Solid Xenon Bolometers for Anti-correlation Studies

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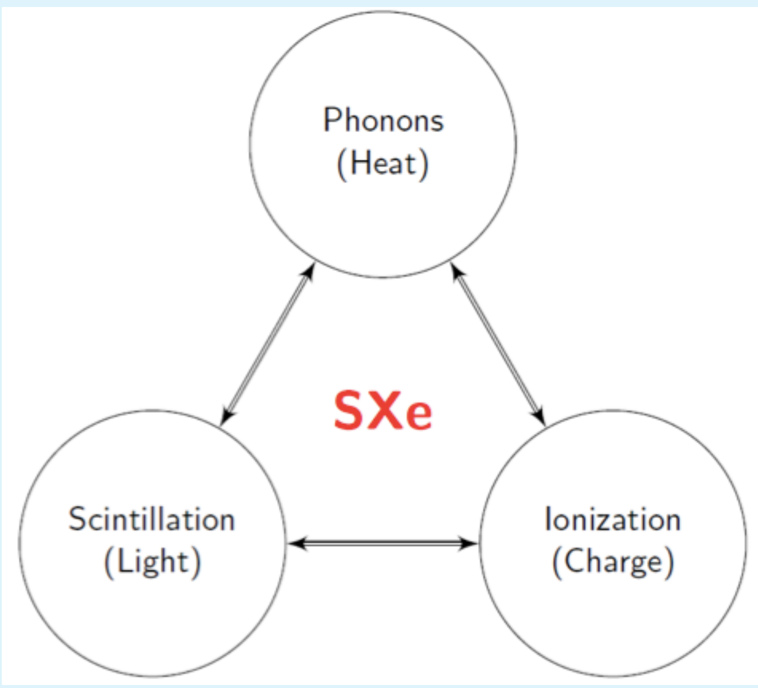
Cryogenic liquid xenon detectors have become a popular technology in the search for rare events, such as dark matter interactions and neutrinoless double beta decay. The power of the liquid xenon detector technology is in the combination of the ionization and scintillation signals, resulting in particle discrimination and improved energy resolution over the ionization-only signal. The improved energy resolution results from a strong microscopic anti-correlation phenomenon that has not been described from first principles. Solid xenon bolometers, under development at Drexel University, would offer an opportunity to study scintillation, ionization, and phonon signals simultaneously. This additional energy channel may offer the final piece of the puzzle in understanding the microscopic anti-correlation phenomenon in detector energy response.



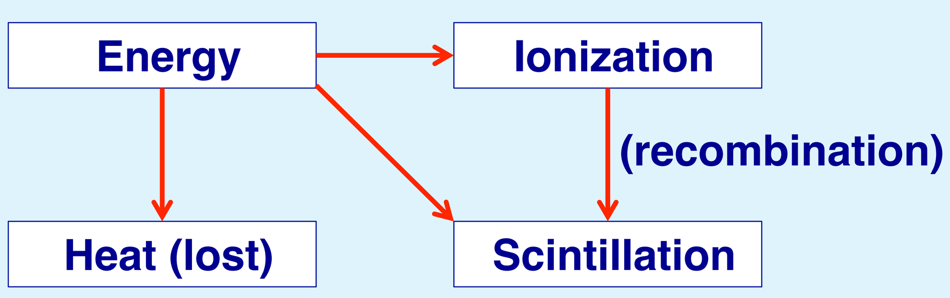
Solid Xenon Detectors

The bolometric detector technique and liquid xenon detectors have both been applied to rare event searches in basic nuclear physics, but they have never before been combined. Solid xenon detectors offer the possibility for a first observation of a detector that combines phonon, scintillation, and ionization readout. Because of the excellent counting statistics in the phonon channel, bolometers are demonstrated to have energy resolution an order of magnitude better than the energy resolution of a liquid xenon detector.

