From Ge(Li) detectors to gamma-ray tracking arrays – AGATA

Jürgen Eberth, University of Cologne
Topics to be discussed

- The 1960ties and 70ties: Ge(Li) detectors
- The 1980ties: HPGe detectors arrays by national collab. OSIRIS, HERA, TESSA
- The 1990ties: EUROBALL and GAMMASPHERE
- The last decade: position-sensitive Ge Detectors MINIBALL, EXOGAM, SEGA
- Under development: the 4π gamma-ray tracking arrays AGATA, GRETA
Ion Drift in an $n$-$p$ Junction*

E. M. Pell

General Electric Research Laboratory, Schenectady, New York
(Received August 19, 1959)

$\Delta E = 21$ keV

661.6 keV

Fig. 1. Pulse-height spectrum from a $p$-$i$-$n$ junction in germanium due to 663 keV $\gamma$-rays from caesium-137

First Ge(Li) detector: D.V. Freck and J. Wakefield
Nature 193, 669 (1962)
Li-drift apparatus
Univ. of Cologne 1967

Coaxial detector 1968
$\Delta E = 3.5 \text{ keV at} \ 1.3 \text{ MeV}$
γ-spectroscopy with Ge(Li) detector
10 -15 % rel. Efficiency (Vol. 50-70 ccm)
Resolution 1.9 – 2.3 keV at 1.3 MeV

But also first segmented and composite detectors
The „five-in-one“ Compton Polarimeter (1974)

two concentric coaxial Ge(Li) detectors, outer detector 4-fold segmented

energy resolution 3.5 – 5 keV at 1.3 MeV

Ge crystal: 65mm diam., 46mm length

Fig. 1. Cross section of the polarimeter. W = thin window, CR = cryostat, C = crystal, T = Teflon insulation, P = crystal holder, F = cold finger.
Composite Ge Detectors

3(4) Ge(Li) detectors in a common cryostat (1976)

resolution 2.1 keV at 1.3 MeV for 3 but not for 4 detectors

FIG. 4. Three-crystal Compton polarimeter. Detector A acts as scatterer, the absorbers B and C are shielded from direct radiation by a 4 cm collimator of Densimed (see text). CR = cryostat, H = heat shielding.
Production of Ge(Li) detectors was abandoned after 1978 when high-purity Ge (HPGe) detectors became commercially available.
The 1980ties

Detector arrays with HPGe detectors and BGO escape suppression shields by national collaborations

OSIRIS Cologne 1986
HERA at LBNL

21 HPGe detectors (25% eff.) with escape suppr. shields
Impact of the arrays on nuclear structure physics: Isolation of rare excitations by $\gamma$-$\gamma$-$\gamma$-coincidences

Super-deformed rotational band

$^{152}$Dy

TESSA3

Abs. Eff. ~ 10%

70 detectors segmented into two halves to reduce the Doppler broadening

EUROGAM II
24 CLOVER detectors with increased eff. (130%) and improved granularity

Late 1980’s:

Discussion of a cluster of seven detectors with large efficiency in add-back mode

Conclusion:

seven hexagonal detectors in a common cryostat

Encapsulation !
capsule and lid sealed by electron-beam welding internal Getter, vacuum $< 10^{-6}$ mb, temperature range -196 °C and +110 °C

**Collaboration: Köln, Jülich, Eurisys**

J. Eberth et al., NIM A369 (1996) 135
The EUROBALL Cluster Detector

10kg HPGe
rel. efficiency. 600%
EUROBALL  1997 - 2003

239 detectors
linear polarization
abs. eff. ~ 10%
New facilities - new challenges

- FAIR
- SPIRAL2
- SPES
- REX-ISOLDE
- EURISOL
- ECOS

Low intensity
- High backgrounds
- Large Doppler broadening
- High counting rates
- High $\gamma$-ray multiplicities

High efficiency
- High sensitivity
- High throughput
- Small solid angle
- Ancillary detectors

Need instrumentation
The last decade: position-sensitive Ge detectors

Position-sensitivity of Ge detectors is based on:

