Partial charge collection and quantum efficiency of a back-illuminated skipper-CCD

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Partial charge collection layer

Region at the back of the CCD:

- Transition between dead layer and Silicon bulk
- High recombination probability
- Only charges escaping to Silicon bulk are collected

Why do we care about PCC?

- Possible background in neutrino and dark matter experiments
- Quantum efficiency of visible light in back-illuminated CCDs
Charge collection efficiency in thinned CCDs

- **New generation Charge Couple Devices (CCD)**

- **LBNL MicroSystems Lab**

- Energy threshold: \(~ 1.1 \text{ eV} \) (Si bandgap)

- Readout noise: \(~ 0.1 \text{ e}^- \)

**Main goals**

- First DM detector with Skipper-CCDs
- Validate technology for DM and ν detection
- Probe DM masses at the MeV scale (e - recoil)
- Probe axion and hidden-photon DM masses > 1 eV (absorption)

**Charge collection efficiency**

- **Dead layer**: 10 + 4 + 2 nm SiO₂ + ZrO₂ + In
- **Partially charged collection layer**: ?
- **Silicon bulk**: \(~ 20000 \text{ nm} \) Si
Summary of previous work

- Comparison between thinned and unthinned skipper-CCDs
- 55Fe X-ray source (5.9 and 6.4 keV)
- Attenuation length ~ 15 um
- Low statistics for thinned CCD
- New work: leverage data from Fano noise measurement

**Experimental setup**

- Vacuum vessel at $<10^{-4}$ torr
- CCD Temperature 123 K
- 3.7 Mpix of 15 µm
- Read-out electronics: low-threshold acquisition board
- 300 skipper samples ⇒ 0.2 e- noise
- Continuous readout
- 677 eV fluorescence x-rays (F)

Reconstruction and quality cuts

- Calibration from deep sub-electron resolution
- Cluster reconstruction (join neighboring pixels with charge > 0.6 e-)
- Remove hot columns and edges
- Compute charge variance in cluster
- Remove (very) asymmetric events
- No other cut
Reconstruction and quality cuts

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Spectrum reconstruction

- **Minimal cuts**
- Geant4 simulation of death layer and Silicon bulk
- No significant compton scattering
- No significant background from environment
- Excess of events around 50 electrons (probably from pile-up)
New generation Charge Couple Devices (CCD) developed by LBNL MicroSystems Lab

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**Method**

- Geant 4 simulation
  
  \[ g(z) = e^{-(z / \lambda)} \]

- Data
  - Data peak at \( q_T \)
  - Data range from \( q_T \) to \( q_C \)
Method

Geant 4 simulation

\[ g(z) = e^{-\frac{z}{\lambda}} \]

\[ G(z) = \int_0^z g(x) \, dx = \int_0^{q_c} f(x) \, dx = F(q_c) \Rightarrow \epsilon(z) = \frac{q_c(z)}{q_T} \]
Attenuation length

- 676 eV X-ray in Silicon: $\lambda = 0.74 \ \mu m$
- Real source geometry unknown
- Toy monte-carlo simulation to determine effective $\lambda$ ($\lambda_{eff}$)
- Far point-like source: mostly normal incidence
- Inclined plane similar to teflon in setup
Charge collection efficiency ($\epsilon$)

- Calculation for two (“opposite”) source geometries
- Analysis limited to 0.1 ~ 0.9 range due to SR background at low energy
- Different source geometries result in a 10% efficiency difference
Comparison with model dependant method

- Method developed for absolute measurement of fano factor and ionization energy
- Assuming $\varepsilon(z)$ shape:
  \[ \varepsilon(z) = 1 - (1 - \varepsilon_0) \exp\left(-\frac{z}{\tau CEE}\right) \]
- Both methods reconstruct a 80% collection efficiency at $z = 230$ nm

Quantum efficiency calculation (QE) for visible wavelengths

- Quantum efficiency (QE) at \( z = \varepsilon(z) \)
- Total QE convolution between \( \varepsilon(z) \) and probability of interaction at \( z \)
- Numerical calculation using measured \( \varepsilon(z) \) and tabulated attenuation

\[
QE(\lambda) = \int_{0}^{200} \frac{1}{\lambda} e^{\frac{-z}{\lambda}} \varepsilon(z) \, dz
\]


Measured charge collection efficiency

Photon attenuation length
Quantum efficiency

- Overestimation of PCC layer size will produce a lower QE in the blue
- No significant difference in source geometry (could be quantified as a systematic uncertainty)
- Reducing backgrounds at low energy (serial register hit) can improve resolution below 400 nm
Summary and outlook

- First **model independent measurement** of partial charge collection layer using 676 eV X-rays
- Simulation and analysis tools acknowledge for **geometry effects** of the X-rays source
- Discussion on method to obtain **quantum efficiency** for visible wavelengths without a calibrated photo-detector or source

- Improve **data quality** by shielding the serial register and reducing occupancy
- Improve **efficiency estimation** with new analysis method
- Implement effects of **optical coating**
- Compare method with **absolute calibration** of quantum efficiency.