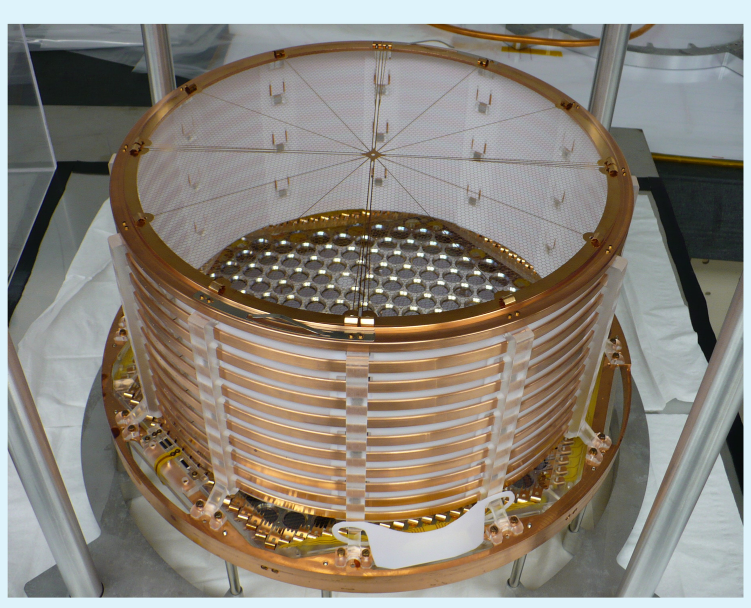
	Gas	Liquid	Solid
W-value [eV]	21.5	15.6[1]	12.4[2] 19.5 [3]
Fano factor	< 0.17	0.0041 [1]	?
Electron drift velocity [cm/sec]	$\sim 10^5$ at 1[kV/cm]	3.0×10^5[4] > 5[kV/cm]	5.0×10^5[4] > 5[kV/cm]
Ion or Hole drift velocity [cm/sec]	Positive ion 0.76 at 1[kV/cm]	Positive ion 0.3 at 1[kV/cm]	Hole 18[4] at 1[kV/cm]

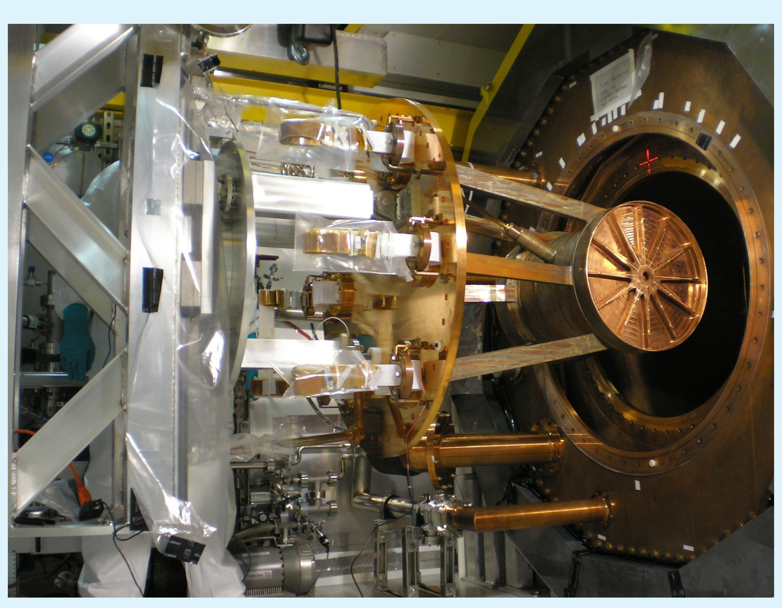
Anti-correlation in liquid xenon

In the past 10 years, cryogenic liquid xenon detectors have become a popular technology in the search for rare events, such as dark matter interactions and neutrinoless double beta decay. The power of the liquid xenon detector technology is in the combination of the scintillation and ionization signals, resulting in particle discrimination and improved energy resolution over the ionization-only signal. The improved energy resolution results from the anti-correlation of the two signals [1].

