Germanium detectors for gamma-ray detection

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Warsaw, March 4th, 2013

Why do we need to detect γ-rays?

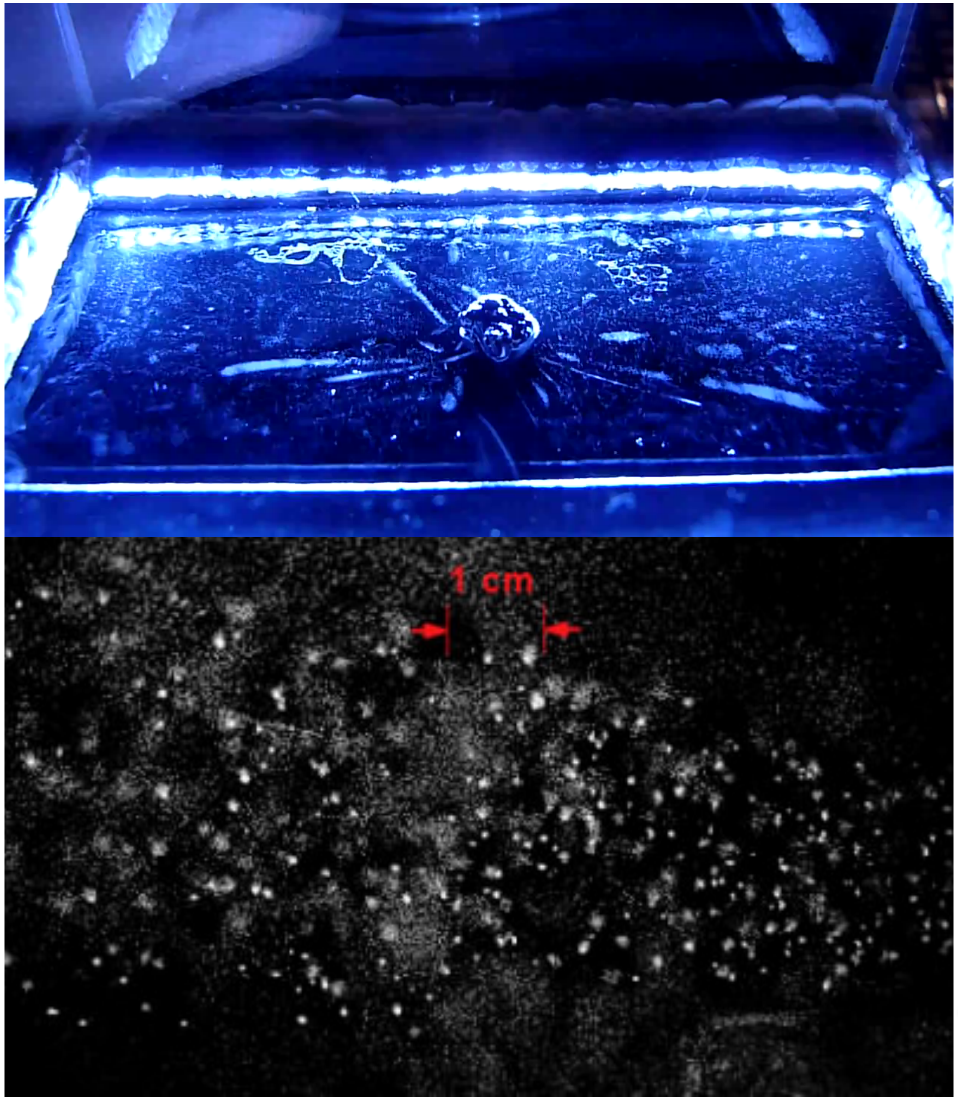
- Gamma spectroscopy = identification and/or quantification of radionuclides by analysis of the gamma-ray energy spectrum
- Some examples:
  - Environmental Radioactivity Monitoring
  - Health Physics Personnel Monitoring
  - Reactor Corrosion Monitoring
  - Nuclear Materials Safeguards and Homeland Security
  - Forensics and Nuclear Forensics
  - Materials Testing
  - Geology and Mineralogy
  - Nuclear Medicine and Radiopharmaceuticals
  - Industrial Process Monitoring
  - **Nuclear Structure**

What is measured?

Interactions in a cloud chamber

Uranium (~ 5MeV alphas)

5.9keV photons from ^{55}Fe



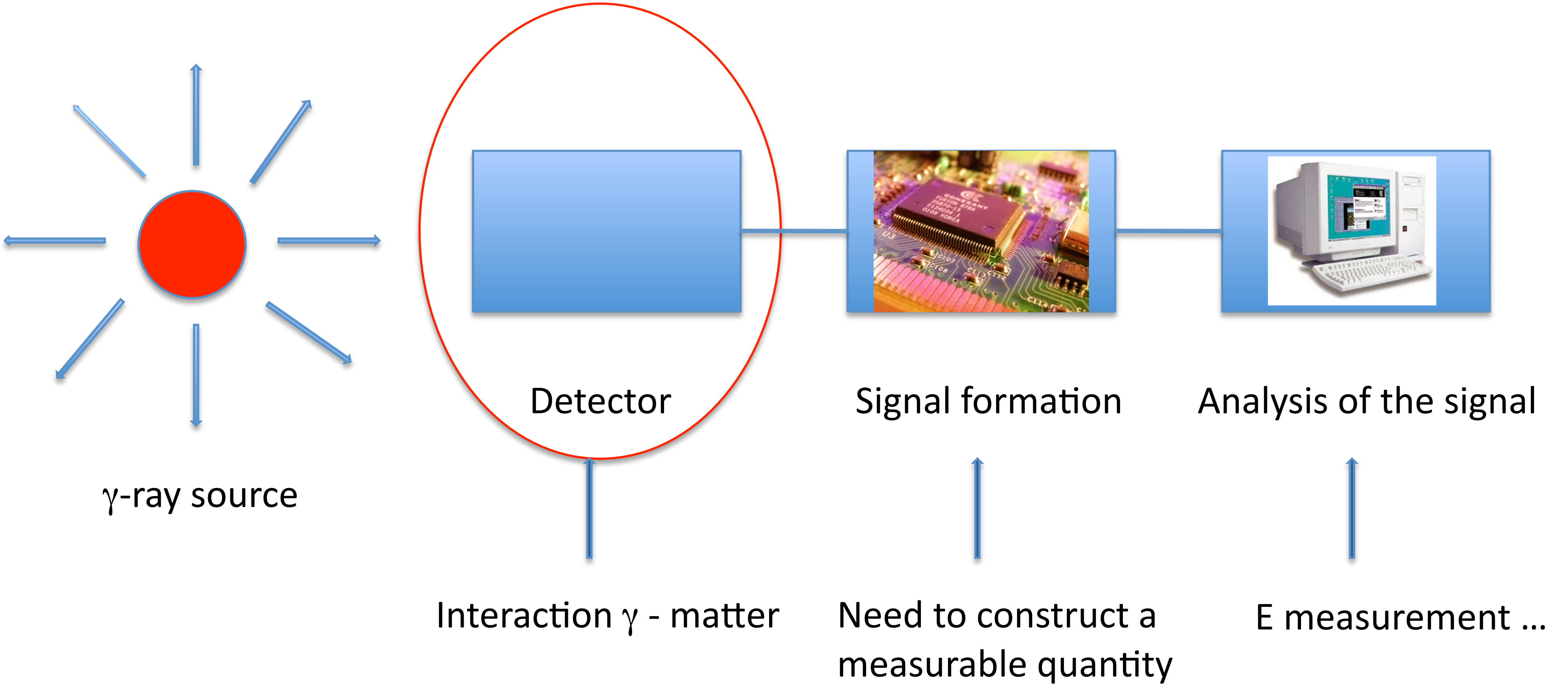
- Gamma rays are much more penetrating than charged particles with comparable energy.
- A beam of photons is **not** degraded in energy, while passing through matter, only attenuated in intensity.
- Attenuation:

$$I(x) = I_0 \exp(-\mu x)$$

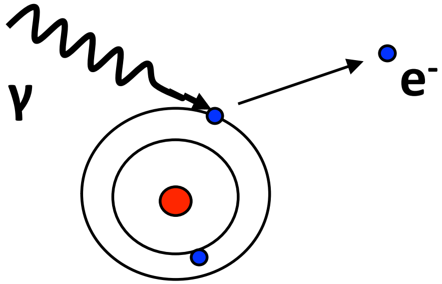
with: I_0 incident beam intensity,
x thickness of absorber,
μ absorption coefficient.

→ Measure the **intensity** of the γ-rays beam

How can we detect the intensity of γ-rays?



γ-ray interaction with matter - 1



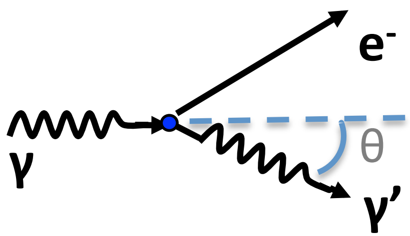
- Photoelectric Effect

absorption of photon by an atomic electron with the subsequent ejection of the photoelectron with energy:

$E = h \cdot \nu$ – binding energy of the electron

Origin of the e: K shell of the atom

Best detection effect as the E is totally transferred to the e!



- Compton Scattering

(incoherent) Elastic scattering of a photon on an electron

Ejection of 1 photon and 1 electron

The E (of γ and e) depends on the angle θ:

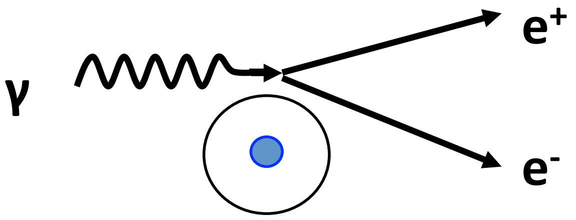
$h\nu' = \frac{h\nu}{1+\alpha(1-\cos\theta)}$ with $\alpha = \frac{h\nu}{m_0c^2}$ and $E_e = h\nu\left(\frac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)}\right)$

$\theta = 0 \Rightarrow h\nu' = h\nu \quad E_e = 0$

$\theta = 180° \Rightarrow h\nu' = \frac{h\nu}{1+2\alpha} \quad E_e = h\nu\frac{2\alpha}{1+2\alpha}$

Background in the spectra due to E ≠ Eγ !

γ-ray interaction with matter - 2

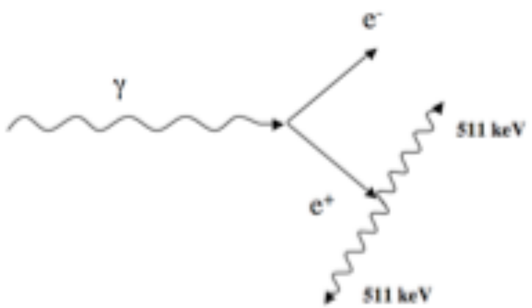


- Pair Production **when E γ > 1022 keV**

Creation of one pair (e+/e-)

The pair shares the energy $E = h\nu - 2 \cdot m_e c^2$

($m_e c^2 =$ Electron rest mass = 511 keV)

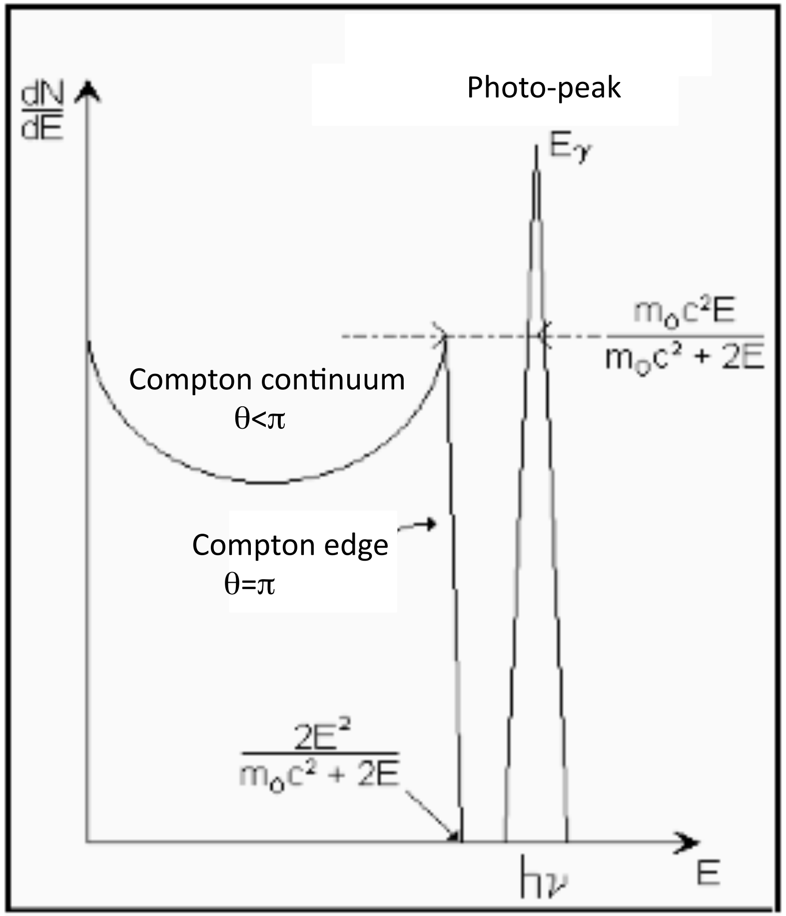


and is followed by positron annihilation: 2 x 511 keV photons emitted back to back.

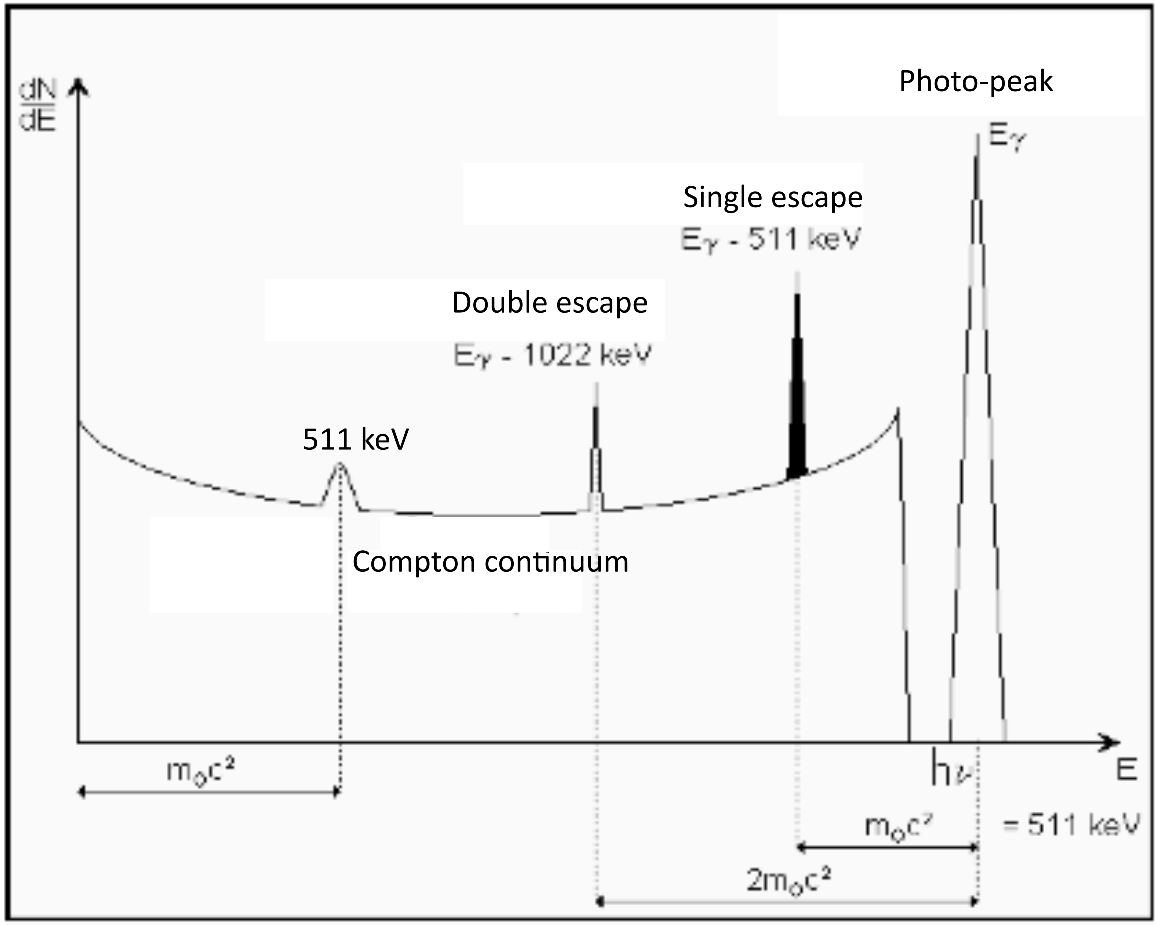
Annihilation photon can escape from detector without interacting with matter

Peaks: Eγ - 511 keV (1x511 keV) single escape
Eγ - 1022 keV (2 x 511 keV) double escape

