Detector technology

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Aim of this talk

You can know the name of a bird in all the languages of the world, but when you’re finished, you’ll know absolutely nothing whatever about the bird... So let’s look at the bird and see what it’s doing - that’s what counts. I learned very early the difference between knowing the name of something and knowing something.

Richard Feynman, Nobel Prize Physicist, 1918 - 1988

Principle of a radiation detector

A radiation detector converts the energy of ionizing particles into charge pulses

Interaction => Ionization track

Free charge carriers
- gas-filled detectors
- semi-conductors

Conversion to luminescence
- Scintillator + photosensor

=> electric signal

Interactions of gamma photons (gas)

Example:
- free-air dose meter

Ionization chamber: gas

charge transport
signal formation

\[ dq = qdV/V \]

\[ i = dq/dt \]

Example: free-air dose meter

Gas-filled detectors: examples

Geiger-Muller detector (saturation detection)
Interaction of gamma’s (semiconductor)

Semiconductor detector

 charge transport

 signal formation

\[ dq = \left( \frac{q_e dV_1 + q_h dV_2}{V} \right) \]

\[ i = \frac{dq}{dt} \]

Examples:
- silicon diode
- germanium detector
- reverse bias, fully depleted

Examples:
- silicon diode
- germanium detector

Semiconductor detectors
- e.g. in digital radiography

Direct Conversion

Principle of a scintillation detector

Components of a scintillation detector

<table>
<thead>
<tr>
<th>Scintillators</th>
<th>Light sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>inorganic crystals</td>
<td>human eye</td>
</tr>
<tr>
<td>organic plastics</td>
<td>photomultiplier tubes</td>
</tr>
<tr>
<td>glass</td>
<td>photodiodes</td>
</tr>
<tr>
<td>liquid</td>
<td>avalanche photodiodes</td>
</tr>
<tr>
<td>gas</td>
<td>silicon photomultipliers</td>
</tr>
<tr>
<td></td>
<td>CCDs</td>
</tr>
<tr>
<td></td>
<td>gas-filled detectors</td>
</tr>
</tbody>
</table>
| | etc ...

Inorganic scintillation crystals

- CdI₂(Tl)
- NaI(Tl)
- CdWO₄
- BGO
- Various, under UV excitation
The scintillation process

Three phases:
1. The interaction phase + thermalization phase (ps)
2. The charge carrier and energy migration phase (ns-ms)
3. The luminescence phase (ns–μs)

Intensity \( I(t) = I_0 \exp\left(-t/\tau\right) \)
with \( I_0 \) given by \( \int_0^\infty I(t) \, dt = E \cdot Y \)
where \( E \) is the absorbed gamma energy (in MeV) and \( Y \) the scintillator light yield (in photons/MeV)

Important scintillator parameters
- high light output \( Y \) (photons/MeV)
- fast scintillation speed \( \tau \) (ns)
- good energy resolution \( R_{\text{FWHM}} \) (%)
- high density for \( \gamma \) detection \( \rho \) (g/cm³)
- large size of crystal \( 10\text{-}100\text{-}1000 \text{ cm}^3 \)
- cost per cm³
- low afterglow (low phosphorescence)
- low background count rate (low intrinsic activity)
- absence of radioactive isotopes

Relative importance depends on application

Properties of some inorganic scintillators

<table>
<thead>
<tr>
<th>scintillator</th>
<th>mass density</th>
<th>index of refraction</th>
<th>decay constant</th>
<th>emission (nm)</th>
<th>ph/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI</td>
<td>3.67</td>
<td>1.75</td>
<td>60</td>
<td>303</td>
<td>76000</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>1.75</td>
<td>230</td>
<td>415</td>
<td>38000</td>
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<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>1.75</td>
<td>3340</td>
<td>340</td>
<td>65000</td>
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<tr>
<td>BaF₂</td>
<td>4.89</td>
<td>1.5</td>
<td>630</td>
<td>310</td>
<td>9500</td>
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<tr>
<td>Bi₄Ge₃O₁₂ (BGO)</td>
<td>7.13</td>
<td>2.15</td>
<td>0.6</td>
<td>220</td>
<td>1400</td>
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<tr>
<td>PbWO₄</td>
<td>8.28</td>
<td>2.20</td>
<td>0.6</td>
<td>220</td>
<td>1400</td>
</tr>
<tr>
<td>Lu₂SiO₅:Ce (LSO)</td>
<td>7.4</td>
<td>1.8</td>
<td>47</td>
<td>420</td>
<td>25000</td>
</tr>
<tr>
<td>YAlO₃:Ce (YAP)</td>
<td>5.37</td>
<td>1.8</td>
<td>27</td>
<td>370</td>
<td>18000</td>
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<tr>
<td>LaCl₃:Ce</td>
<td>3.7</td>
<td>1.8</td>
<td>35</td>
<td>350</td>
<td>50000</td>
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<tr>
<td>LaBr₃:Ce</td>
<td>5.1</td>
<td>2.1</td>
<td>17</td>
<td>380</td>
<td>70000</td>
</tr>
</tbody>
</table>

