing of the liquid [13]. Freezing after supercooling produces a large and unmistakable signature: a growing solid snowball, an enormous exothermic spike in temperature readings, and a change in dielectric constant. Controlling the temperature and/or pressure allows one to control the critical radius for nucleation, and thus the particle detection thresholds for both the energy and $\frac{dE}{dx}$ [14], which provides the ability to make the detector insensitive (and selective) to different particle interactions [15, 16]. As the supercooled temperature is lowered, the detector response thresholds are correspondingly lowered [17].

Direct Searches for Particle-Like Dark Matter

A supercooled water detector can be tuned so that freezing only occurs for proton recoils, by virtue of its sensitivity to the $\frac{dE}{dx}$ of the particle track [18, 19]. Such a proton-rich detector would record orders of magnitude fewer backgrounds from the neutrino floor than a conventional dark matter detector due to the nearly vanishing weak charge of the proton. Furthermore, water is not an expensive medium, allowing for the construction of very large-scale experiments. Sensitivities are envisioned down to at least $O(10^{-43}\ \mathrm{cm}^2)$ WIMP-nucleon cross-section (spin-independent), in only 1 kg-year. From the point of view of backgrounds, a proton-rich detector will benefit from significant self-shielding of neutrons, which can be identified and rejected when they inevitably multiple-scatter. It is important to point out, however, that the neutrino floor for oxygen recoils is a potential source of background. Tuning the detector to be insensitive to oxygen nuclear recoils could limit the low energy threshold achievable for the proton recoils. Thus, a full characterization of the recoil thresholds and efficiencies for proton, oxygen, and e^- recoils as a function of the temperature and pressure [20, 21] is necessary. The intrinsic backgrounds, such as those from radon, are also not fully known [22–24]. It is expected that these can be mitigated by purifying the water or by studying alternate signal channels for discrimination (*e.g.*, acoustic or crystal phonon signatures).

In addition to pushing into the low-cross-section portions of parameter space, this concept should also be able to push to lower dark matter particle masses (∼200 MeV up to 20 GeV / c^2). Supercooled liquids should intrinsically possess lower energy thresholds than needed for ionization, for example [25, 26]. Water supercooled to -20° to -40° C [27, 28] should achieve O(keV)-level thresholds, or below [29–31], although this needs to be explored with dedicated measurements [32]. The light mass of the proton also kinematically favors energy transfers in elastic scattering from lighter primary particles. While CEνNS backgrounds on oxygen are a concern that is tightly coupled to the detector threshold, the background discrimination capability for betas and gamma-rays, for instance, is unknown at lower thresholds, and needs to be characterized as well.

There is also the potential to make dramatic improvements in spin-dependent dark matter searches [33]. The coupling to an unpaired proton provides a fairly unique sensitivity to spin-dependent scattering on protons. Such searches do not benefit from the putative A^2 coherent coupling for spin-independent interactions.

This relative loss of sensitivity can be counteracted by the potential for very large deployments [34] with very low proton recoil thresholds, which are feasible with modest purification and straightforward temperature control. Such large deployments must, of course, take a modular, and potentially internationally distributed form. This approach has the additional benefit of circumventing the negative impact of the long dead-time associated with resetting the supercooled phase in each module, which could be further mitigated through a droplet approach [28, 35, 36], use of microwaves, or other aggressive heating elements. A deployment above ground may permit searches for SIMPs (Strongly Interacting Massive Particles) or similar exotica [37].

Neutrino Scattering Experiments

A supercooled liquid detector also has the potential to play a role in numerous neutrino experiments. It is likely possible to reach operational conditions wherein such a detector will respond to oxygen nucleus recoils [7]. The detector would thus be sensitive to the CEνNS interaction [8] but with a low-mass even-even nucleus. Precision tests of the standard model cross-section (*e.g.*, Non-standard Interactions) would then be possible [38, 39], devoid of the complicating uncertainties due to the nuclear form factor, and the less-well-predicted axial current contributions to neutrino cross-section. For homeland security applications, a (compact) water CEνNS detector could detect reactor neutrinos [40]. Low-cost and modular designs would enable searches for sterile neutrinos with a total neutral current disappearance experiment at multiple baselines [41]. A large-scale world-wide deployment would also play an important role for supernova neutrino burst detection. Lastly, a detector using deuterated water could be a viable technology for normalizing low-energy neutrino fluxes from stopped-pion beams. Unfortunately, as it is only a threshold detector, each supercooled liquid module provides no spectral information on the nuclear recoils. This deficiency could be mitigated, however, through the use of a large modular array, with modules at slightly different thresholds, or with doping (future work).

Future Work

The "Snowball Chamber" detector concept has the potential to make significant sensitivity gains for future dark matter direct detection experiments, and to play an important role in several related areas of neutrino physics. There is also a great deal of untapped potential that has yet to be completely explored. In addition to proton and oxygen recoils, the search for dark matter scattering off electrons is an intriguing possibility. Coupled with the low mass of the electron, the intrinsically low energy threshold of the supercooled detector could allow searches for axion-like particles and bosonic super-WIMPs [42]. Due to intense hydrogen bonding and other microphysics effects, water has the potential for encoding the direction of the recoils [43–45], which could be used to further reject solar neutrino backgrounds for WIMP searches.

Hybrid detection schemes should also be explored for use in neutrino, dark matter, or calorimetry physics. Incorporation of water-based liquid scintillator [46], or the doping of the water [47] with quantum dots [48], may augment the freezing signal with a signature proportional to the energy deposited. Alternatively, the Cherenkov signal could be recorded along with any coincident freezing event [49]. The pin-point nucleation centers at the onset of a freezing event would provide high-position-resolution images for tracks, allowing for a new directional *neutron* detector class. Finally, other supercooled liquids could also be explored, including noble elements such as Xe and Ar [50]. Such targets provide opportunities to tune the target's mass (A), while also providing alternative signal channels (*e.g.* scintillation). All these uses, however, still suffer from long thaw times. While still in its infancy, the supercooled liquid detector program detailed above should be pursued in detail, as there is significant untapped potential in the technology in particle physics applications.

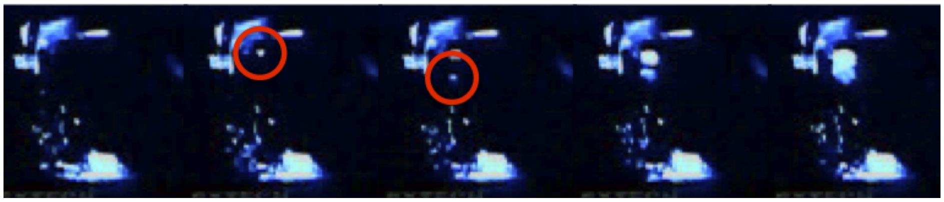

Fig. 1: Example of the formation of two merging snowballs, likely to be caused by the same neutron. There are 150 ms in between frames.

1 References

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