Frame Title

Development of a Single Phase Liquid Xenon Detector for Reactor Antineutrino Detection

Jianyang Qi

University of California, San Diego

November 29, 2022

Acknowledgement: This work is supported by a DARPA Award (K. Ni) and DOE HEPCAT Graduate Fellowship (J. Qi)

Motivation

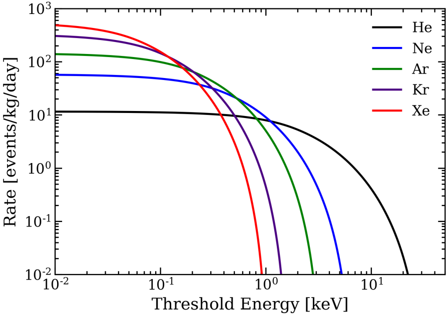


Figure: Integrated CEvNS rate on different noble elements [1]

- Coherent Elastic Neutrino Nucleus Scattering (CEνNS) is the lowest energy standard model process
- CEνNS has been detected before by COHERENT at the Spallation Neutron Source [2][3] but not yet at a nuclear reactor
- Reactors provide a pure source of electron antineutrinos with a high flux, but sub-keV nuclear recoils in Liquid Xenon (LXe)

Dual Phase vs Single Phase

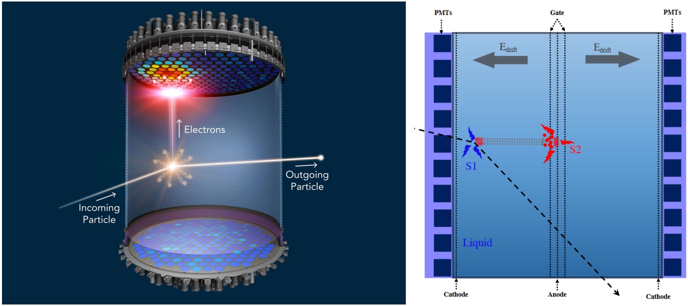


Figure: Left: LZ dual phase detector. Right: Principle of a single phase detector (Qing Lin arXiv: 2102.06903)

- S1: Prompt scintillation light
- S2: Scintillation light proportional to the number of ionization electrons

Dual Phase vs Single Phase

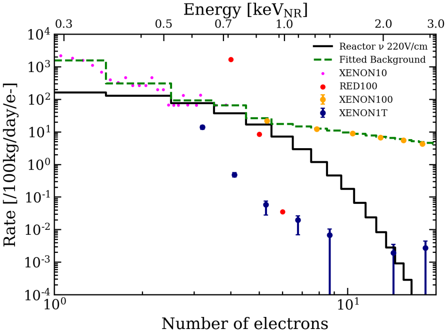


Figure: Estimated CEνNS rate per electron on LXe [1]

- CEνNS from nuclear reactors is too low energy to make S1s
- CEνNS can still make S2s of a few electrons!
- Dual phase LXe detectors have a known single electron background after a large ionization signal (S2) [4][5]
  - Can a single phase design mitigate this background?

Single Phase Design

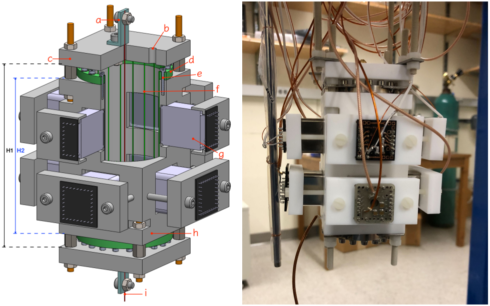


Figure: Left: Design of our cylindrical LXe detector. Right: Our detector while installing a 10μm diameter anode. One of the PMTs was shorted to the cathode, so the cathode was grounded in this run.

