Gamma-ray Spectroscopy

An introduction:
gamma rays, detectors, spectrometers

Exotic Beams Summer School 2011, MSU

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Outline

Basics

Gamma rays, their interactions, and basic properties of a spectrum

Gamma-Ray Detectors

Scintillators, Semiconducter, Ge-detectors and modern ones

Gamma-Ray Spectrometer

Just many detectors? Resolving power

SeGA, CAESAR, GAMMASPHERE, GRETA/GRETINA

Literature

- "Techniques for Nuclear and Particle Physics Experiments" by W.R. Leo
  (my recommendation, but out-of-date in some areas)
- "Measurement And Detection Of Radiation" by N. Tsoulfanidis and S. Landsberger
  (recent 3rd edition, pretty up-to-date)
- "Radiation Detection And Measurement" by G. Knoll
  (The device physicists' bible, but beginners may get lost soon…)

(most pictures presented in this lecture are taken from those books and referenced as [LEO], [TSO], [KNO])

Gamma-ray transition

A list of decay modes for an *excited* state of a nucleus:

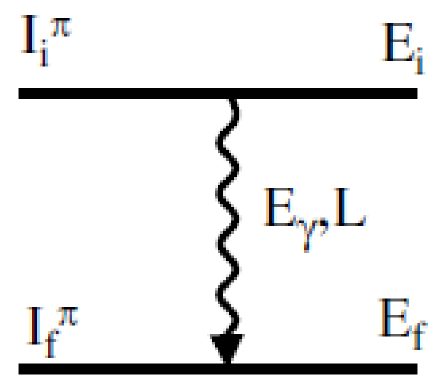
- β^+, β^-, Electron-Capture (e.g. $^{177}Lu^m$)
- Proton, Neutron emission (e.g. $^{53}Co^m$)
- Alpha emission (e.g. $^{211}Po^m$)
- Fission (e.g. $^{239}Pu^m$)
- Internal Conversion
- **Emission of gamma ray**

Gamma-ray emission is usually the dominant decay mode

Measurement of gamma rays let us deduce:

Energy, Spin (angular distr./correl.), Parity (polarization), magnetic moment, lifetime (recoil distance Doppler-shift), ….

of the involved nuclear levels.



