Response of Xe to low energy electron recoils from tritium with the LUX detector

Attila Dobi
LBL
Self-shielding makes external gamma sources impractical.

Having constructed such a background-insensitive instrument, we are faced with a new challenge:

How can we calibrate such a device with radioactive sources?
Methane diffuses much slower than bare tritium.
- Dissolved uniformly in the xenon.
- Removed with standard purification technology.
- Used to calibrate the fiducial volume.

- Single Scatter ER events in energy region of interest: 0.1 keV to 18 keV
  - Mean energy: 5 keV
  - Peak energy: 2.5 keV
The S1 signal ~ Photons
The S2 signal ~ Electrons

top hit pattern: 
ex-y localization

The S2 signal ~ Electrons
Energy Reconstruction

Platzmann Model

\[
\frac{E}{W} = n_\gamma + n_e = \frac{S_1}{g_1} + \frac{S_2}{g_2}
\]

- For electronic recoils in xenon \( W = 13.7 \) eV
- Measure \( S_1 \) and \( S_2 \) then convert to photons and electrons with gains \( g_1 \) and \( g_2 \)

Tritium Energy Spectrum as Measured in the LUX Fiducial Volume

150,000 tritium decays and \(~3\) non-tritium events

Tritium Data/Theory
In our 2013 analysis we used a low stats tritium injection to define the ER band location. Since then we have increase the stats by 20x to produce a more detailed understanding of LY, QY in order to model backgrounds.
Understanding the WIMP and Background Signals

Electron Recoil Band Mean:
\[ \log_{10}(S2/S1) = \log_{10}(QY/LY) + \log_{10}(g1/g2) \]

Electron Recoil Band Variance: (from recombination)
\[ \text{Var}_{\log_{10}(S2 / S1)} = \frac{1}{(\log(10))^2} \times \sigma_R^2 \left( \frac{-(\alpha + 1)}{(1 - r)(r + \alpha)N_1} \right)^2 \]

Relying on modeling introduces systematics as \( \alpha \) (exciton-to-ion ratio) and \( \sigma_R \) are dependent on field, Energy deposit, detector conditions. Ideally want to calibrate in-situ.
Yields Measured in LUX Fiducial Volume

Light Yield

Charge Yield

Data

NEST

NEST

Charge Yield

Data

Light Yield

10.1088/1748-0221/8/10/C10003

The Noble Element Simulation Technique (NEST)
Recombination Fluctuations

We still do not have a physical model to predict recombination variance… but we can measure it with tritium

\[ \sigma_R = C \times N_{\text{ions}} \]
• With the tritium calibration source we can extract yields and model WIMP search backgrounds accurately in-situ
  
  • Systematics from interpolations and using measurements from other detectors removed.
  
• Since 2013 LUX results, we have high stats tritium injections and new DD data. We are working on updating the WIMP search analysis.
  
  • Will be applied to 2014-2015 data

• LY, QY, R are fundamental properties of liquid xenon. Depend on energy, electric field and LXe density.
  
  • Feed latest tritium data into NEST model to improve predictive power.

  1. For DD neutron generator talk from James Verbus.

  2. QY Measurement at 0.2 and 1.1 keV from Dongqing Huang

  3. Tritium Source, Richard Knoche
Thank you
Backup
Injection and removal of tritiated methane from LUX, August 2013

Success! (Failure not optional with long lived isotope)

Rate consistent with natural methane removal

August 8, 2013

\( \tau_1 = 6.0 \pm 0.5 \text{ Hours} \)

\( \tau_2 = 6.4 \pm 0.1 \text{ Hours} \)
Figure 7.3: In black, the response to scintillation from $^{83m}$Kr at the center of the detector normalized to the first data point before the natural methane (CH$_4$) injection. The dashed magenta lines represent the time window from the beginning of the natural methane injection to the time the background of 5 ppt is reached. The blue points represent that methane concentration in the gas returning from the bulk liquid of the detector. The concentration in the liquid xenon is roughly 1/6 of the concentration measured in the gas phase due to solubility.
Tritiated-Methane, The Ideal ER Calibration Source

- Single Scatter events in energy region of interest:
  - $Q = 18.6$ keV
  - Mean energy: 5 keV
  - Peak energy: 2.5 keV

- Bare tritium diffuses quickly into detector components.
- Must be removed after calibration.
- Can’t afford to simply wait for activity to decay away.
- 12.3 year half-life!

