Detection of $\gamma$-rays from nuclear decay: $0.1 < E_\gamma < 20$ MeV

- Basic concepts of radiation interaction & detection
- Compound Nucleus reactions and $\gamma$-ray emission
- High resolution detectors: the semiconductor Ge's
- Present Ge Arrays: EUROBALL
- Future Arrays: AGATA
\( \gamma \)-decay of Compound Nucleus

\( ^{124}\text{Sn} \) \( ^{164}\text{Er} \)

\( ^{40}\text{Ar} \sim 5 \text{ MeV/A} \)

Giant Dipole Resonance
- \( E_\gamma \sim 15 \text{ MeV} \)
- FWHM \( \sim 5-7 \text{ MeV} \)
- \( P_\gamma / P_{\text{part}} \approx 10^{-3} \)

\( \gamma \)-decay below n-threshold
- \( E_\gamma \leq 8 \text{ MeV} \)
- FWHM \( \sim 2-10 \text{ keV} \)
- \( M_\gamma \sim 20-30 \) (within few ps)
γ-ray patterns reveal nuclear structure

Collective rotation leads to regular band structures

Single-particle generation of spin leads to an irregular level structure

γ detector
Δt ~ 10⁻⁹ sec

Eγ₁

10⁻¹⁵ sec

Eγ₂

Deformed Nucleus

Near Spherical Nucleus

E (MeV)

158 Er

147 Gd

Rotation axis

I
there is NO detector providing *simultaneous* measurement of high-energy and low-energy $\gamma$-rays with optimal conditions

**Low-energy:**
Ge detectors
good energy resolution

**Arrays**
dedicated or coupled

**High-energy:**
Scintillators (NaI, BaF$_2$, ...)
high efficiency, good timing, particle discrimination

<table>
<thead>
<tr>
<th>Cristallo</th>
<th>Densità</th>
<th>$\Delta T$ (FWHM)</th>
<th>$\Delta E/E$</th>
<th>Vol Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BaF_2$</td>
<td>4.88 56</td>
<td>$\sim 0.4$ ns</td>
<td>$\sim 11%$</td>
<td>$&gt; 4 \text{ dm}^3$</td>
</tr>
<tr>
<td>NaI</td>
<td>3.67 53</td>
<td>$\sim 1.5$ ns</td>
<td>$\sim 7%$</td>
<td>$&gt; 4 \text{ dm}^3$</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13 83</td>
<td>$\sim 5.0$ ns</td>
<td>$\sim 15%$</td>
<td>$&gt; 4 \text{ dm}^3$</td>
</tr>
<tr>
<td>HpGe</td>
<td>5.32 32</td>
<td>$\sim 3.0$ ns</td>
<td>$\sim 0.2%$</td>
<td>$&lt; 0.2 \text{ dm}^3$</td>
</tr>
</tbody>
</table>

**Future**
Arrays of segmented Ge detectors ...

Pulse shape & tracking
(particle-$\gamma$ discrimination ?)
The energy resolution depends directly on the number \( N \) of charge carriers.

\[
R \approx \frac{2.35}{\sqrt{N}}
\]

in a scintillator \( \sim 100 \text{ eV/photoelectron} \) \( \Rightarrow N = 10^4 @ 1 \text{ MeV} \)

in a semiconductor \( \sim 3 \text{ eV/photoelectron} \) \( \Rightarrow N = 3 \times 10^5 @ 1 \text{ MeV} \)
High-energy $\gamma$-rays

**Energy Delay (after 30 cm)**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$\sim$ 14</td>
</tr>
<tr>
<td>4</td>
<td>$\sim$ 10</td>
</tr>
<tr>
<td>6</td>
<td>$\sim$ 8</td>
</tr>
<tr>
<td>10</td>
<td>$\sim$ 6</td>
</tr>
<tr>
<td>14</td>
<td>$\sim$ 5</td>
</tr>
<tr>
<td>20</td>
<td>$\sim$ 4</td>
</tr>
</tbody>
</table>

**Photopeck Efficiency**

$$\varepsilon_a = \varepsilon_p \left( \frac{\Omega}{4\pi} \right)$$

**Absolute Efficiency**

- $\varepsilon_p$ for 10 cm source
- $4.2 \times 4.2 \text{ cm}^2$
- $7.5 \times 7.5 \text{ cm}^2$

**Graphs**

- Counts vs. Energy (MeV)
- Absolute Efficiency for Point Source at 25 cm
- Time of Flight (ToF) vs. [ns]

