PET Detector

David Spülbeck

29. April 2019
1. General Idea
2. Detector Setup
3. Data Analysing and Operation Modi
4. Technical Development
Table of Contents

1 General Idea

2 Detector Setup

3 Data Analysing and Operation Modi

4 Technical Development
Photon Production by Pair Annihilation

- $\beta^+$ emitter is coupled to a molecule, which is injected to the body
  → positrons are emitted inside the human body
- the positron annihilates with an electron

![Diagram showing positron emission and annihilation](image-url)
 Photon Production by Pair Annihilation

- $\beta^+$ emitter is coupled to a molecule, which is injected to the body
  - positrons are emitted inside the human body
- the positron annihilates with an electron

![Diagram showing positron annihilation and two 511 keV photons being emitted antiparallel]

- two photons are emitted with the energy of the electrons rest mass of 511 keV
- their directions are antiparallel
two detectors are needed to be arranged on photons travelling line

→ with only two detectors one cannot measure every event
two detectors are need to be arranged on photons travelling line

→ with only two detectors one can not measure every event

→ the detectors arrangement forms a ring, which scans the body
Table of Contents

1. General Idea
2. Detector Setup
3. Data Analysing and Operation Modi
4. Technical Development
## Convenient detectors

<table>
<thead>
<tr>
<th>Gaseous Detectors</th>
<th>Semiconductor Detectors</th>
<th>Scintillation Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
</tbody>
</table>

[1]
## Convenient detectors

<table>
<thead>
<tr>
<th>Gaseous Detectors</th>
<th>Semiconductor Detectors</th>
<th>Scintillation Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Gaseous Detectors Diagram]</td>
<td>![Semiconductor Detectors Diagram]</td>
<td>![Scintillation Detectors Diagram]</td>
</tr>
<tr>
<td>- low energy resolution</td>
<td>- low stopping efficiency</td>
<td></td>
</tr>
<tr>
<td>- low stopping efficiency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[1]
### Convenient detectors

<table>
<thead>
<tr>
<th>Gaseous Detectors</th>
<th>Semiconductor Detectors</th>
<th>Scintillation Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="gaseous.jpg" alt="Image" /></td>
<td><img src="semiconductor.jpg" alt="Image" /></td>
<td><img src="scintillation.jpg" alt="Image" /></td>
</tr>
<tr>
<td>- low energy resolution</td>
<td>+ excellent energy resolution</td>
<td></td>
</tr>
<tr>
<td>- low stopping efficiency</td>
<td>- low stopping efficiency</td>
<td></td>
</tr>
</tbody>
</table>
Convenient detectors

<table>
<thead>
<tr>
<th>Gaseous Detectors</th>
<th>Semiconductor Detectors</th>
<th>Scintillation Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Gaseous Detectors" /></td>
<td><img src="image2" alt="Semiconductor Detectors" /></td>
<td><img src="image3" alt="Scintillation Detectors" /></td>
</tr>
<tr>
<td>- low energy resolution</td>
<td>+ excellent energy resolution</td>
<td>+ fine energy resolution</td>
</tr>
<tr>
<td>- low stopping efficiency</td>
<td>- low stopping efficiency</td>
<td>+ high stopping efficiency</td>
</tr>
</tbody>
</table>

→ *Scintillation Detectors are used in PET*  
It consists of 3 elements: Scintillator, Photo-Detector, Readout
Scintillation Effect

- incoming photon produces electron hole pair (exiton)
- exiton travels through the solid state structure without obstruction
- doping atoms absorb exiton by emitting scintillation photons

band structure of anorganic scintillator
most common Scintillator is BGO (bismuth germanate, $Bi_4Ge_3O_{12}$)

- energy resolution $\frac{\Delta E}{E} \approx 10\%$
- density $7.13 \ \frac{g}{cm^3}$
- highest stopping efficiency yields to a high detection rate
- decay constant $\tau \approx 300 \text{ ns} \rightarrow$ bad time resolution
PIN-Diode or Photomultiplier?

