2456-7

Joint ICTP-IAEA Workshop on Advances in Digital Spectroscopy

6 - 10 May 2013

Gammas contd.

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IAEA International Atomic Energy Agency

Digital Gamma-Ray Spectroscopy

Joint ICTP-IAEA Workshop on Advances in Digital Spectroscopy
May 7th 2013

BERKELEY LAB Lawrence Berkeley National Laboratory

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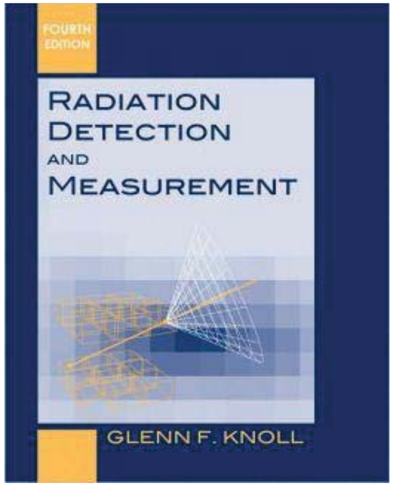
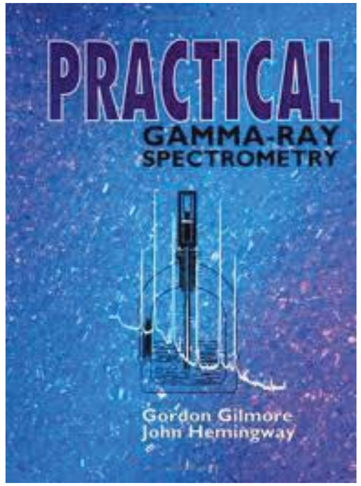
Lawrence Berkeley National Laboratory, USA

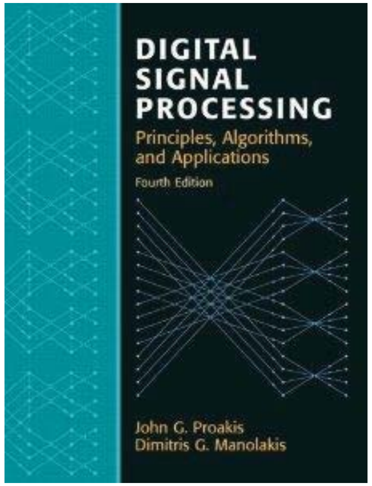
Literature



"Radiation Detection and Measurement"
Glenn Knoll



"Practical Gamma-Ray Spectrometry"
Gilmore and Hemingway



"Digital Signal Processing"
Proakis and Manolakis

Lecture Notes, Helmuth Spieler
www.physics.lbl.gov/~spieler

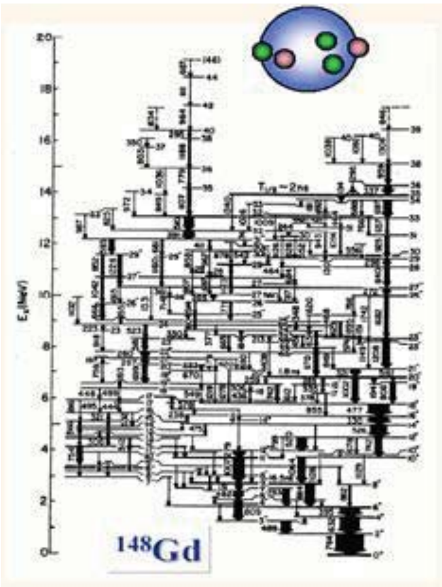
Overview

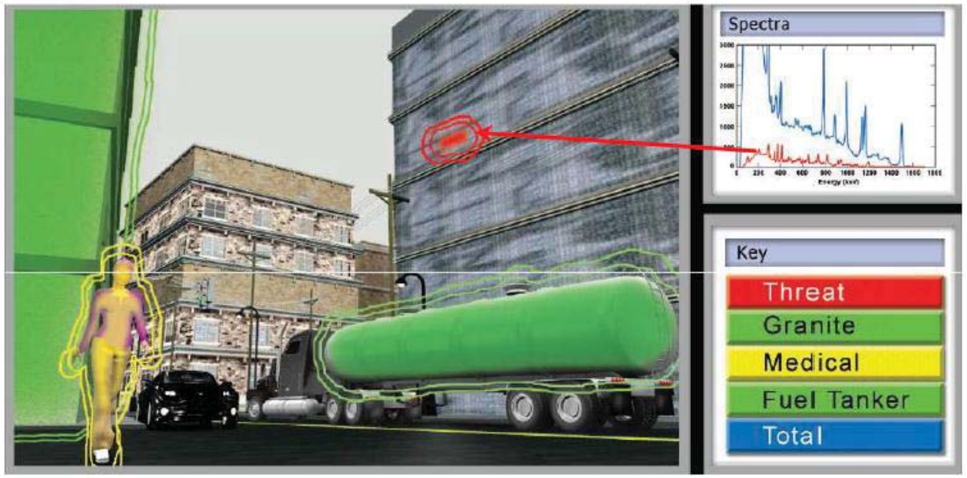
From some basic concepts to some modern applications….

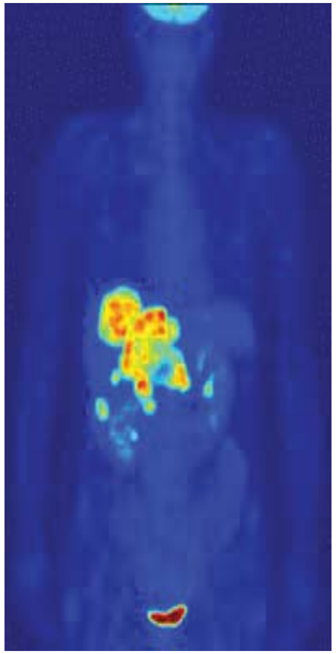
- Gamma-Ray Detection: Why and How?
- Semiconductor Detectors
- Digital Electronics for Gamma-Ray Spectroscopy
- Digital Signal Processing Techniques
- Applications

Gamma-Ray Detection: Why?

- Gamma rays are emitted following discrete nuclear transitions
- These transitions are defined by the structure of the decaying nucleus
- Gamma rays are penetrating and have well defined interaction kinematics







Gamma-Ray Detection: How?

- Measure the charge created in some detection medium from the interaction of gamma rays
- Collect this charge and induce an electronic signal

Ideally…..

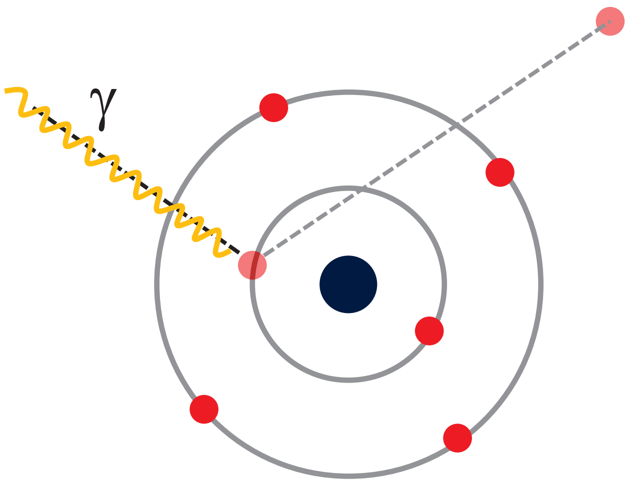
- The amount of charge is proportional to the **energy** deposited
- The signal allows us to define the **time** of the event
- The evolution of the signal with time might change with **position**

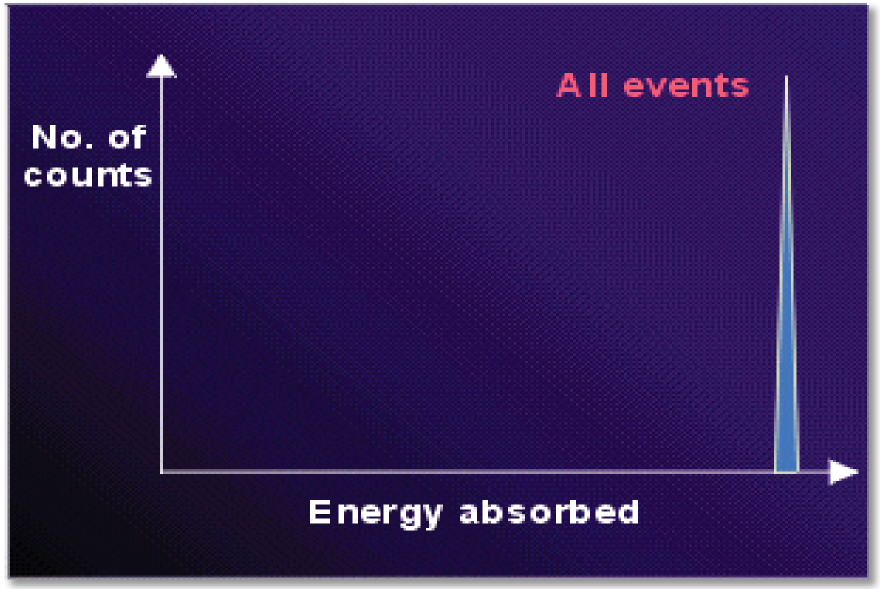
- **Interaction via three main processes** (in the energy range of interest)

Gamma-Ray Interactions

- Photoelectric Absorption
- Compton Scattering
- Pair Production

$$E_e = E_\gamma - E_{binding}$$

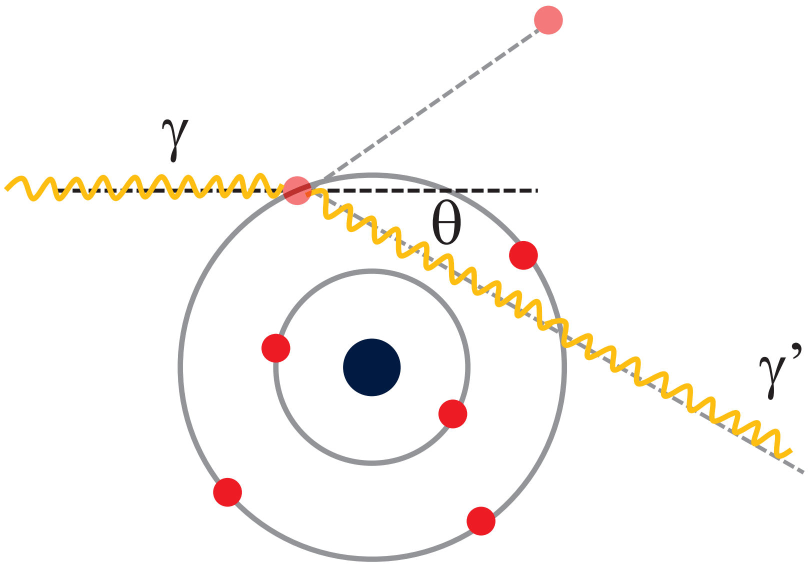


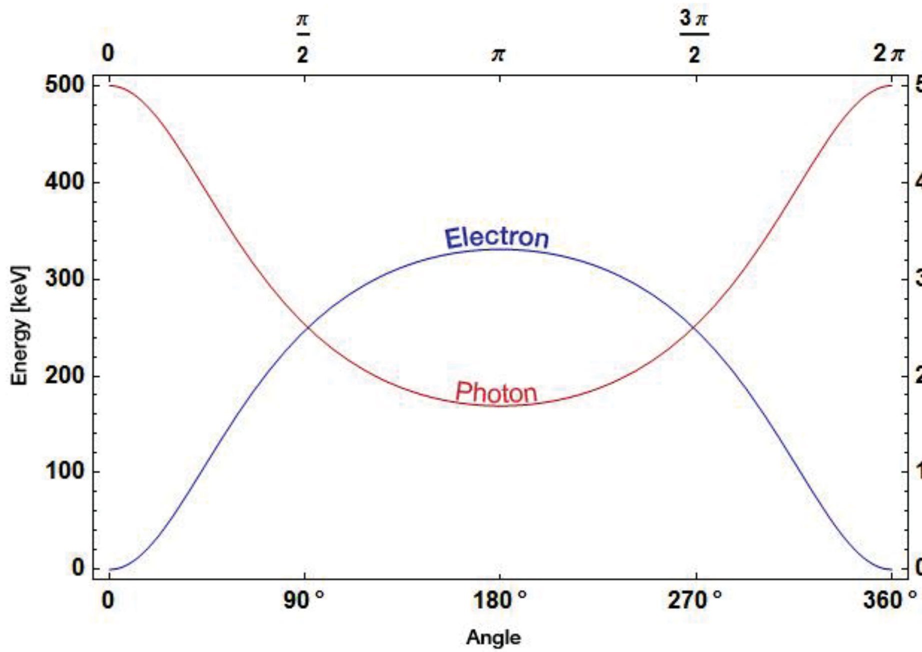


Gamma-Ray Interactions

- Photoelectric Absorption
- Compton Scattering
- Pair Production

$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2}(1 - cos\theta)}$$





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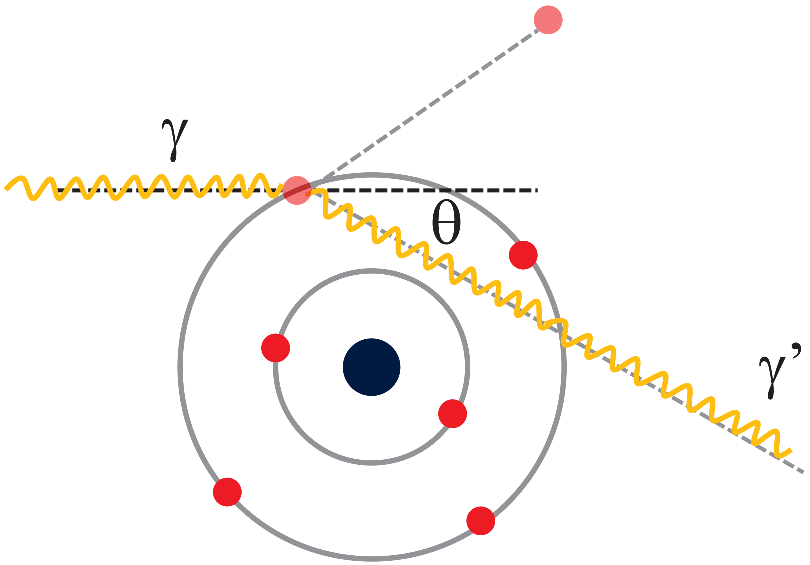
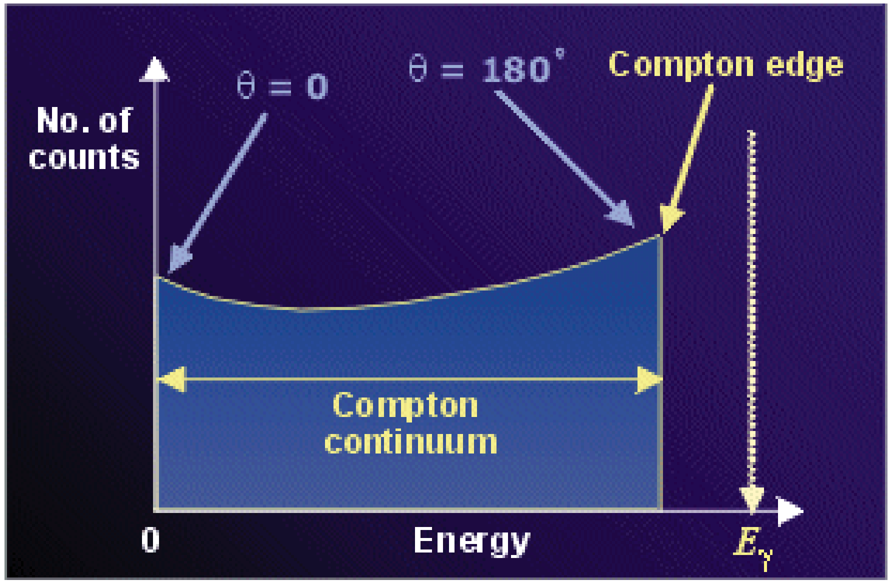