Theoretical spectra

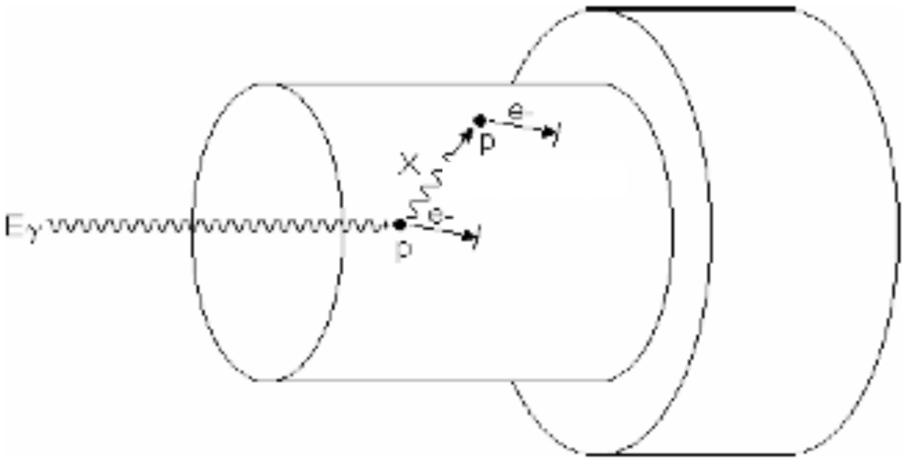


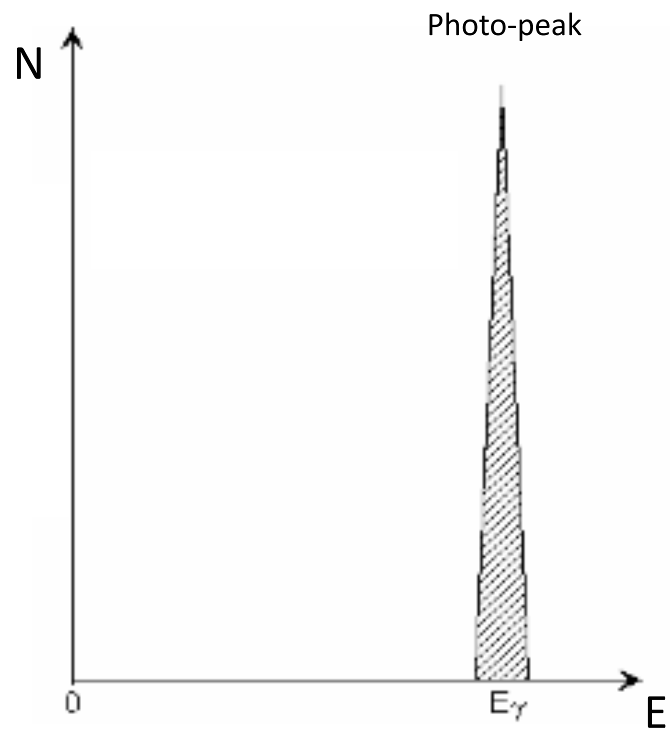
hν < 1.022 MeV



hν > 1.022 MeV

Spectrum from photoelectric effect

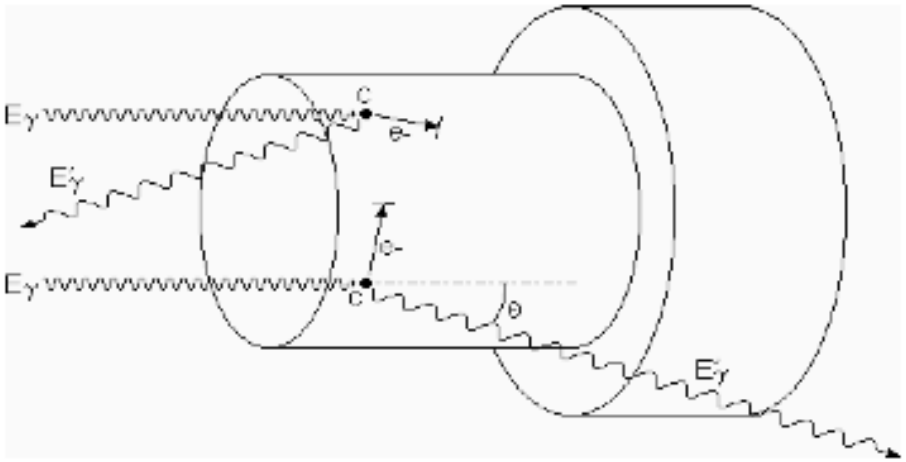


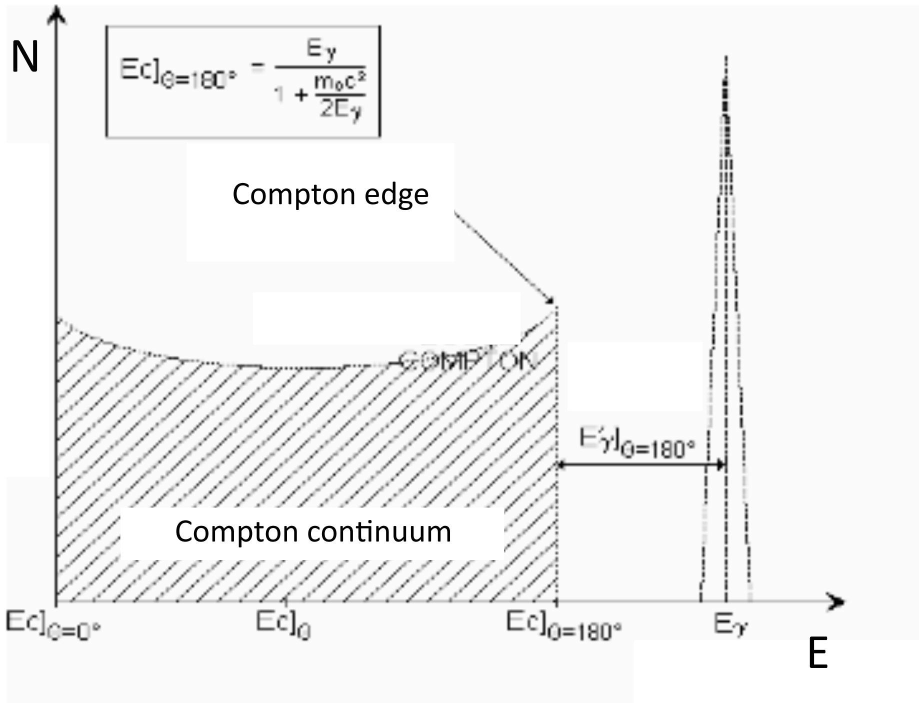


+ : Give a photo-peak – the E of this peak = Eγ

→ Detector point of view: favour this effect

Spectrum from Compton effect

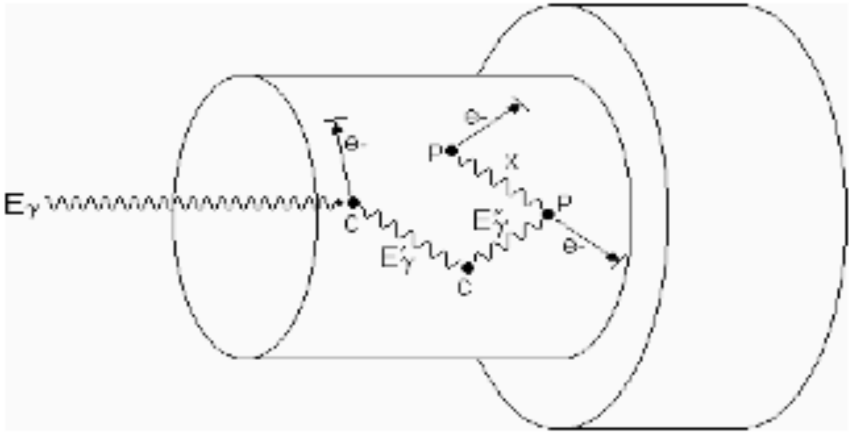


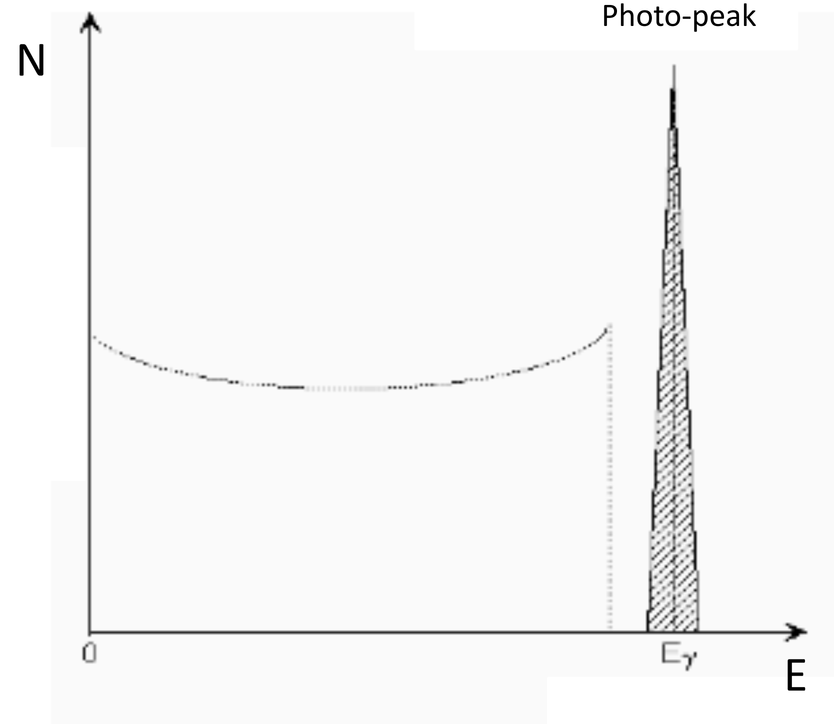


- : Give background – no information on the Eγ

→ Detector point of view: find a way to reduce the background

Several Compton effects leading to a totale absorption of the incident energy

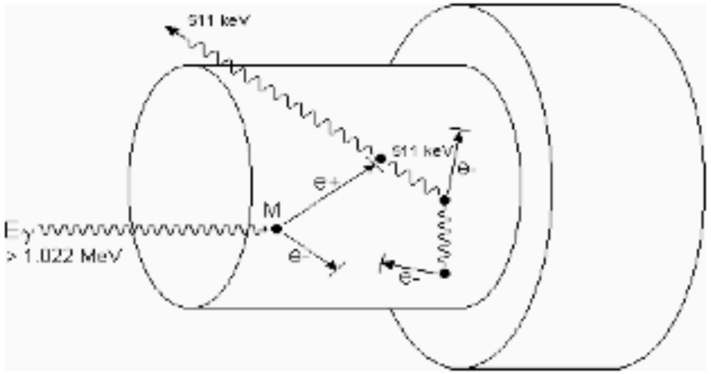


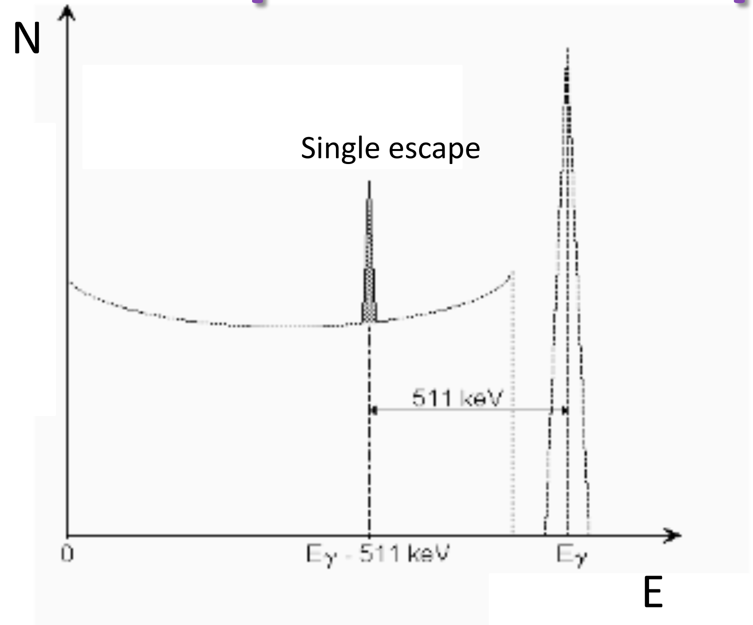


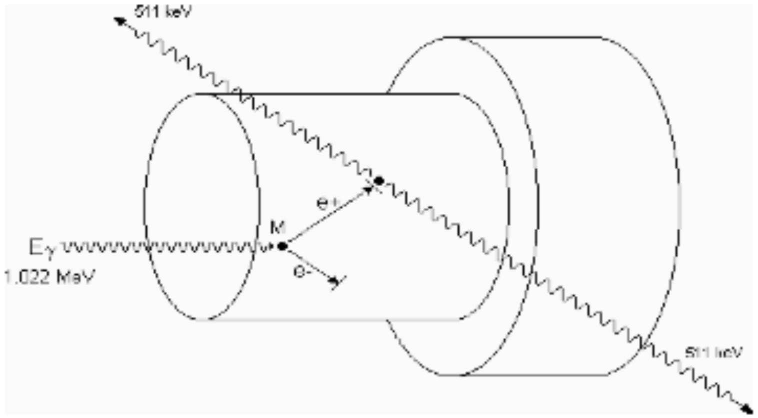
+ : Give a photo-peak – the E of this peak = Eγ

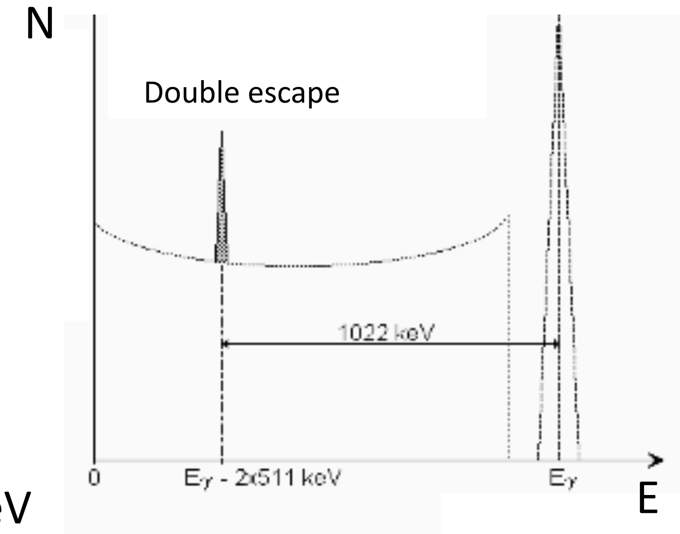
→ Detector point of view: need large detector to have a totale absorption

Spectra with 1 or 2 annihilation photons escape



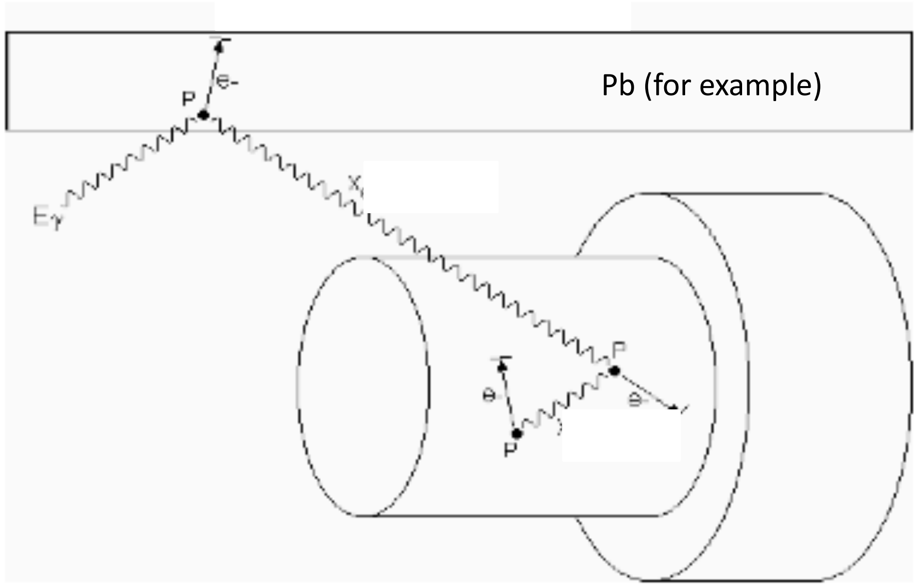


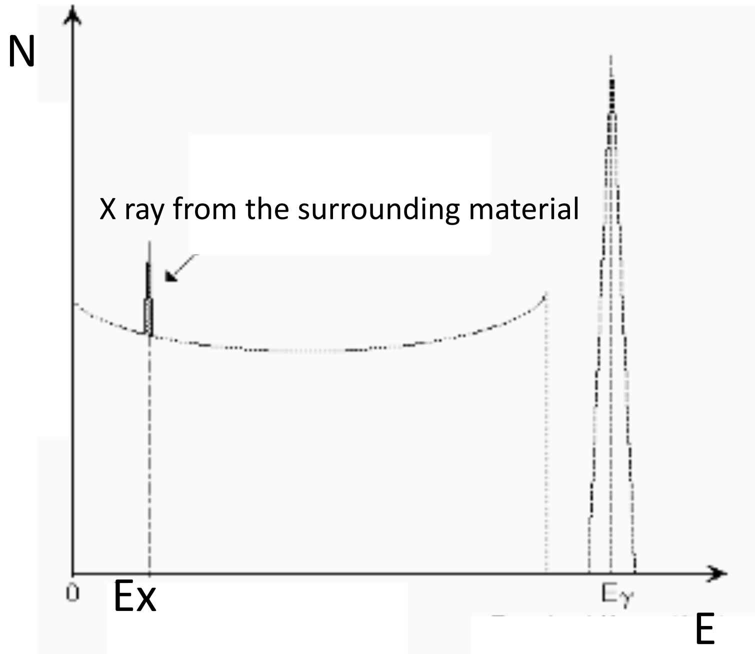




- : Give peaks at Eγ − 511 keV or Eγ − 1022 keV

X rays from the surrounding material

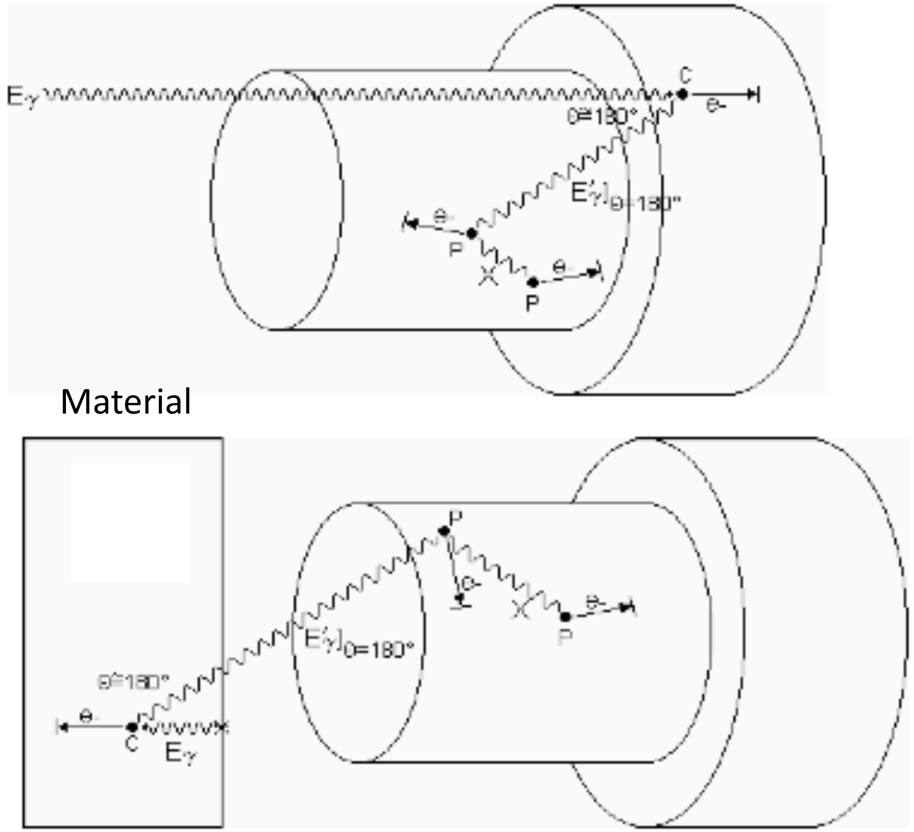


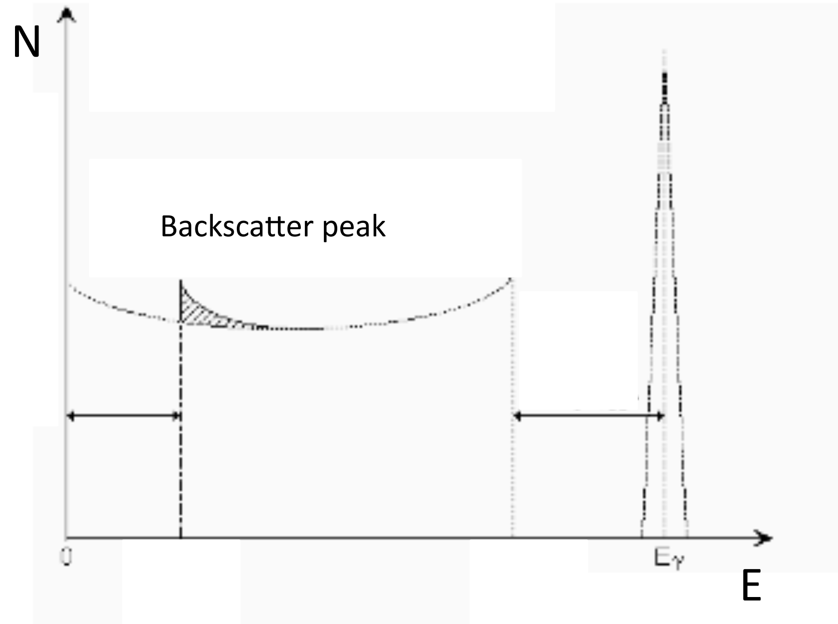


- : no information on Eγ

→ Detector point of view: reduce the surrounding material

Backscattered photon

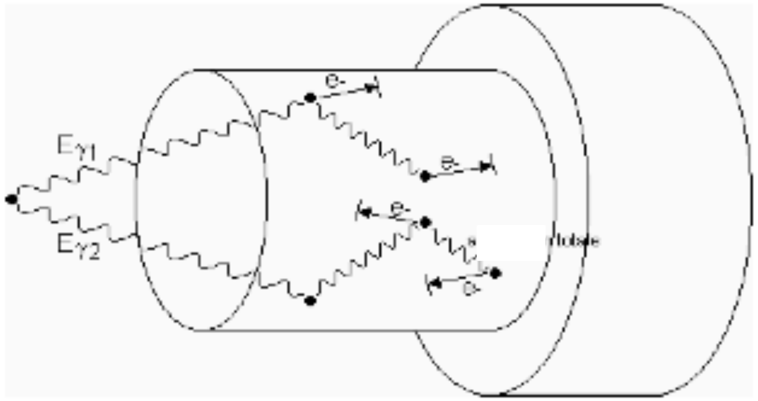


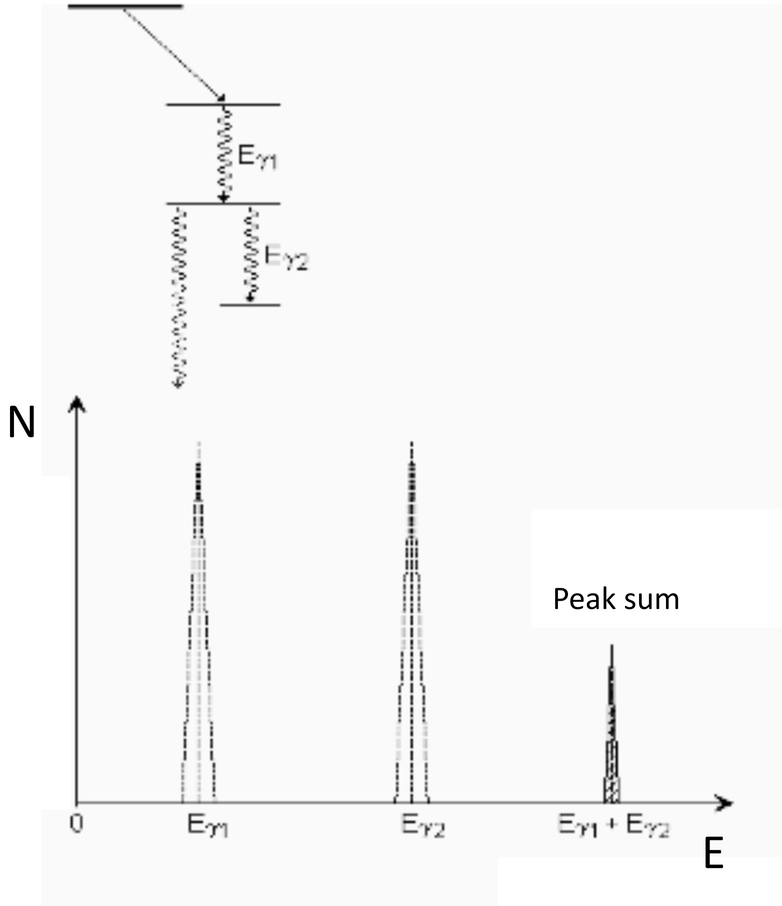


- : no information on Eγ

→ Detector point of view: reduce the surrounding material

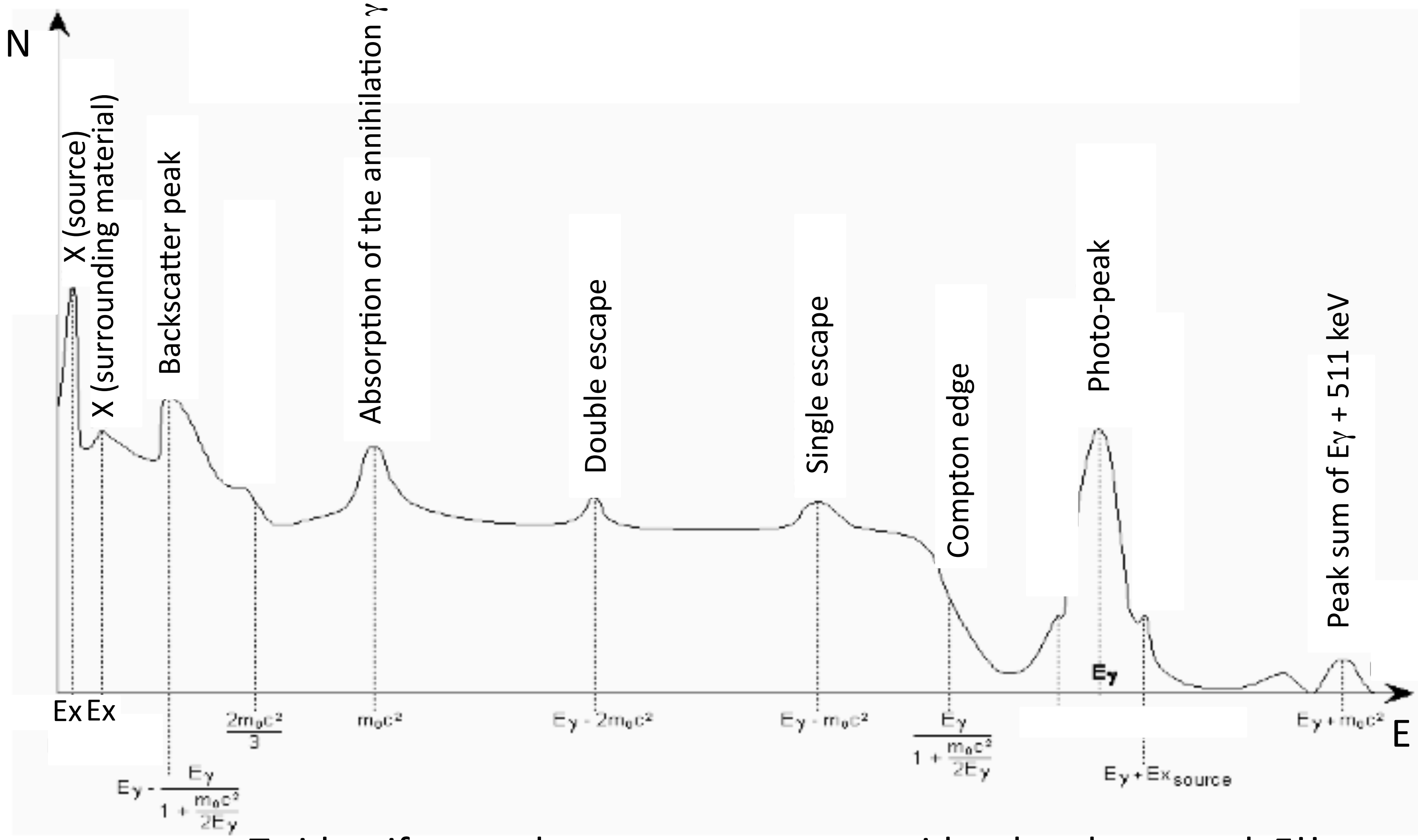
Sum of γ-ray energies





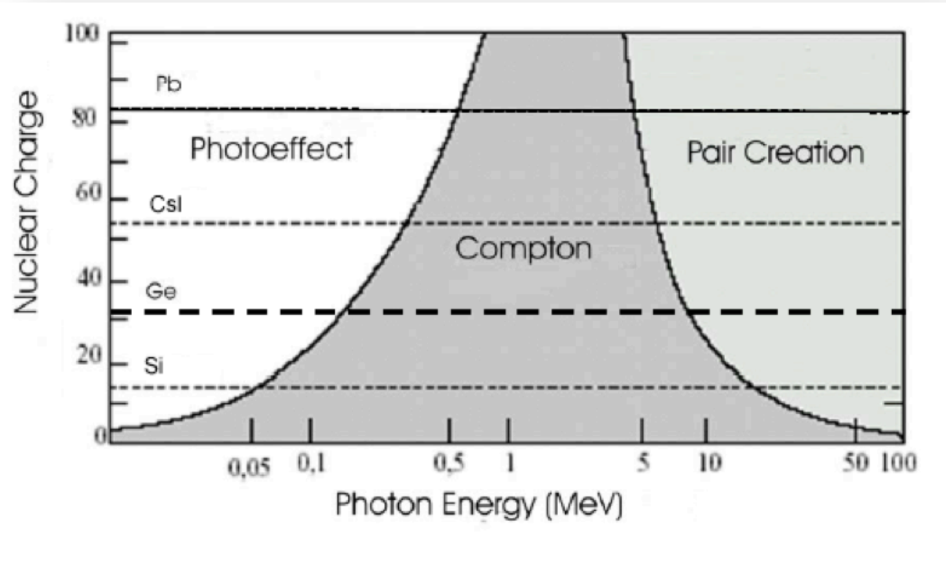
- : Give peaks at $E\gamma_1 + E\gamma_2$

Final spectrum for 1 given energy



→ To identify an unknown spectrum, consider the photo-peak E!!

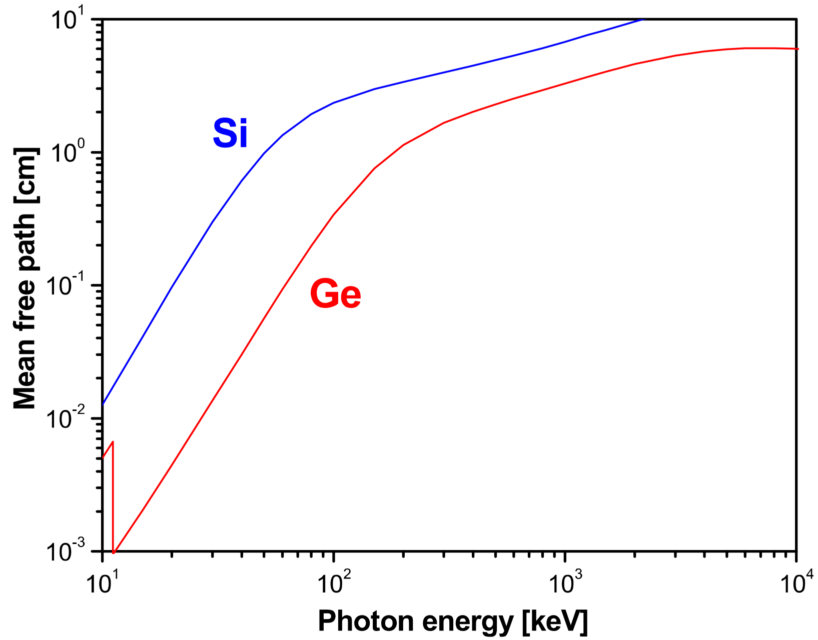
γ-ray interaction with matter - 3



Photoeffect : $\sigma \sim Z^{4\text{-}5}$

Compton : $\sigma \sim Z$ → Detector material with high Z

Pair creation : $\sigma \sim Z^{2}$

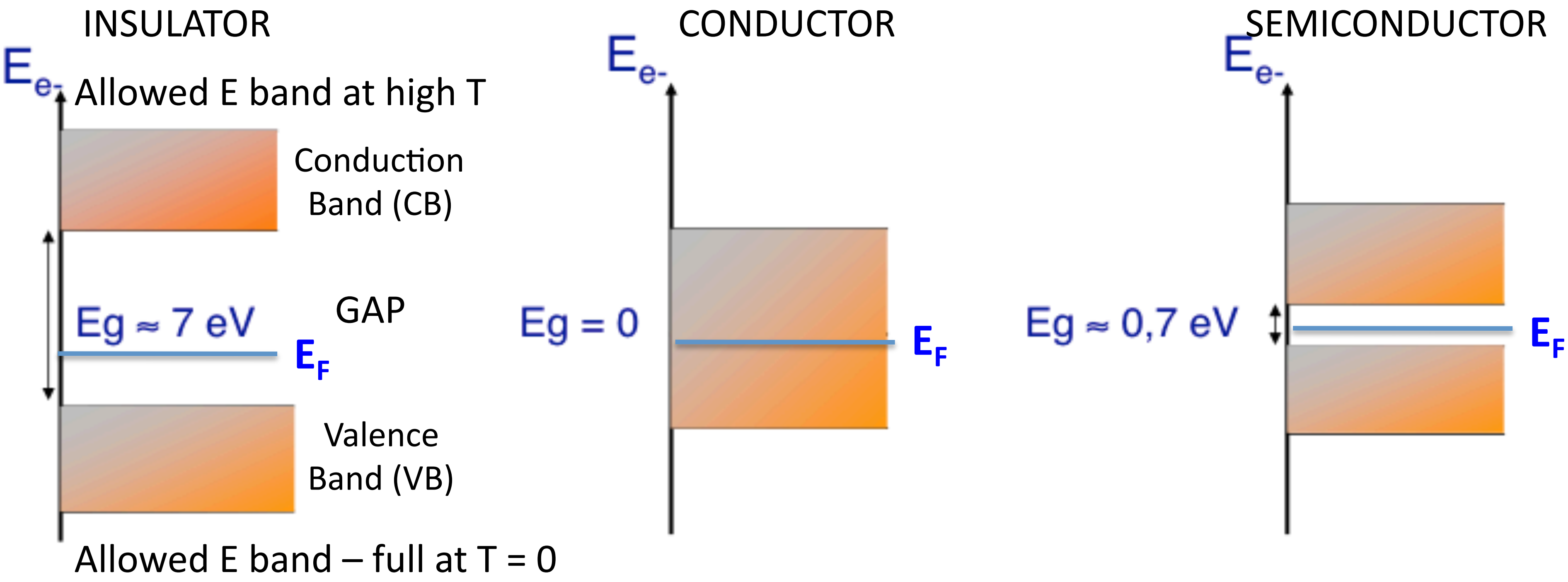


Mean free path in Ge for a γ of 1 MeV is 2 cm!

