Electronic vs. nuclear recoil discrimination and single electron emission in PIXeY

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PIXeY: Particle Identification in Xenon at Yale

- R&D-scale xenon two-phase liquid/gas TPC, operated at Yale in 2014-16
  - 3 kg liquid Xe active volume
- Completed + ongoing analyses on calibrations, extraction efficiency, **signal/background discrimination**, and **single electron backgrounds**
Backgrounds for Nuclear Recoil Searches

Dominant backgrounds for WIMP dark matter nuclear recoil (NR) searches are electron recoils (ER). Upcoming experiments will face challenging backgrounds that cannot be eliminated by shielding and fiducialization.
Nuclear Recoil (NR)

Energy Deposition
10 keV
200 V/cm

Xe

Xe\textsuperscript{*}

Xe\textsubscript{2}

62 excimers

18 fast photons

\(\tau_{\text{fast}}\)

62 slow photons

\(\tau_{\text{slow}}\)

Recombination

Xe\textsuperscript{+}/e\textsuperscript{-}

77 e-ion pairs

58 escaping electrons

Heat (not observed)

S1

S2

Graphic made with Xenimation
Electronic Recoil (ER)

Energy Deposition
10 keV
200 V/cm

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\begin{align*}
\text{Xe} & \rightarrow \text{Xe}^* \\
& \rightarrow \text{Xe}^+ / e^- \\
& \rightarrow \text{e}^- \\
& \rightarrow \text{Heat (not observed)}
\end{align*}
\]

\[
\begin{align*}
\tau_{fast} & \rightarrow 37 \text{ fast photons} \\
\tau_{slow} & \rightarrow 419 \text{ slow photons} \\
& \rightarrow 392 \text{ recombining electrons} \\
& \rightarrow 286 \text{ escaping electrons}
\end{align*}
\]

Graphic made with Xenimation
ER/NR Discrimination

- Discriminate ER from NR by using the ratio of charge-to-light produced by the recoil
  - In practice, discrimination variable is: $\log_{10}(S_2 / S_1)$

- PIXeY calibrations for ER and NR allow us to study discrimination as a function of parameters like drift field and energy

- Detector parameters and data parameters for this analysis:
  - Data collected with single-scatter recoils isolated: one S1 pulse, followed by one S2 pulse
  - Additional cuts applied for quality and fiducial volume selection
  - Extraction gas field: 8.0 kV/cm
  - Drift fields: 117 V/cm and 213 V/cm
  - $g_1 = 0.110$ phe / photon created
  - $g_2 = 30.2$ phe / escaped electron
**PIXeY Calibrations**

**Electronic Recoils:** $^{22}\text{Na}$

Gamma source

Tag recoils with an external NaI detector

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**Nuclear Recoils:** $^{2}\text{D}$-$^{2}\text{D}$

2.5 MeV monoenergetic neutrons generated from deuterium fusion

Recoil spectrum $\sim$ 60 GeV WIMP

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**Detector Effects Calibration:** $^{83m}\text{Kr}$

Two-step decay, depositing 32.1 and 9.4 keV conversion electrons

Dissolved in liquid xenon; recoil events uniformly fill the detector

Allows us to identify clean mono-energetic signals and characterize position-dependent and field-dependent phenomena
Events are split into bins of $S_{1c} \rightarrow$ the distribution of $\log_{10}(S_{2c}/S_{1c})$ is fit to a Gaussian.

The ER band median and width ($1\sigma$) are extracted.

Skewness ignored for now.
The NR band median and width are extracted the same way.
Leakage and Discrimination

Extrapolate the ER band Gaussian fit below the NR band to calculate leakage fraction

Leakage improves dramatically with energy, as seen by others (e.g. LUX)

$\leq 10^{-6}$ leakage at $S1 = 100$ phe

Leakage over the WIMP search range (0-80 phd) is $2 \times 10^{-3}$, substantially better than the LZ requirement of $5 \times 10^{-3}$

(LZ requirement in arxiv:1509.02910)
LUX Comparison

PIXeY: $g_1 = 0.110$,  
drift field = 213 V/cm  
LUX 2013: $g_1 = 0.117$,  
drift field = 180 V/cm  

Lower band median and width in  
LUX make sense, because of higher  
g1 and lower field  

LUX “ER width” is $\sigma_-$, the width of  
the downwards fluctuations. By  
definition: $\sigma_- < \sigma$. Thus using $\sigma_-$ with  
skewness will give better leakage.

(LUX data from Phys. Rev. D 102, 112002 (2020))
Comparison to LUX Data and NEST Simulation

Simulated PIXeY with NEST, using correct detector parameters for g1, g2, drift and extraction fields, etc.

PIXeY leakage matches LUX and NEST remarkably well!

