Snowmass2021 - Letter of Interest

Multi-ton scale bubble chambers

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☑ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Collaboration: PICO Collaboration

Abstract: (maximum 200 words)
Bubble chambers are outstanding instruments for dark matter searches with sensitivity to numerous dark matter-nucleon couplings while maintaining low inherent sensitivity to electron-recoils from background radiation. The PICO collaboration has pushed the forefront of spin-dependent sensitivity in operating several generations of ever larger bubble chambers. The first components of the ton-scale PICO-500 detector are currently under construction. PICO is interested in developing this inexpensive and reliable technology to allow 50t scale detectors that will exceed the sensitivity to spin-dependent dark-matter/nucleon couplings that other targets can attain due to neutrino backgrounds. Bubble chambers also promise excellent versatility by allowing for changes of target material to determine coupling parameters of a dark matter candidate.
Our proposed white paper will explore the key figures of merit and modest advances in detector development required to construct a 50-ton bubble chamber to search for dark matter.

The PICO collaboration and the COUPP collaboration before it have developed bubble chambers into a sensitive and cost-effective method for building ton-scale dark matter detectors. The target material in any of these devices is a homogeneous fluid held in a superheated state by dropping its pressure below its vapour pressure at a given temperature. This state is maintained, for O(10) minutes or more in a low-background environment, until a particle interaction nucleates boiling. Within milliseconds the bubble grows to visible size and continues to grow until the chamber is compressed, driving the fluid back to a stable liquid state.

While background mitigation for other dark matter detector technologies drives their cost, limits on the background radioactivities required for large bubble chambers have already been demonstrated with other technologies. In common with the lowest background detectors in the world, such as liquid scintillator filled neutrino detectors, the active volume can be contained by a thin vessel and surrounded by a high-purity liquid as a hydraulic fluid which could also act as a veto. Since in order to nucleate a bubble, O(keV) of energy needs to be deposited on the scale of 10s of nanometers, bubble chambers are insensitive to low-ionizing electron-recoil backgrounds that limit the low-energy sensitivity of other experiments. Since 2004, continuously superheated bubble chambers or their precursor technology, superheated droplet detectors, have produced world-leading limits in the search for spin-dependent dark matter-nucleus interactions [1-8].

In addition to their capability to discover the dark matter particle, bubble chambers provide an effective means to verify a discovery and explore the detailed properties of a dark matter particle. Bubble chambers can employ a variety of nuclear targets without adding systematic uncertainties in comparing the results of different detectors. This ability to verify other claims has already been exploited with PICO-60 to directly exclude the possibility that iodine nuclear recoils produce the DAMA excess [6]. The PICO collaboration has operated large detectors using various combinations of fluorine, carbon, and iodine, while tests have shown the feasibility of targets containing hydrogen, chlorine, and/or bromine that meet the criteria for use underground of being non-flammable and non-toxic. Doping the detector can extend the technique's sensitivity to other nuclei.

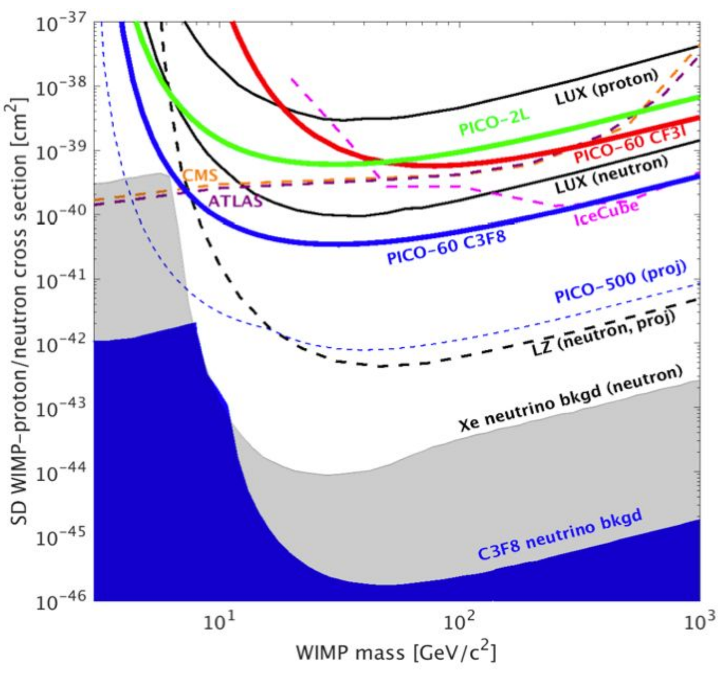

Fig 1: Projected sensitivity of PICO-500. PICO-500 would be sensitive to 3 solar ^{8}B neutrinos after 6 mo. at a low (3.2 keV) threshold necessitating an increase in the threshold for a further 1 year of operation in this projection.