→ **Large detector with high Z material**: to favour the photoeffect, to absorb totally the γ after several compton scattering, but probability that γ escape is high

→ What type of detector is used?

Semiconductor properties



Thermal energy shared by the electrons in the crystal → electron: from the VB to the CB

→ electron (CB – q<0) – hole (VB – q>0) pair created

	Ge (eV)	Si (eV)
E per e-h pair (300 K)	-	3.62
E per e-h pair (77 K)	2.96	3.76

Good resolution!

Mobility of the charge carriers

Mobility of the charges in a crystal due to: thermal energy + the applied electric field

Velocity = mobility x electric field

Temperature	Charge	Mobility (cm2/V.s) in Si / Ge
300 K	electrons holes	1350 / 3900 480 / 1900
77 K	electrons holes	21000 / 36000 11000 / 42000

Typical time with a voltage of 100 V on a semiconductor of 0.1 cm: 10 ns

→ Not as good as scintillator time response

Impurities and dopants

Intrinsic semiconductors

Electrons in the CB and holes in the VB **only** by thermal excitation or γ-ray

Number of electrons (n) = number of holes (p)

Hyper pur semiconductor

Extrinsic semiconductors

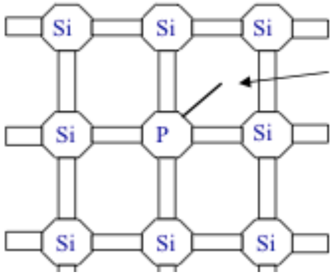
Hyper pur + small concentration of impurity:

n-type semiconductors	**p-type semiconductors**
Pentavalent impurity: **P**	Trivalent impurity: **B**
1 extra electron	1 extra « hole » (not same E)
Donor impurity	Acceptor impurity
Little E to dislodge & form a conduction electron	Little E to fill these sites with e & form h in the VB
Recombinaison important	Recombinaison with e from CB
e = majority carrier	h = majority carrier
e dominate conductivity	h dominate conductivity

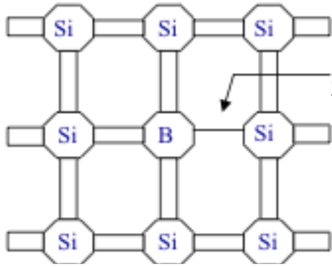
conductivity (or resistivity (inverse)) = mobility x nb free charge

Doped semiconductors

e dominate
the conductivity

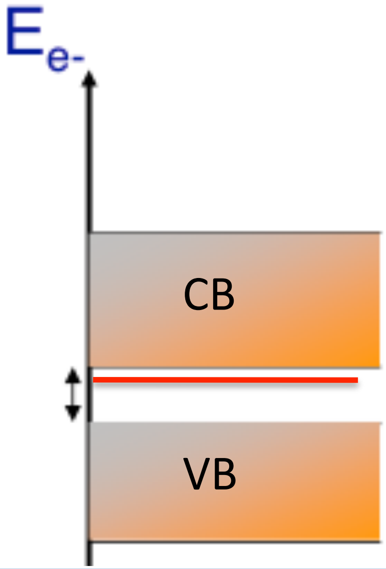


Donor
electron

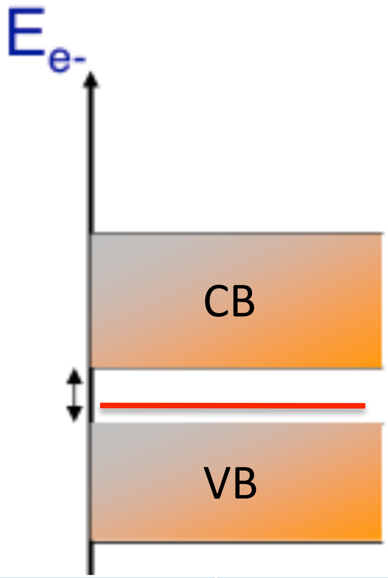


Acceptor site

h dominate
the conductivity



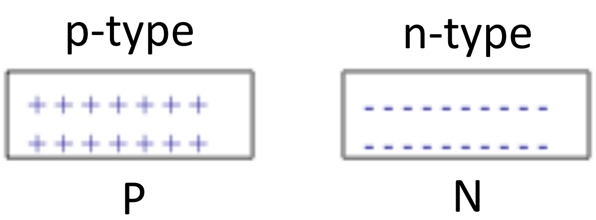
Donor level



Acceptor level

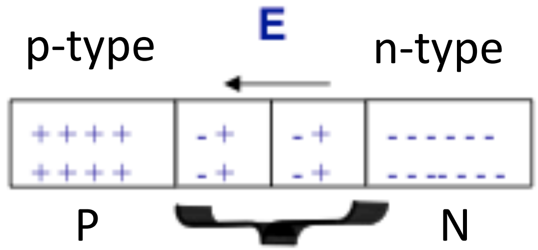
	Si	Ge
Densities for intrinsic hole or electron at 300 K (cm^{-3})	1.5×10^{10}	2.4×10^{13}
Number of atoms/cm^3 (Impurity in HPGe : 10^{10} atoms/cm^3)	4.96×10^{22}	4.41×10^{22}

The NP semiconductor junction



e diffusion from N to P → P with extra e

h diffusion from P to N → N with extra h

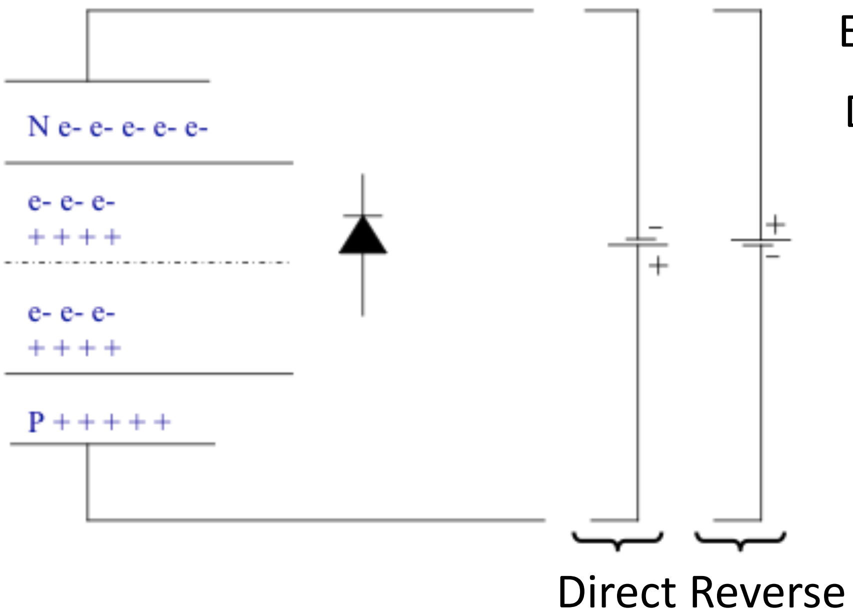


→ E field created – limits the diffusion

Depletion zone (no free charges)

= sensitive volume

+ external voltage:



E not intense enough for charge collection → bias

Direct: depletion zone is thiner - large current due to majority carriers

Reverse: low inverse current due to minority carriers

h towards p contact
e towards n contact
→ Increase the depletion zone
Increase the sensitive volume

No mobility of the majority carrier

More efficient charge collection due to γ-rays

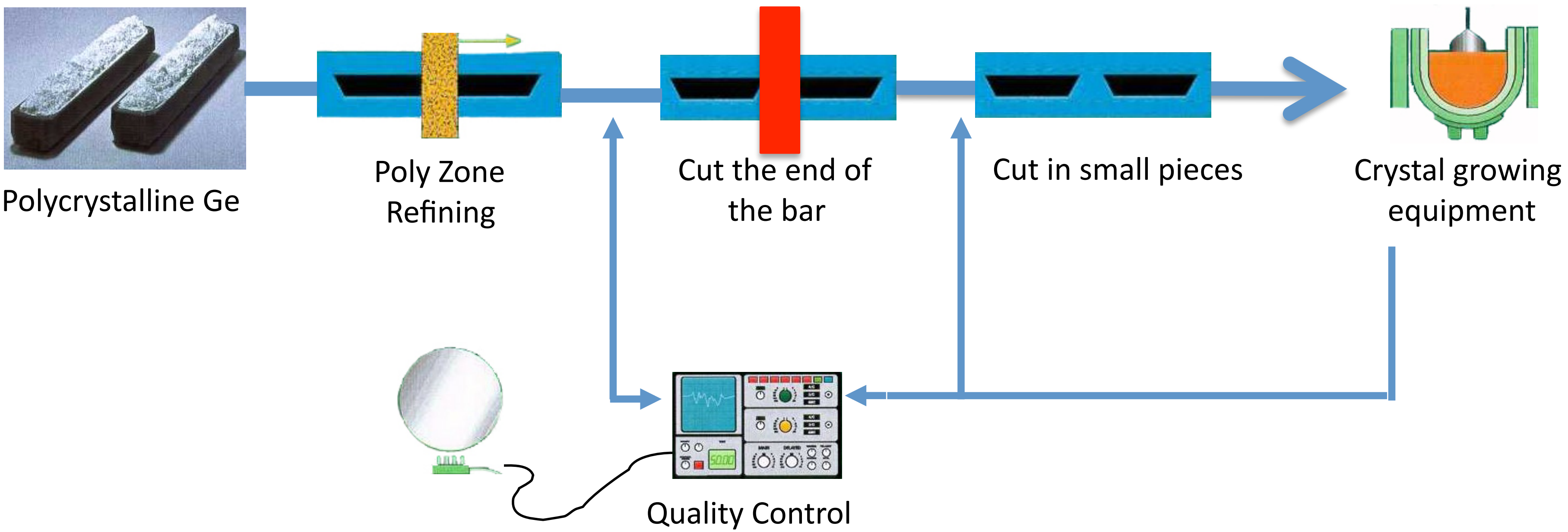
Ge crystal growth

Principle: Impurities concentrate in the liquid phase when freezing – Ge bar is melt step by step

Impurities at 1 end of the bar

Reduction by a factor 100 the impurity concentration

The purest bulk material in the world: 99,99999999999 % (13N) Ge



Czochralski technique

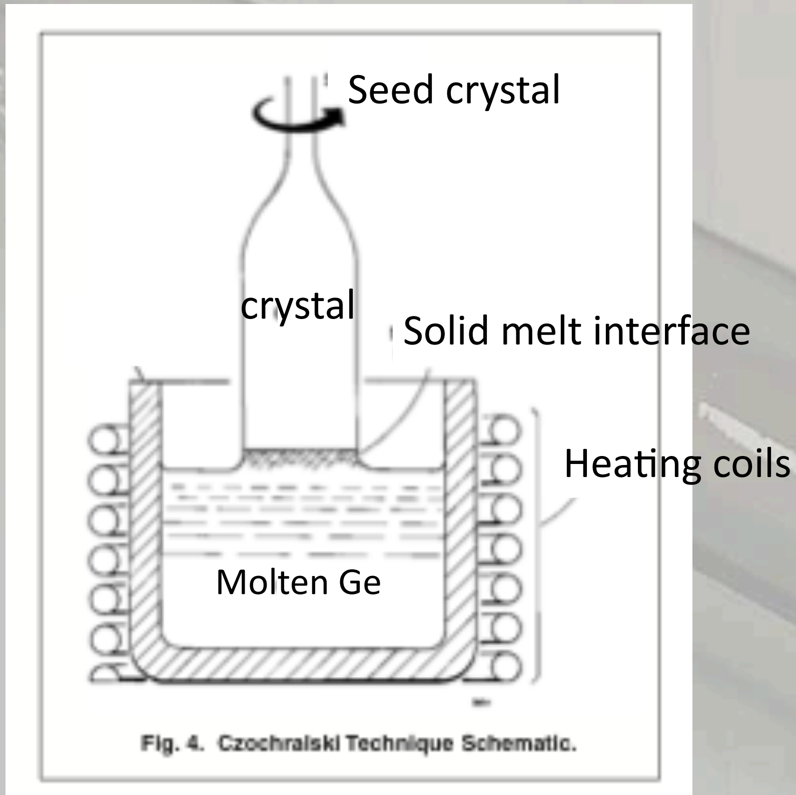
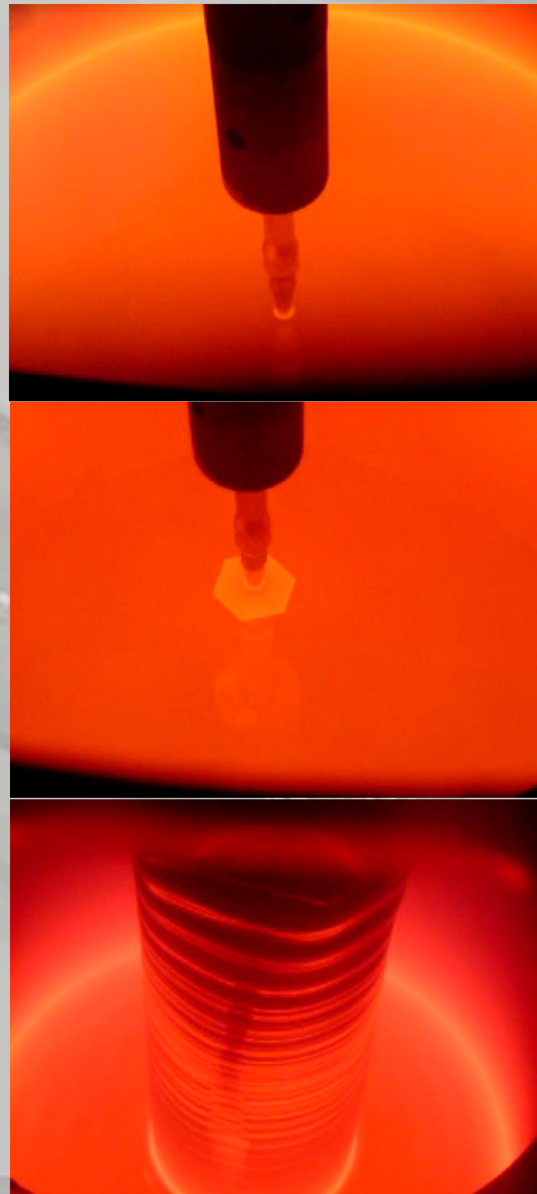


Fig. 4. Czochralski Technique Schematic.



HPGe detector types

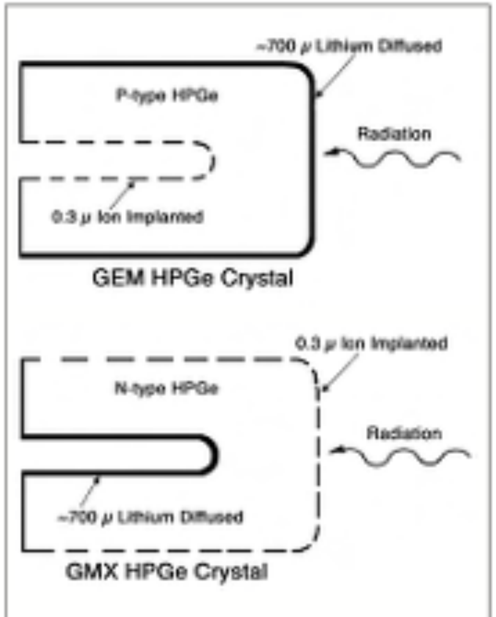
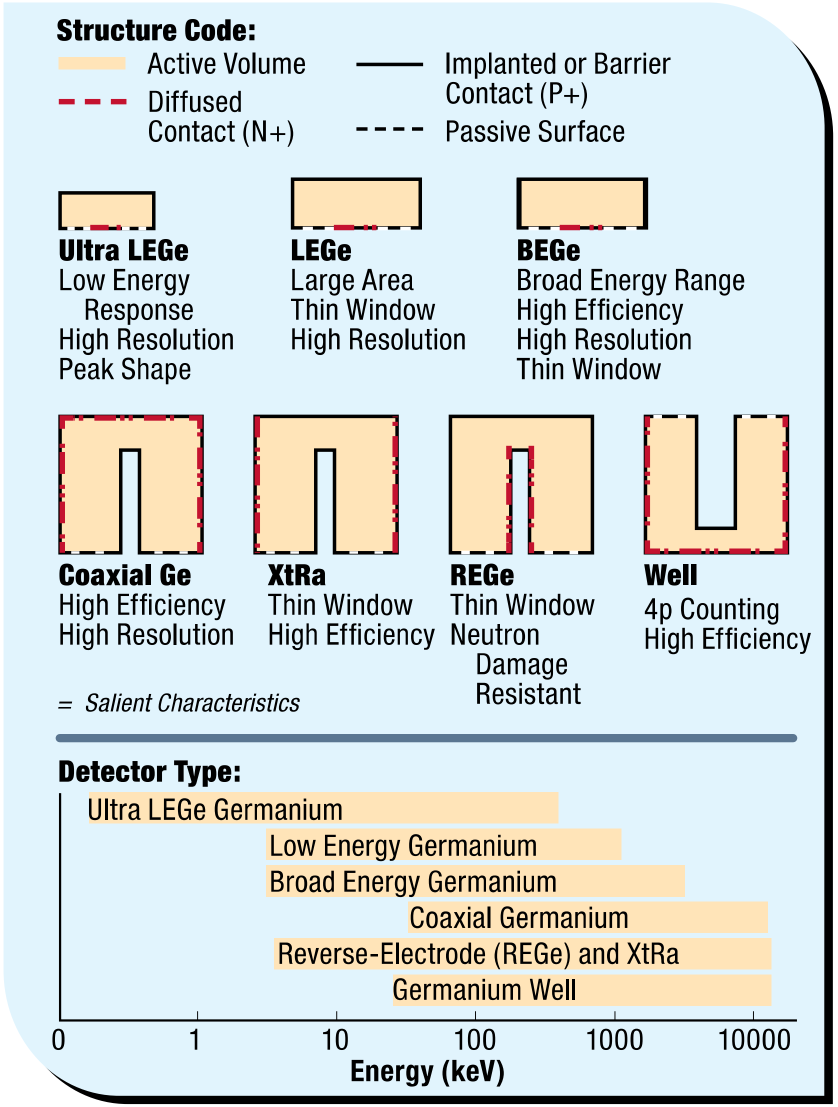


Fig. 8. Schematic of Both P-Type and N-Type Coaxial Detectors.

To collect the charges:

Heavily doped layer:

Li diffusion for n+
B implantation for p+

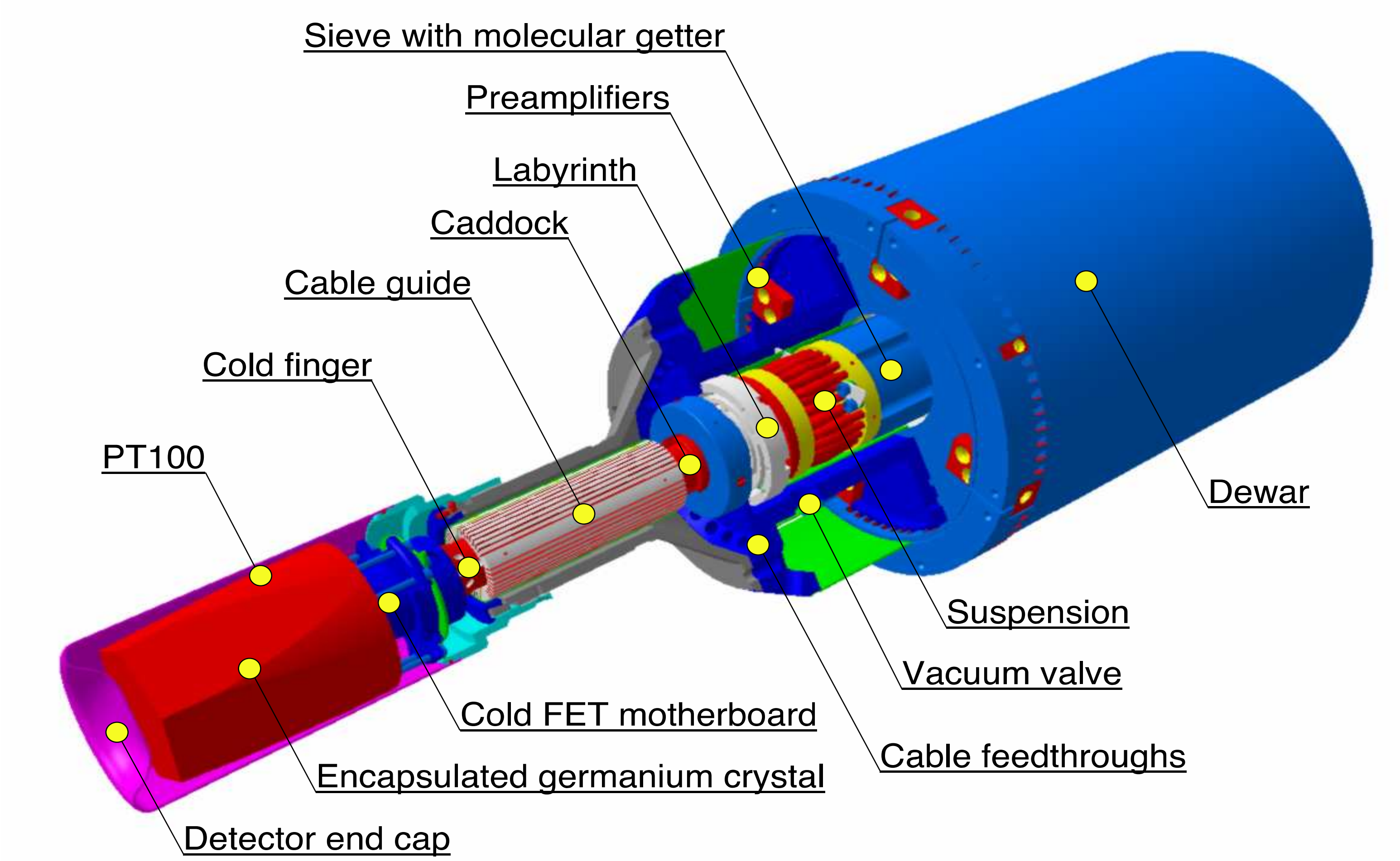


- Planar or Coaxial
- P-type or N-type
- Canberra or Ortec

- Common (for us) = Coaxial N-type HPGe
  + Largest energy range (OK below 10 keV due to thin implanted contact)
  + More resistant to neutron damage

A single detector (Miniball) cryostat

Why? To reduce the large thermally induced leakage current due to the small bandgap



What is needed?

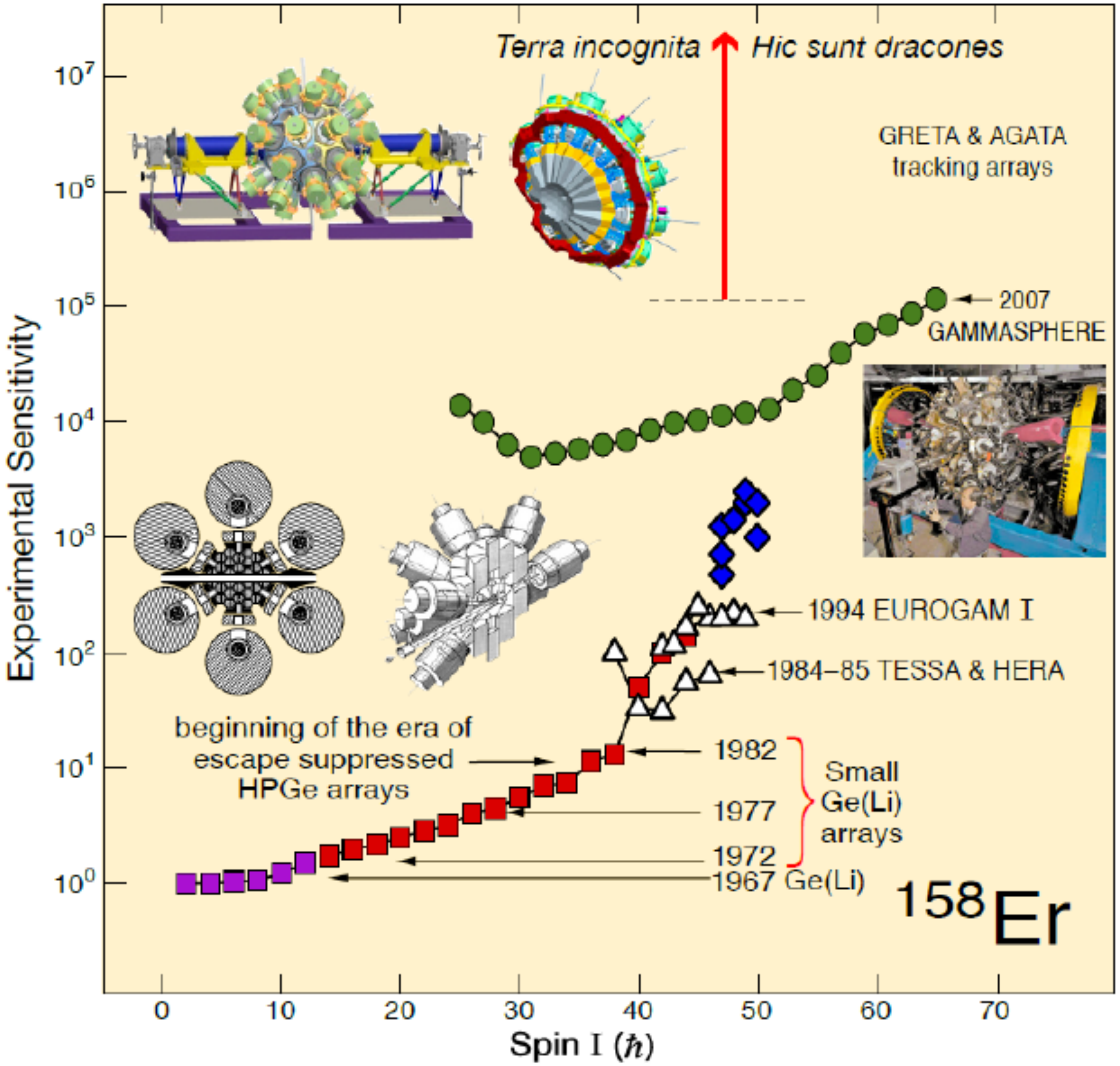
- A sufficient active volume to absorb 'totally' the γ-ray
- A high mobility of the charges to decrease the collection time (10^{-7} – 10^{-8} s)
- A sufficient lifetime of the charges to be able to collect them

  Lifetime of charge carriers before recombination: 10^{-5}s

  Dominated by the impurity level

- A high resistivity to be able to apply a voltage that allow us to collect rapidly the charges
- A depth of the depletion zone bigger than the distance of the charges to be collected

The history of the Ge detectors



Good E resolution
(2 keV @ 1.3 MeV)

Large volume

Time resolution: OK

Efficiency: OK but..