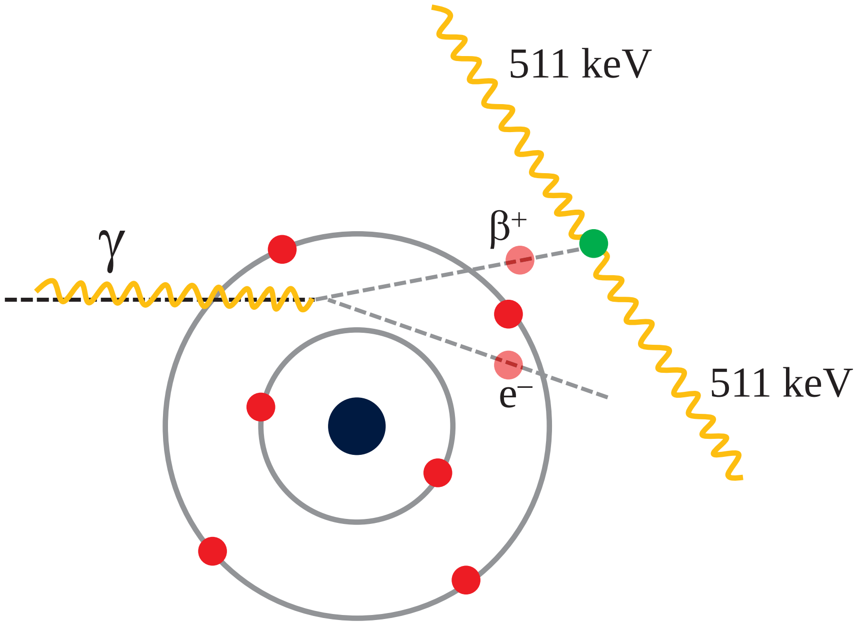


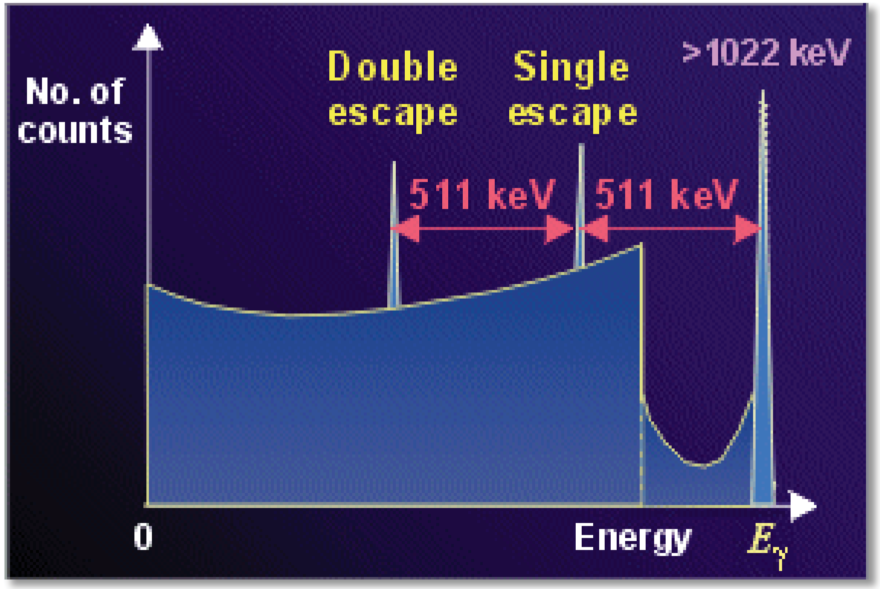
Gamma-Ray Interactions

- Photoelectric Absorption
- Compton Scattering
- Pair Production

$$E_{e^-} + E_{\beta^+} = E_\gamma - 2m_0c^2$$

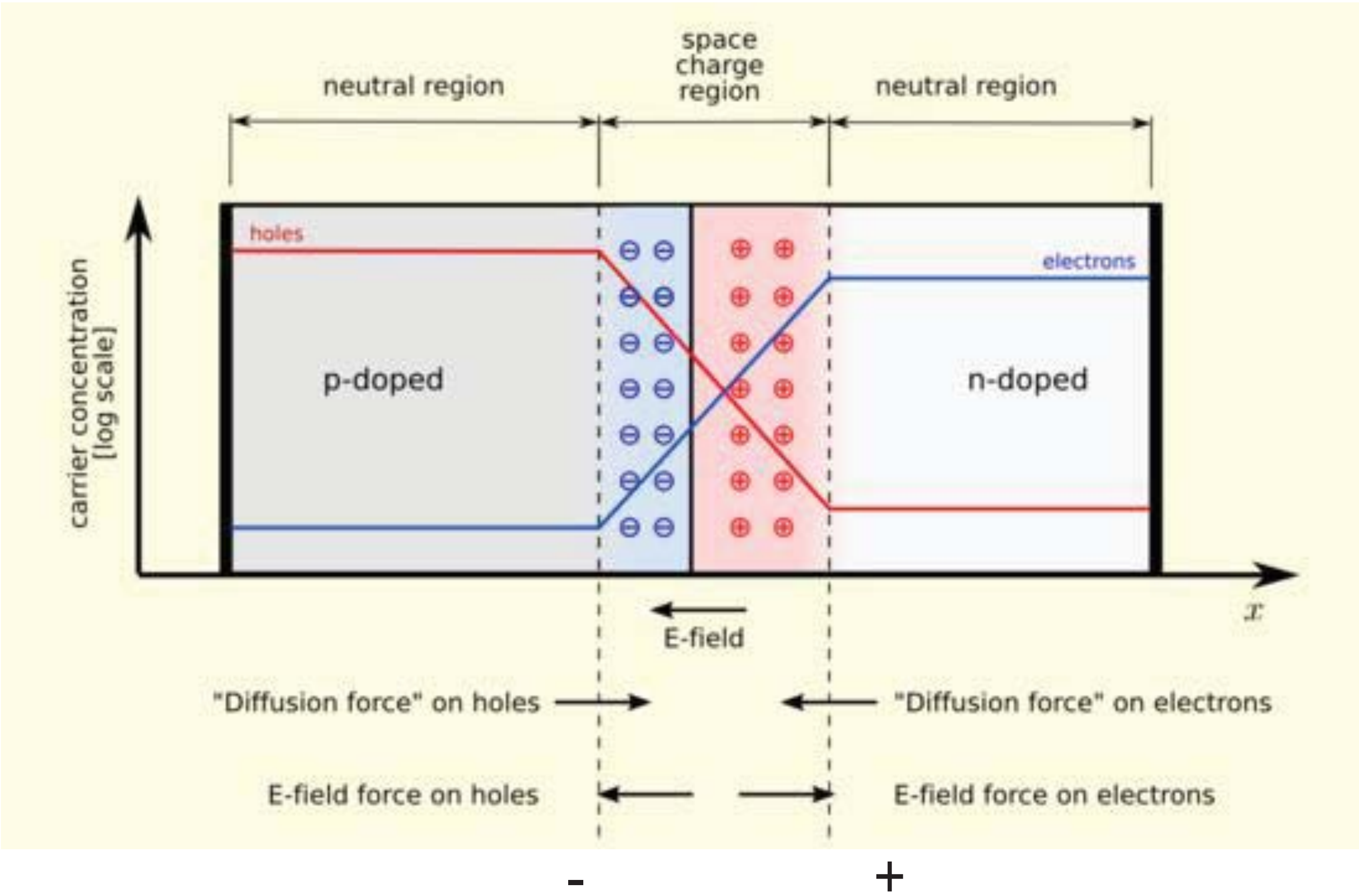
$$E_\gamma > 1022\ keV$$





Semiconductor Detectors

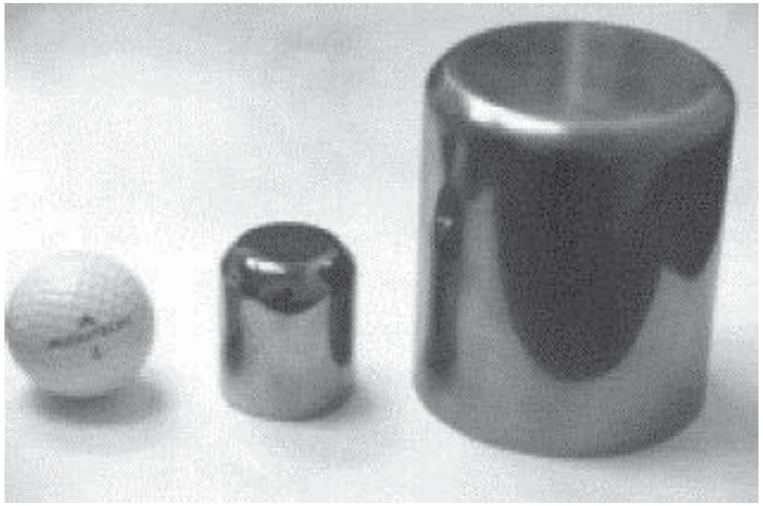
Reverse biased p-n junctions

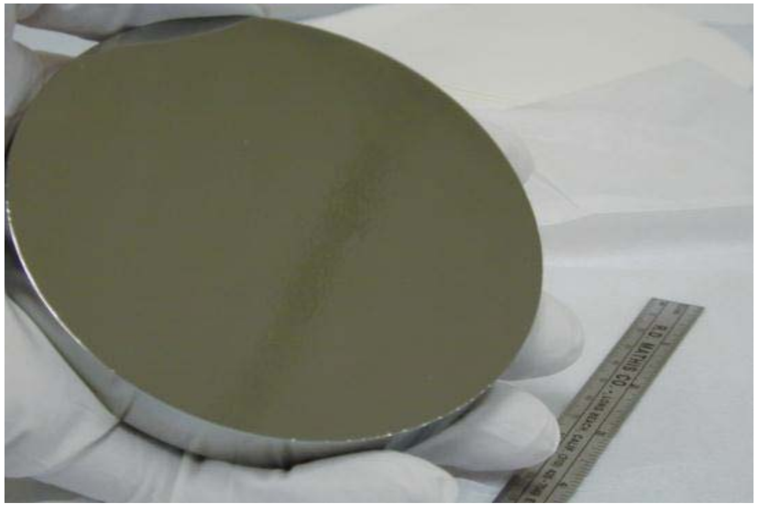


HPGe is the semiconductor detector of choice for gamma-spectroscopy

HPGe Detectors

"The workhorse of gamma-ray spectroscopy"

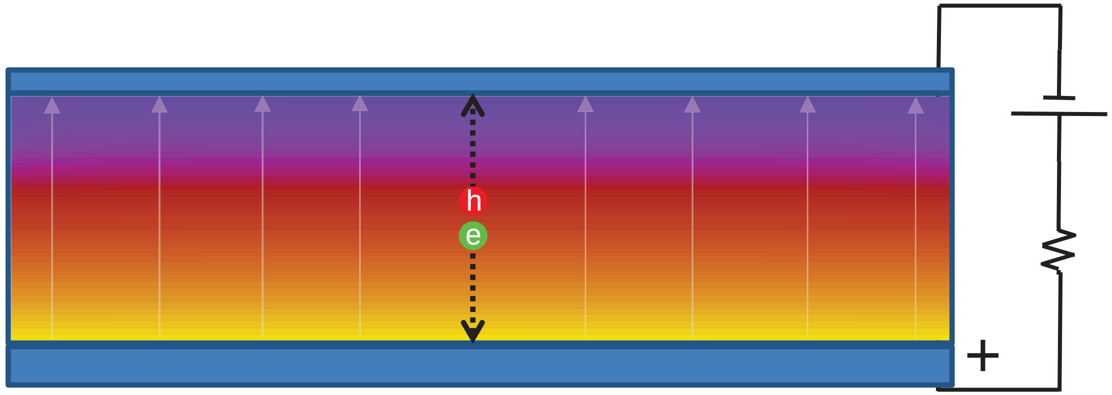




- Very good energy resolution (0.2 – 1%)
- Extremely low noise
- Coaxial detectors:
  - cylinder 60-80 mm diameter
  - 60-100 mm long
- Planar detectors:
  - 60-80 mm square
  - up to 20 mm thick

Segmented HPGe Detetors

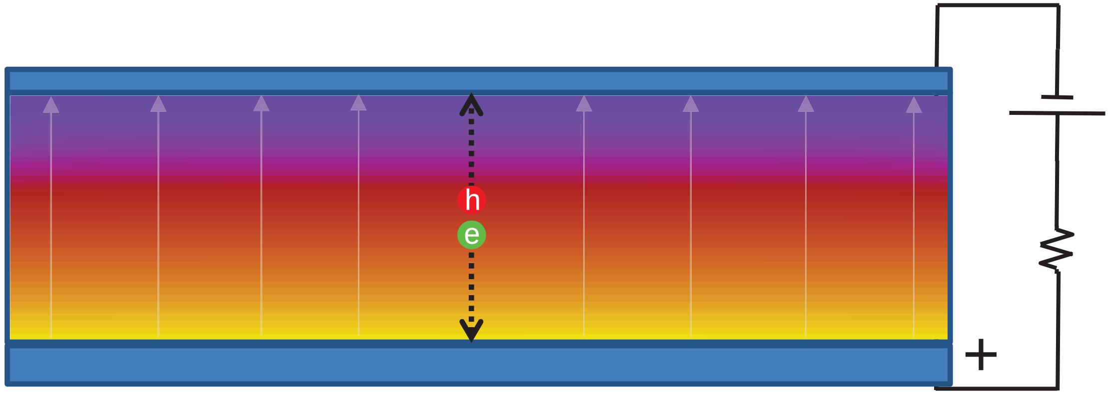
Electrical segmentation of outer, charge collecting contact(s)



- Planar or coaxial geometry
- Instrument every channel
- Position sensitivity
- Count rate

Segmented HPGe Detectors

Electrical segmentation of outer, charge collecting contact(s)



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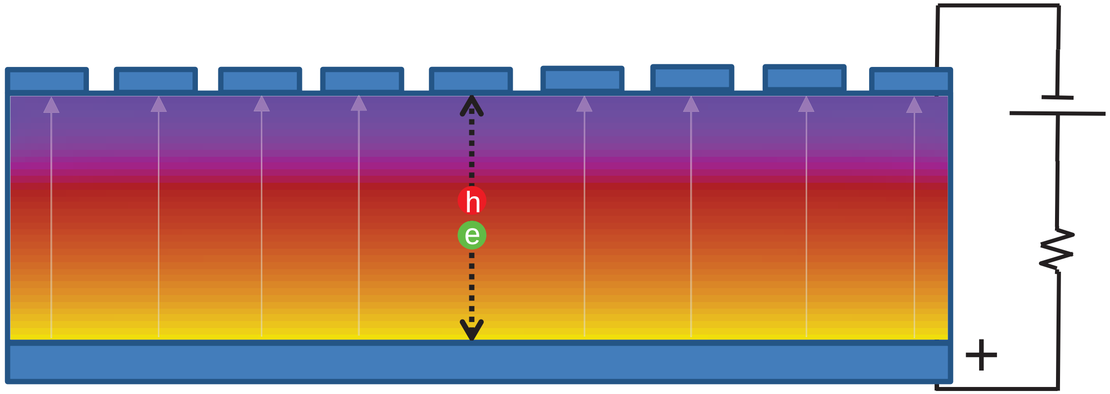


HPGe Detectors: Signal Generation

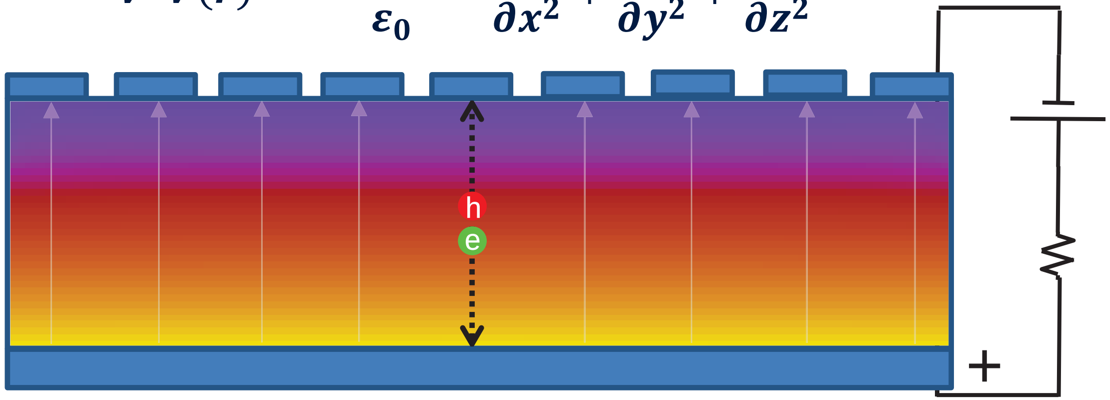
Charge transport dynamics defines signal shape

- Charge trajectory defined by electric field
- Induced signal defined by weighting potential

$$\nabla^2 V(r) = -\frac{\rho(r)}{\varepsilon_0} = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}$$

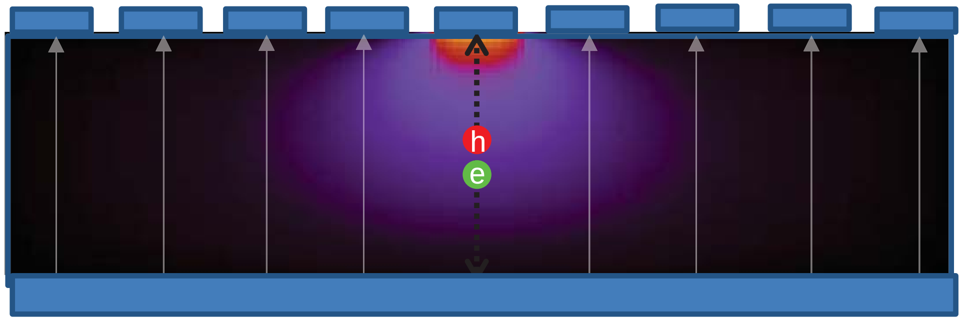
<u>Electric Field</u>

- Created by bias
- ~1000V/cm
- Defines drift velocity



<u>Weighting Potential</u>

- Defined by geometry
- Solve Poisson equation with collecting contact at unit potential
- Other contacts at ground



HPGe Detectors: Signal Generation

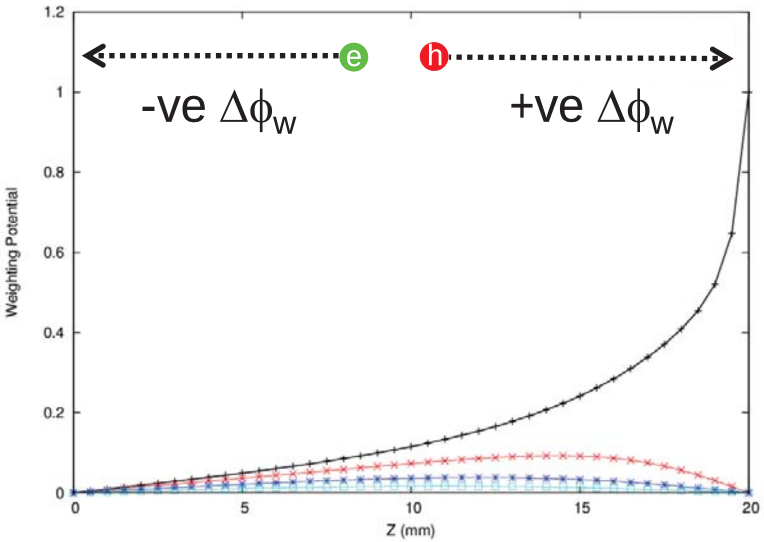
Charge transport dynamics defines signal shape

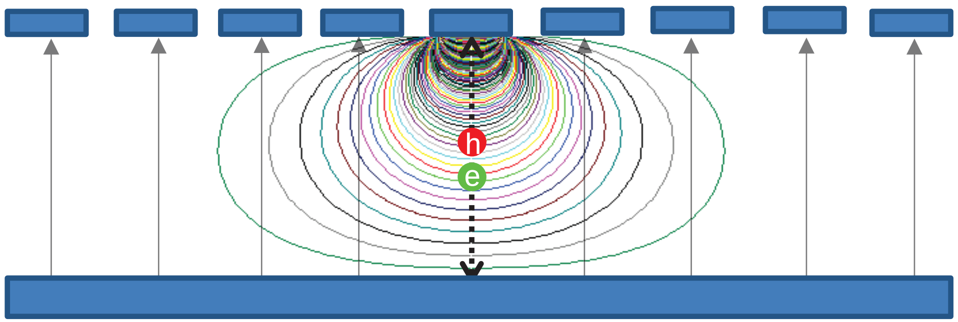
- Both carriers contribute to signal
- Can have a linear e-field but non-linear signal response

charge signal → *hole* → ***electron***

$$\boldsymbol{Q(t) = (+q)(\Delta\varphi_W) + (-q)(\Delta\varphi_W)}$$

change in W.P. per time step

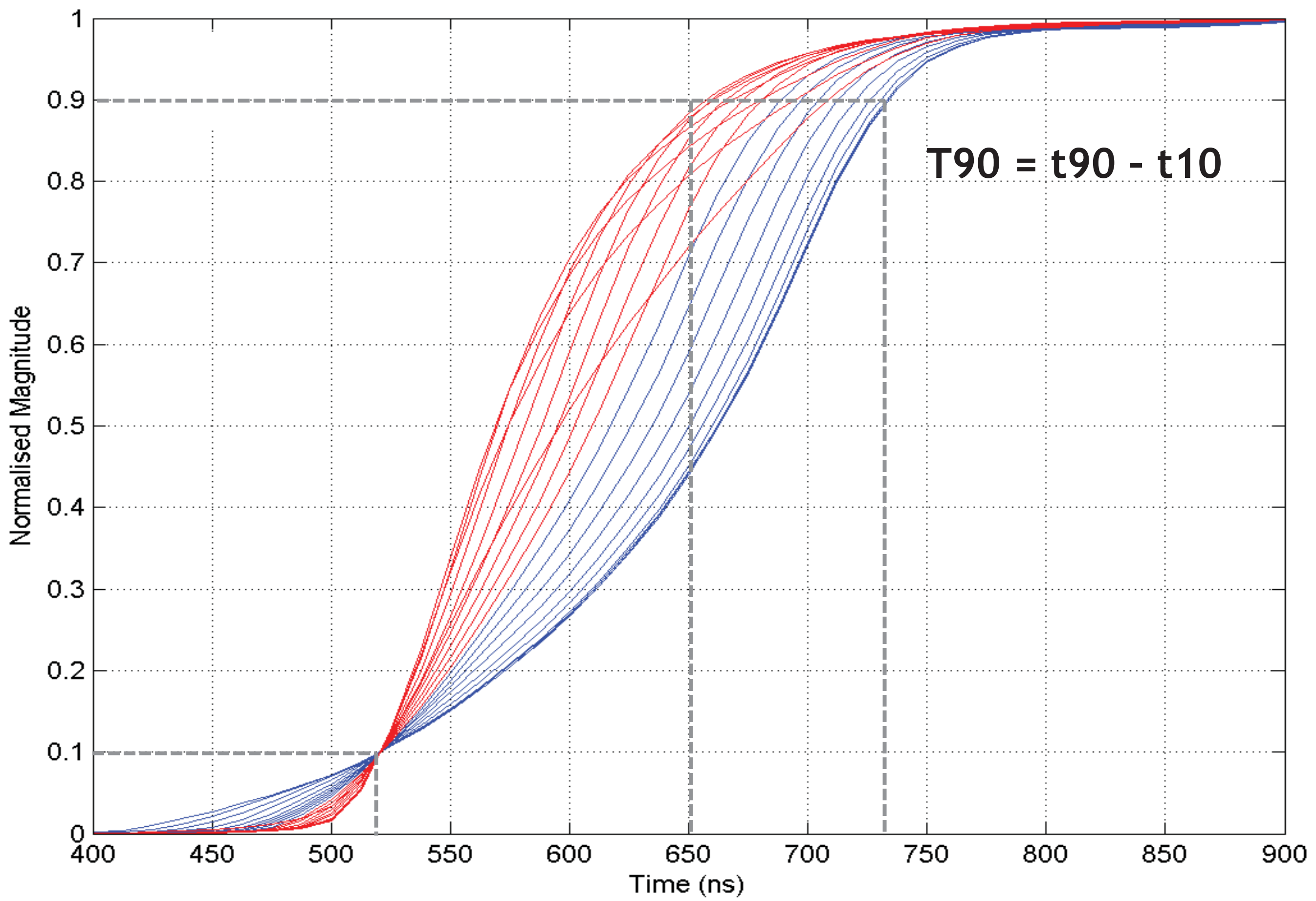




HPGe Detectors: Signal Generation

Strong variation in shape of charge signal with interaction "depth"