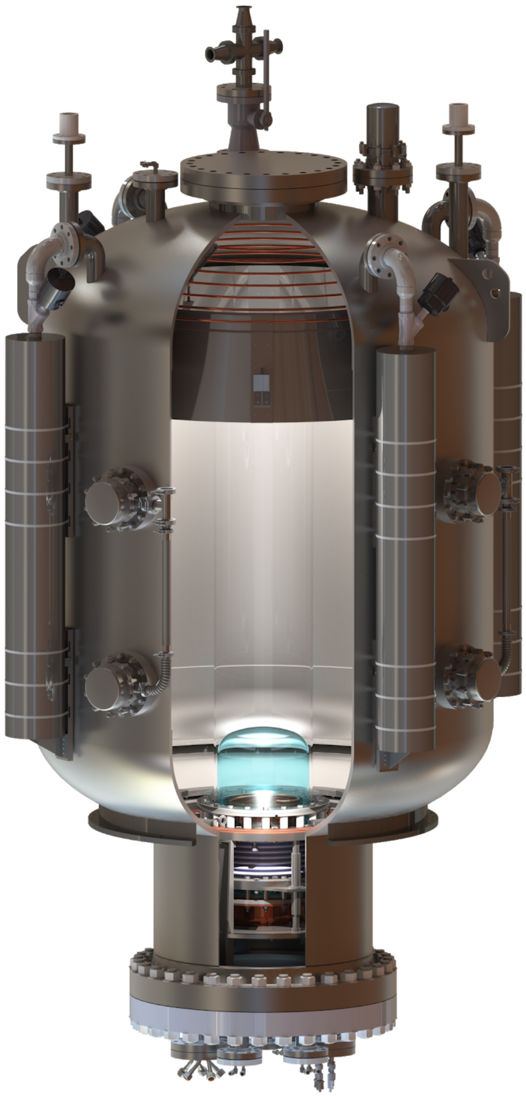

Fig 2: Rendering of PICO-500 inside its pressure vessel.

Using the largest synthetic silica vessels that can be produced, PICO-500, with 340 kg of perfluorinated alkene target fluid is under construction at SNOLAB. A background unique to previous PICO bubble chambers due to the formation of metastable particular-borne water droplets has been eliminated in this design. Whereas previous chambers had used water as a buffer to isolate potential nucleation surfaces, all future chambers are using thermal gradients to cool and stabilize the fluid around these rough surfaces, seals, and fill valves.

Scaling a one-year exposure of PICO-500 by approximately 3 orders of magnitude would allow a bubble chamber to detect scattering from atmospheric neutrinos. This neutrino floor for fluorinated or hydrogenated targets provides the potential for many orders of magnitude greater sensitivity to spin-dependent interactions than can be provided by liquid noble gas detectors while providing comparable sensitivity to spin-independent interactions [9]. Multi-ton scale dark matter detectors are also sensitive to the early neutrinos from a galactic supernova [10].

A 50 ton detector operating for over 5 live-years at zero background could achieve sensitivity to atmospheric neutrinos while also reaching the demonstrated limit on the potential size of such a chamber. This limit is defined by stringent requirements of order 5 nBq/cm^2 on the alpha radioactivity of the inner surface of the active fluid container. Although bubbles from such decays are efficiently identified as a background, they contribute to the detector deadtime due to the need to arrest bubble growth and regain thermal equilibrium.

PICO is interested in pursuing the required technological development and construction of a multi-ton scale bubble chamber. Our white paper will outline the current goals of the PICO program, and the key drivers and development milestones, siting requirements, and outside expertise necessary in order to consider a scaled up detector. These subjects include the development of low-background active fluid containers other than synthetic silica glass, efficient vetoing of muon-induced backgrounds, the physical design of a large detector, and the use of high-density liquid scintillators as hydraulic fluid.

References: (hyperlinks welcome)

[1] Barnabé-Heider *et al.* (PICASSO Collaboration), "Improved spin-dependent limits from the PICASSO dark matter search experiment," Phys. Lett. B624, 186-194, (2005).

[2] E. Behnke *et al.* (PICASSO Collaboration) "Final Results of the PICASSO dark matter search experiment," Astroparticle Physics **90,** 85-92, (2017).

[3] E. Behnke et *al.* (COUPP Collaboration), "Improved limits on spin-dependent WIMP-Proton interactions from a two liter CF_3I bubble chamber," Phys. Rev. Lett. **106** 021303 (2011).

[4] E. Behnke *et al.* (COUPP Collaboration), "First dark matter search results from a 4-kg CF_3I bubble chamber operated in a deep underground site," Phys. Rev. D **86** 052001 (2012). Erratum Phys. Rev. D **90**, 079902 (2012).

[5] C. Amole *et al.* (PICO Collaboration), "Dark matter search results from the PICO-2L C_3F_8 bubble chamber," Phys. Rev. Lett. **114** 231302 (2015).

[6] C. Amole *et al.* (PICO Collaboration), "Dark matter search results from the PICO-60 CF_3I bubble chamber," Phys. Rev. D **93** 052014 (2016).

[7] C. Amole *et al.* (PICO Collaboration), "Improved dark matter search results from PICO-2L Run 2," Phys. Rev. D **93** 061101(R) (2016).

[8] C. Amole *et al.* (PICO Collaboration), "Dark matter search results from the PICO-60 C_3F_8 bubble chamber," Phys. Rev. Lett. **118** 251301 (2017).

[9] J. Billard, E. Figueroa-Feliciano, and L. Strigari, "Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments," Phys. Rev. D **89**, 023524 (2014).

[10] T. Kozynets, S. Fallows, and C. B. Krauss, "Sensitivity of the PICO-500 bubble chamber to supernova neutrinos through coherent nuclear elastic scattering," Astroparticle Physics **105**, 25-30 (2019).

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