Response and discrimination of Low-Energy Electronic and Nuclear Recoils in Liquid Xenon

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What to measure in LXe


Gamma Background $\rightarrow$ ER
DM Candidate WIMP $\rightarrow$ NR
DM Candidate Axion $\rightarrow$ ER

Electronic Recoils (ER) ROI
Nuclear Recoils (NR) ROI

ER/NR discrimination
ER/NR signal response
Detector (LXe-TPC)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC Diameter [mm]</td>
<td>57</td>
</tr>
<tr>
<td>maximum drift length [mm]</td>
<td>10</td>
</tr>
<tr>
<td>Cathode-Screen [mm]</td>
<td>21</td>
</tr>
<tr>
<td>Anode-Gate [mm]</td>
<td>5</td>
</tr>
<tr>
<td>Sensitive Volume [g]</td>
<td>77</td>
</tr>
<tr>
<td>Fiducial Volume [g]</td>
<td>3</td>
</tr>
<tr>
<td>Top PMT number/Type</td>
<td>4/R8520</td>
</tr>
<tr>
<td>Bottom PMT number/Type</td>
<td>1/R11410</td>
</tr>
</tbody>
</table>
Detector performance

Reconstruction resolution 0.37\(+\)-0.06mm

Best resolution \((\sigma/E)\) = 1.60\% @ 662keV @ 500V/cm

Very good energy resolution in LXe, meaning the systematic fluctuation of our detector is small.
Signal model in LXe

\[ S1 = a \cdot N_{ph} = a \left( \frac{N_{ex}}{N_i} + r \right) N_i \]

\[ S2 = b \cdot N_e = b(1 - r) N_i \]

- \( N_i \) -- number of ion-electron pairs
- \( a \) -- photon detection efficiency (PDE)
- \( b \) -- electron amplification factor (EAF)
- \( r \) -- recombination fraction
Recombination model

\[
\frac{\partial N_+}{\partial t} = -\mu_+ E \cdot \nabla N_+ + d_+ \nabla^2 N_+ - \alpha N_+ N_- \quad \text{ION}
\]

\[
\frac{\partial N_-}{\partial t} = \mu_- E \cdot \nabla N_- + d_- \nabla^2 N_- - \alpha N_+ N_- \quad \text{ELECTRON}
\]

**Birk-Doke Law** (High-energy case, Drift and diffusion process neglected):

\[
r = \frac{A \cdot (dE / dx)}{1 + B \cdot (dE / dx)} + C
\]

A and B proportional to \( \alpha \), A/B+C=1

**Thomas-Imel Box (TIB) model** (Low-energy case, drift of electron taken into account):

\[
r = 1 - \frac{1}{\xi} \ln(1 + \xi), \quad \xi = \frac{\alpha N_i}{4a_0^2 \mu E}
\]

From NEST (JINST 6, P10002)
Detector operation

COMSOL simulation shows the field = \textbf{3.93}kV/cm.

$^{137}$Cs calibration every day

<table>
<thead>
<tr>
<th></th>
<th>Field[V/cm]</th>
<th>PDE[%]</th>
<th>EAF[PE/e-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS above gate</td>
<td>236 - 1920</td>
<td>15.5+-.2</td>
<td>31.8+-.5</td>
</tr>
<tr>
<td>LS below gate</td>
<td>3930</td>
<td>20.0+-.1.7</td>
<td>20.0+-.1.7</td>
</tr>
</tbody>
</table>
The 3.0% and 2.6% variation of the PDE and EAF (CA), respectively, between anti-correlation and 1kV/cm data are within the 4% uncertainty of NEST.

\[
\begin{align*}
\frac{S1}{\varepsilon} &= a\left(\frac{N_{ex}}{N_i} + r\right)W_i \\
\frac{S2}{\varepsilon} &= b\left(1 - r\right)W_i
\end{align*}
\]

\[
W_q = \frac{W_i}{(N_{ex}/N_i + 1)} = 13.7\text{eV}
\]

Slope = \(-b/a\)

Intercept (Light yield) = \(a\ W_q\)

Intercept (S2 yield) = \(b\ W_q\)
Measured recoils

NR matches with NEST prediction.
ERs don't.
Update TIB parameters

\[ r = 1 - \frac{1}{\xi} \ln(1 + \xi), \quad \xi = \frac{\alpha N_i}{4a_0^2 \mu E} \]

Source of systematics | Value on (PDE and EAF)
--- | ---
Gain difference between $^{137}$Cs calibration and recoil measurements | 7.2%
PDE and EAF evolution | 1.5%
NEST global uncertainty | 4%
E-life induced S2 variation | 1.2%
The PDE(EAF) is 4.5% (11.9%) lower if using whole volume than using FV in this work.