Development of high purity Ge at LBNL, Ortec, Umicore

ERDA NEWS September 19, 1977

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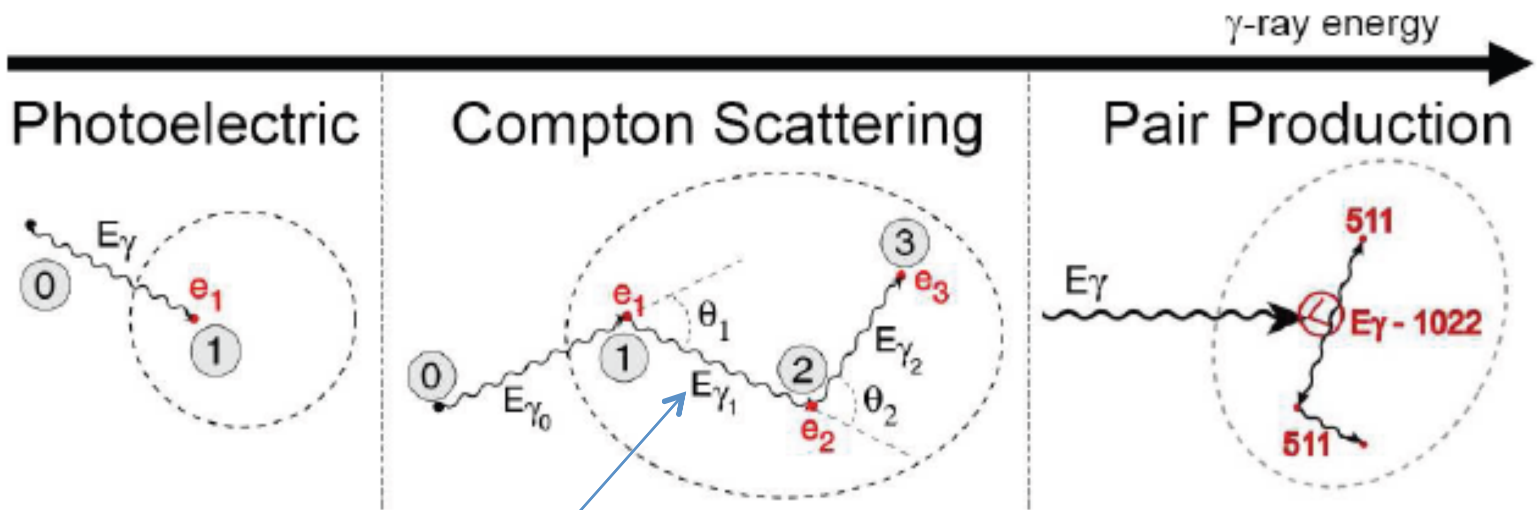
PURE AND COSTLY—Lawrence Berkeley Lab scientists (l-r) William Hansen, Eugene Haller and Scott Hubbard gaze at a germanium crystal worth about $15,000. Purified germanium has scientific applications in archeological dating, geological and chemical analysis, nuclear chemistry, physics and medicine. (LBL Photo)

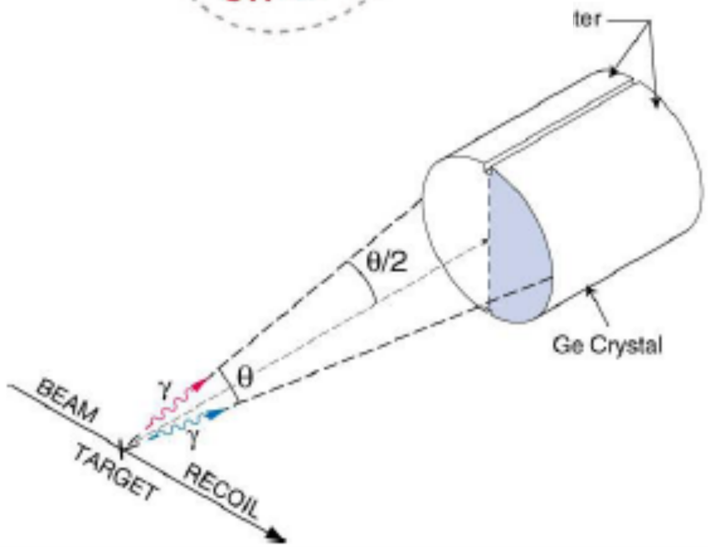
→ Production of Ge(Li) detectors was abandoned after 1978 when HPGe detectors became commercially available

Some problems to be solved?

- ❑ In nuclear spectroscopy, we aim to detect γ-rays with energies from few 10 keV to few MeV

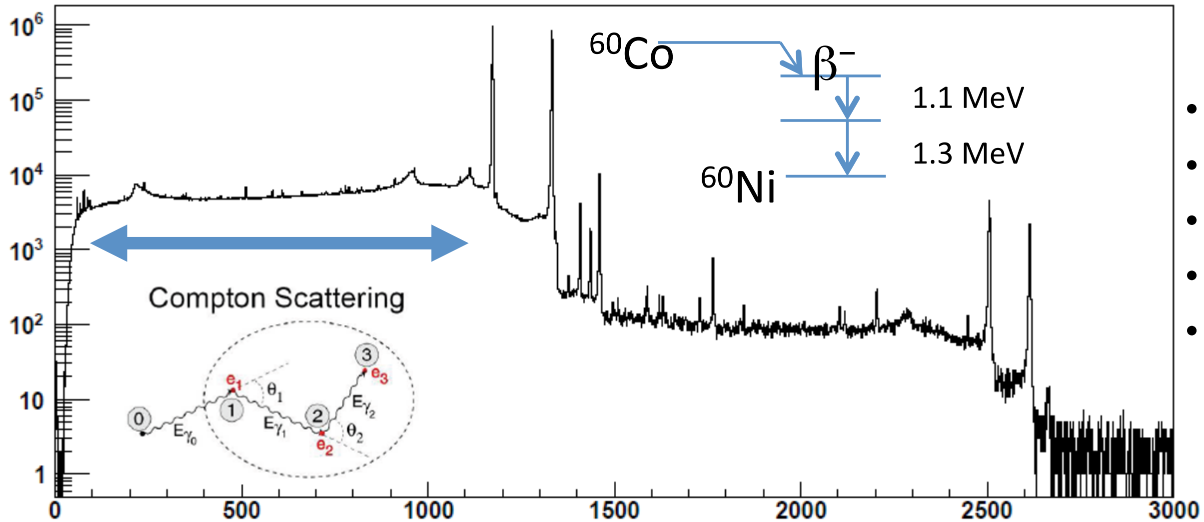


Mean free path *~ 2 cm*

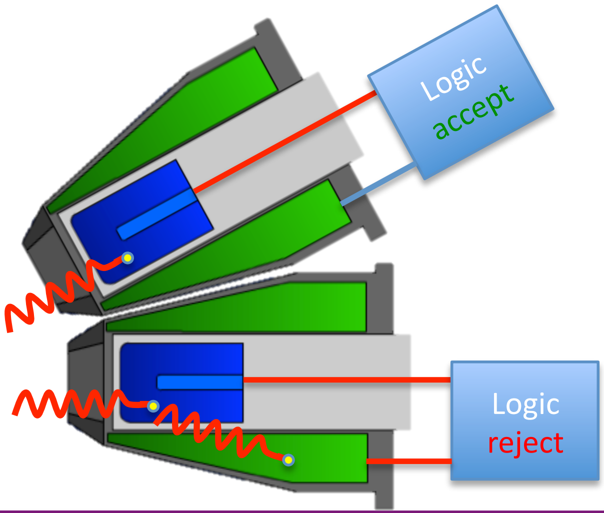


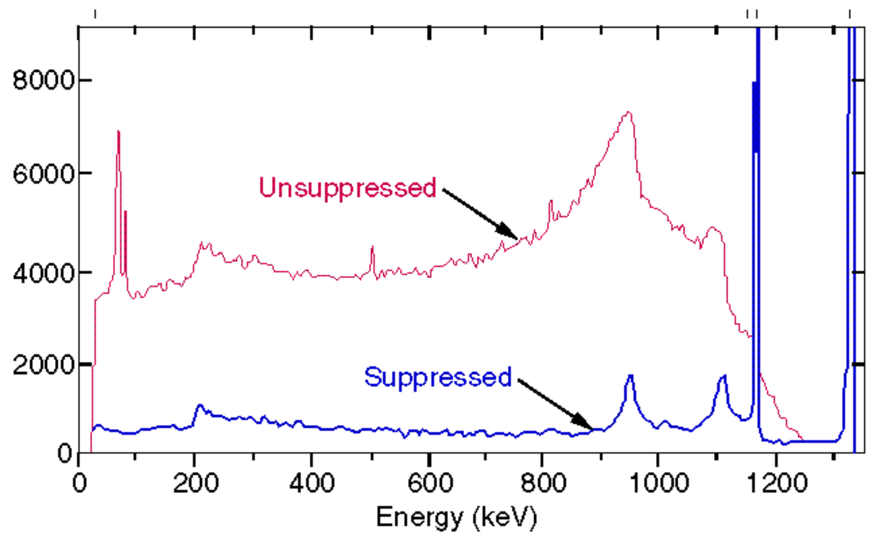
- ❑ And dealing with fast emitters (β ~ 10-50%) :
  →Doppler shift

The scattering problem

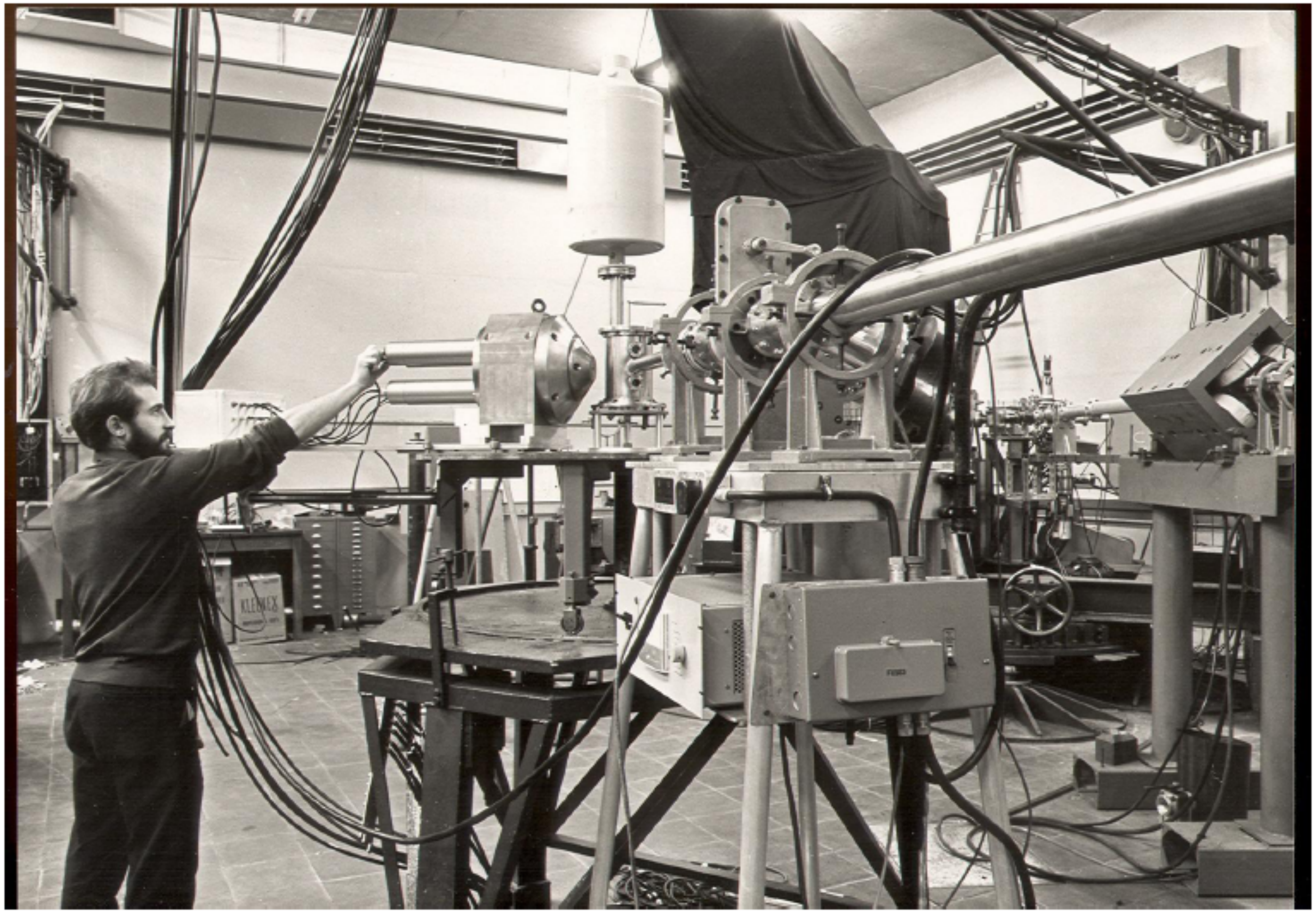


- Reduce background
- Reject events with compton event signature
- Need to have suppression shield around Ge
- Use fast, high efficiency detectors, high Z:
- NaI - BGO scintillators





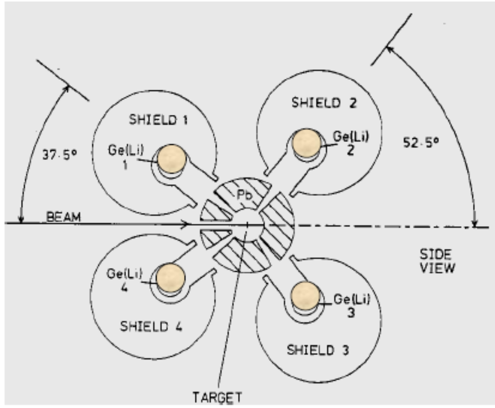
The First Escape Suppressed Spectrometer at Liverpool



John Francis Sharpey-Schafer 1968

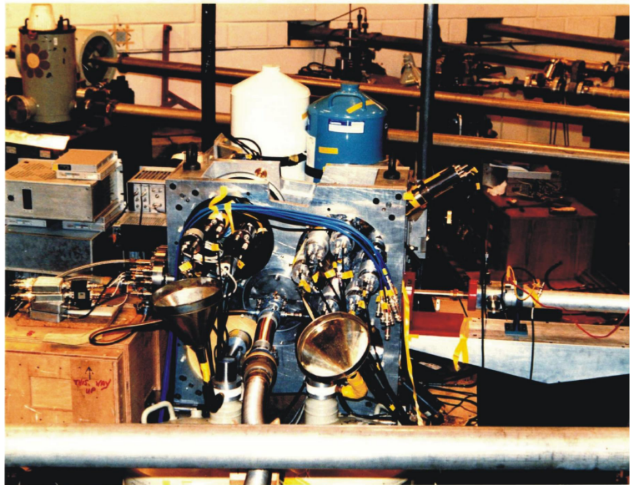
Arrays of escape suppressed spectrometers

TESSA0 The Escape Suppressed Spectrometer Array

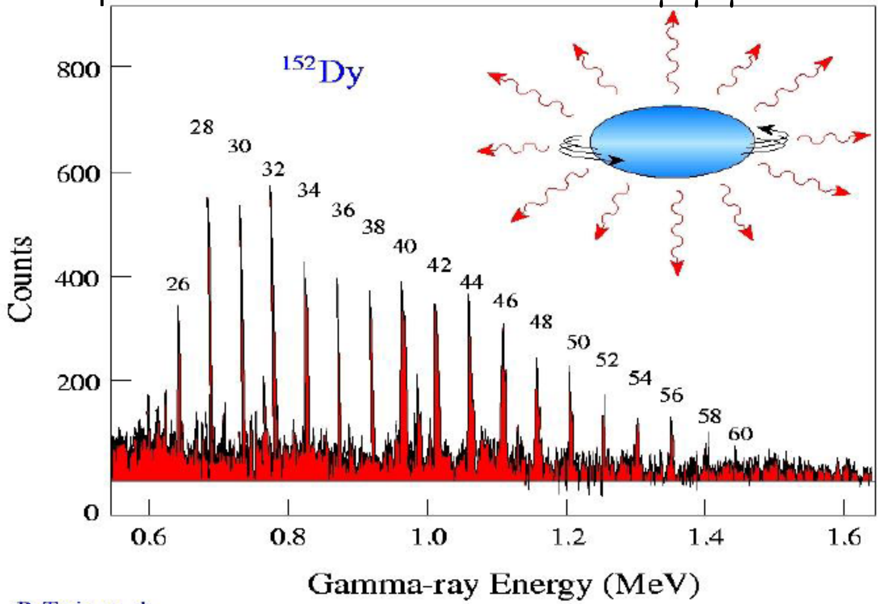


~1980-1982 TESSA

5 Ge(Li) + 5 NaI(Tl) as suppression shields

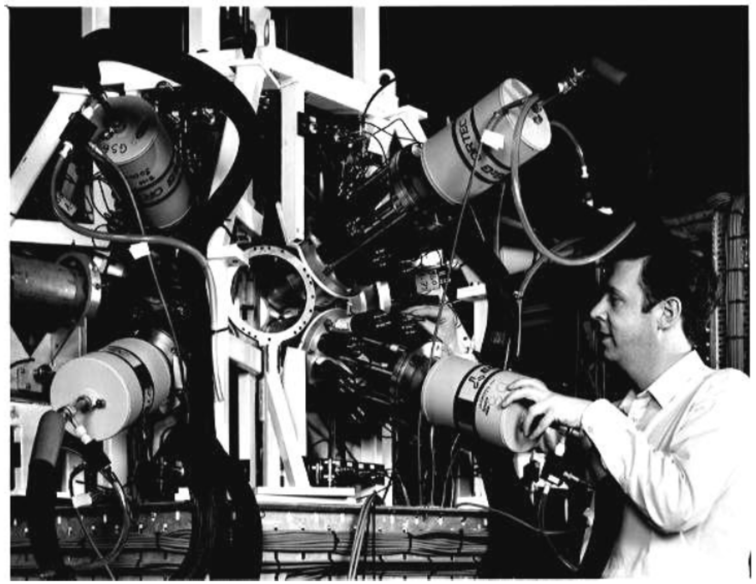


Super-deformed rotational band with γ–γ–γ coincidences

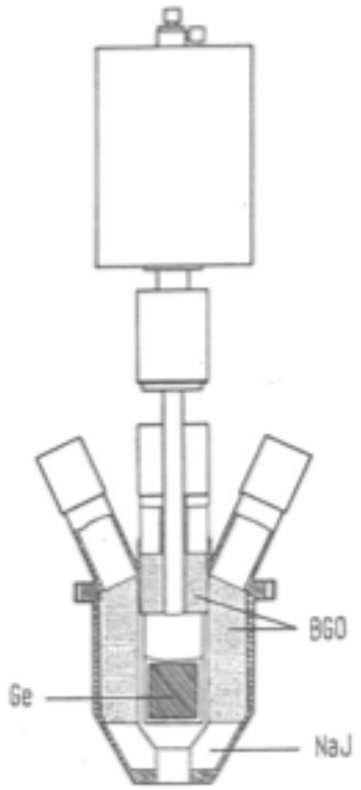


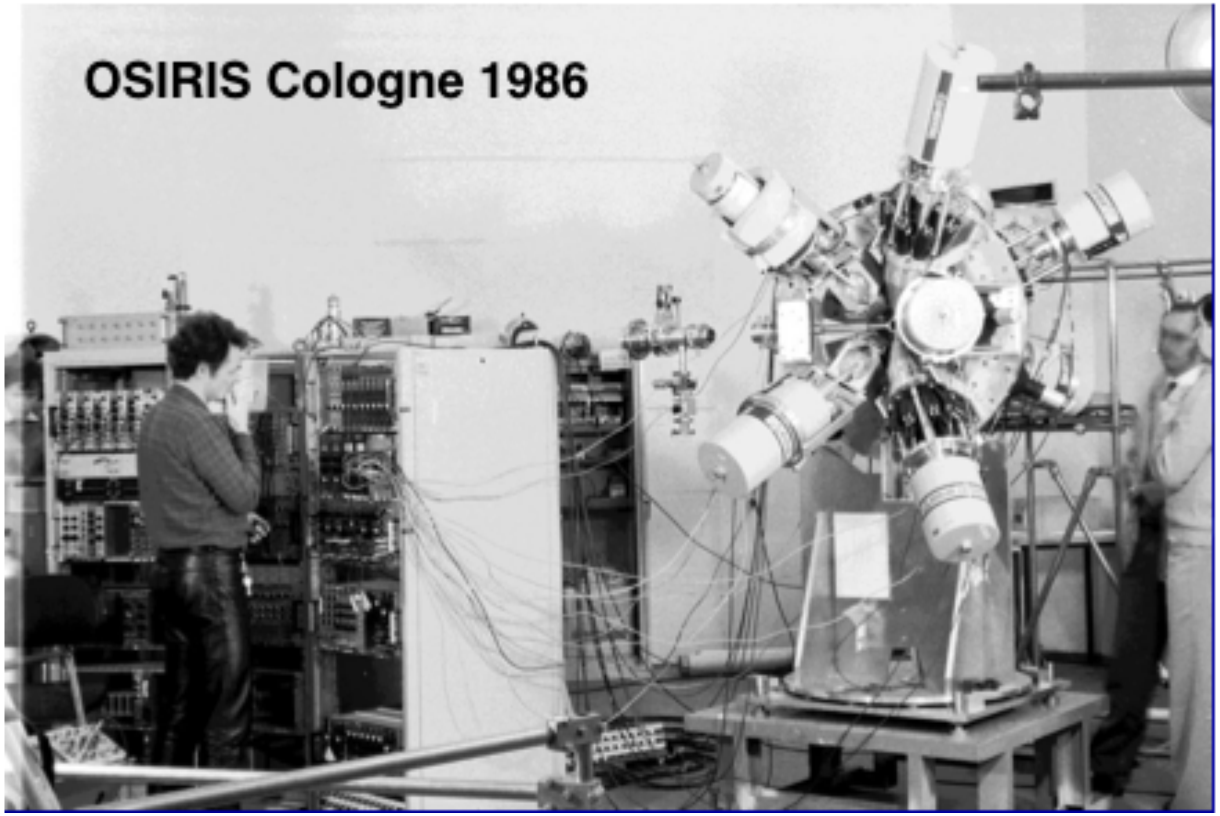
P. Twin et. al
Phys. Rev. Lett. 57 (1986)

TESSA3



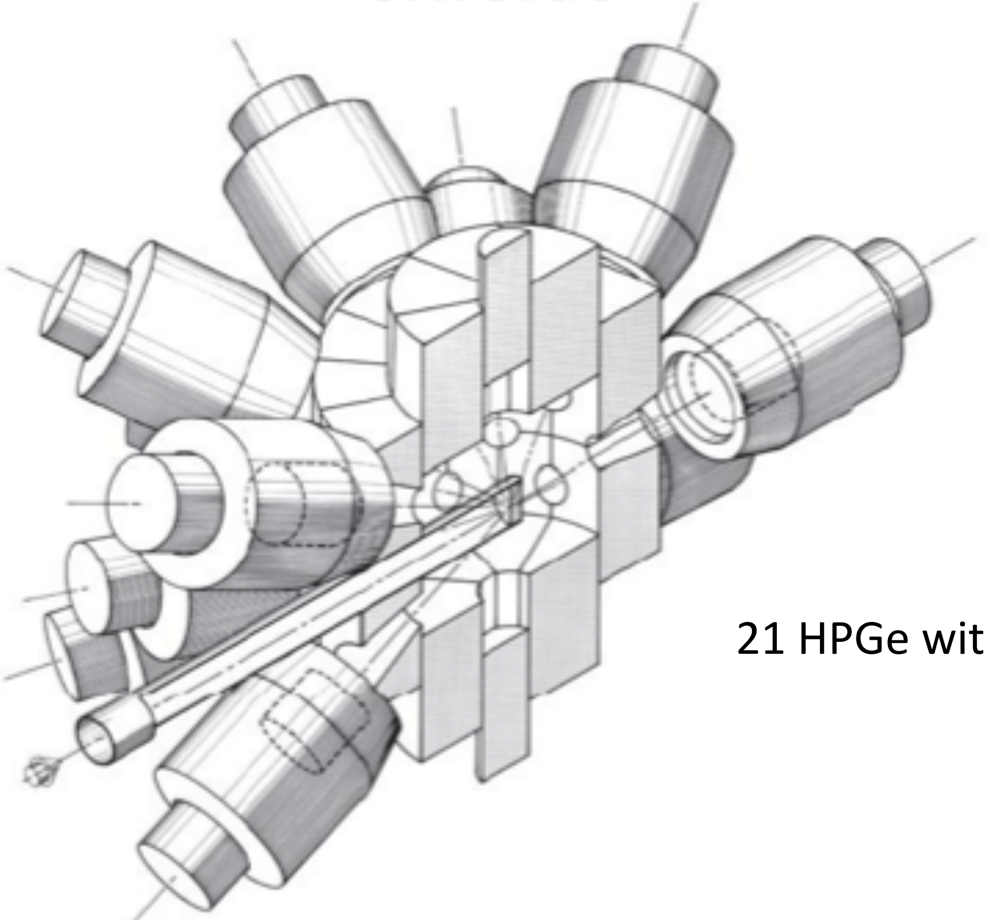
The 80ties: detector arrays with HPGe and BGO/NaI shields





The 80ties: detector arrays with HPGe and BGO shields

HERA at LBNL

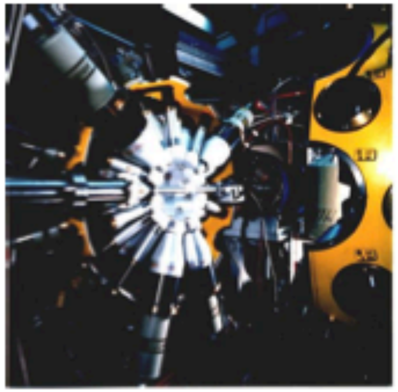


21 HPGe with BGO compton shields

→ Reduce the background, but..