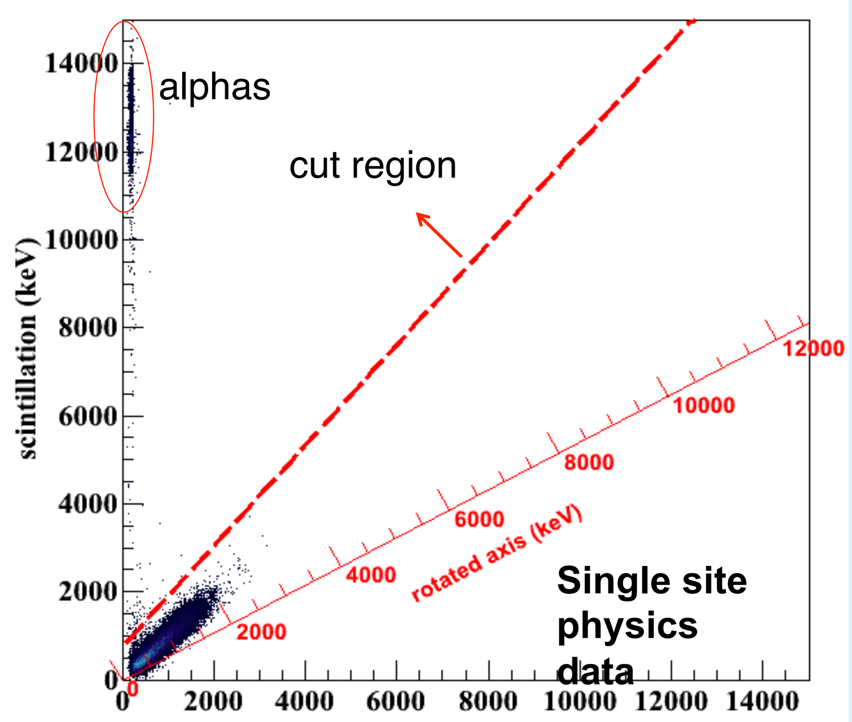


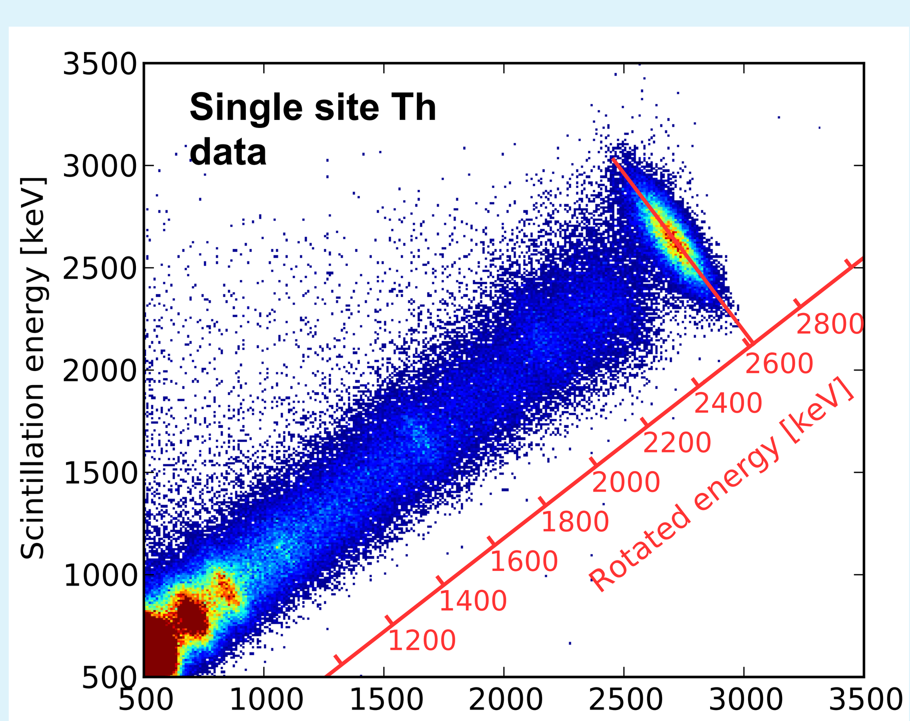
I will focus on EXO-200 as a case study. EXO-200 is a liquid xenon time projection chamber searching for $0\nu\beta\beta$ of ^{136}Xe [1]. The EXO-200 detector has demonstrated an energy resolution of σ/E = 1.25% at the Q-value and set a strong limit of $T_{1/2} > 1.1\times10^{25}$ years at 90% confidence level for $0\nu\beta\beta$ of ^{136}Xe [2]. The next generation experiment nEXO is planned to build on the success of EXO-200.





