Developing a Xenon-Doped Argon Ionization Detector with Direct VUV Light Readout

Nuclear Science & Security Consortium

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Abstract

At Lawrence Livermore National Laboratory we are developing a liquid argon detector system (CHILLAX), which can operate stably at a high xenon doping rate.

CHILLAX is designed to house 1 L of liquid argon and has deployed VUV-sensitive silicon photomultipliers (SiPMs) which can directly detect argon scintillation light with appreciable photon detection efficiency.

We have installed instruments for precision measurements of xenon in the argon gas and liquid as well as a camera to visually monitor the stability inside the detector can.

We are currently experimenting with novel techniques to improve the stability of heavily-doped argon-xenon liquid mixtures.

Motivation and Challenges

Argon is utilized at a multi-ton scale for dark matter and neutrino experiments (e.g., DarkSide20k, DUNE). However, it has undesired features, including its long scintillation lifetime (limits timing resolution), shorter scintillation wavelength (photosensors typically perform better at longer wavelengths), and a higher ionization energy (fewer excitations per drift electron in a TPC).

Property	Gas scintillation wavelength	Gas scintillation lifetime	Liquid phase ionization energy	Kinetic match to light particles
Argon	128 nm	~ 3.2 μs	14.3 eV	A = 39.95
Xenon	178 nm	~ 22 ns	12.13 eV	A = 131.29

Argon could benefit from making its light more "xenon-like". This could be achieved by doping argon with xenon at the O(1%) level.

Challenge in xenon doping: major difference in melting/boiling points!

	Melting Point (1 atm)	Boiling Point (1 atm)
Ar	84 K	87 K
Xe	161 K	165 K

Unwanted Distillation

Xenon prefers to dwell in liquid over gas.

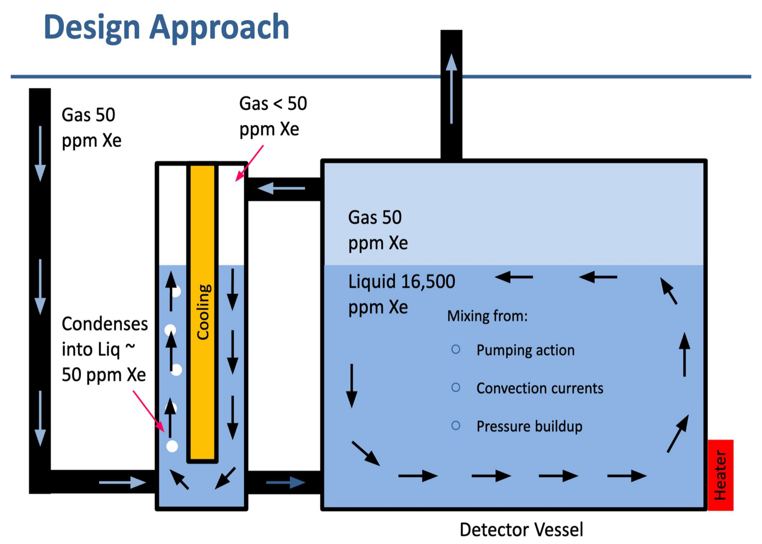
Freezing

Xenon is easily frozen in liquid argon temperatures.

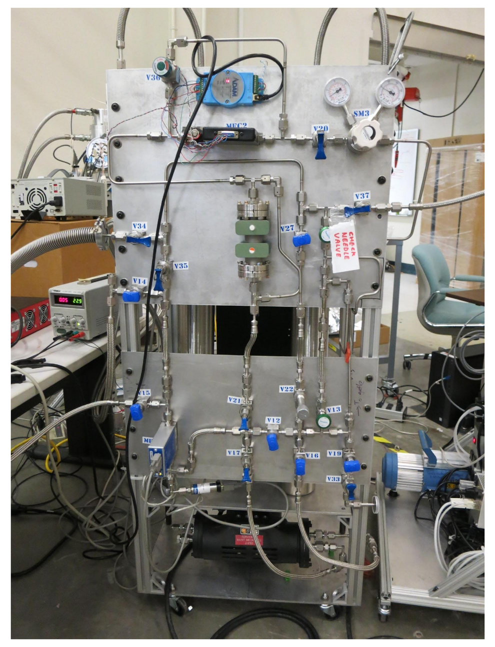
CHILLAX Test Stand

The CHILLAX detector is capable of stably housing 1 L of liquid argon with ±0.5 K and ±0.001 bar stability. Xenon has been doped in the argon at concentrations as high as 4%. SiPM modules immersed in the liquid allow us to monitor how scintillation light changes in response to the xenon concentration.