- Segmentation of the detector contacts
- Signal processing with digital electronics
- Pulse shape analysis

Segmented detectors: SEGA, EXOGAM, TIGRESS

MINIBALL at REX-ISOLDE:
The first array with segmented detectors and digital signal processing
The 6-fold segmented, encapsulated MINIBALL detector

Collaboration: Köln, Heidelberg, München, Leuven
Scan of a MINIBALL detector with a collimated $^{137}$Cs source

position resolution
~ 5 mm

Pulse shape analysis:
Time to steepest slope vs. asymmetry of mirror charges
MINIBALL at REX-ISOLDE, CERN

24 Ge detectors in 8 cryostats, 6-fold segmented

abs. eff. 8.5 %

The idea of $\gamma$-ray tracking

Compton Shielded Ge

- $\varepsilon_{ph} \sim 10\%$
- $N_{det} \sim 100$
- $\Omega \sim 40\%$
- $\theta \sim 8^\circ$

Large opening angle means poor energy resolution at high recoil velocity.

Previously scattered gammas were wasted. Technology is available now to track them.

Ge Tracking Array

- $\varepsilon_{ph} \sim 50\%$
- $N_{det} \sim 100$
- $\Omega \sim 80\%$
- $\theta \sim 1^\circ$

Combination of:
- segmented detectors
- digital electronics
- pulse processing
- tracking the $\gamma$-rays

Euroball / Gammasphere

Euroball / Gammasphere
<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 hexagonal crystals</td>
<td>3 shapes</td>
</tr>
<tr>
<td></td>
<td>60 triple-clusters</td>
</tr>
<tr>
<td></td>
<td>all equal</td>
</tr>
<tr>
<td>Inner radius (Ge)</td>
<td>23.5 cm</td>
</tr>
<tr>
<td>Amount of germanium</td>
<td>362 kg</td>
</tr>
<tr>
<td>Solid angle coverage</td>
<td>82 %</td>
</tr>
<tr>
<td>36-fold segmentation</td>
<td>6480 segments</td>
</tr>
<tr>
<td>Singles rate</td>
<td>~50 kHz</td>
</tr>
<tr>
<td>Efficiency:</td>
<td></td>
</tr>
<tr>
<td>(M_\gamma=1)</td>
<td>43%</td>
</tr>
<tr>
<td>(M_\gamma=30)</td>
<td>28%</td>
</tr>
<tr>
<td>Peak/Total:</td>
<td></td>
</tr>
<tr>
<td>(M_\gamma=1)</td>
<td>58%</td>
</tr>
<tr>
<td>(M_\gamma=30)</td>
<td>49%</td>
</tr>
</tbody>
</table>

6660 high-resolution digital electronics channels

Pulse Shape Analysis → position sensitive operation mode

\( \gamma \)-ray tracking algorithms to achieve maximum efficiency.

Coupling to ancillary detectors for added selectivity
AGATA detectors and the AGATA triple-cluster

Symmetric detectors
- 3 in use since 6 years
- Used in single cryostats or as a triple cluster

Asymmetric detectors
- 31 ordered
- 15 accepted
- 4 clusters operational

~2 kg
80 mm
90 mm
6x6 segmented cathode
Asymmetric AGATA Tripel Cryostat

- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals

Challenges:
- mechanical precision
- microphonics
- noise, high frequencies
- LN2 consumption

- D. Lersch et al. NIM A (2011) accepted
Performance: Energy resolution

Averages of the segment resolutions measured in Köln and Legnaro

@ 60 keV:
- A001: 1011 +/- 53 eV
- B002: 1039 +/- 70 eV
- C002: 965 +/- 63 eV

@ 1333 keV:
- A001: 2.19 keV / 2.00 keV
- B002: 2.09 keV / 1.98 keV
- C002: 2.1 keV / 1.94 keV
Ingredients of Gamma-Ray Tracking

1. Highly segmented HPGe detectors
2. Digital electronics to record and process segment signals
3. Pulse Shape Analysis to decompose recorded waves
4. Reconstruction of tracks evaluating permutations of interaction points
   - Identified interaction points \((x,y,z,E,t)_i\)
   - Reconstructed gamma-rays
Pulse Shape Analysis concept

<table>
<thead>
<tr>
<th>A3</th>
<th>A4</th>
<th>A5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B3</th>
<th>B4</th>
<th>B5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C3</th>
<th>C4</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4

(z = 46 mm)
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4

(10,25,46)
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

Result of Grid Search Algorithm

(10, 25, 46)

791 keV deposited in segment B4
Cross talk correction: Motivation

- Crosstalk is present in every segmented detector
- Creates strong energy shifts proportional to fold
- Tracking needs segment energies!

