Snowmass2021 - Letter of Interest

Enabling the next generation of bubble-chamber experiments for dark matter and neutrino physics

IF Topical Groups: (check all that apply □/■)
□ (IF1) Quantum Sensors
□ (IF2) Photon Detectors
□ (IF3) Solid State Detectors and Tracking
□ (IF4) Trigger and DAQ
□ (IF5) Micro Pattern Gas Detectors (MPGDs)
□ (IF6) Calorimetry
□ (IF7) Electronics/ASICs
■ (IF8) Noble Elements
□ (IF9) Cross Cutting and Systems Integration
□ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter: Eric Dahl (Northwestern University and Fermilab) [cdahl@northwestern.edu]
Collaborations: PICO (PICASSO-COUPP), SBC (Scintillating Bubble Chamber)

Related Snowmass2021 LOIs:
Multi-ton scale bubble chambers (CF1)
Reaching the solar CEνNS floor with noble liquid bubble chambers (CF1)
Neutrino physics with noble liquid bubble chambers (NF3)

Abstract:
The bubble chamber technique offers virtually background-free detection of low-energy nuclear recoils, *e.g.* for the direct detection of dark matter or coherent elastic scattering of neutrinos. This Letter of Intent describes the continued development necessary to enable the next generation of bubble chamber experiments, including R&D toward multi-ton-scale bubble chambers and efforts to extend the physics reach of bubble chambers in new directions. Specific thrusts supporting scalability include surface bubble nucleation studies to find alternatives to fused silica flasks, acoustic bubble imaging, and active-veto hydraulic fluids. Specific thrusts supporting new physics goals include the characterization of new bubble chamber target fluids, precision calibrations of bubble nucleation thresholds, and development of event-by-event energy reconstruction techniques.

I. INTRODUCTION

This Letter of Intent from scientists across the bubble chamber community describes the detector development needed over the next 5+ years to enable a new generation of experiments using large-scale bubble chambers. For the past decade, freon-based bubble chambers have played a key role in dark matter direct detection, leading the field in sensitivity to spin-dependent couplings between dark matter and protons [1–5]. This role will become central in the coming generation of experiments, as large-scale freon chambers probe parameter space fundamentally inaccessible to Xe, Ar, Ge, and Si-based detectors due to the neutrino floor [6] (see also the LOI to CF1 titled *Multi-ton scale bubble chambers*). At the same time, developments with low-threshold noble-liquid bubble chambers [7] have created new opportunities to search for low-mass dark matter [6] (see also the LOI to CF1 titled *Reaching the solar CEvNS floor with noble liquid bubble chambers*) and to measure neutrino properties via coherent scattering of reactor neutrinos [8] (see also the LOI to NF3 titled *Neutrino physics with noble liquid bubble chambers*).

Realizing the potential of bubble chambers for dark matter and neutrino physics will require continued technical development, much of which meets common needs across multiple experiments. The needed R&D falls in two categories: developments enabling larger background-free exposures, and developments enabling the exploration of new parameter spaces and physics topics. Specific thrusts within each category are described in the following sections.

II. R&D ENABLING MULTI-TON-SCALE DEVICES

The PICO-500 experiment will be the largest low-background bubble chamber to date, with a target ton-year exposure. Larger chambers for future dark matter searches and high-statistics neutrino measurements will benefit from the following planned developments:

- **Surface nucleation studies**
  Long-exposure bubble chambers must keep bubble nucleation rates on the surfaces wetted by the superheated target fluid at or below $O(100)$ events/day. This can be achieved using fused silica flasks for chambers up to several hundred liters, but at that scale the flasks are both the most expensive and most fragile element of the detector, and fabrication of fused silica flasks for larger chambers becomes increasingly cumbersome. The identification of new materials and surface treatments suitable for low-background bubble chambers is a key concern for future large-scale experiments. Directions of investigation may include rigid polymers, flexible (balloon-style) enclosures, all-metal containers, or combinations of the above.

- **Acoustic bubble imaging**
  The ability to robustly reconstruct bubble positions through photography is one of the great strengths of the bubble chamber. However, the requirement that the bubble chamber flask be optically transparent severely restricts the materials available for the flask, which in turn drives the surrounding bubble chamber design. The ability to locate bubbles without a transparent jar, *e.g.*, through passive or active acoustic imaging, would greatly simplify bubble chamber design and expand the range of viable solutions to the first bullet above.