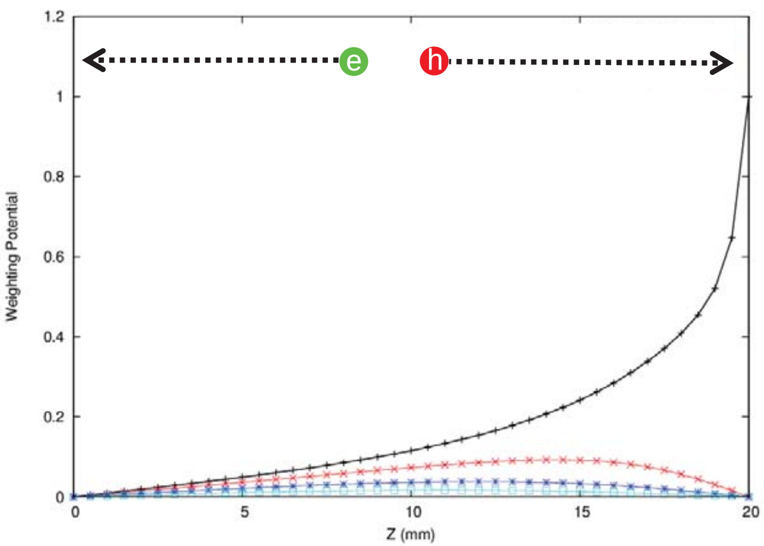
- Typically characterised by the rise-time



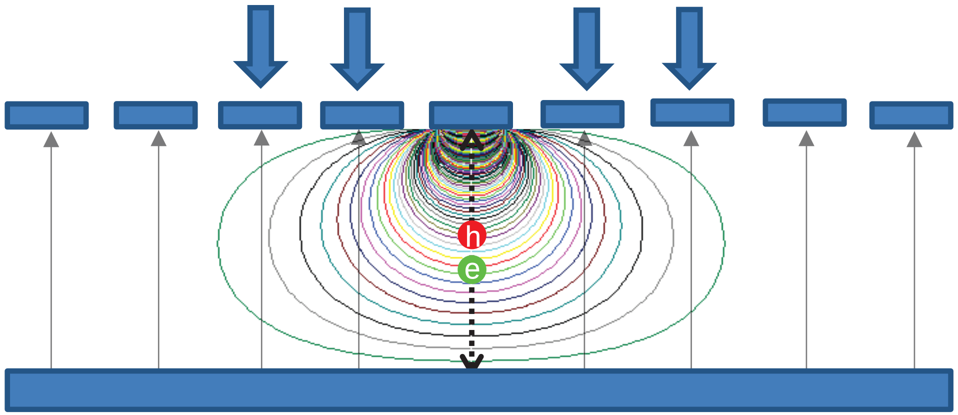
HPGe Detectors: Signal Generation

The story doesn't end there…..

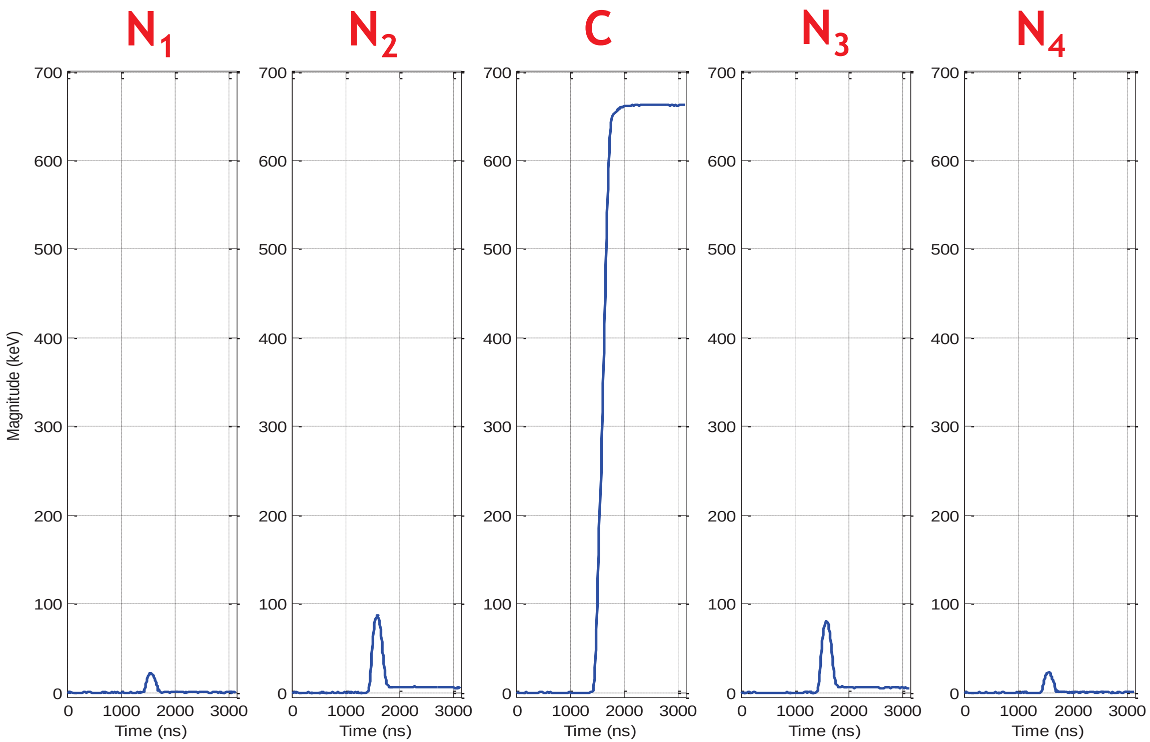
- The weighting potential extends out of the charge collecting strip
- The carriers are coupled to the neighbouring segments
- No net charge is collected on the neighbouring strips
- The weighing potential looks very different
- Image charges (transients) are induced

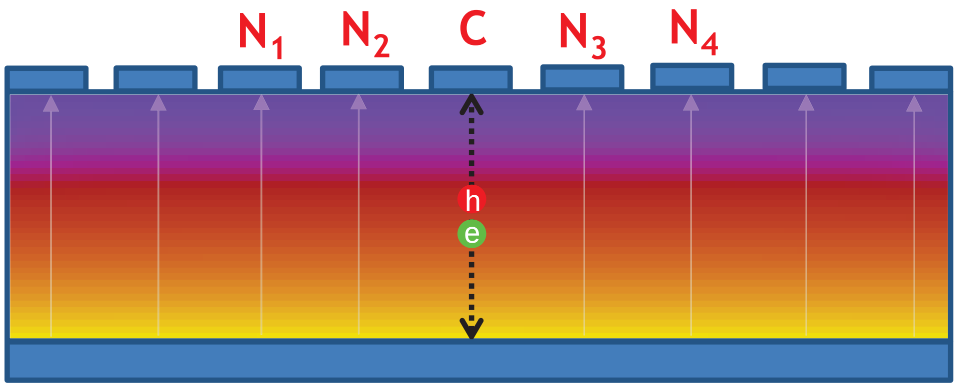


$$Q(t) = (+q)(\Delta\varphi_W) + (-q)(\Delta\varphi_W)$$



HPGe Detectors: Signal Generation II





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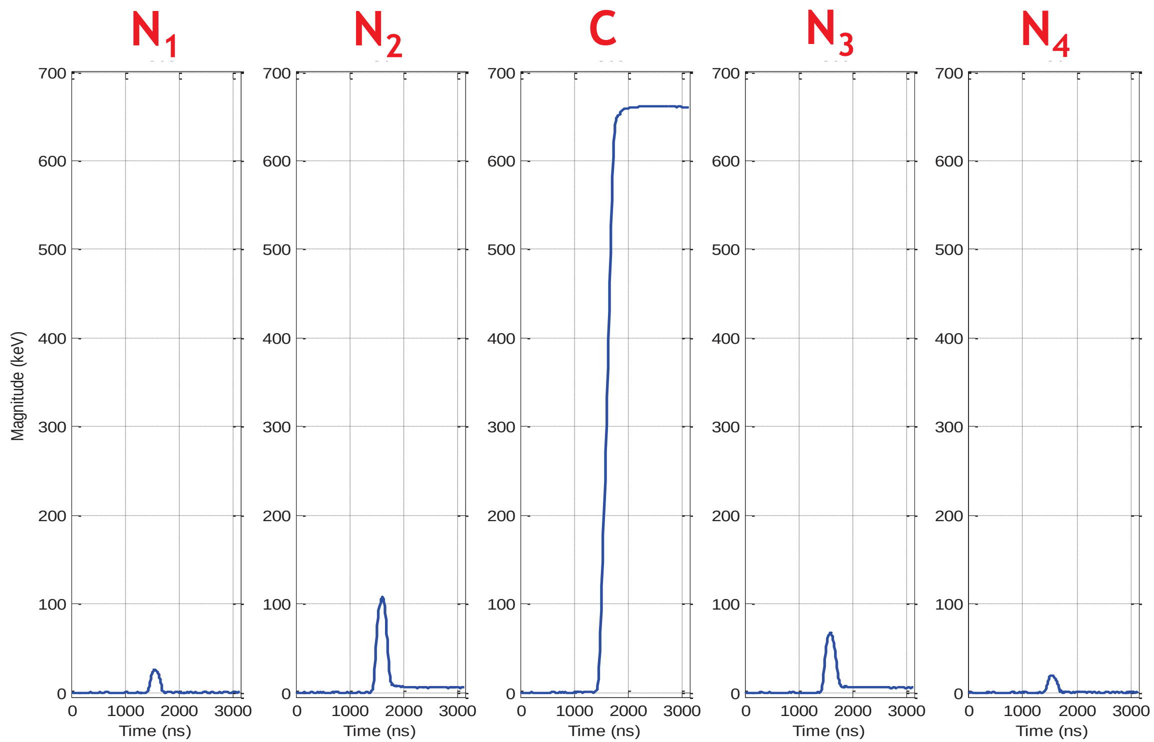

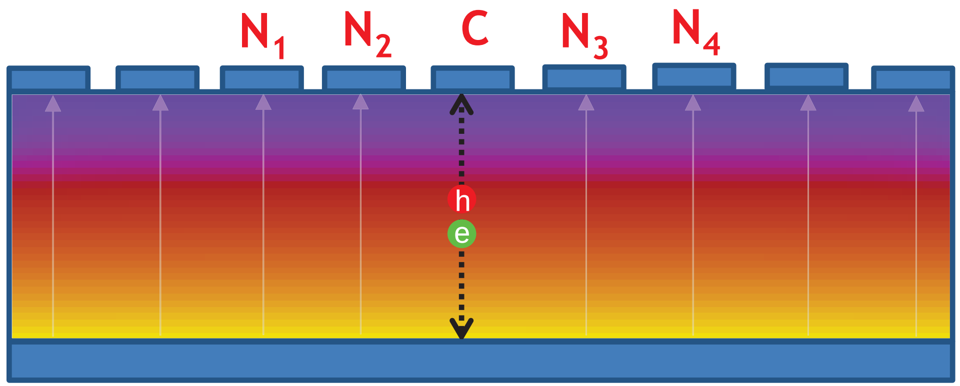

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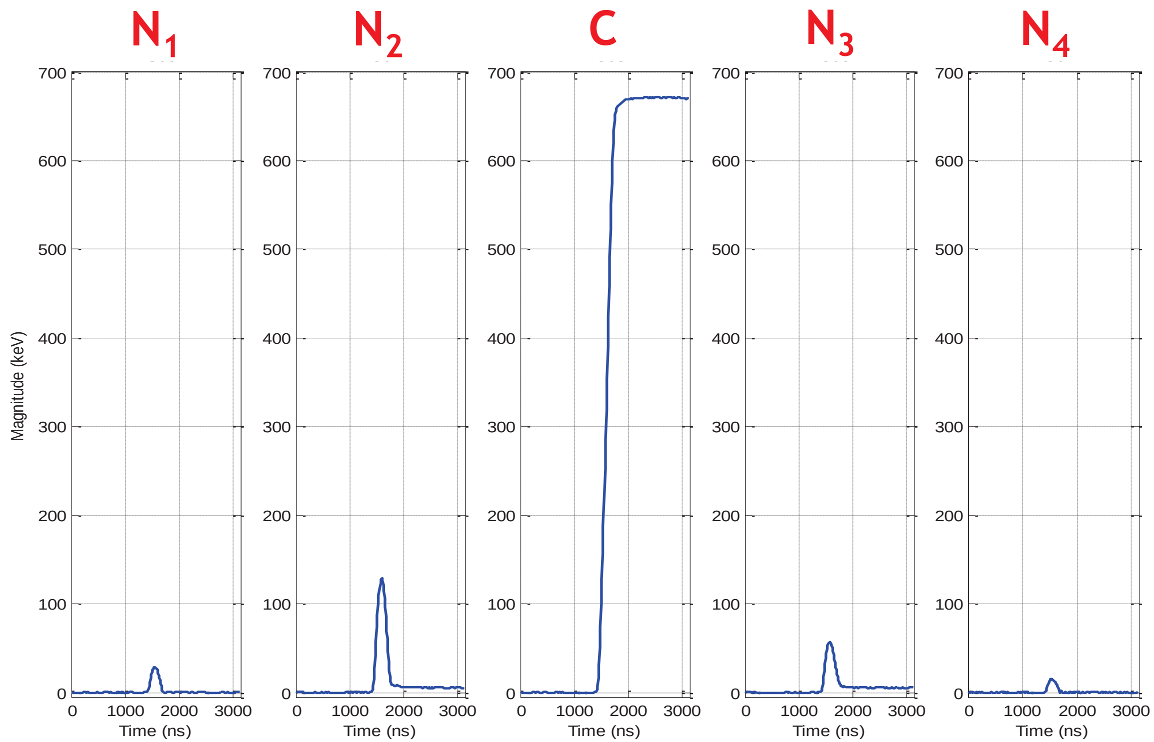

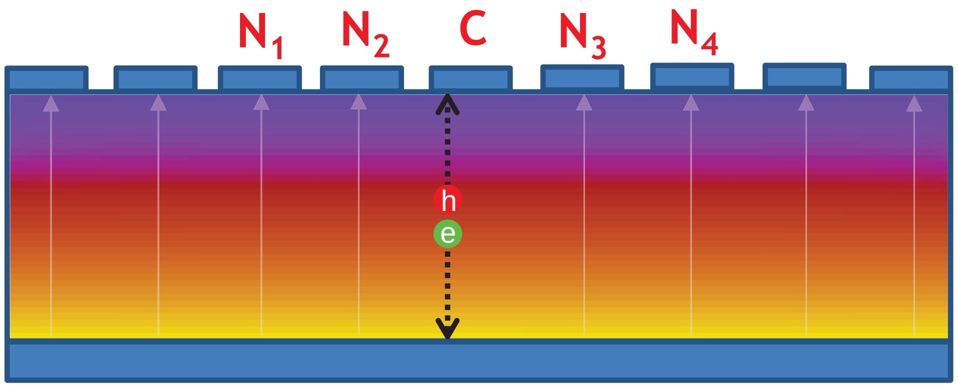

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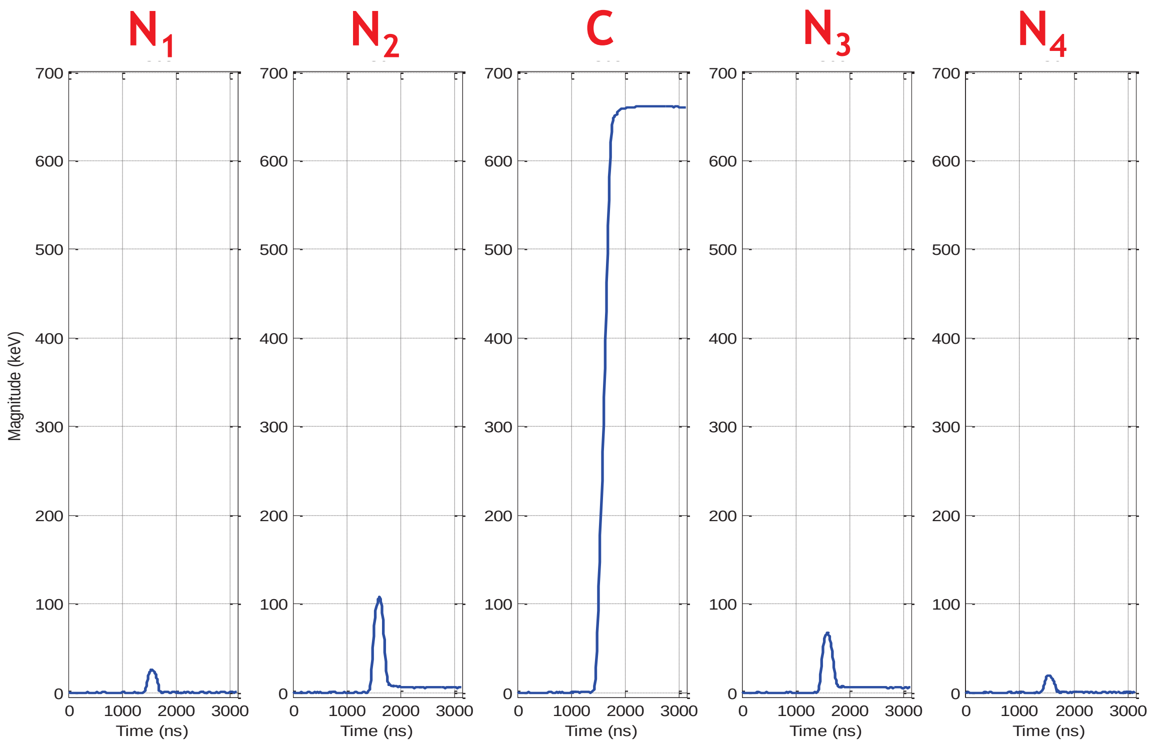