...All possible 2fold combinations

![Graph showing energy distribution with 1-fold and 2-fold percentages and centroids labeled as 'Core' and 'Segment sum'.]
On line Cross Talk Correction

Details: 1.3MeV line

B. Bruyneel et al., NIM A 599 (2009) 196

<table>
<thead>
<tr>
<th>fold</th>
<th>Segsum</th>
<th>corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.99</td>
<td>1.91</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>2.06</td>
</tr>
<tr>
<td>3</td>
<td>3.06</td>
<td>2.14</td>
</tr>
<tr>
<td>4</td>
<td>3.63</td>
<td>2.19</td>
</tr>
<tr>
<td>5</td>
<td>4.07</td>
<td>2.22</td>
</tr>
<tr>
<td>6</td>
<td>4.38</td>
<td>2.23</td>
</tr>
<tr>
<td>7</td>
<td>4.69</td>
<td>2.34</td>
</tr>
</tbody>
</table>

FWHM 60keV: 1.20 → 1.02 !

Details: 1.3MeV line

Xtalk Corrected

Uncorrected

On line Cross Talk Correction

B. Bruyneel et al., NIM A 599 (2009) 196
Performance: Crosstalk

- No crosstalk observed between detectors
- Within one detector, the theoretical crosstalk limit is reached
- Online cross talk correction implemented
All n-type Ge detectors suffer from electron trapping. Knowing the interaction position and charge collection path, the trapping effects can be corrected.

**Example:** Ring 1 energy @ 1.3 MeV

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Core corrected</th>
<th>Core segments average</th>
<th>Core segments Average corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.194 keV</td>
<td>2.194 keV</td>
<td>2.120 keV</td>
<td>1.893 keV</td>
</tr>
<tr>
<td>2.011 keV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Correction of neutron damage

- Core
- Seg
- C+S

FWHM | FWTM
---|---
1.3 MeV | 2.06 | 1.91
2.06 | 2.44 | 1.83
2.44 | 2.51 | 1.83
2.51 | 2.88 | 2.34
2.88 | 2.30 | 1.83
2.30 | 2.34 | 1.83
2.34 | 2.34 | 1.83
AGATA online

1st experiment with AGATA (18/02/10)

- < 5mm FWHM resolution obtained
- psa online at rates > 5kHz per crystal
Doppler correction using center of crystals
FWHM ~ 20 keV

Total projection. Detector FWHM = 2.2 keV

Doppler correction using center of hit segments
FWHM = 7 keV
(3.5 keV if only single hits)

Doppler correction using center of crystals
FWHM ~ 20 keV

E(2\textsuperscript{+}) = 846.8 keV

v/c \sim 8\%

220 MeV \textsuperscript{56}Fe \rightarrow \textsuperscript{197}Au
ATC1 + DANTE

\textsuperscript{56}Fe \rightarrow \textsuperscript{197}Au
\textsuperscript{56}Fe \rightarrow \textsuperscript{198}Au
\textsuperscript{56}Fe 2\textsuperscript{+} \rightarrow 0\textsuperscript{+}
846.8 keV

\textsuperscript{56}Fe 4\textsuperscript{+} \rightarrow 2\textsuperscript{+}
1238.3 keV
4.8 keV FWHM

\textsuperscript{56}Fe 2\textsuperscript{+} \rightarrow 0\textsuperscript{+}
846.8 keV

\textsuperscript{56}Fe 4\textsuperscript{+} \rightarrow 2\textsuperscript{+}
1238.3 keV
4.8 keV FWHM