- **Hydraulic fluid as an active-veto**
  Large exposures must be accompanied by correspondingly low backgrounds to reach physics goals. Virtually all large scale low-background nuclear recoil detection experiments now use active vetoes to combat neutron backgrounds. The natural location for an active veto in a bubble chamber is in the hydraulic volume surrounding the active fluid. Developing liquid scintillators, scintillation detectors, and readout schemes that are compatible with the pressures and temperatures required for bubble chamber hydraulics is a necessary step towards the next generation of low-background bubble chamber experiments.

III. R&D ENABLING NEW PHYSICS

As virtually background-free nuclear recoil detectors capable of operating with nearly any target nucleus, the potential physics reach of the bubble chamber technology is much broader than is covered by the current suite of experiments (searches for spin-dependent scattering of >10 GeV dark matter particles in PICO, and spin-independent scattering of 0.7–10 GeV dark matter particles in SBC). The following R&D thrusts will open new physics opportunities to the bubble chamber technology:

- **Characterization of new bubble chamber target fluids**
  Bubble chambers can operate using any fluid with a vapor pressure, and the technique's physics reach can be enhanced by the use of multiple target fluids. This strength has already been utilized by PICO-60, which used a CF_3I target to search spin-independent parameter space and to exclude iodine-specific interpretations of the DAMA modulation [2], then used a C_3F_8 target to produce world-leading spin-dependent limits [5]. The use of liquid noble targets has also opened new doors, adding a scintillation channel and allowing operation at reduced thresholds. Untapped opportunities with new fluids include operation with hydrogenated fluids, using proton recoils to search for low-mass dark matter with spin-dependent or spin-independent coupling, and operation with liquid-nitrogen, adding spin-dependent sensitivity to both protons and neutrons to the low-threshold cryogenic chamber program.

- **Precision bubble nucleation threshold calibrations**
  Each bubble chamber fluid must undergo a basic characterization to find its sensitivity to electron and nuclear recoils as a function of superheat. Precision cross-section measurements, however, either for neutrino physics or for future characterization of a dark matter signal, require further, precision calibration of the pressure, temperature, and energy dependence of bubble nucleation by nuclear recoils, and potentially dependence on new parameters as well (*e.g.*, applied electric field and nuclear recoil direction). Given the limited event-by-event energy information and overall rate limitations inherent to bubble chamber operations, these calibrations can be as challenging as the low background experiments themselves. The bubble chamber community is continuing to develop the experimental, analysis, and modeling techniques needed to achieve these calibrations.

- **High-resolution event-by-event energy reconstruction**
  While the energy threshold for bubble-nucleation may be very sharp, reconstructing the energy of the recoil that led to a bubble is challenging. Freon-based bubble chambers have achieved $\sim$1-MeV resolution by measuring the acoustic signals from growing bubbles, while scintillating noble-liquid chambers can measure nuclear recoil energies with $\sim$10-keV resolution. Improving this energy resolution both addresses potential backgrounds and aids the precision calibrations described above. Specific efforts to improve energy reconstruction may include the identification of additional scintillating bubble chamber target fluids, increasing light collection via improved reflectors and doping schemes, and exploration of infra-red scintillation, as well as continued development of acoustic techniques for non-scintillating chambers.

- **New operational modes**
  Bubble chambers for dark matter and reactor neutrino CEvNS detection operate in a mode suitable for a constant, low interaction rate. Bursts of activity, such as from a supernova or a beam spill, may be better observed with specialized expansion/compression schemes, *e.g.* delayed compression to allow detection of "late" nucleation sites. Efforts in this direction aim to develop operational modes that allow extended exposures to these "bursts" while preserving the thermodynamic state of the chamber.

REFERENCES

[1] C. Amole *et al.* (PICO), *Dark Matter Search Results from the PICO-2L C_3F_8 Bubble Chamber*, Phys. Rev. Lett. **114**, 231302 (2015). arXiv:1503.00008 [astro-ph.CO].

[2] C. Amole *et al.* (PICO), *Dark matter search results from the PICO-60 CF_3I bubble chamber*, Phys. Rev. D **93**, 052014 (2016). arXiv:1510.07754 [hep-ex].

[3] C. Amole *et al.* (PICO), *Improved dark matter search results from PICO-2L Run 2*, Phys. Rev. D **93**, 061101 (2016). arXiv:1601.03729 [astro-ph.CO].

