Characterization of low energy ionization signals from Compton scattering in a CCD Dark Matter detector

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Motivation

- Solid state ionization detectors are integral component of next-generation dark matter searches due to their very low noise and the small band gap of semiconductor targets.
- However in this low energy search regime (2-1000e-) dominant background from environmental radiation are low-energy electron recoils due to small-angle Compton Scattering of external gammas.
- Flux is orders of magnitude higher than fast neutrons – the usual consideration for external source of signals
- Irreducible Electron Recoil background $\rightarrow$ any potential Dark Matter can only be identified by energy spectrum.
  $\rightarrow$ Need complete understanding of low-energy spectral features.
  $\rightarrow$ Expose UChicago Silicon CCD detector to gamma source
Motivation II

- Expose to γ-ray source
  - Compton features + ?
Modeling

- Generically scattering cross-section given by textbook Klein-Nishina. However dealing with bound electrons.
  - Expect effectively flat spectrum (with these added steps)

- **Impulse Approximation**: Each atomic shell treated independently. Bound electrons are modeled as free with constrained momentum distribution derived from bound-state wave function.
  - Valid in our region of interest with low energy and momentum transfers

- Useful since we can obtain differential cross section expressions per atomic electron with quantum numbers $n, l$
Expected Spectrum

- **Silicon Target**
- **Visible Step features**
  - Binding Energies
  - Provide linear parameterization (since in aggregate an unknown spectrum can be fit with straight lines...)

### Table

<table>
<thead>
<tr>
<th>Atomic Shell</th>
<th>n</th>
<th>l</th>
<th>Binding Energy [eV]</th>
<th>Number of e⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>1</td>
<td>0</td>
<td>1839</td>
<td>2</td>
</tr>
<tr>
<td>L₁</td>
<td>2</td>
<td>0</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>L₂,3</td>
<td>2</td>
<td>1</td>
<td>99.3</td>
<td>6</td>
</tr>
<tr>
<td>Valence</td>
<td>3</td>
<td>-</td>
<td>1.12</td>
<td>4</td>
</tr>
</tbody>
</table>
II. Experiment

Testbed (UChicago)

<table>
<thead>
<tr>
<th>Source</th>
<th>Activity [μCi]</th>
<th>Half-Life [y]</th>
<th>$E_\gamma$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{57}$Co</td>
<td>8.7</td>
<td>0.745 (1)</td>
<td>14.4130 (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>122.0607 (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>136.4736 (3)</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>22</td>
<td>432.6 (6)</td>
<td>26.3446 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>59.5409 (1)</td>
</tr>
</tbody>
</table>
Detection Principle

coherent elastic scattering

charge diffusion $\sigma$ along $z$ axis

3-phase CCD structure
Poly gate electrodes
Buried p channel
Ionization
Hidden Photon

DAMIC CCD: 15x15 $\mu$m$^2$ pixels

Energy measured by pixel / keV
1x1 Data & MCNP Simulation Model

III. Results

![Graph showing 1x1 Data & MCNP Simulation Model with annotations]

- **Fluorescence**
- **Compton Edges**
- **Photoelectric Absorption Peaks**

**Graph Details:**
- **57Co 1x1**
- **MCNP**

**Y-axis:** Number of events [(50 eV)^{-1}]

**X-axis:** E [keV]

**Legend:**
- Blue line: 57Co 1x1
- Red line: MCNP
III. Results

Fano Factor (@ 130 K)

![Graph showing Fano Factor analysis with peaks at Cr Kα, Mn Kα, Fe Kα, Fe Kβ, Ni Kα, Cu Kα, and a Fano Best Fit with F = 0.128(2).]
Results - Cobalt

![Graph showing residuals and number of events vs. energy for Cobalt measurements.](image)
Results - Americium
L-Step

- Fano model should be valid
  - External modeling of all low-energy electrons emitted in Auger cascade (RELAX atomic relaxation spectra code)
- Calibration with Oxygen fluorescence x-rays → 21 eV resolution at $E_g = 525$ eV
- Interpret decreased resolution as coming from softened L step in electron spectrum
  - Assumption that each atomic shell can be treated as independent does not hold? Many-body effects?
Model

- From 0.5-4 keV
- Initial 3 parameter model with fixed step heights discarded
- 6 parameter model
  - 2 slopes
  - K step height
  - L step location and resolution ($\sigma_L$)
  - Normalization

\[
f(E) = A \times \begin{cases} 
  a_1(E - E_K) + 1 & E \geq E_K \equiv E_{10} \\
  a_2(E - E_K) + b_2 & E_L \leq E < E_K \\
  b_3 & E < E_L,
\end{cases}
\]

\[
b_3 = \frac{Z - 10}{Z - 2} [b_2 + a_2(E_L - E_K)].
\]
Model II

- 6 parameter model
  - 2 slopes
  - K step height
  - L step location and resolution
  - Normalization

- Able to model fit in <4 keV range to within 5% without accurate background knowledge

- Flattens out at high $\gamma$ energies
Takeaway

Primary

- Report, for first time, spectral Compton features associated with the atomic structure of the target.
- Characterize the spectrum of low-energy ionization signals from electrons Compton scattered by radiogenic $\gamma$-rays, vital for future DM searches
- Validate applicability of simple linear model