Because different kinds of particle interactions result in different ratios of scintillation to ionization, liquid xenon detectors have an excellent particle discrimination capability for background rejection.

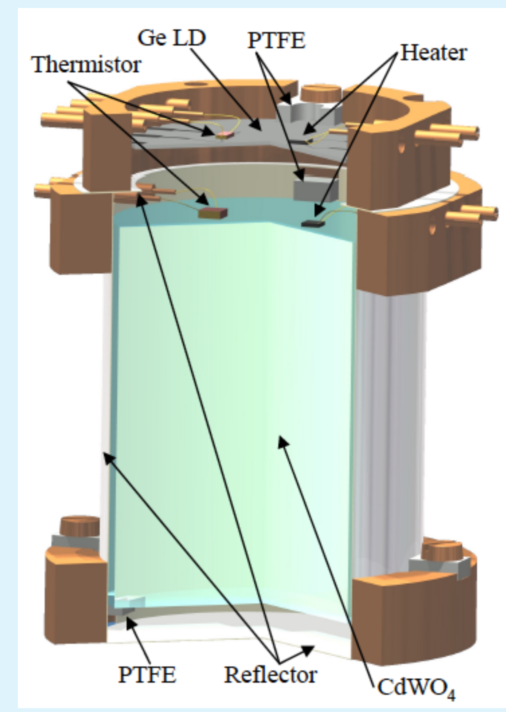


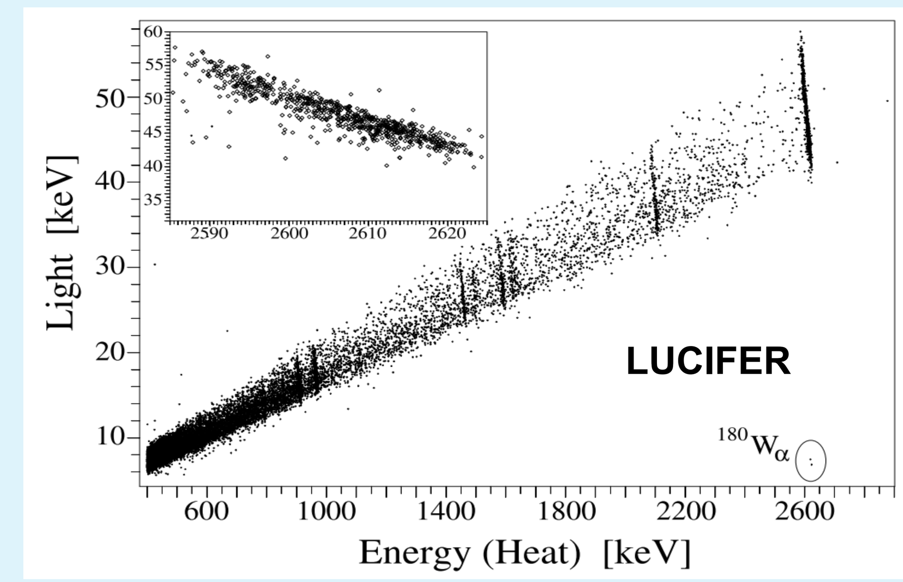


In addition, the combination of ionization and scintillation signals results in improved energy resolution over the ionization-only signal. Liquid xenon displays a microscopic anti-correlation behavior caused by large correlated fluctuations between the ionization and scintillation channels [1]. This phenomenon allows for improved energy resolution through a linear combination of scintillation and ionization signals. It is only in this rotated energy frame that EXO-200 achieves 1.25% energy resolution. While this effect is an important component of the detector response that has been modeled empirically [5], it has not been described from first principles. Because they can detect the normally unusable heat signal directly, solid xenon bolometers may offer the final piece of the puzzle in understanding xenon detector energy response.