**Materials**

- BaF$_2$
- Ge

**Dimensions**

- Ge from ORTEC
- BaF$_2$ 14 cm x 18 cm
- BaF$_2$ 64 mm x 90 mm
- Ge 65 mm x 76 mm

**Counts**

- BaF$_2$ / 10
- HpGe
High Purity Ge Detectors

impurity concentration \( N \sim 10^{10} \) atoms/cm\(^3\)

Characteristics

- size: \( \varnothing \sim 10\) cm, \( L \sim 9\) cm
- shape: coaxial
- n-type
- less sensitive to radiation damage
- operating temperature: \(< 85 \) K
- rates: \( \sim 10 \) kHz to prevent pile-up
- energy resolution: 2 keV at 1.332 MeV (0.2 \%)
- time resolution: 4-5 ns (with CFD), 200-300 ns total rise time
- efficiency*: up to 200\%  

\[ d \approx \sqrt{\frac{2eV}{eN}} \]

\( V \sim 2500-4500V \)

* relative to 7.5x7.5 cm NaI(Tl) for 1.33 MeV \( \gamma \)-rays emitted by \(^{60}\text{Co}\) source at 25 cm from detector (\( \epsilon_a = 1.2 \times 10^{-3} \))
γ-ray interaction

ionization occurs in limited regions of the absorber

\[ \gamma \text{-ray interaction} \]

Linear attenuation coefficient (probability per unit path)

\[ I = I_0 e^{-\mu x} \]

\[ \mu = \sigma_{ph} + \sigma_C + \sigma_{pp} \]

\[ \sigma_{ph} \approx \frac{Z^n}{E_\gamma^{3.5}} \]

\[ \sigma_C \approx Z \frac{\ln E_\gamma}{E_\gamma} \]

\[ \sigma_{pp} \approx Z^2 \ln E_\gamma \]

\[ n = 4 - 5 \]
Important characteristics:

- energy resolution: $\delta E_{\gamma}/E_{\gamma} = \text{FWHM}/E_{\gamma}$
- peak-to-total: $P/T = \frac{\text{Area}_{\text{peak}}}{\text{Area}_{\text{total}}}$
Ge Response function (+ Anti-Compton Shield)

- P/T ~ 20%
- P/T ~ 60%

Anular detector used with heavy metal collimators in front

Used material: BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)
- Density $\sim 7.3$ g/cm$^3$
- Z = 83
- 3 times more efficient than NaI

⇒ ideal for very compact geometry (small spaces)

N.B. in some cases NaI nose is used to improve the light output far away from PM tube.
Compton scattering angular distribution

\[ E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma / m_ec^2)(1 - \cos \theta)} \]

**NaI nose**: improvement of light output far away from PM tubes (low-energy \( \gamma \)-rays)

**BGO back-catcher**: improvement of high-energy Compton scattering (high-energy \( \gamma \)-rays)

**high-energy \( \gamma \)-ray**: forward scattering

**low-energy \( \gamma \)-ray**: forward & backward
Towards a $4\pi$ detection array: The European $\gamma$-ray detection systems

- **TESSA**
  - 5 Ge (25%)
  - +ACS (NaI)
  - $P_{ph} \sim 0.5-1\%$

- **ESSA30**
  - 30 Ge (25%)
  - +ACS (NaI)
  - $P_{ph} \sim 5\%$

- **EUROGAM** (45 CSGe)
  - $P_{ph} \sim 10\%$

- **EUROBALL III** (> 200 CSGe)
  - + IB

- **GASP** (40 CSGe) + IB

- **EUROBALL IV** (> 200 CSGe) + IB

- 1980
- 1986
- 1992
- 1996
GAMMA-DETECTOR Systems

- Ge detector + BGO shields
- Multiplicity filter (BGO or BaF2)
- Si detectors for particles (p, α, d)
- RMS, PPAC (for recoil detection)
4π Ge detector Array
EUROBALL

References:

Achievements with the EUROBALL Spectrometers
Scientific and Technical Activity Report 1997-2003
W. Korten & S. Lunardi Editors