Secondary

- Demonstrate again CCD resolution down to $\sim 60$ eV
- Measure Fano Factor @ operating temperature

Remains an open question as to what happens at low energies?
Questions?
Exclusion Plot

A. Aguilar-Arevalo et al. (DAMIC Collaboration) Phys. Rev. D 94, 082006
Impulse Approximation

\[ \frac{d\sigma}{dE}_{nl} \left| \right. = C \int_{-1}^{1} \frac{(1 - \delta)(1 + \cos^2 \theta) + \delta^2}{|\vec{q}|} J_{nl}(p_z) \, d\cos \theta \]

\[ p_z = \frac{(E_\gamma / c)(1 - \delta)(1 - \cos \theta) - \delta mc}{|\vec{q}|} \]

\[ |\vec{q}| = \sqrt{2(1 - \delta)(1 - \cos \theta) + \delta^2}. \]

Expression valid only for \( E > E_{nl} \), the target electron’s binding energy. Otherwise it’s 0 as the min. energy photon can lose is that required to free the target electron.

\( J_{nl}(p_z) \) are the Compton profile functions, which encode the momentum distribution of the target electron and is taken from tabulated data. Further the integral can only be evaluated numerically.
Source Selection

\[ \text{Cross Section [cm}^2/\text{g]} \]

\( \begin{align*}
\text{Compton Scattering} \\
\text{Coherent Scattering} \\
\text{Photoelectric Absorption} \\
\text{Total}
\end{align*} \)

\[ \begin{align*}
\text{\( ^{57}\text{Co} \) } 122.1 \text{ KeV} \\
R_{\text{Comp.}} = 11.7 \\
\text{\( ^{241}\text{Am} \) } 59.5 \text{ KeV} \\
R_{\text{Comp./Photo.}} = 3.8
\end{align*} \]
Binning

- Hardware adding of neighboring pixels at serial register
  - e.g. $1 \times 100 \rightarrow 100$ rows (y) transferred into serial register before clocking in x (column) direction
  - Fewer pixels but same noise per pixel
Dataset

- Cobalt dataset taken early 2016, Americium early 2017
- Single 4k x 2k CCD (2.2 g mass)
- Analysis conducted using 4x4 data (1x1 used for validation)

<table>
<thead>
<tr>
<th>Binning</th>
<th>Source</th>
<th>N images</th>
<th>$V_{sub}$ [V]</th>
<th>Event density [keV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1×1</td>
<td>$^{57}$Co</td>
<td>1981</td>
<td>45</td>
<td>$3.5 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td>1235</td>
<td>45</td>
<td>$4.3 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>$^{241}$Am</td>
<td>971</td>
<td>45</td>
<td>$4.7 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td>2062</td>
<td>45</td>
<td>$2.4 \times 10^3$</td>
</tr>
<tr>
<td>4×4</td>
<td>$^{57}$Co</td>
<td>1981</td>
<td>127</td>
<td>$2.5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td>10276</td>
<td>127</td>
<td>$2.6 \times 10^2$</td>
</tr>
<tr>
<td></td>
<td>$^{241}$Am</td>
<td>9828</td>
<td>127</td>
<td>$2.5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td>2062</td>
<td>127</td>
<td>$1.1 \times 10^3$</td>
</tr>
</tbody>
</table>
Image Processing

- Pedestal (DC offset) subtraction → Pixel values centered at 0 with noise $\sigma_{\text{pix}}$
- Mask “hot” pixels & lattice defects (~10% removed)
- Energy calibration done with fluorescence & P.E peaks
  - Linearity previously demonstrated using this setup
- $1 \times 1$ datasets
  - Clustering done by $11 \times 11$ moving window maximizing difference in log-likelihood between 2 hypotheses: 2D Gaussian+Noise or just Noise.
- $4 \times 4$ datasets
  - Clusters identified as ionization events with contiguous pixels $> 4 \sigma_{\text{pix}}$
1x1 Diffusion Modeling

- Simulated events with uniform energy distribution between 0-1 keV and uniform spatial distribution, using diffusion parameters tuned at high energies, and compared to data.

Verifies that recorded spatial distribution is consistent with the signal from Compton scattering, with negligible contamination from surface events.
Based on simulation, able to construct detector efficiency curves

- 90%+ efficient at energies > 60 eV; > 99% above 80 eV
Consider only single pixel events between 60-80 eV

- Energy threshold chosen to exclude readout noise.
- Negligible single pixel readout noise $> 60$ eV, but present for 2+ pixels until 80 eV.
“Sensei”

- Repeat measurement in near future
- Non destructive “skipper” readout R&D project.
- Perform $N$ uncorrelated measurements for $\sim 1/\sqrt{N}$ noise reduction.

Technology will allow 2 e-(few eV) threshold.

\[ \begin{align*}
\text{Entries} & \quad 1635 \\
\chi^2 / \text{ndf} & \quad 19.6 / 25 \\
\text{Mean} & \quad -0.002 \pm 0.0016 \\
\text{Sigma} & \quad 0.06 \pm 0.001
\end{align*} \]