Anti-correlation in scintillating bolometers

The combined measurement of any two energy channels can provide particle discrimination, and the combination of all three could be extremely powerful for both detector physics and fundamental physics applications. Scintillating bolometers are under development for $0\nu\beta\beta$ physics, and the CRESST experiment uses scintillating bolometers to search for dark matter [6]. As a case study, data from CdWO4 bolometers being developed for $0\nu\beta\beta$ are shown below demonstrating anti-correlation in the scintillation and phonon channels [7].

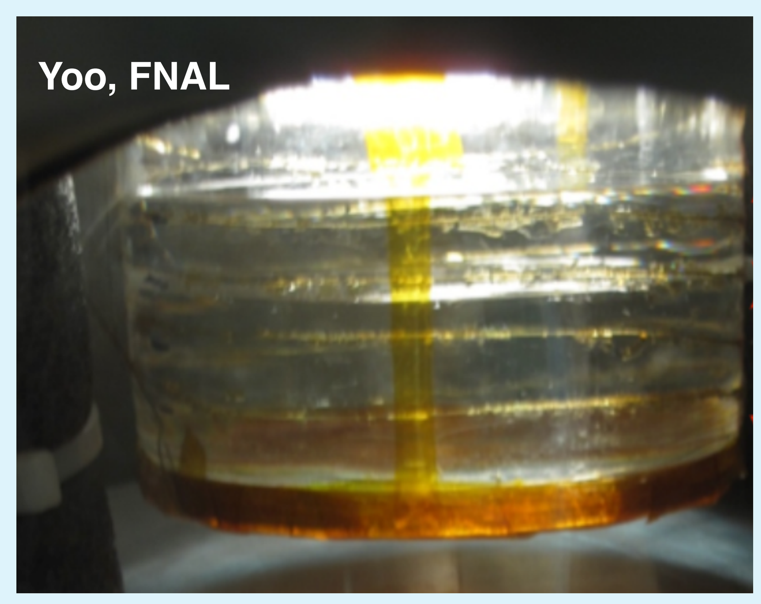




A detector that could simultaneously demonstrate correlated fluctuations in scintillation, ionization, and phonon channels would provide valuable inputs to the understanding of microscopic anti-correlation phenomena. In particular, studying detector response as a function of electric field could help to disentangle the microphysics at work. Interpretation of this data will be complicated by the Neganov-Luke effect.

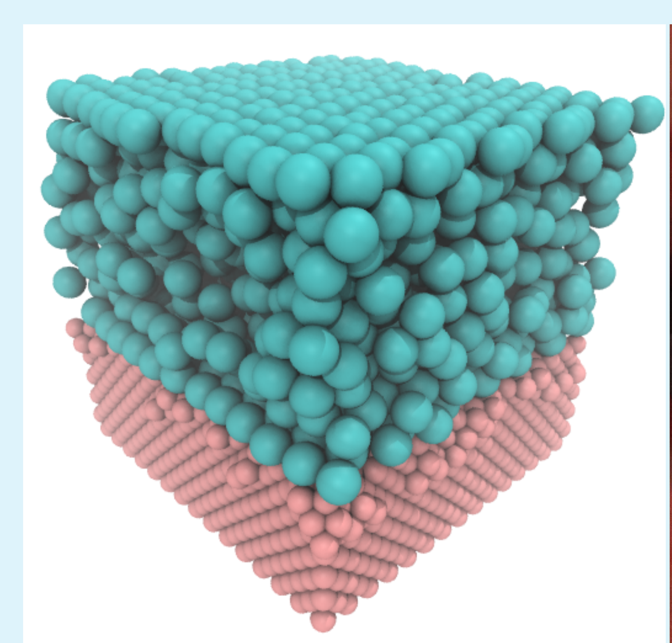
Development of solid xenon bolometers

The Drexel group is developing a technique to grow the Xe absorbers *in situ* in a dilution refrigerator, with an ultimate goal of instrumenting scintillating Xe bolometers.

