Ionization Efficiency Studies for Nuclear Recoils in Silicon

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Abstract

The Damic Collaboration has set up an experimental array of Charge-Coupled Devices (CCDs) in a nickel mine, and has developed all analysis tools to discern any known trace of conventional matter from what a DM particle could produce when crossing the CCDs. In order to calibrate the signals from these CCDs, scientists in the Antonella Collaboration have designed experiments to quantify neutron-silicon interactions, assuming that neutrons can mimic DM interactions in the CCDs. Here we present preliminary results from the analysis of data obtained in these experiments, in particular, the measurement of ionization efficiencies in Silicon and a plastic scintillator.
CCD operation

Detector

Charged particles produce ionization in CCD bulk

3.62 eV for e-h pair

Charge drifted up and held at gates

Charge collected by each pixel on CCD plane is read out

~2 e\(^-\) RMS read-out noise
Ionization efficiency studies

- Damic CCD's measure ionization energy
- Nuclear recoil energy from DM-Si interaction

Ionization efficiency in Si

AND Ionization efficiency in plastic scintillator

Antonella Collaboration

Antonella experiment

Target may be SiDet or a scintillator
PMT's characterization

To characterize the signal in a PMT, the experimental setup consisted of two scintillator bars, with a PMT at each end of the bars.
Scintillator EJ200

Experimental setup at FTB facility
ADC distributions

The ADC distributions may be calculated using a continuous approach, or a discrete approach.

Gaussians

\[ x_p, x_0, \sigma_0 \]

\[ x_1, \sigma_1 \]

\[ x_n = nx_1, \]

\[ \sigma_n^2 = n\sigma_1^2 \]

\[ P(0) = \frac{N_{ped}}{N_{trig}} = e^{-\mu} \]

\[ P(2) = \frac{\mu}{2} \]

\[ \text{SER}_0(x) = \frac{1}{\sqrt{2\pi}\sigma_0} \frac{1 - pE}{gN} e^{-\frac{(x-x_0-x_0)^2}{2\sigma_0^2}}, x > 0 \]

\[ g_N = \frac{1}{2} \left( 1 - \text{erf} \left( -\frac{x_0}{\sqrt{2}\sigma_0} \right) \right) \]

\[ M(x) = \sum_{n=2}^{N_M} \frac{P(n; \mu)}{\sqrt{2n\pi}\sigma_1} e^{-\frac{(1/2n)^2}{2\sigma_1^2}} \]

\[ x_1 = \left( x_0 + \frac{\sigma_0}{\sqrt{2\pi g_N}} \exp \left( -\frac{1}{2} \left( \frac{x_0}{\sigma_0} \right)^2 \right) \right) \]

\[ \sigma_n^2 = \frac{1}{2\pi g_N} \exp \left( -\frac{1}{2} \left( \frac{x_0}{\sigma_0} \right)^2 \right) \left( x_n - nx_1 - x_0 \right)^2 \]

NIMA 451 (2000) 623
R.Dossi et al.
Methods for precise PE counting with PMTs (LEDs)
ADC distributions

Charge distributions with two paper masks: one tiny hole of 0.035 mm in radius, and two small holes of 1.19 mm radius
TDC distributions

\[ f(t) = \frac{p_1}{\tau_s - \tau_f} \left\{ \exp\left[\frac{-(t-t_0)}{\tau_s}\right] - \exp\left[\frac{-(t-t_0)}{\tau_f}\right] \right\} + \frac{p_2}{\tau_3 - \tau_f} \left\{ \exp\left[\frac{-(t-t_0)}{\tau_3}\right] - \exp\left[\frac{-(t-t_0)}{\tau_f}\right] \right\} \]

Histogr.s: TDC for selected ADC bar  
Lines: normalized TDC prediction
Antonella at UND

collimator

scintillator bar array

$p$

$n$

silicon detector
We used an X-ray detector which is a Silicon Drift Diode, 29mg mass
Ionization efficiency

Broad neutron spectrum $E_n$ in [50, 600] keV

\[ E_n = \frac{m}{2(\Delta t)^2} \left[ l + r \frac{(A + 1)}{\cos \theta + \sqrt{A^2 - \sin^2 \theta}} \right]^2 \]  \hspace{1cm} (1) \hspace{1cm} \Delta t = \text{neutron total Time-of-flight}

\[ E_{NR} = E_n \frac{2}{(A + 1)^2} \left[ A \sin^2 \theta - \cos \theta \sqrt{A^2 - \sin^2 \theta} \right] \]  \hspace{1cm} (2)

Program:

1. Measure neutron energy by time-of-flight (1)
2. Detect a scattered neutrons in a neutron detector
3. Measure charge produced by ionization
4. Calculate the nuclear recoil energy with kinematics (2)
Systematic uncertainty dominated by the X-ray detector linear response
Scientific run

- Took data for 10 day

- ~ \(10^6\) gamma+neutron hits in silicon detector

- Trigger rate ~ 170 Hz (of which ~ 4 Hz real particles hitting the silicon detector)

- \(1.5 \times 10^8\) triggers, mostly noise from the silicon detector

- \(1.8 \times 10^5\) events, after requesting hit in a Bar (PMT in coincidence)

- \(5.1 \times 10^3\) events, after timing and no-saturation cuts (reject gamma prompt)
Antonella data

$E_{\text{ionization}}$ vs time-of-flight for Bar 6

gamma prompt hitting a bar

high energy deposited in SiDet + environmental bkg on a bar

following beam bunch

neutrons arrival interval
Antonella data

$E_{\text{recoil}}$ vs. $E_{\text{ionization}}$ for All Bars
Preliminary results

Ionization efficiency vs Nuclear Recoil energy

- This Work
- Systematic uncertainty
- Gerbier et al. (1990)
- Sattler (1965)
- Lindhard calculation (1963)
Conclusions

Scintillator+PMT response was studied

Antonella's results: best measurement on Si IE up to date

Ongoing analysis on scintillator IE
N-Si collisions

Monochromatic neutrons

\[ E_{NR} = E_n \frac{2}{(A + 1)^2} \left[ A + \sin^2 \theta - \cos \theta \sqrt{A^2 - \sin^2 \theta} \right] \]

- \( \theta \) Scattering angle
- \( A \) Atomic mass
- \( E_n \) Neutron energy
- \( E_{NR} \) Energy of Nuclear recoil

\( \text{Ion}_{\text{eff}} = \frac{E_{\text{ionization}}}{E_{NR}} \)

measured in a silicon detector calibrated with electron recoils
calculated from kinematics
Backup slides
Antonella DAQ