Physics programme required a much more efficiency array with
high resolving power to lower the intensity limit by orders of magnitude

How to increase the detection efficiency?

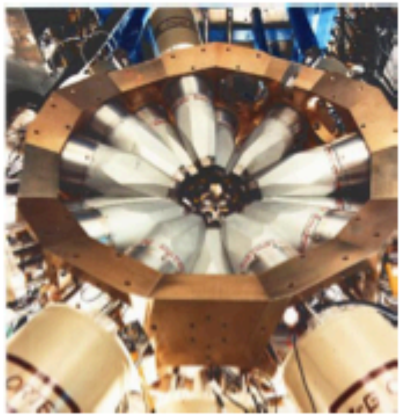


Use more Ge detectors

Use large Ge detectors 70% - 80%

Composite Ge detectors (Clovers, Clusters)

GaSp, Legnaro, Italy 40 detectors

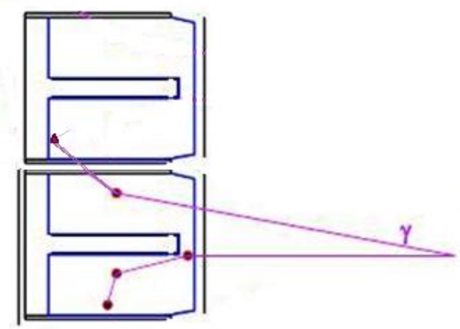


Eurogam 1 Daresbury UK/France 45 detectors

Euroball Strasbourg, Legnaro

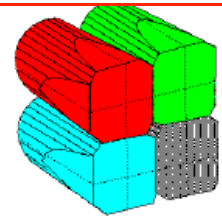
Gammasphere E.I. 30-100 detectors. LBNL ANL

Development of composite detectors

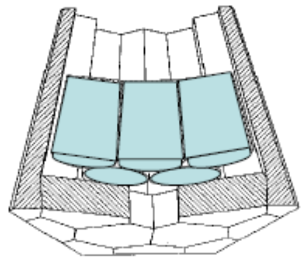


Increase photopeak efficiency from 5% to ~10%
Increase granularity, increase resolving power
Use composite Ge detectors
Detector with more than 1 Ge crystal in the same cryostat

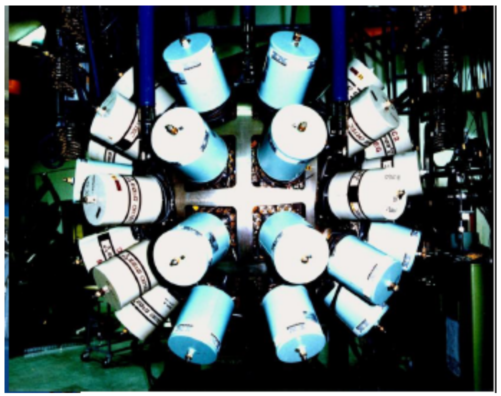
Clover detector
4 crystals per detector
Eurogam II, Euroball



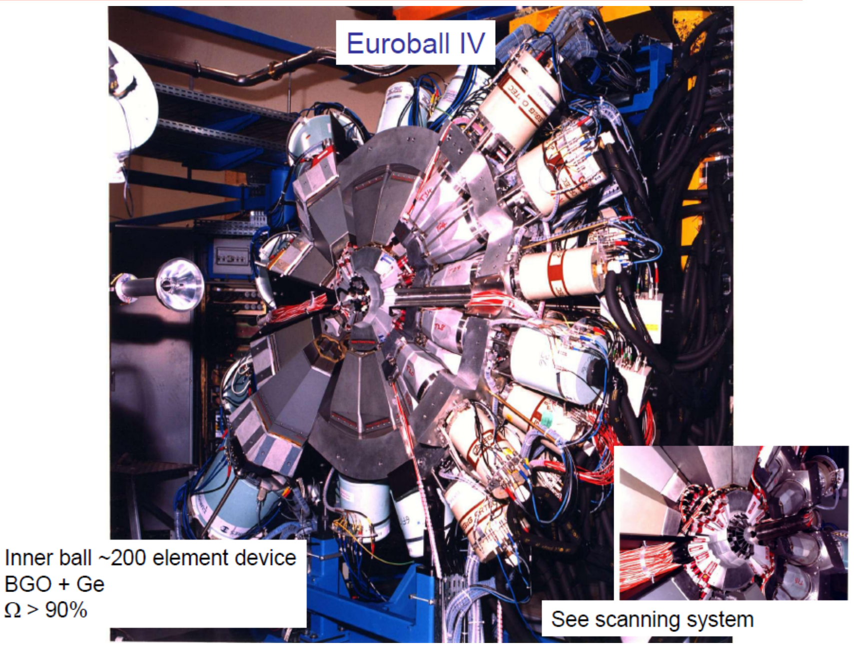
Cluster detector
7 crystals per detector
encapsulated detectors



EUROGAM II

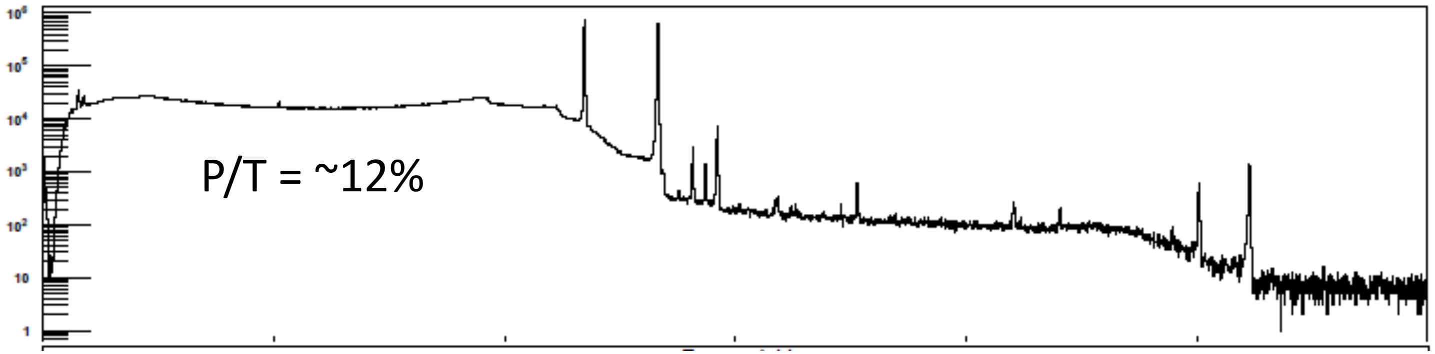


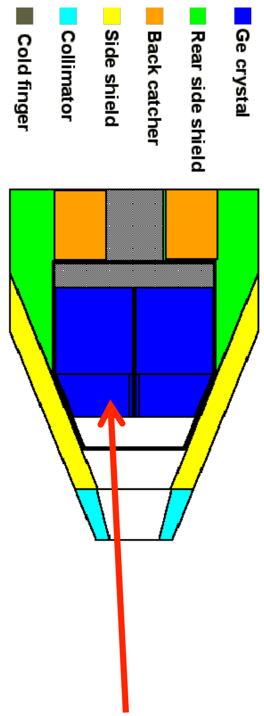
EUROBALL III



The EXOGAM detector

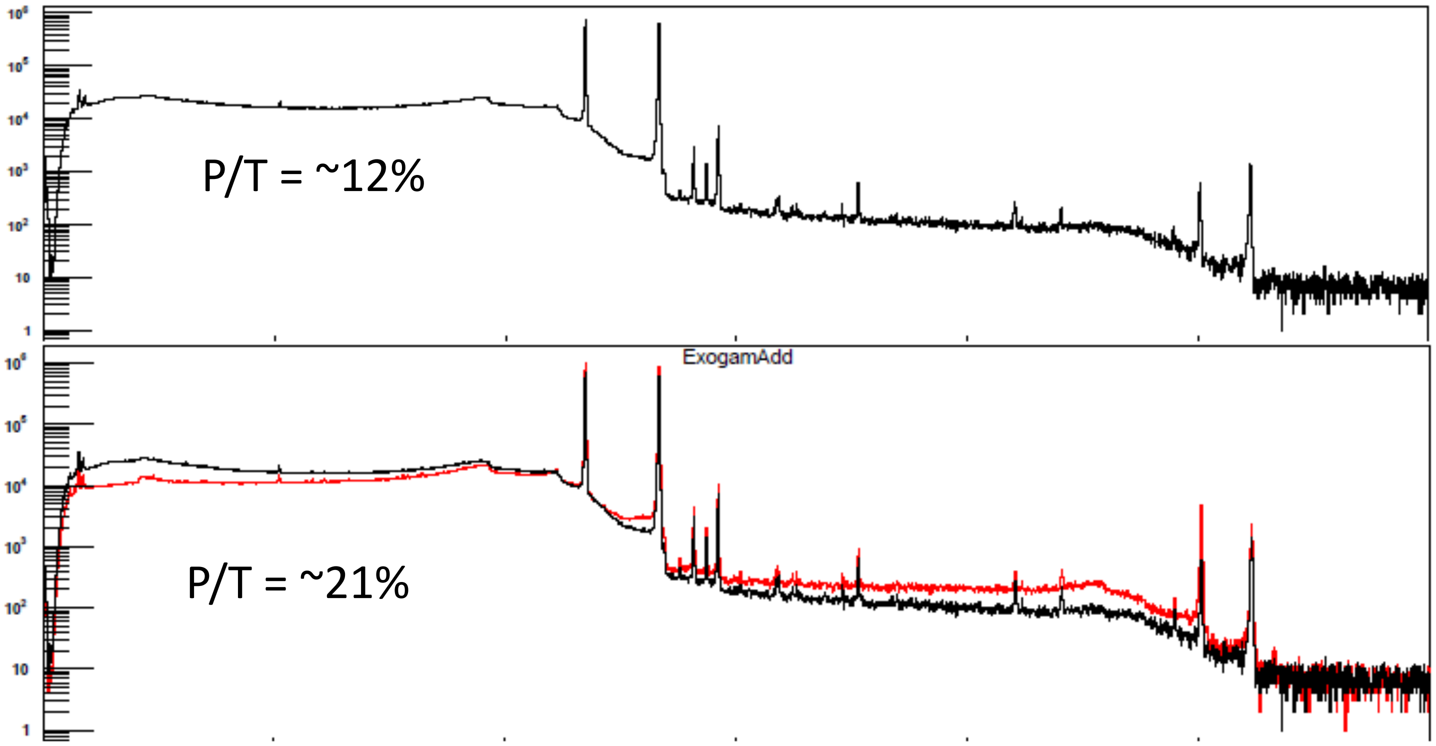
Anti-Compton + Composite detector : State of the art = EXOGAM

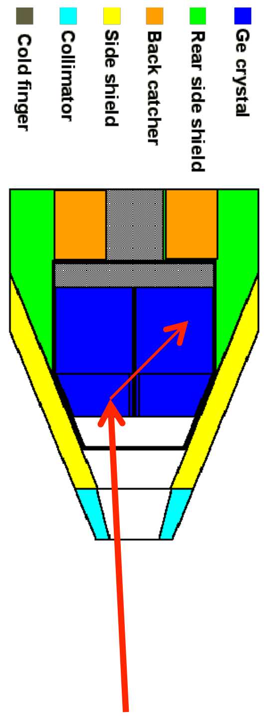




The EXOGAM detector

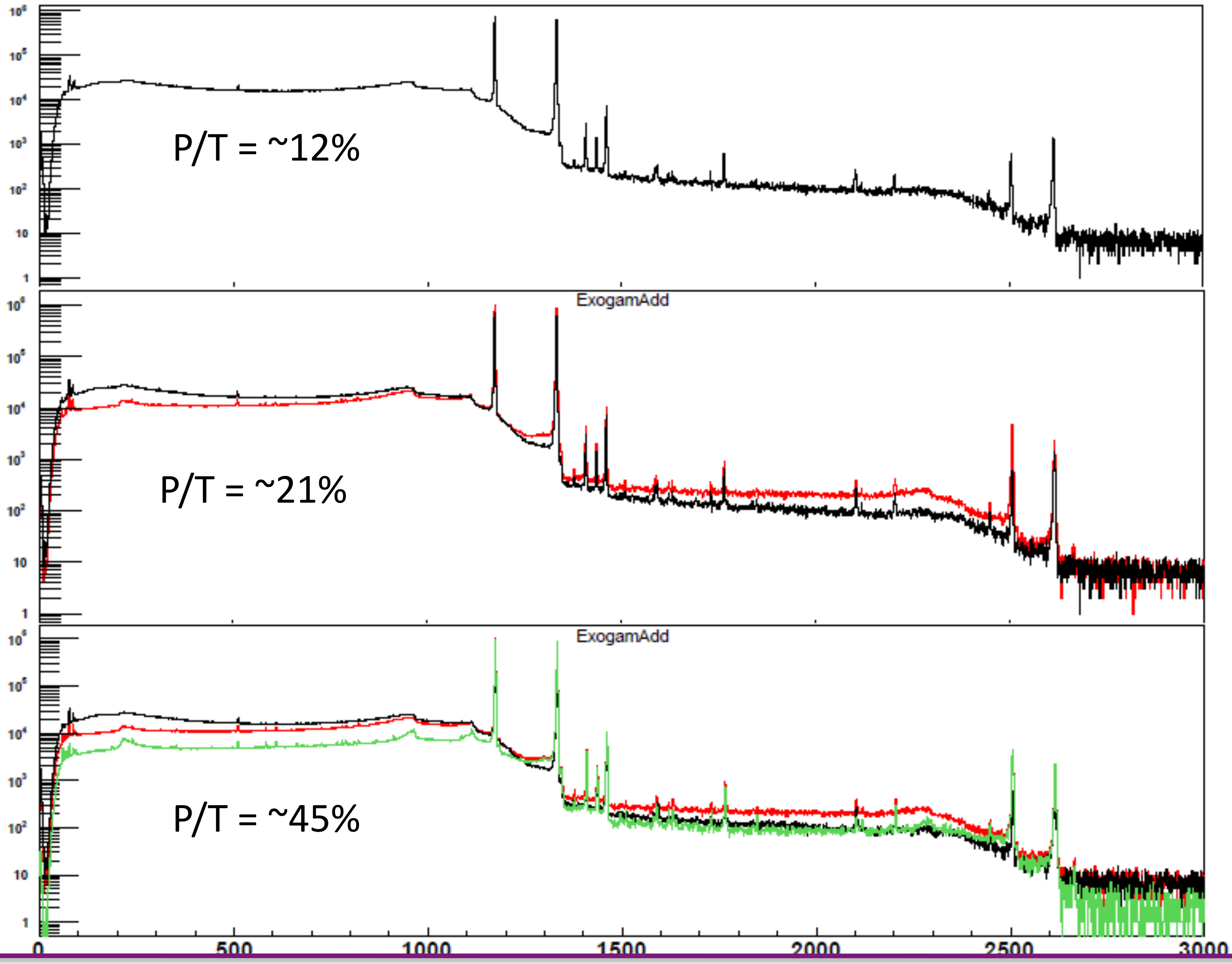
Anti-Compton + Composite detector : State of the art = EXOGAM

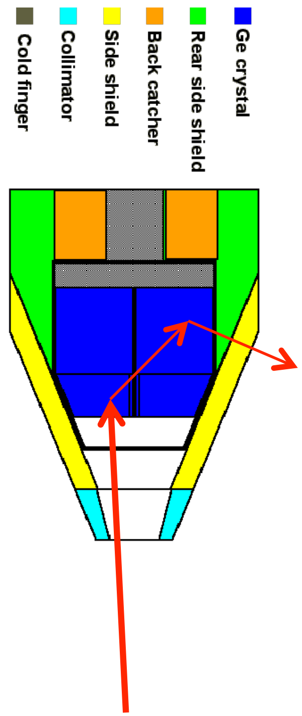




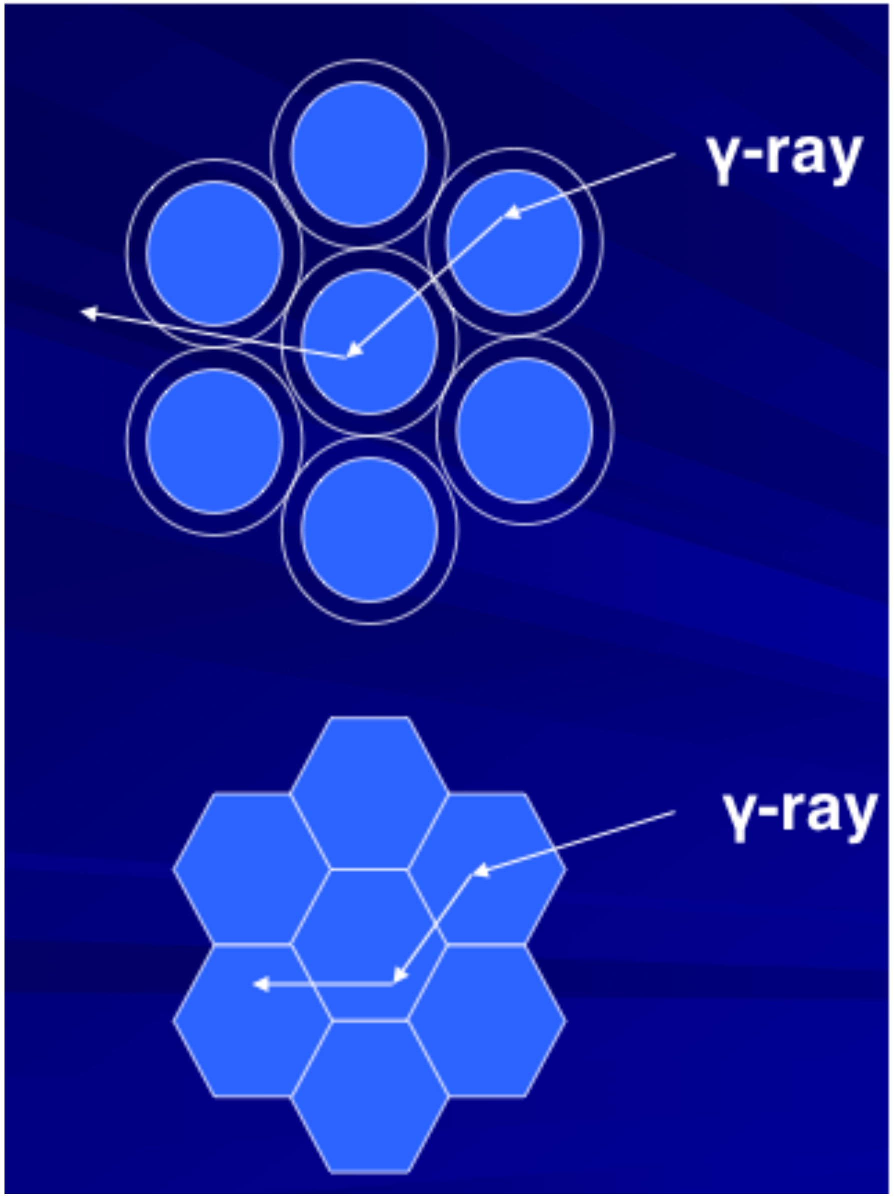
The EXOGAM detector

Anti-Compton + Composite detector : State of the art = EXOGAM





The encapsulation idea



Late 1980's :

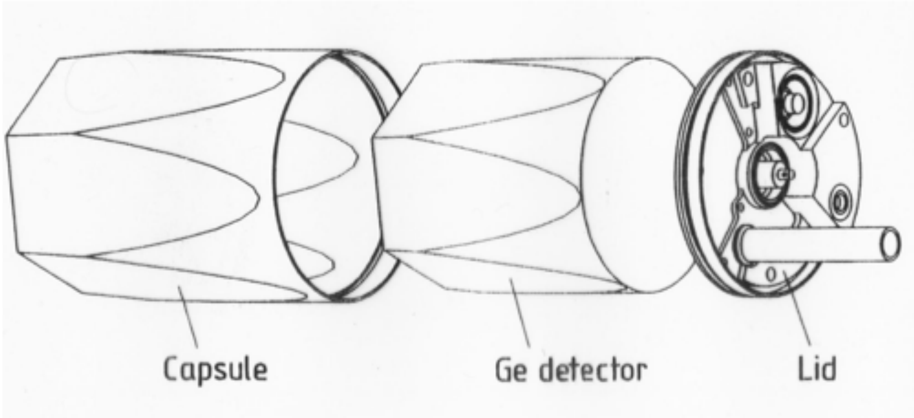
Discussion of a cluster of seven detectors with large efficiency in add-back mode

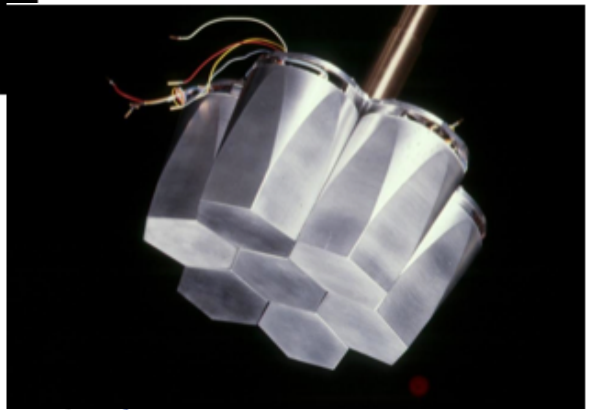
Conclusion:
seven hexagonal detectors in a common cryostat

Encapsulation !

The encapsulation

Cluster detector





Encapsulated Ge detector

Hexagonal tapered crystals ~60 mm dia, ~ 70mm length

Crystal sealed in an Al capsule

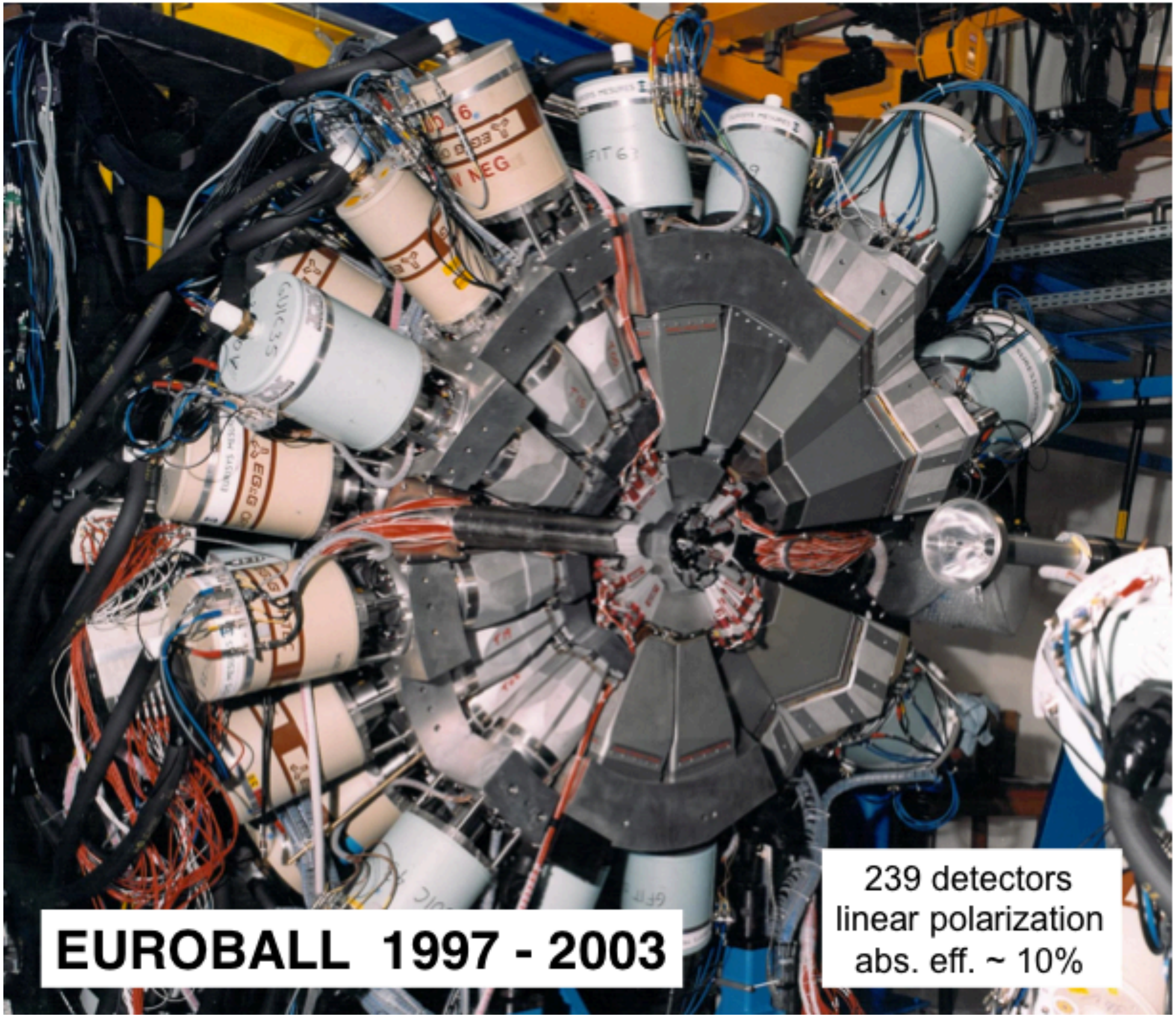
Vacuum of crystal and cryostat decoupled

Close packing

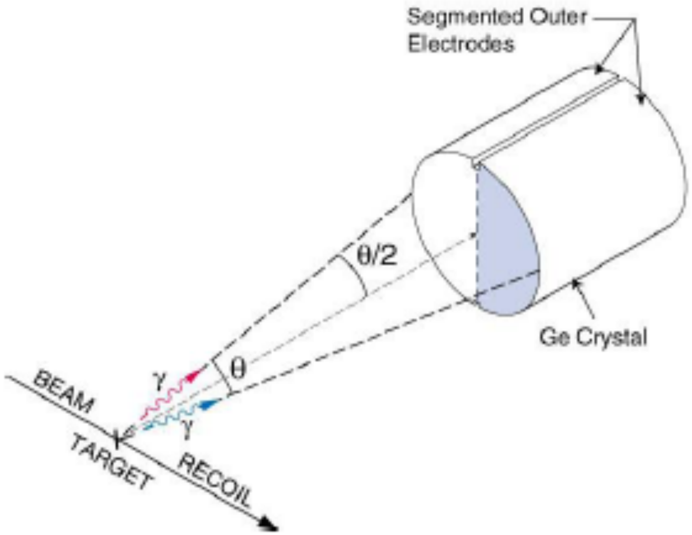
Crystal never exposed

Easy handling and repairs, annealing

J.Eberth et al., Prog. Part. Nucl. Phys 28 (1992) 49


EUROBALL 1997 - 2003
239 detectors
linear polarization
abs. eff. ~ 10%

Doppler effect problem



$$E_{mes} = E_0 \times (1-\beta^2)^{1/2} / (1-\cos\theta)$$

Where did the γ impact first in the detector ?