\textsuperscript{56}Fe \rightarrow \textsuperscript{197}Au
\textsuperscript{56}Fe 2\textsuperscript{+} \rightarrow 0\textsuperscript{+}
846.8 keV

\textsuperscript{56}Fe 4\textsuperscript{+} \rightarrow 2\textsuperscript{+}
1238.3 keV
4.8 keV FWHM

E_\gamma (keV)
Summary

From Ge(Li) detectors to γ-ray Tracking Arrays

Gain: 7 orders of magnitude in resolving power

Position-sensitive Ge detectors:
A challenging technology

Allows for γ-ray tracking, improves energy resolution, gives a better understanding of the interactions of radiation with the detector

Almost optimal performance achieved for the AGATA triple-cluster detector

Can this technology be transferred to low-background experiments?
The AGATA collaboration:

IPN Lyon, France
Univ. Lund, Sweden
Univ. Manchester, UK
INFN/Univ. Milano, Italy
TU München, Germany
INFN Napoli, Italy
CSNSM Orsay, France
IPN Orsay, France
INFN/Univ. Padova, Italy
Univ. Paisley, UK
INFN Perugia, Italy
CEA Saclay, France, Dapnia
Univ. Sofia, Bulgaria
KTH Stockholm, Sweden
Ines Strasbourg, France
Univ. Surrey, UK
IPJ Swierk, Poland
Univ. Warsaw, Poland
Univ. Uppsala, Sweden
Univ. York, UK

AGATA Homepage: [http://www-w2k.gsi.de/agata/](http://www-w2k.gsi.de/agata/)
Coulomb excitation of neutron-rich Zn isotopes

J. Van der Walle et al., PRL 99 (2007) 142501
Simulating the detector response

- Weighting Fields
- Charge dynamics
- Electronic Response

Shockley-Ramo theorem:
Gives charge induced at the electrode by a unit charge as function of its place in the detector

NIM A 463 (2001) 250-267
Imaging of $E_\gamma = 1332$ keV gamma rays
AGATA used as a big Compton Camera

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

Source at 51 cm $\Rightarrow \Delta x \sim \Delta y \sim 2$ mm $\Delta z \sim 2$ cm

Francesco Recchia
Doppler correction using PSA results

Experiment performed at Köln in 2005

d(\textsuperscript{48}Ti, \textsuperscript{49}Ti)p

Position resolution derived by comparing with MC
→ 4.5 mm FWHM
New challenges in nuclear structure and nuclear astrophysics

Shell structure in nuclei
- Structure of doubly magic nuclei
- (effective) interactions

Proton drip line and N=Z nuclei
rp-process nuclei

Neutron rich heavy nuclei (N/Z → 2)
r-process nuclei

Shape coexistence
Transfermium nuclei

Nuclei at the neutron drip line (Z→25)
The AGATA Demonstrator
Objective of the R&D phase 2003-2009

5 asymmetric triple-clusters
15 36-fold segmented crystals
540 segments
555 high-resolution digital-channels
Eff. 3 - 8 % @ M_γ = 1
Eff. 2 - 4 % @ M_γ = 30

Real time operation
Pulse Shape Analysis
γ-ray Tracking

Hosting sites
LNL → 2009-2011
GSI → 2012
GANIL → 2014
A model to describe cross talk

Cross talk is intrinsic property of segmented detectors!

Proportional cross talk - Energy
Derivative cross talk - PSA

B. Bruyneel et al., NIM A 599 (2009) 196
Electron trapping present in any n-type detector

<table>
<thead>
<tr>
<th></th>
<th>FWHM</th>
<th>FWTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 MeV</td>
<td>1.80</td>
<td>1.85</td>
</tr>
<tr>
<td>1.80</td>
<td>1.87</td>
<td>1.85</td>
</tr>
<tr>
<td>1.93</td>
<td>1.98</td>
<td>1.83</td>
</tr>
<tr>
<td>2.12</td>
<td>2.25</td>
<td>1.83</td>
</tr>
</tbody>
</table>