- Central thin anode wire produces a high electric field to produce S2s directly in liquid

Cs137 Calibration Waveform

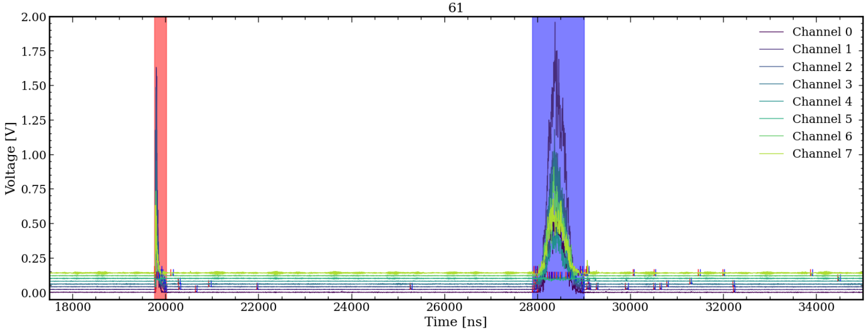


Figure: Waveform for a Cs137 event for 3kV anode and grounded cathode. S1 highlighted in red, S2 highlighted in blue.

Cs137 Calibration Data Selection: z-Cut

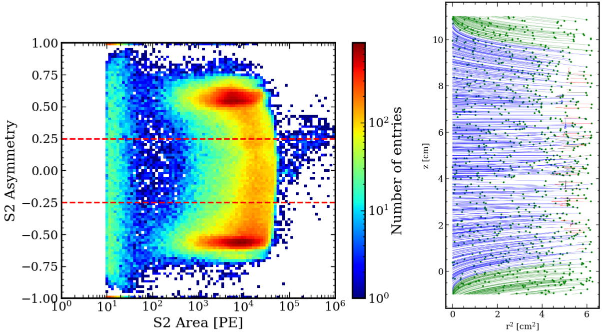


Figure: Left: Asymmetry vs S2 area distribution. Right: Electron cloud tracks through r and z.

- $Asymmetry = \frac{S2_{\text{top 4}} - S2_{\text{bottom 4}}}{S2_{\text{top 4}} + S2_{\text{bottom 4}}}$, indicator of z
- Cut the top and bottom events since the electron trajectories are bent
- Also used a standard multiple scatter cut

Cs137 Calibration Data Selection

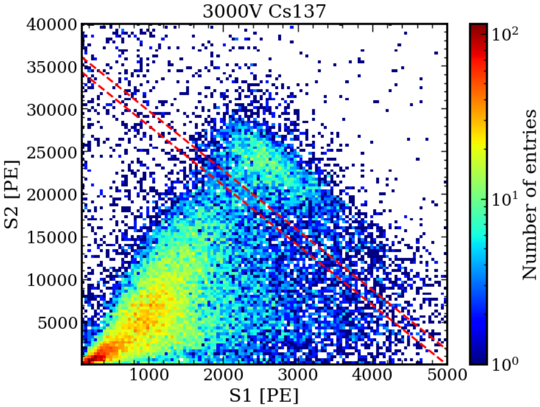


Figure: Cs137 selection boundary for a 3000V anode and grounded cathode.

- Cuts from previous slides are applied
- Photopeak is selected using the red dashed line
- Top line's S2 intercept is 5% higher than bottom
- Use the photopeak to determine the mean S1 and S2
- Position of the line factors into the systematic uncertainty of this mean

