Xenon Detectors Response to Low Energy Recoils for Dark Matter Searches

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Outline

- Energy response to low energy recoils
  - Absolute calibration
  - Comparison of relative and absolute calibration
  - Reconstruct recoil energy using absolute calibration

- Impact of energy resolution on discrimination of nuclear recoils from electronic recoils
  - Fano factor for electronic recoils and nuclear recoils
  - Discrimination of nuclear recoils and electronic recoils based on Fano factor
Relative Calibration:

Electronic Recoils: \( E_{\text{eff}} = \alpha E_R \quad \alpha = 1 \)

Nuclear Recoils: \( E_{\text{eff}} = L_{\text{eff}} \times E_R \quad L_{\text{eff}} = \frac{\#N_{\text{pe}}^{NR}/ENR}{\#N_{\text{pe}}^{ER}/EE_R} \)

\( L_{\text{eff}} = \eta \times \mu \)
\( \eta: \) Lindhard quenching
\( \mu: \) Hitachi quenching

This assumes the detector response to electronic recoils is linear below energy 10 or 122 keV, which is not true from a measurement by L. Baudis et al, Phys.Rev.D87:115015,2013
This behavior can be described by Birks’ Law:

\[ R_e = \frac{\alpha_r}{1 + kB_r \frac{dE_R}{dx}} \]

\( \alpha_r \) and \( kB_r \) can be determined using the experimental data shown in the plot.

NR: Energy Response Function

- **Lindhard quenching:** \( E_{\text{eff}} = E_R \times \eta \), \( \eta = \frac{kg(E_R)}{1+kg(E_R)} \)

- **Birks’ Law:** \( E_{\text{vis}} = E_{\text{eff}} \times \nu \), \( \nu = \frac{\alpha}{1+kB \frac{dE_{\text{eff}}}{dx}} \)

**total scintillation efficiency:** \( \eta \times \nu \)

**An absolute energy calibration**
Determine $\alpha$ and $kB$

Data points are from L. Baudis et al, Phys.Rev.D87:115015,2013

$\frac{dE_{vis}}{dx} = \frac{E_g}{W_i} R_e \frac{dE_R}{dx} = \frac{\alpha \frac{dE_R}{dx}}{1 + kB \frac{dE_R}{dx}}$

$\alpha = 0.6467 \pm 0.0156$

$kB = 0.01951 \pm 0.004321$
$W_i$ as a Function of Energy

- $W_i$ increases as energy decreasing below 1keV.
- Above 4keV, $W_i$ increases as energy increasing.
NR Relative Scintillation Efficiency in Comparison with Absolute Efficiency

\[
\frac{E_{vis}}{E_R} = L_{eff} \\
\frac{E_{vis}}{E_R} = \frac{\alpha}{1 + k_B \frac{dE_{eff}}{dx}} \times \eta
\]

- Lindhard quenching predicts scintillation efficiency decreases as energy decreasing.
- At low energies, scintillation efficiency increases as energy decreasing.
NR Absolute Scintillation Efficiency Comparison

- Normalize the data to absolute energy scale, the agreement between the data and our model is reasonable.
NR Energy Reconstruction

• Relative calibration:

\[ E_{NR} = \frac{\#N_{pe}^{nr}}{L_{eff} \#N_{pe}^{er}/E_{ER}} \]

If \#N_{pe}^{nr} = 3, \#N_{pe}^{er}/E_{ER} = 8.8/keV, E_{NR} = 3keV

• Absolute calibration:

\[ E_{NR} = \frac{E_g}{\eta V} \left( \frac{S_1}{\varepsilon_1} + \frac{S_2}{M_f \varepsilon_{ext}} \right) \]

If \#N_{pe}^{nr} = 3, S_2 = 50, \varepsilon_1 = 0.14, M_f = 24.55, \varepsilon_{ext} = 0.65, E_{NR} = 6.8keV

\( \varepsilon_1 \): the product of photon detection efficiency and photoelectron quantum efficiency

\( \varepsilon_{ext} \): electron extraction efficiency

\( M_f \): photon multiplication factor
Energy Resolution and Fano factor

- Different sources of fluctuation in the signal chain contributing to the overall energy resolution

- Energy dependence of resolution: \( \frac{\sigma(E)}{E} = \frac{c_1}{E} + c_2 \)

\[ \sigma_{stat} = \sqrt{W_i(E)F(E)E} \]


T.Papp et al, Wiley Science, DOI:10.1002/xrs.754

\[ F_n = \frac{1.9^2}{15.6 \times 10^{-6}} \approx 23 \]
Formulism for Fano factor

\[ F_N = \sqrt{\frac{E_x}{E_g}} \left( \frac{W_i}{E_g} - 1 \right) \]

\[ F_n = \sum_{i=1}^{m} \left( 1 + \epsilon (F_N - 1) \right) \]

- If \( F_n = 23 \), with one PMT, \( \bar{F}_n = 0.95 \). Then, about 24 PMTs are triggered.

- If \( F_N = 0.059 \), \( \epsilon = 9\% \), \( F_n = 0.91 \) for one PMT.

- Nuclear recoils Fano factor is always greater than that for electronic recoils.
Discrimination on ER and NR

- At low energies, statistical variation dominates energy resolution.

  - Number of electron-hole pairs decreases as energy decreasing, Fano factor becomes larger, subsequently, statistical variation becomes larger.
  
  - $W_i$ increases as energy decreasing.
Conclusions

• Energy response to both electronic recoils and nuclear recoils are non linear.
• Due to high ionization density at low energies, additional quenching is involved.
• Absolute energy calibration requires low energy electronic recoil calibration.
• Fano factor dominates the energy resolution in the low energy region.
• Average energy per electron-hole pair leads to the difference of Fano factor between NR and ER.
• The difference in Fano factor impact on the nuclear band width and electronic recoil band width.
Thanks