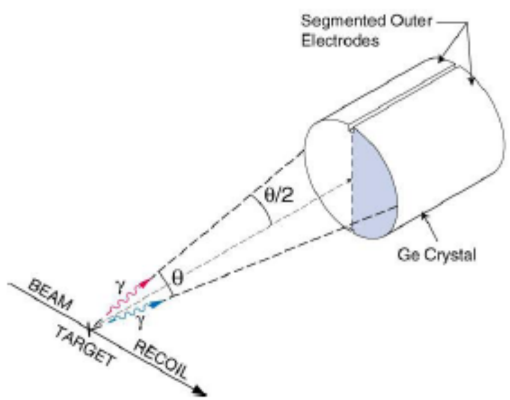
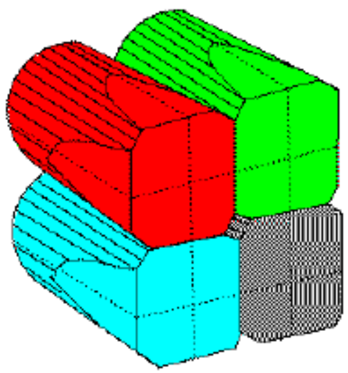
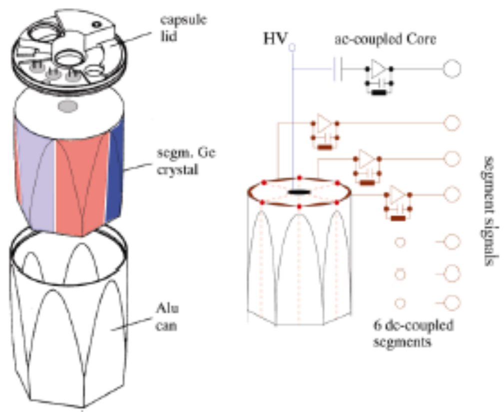
$$\left(\frac{\Delta E_\gamma^{CM}}{E_\gamma^{CM}}\right)^2 = \left(\frac{\beta \cdot \sin\theta^{Lab}}{1-\beta \cdot \cos\theta^{Lab}}\right)^2 (\Delta\theta)^2 + \quad \text{Opening}$$

$$\left(\frac{\beta - \cos\theta^{Lab}}{(1-\beta^2)(1-\beta \cdot \cos\theta^{Lab})}\right)^2 (\Delta\beta)^2 + \quad \text{Recoil}$$

$$\left(\frac{\Delta E_\gamma^{Lab}}{E_\gamma^{Lab}}\right)^2 \quad \text{Intrinsic}$$

Segmentation of the detectors

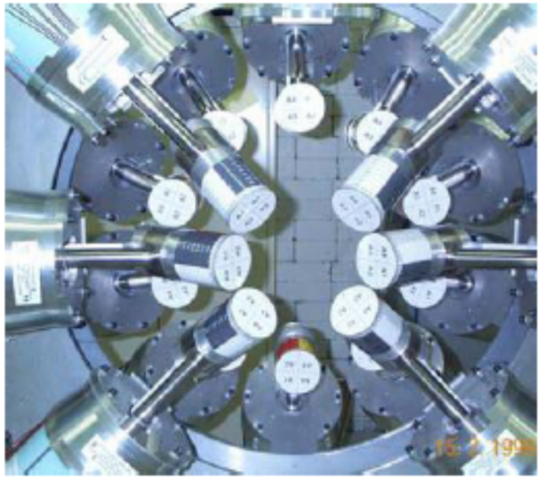
Improve granularity (reduce Doppler broadening)

Gammasphere	Exogam	Miniball
		
2-fold segmentation Single crystal Ge detector	4-fold segmentation Clover Ge detector	6-fold segmentation Encapsulated Ge detector

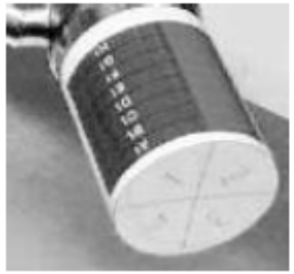
Higher is the granularity, better is the angle measurement but more and more expensive

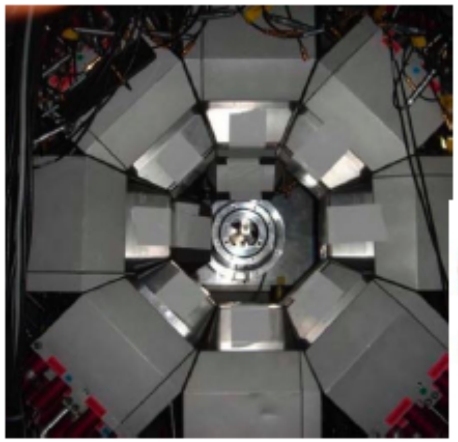
Some examples of segmented detectors

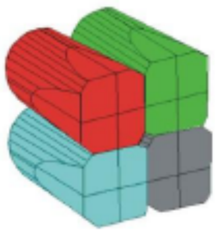
MINIBALL triple-clusters
with 6 and 12 fold segmentation



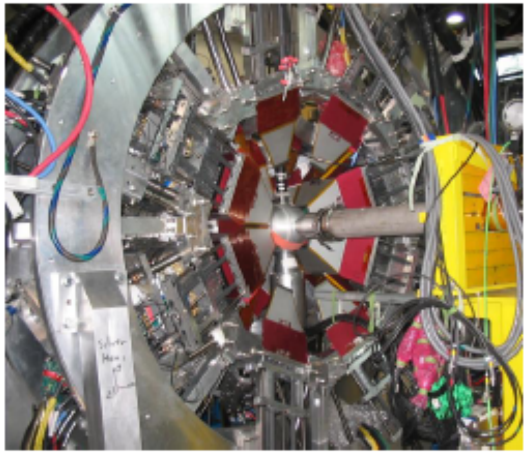
SeGA (Segmented Germanium Array at NSCL) with 32-fold segmentation



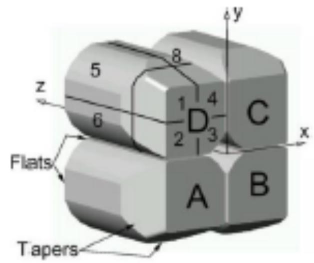




EXOGAM at GANIL
with 4-fold segmented clovers



TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) with 32 fold segmentation (8-fold segmented clovers)



Next generation?

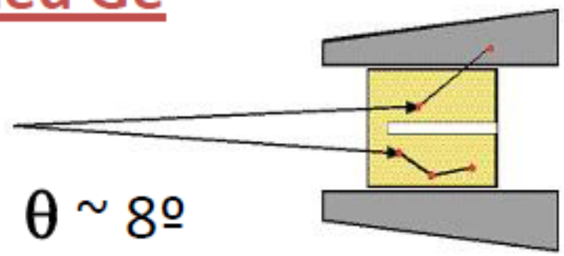
Can we do better ?

Better angle measurement
Higher efficiency with lower background

Compton Shielded Ge

ε_{ph}	~ 10%
N_{det}	~ 100

Ω ~40%



Next generation?

Can we do better ?

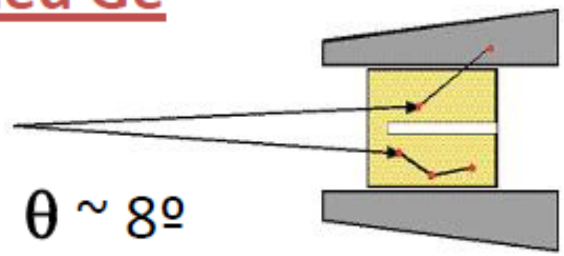
Better angle measurement
Higher efficiency with lower background

Anti-Compton shields take place !

Compton Shielded Ge

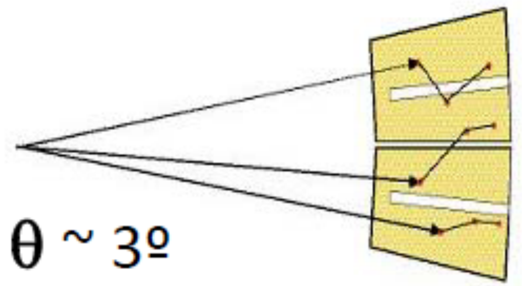
ε_{ph}	~ 10%
N_{det}	~ 100

Ω ~40%



Ge Sphere

ε_{ph}	~ 50%
N_{det}	~ 1000



Next generation?

Can we do better ?

Better angle measurement
Higher efficiency with lower background

Anti-Compton shields take place !

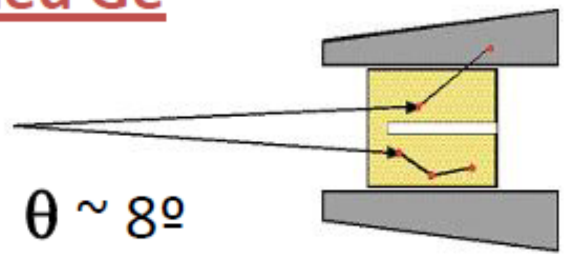
Summing algorithms in composite detectors has a limit at higher multiplicity and/or higher counting rate or when putting closer to the source

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

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100

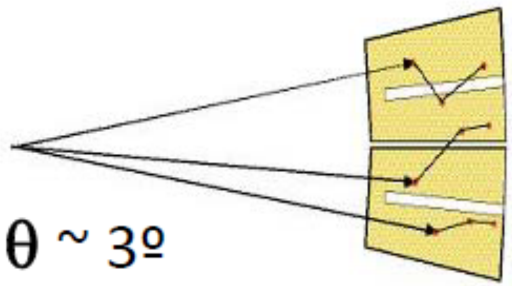
Ω ~40%



θ ~ 8º

Ge Sphere

ε_{ph} ~ 50%
N_{det} ~ 1000

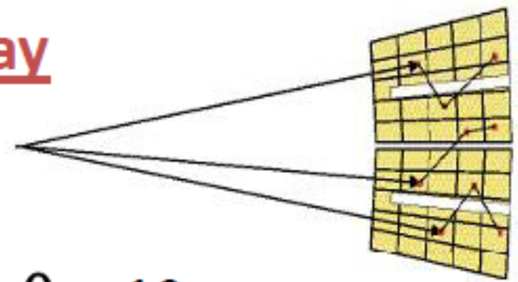


θ ~ 3º

Ge Tracking Array

ε_{ph} ~ 50%
N_{det} ~ 100

Ω ~80%



θ ~ 1º

AGATA/GRETA !

Why do we need AGATA?

FAIR
SPIRAL2
SPES
REX-ISOLDE
MAFF
EURISOL
HI-Stable

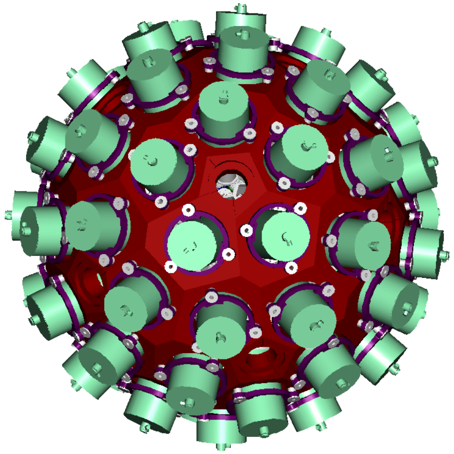
- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High γ-ray multiplicities

Harsh conditions!
Need instrumentation with

High efficiency
High sensitivity
High throughput
Ancillary detectors

Conventional arrays will not suffice!

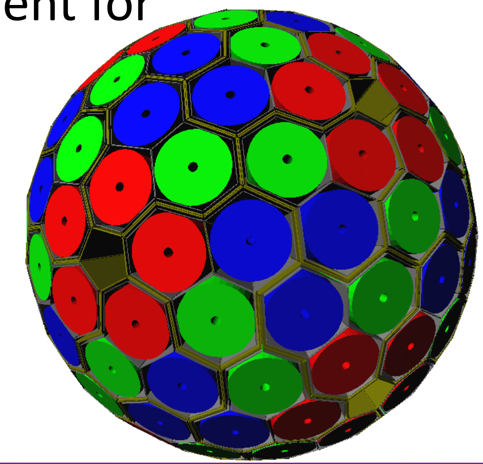
AGATA
(**A**dvanced **GA**mma **T**racking **A**rray)



The innovative combination of:

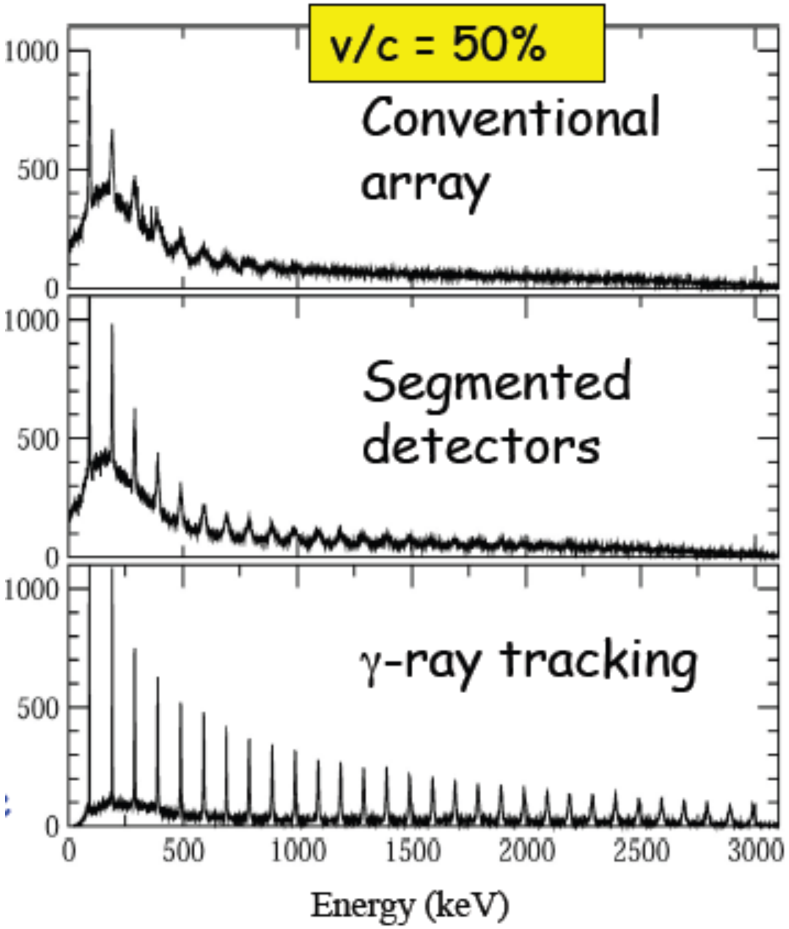
- segmented detectors
- digital electronics
- pulse shape analysis
- γ-ray tracking use of detectors

will result in high efficiency (~40%) and excellent energy resolution, making AGATA the ideal instrument for spectroscopic studies of weak channels.



http://www.facebook.com/agata.detector

AGATA



180 hexagonal crystals	3 shapes
60 triple-clusters	all equal
Inner radius (Ge)	23.5 cm
Amount of germanium	362 kg
Solid angle coverage	82 %
36-fold segmentation	6480 segments
Total:	6660 channels
Singles rate	>50 kHz

Efficiency:	43% (M_γ=1)	28% (M_γ=30)
Peak/Total:	58% (M_γ=1)	49% (M_γ=30)

Pulse Shape Analysis → position sensitive operation mode

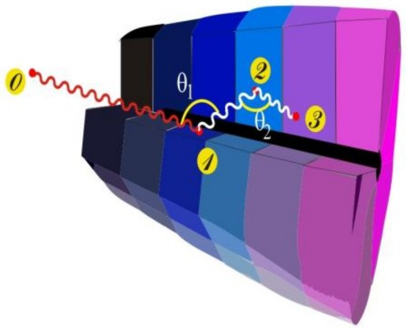
γ-ray tracking algorithms to achieve maximum efficiency

Coupling to complementary detectors for added selectivity

Ingredients of γ-ray tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

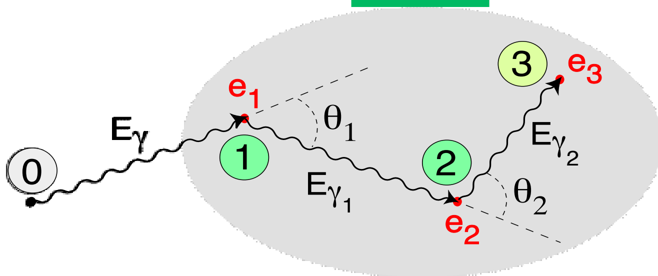
Pulse Shape Analysis to decompose recorded waves

Identified interaction points

$(x,y,z,E,t)_i$

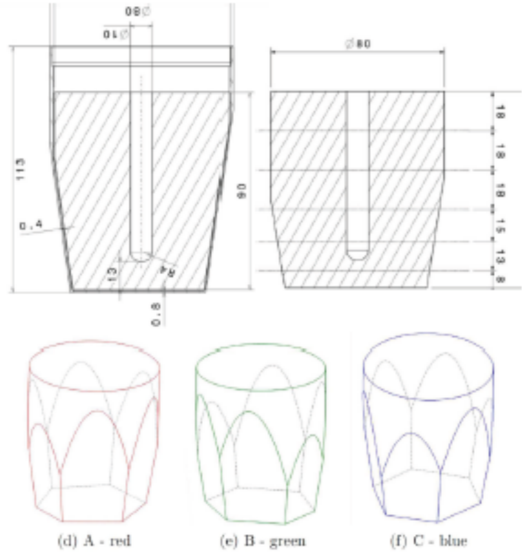
4

Reconstruction of tracks evaluating permutations of interaction points

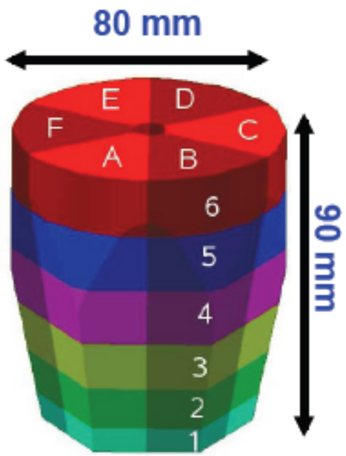


Reconstructed gamma-rays

The AGATA detectors



Volume ~370 cc   Weight ~2 kg
(shapes are volume-equalized to 1%)

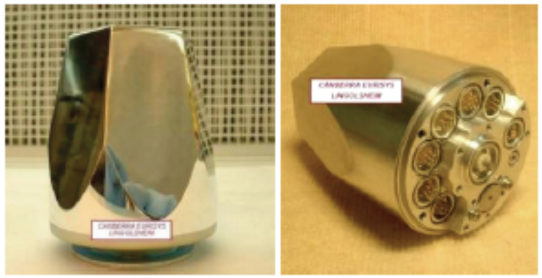


6x6 segmented cathode

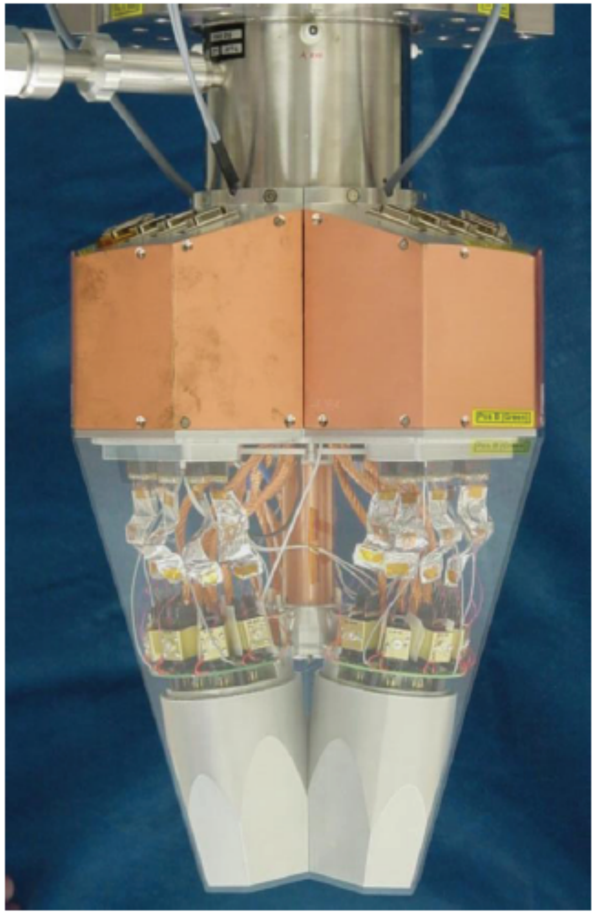
Cold FET for all signals

Energy resolution
Core: 2.35 keV
Segments: 2.10 keV
(FWHM @ 1332 keV)