Cs137 Calibration Data Selection

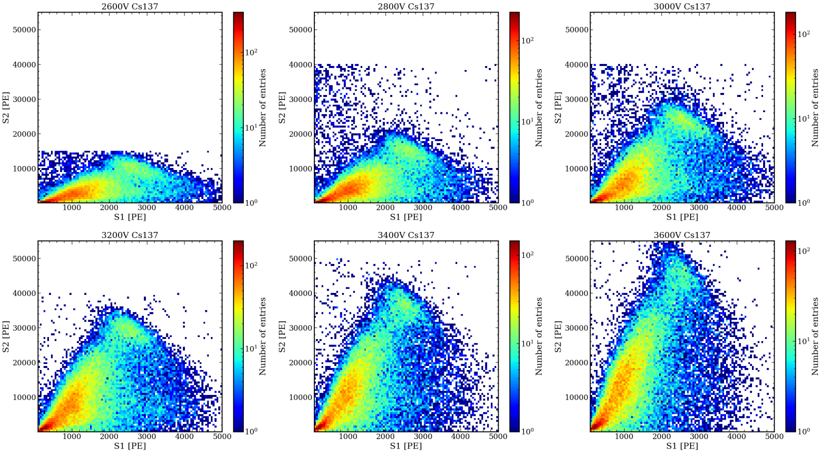
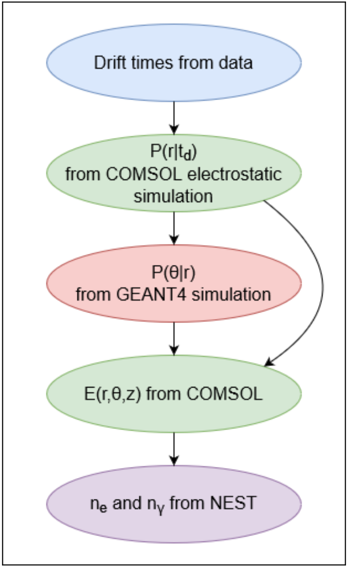


Figure: Cs137 S2 vs S1 distribution for different anode voltages.

Cs137 Calibration Simulation



- $g_1 = \langle S1 \rangle / \langle n_\gamma \rangle$ and $g_2 = \langle S2 \rangle / \langle n_e \rangle$
  - $\langle S1 \rangle$ and $\langle S2 \rangle$ are the centers of the Cs137 photopeak from Fig. 8 once fitted with a 2-d gaussian
- Get the drift time (t_d) from data
- Draw corresponding r coordinate from $P(r|t_d)$
- Draw θ from $P(\theta|r)$
- Sample z uniformly
- Draw electric field from COMSOL
- Input field and energy (661.7keV gamma) into NEST to get n_e and n_γ

Field Simulation

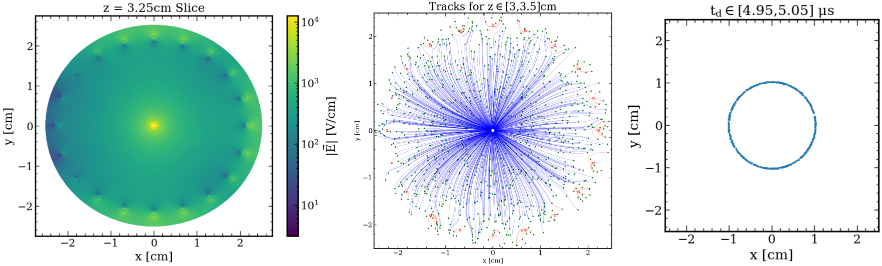


Figure: Left: Field map at z = 3.25cm. Middle: Tracks of electrons. Right: Position distribution for a given drift time.

- Bottom left PMT grounded, cathode grounded as well
- Charge insensitive volume around the cathode wires
- Assumed a 3mm cathode sag

GEANT4 Simulation

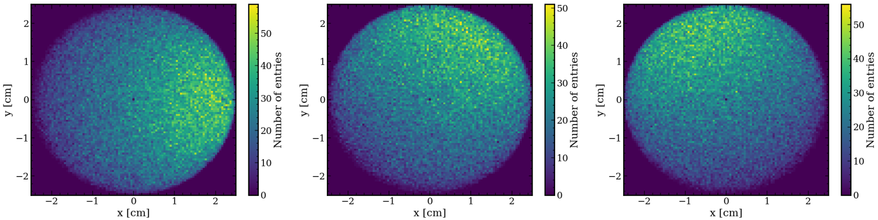


Figure: GEANT4 Cs137 photopeak distributions with a source placed at different locations.