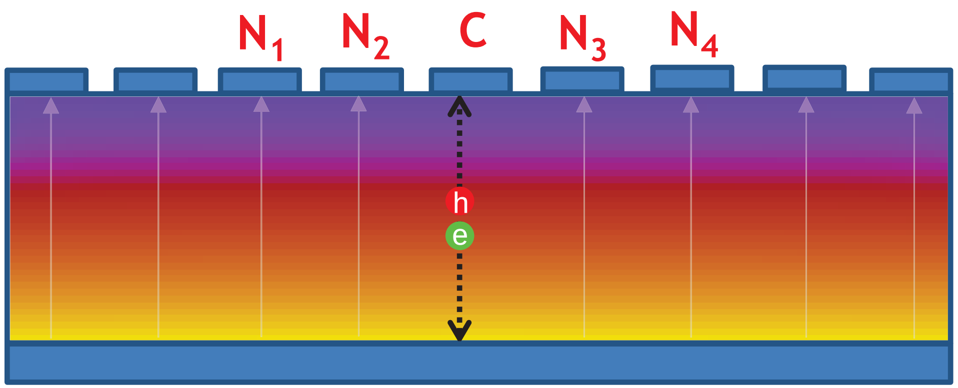

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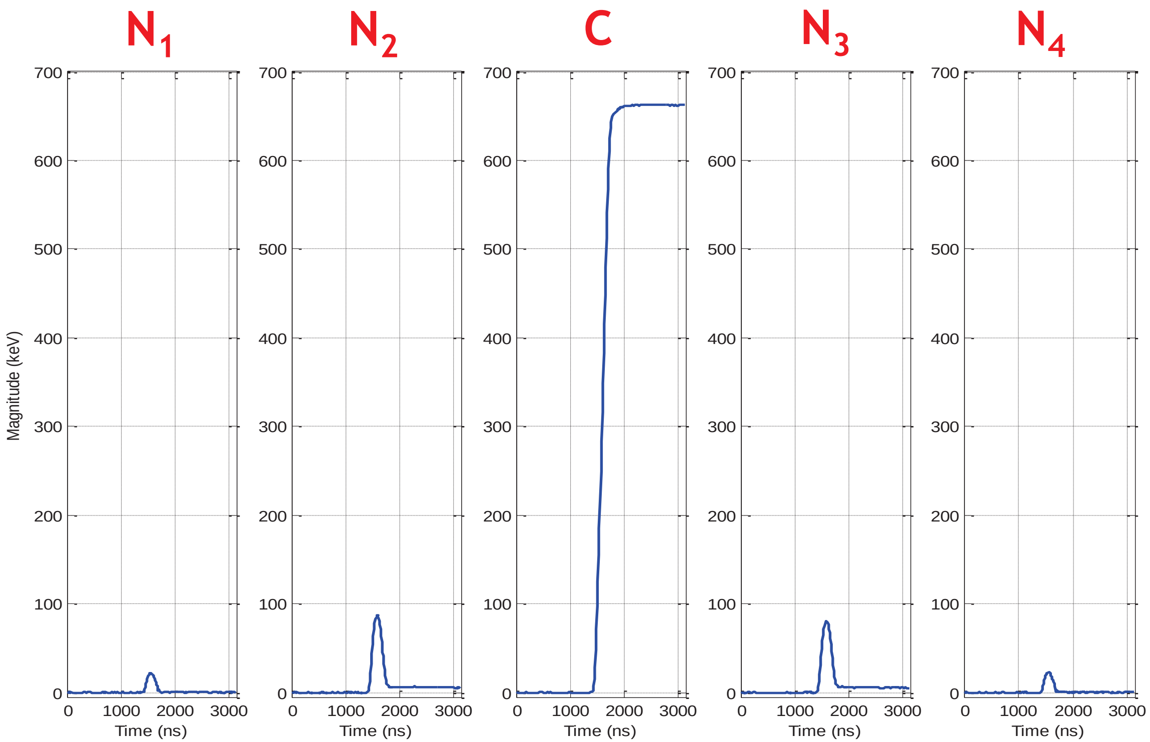

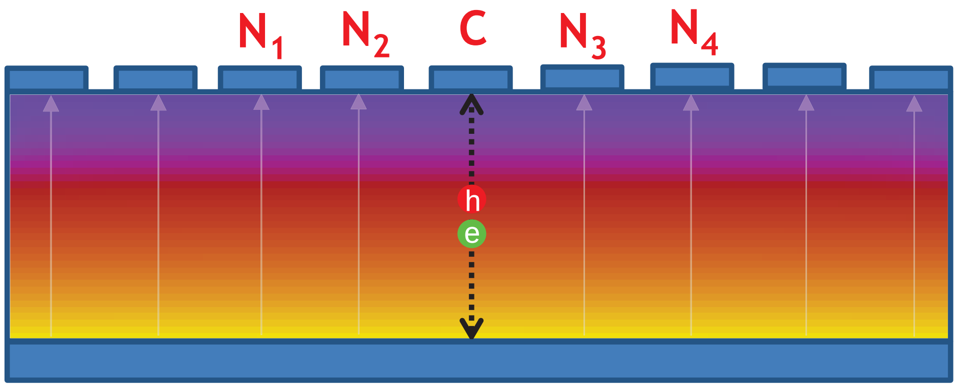

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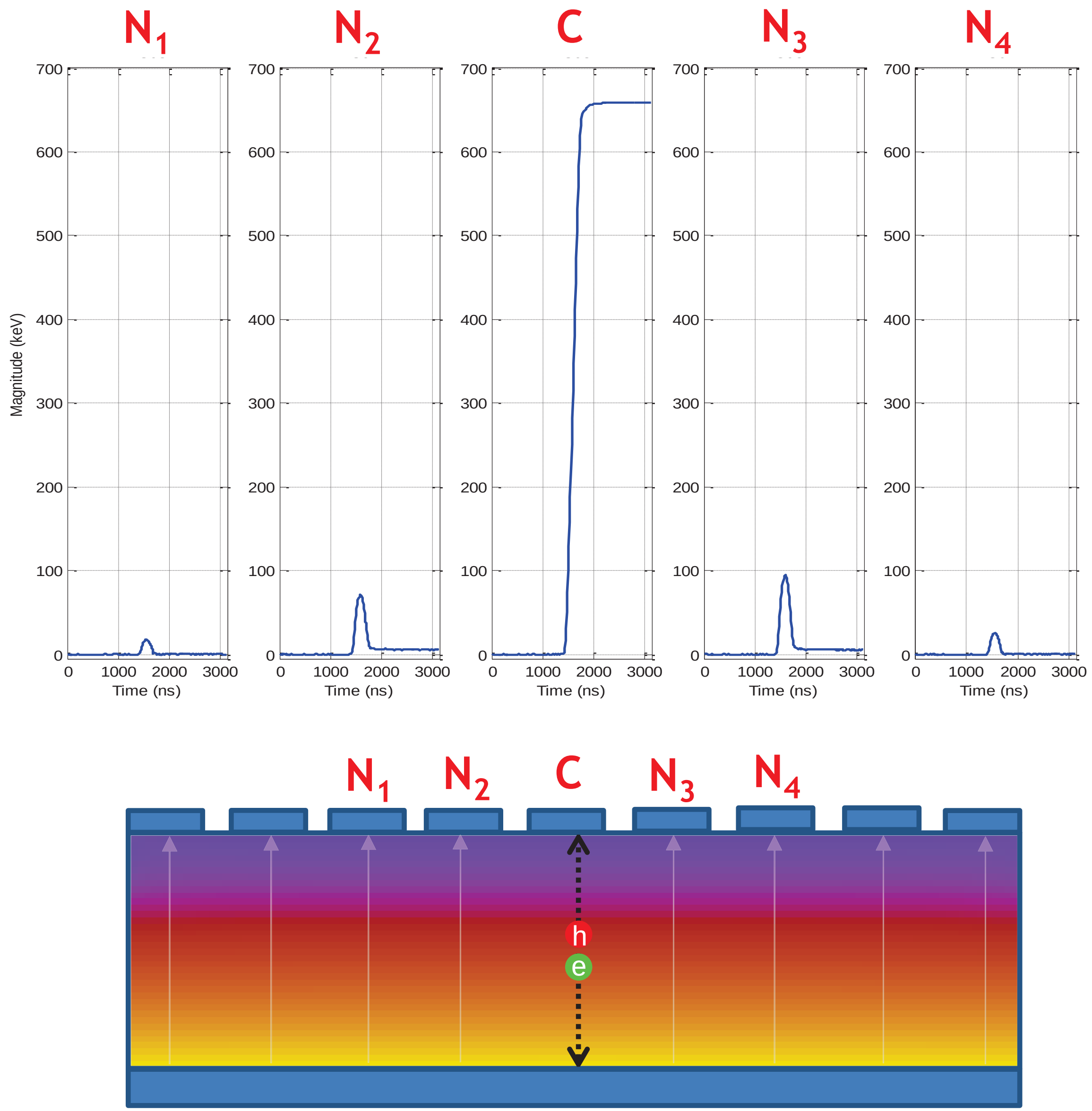

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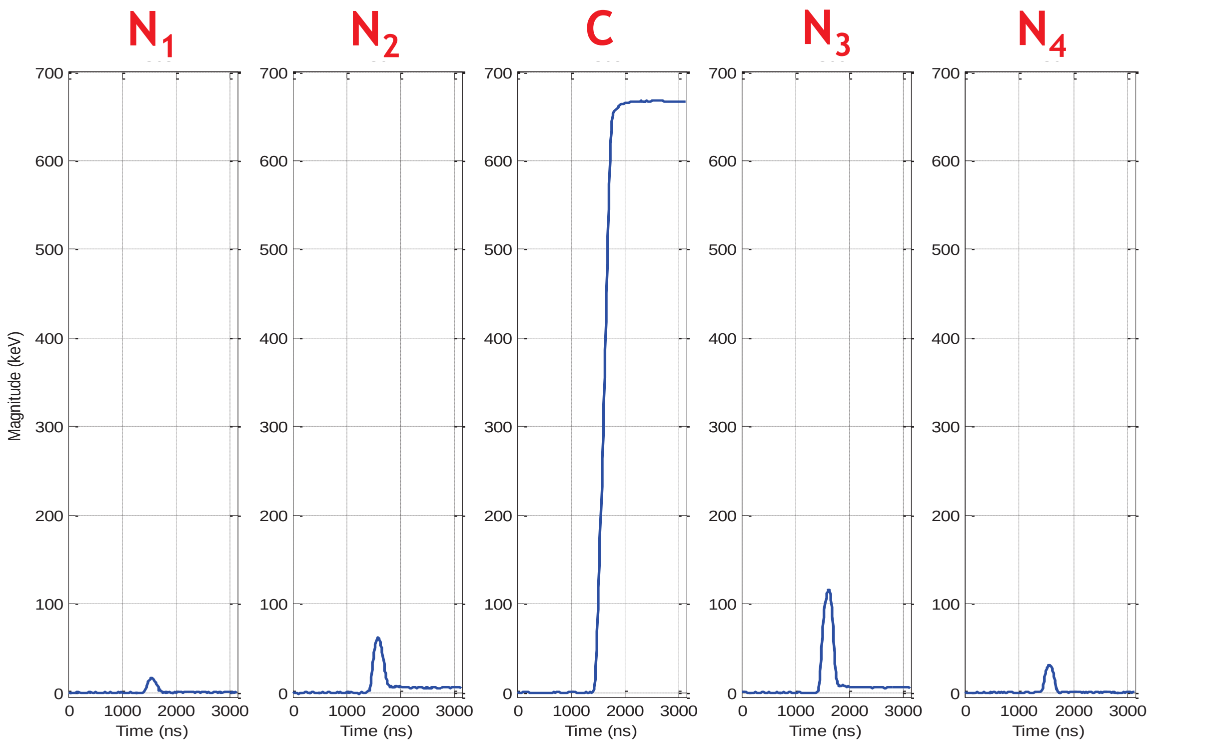

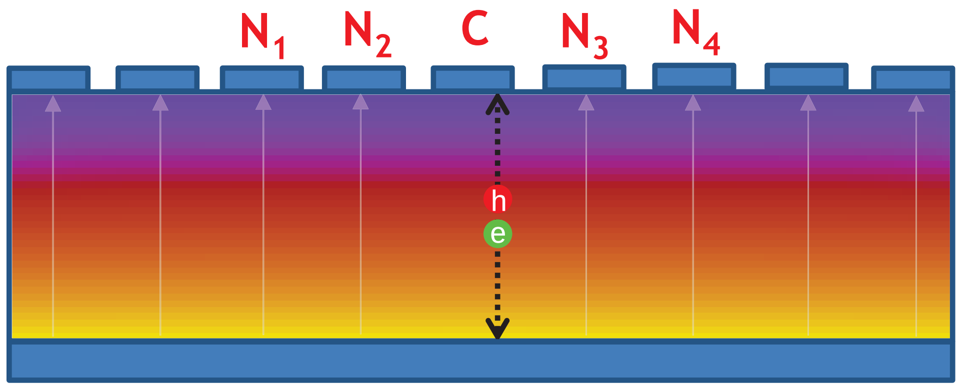

Literature: HPGe Detectors

BERKELEY LAB
Lawrence Berkeley National Laboratory

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Progress in Particle and Nuclear Physics 60 (2008) 283–337
Progress in Particle and Nuclear Physics
www.elsevier.com/locate/ppnp

Review

From Ge(Li) detectors to gamma-ray tracking arrays – 50 years of gamma spectroscopy with germanium detectors

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[b] *STFC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*

Recent Developments in the Fabrication and Operation of Germanium Detectors

Kai Vetter*

Glenn T. Seaborg Institute, Lawrence Livermore National Laboratory, Livermore, California 94550; email: kvetter@llnl.gov

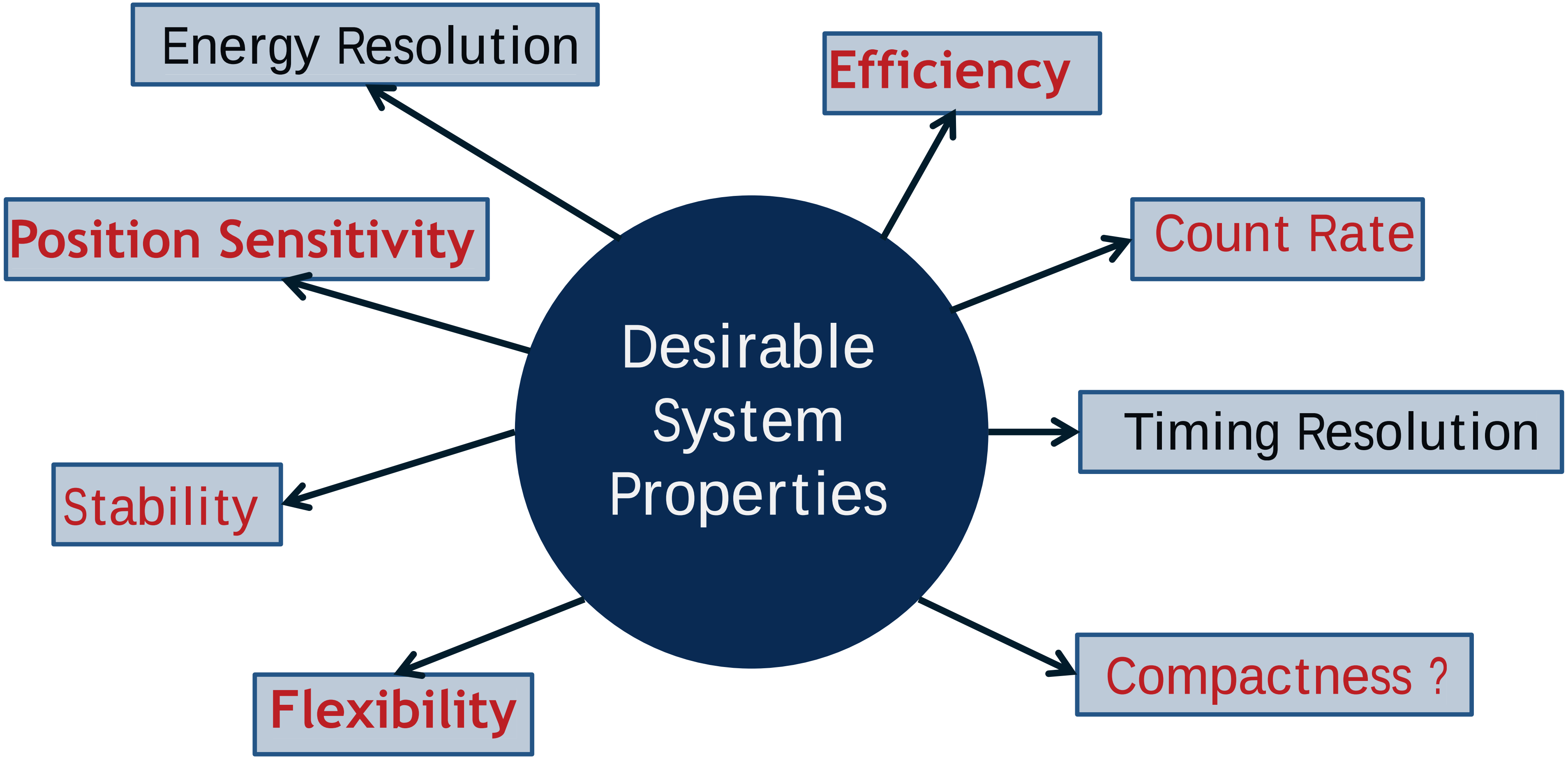
Annu. Rev. Nucl. Part. Sci. 2007. 57:363–404

First published online as a Review in Advance on June 28, 2007

The *Annual Review of Nuclear and Particle Science* is online at http://nucl.annualreviews.org

Why Use Digital Electronics?