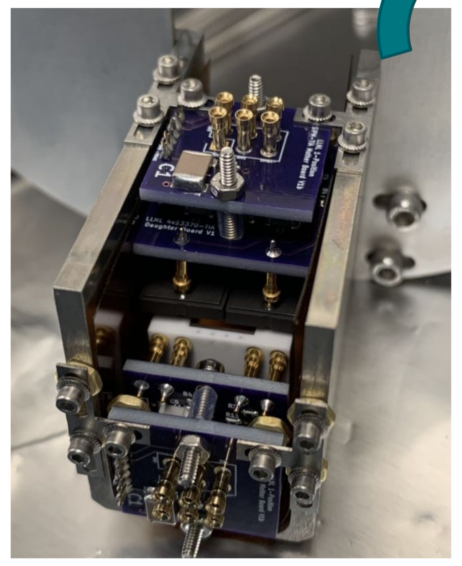
CHILLAX condensation stand with vacuum jacket removed. Argon is continuously circulated through a thermosiphon.



Detector design is optimized to mitigate xenon distillation and freezing.



A gas panel handles circulation of noble gas through a purifier, as well as contains a xenon injection and mixing scheme.



A 3-channel SiPM cell is deployed in the detector to observe argon scintillation light.

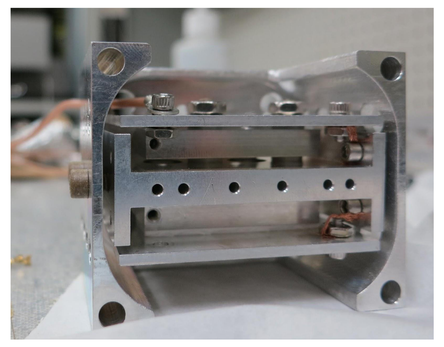
Quantifying Xenon Concentration in CHILLAX

Measuring Xenon in Liquid Argon

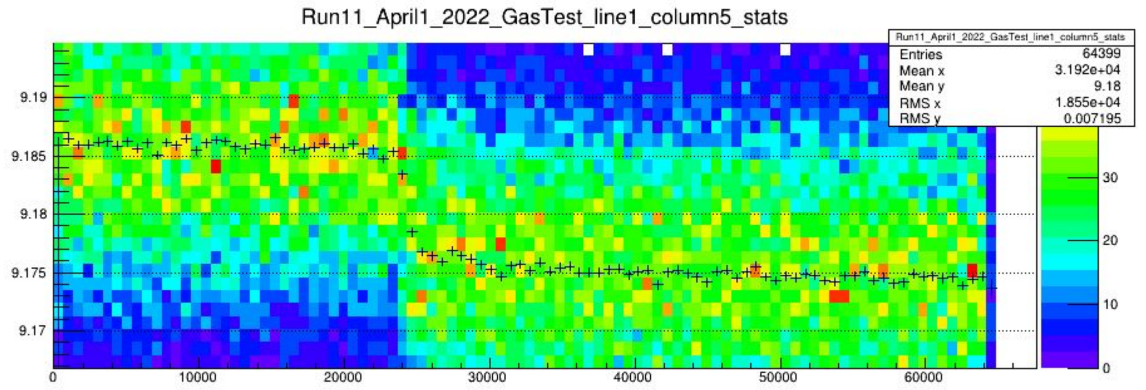
Cryogenic capacitors are deployed in the bottom of the detector to monitor xenon concentration in the liquid.

They operate by detecting changes in the dielectric constants of liquid argon (1.505) and xenon (1.85).

Capacitors boast 1 fF sensitivity, equivalent to [0.05%,0.1%] levels of xenon!



Capacitor before deployment in detector.

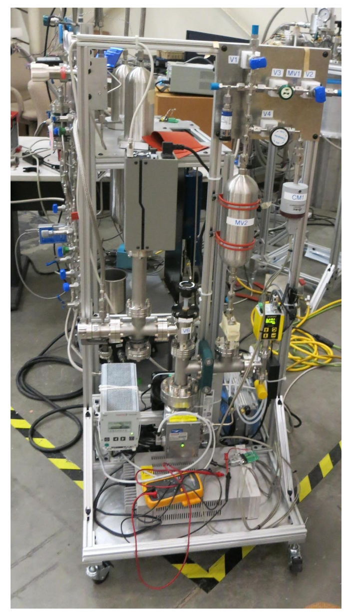


Capacitance change from dielectric change of xenon gas to vacuum ($\Delta\varepsilon \approx 0.0015$).

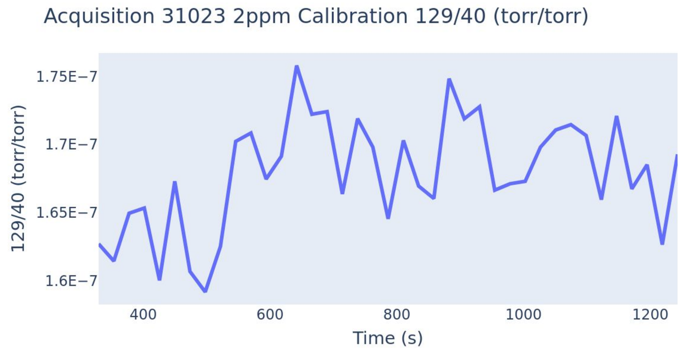
Measuring Xenon in Argon Gas

An RGA samples gas from CHILLAX to quantify xenon concentration.