EUROBALL
(239 Ge Crystals)

inner radius 25-40 cm

30 TAPERED GE-DETECTORS
26 CLOVER GE-DETECTORS
15 CLUSTER GE-DETECTORS

BEAM LINE

<table>
<thead>
<tr>
<th>30 Tapered</th>
<th>26 Closers</th>
<th>15 Clusters</th>
<th>71(239)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>5 at 18°</td>
<td>13 at 77°</td>
<td>5 at 130°</td>
</tr>
<tr>
<td></td>
<td>10 at 35°</td>
<td>13 at 103°</td>
<td>5 at 137°</td>
</tr>
<tr>
<td></td>
<td>15 at 52°</td>
<td></td>
<td>5 at 157°</td>
</tr>
<tr>
<td>Distance</td>
<td>37.5 cm</td>
<td>-26.9 cm</td>
<td>44.5 cm</td>
</tr>
<tr>
<td>ε_{ph}(%)</td>
<td>1.3</td>
<td>3.7</td>
<td>4.4</td>
</tr>
<tr>
<td>effective*</td>
<td>1.1</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>R</td>
<td>9.3</td>
<td>8.3</td>
<td>10.5</td>
</tr>
<tr>
<td>effective*</td>
<td>7.9</td>
<td>6.8</td>
<td>8.9</td>
</tr>
</tbody>
</table>

\( E_{\gamma} = 1.3 \text{ MeV}, \ SE_{\gamma} = 70 \text{ keV}, \ M_\gamma = 30, \ v/c=2\% \)

Composite Ge detectors

HPGE CLOVER
\( \epsilon \approx 20\% \)

HPGE CLUSTER
\( \epsilon \approx 60\% \)

EUROBALL
\( M_\gamma = 30, \ v/c = 2\% \)
\( \epsilon_\gamma \approx 7\% \)
\( P/T \approx 40\% \)
\( \Omega \approx 40\% \)

Full Ball: Ge+BGO \( \approx 4\pi \)
Composite & encapsulated detectors

bare crystal  encapsulated (0.7 mm aluminum)
under vacuum (10^{-6} mbar)

CLOVER

EB-CLUSTER
Mounting of a EUROBALL Cluster Ge detector (Kholn, Milano, LNL, Manchester, Lund)

Encapsulated detectors have proven to be reliable, easy to handle and repair: they have also been used in space missions.

Figure 10.10: Mars Odyssey.

Figure 10.11: 19 encapsulated detectors to be used in the INTEGRAL mission.
Advantages of composite Ge Detectors:

1. enhanced efficiency (more volume & add back)
2. reduced Doppler broadening
3. polarization studies

References

CLOVER specifications from Canberra
G. Duchene et al, NIMA432(1999)90
P.K. Joshi et al, NIMA399(1997)51
P.M. Jones et al., NIMA362(1995)556
M. Wilhelm et al., NIMA381(1996)462
B. Million et al., NIMA452(2000)422
1. Efficiency

- **more Ge volume:** \( V_{\text{cluster}} = 1832 \, \text{cm}^3, \Omega = 0.91 \% \)
  \( \varepsilon_{\text{ph}} = 29.2 \%, \varepsilon_a = \varepsilon_{\text{ph}} \times \Omega = 0.265 \% \)

- **add-back procedure:**
  improved efficiency & spectrum quality

  As a consequence of Compton scattering, \( \gamma \)-rays can scatter in adjacent capsules:
  - Full energy peak: \( E_{\gamma}' = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + \ldots \) (add-back)
  - the highest energy is released in the first interaction
  - the \( \gamma \)-ray incident angle \( \theta \) is given by the first interaction (better Doppler correction)

**CLUSTERs add-back scheme**

Add-back is performed among adjacent hits only

Basic idea of future tracking arrays ...
- Gain in efficiency

\[ F = \frac{\text{(summing effects)}}{\text{(add-back factor)}} \]

- Gain in spectrum quality

\[ F = \frac{\text{(# photopeak events)}_{\text{TOTAL}}}{\text{(# photopeak events)}_{\text{SINGLE-HIT}}} \]
2. Doppler broadening

Doppler Effect

\[ E_γ = E_{γ0} \frac{\sqrt{1 - \left(\frac{v}{c}\right)^2}}{1 - \frac{v}{c} \cos θ} \approx E_{γ0} \left(1 + \frac{v}{c} \cos θ_γ\right) \frac{v}{c} \ll 1 \]

Doppler broadening

\[ ΔE_γ = 2E_{γ0} \frac{v}{c} \sin θ_γ \sin Δθ \]

Ge detectors with large opening angle suffer of a considerable energy deterioration

in-beam NORDBALL data: \(^{163}\)Tm

- \(θ=79^0, 101^0\)
- \(θ=37^0, 143^0\)

- \(θ=90^0\)

maximum broadening is reached at \(90^0\)
Composite Detectors: compromise between efficiency & resolution

**Source at rest:**
- intrinsic resolution is reached
- $\varepsilon_a$ decreases with increasing distance $d$ detector-source (smaller $\Omega$)