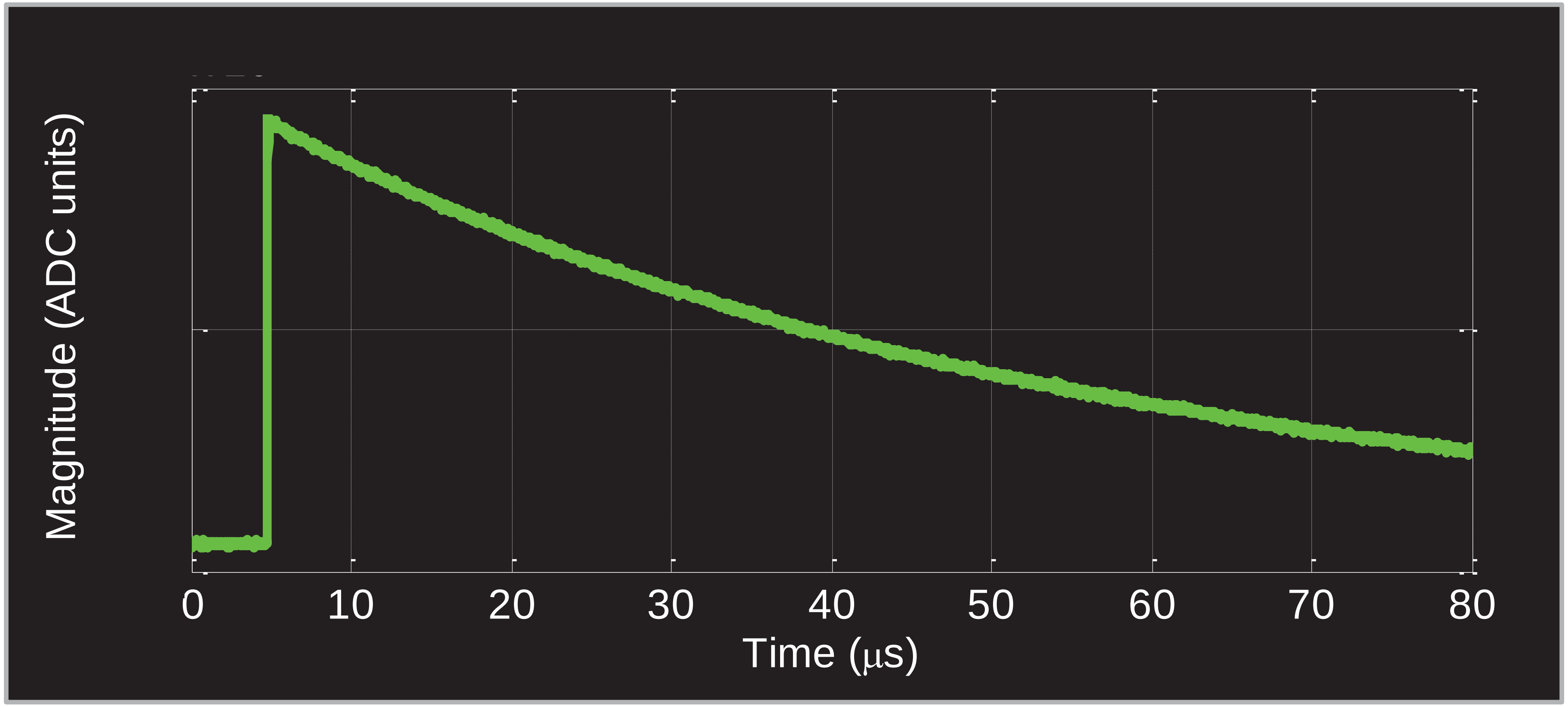
So we can access more information about the physics event



A Digitised Signal

Two major components: Fast rise and slow fall

- Extract **energy** from the maximum pulse height
- Extract **position** from the signal shape
- Extract charge arrival **time** from the slope

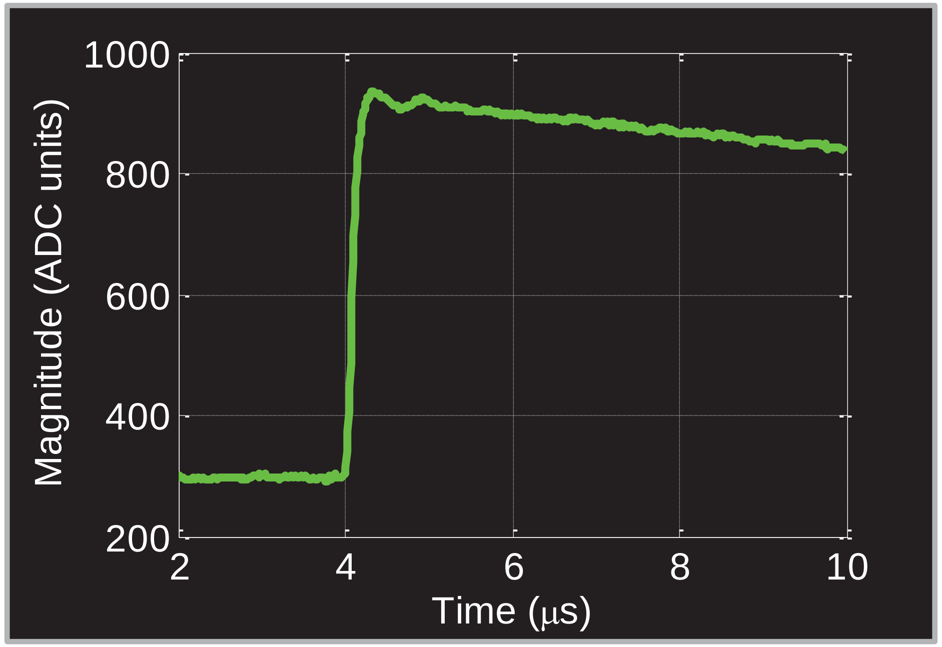


Energy Extraction

Application of filters in the time domain to extract the pulse height

- Signal-to-noise ratio determines the performance
- Baseline correction, pole-zero correction, and pulse shaping
- Trapezoidal filtering is common for HPGe – develop a flat top

Jordanov et al., Nucl. Instr. and Meth. A 353 (1994)



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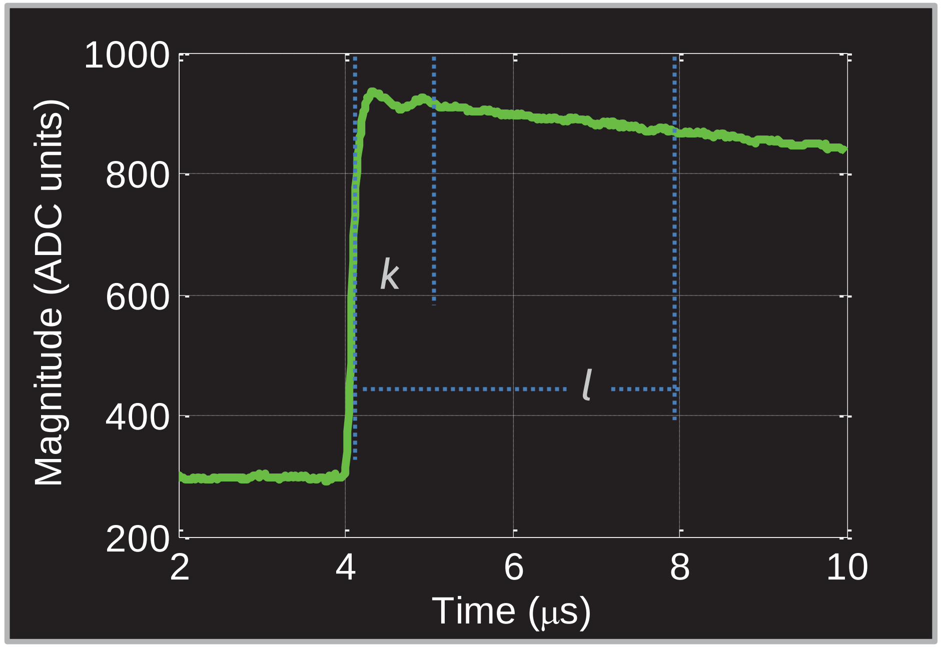

1. Differentiate (baseline restore) and decay correct
   - attenuate low frequency noise

$$Md(n)^{k,l} = \mathrm{v(n) - v(n-k) - v(n-l) + v(n+l)}$$

$$d(n)^{k} = \mathrm{v(n) - v(n-k)}$$

$$d(n)^{k,l} = d^{k}\mathrm{(n) - v(n-l)}$$

Jordanov et al., Nucl. Instr. and Meth. A 353 (1994)

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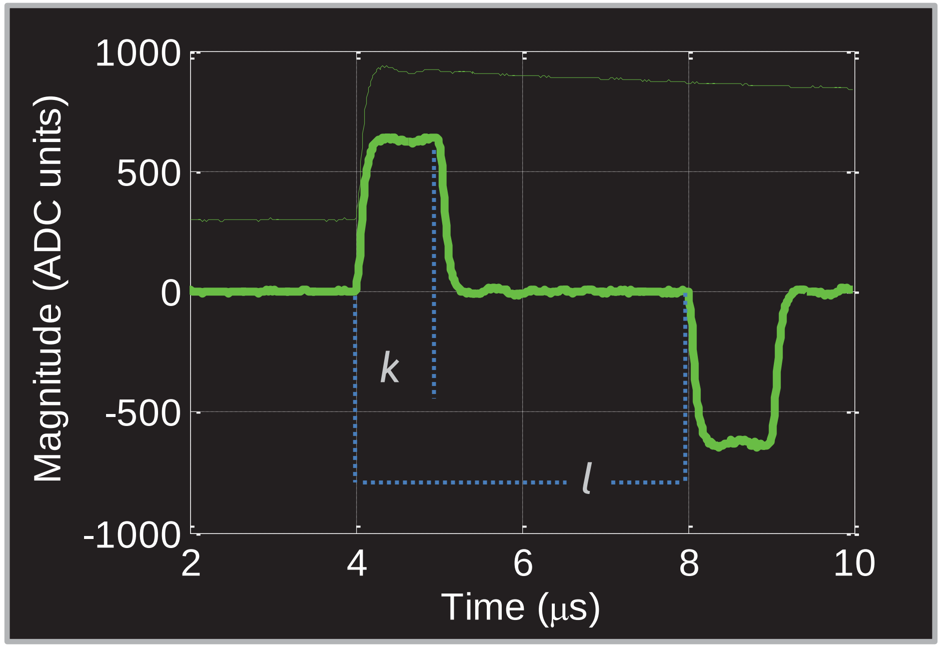

1. Differentiate (baseline restore) and decay correct
   - attenuate low frequency noise
2. Integrate
   - attenuate high frequency noise

Energy Extraction

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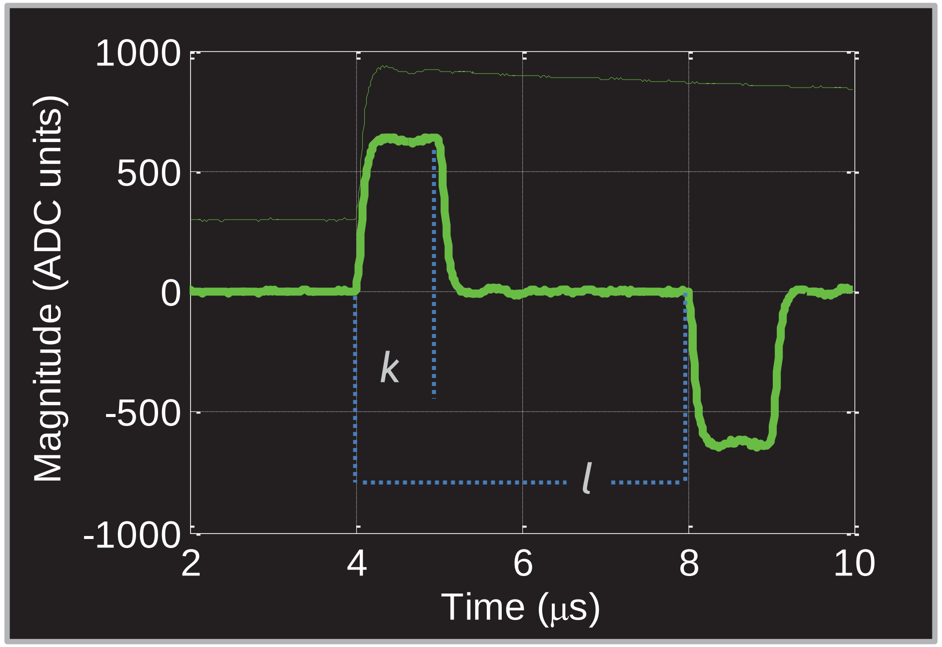
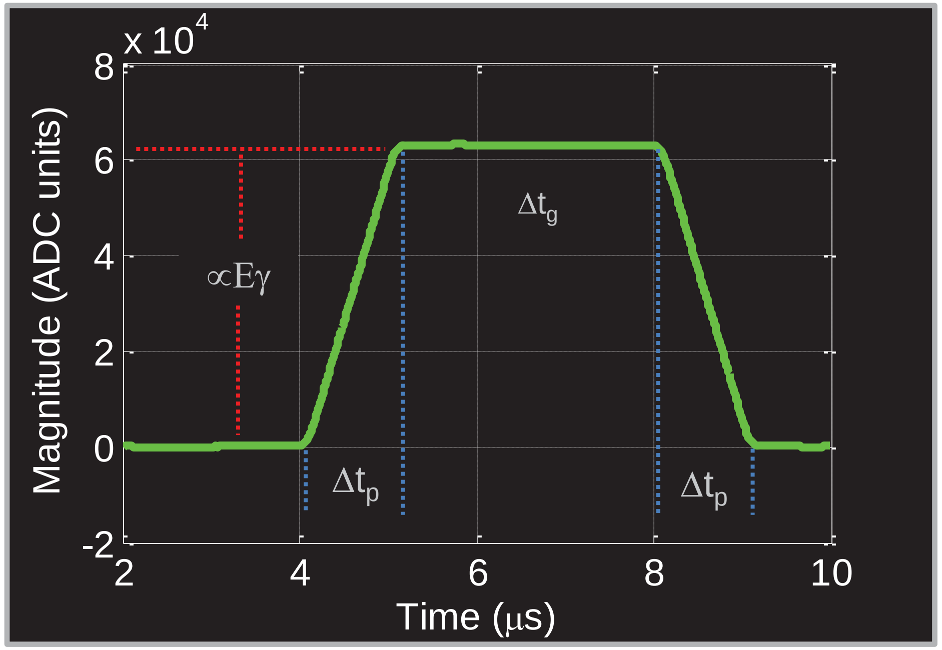
Gap Time, $\Delta t_g = l - k = 3\ \mu s$
Peaking Time, $\Delta t_p = k = 1\ \mu s$





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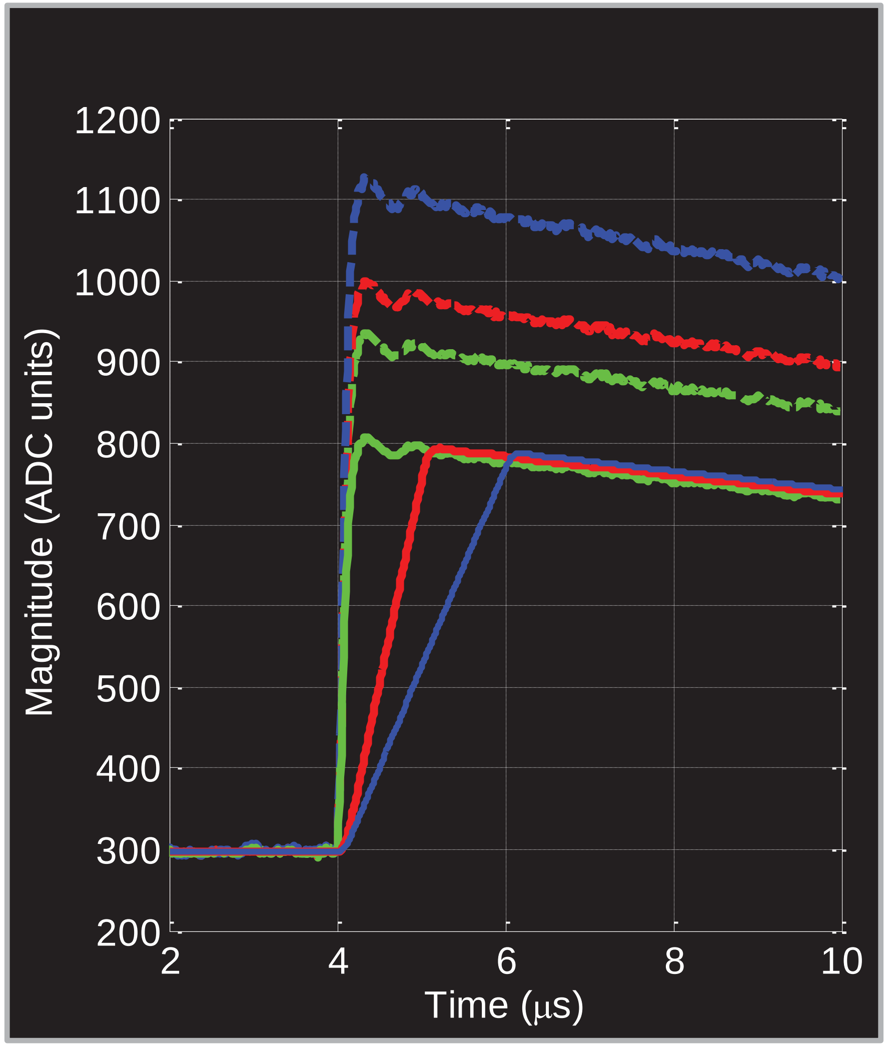