- Simulated three positions of the Cs137 source to estimate the systematic uncertainty
- Slice in r to get the θ distributions

g1 and g2 from Cs137 Calibration

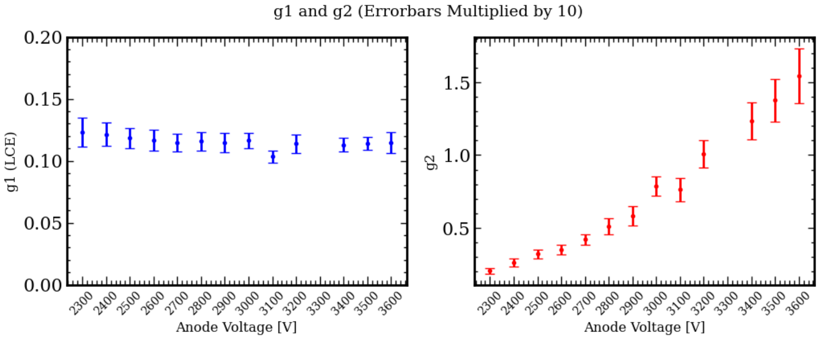
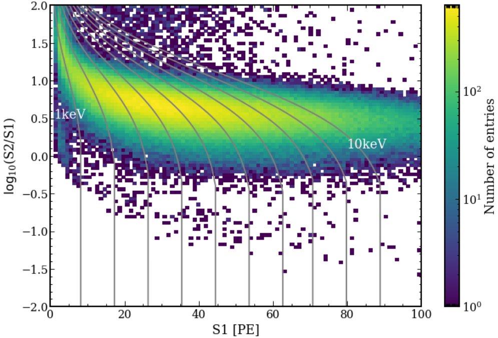
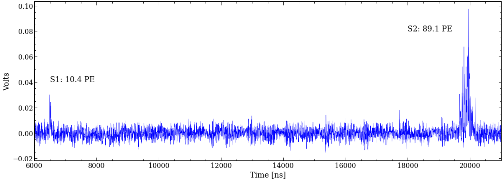


Figure: g_1 and g_2 for the values of the voltage sweep. Systematic uncertainty comes from the possible positions of the Cs137 source, and the photopeak selection in S2 vs S1 space.

Tritium Calibration





- System was kept at an anode voltage of 3.6kV
- Low energy ER band from tritium at a 3.6kV anode. Contours are using $E = W(S1/g_1 + S2/g_2)$ where g_1 and g_2 are from the Cs137 calibration
- Bottom population is accidental coincidences

Evidence of Electrons

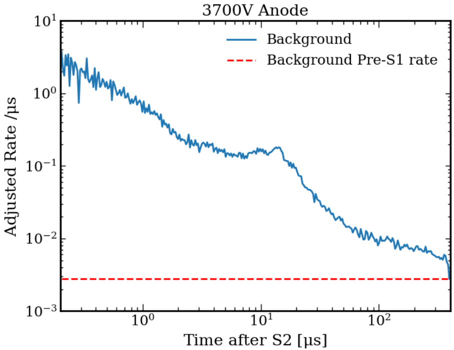


Figure: Rate of peaks after a large S2 with at least 2-fold coincidence. Photoionization electrons are evidenced by a shoulder that ends at around 20μs.