**Moving Source:**
- effective resolution depends on $d$ (Doppler broadening)

Composite detectors allow to obtain large solid angle without suffering of energy resolution deterioration.

$$\varepsilon_a = \varepsilon_p \frac{\Omega}{4\pi}$$
$$\Omega \approx \frac{\pi R^2}{d^2}$$

$^{30}\text{Si} + ^{124}\text{Sb} \rightarrow ^{149}\text{Gd}$
$E_{\text{beam}}=158\text{MeV}$
$v/c=2.1\%$
3. Polarisation measurements: composite detectors as Compton polarimiters

The E or M character of the $\gamma$-ray can be determined by the polarization $P$

$$P = \frac{I_{\text{vertical}} - I_{\text{horizontal}}}{I_{\text{vertical}} + I_{\text{horizontal}}}$$

$P > 0$ for $E$ and $P < 0$ for $M$.

$^{126}$Ba: EUROBALL data

P.M. Jones et al., NIMA362(1995)556
Large Number of Detectors: Resolving Power

\[
\frac{P}{T} = 0.5 \\
SE_\gamma = 50 \text{ keV} \\
\Delta E_\gamma = 5 \text{ keV}
\]

\[
N_1 = \frac{P}{T} N \\
B_1 = \frac{\Delta E_\gamma}{SE_\gamma} B_{unc}
\]

\[
\frac{N_1}{B_1} = \left(\frac{P}{T} \times \frac{SE_\gamma}{\Delta E_\gamma}\right) \frac{N}{B_{unc}}
\]

\[
N_2 = \frac{P}{T} N_1 = \left(\frac{P}{T}\right)^2 N \\
B_2 = \frac{\Delta E_\gamma}{SE_\gamma} B_1 = \left(\frac{\Delta E_\gamma}{SE_\gamma}\right)^2 B_{unc}
\]

\[
\frac{N_2}{B_2} = \left(\frac{P}{T} \times \frac{SE_\gamma}{\Delta E_\gamma}\right)^2 \frac{N}{B_{unc}}
\]

\[
array capability of identifying weak \gamma cascades out of a large background increases with fold \ F
\]

\[
F = \# measured \gamma's
\]

Resolving power

\[
R_F = \left(\frac{SE_\gamma}{\Delta E_\gamma} \times \frac{P}{T}\right)^F
\]

\[
SE_\gamma = \gamma\text{-ray energy spacing} \\
\Delta E_\gamma = \gamma\text{-ray energy resolution} \\
\frac{P}{T} = \text{Peak-to-total (Compton)} \\
F = \text{Measured fold}
\]

\[
< F > = P_{ph} M_\gamma
\]

\[
N_{Ge} \Omega \epsilon_{ph} P_i = \text{Total photopeak efficiency}
\]
Approximate selection of **angular momentum** is achieved by selecting the **fold** number.

**ARRAY Trigger**: high folds events of “clean” or “dirty” Ge (with or without Compton suppression)
NORDBALL DATA: $^{143}$Eu SD band $^{37}$Cl+$^{110}$Pd, $E_{\text{beam}} = 160$MeV

**Observation Limit**

**TOTAL spectrum**

**Single gated**

**Double gated**

**Triple gated**

**Compton-Suppression - HPGe**

**Small Arrays**

**G-M Absorbers**

**NaI**

**Gamma-Ray Spectroscopy**

**Backbending Coriolis Effects**
Evolution of High-Spin $\gamma$-ray Spectroscopy in $^{156}$Dy

Light ions
scintillators detectors

1963
Morinaga & Gugelot
($\alpha$, 4n)
NaI(Tl)

1973
Ryde et al.
($\alpha$, 4n)
2xGe(Li)

1978
Ward et al.
($^{12}$C, 5n)
2xGe(Li)

1988
Riley et al.
($^{36}$S, 4n)
TESSA 2

Light ions
Ge detectors: 1 $\gamma$

Heavy Ions
Ge detectors: 1 $\gamma$

Heavy Ions
Ge detectors: $\geq 2$ $\gamma$

Heavy Ions
Ge detectors: $\geq 3$ $\gamma$

1998
Kondev et al.
($^{36}$S, 4n)
GAMMASPHERE
Ancillary Detectors for Ge Arrays (EUROBALL/AGATA)

- **HECTOR**: high-energy $\gamma$-rays
- **Innerball**: calorimeter
- **Diamant**: charged particles
- **MiniOrange**: conversion electrons
- **Neutron wall**: n identification
- **Recoil filter**: evaporation residua
- **Saphir**: fission fragments

see next lectures ...