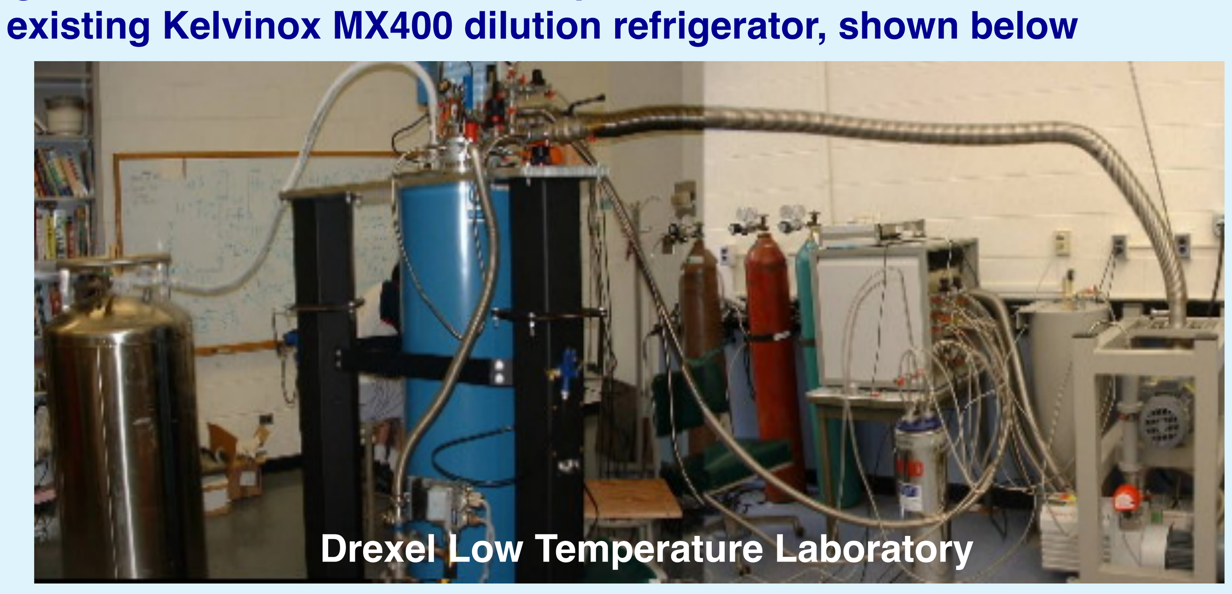


A group at Fermilab has built on work done at Syracuse University using a cryobath method to produced large (~1 kg) solid xenon crystals at a temperature of ~160 K [8]. This work demonstrates the feasibility of growing large, transparent solid xenon crystals, although it is not well-suited for bolometer growth. The group has demonstrated ionization collection in solid xenon at high temperature [9].

Growth studies in an external vacuum chamber using xenon vapor deposition are planned at 4 K using an ARS CS202*B Cryocooler. The growth has been simulated using the LAMMPS molecular dynamics simulation software. The simulation to the right is for 1 ns of deposition and annealing. The group will use the simulations and growth chamber studies to tune the parameters for eventual solid xenon growth within a dilution refrigerator. Also pictured is an early design for a detector growth plate.



The ultimate goal is to demonstrate the operation of xenon bolometers with multi-channel readout in an existing Kelvinox MX400 dilution refrigerator, shown below



Powerful liquid Xe detector technology, scintillating bolometer technology, and the growth of large transparent Xe crystals have all been demonstrated. The Drexel group is working toward the synthesis of these technologies in order to develop and characterize low temperature detectors based on solid Xe.

References and acknowledgments

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