Pulse shape simulation for segmented germanium detectors

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What is pulse shape simulation ...
Internal or external radiation can create electron-hole pairs inside a germanium detector.
electron-hole pairs drift to electrodes if high voltage is applied to the detector
Charges, $Q(t)$, are induced on the electrodes when electron hole pairs drift away from each other.
This change on the electrodes can be recorded by the electronics, giving us hints on what's happening inside the detector.
Modeling of electric signal formation process in germanium detector system in computer is called Pulse Shape Simulation (PSS in short)
Why pulse shape simulation (PSS)

- Estimate PS Analysis (PSA) efficiency
  - Generate single or multi-site event samples
- Help on experiment design
  - Try different detector configurations
- Improve understanding of germanium detector
  - Study impurity distribution, for example
- Help analysis
  - Generate PS library for NN, for example
How to do it ...
1. Simulate interactions using Geant4 (Prof. Yu's talk)

Internal or external radiation can create electron-hole pairs inside a germanium detector.
Group hits based on position and time resolution to increase efficiency

Electron multiple scattering in germanium simulated by Geant4

1.02 MeV electron
2. Electric field calculation

electron-hole pairs drift to electrodes if high voltage is applied to the detector
Electric field calculation:
*home made codes or commercial software (Prof. Li's talk)*

Poisson’s equation:
\[
\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon},
\]

Space charge density from impurity

Calculation can be optimized if detector has symmetric configuration

Electric potential of a true co-axial HPGe (XY cross section)

Electric potential of a BEGe (XZ cross section)
Effect of impurity on electric field inside a germanium detector

Change of the radial electric field strength as a function of the radius for different active bulk impurity densities $\rho$ and fixed applied electric potential of 3000 V. For each calculation the impurity density was constant throughout the detector. At $\rho = 1.0 \cdot 10^{10} \text{ cm}^{-3}$ the detector is not fully depleted anymore.
Impurity $\rightarrow$ electric field $\rightarrow$ pulses

**Pulses for impurity**

- $\rho = 0 \cdot 10^{10} \text{ cm}^{-3}$
- $\rho = 0.83 \cdot 10^{10} \text{ cm}^{-3}$
3. Drift of charge carriers

electron-hole pairs drift to electrodes if high voltage is applied to the detector
Germanium crystal structure and axes

Crystal axes and detector coordinate system

Crystal axes (Miller index)

Crystal basic configuration

atom convalent bond
Drift velocity

\[ \mathbf{v}_{e/h}(\mathbf{r}) = \mu_{e/h} \mathbf{E}(\mathbf{r}) \]

Degenerate along \langle111\rangle & \langle100\rangle

\[ v = \frac{\mu_0 E}{1 + \left(\frac{E}{E_0}\right)^\beta}^{1/\beta} - \mu_n E \]

Mobility (tensor)

E field (vector)

Drift velocity (vector)

Mobility (just a number)

Parameters can be measured
Effect of crystal structure on drift trajectories

Holes drift inward from outer surface

Electrons drift outward from inner surface
4. Charges induced on electrodes

Charges, $Q(t)$, are induced on the electrodes.

Diagram:

- Ge Detector
- $\gamma$
- Electrons (e), holes (h)
- Electric field ($E$)
Induced charge is proportional to the Weighting Potential seen by charge carriers along their trajectories (Ramo's theory)
Weighting potential calculated for one segment

Not affected by impurity

\[ \nabla^2 \varphi(r) = 0 \]

Weighting potential of a central segment electrode of a true coaxial 18-fold segmented germanium detector in (a) horizontal cross section \((z=0)\) and in (b) vertical cross section \((y=0)\). The weighting potential equals unity on the considered electrode and zero on all other electrodes.
5. Fold in electronic effects

This change on the electrodes can be recorded by the electronics, which is normally not perfect...
Can PSS be trusted ...
Compare simulation to data

Scanning the outer surface of a segmented HPGe detector with a collimated gamma source.

Core pulse from surface scanning data (electrons drift inward from outside).

**Graph:**
- **Y-axis:** Charge [A.U.]
- **X-axis:** Time [ns]
- Data points and fitted simulated pulse.

- **Time scale factor:** $0.90 \pm 0.01$
- **$\chi^2$/dof:** 184/146
Let's put it into real use!

(an example in detector design)
Advantage & disadvantage of segmented HPGe detectors

Disadvantages:
- Big capacity → noisy
- Short drift length → Short rise time
- Segmentation → more material

Advantages:
- More information is available from segment pulses
Advantage & disadvantage of PPC or BEGe

Excellent in distinguishing single-site and multi-site events (Dusan's talk)

Advantages:
- Low capacity → Low noise
- Low field in bulk → long drift
- Singleton WP → shape rise at the end

Disadvantages:
- Less information
Segmented HPGe  ❤  Point-contact or BEGe
LBNL fabricated segmented PPC (SPPC)

Simplest segmentation:
- two segments
- readout one
Even one single segment gives much more information

\[ \theta \text{ gives location along the } \tau_2 \text{ contour line and is determined by the } Q_{fc} \text{ signal amplitude and shape} \]
Simulated pulses from a 5 keV energy deposition with electronic noise of 400 eV

Determine time zero using segment pulse
More examples

Equipped with PSS tools we can easily investigate different configurations in a quick and efficient way!

Point-contact deep inside
I am sure you have better ideas
Thank you!
backup
Average out noise

Scanning the outer surface of a segmented HPGe detector with a collimated gamma source

Averaged core pulses from data and simulation

![Diagram of segmented HPGe detector and scanning setup](image)

![Graph showing averaged core pulses](image)
Segment pulses give more information about the interaction
Fig. 16  Mean time scaling-factors, points, as extracted for each $\phi$. The uncertainties were taken from the Gaussian fits. The result of a straight line fit to the points is given as a *solid line*
Fig. 11  Simulated core pulses for different impurities, $\rho_{\text{imp}}$
Fig. 10  Simulated core pulses for two different sets of input parameters for the electron mobility. The result of a time scaling of the longer pulse is also shown.
Accurate Geant4 simulation gives a good start
Why pulse shape simulation is needed ...
Pulses from a single-site event

0vbb or DM events are single sited
Pulses from a multiple-site event

Background events are multiple sited
Efficiency of PSA on 0vbb signal is estimated based on single-site event samples taken from single Compton scattering events.
Single-site event data samples are not perfect.

DEP samples suffer from different energy and spacial distribution.

Single Compton scattering samples suffer from low event rate.
Why pulse shape simulation (PSS)

- Estimate PS Analysis (PSA) efficiency
BEGe

Segmented HPGe

PPC