RGA is capable of measuring xenon gas concentrations at the O(1 ppm) level!



RGA Cart built by E. Mizrachi.

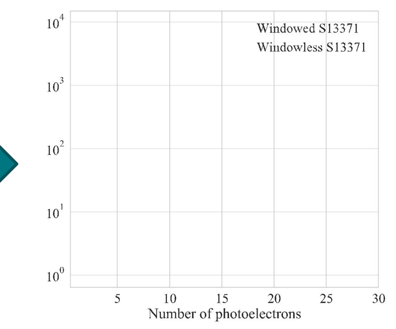


Xe-129:Ar-40 ratio drifts on the order of O(0.1 ppm) over a 15-minute time scale

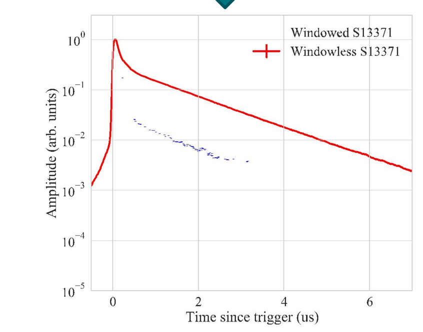
SiPM Characterization with Argon Light

VUV-sensitive Hamamatsu SiPMs were deployed in CHILLAX and characterized with liquid argon light. (arXiv:2202.02977)

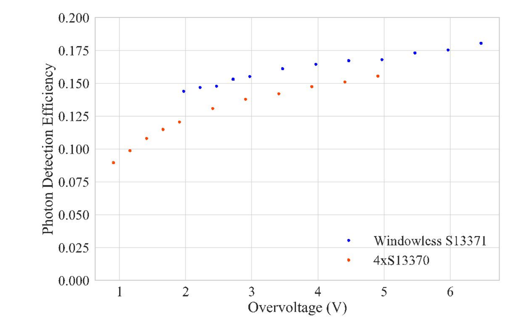
Confirmation of SiPM capability to directly observe argon scintillation light!



Quartz window blocks VUV light.



Exponential time constant for argon triplet and singlet/triplet light ratio agree with literature.



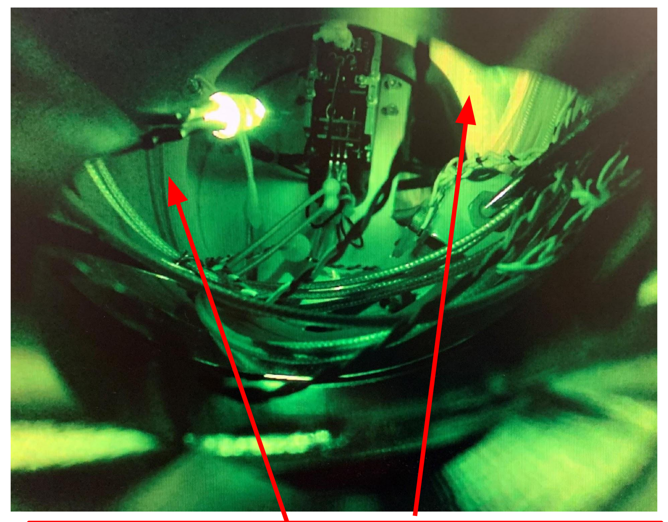
SiPM PDE values consistent with Hamamatsu.

Current Challenge: Xenon Ice

Problem: Xenon Icing

Xenon ice forms above the liquid level on detector walls at ~0.2% despite doping levels far below the xenon solubility limit (~7% at 2 bar).

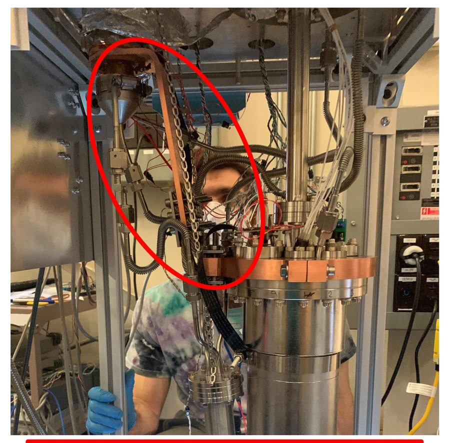
It is likely that liquid argon travels up walls by capillary action, evaporates, and leaves behind xenon residue.



Xenon ice forms a "rime" around the can wall. Camera built by R. Smith.

Solution: Cooling Detector Flange

If argon sweat can trickle down the can wall, xenon ice may be dissolved. A copper piece thermally connects the condenser to the top of the detector flange, which did not cause argon sweat but dramatically slowed xenon ice buildup. More aggressive cooling schemes are planned to induce argon sweat.



A copper link keeps the top flange cold.

Conclusion

The CHILLAX detector is investigating the challenges of doping xenon in liquid argon while developing tools to precisely quantify the whereabouts of xenon in the system. Meanwhile, the detector has served as a test stand to directly characterize VUV-sensitive SiPMs in a liquid argon environment with liquid argon scintillation light.

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National Nuclear Security Administration