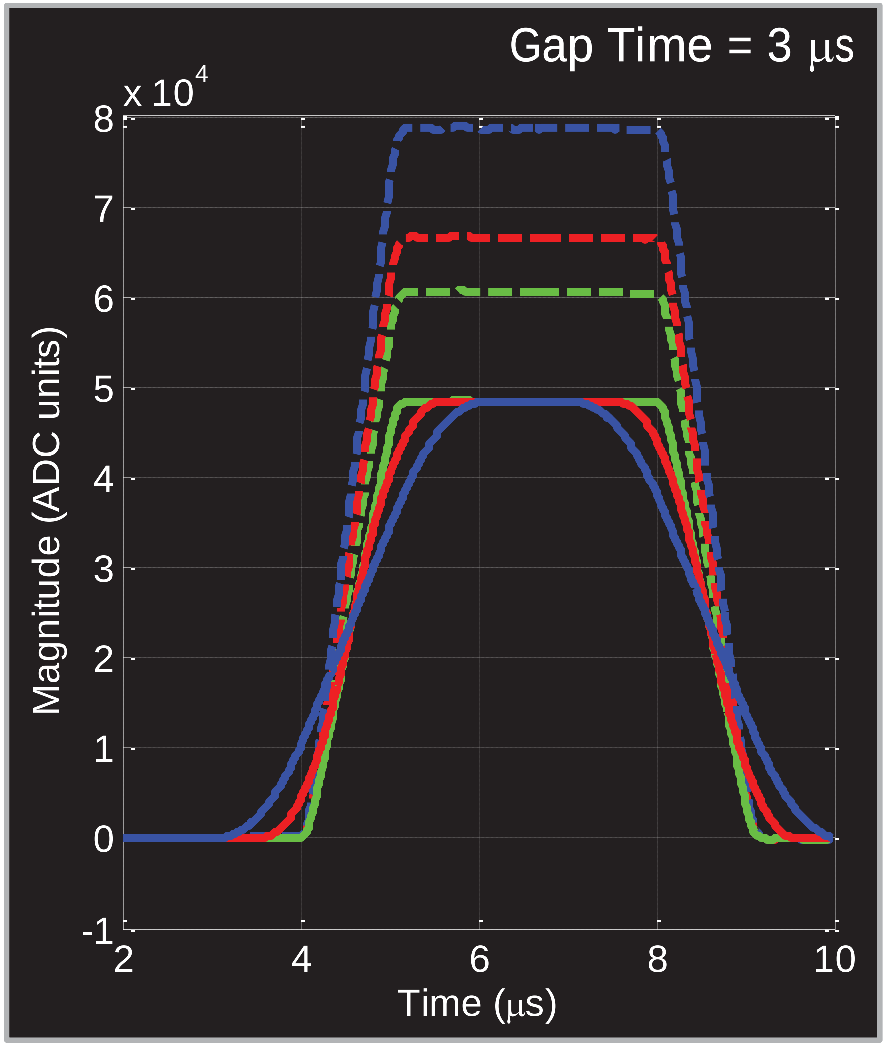

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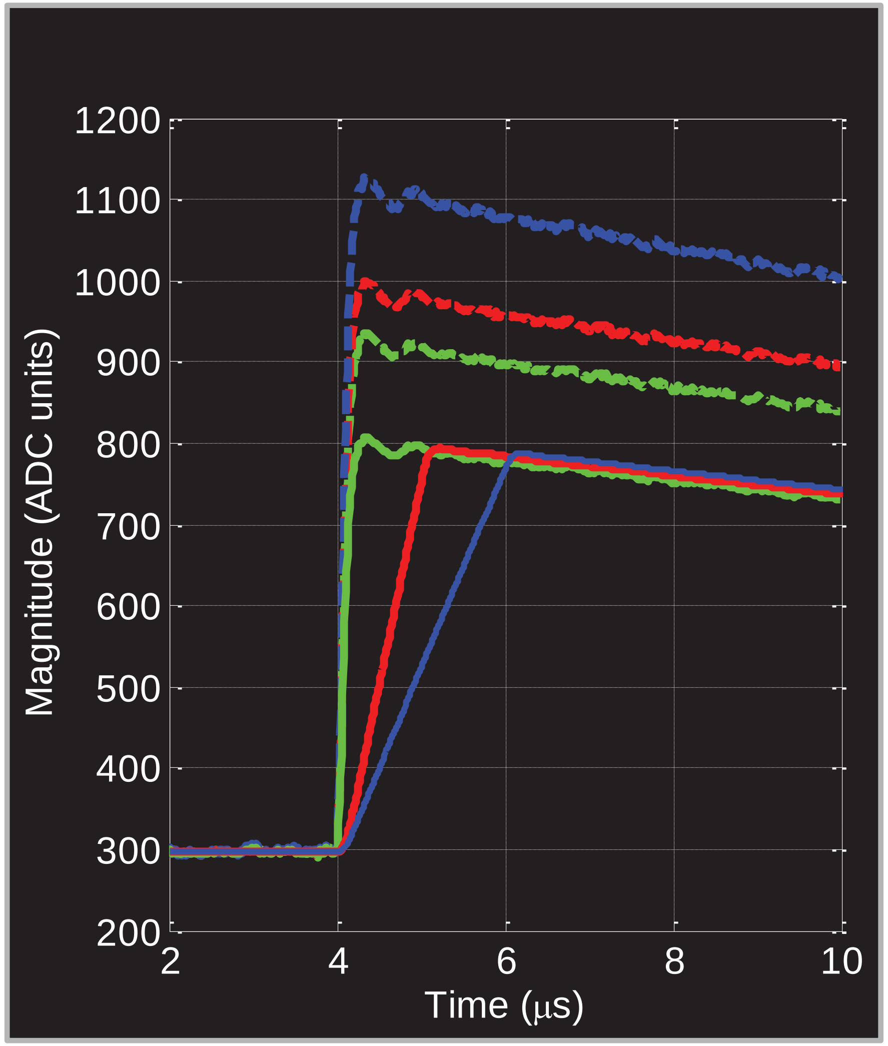
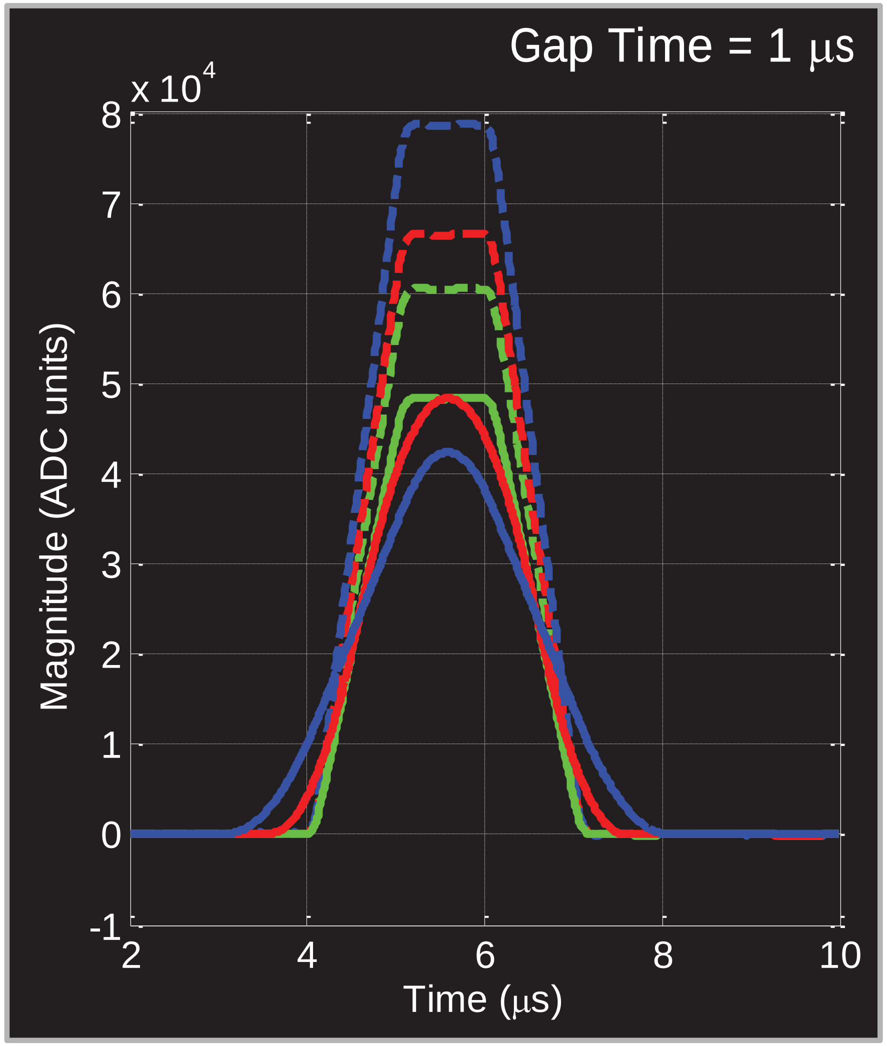
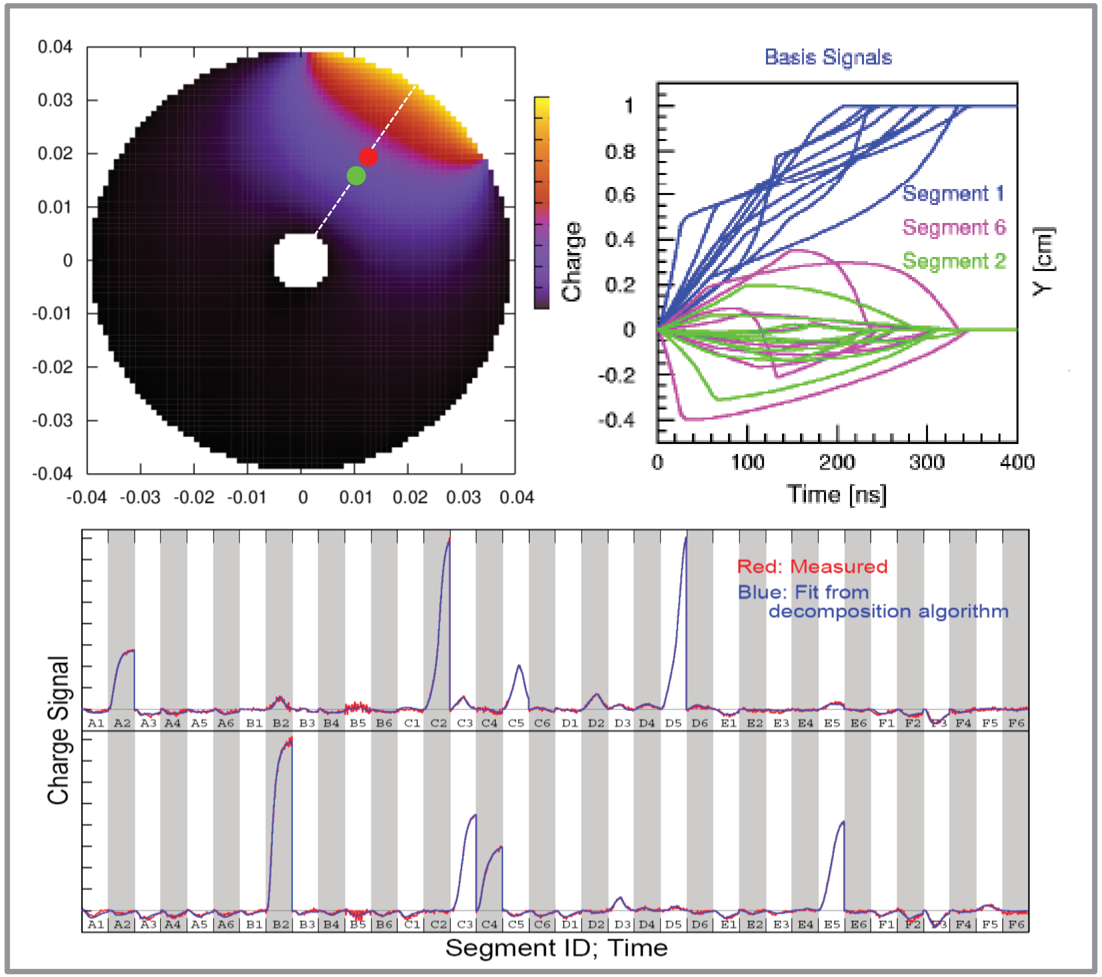


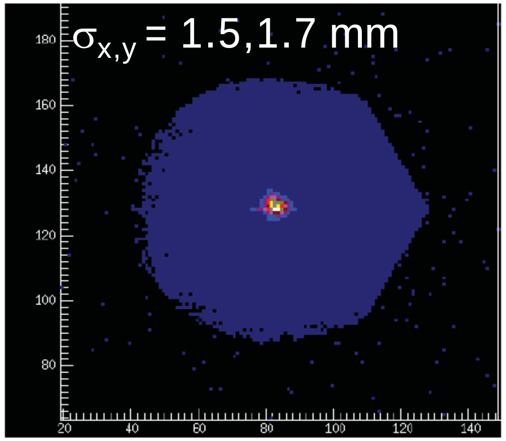


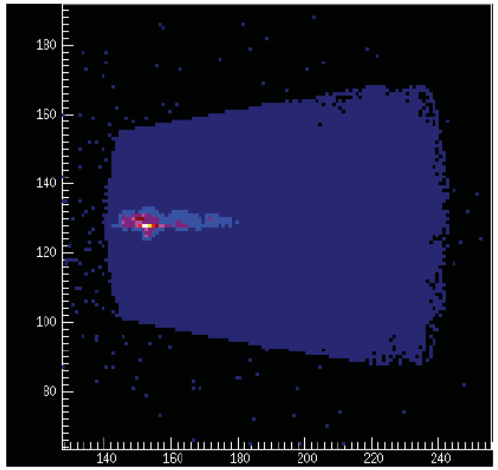
Position Extraction

Extraction of signal features strongly correlated with hit position

- Parametric and/or “basis” driven approaches
- Millimeter-order resolution in large volume HPGe detectors







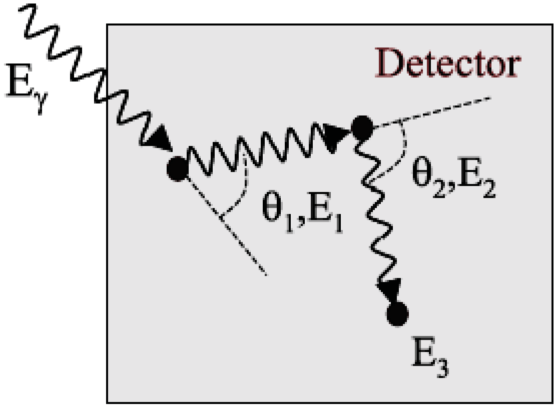
Gamma-Ray Tracking

What can we do with all this information?

- Reconstruct the sequence of the event
- Compton scattering kinematics are well defined

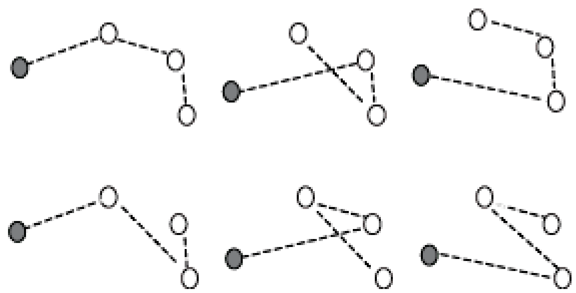
$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - cos\theta)}$$

1 MeV



$$\chi_j^2 = \sum_{n=1}^{N-1} \left(\frac{\theta_m - \theta_c}{\sigma_\theta} \right)_n^2$$

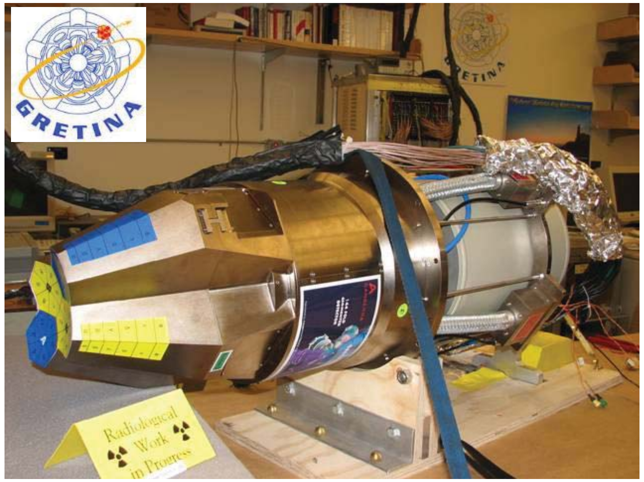
3!=6 permutations



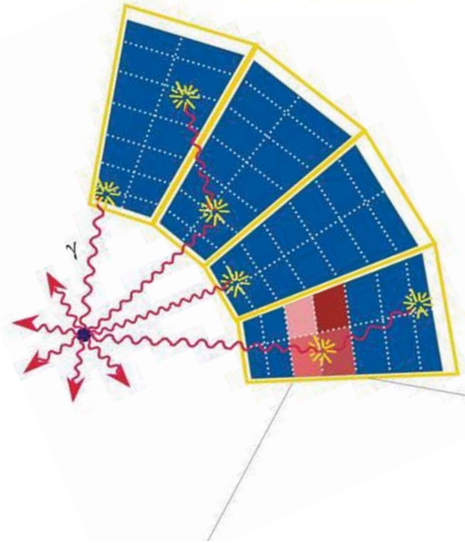
- F.O.M for all permutations to find most probable sequence
- Associate multiple hits from the same event
- “Add-back” energy
- Reject “bad”/Compton escaped events
- Increased efficiency

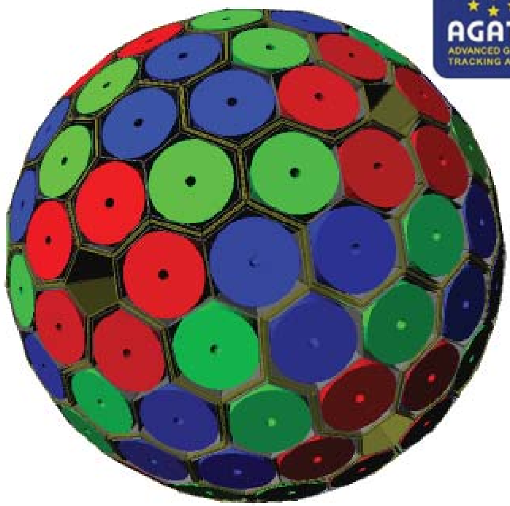
I.Y. Lee et al., Rep. Prog. Phys. 66 (2003)

Applications: Gamma Spectroscopy

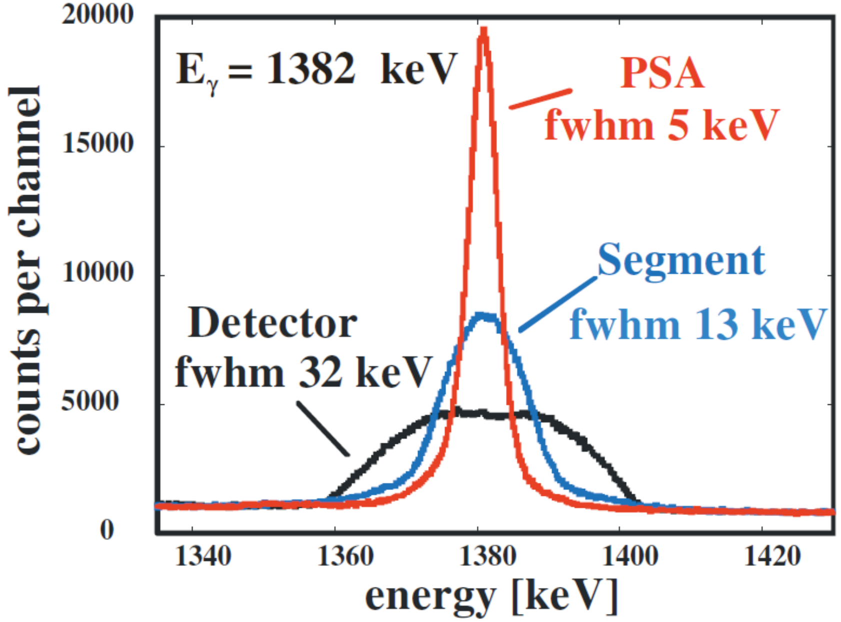


- **Efficiency**
  - Summing of scattered gammas
- **Peak-to-background**
  - Reject Compton events
- **Doppler Correction**
  - Position of 1st hit
- **Counting rate**
  - Many Segments





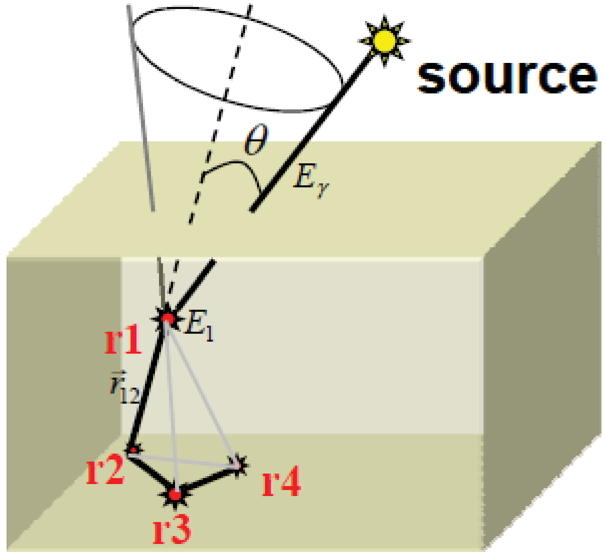
AGATA
ADVANCED GAMMA TRACKING ARRAY



Applications: Compton Imaging

- Event-by-event reconstruction of scattered gamma rays

$$\cos(\theta) = 1 + m_0c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - E_1}\right)$$



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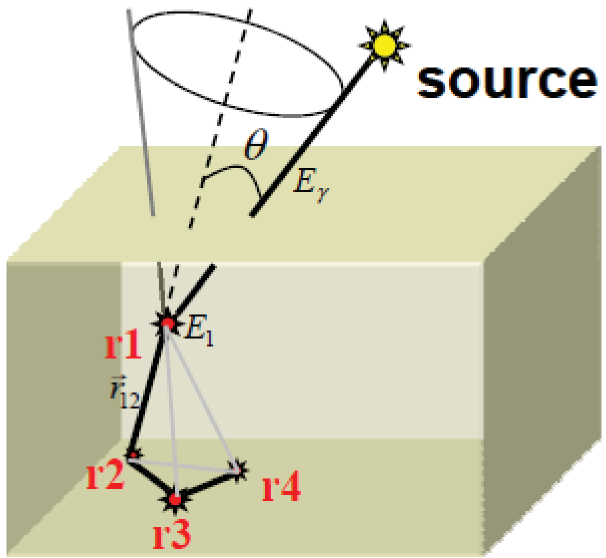