Methane is non-polar, and has saturated covalent C-H bonds, which makes it chemically very inert.
- Well-known that methane will dissolve in liquid xenon.
- As a larger molecule, tritiated methane has a smaller diffusion constant than bare tritium.
- Methane diffusion and permeability in Teflon is 11x less than tritium.

We have characterized the SAES getter for methane and the chemically identical tritiated methane
- DOI: 10.1016/j.nima.2010.04.152
- DOI: 10.1016/j.nima.2010.03.151,
- DOI:10.13016/M24P5P.
- See Richard Knoche and Jon Balajthy’s talk

LUX (2013) WIMP Search
ER band Gaussianity, Tritium Calibration
Typical Event in LUX
The tritium Beta calibration applies to our ER backgrounds (mainly gamma).

Sub ppt Methane in xenon does not quench light yield
Recombination Results

Electric field dependence

Energy dependence

Energy keV<sub>ee</sub>

σ<sub>R</sub> (quanta)

Mean, Width

Combined Energy [keV<sub>ee</sub>]
## Energy Scale Calibration using line sources

### Source Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy [keV]</th>
<th>Decay Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe K shell</td>
<td>29.7, 34</td>
<td>X-ray</td>
</tr>
<tr>
<td>$^{83m}$Kr</td>
<td>41.55</td>
<td>Internal Conversion</td>
</tr>
<tr>
<td>$^{131}$Xe</td>
<td>163.9</td>
<td>Internal Conversion</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>203 or 375</td>
<td>$\gamma$-emission</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>33.8</td>
<td>K$_b$ shell X-ray</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>5.3</td>
<td>L shell X-ray</td>
</tr>
<tr>
<td>$^{129m}$Xe</td>
<td>236.1</td>
<td>Internal Conversion</td>
</tr>
<tr>
<td>$^{214}$Bi</td>
<td>609</td>
<td>$\gamma$-emission</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>661.6</td>
<td>$\gamma$-emission</td>
</tr>
</tbody>
</table>

### Platzmann Model

\[
\langle n_\gamma \rangle = \frac{\langle S_1 \rangle}{g_1} \\
\langle n_e \rangle = \frac{\langle S_2 \rangle}{g_2}
\]

\[
S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g_1}{W}
\]

\[
S2/E = \frac{n_e}{(n_\gamma + n_e)} \times \frac{g_2}{W}
\]
ER diagram

Light Yield

\( \frac{E}{W} = n_{\text{ex}} + n_i \)

\( \alpha = \frac{n_{\text{ex}}}{n_i} \)

Charge Yield

light collection (detector photon resolution)

S1 = g1*Ng

light collection (detector electron resolution)

S2 = g2*Ne

\( n_r = n_{\text{ex}} + n_i \)

\( n_e = n_i (1 - r) \)

E/W = n_{\text{ex}} + n_i

\( \text{vs field} \& \text{energy} \)

\( \pm \) Recombination Fluctuation
ER Band Width (Fluctuations)

\[ ^{131}\text{Xe}: 164 \text{ keV} \]

\[ \text{Tritium: 1-18 keV} \]

- LY, QY yield the mean photons and electrons produced.
- Recombination fluctuations and detector resolution give rise to the width of the ER band in discrimination space (S2/S1) vs. S1.
- Given infinite resolution, the fundamental limitation of ER and NR discrimination is set by recombination fluctuations.

red: recombination fluctuation expected from binomial process
… will add \( \sqrt{N_i} \) to the plot. (similar to binomial)
black: Observed recombination fluctuation.
Much worse than Normal, Poisson or Binomial