Properties of some inorganic scintillators

Photomultiplier tubes

The main PMT elements
- photocathode
- photon \( \rightarrow \) photoelectron
- quantum efficiency (e.g., ~25%)
- electron-optics
- focusing of photoelectron
- preservation of time information
- multiplication stage
- 6 to 12 dynodes
- charge pulse at anode output
Quantum efficiency of photocathode 0.01 – 0.4 photoelectrons/photon
Overall electron gain is sensitive to applied voltage (typically 1 kV – 2.5 kV)
Secondary emission factor of dynodes δ typically 4-8
Typical gain = $10^6$-$10^7$ (number of dynodes $N = 8-12$)

Scintillation detectors in nuclear medicine

- Gamma camera (planar scintigraphy)
- SPECT scanner (single photon emission computed tomography)
- PET scanner (positron emission tomography)
  - Time-of-Flight PET (TOF-PET)

Conversion and multiplication

Scintillation detectors in nuclear medicine

Simplest case: planar scintigraphy

2D position sensitive detector: gamma camera

Collimator
Photomultiplier tubes
Scintillator plate
Radiopharmaceutical

Gamma camera

Nal:TI crystal of gamma camera
7 to 61 photomultipliers
Nal:TI crystal 20-60 cm diameter, 2-25 mm thick (often 9.5 mm)

Position Estimation (Anger logic)

Energy: $E = \sum_{k=1}^{7} a_k$

Position: $X = \frac{1}{E} \sum_{k=1}^{7} a_k x_k$, $Y = \frac{1}{E} \sum_{k=1}^{7} a_k y_k$
Positron emission tomography (PET)

Neutron-deficient radionuclide

Detector

$\beta^+ = p + n + e^+ + \nu_e$

Detector range

511 keV annihilation photon

PET detectors: classic “block” detector

• Several block detectors are assembled into a ring
• A scanner may consist of several detector rings

PET detectors: classic “block” detector

• Saw cuts direct light toward PMTs.
• Depth of cut determines light spread at PMTs.
• Crystal of interaction found with Anger logic (i.e. PMT light ratio).

PET detectors: Anger logic

• Identify crystal of interaction using lookup table
• Position given by crystal ID

Energy: pulse height spectrum

The height (amplitude) of the charge pulses produced by a scintillation detector are proportional to the number of scintillation photons detected and, thus, to the energy of the energy deposited by the gamma photon

Example: NaI:Tl pulse height spectrum

Counts

Energy (keV)
Scattering in patient

- Compton scattering
- Incorrect LOR
- Line of response (LOR)

Energy discrimination

Energy window

PET: coincidence detection

Coincidence window

Coincidence

Tube or Line Of Response (LOR)

Coincidence:

\[ t_1, t_2 < 10 \text{ ns} \]

Random coincidences

Random coincidences:

\[ R \sim 2 \tau \] where \( \tau \) is the width of the coincidence time window and \( S_1 \) and \( S_2 \) the singles rates of two opposing detectors

- Detector timing resolution must be \( \leq \tau \)
- High time resolution (~ns) needed!

Time-of-flight PET

\[ \Delta x = \text{uncertainty in position along LOR} = c \cdot CRT/2, \]

where \( c \) is the speed of light.

The TOF benefit is proportional to \( \Delta x/D \), where \( D \) is the effective patient diameter.

\[ \Delta x \approx \frac{7.5 \text{ cm}}{500 \text{ ps}} \]

Time-of-flight PET: concept of CRT

- Annihilation
- 511 keV
- LOR

\[ t_2 - t_1 < 10 \text{ ns} \]

\[ 511 \text{ keV} \]

\[ 511 \text{ keV} \]

Without TOF

With TOF

State-of-the-art: CRT \approx 500 \text{ ps} \Rightarrow \Delta x \approx 7.5 \text{ cm.}
Silicon Photomultiplier (SiPM)

- Array of many single-photon avalanche diodes (microcells) connected in parallel
- Increasingly interesting as replacement for PMTs:
  - high gain (~10^6)
  - high PDE
  - compact and rugged
  - transparent to $\gamma$-photons
  - fast response (ns)
  - insensitive to magnetic fields

SiPM-array based PET detectors

- For example:
  - crystal matrix composed of e.g. 4 mm x 4 mm x 20 mm crystals
  - each crystal coupled 1-to-1 to an individual SiPM
- => high spatial resolution
- => high energy resolution
- => excellent timing

100 ps barrier broken using SiPMs

Made possible by the combination of:
- Small LaBr$_3$:Ce(5%) crystals (3 mm x 3 mm x 5 mm)
- Silicon Photomultipliers (Hamamatsu MPPC-S10362-33-050C)
- Digital Signal Processing (DSP)

Multimodality: PET + MRI

Now: avalanche photodiodes (APDs)
Next generation systems: SiPMs !!!