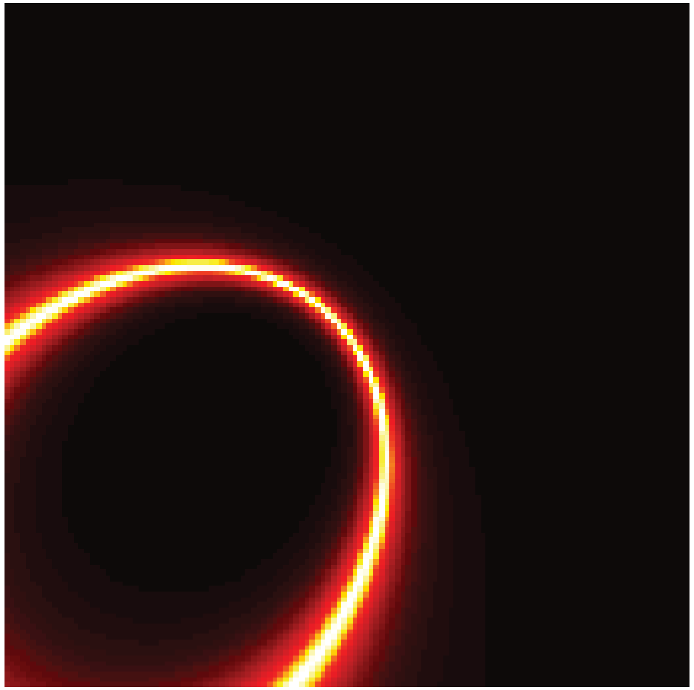

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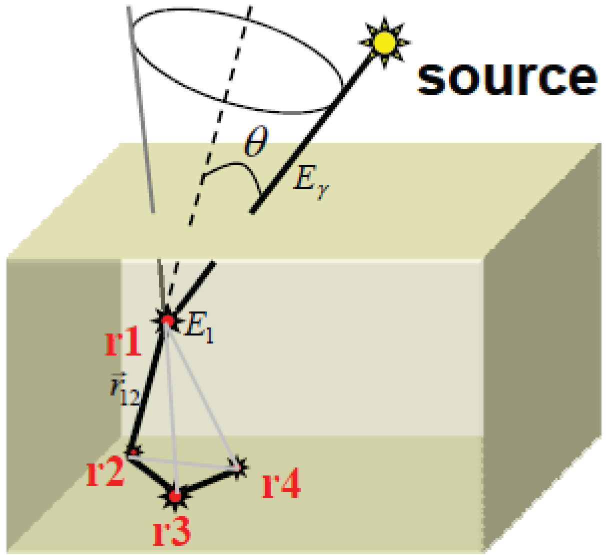

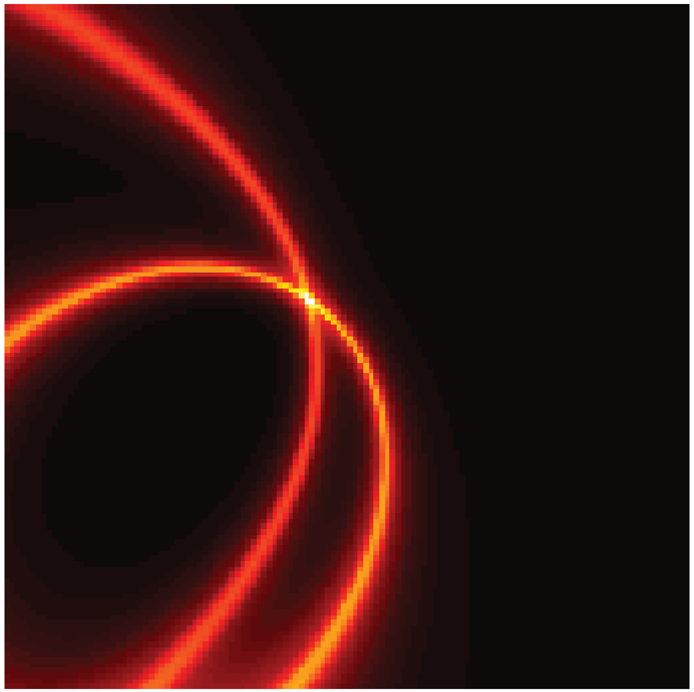

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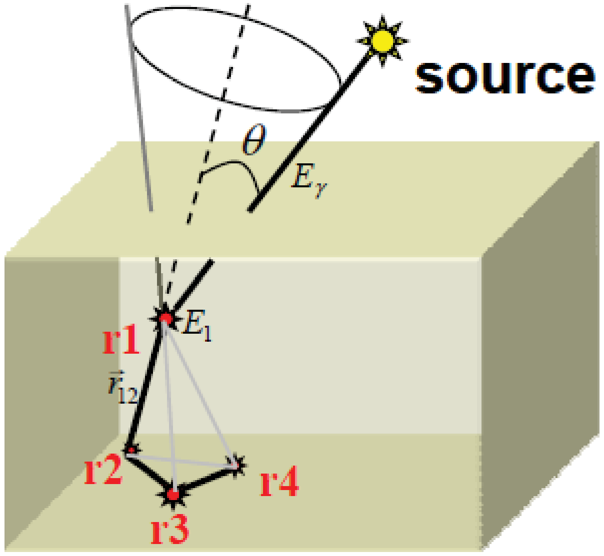

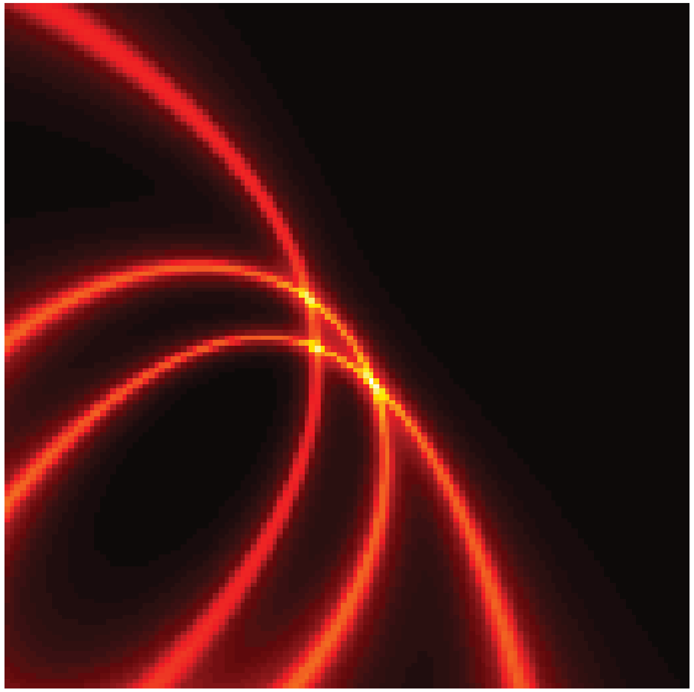

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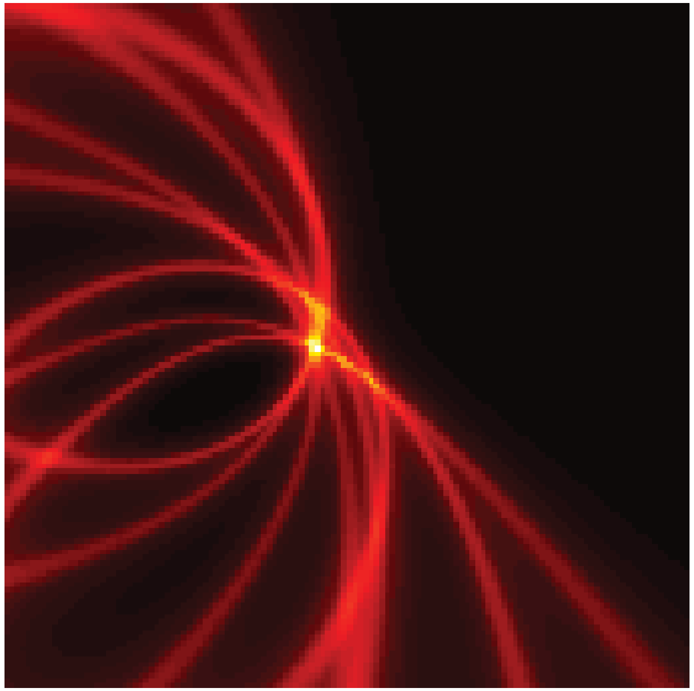
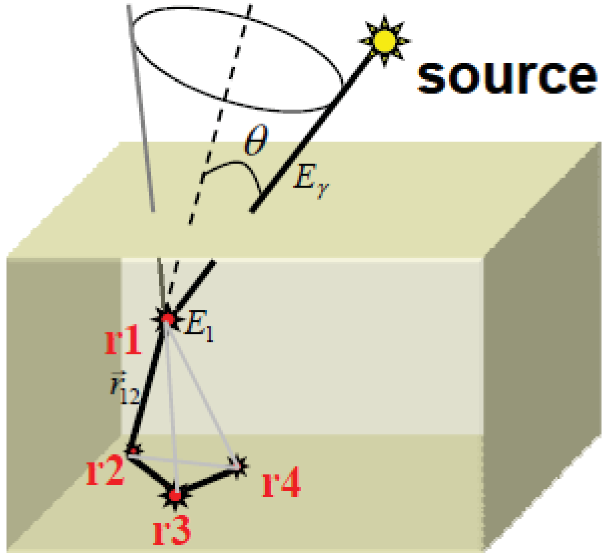
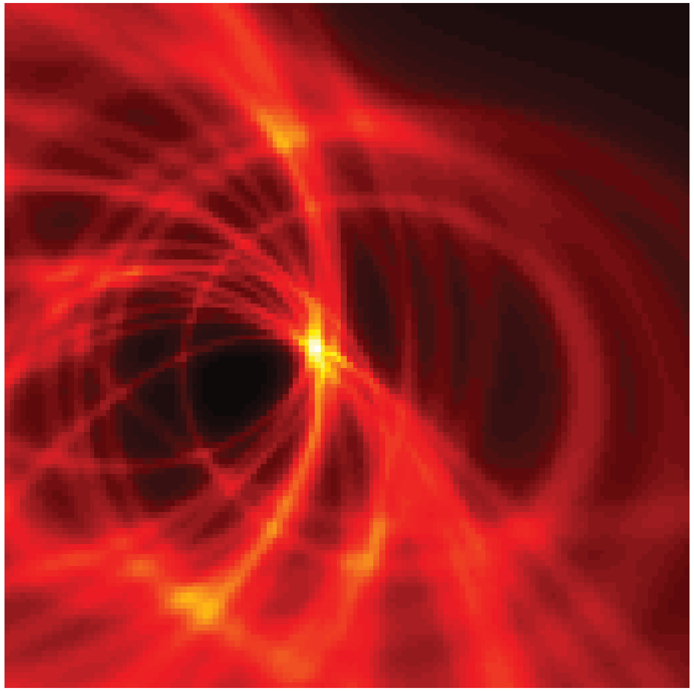


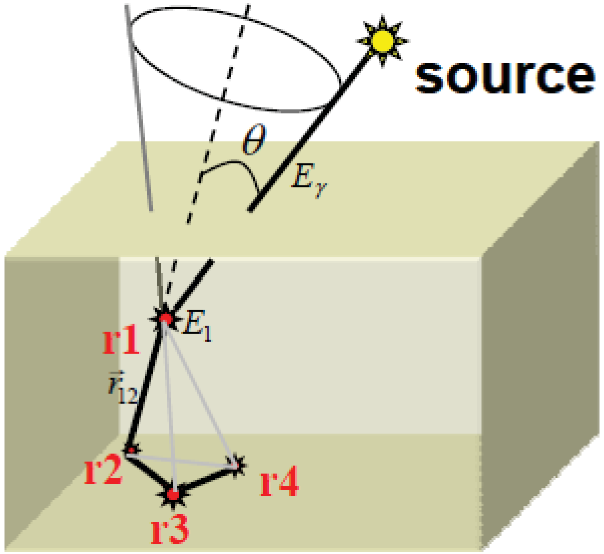


Applications: Compton Imaging

- Event-by-event reconstruction of scattered gamma rays

$$\cos(\theta) = 1 + m_0 c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - E_1} \right)$$





Applications: Compton Imaging

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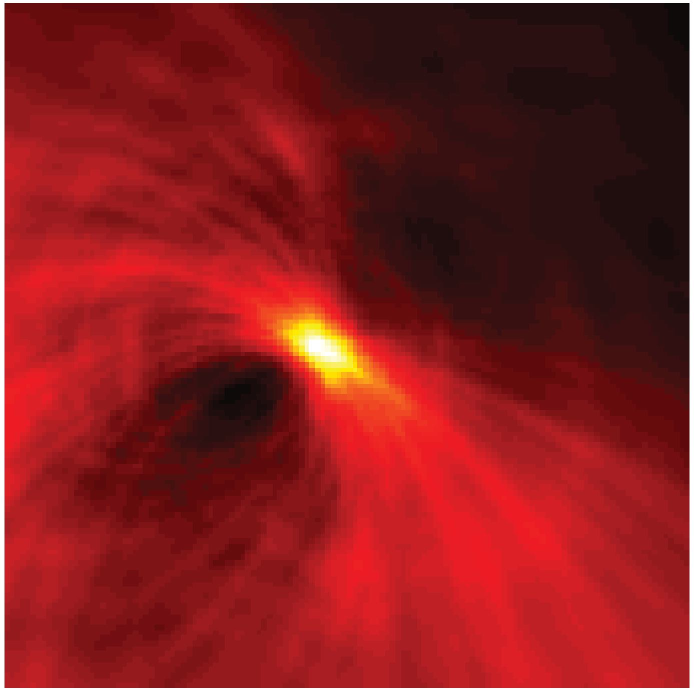

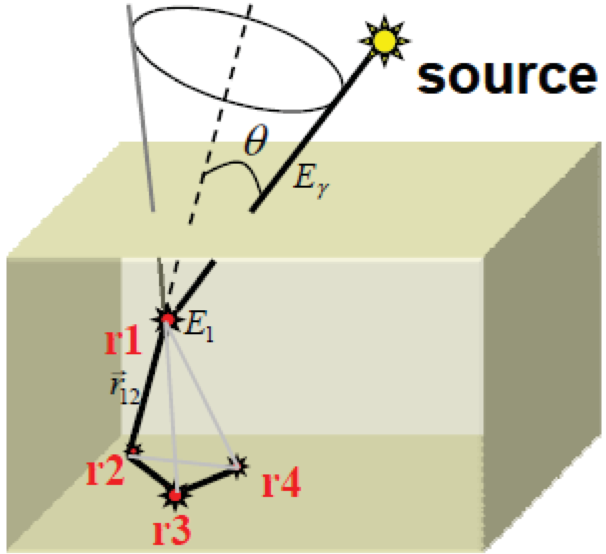

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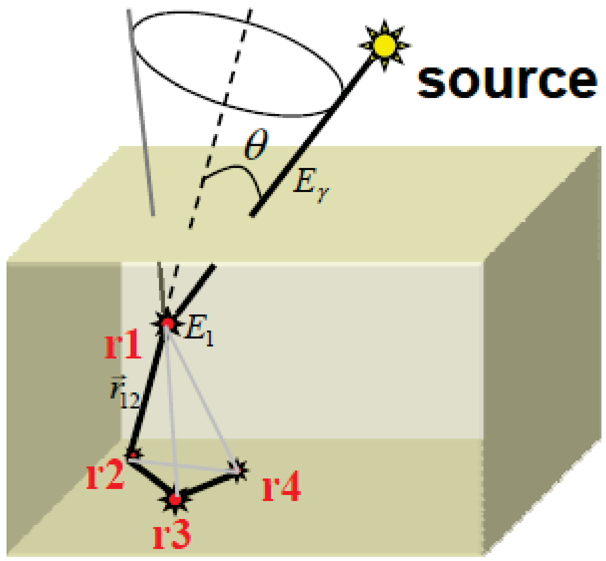


- Potential for high sensitivity, high specificity imaging
- Applications in security, medicine, monitoring etc.
- Fusion with contextual data

Sources of Reconstruction Error:

- Position resolution (axis)
- Energy resolution (angle)
- Doppler broadening (angle)
- Incorrect sequencing (direction)

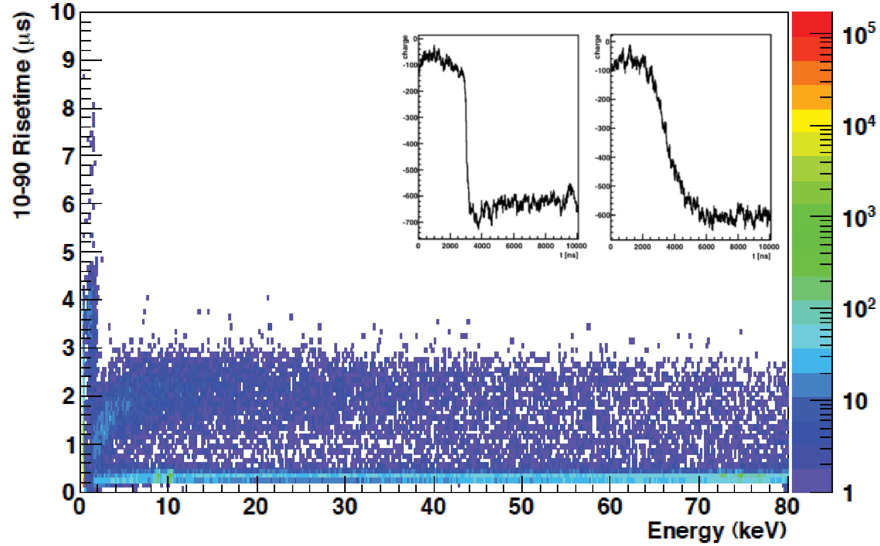
Applications: Compton Imaging

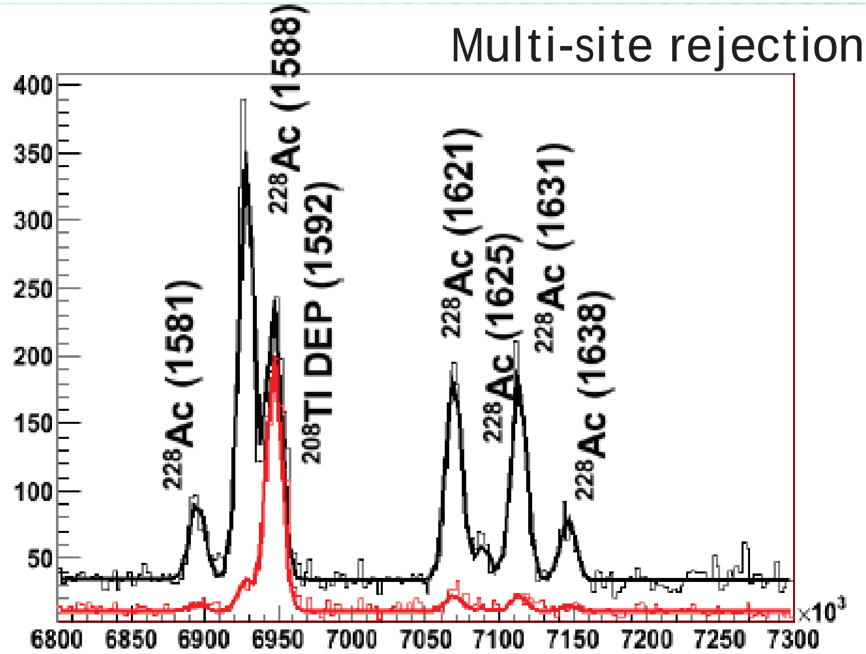
Courtesy of Lucian Mihailescu, LBNL

Applications: Low Background Counting

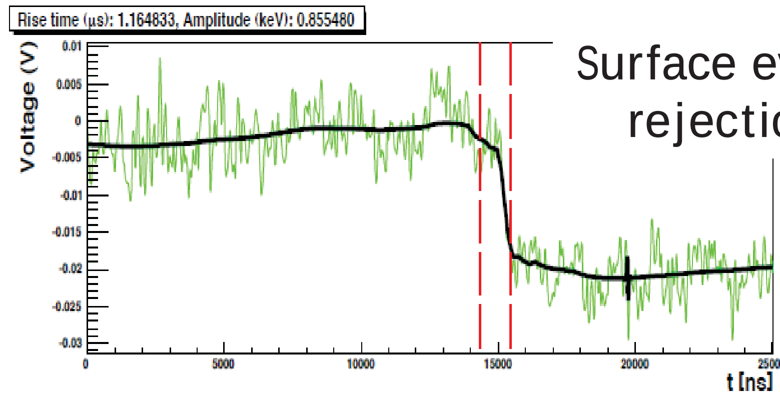
Noise suppression and 'background' rejection

- Maximise energy resolution, peak-to-background, and threshold
- Counting environmental samples
- Rare-event physics