→ PIN-Diode SNR is several orders of magnitudes lower than the PMTs

→ PIN-Diode is highly prone to changes in temperature
PIN-Diode or Photomultiplier?

- PIN-Diode SNR is several orders of magnitudes lower than the PMTs
- PIN-Diode is highly prone to changes in temperature

Photomultiplier
- the scintillation photons intensity is proportional to the energy of the incoming photons (511 keV)
- as the excited energy levels of the exciton band decay exponentially, either does the intensity ($\tau$)
both the integral and the width of the signal are proportional to the deposited energy
1. one-to-one coupling: Scintillator is glued to the Photo detector
   - the size of the PMT limits the spatial resolution (4 mm)
1. one-to-one coupling: Scintillator is glued to the Photo detector
   - the size of the PMT limits the spatial resolution (4 mm)

2. several Scintillators are coupled to 4 PMT
   - by comparing the signals of the 4 PMT, the incoming photon can be located

\[
\begin{align*}
  x &= \frac{(B+D)-(A+C)}{A+B+C+D} \\
  y &= \frac{(A+B)-(C+D)}{A+B+C+D}
\end{align*}
\]
**Coupling of PMT and Scintillator**

1. one-to-one coupling: Scintillator is glued to the Photo detector
   - the size of the PMT limits the spatial resolution (4 mm)

2. several Scintillators are coupled to 4 PMT
   - by comparing the signals of the 4 PMT, the incoming photon can be located

\[
\begin{align*}
    x &= \frac{(B+D)-(A+C)}{A+B+C+D} \\
    y &= \frac{(A+B)-(C+D)}{A+B+C+D}
\end{align*}
\]
Ring Detector

- about 40 detector blocks are arranged as a ring

- about 8 rings form the whole detector
  → about 1200 PMTs and 20000 Scintillators generate the whole system

- comparing two opposite detector blocks: reconstruction of line of photons direction
about 40 detector blocks are arranged as a ring

about 8 rings form the whole detector
→ about 1200 PMTs and 20000 Scintillators generate the whole system
→ but where did the annihilation take place on this line?

comparing two opposite detector blocks: reconstruction of line of photons direction
Time of Flight (ToF)
Time of Flight (ToF)

- calculating **point of annihilation**
- \(2\tau\) is the time of coincidence: \((2\tau)_{\text{max}} = \frac{1}{c} \approx 4\text{ ns}\)
Time of Flight (ToF)

- calculating point of annihilation

- $2\tau$ is the time of coincidence: $(2\tau)_{max} = \frac{1}{c} \approx 4 \text{ ns}$ → not possible with BGO ($\tau \approx 300 \text{ ns}$)
511 keV Photon deposits energy in human body by $I(d) = I_0 \cdot e^{-\mu d}$
511 keV Photon deposits energy in human body by $I(d) = I_0 \cdot e^{-\mu d}$

\[ \frac{I_1}{I_2} = e^{-\mu d_1} \cdot e^{\mu d_2} \]

\[ \Leftrightarrow d_2 - d_1 = \frac{1}{\mu} \cdot \ln \left( \frac{I_1}{I_2} \right) \]

- reconstruction of **point of annihilation** with BGO possible
Ready to use

- the body needs to be hold in place
- patient can get moved through the scanner
Table of Contents

1 General Idea

2 Detector Setup

3 Data Analysing and Operation Modi

4 Technical Development
Valid Events

- a real event satisfies three conditions
Valid Events

- a real event satisfies three conditions
  1. two photons are detected within the given time window
Valid Events

- A real event satisfies three conditions
  1. Two photons are detected within the given time window
  2. The line of response inside an realistic range
Valid Events

- a real event satisfies three conditions
  1. two photons are detected within the given time window
  2. the line of response inside an realistic range
  3. the detected energy is inside the valid energy range
1. **static scanning**
   - summing up all events up to a 3d picture
   - 3 min – 4 min scanning time
   - patient is moving too much within an extended scanning time

2. **dynamic scanning**
   - reconstructing different time windows (≈ 20 s)
   - used in neurology to analyse processes of receptors