Slightly better leakage in LUX at low energies explained by their use of a skew-Gaussian extrapolation. E.g., LUX leakage is 0.1% (vs 0.2% in PIXeY) in WIMP ROI.
Varying Drift Electric Field

Analysis repeated with a drift field of 117 V/cm

Leakage similar to 213 V/cm, but slightly worse → consistent with LUX findings of minimum leakage at 300 V/cm

Matches NEST again, except at S1 < 10 phe; discrepancy most likely due to threshold effects, currently under study.
Backgrounds for Low-Energy Searches

- Single electron (SE) backgrounds in xenon TPCs are a hindrance
  - Can be incorrectly classified as S2 pulses associated with an S1
  - Worsens energy resolution
  - Increases DAQ/trigger dead time
  - **Dangerous background for low-mass dark matter searches!**
    - In particular, “S2-only” searches (without an S1), looking for DM at ~few GeV

- Conducted an analysis of electron backgrounds using PIXeY $^{83m}$Kr data (arXiv:2101.03686)

- Single electron backgrounds studied as a function of:
  - Drift and extraction fields
  - Timing (i.e. before the S1, between the S1 and S2, after the S2)
Identify single electrons between the S1’s and S2

Rate increases with extraction field → suggests the source of the SE’s is photoionization of impurities by S1 photons

Rate decreases with drift field. Few potential causes:

- Increased drift velocity → decreased interaction time between e-’s and impurities → lower density of anions
- Electron capture cross-section varies with field
- Charged impurities are drifted out of the detector more quickly
Photoionization from the S2 Light

Identify single electrons after the S2

Same behavior → suggests the same cause
SE Background
Uncorrelated with S1 and S2

Identify single electrons long after the S2 (top) or before the S1 (bottom)

Same behavior as previous, but understood to be from:
- Field emission from the gate grid
- Delayed release of electrons from impurities
Field Emission

- Fowler-Nordheim theory offers a guide to a better understanding of field emission
  - Electric field on gate grids $\rightarrow$ metallic conduction band electrons tunnel into LXe
  - Electron emission dependent on applied field, material, and grid surface roughness
- PIXeY measurements are consistent with the predicted electron emission rate
Summary and Conclusions

- Demonstrated robust ER/NR discrimination at high energies, achieving a factor of $\sim 10^6$ ER rejection at $S_1 = 100$ phe ($E = 70$ keVnr)
- Future discrimination work will focus on ER skewness and variation of drift field
- Better of understanding of single electron backgrounds: their dependence on field, timing, and their sources
- Full details of single electron analysis located at arXiv:2101.03686; includes more details about SE timing
Thank you!
Any questions?
Backup
PIXeY Detector Parameters

Calculate $g_1$ and $g_2$ using the “Doke” technique

- These represent the average signal size for each photon and electron leaving the recoil site

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g_1 = 0.110 \pm 0.002 \text{ phe/photon} \]
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g_2 = 30.2 \pm 0.7 \text{ phe/electron} \]
Position Corrections

- Pulse areas are dependent on the z-position of the event; S1 sizes grow with drift time, while S2 sizes fall with drift time.
- S1 sizes grow with drift time (i.e. shrink with height) due to total internal reflection at the liquid-gas interface.
- S2 sizes shrink with drift time (i.e. grow with height) due to ionized electrons capturing on electronegative impurities.
Energy Weighting

Electronic recoil events are weighted to mimic a flat spectrum in combined energy Dark matter ER backgrounds from $^{136}$Xe double beta decay, Rn/Kr internal contaminants, and solar neutrinos are roughly flat in energy

$$E = W \left( \frac{S_{1c}}{g_1} + \frac{S_{2c}}{g_2} \right)$$
Noble Element Simulation Technique (NEST)

- Inter-collaboration collaboration of liquid xenon and argon physicists who construct models of energy deposition in a noble detector, as well as code to implement simulations
  - Members from LUX, LZ, XENON, (n)EXO, RED100, COHERENT, DUNE, ICARUS, MicroBooNE, SBN
- Models are based on physical principles and world averages of existing data
- PIXeY simulation:
  - Template detector file, which represents LUX WS2013
  - Detector parameters like g1, g2, drift field, extraction efficiency were adjusted to their correct values
  - Simulated a flat ER energy distribution and DD neutrons → calculated ER + NR bands and leakage fraction
- Code and more information:
  - http://nest.physics.ucdavis.edu/
  - https://github.com/NESTCollaboration
Used NEST to simulate the PIXeY experiment, with proper $g_1$, $g_2$, drift field, and other detector parameters.

Matches pretty well, although there are some discrepancies.

NEST matches LUX 2013 very well, although the detector parameters are slightly different.

$E_{\text{drift}} = 213 \text{ V/cm}$