- g_2 is the same as the single electron gain since no liquid gas interface means 100% extraction
- LXe scintillation light can free electrons via the photoelectric effect
- This leads to a background of photoionization electrons up to one full drift time (roughly 20μs) after a large signal (either S1 or S2)
- Unfortunately, $g_2 \approx 1.7PE/e^-$ means that electrons are hard to distinguish from piled-up photons

A (developing) Model for Liquid Phase Electroluminescence

- This model treats LXe as a very dense gaseous Xenon (GXe)
- In GXe, electron motion follows the Boltzmann Transport Equation:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{d\vec{r}}{dt} \cdot \nabla_{\vec{r}} f + \frac{d\vec{v}}{dt} \cdot \nabla_{\vec{v}} f = \left.\frac{\partial f}{\partial t}\right|_{coll} \tag{1}$$

  which gives us $f(\vec{r}, \vec{v}; t) d^3\vec{r} d^3\vec{v}$, which is the probability of finding your particle in the phase space element $d^3\vec{r} d^3\vec{v}$

- "Relaxation Approximation" states that there exists some time τ which is the mean time between collisions, such that

$$\left.\frac{\partial f}{\partial t}\right|_{coll} = -\frac{f - f_0}{\tau} \tag{2}$$

  (i.e. the distribution relaxes to an equilibrium distribution f_0)

A (developing) Model for Liquid Phase Electroluminescence

- $\tau = \frac{\lambda}{v}$, $\lambda = \frac{1}{n\sigma}$, so $\tau = \frac{1}{n\sigma v}$
- Assumption: If f has no *explicit* time dependence, and f is dependent only on velocities, then $\vec{E}$ and n are coupled together and only show up as $\vec{E}/n$, the reduced electric field
- If a liquid is to be treated as a dense gas, then a gas with electric field $\vec{E}$ and density n_{liq} should have the the same f as a gas with field $\vec{E}\frac{n_{gas}}{n_{liq}}$
- f can be integrated to obtain the energy distribution $F(\epsilon)$, and if the electron energy distributions are the same, then the probability of producing an excitation collision is the same as well
- **Therefore, the average number of collisions for gases of the same reduced electric field will scale as the density**
- Boltzmann transport equation is solved by GARFIELD++, which is faster for lower density gases

A (developing) Model for Liquid Phase Electroluminescence

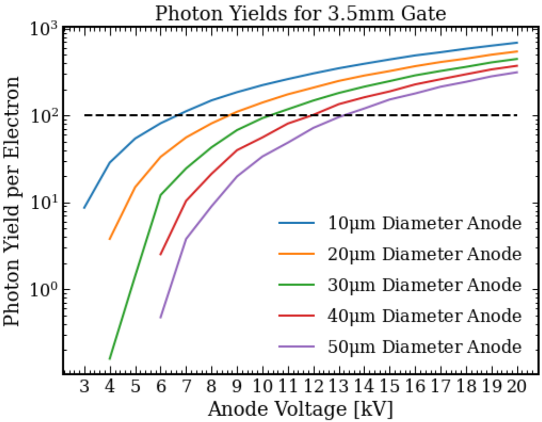


Figure: Photon yields for different anode diameters with a 3.5mm surrounding gate

Future Steps: A High Light Collection Design

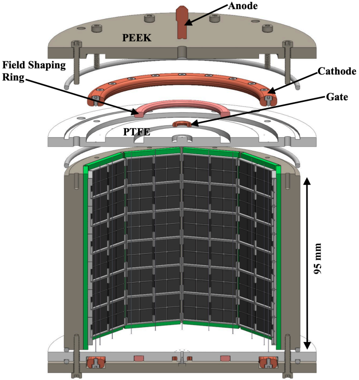


Figure: NUXE 3kg prototype proposed design, drawing by Haiwen Xu

- Prototype to be built in the next year
- 120 Hamamatsu VUV4-MPPCs ganged to 32 channels, capable of seeing Xe VUV light
- Weighted electrode wires to better control for bending
- Added gate wires for higher gain
- Sealed detector for better circulation efficiency
- First step in the Neutrino Detector with Xenon (NUXE) project

Future Steps/Current Progress: A Planned 30kg Detector

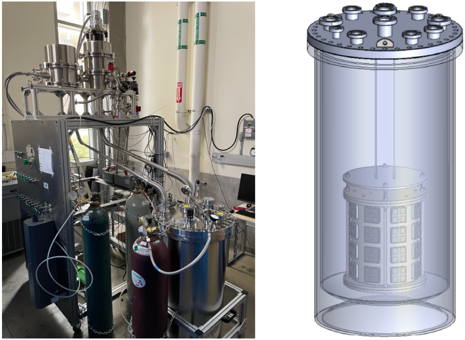


Figure: Left: NUXE cryogenics system. Right: Proposed 30kg detector.