3. **triggered scanning**
   - heart beat and breathing are measured
   - only events of the same point of these periodic processes are considered
1. General Idea
2. Detector Setup
3. Data Analysing and Operation Modi
4. Technical Development
Technical Development

- inventors Michel Ter-Pogossian and Michael E. Phelps (Physicists from U.S.A)
- first scan in year 1975
Technical Development

- inventors Michel Ter-Pogossian and Michael E. Phelps (Physicists from U.S.A)
- first scan in year 1975

advantages
- not invasive
- highly sensitive information about different metabolism

disadvantages
- bad resolution with about 4 mm – 6 mm
Technical Development

- inventors Michel Ter-Pogossian and Michael E. Phelps (Physicists from U.S.A)
- first scan in year 1975

advantages

- not invasive
- highly sensitive information about different metabolism

→ to use the benefits of two medical imaging systems:

PET/CT scanner, PET/MRI scanner

disadvantages

- bad resolution with about 4 mm – 6 mm
PET/CT Scanner

- combining information about metabolism (PET) with high resolution (CT)

- Do the two tomographs effect each other?
PET/CT Scanner

- combining information about metabolism (PET) with high resolution (CT)

Do the two tomographs effect each other?
PET/CT Scanner

- combining information about metabolism (PET) with high resolution (CT)

Do the two tomographs affect each other?

→ No, they do not!
better localisation is possible
shorter scanning time and higher medical validity
better localisation is possible
shorter scanning time and higher medical validity
→ since 2004 only PET/CT devices are acquired in german hospitals
first device was installed in Jülich 2007 with approx. 3 Tesla

challenge: Photomultipliers will not work inside such a high mag. field
first device was installed in Jülich 2007 with approx. 3 Tesla

challenge: Photomultipliers will not work inside such a high mag. field

use shielding or other photo detectors
solution 1 (sequentially):
- both tomographs are separated by 3 m
- connected by a movable couch

solution 2:
- using other photodetectors with a worse resolution
Summary

- Annihilation $e^+ + e^- \rightarrow 2\gamma_{511\text{keV}}$

- Coincidences are measured to reconstruct the point of annihilation

- Scintillation Detectors because of high stopping efficiency

- Visible process of metabolism

- combining Imaging systems: PET/CT, PET/MRI
Thanks for your attention
List of Literature

[1] PET Springer 2005
- only detectors of the same ring can measure a coincidence
- low data efficiency
only detectors of the same ring can measure a coincidence
low data efficiency

Real

- wolfram filter are fixed to the scintillators
- only real events are measured
- focusing on a certain area
- only detectors of the same ring can measure a coincidence
- low data efficiency

**real**
- wolfram filter are fixed to the scintillators
- only real events are measured
- focussing on a certain area

**electronic**
- no filter
- electronic assigning of events
- detectors of all rings can measure a coincidence
- high data efficiency ($10^5$ times higher as 2d)
- high performance encoding is necessary
picture constructing algorithm

interactive reconstruction

- comparing to a supposed tracer distribution
  1. projecting the supposed tracer distribution according systems properties
  2. taking the difference to the measured distribution
  3. calculating a factor of correction and the new tracer distribution to compare with
  4. iterating this process until criterion of abortion
picture constructing algorithm

**interactive reconstruction**

- comparing to a supposed tracer distribution
  1. projecting the supposed tracer distribution according systems properties
  2. taking the difference to the measured distribution
  3. calculating a factor of correction and the new tracer distribution to compare with
  4. iterating this process until criterion of abortion

- advantages:
  - improves signal to noise ratio up to 60% (compared with filtered projection)
  - Siemens guarantees a resolution of 2 mm (laboratory condition)
### Valid events

- **True**
  - Energies of both detected photons are located in the range of photo peak.

- **Scatter**
  - Energy of the scattered photon is lower than photo peak.
  - Line of response needs to be corrected.
Invalid events

- seem to be a true event
- spatially uncorrelated with the distribution of tracer
- Random rate of detector a und b: $R_{ab} = 2\tau N_a N_b$

- tree photon are detected
- similar to random event
- these events are simply disregarded