A. Wiens et al. NIM A 618 (2010) 223
D. Lersch et al. NIM A 640(2011) 133

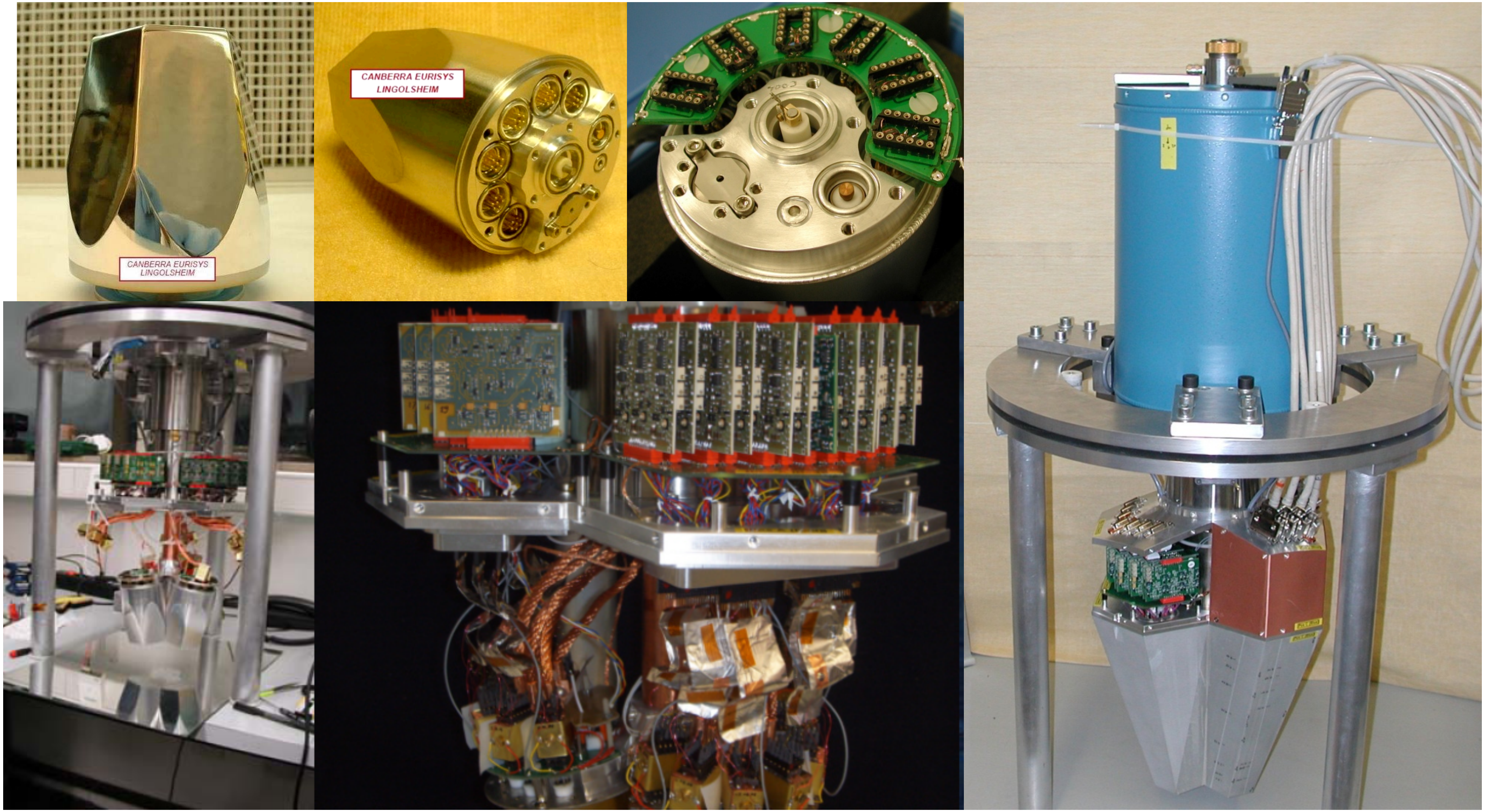


AGATA Asymmetric Crystals
Manufactured by Canberra France



AGATA Asymmetric Triple Cryostat
Manufactured by CTT

AGATA detector construction



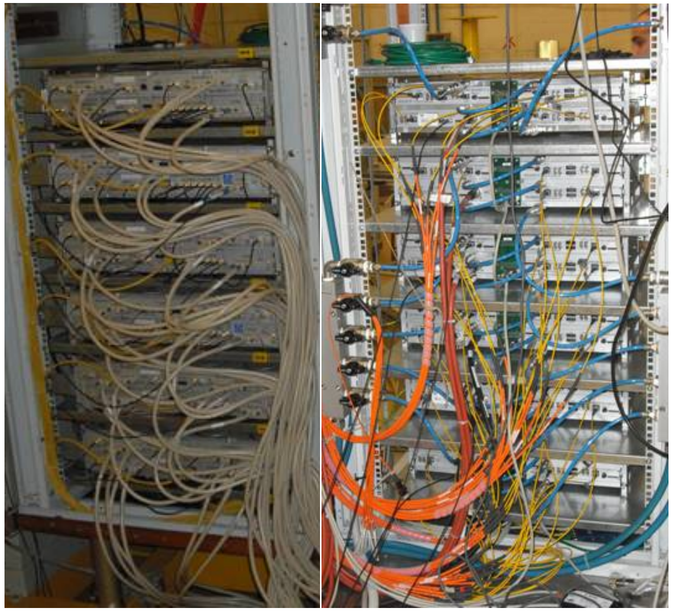
AGATA: Digital Electronics

Digitisers
in the experimental hall

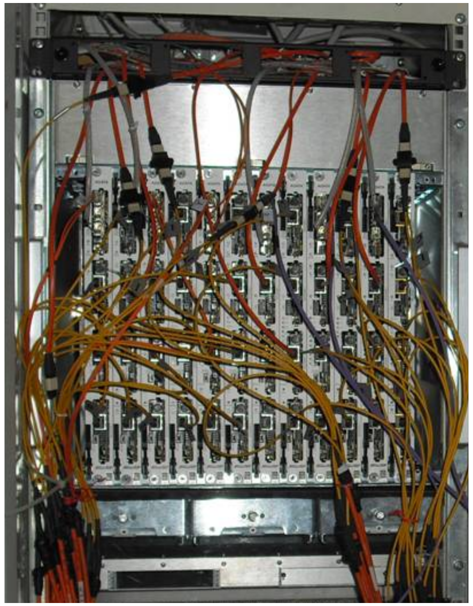
Digital proc. electronics
in the users area

Computer farm
in the computing room

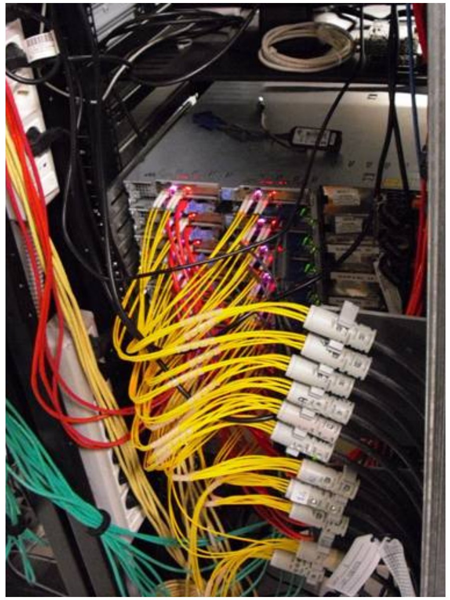
10 m long MDR cables



80 m long optical fibers



20 m long optical fibers



LAN to the disk servers

100Mhz, 14 bit
Synchronous &
continuous

→ (7.6GB/s/crystal)

Triggering
Energy
Trace capture

→ (10 kB/evt/crystal)

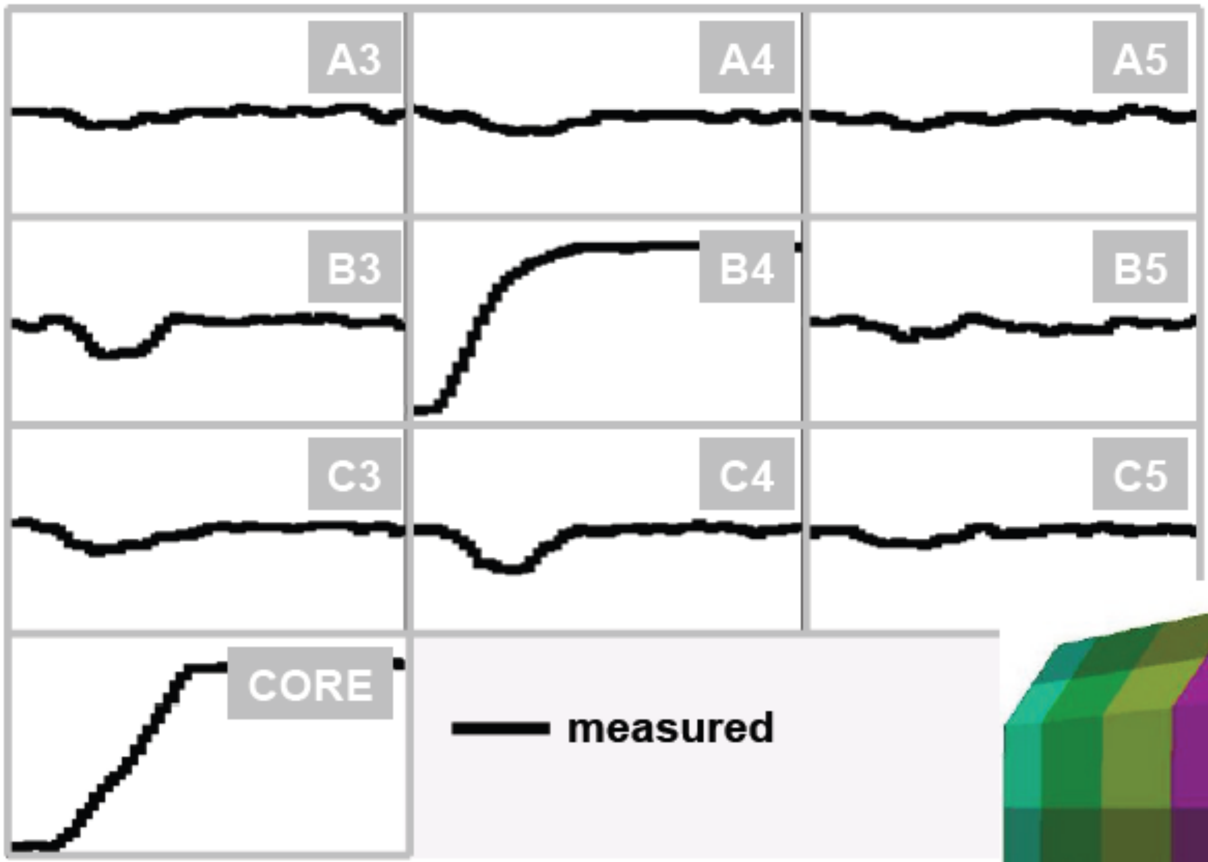
Preprocessing
PSA
Tracking

Global
Triggering
System

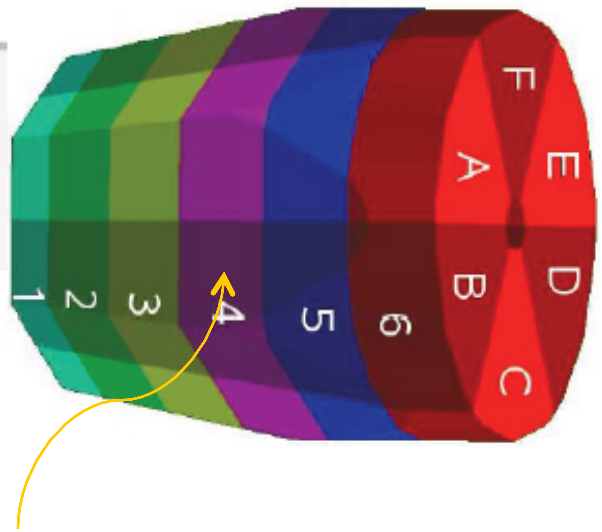
GTS

Clock &
Trigger validation

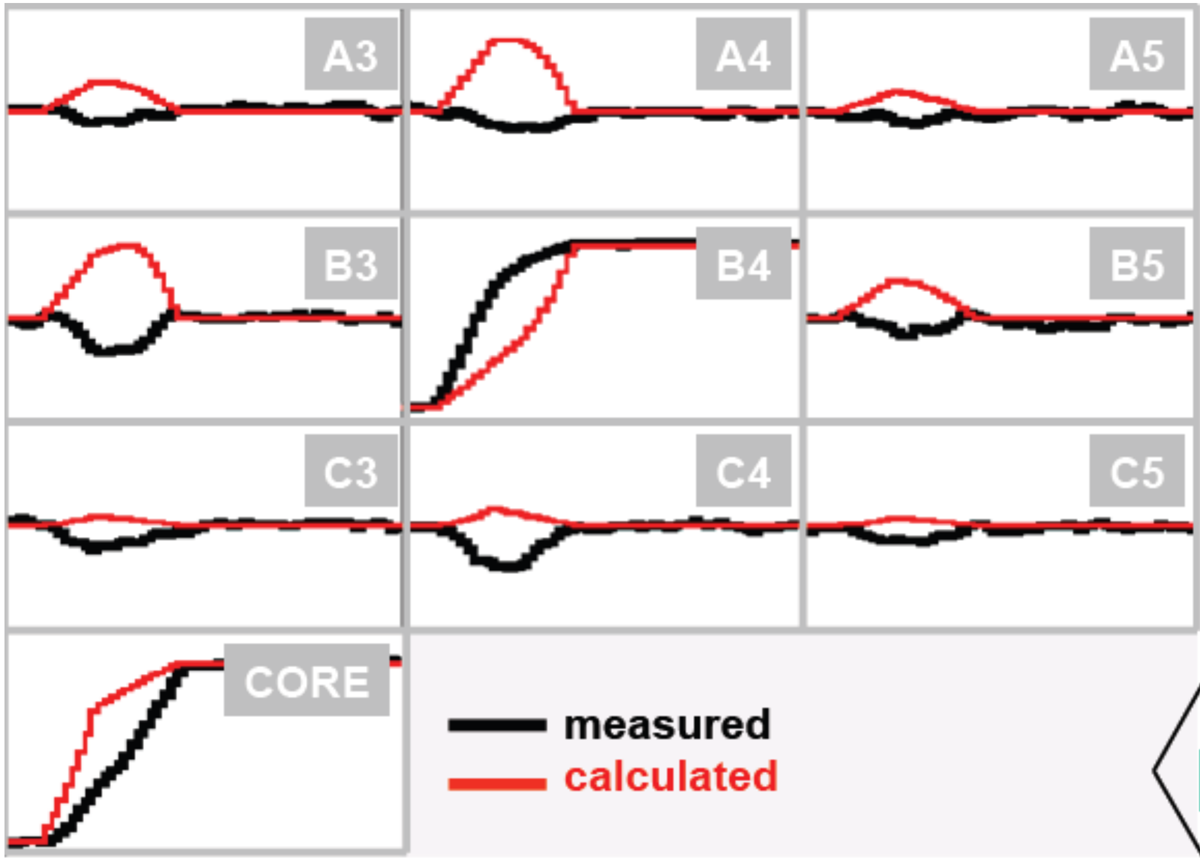
PSA to find the interaction point



791 keV deposited in segment B4

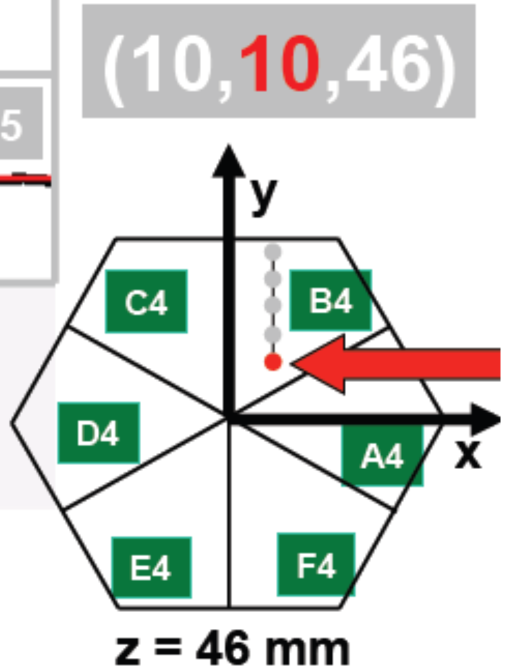


PSA to find the interaction point

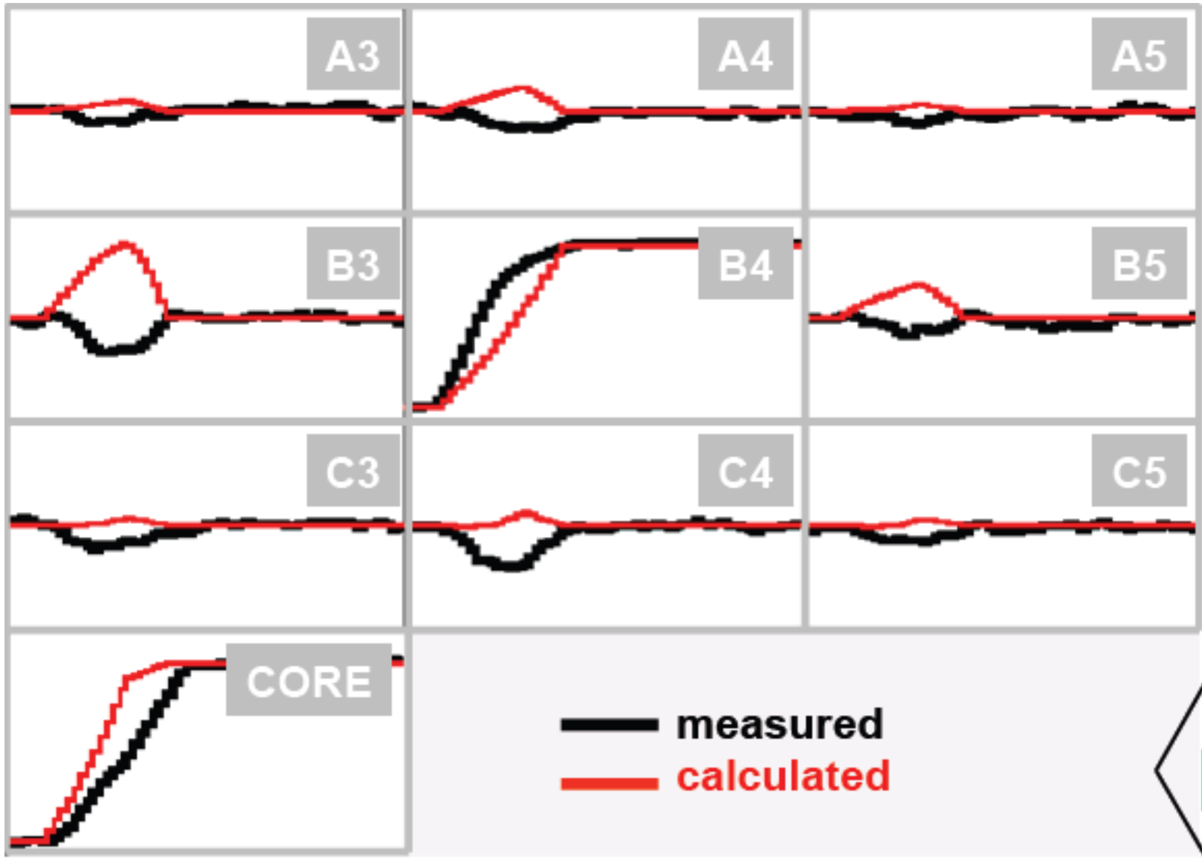


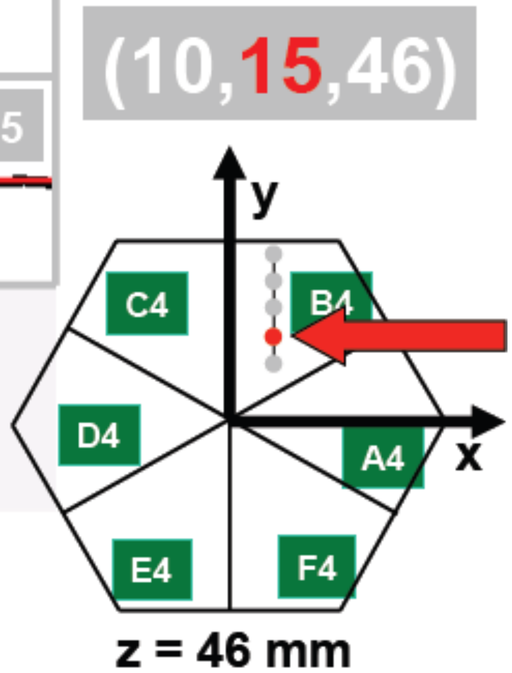
791 keV deposited in segment B4

Library generation
Different codes
ADL (C)
JASS (Java)
MGS (Mathlab)



PSA to find the interaction point





791 keV deposited in segment B4

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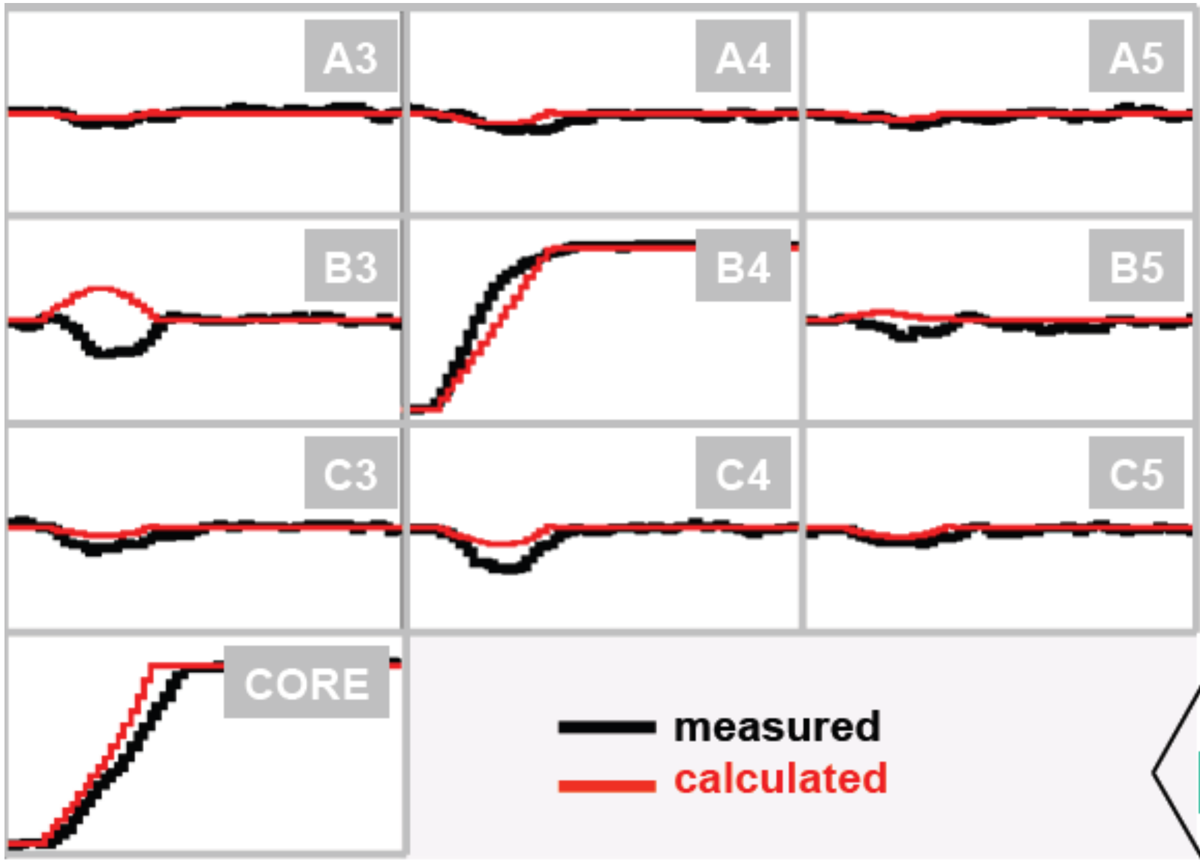
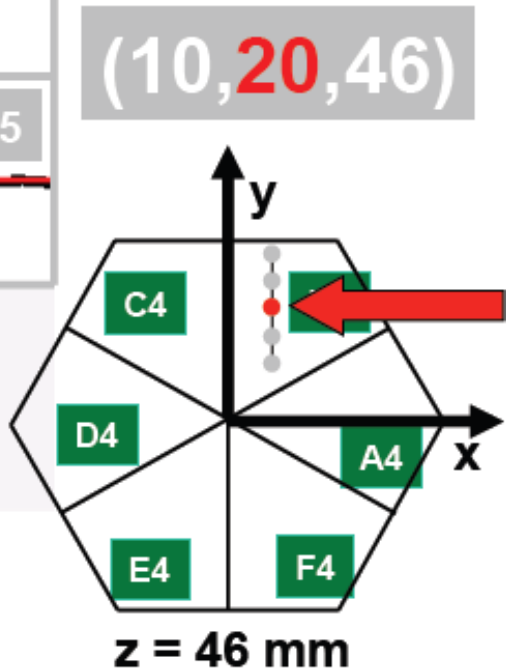
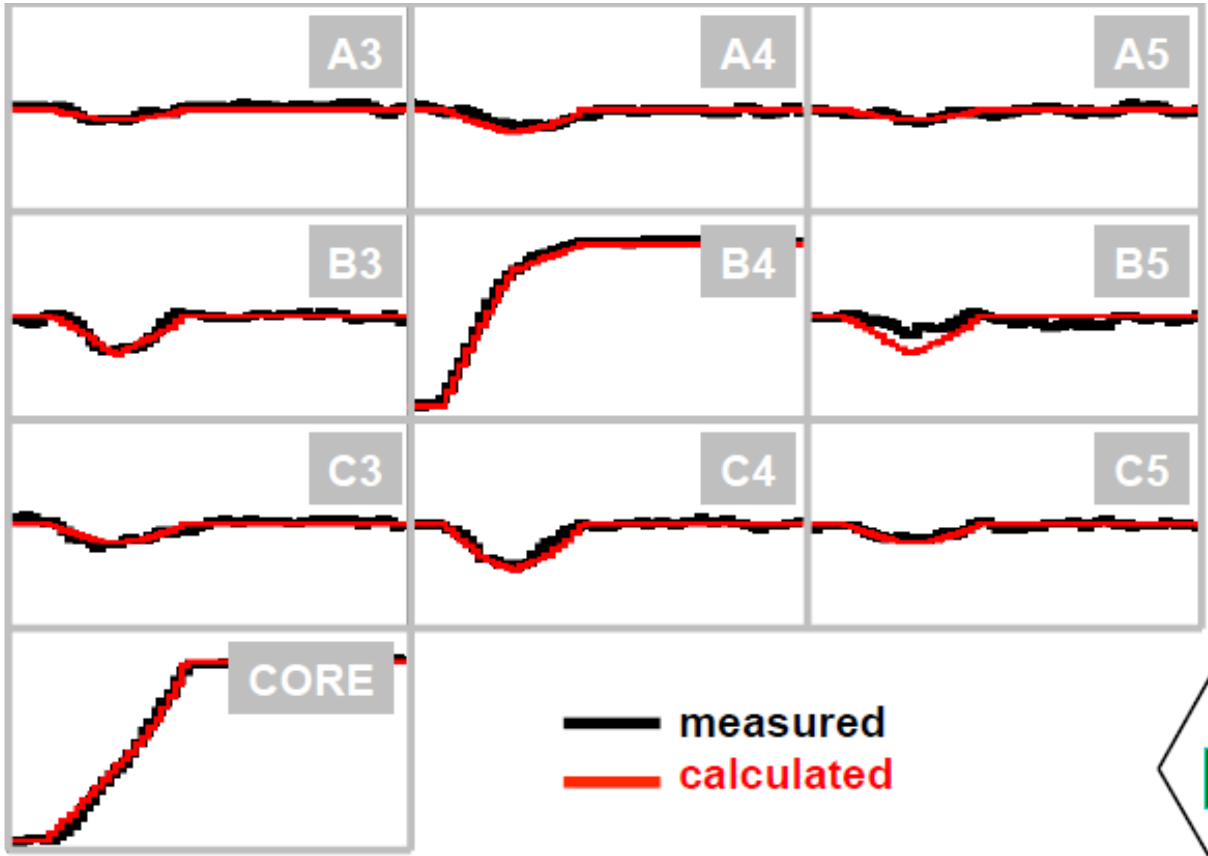