Multi-site rejection



Surface event rejection

The Abdus Salam International Centre for Theoretical Physics

IAEA
International Atomic Energy Agency

Digital Gamma-Ray Spectroscopy

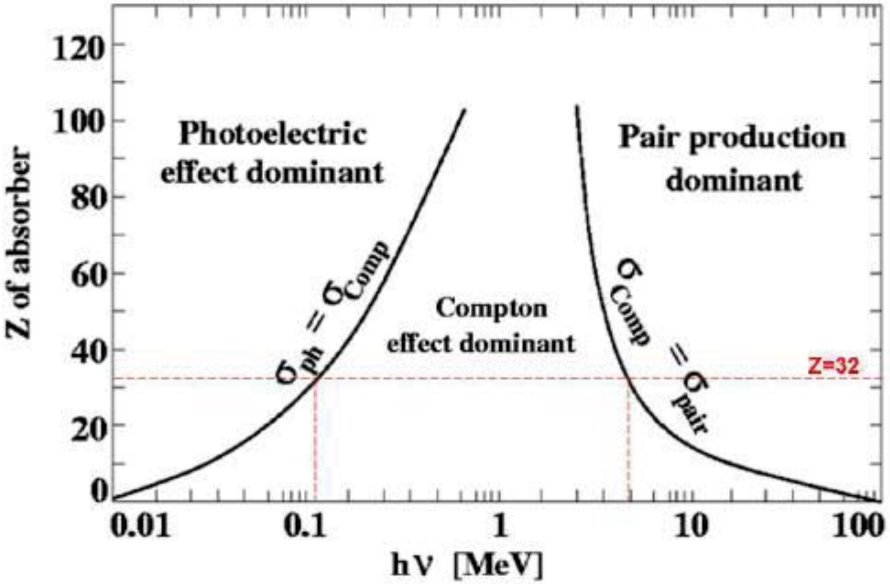
Joint ICTP-IAEA Workshop on Advances in Digital Spectroscopy
May 7th 2013

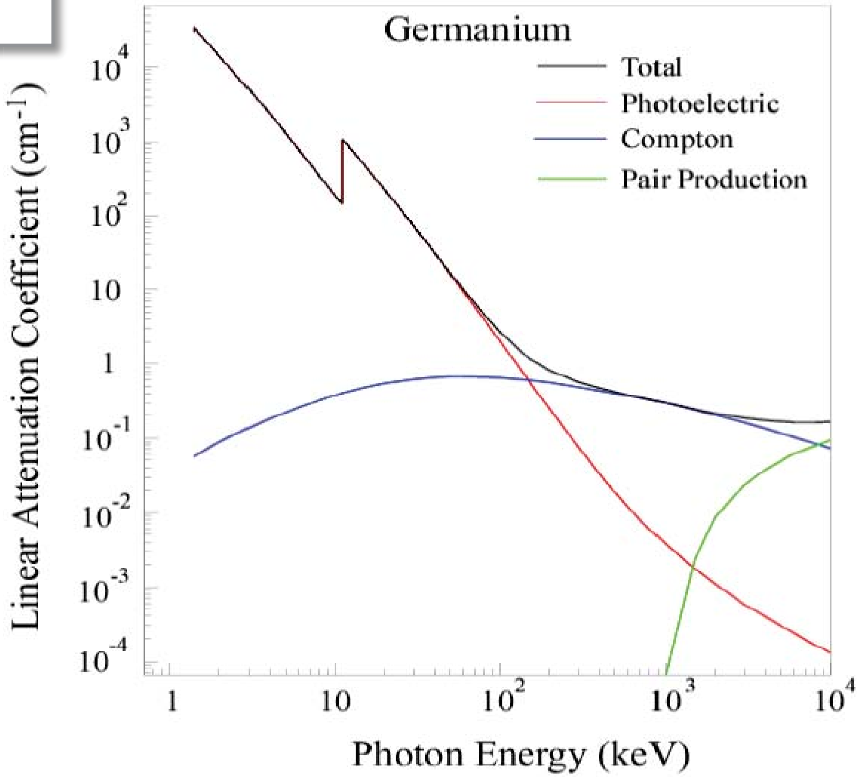
BERKELEY LAB
Lawrence Berkeley National Laboratory

Ren Cooper
Lawrence Berkeley National Laboratory, USA

Gamma-Ray Detection: How?

- Photoelectric Absorption $\sim\frac{Z^{4-5}}{E^{3.5}}$
- Compton Scattering $\sim\frac{Z}{E}$
- Pair Production $\sim Z^2$





Solid State Gamma-Ray Detectors

- Scintillators and Semiconductors

<u>Scintillation</u> detectors usually have:

- Poorer energy resolution
- Higher density
- Higher Z
- Fast timing

→ High efficiency

<u>Semiconductor</u> detectors usually have:

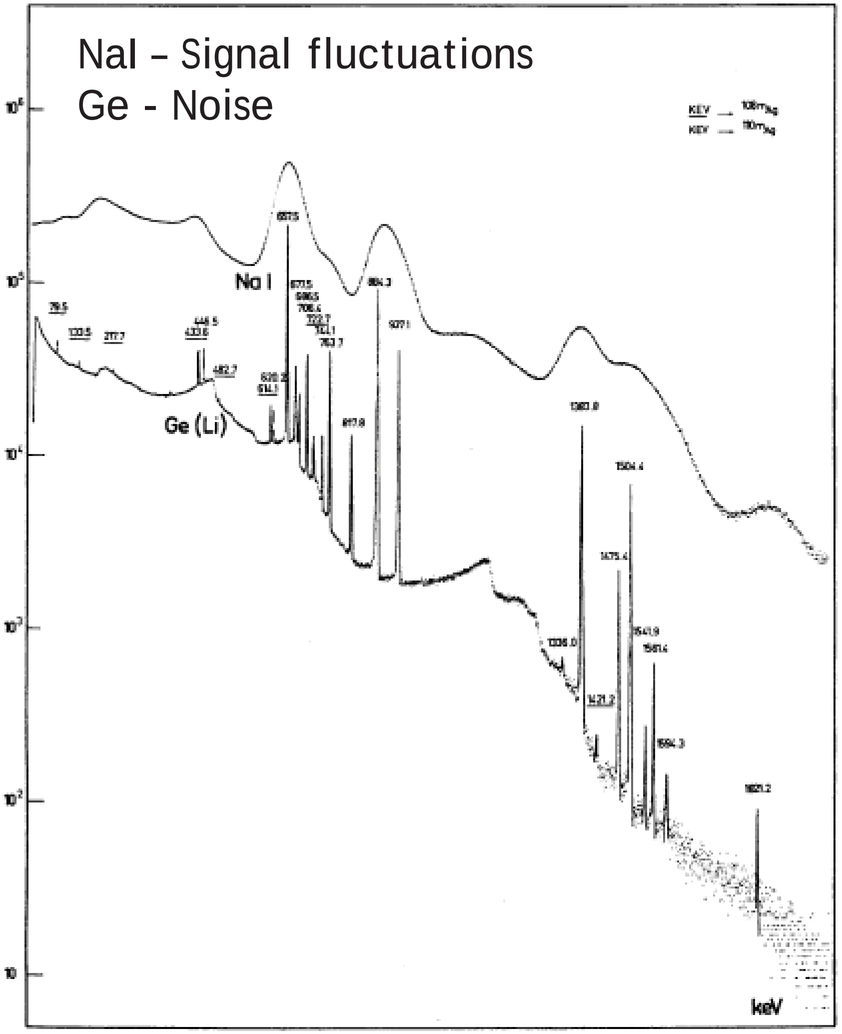
- Better energy resolution
- Lower efficiency and "peak-to-total"

And…

- May be hard to make into big crystals
- May require cooling

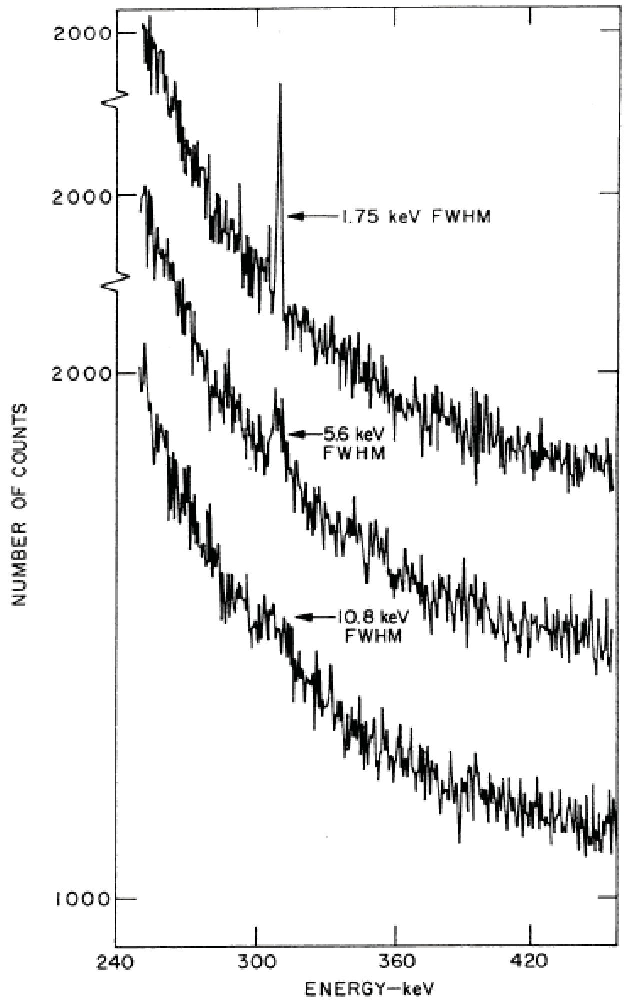
Gamma-Ray Spectroscopy

NaI – Signal fluctuations
Ge - Noise



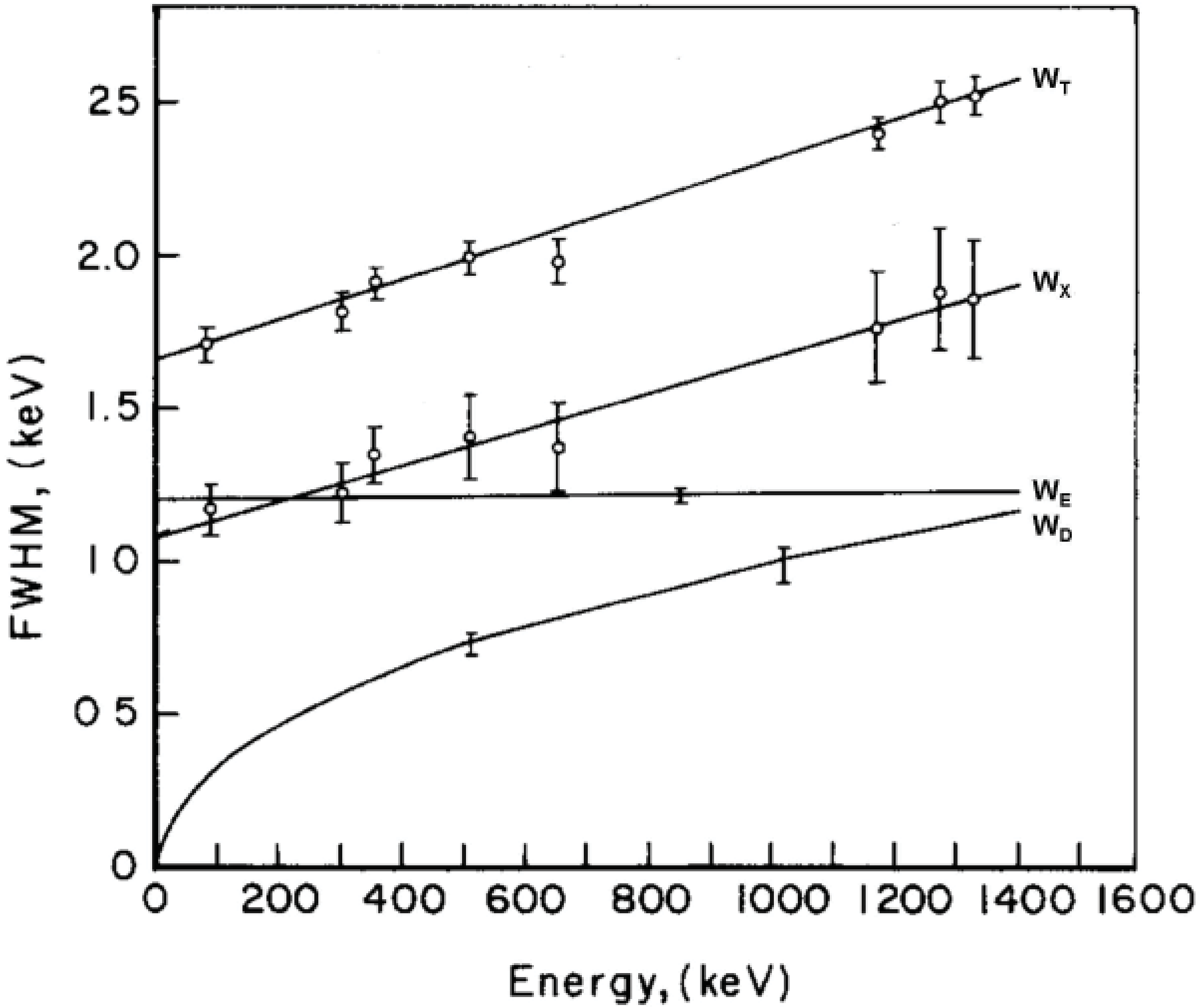
(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)

Signal-to-background/Signal-to-noise

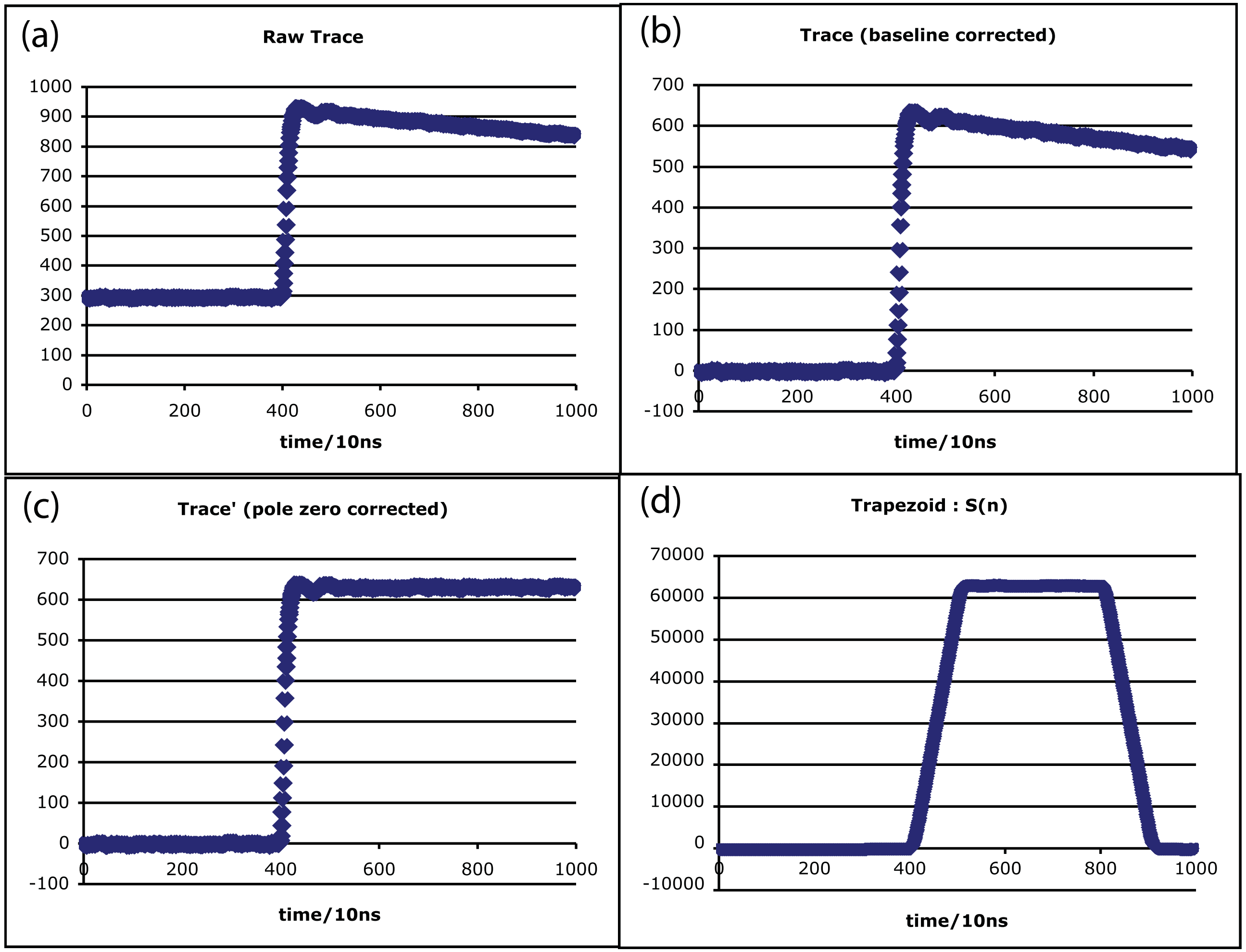


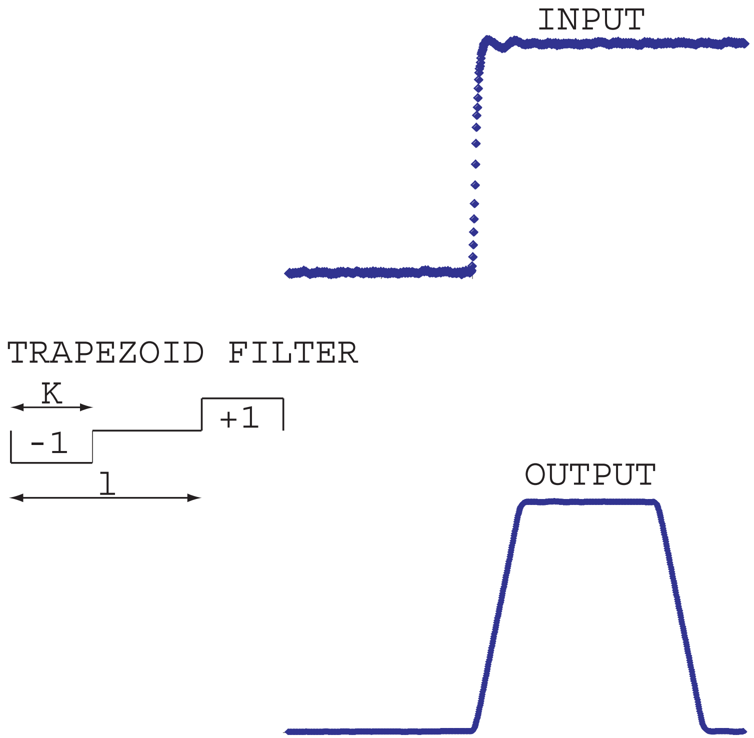
G.A. Armantrout, *et al.*, IEEE Trans. Nucl. Sci. NS-19/1 (1972) 107

Energy Resolution



"Radiation Detection and Measurement", Glenn Knoll


(a)
Raw Trace
1000
900
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
time/10ns
(b)
Trace (baseline corrected)
700
600
500
400
300
200
100
0
-100
0
200
400
600
800
1000
time/10ns
(c)
Trace' (pole zero corrected)
700
600
500
400
300
200
100
0
-100
0
200
400
600
800
1000
time/10ns
(d)
Trapezoid : S(n)
70000
60000
50000
40000
30000
20000
10000
0
-10000
0
200
400
600
800
1000
time/10ns


INPUT
TRAPEZOID FILTER
K
-1
+1
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OUTPUT