Snowmass2021 - Letter of Interest

A crystalline future for dual phase xenon direct detection instruments

Thematic Areas: (check all that apply ☐/■)

■ (IF8) Noble Elements
■ (CF1) Dark Matter: Particle Like

Authors: S. J. Haselschwardt (scotthaselschwardt@lbl.gov), S. Kravitz (swkravitz@lbl.gov), R. Mahapatra (mahapatra@physics.tamu.edu), P. Sorensen (pfsorensen@lbl.gov)

Abstract: A dual-phase (crystal/vapor) xenon Time Projection Chamber should be considered for future rare-event searches. It could potentially offer near-total mitigation of radon backgrounds, which are presently the limiting background to state-of-the art dark matter search experiments such as XENON1T. It is additionally hypothesized that crystalline xenon may offer improved particle discrimination compared with liquid. Further R&D also offers the possibility of detecting phonons from particle recoil within the crystalline xenon, using athermal phonon sensors. This would allow detection of keV-scale nuclear recoils without Lindhard suppression, if operated at sub-100 mK temperatures.

1 Crystalline xenon for radon exclusion and tagging

A new generation of massive dark matter direct detection experiments, including LZ [1] and XENONnT [2], will soon begin operations. Their detector technology is a liquid xenon time projection chamber (TPC), and they will search a significant new region of dark matter parameter space. However, they will be limited by radon backgrounds rather than by the irreducible neutrino flux from solar, atmospheric and diffuse cosmic sources. Whatever the experimental outcome − improved exclusion limits, a few tantalizing events, or a dark matter signal detection − there will be strong motivation to reach the irreducible neutrino detection limit. These experiments already possess sufficient intrinsic sensitivity to reach the neutrino detection limit, but we need to mitigate radon backgrounds.

A dual phase (crystal/vapor) crystalline xenon TPC is expected to offer two (or more, see below) significant new instrumental advantages: (1) exclusion of radon which emanates from detector materials, and (2) full tagging of radon or radon daughter nuclei which decay in the active xenon target. The former remains to be experimentally verified, while the latter has already been demonstrated in other crystalline targets [3]. This tag signature mostly vanishes [4] in the liquid state due to convective fluid flow, which destroys the spatial correlation between radon decays and their daughter isotopes.

As a potential upgrade path, it is expected that a crystalline target would maximally preserve the key detector mechanics and metrics of instruments such as LZ and XENONnT. It would also present several instrumental challenges. One of the most significant is in-situ growth of the crystal while maintaining the ultra-high purity that is needed to preserve electron drift across the target. The Berkeley Lab group is presently working towards a demonstration of the feasibility of this approach at the table-top scale, including complete suppression of radon backgrounds via radon-daughter tagging. Initial R&D goals include establishing operating parameters compatible with high purity, optical transparency and single electron sensitivity.

It is important to note that radon reduction is an active area of research. Two primary techniques for removing radon atoms from xenon gas: adsorption on charcoal [5], and cryogenic distillation [6]. Both are effective, with reported reduction factors of $\times 14$ and $\times 27$ respectively. In fact, the charcoal adsorption technique is also used to successfully remove radioactive ^{85}Kr from LZ xenon [7]. However, neither technique is presently sufficient, nor is it yet obvious that either will be. One aspect of this problem is due to the fact that removal of radon emanated into the bulk liquid xenon is limited by the xenon circulation rate.

2 Liquid to Crystal Phase Change Preserves Core Instrument Functionality

A basic premise of this idea is that all of the core functionality of the liquid xenon TPC will be preserved in a crystalline xenon TPC. At 161 K, the triple point of xenon is only a few degrees lower than typical liquid xenon TPC operating conditions. Xenon can be crystallized around photomultipliers without affecting their operation. Key parameters for signal generation and detection are summarized in Table 1 and discussed further below.

The available signal for detection of keV-scale particle interactions is remarkably similar in both liquid and solid xenon [12]. This is expected due to the similarity of the band gap. Detector energy threshold is set by the detection of scintillation photons (S1), which has been measured to be about 15% smaller in the crystalline state [12]. This mild reduction is hypothesized to arise because a small fraction of the scintillation in the crystalline state is shifted to wavelengths as low as 148 nm at T=4.7 K [13]. It may be possible to recoup some or all of the previously observed 15% loss by using vacuum ultraviolet sensitive silicon photo-multipliers.