\[
py' = \frac{S_1}{(S_1/a' + S_2/b')} \cdot W_q
\]

\[
= \frac{1}{W_q} \cdot \frac{\frac{b}{b'}}{\frac{a}{a'}} \cdot py
\]

\[
\frac{b}{b'} < 1 \Rightarrow py' > py
\]

\[
\frac{a}{a'}
\]
Discrimination observed in previous experiments

<table>
<thead>
<tr>
<th>Field [kV/cm]</th>
<th>PDE [%]</th>
<th>energy ROI</th>
<th>Gamma rejection power [%]</th>
<th>Nuclear recoil acceptance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEPLIN-II[14]</td>
<td>1.00</td>
<td>5-20 keVee</td>
<td>98.5</td>
<td>50</td>
</tr>
<tr>
<td>XENON10[9]</td>
<td>0.73</td>
<td>4.5-26.9 keVnr</td>
<td>99.86</td>
<td>45 ~ 49</td>
</tr>
<tr>
<td>XENON100[7]</td>
<td>0.53</td>
<td>6.6-43.3 keVnr</td>
<td>99.75</td>
<td>20 ~ 60</td>
</tr>
<tr>
<td>LUX[8]</td>
<td>0.18</td>
<td>3.4-25.0 keVnr</td>
<td>99.6</td>
<td>50</td>
</tr>
<tr>
<td>PandaX</td>
<td>0.67</td>
<td>4-10 keVnr</td>
<td>99.6</td>
<td>50</td>
</tr>
</tbody>
</table>

Electric field [kV/cm]
Review of signal fluctuation

Incoming particle

Xe

Xe*

Xe^+

Xe_2^+

e^-

Fano fluctuation
Gaussian
\(\sim \sqrt{FN}\)
F=0.059

PMT

\(\text{PMT}\)

\(S1\)

\(S2\)

\(\text{photon detection}\)

\(\text{Poisson}\)

\(\text{Electron extraction}\)

\(\text{Binomial}\)

Recombination fluctuation
Binomial
\(\Delta r_{\text{stat}} + \Delta r_{\text{sys}}\)
Discrimination measurement

No observation of discrimination level increasing as field!
Discrimination measurement

- 8 < S1 < 12
- 12 < S1 < 16
- 16 < S1 < 20
- 20 < S1 < 24
- 24 < S1 < 28
- 28 < S1 < 32
\[ \frac{\partial N_+}{\partial t} = -\mu_+ E \cdot \nabla N_+ + d_+ \nabla^2 N_+ - \alpha N_+ N_- \]

Drift

\[ \frac{\partial N_-}{\partial t} = \mu_- E \cdot \nabla N_- + d_- \nabla^2 N_- - \alpha N_+ N_- \]

Diffuse

Recombine

**Diffusion Eq**

**Birk-Doke Law:**

\[ r = \frac{A \cdot (dE / dx)}{1 + B \cdot (dE / dx)} + C \]

A&B proportional to \( \alpha \)

\[ \Delta r = \left[ (r - C) - \frac{(r - C)^2}{1 - C} \right] \cdot \frac{\Delta \alpha}{\alpha} \]

\[ \frac{\Delta Q}{Q} = \left[ \frac{r - C}{1 - r} - \frac{(r - C)^2}{(1 - C)(1 - r)} \right] \cdot \frac{\Delta \alpha}{\alpha} \]

**IONS**

**Electrons**

Best fit: \( \Delta \alpha/\alpha = (24.2 \pm 0.6)\% \)
Low energy $\Delta \alpha$

\[ r(\xi) = 1 - \frac{1}{\xi} \ln (1 + \xi), \quad \xi \equiv \frac{N_i \alpha}{4 \alpha^2 \mu E} \]

\[
\Delta r = \left[ \frac{1}{\xi} \ln(1 + \xi) - \frac{1}{1 + \xi} \right] \frac{\Delta \alpha}{\alpha}.
\]

$\Delta r/r = 4\%$

$\Delta r/r = 30\%$
Low energy $\Delta \alpha$

\[ E_c = \left( \frac{S1}{PDE} + \frac{S2}{EAF} \right) \cdot W_q \]

Solid lines:

\[ \Delta r = \left[ \frac{1}{\xi} \ln(1 + \xi) - \frac{1}{1 + \xi} \right] \frac{\Delta \alpha}{\alpha} \]
Expected Leakage fraction with the model

If assume a log linear $\Delta \alpha/\alpha$ on field.

PDE=15.6%

There's no field dependence of the rejection.
Expected Leakage fraction with the model

PDE=10%

\[ \frac{\bar{\mu}_{cr} - \mu_{cr}}{\sigma_{cr}} \]

Field [V/cm]

PDE=20%

\[ \frac{\bar{\mu}_{cr} - \mu_{cr}}{\sigma_{cr}} \]

Field [V/cm]

PDE=50%

\[ \frac{\bar{\mu}_{cr} - \mu_{cr}}{\sigma_{cr}} \]

Field [V/cm]

PDE=100%

\[ \frac{\bar{\mu}_{cr} - \mu_{cr}}{\sigma_{cr}} \]

Field [V/cm]
Summary

1. Response of low energy NR and ER in LXe at different fields (236V/cm - 3.93kV/cm) were measured. NR data are consistent with NEST, while ER showed a deviation of photon yield by 5ph/keVee from NEST (Q. Lin et al., Phys. Rev. D 92, 032005, 2015).

2. An average ER rejection around 99.99% (with 50% NR acceptance) was achieved at different fields.

3. Preliminary study shows the ER rejection doesn't depend significantly on the field, while Δα/α follows a log-linear dependence with field in our measurement.
Thank you!
Float also $N_{ex}/N_i$

$N_{ex}/N_i = 0.11 \pm 0.07$
Compare to existing measurements

Need more measurements of low energy ER to confirm
energy spectrum dependence of signal response
3-D simulation result (with liquid level 2mm below gate mesh)