[4] C. Amole *et al.* (PICO), *Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber*, Phys. Rev. Lett. **118**, 251301 (2017). arXiv:1702.07666 [astro-ph.CO].

[5] C. Amole *et al.* (PICO), *Dark Matter Search Results from the Complete Exposure of the PICO-60 C_3F_8 Bubble Chamber*, Phys. Rev. D **100**, 022001 (2019). arXiv:1902.04031 [astro-ph.CO].

[6] M. Battaglieri *et al.*, in *U.S. Cosmic Visions: New Ideas in Dark Matter* (2017) arXiv:1707.04591 [hep-ph].

[7] D. Baxter *et al.*, *First Demonstration of a Scintillating Xenon Bubble Chamber for Detecting Dark Matter and Coherent Elastic Neutrino-Nucleus Scattering*, Phys. Rev. Lett. **118**, 231301 (2017). arXiv:1702.08861 [physics.ins-det].

[8] *Proceedings of The Magnificent CEνNS Workshop 2018* (2019) arXiv:1910.07450 [hep-ex].

AUTHORS

E. Alfonso-Pita,[1] M. Ardid,[2] I. J. Arnquist,[3] D. M. Asner,[4] M. Baker,[5] D. Baxter,[6] E. Behnke,[7] D. Biaré,[5] A. Brandon,[8] M. Bressler,[9] K. Clark,[10,11] J. I. Collar,[6] R. Coppejans,[8] M. Crisler,[12,3] R. Curtis,[11] C. E. Dahl,[8,12] M. Das,[13] D. Durnford,[5] S. Fallows,[5] R. Filgas,[14] J. Farine,[15] P. Giampa,[11] G. Giroux,[10] J. Hall,[16,15] O. Harris,[17] P. Hatch,[10] H. Herrera,[10] E. W. Hoppe,[3] C. M. Jackson,[3] C. B. Krauss,[5] Y. Ko,[5] N. Lamb,[9] M. Laurin,[18] I. Lawson,[16,15] I. Levine,[7] C. Licciardi,[15] W. H. Lippincott,[19] D. J. Marín-Lámbarri,[1] B. Loer,[3] R. Neilson,[9] A. J. Noble,[10] S. Pal,[5] J. Phelan,[8] M.-C. Piro,[5] S. Priya,[20] A. E. Robinson,[18] S. Seth,[13] Z. Sheng,[8] A. Sonnenschein,[12] N. Starinski,[18] I. Štekl,[14] E. Vázquez-Jáuregui,[1,15] T. J. Whitis,[19] U. Wichoski,[15] S. Windle,[9] A. Wright,[10] V. Zacek,[18] and A. Zuñiga-Reyes[1]

[1]*Instituto de Física, Universidad Nacional Autónoma de México, México D. F. 01000, México*
[2]*Departament de Física Aplicada, IGIC - Universitat Politècnica de València, Gandia 46730 Spain*
[3]*Pacific Northwest National Laboratory, Richland, Washington 99354, USA*
[4]*Brookhaven National Laboratory, Upton, New York, 11973, USA*
[5]*Department of Physics, University of Alberta, Edmonton, T6G 2E1, Canada*
[6]*Enrico Fermi Institute, Kavli Institute for Cosmological Physics, and Department of Physics, University of Chicago, Chicago, Illinois, 60637, USA*
[7]*Department of Physics, Indiana University South Bend, South Bend, Indiana 46634, USA*
[8]*Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[9]*Department of Physics, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[10]*Department of Physics, Queen's University, Kingston, K7L 3N6, Canada*
[11]*TRIUMF, Vancouver, BC V6T 2A3, Canada*
[12]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[13]*Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, Kolkata, 700064, India*
[14]*Institute of Experimental and Applied Physics, Czech Technical University in Prague, Prague, Cz-12800, Czech Republic*
[15]*Department of Physics, Laurentian University, Sudbury, P3E 2C6, Canada*
[16]*SNOLAB, Lively, Ontario,P3Y 1N2, Canada*
[17]*Northeastern Illinois University, Chicago, Illinois 60625, USA*
[18]*Département de Physique, Université de Montréal, Montréal, H3C 3J7, Canada*
[19]*Department of Physics, University of California Santa Barbara, Santa Barbara, California, 93106, USA*
[20]*Materials Research Institute, Penn State, University Park, Pennsylvania 16802, USA*