- Cryogenics system is complete! Can fill O(100kg) of LAr
- Slow control system is finished as well
- Ultimate goal: make a 30kg electron counting chamber and deploy it at a power reactor

[1] Kaixuan Ni, Jianyang Qi, Evan Shockley, and Yuehuan Wei. Sensitivity of a liquid xenon detector to neutrino–nucleus coherent scattering and neutrino magnetic moment from reactor neutrinos. *Universe*, 7(3), 2021.

[2] COHERENT Collaboration. First measurement of coherent elastic neutrino-nucleus scattering on argon. *Physical Review Letters*, 126(1), jan 2021.

[3] COHERENT Collaboration. Measurement of the coherent elastic neutrino-nucleus scattering cross section on CsI by COHERENT. *Physical Review Letters*, 129(8), aug 2022.

[4] A. Kopec, A.L. Baxter, M. Clark, R.F. Lang, S. Li, J. Qin, and R. Singh. Correlated single- and few-electron backgrounds milliseconds after interactions in dual-phase liquid xenon time projection chambers. *Journal of Instrumentation*, 16(07):P07014, jul 2021.

[5] LUX Collaboration. Investigation of background electron emission in the lux detector. *Phys. Rev. D*, 102:092004, Nov 2020.

Backup: Single Scatters

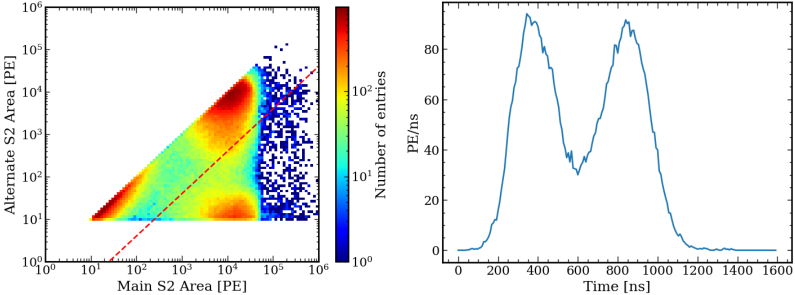


Figure: Left: Cut in alternate vs main S2 area, multiple scatters are above the cut line. Right: Waveform where the S2s are merged.

- Cut alternate (second largest in time window) S1s and S2s which are comparable in size to the primary
- Cut S2s which are merged together (via natural breaks)

Backup: Tritium Calibration

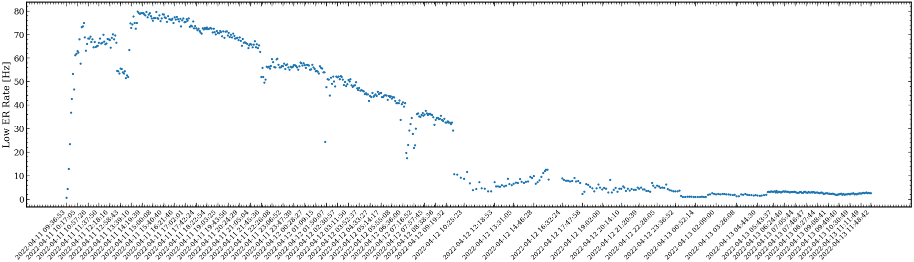


Figure: Rate of events in the low energy electronic recoil band. Not corrected for dead-time.

- Tritium emits betas of up to 20keV
- We injected a tritiated methane source
- Getter removed the source