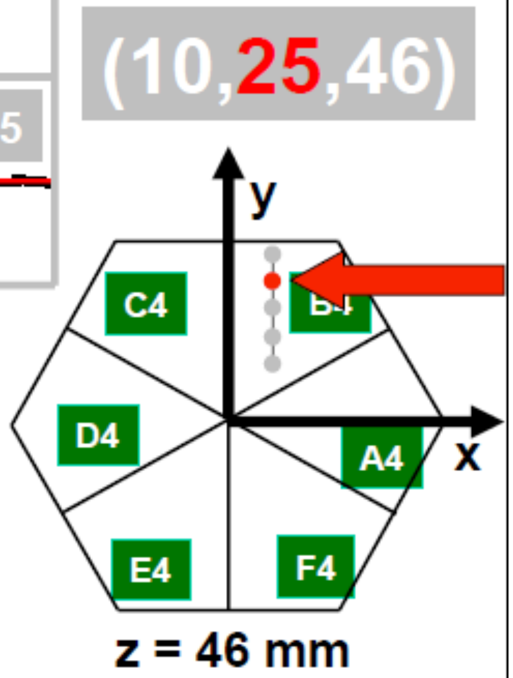
791 keV deposited in segment B4



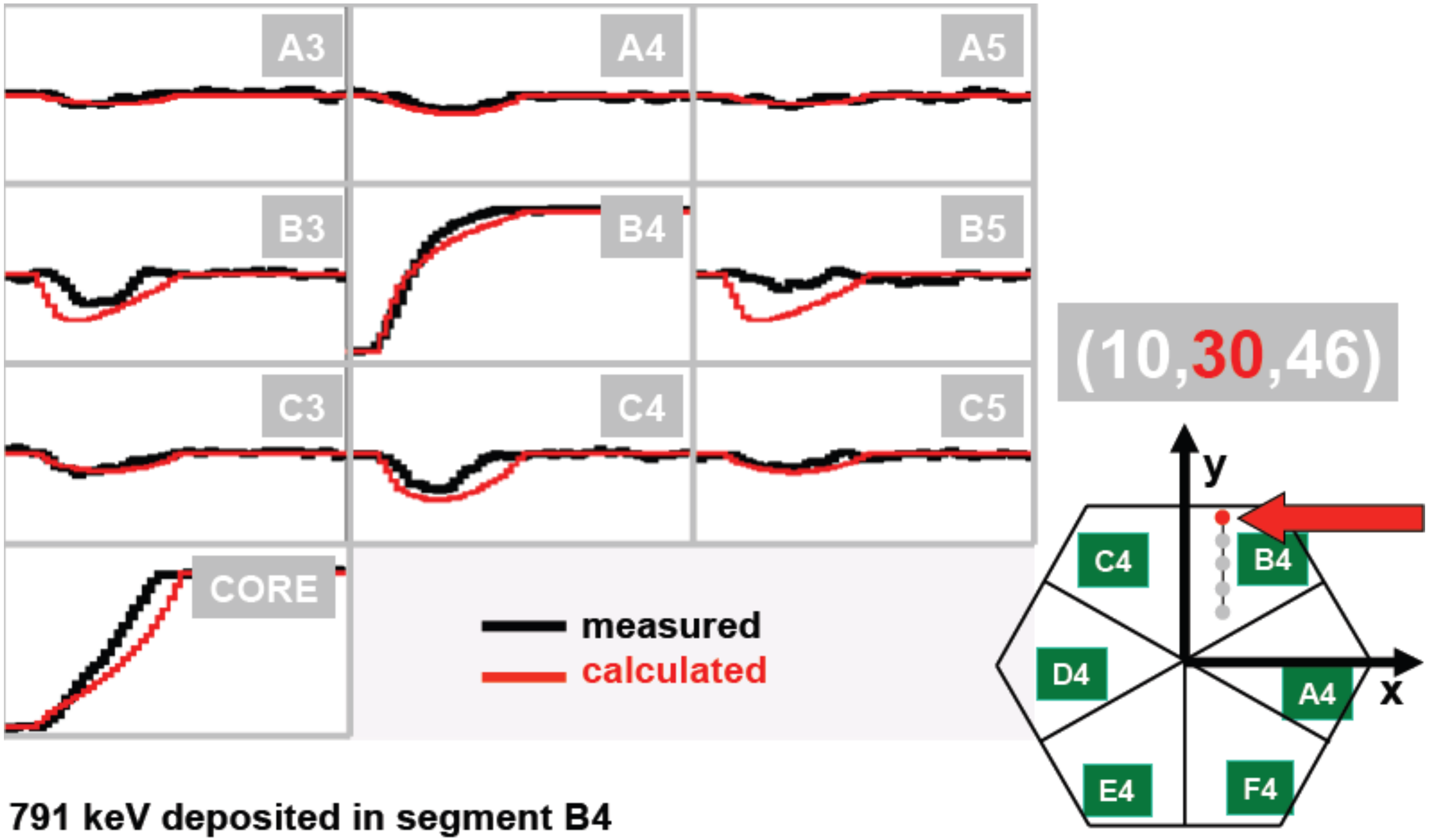
PSA to find the interaction point



791 keV deposited in segment B4



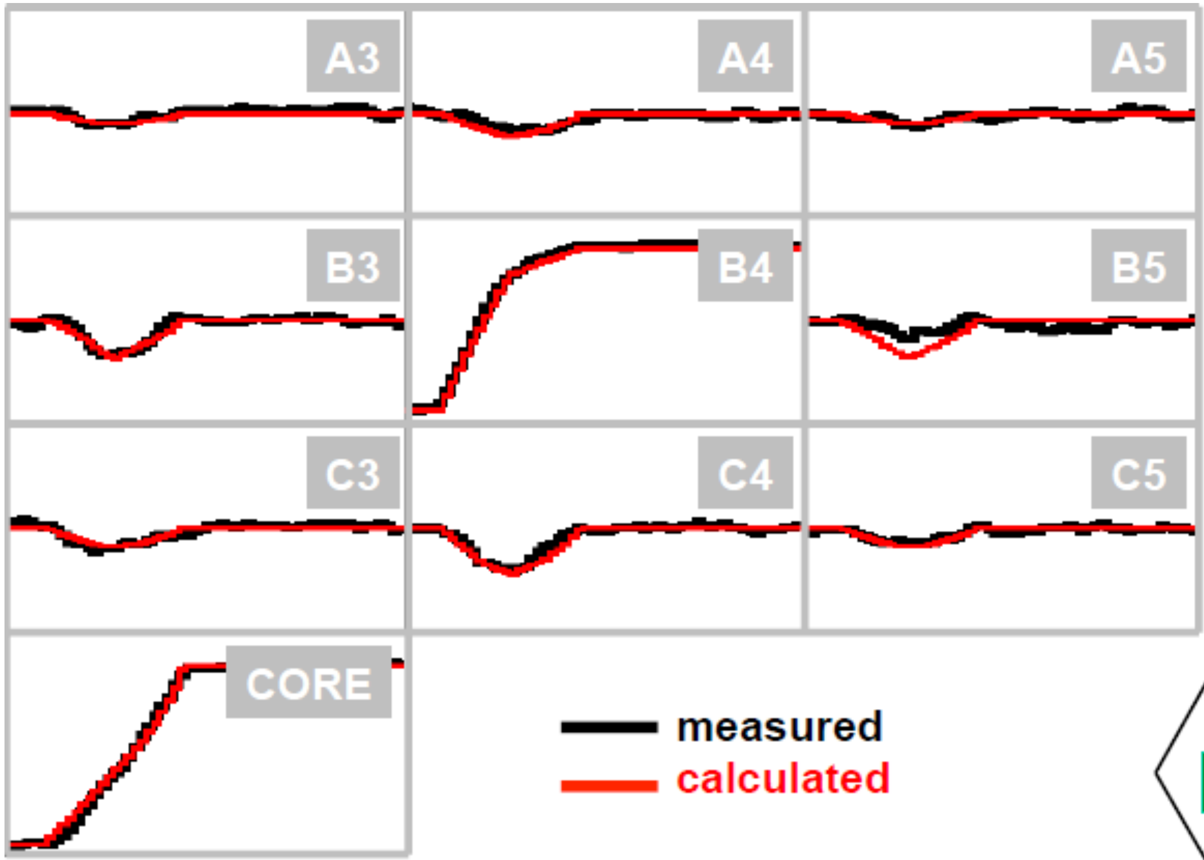
PSA to find the interaction point



791 keV deposited in segment B4

z = 46 mm

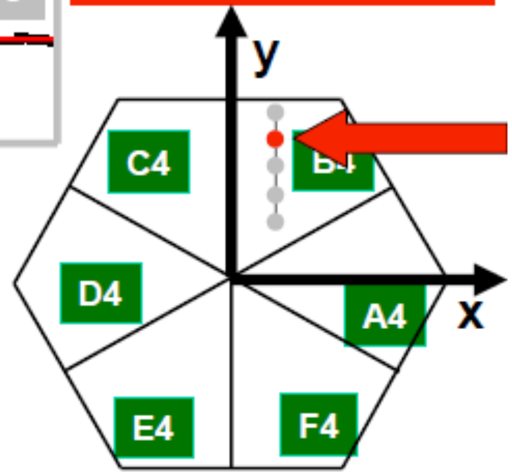
PSA to find the interaction point



791 keV deposited in segment B4

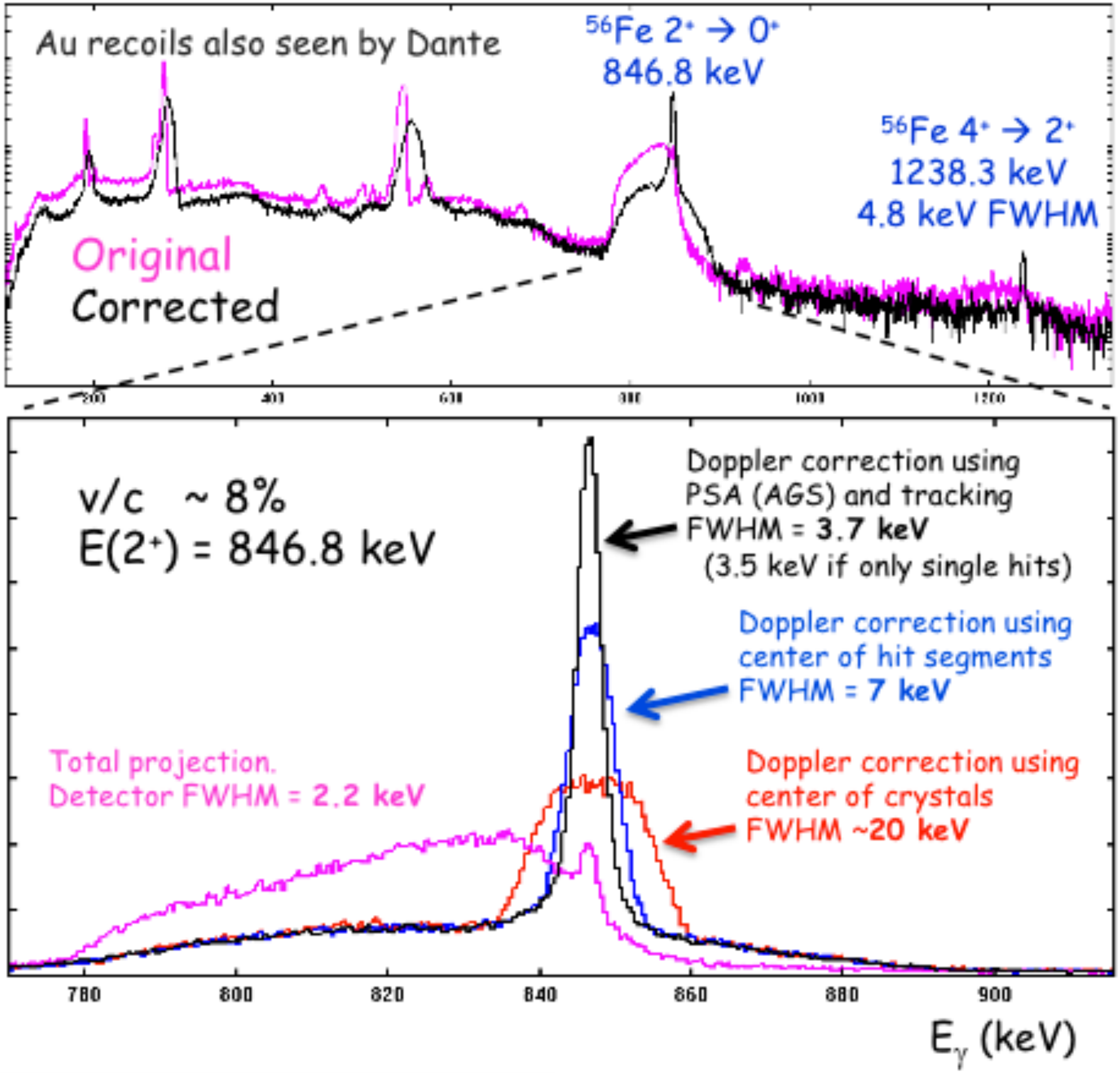
Result of
Grid Search
Algorithm

(10,25,46)



z = 46 mm

220 MeV ^{56}Fe + ^{197}Au with ATC1

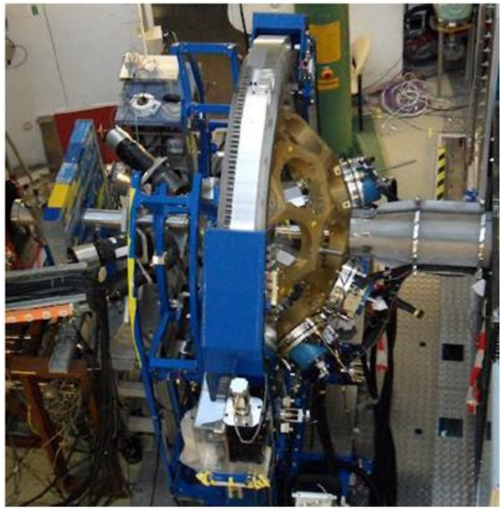


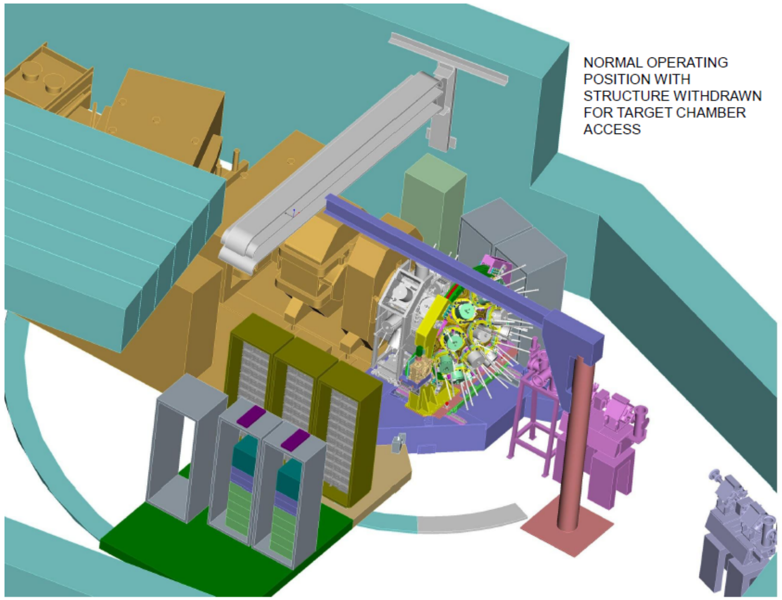
The experimental program

2010 → LNL
5TC

2012 → GSI
5TC + 5DC

2014 → GANIL
15TC





AGATA + PRISMA

Total Eff. ~6%

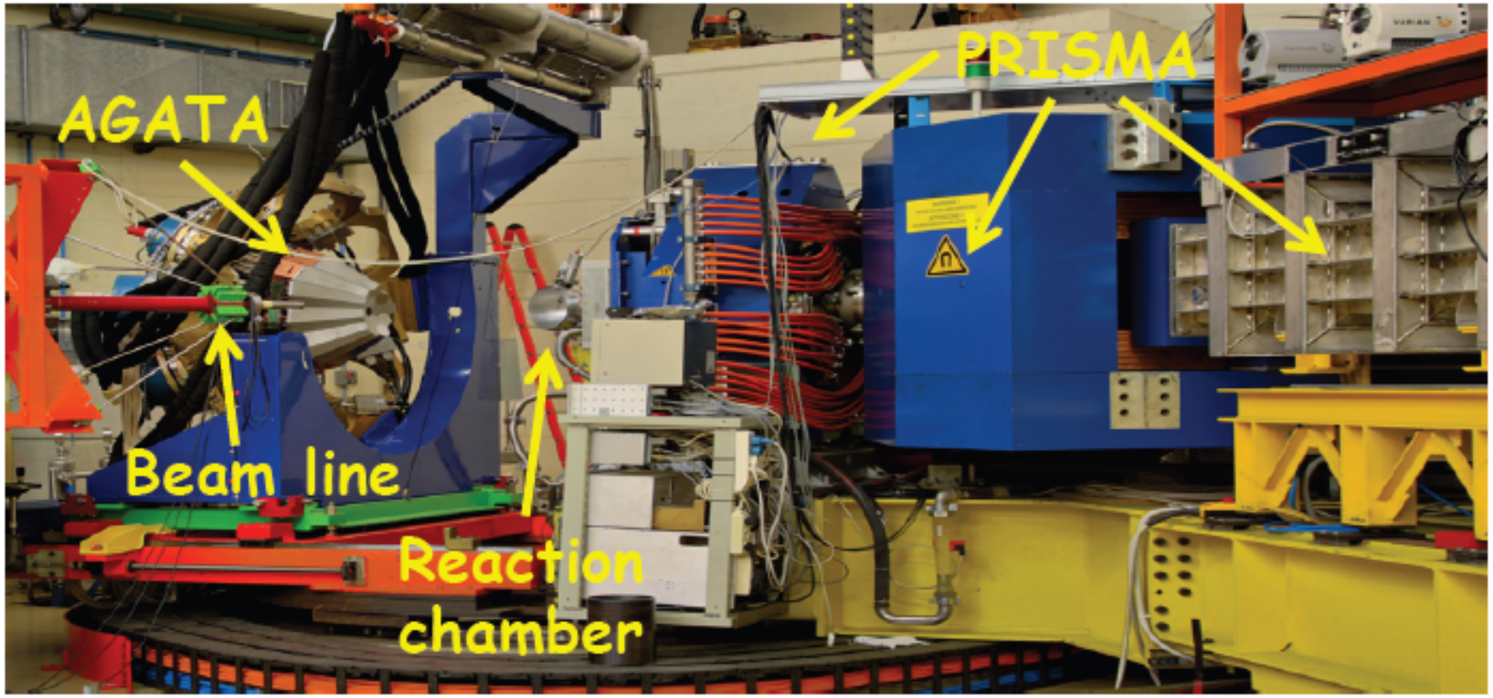
AGATA + FRS

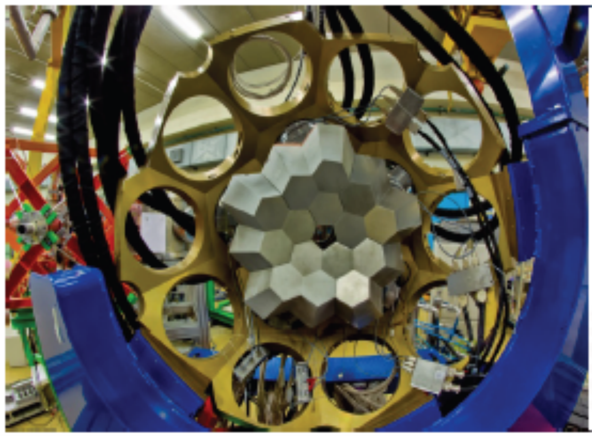
Total Eff. ~ 10%

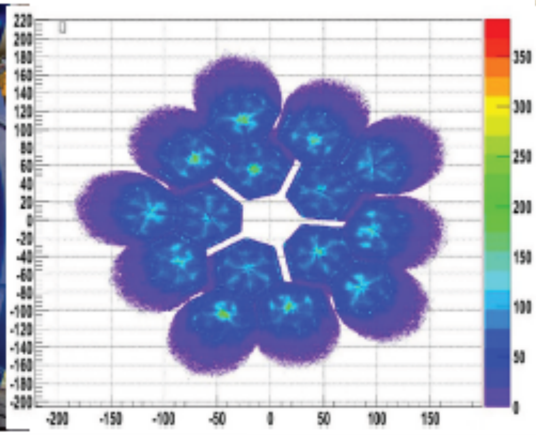
AGATA + VAMOS

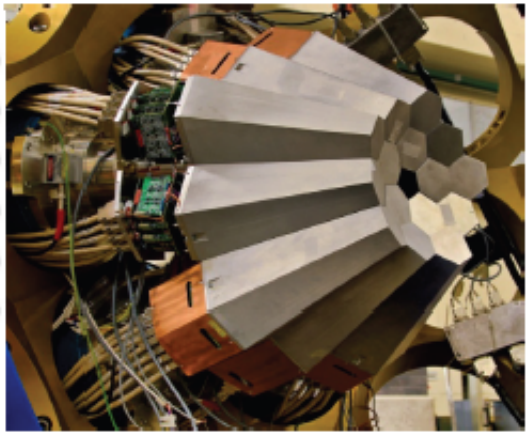
Total Eff. ~ 15%

AGATA @ LNL

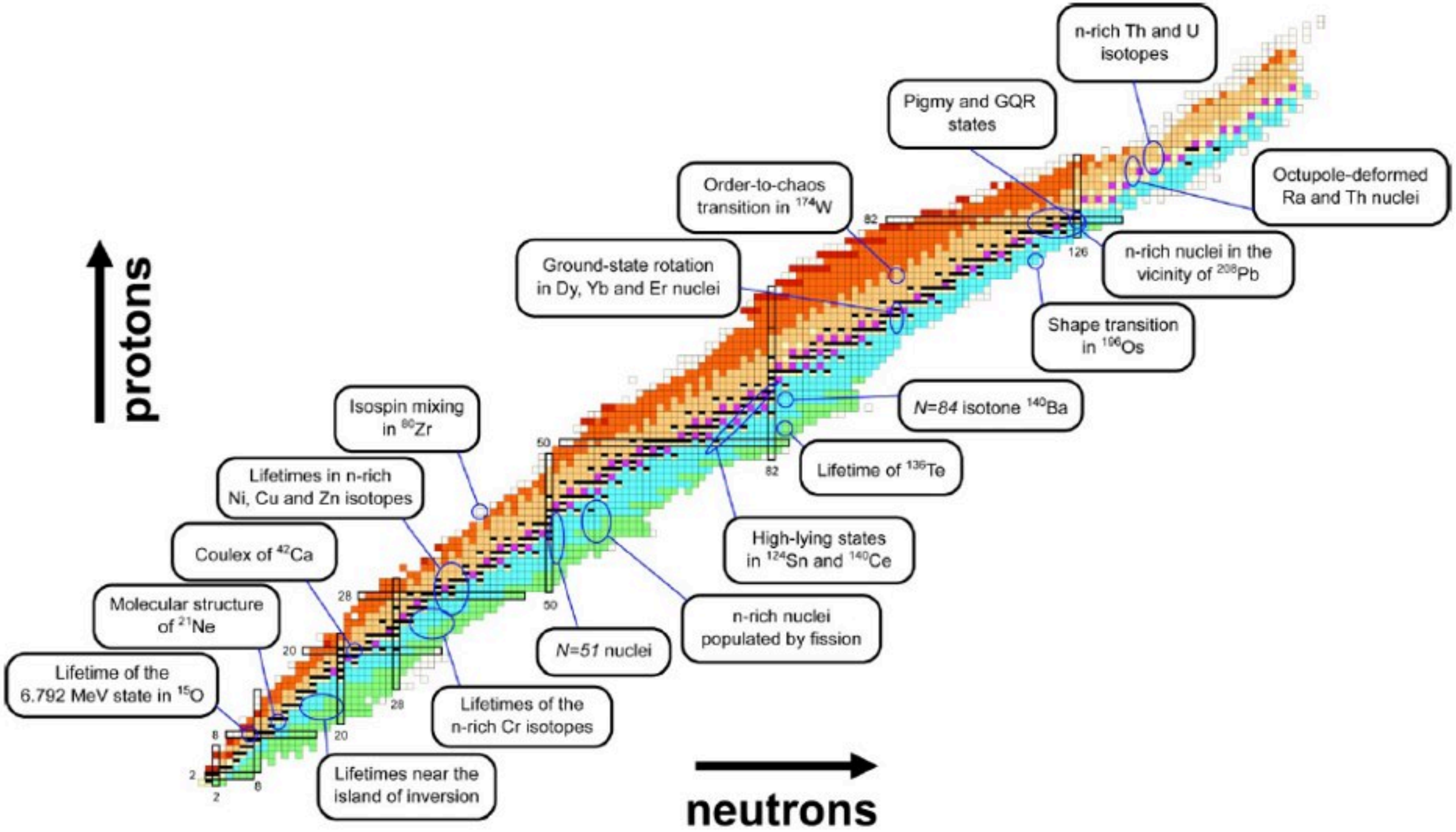








AGATA @ LNL



n-rich Th and U isotopes
Pigmy and GQR states
Order-to-chaos transition in 174W
Octupole-deformed Ra and Th nuclei
Ground-state rotation in Dy, Yb and Er nuclei
n-rich nuclei in the vicinity of 208Pb
Shape transition in 196Os
protons
Isospin mixing in 80Zr
N=84 isotone 140Ba
Lifetimes in n-rich Ni, Cu and Zn isotopes
Lifetime of 136Te
Coulex of 42Ca
High-lying states in 124Sn and 140Ce
Molecular structure of 21Ne
n-rich nuclei populated by fission
N=51 nuclei
Lifetime of the 6.792 MeV state in 15O
Lifetimes of the n-rich Cr isotopes
Lifetimes near the island of inversion
neutrons
2
8
20
28
50
82
126

AGATA @ GSI