Table 1: Summary of the similarities and differences between liquid and solid xenon, in regard to their suitability as particle detection target.

Property	Solid	Liquid	Unit	Reference
band gap	9.27	9.22	eV	[8]
electron emission	90	86	% at E=4 kV/cm	[9]
electron mobility	4.5×10^3	2.2×10^3	cm^2/V/sec	[10]
density	3.4	2.9	g/cm^3 at T=161 K	[11]

Other key benefits of crystal include: (a) higher electron emission probability across the solid-vapor interface [9]; (b) lower pileup due to a factor ×2 improvement in electron [10] (and positive hole [14]) mobility; (c) a 17% increase in target mass (density of the crystalline phase) for an instrument of the same physical volume; (d) possibility for improved position resolution, since diffusion of drifting electrons increases with the square root of the electron transit time; (e) a possibility of improved incident-particle type discrimination. This is hypothesized on account of the increased electron mobility, which would tend to allow electrons to travel further from an initial ionization track, thereby decreasing recombination fluctuations. Items (d) and (e) remain to be experimentally confirmed.

3 New directions with crystalline xenon

A related new direction in such a dual-phase solid xenon detector technology will be explored by implementing athermal phonon sensors that will be in contact with the solid xenon. There are expected to be several advantages from measuring vibrations in the crystal that result from particle scattering event: (a) in contrast to electromagnetic signal channels, phonons do not have known large Lindhard suppression, (b) phonon measurement allows for very low energy recoil measurement, (c) significantly improved discrimination from an additional energy measurement that doesn't depend on the type of interaction and (d) ability to detect microphonic or crystalllagraphic instability induced signals that may be harder to reject using light and ionization. However, this detection mode requires the cryogenic system to be operated at sub-100 mK temperatures. This may not be incompatible with traditional dual-phase operation, if for example the athermal phonon sensors are operated at sub-100 mK temperatures at the end of a cold finger, while the bulk crystalline xenon operates at 161 K through an appropriately chosen window separating them thermally.

References

[1] D. S. Akerib *et al.* [LUX-ZEPLIN], Phys. Rev. D **101**, no.5, 052002 (2020) doi:10.1103/PhysRevD.101.052002 [arXiv:1802.06039 [astro-ph.IM]].

[2] E. Aprile *et al.* [XENON], [arXiv:2007.08796 [physics.ins-det]].

[3] A. Aguilar-Arevalo *et al.* [DAMIC Collaboration], JINST **10**, no. 08, P08014 (2016) doi:10.1088/1748-0221/10/08/P08014 [arXiv:1506.02562 [astro-ph.IM]].

[4] E. Aprile *et al.* [XENON Collaboration], Phys. Rev. D **95**, no. 7, 072008 (2017) doi:10.1103/PhysRevD.95.072008 [arXiv:1611.03585 [physics.ins-det]].

[5] K. Abe et al (XMASS Collaboration), Nucl. Instr. Meth. A **661** 50 (2012).

[6] E. Aprile *et al.* [XENON100 Collaboration], Eur. Phys. J. C **77**, no. 6, 358 (2017) doi:10.1140/epjc/s10052-017-4902-x [arXiv:1702.06942 [physics.ins-det]].

[7] D. S. Akerib *et al.* [LUX Collaboration], Astropart. Phys. **97**, 80 (2018) doi:10.1016/j.astropartphys.2017.10.014 [arXiv:1605.03844 [physics.ins-det]].

[8] U. Asaf and I. T. Steinberger, Phys Rev B **10** 4464 (1974).

[9] E.M. Gushchin, A.A. Kruglov and I.M. Obodovskii, Sov. Phys. JETP **55** (5) 1982.

[10] L. S. Miller, S. Howe, and E. Spear, Phys. Rev. **166** 871 (1968).

[11] Rabinovich, V.A., Vasserman, A.A., Nedostup, V.I., and Veksler, L.S.. Thu . “Thermophysical properties of neon, argon, krypton, and xenon.” United States (1987).

[12] J. Yoo, H. Cease, W. F. Jaskierny, D. Markley, R. B. Pahlka, D. Balakishiyeva, T. Saab and M. Filipenko, arXiv:1410.6496 [physics.ins-det].

[13] D. Varding, I. Reimand and G. Zimmerer, Phys. Stat. Sol. **b 185** 301 (1994).

[14] O. Hilt. W.F. Schmidt, Chemical Physics 183 147 (1994).