$$E_\gamma = E_i - E_f$$

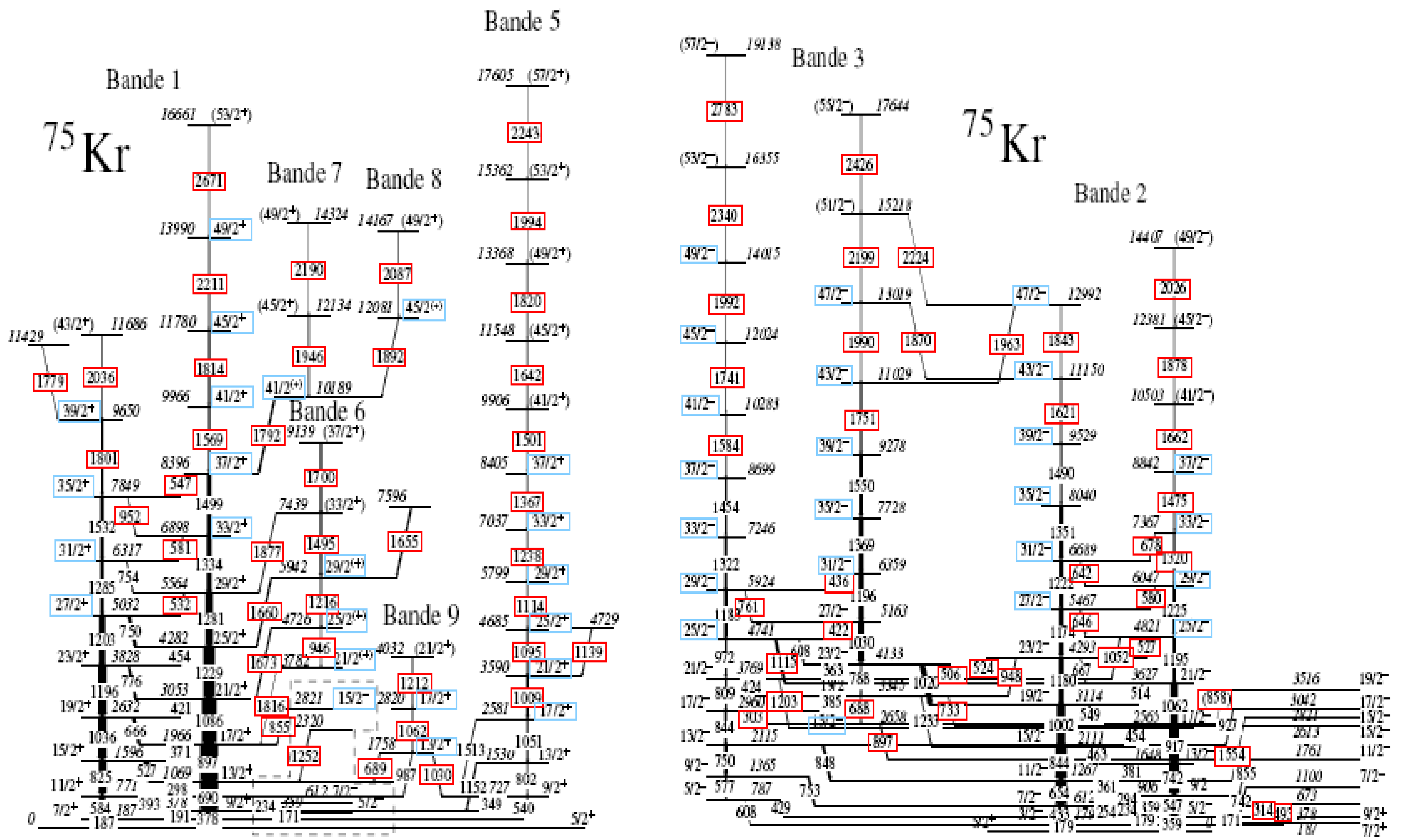
$$|I_i - I_f| \leq L \leq I_i + I_f$$

$$\Delta\pi(EL) = (-1)^L$$

$$\Delta\pi(ML) = (-1)^{L+1}$$

A partial level scheme of ^{75}Kr…

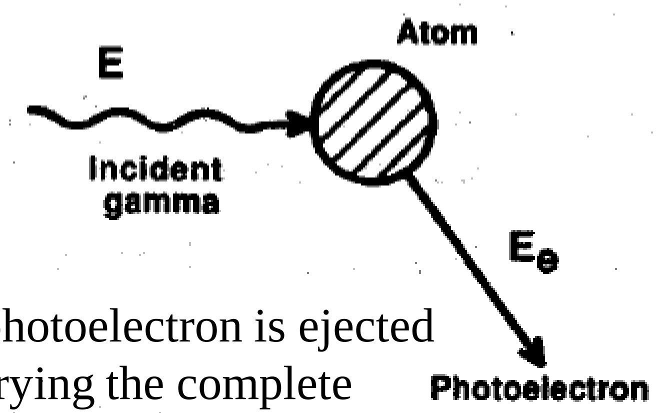
…as an example for the richness of gamma-ray spectroscopic information.



Th. Steinhardt, PhD thesis, Köln (2005)

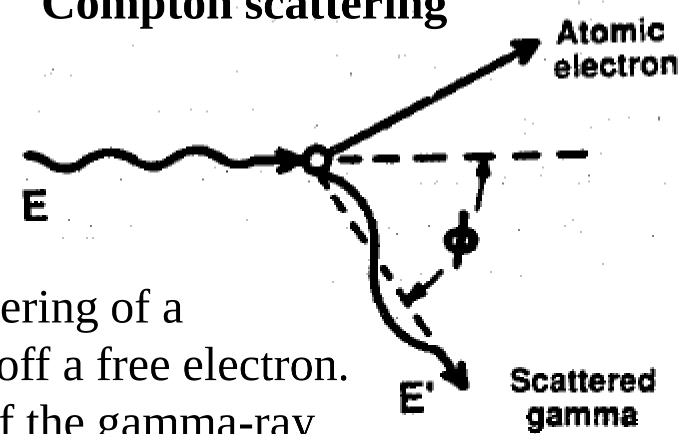
Interaction of gamma rays with matter

Photo effect



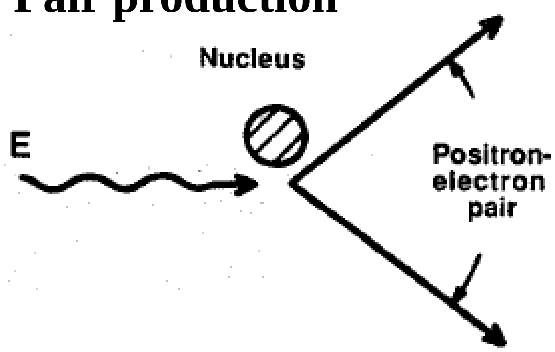
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering



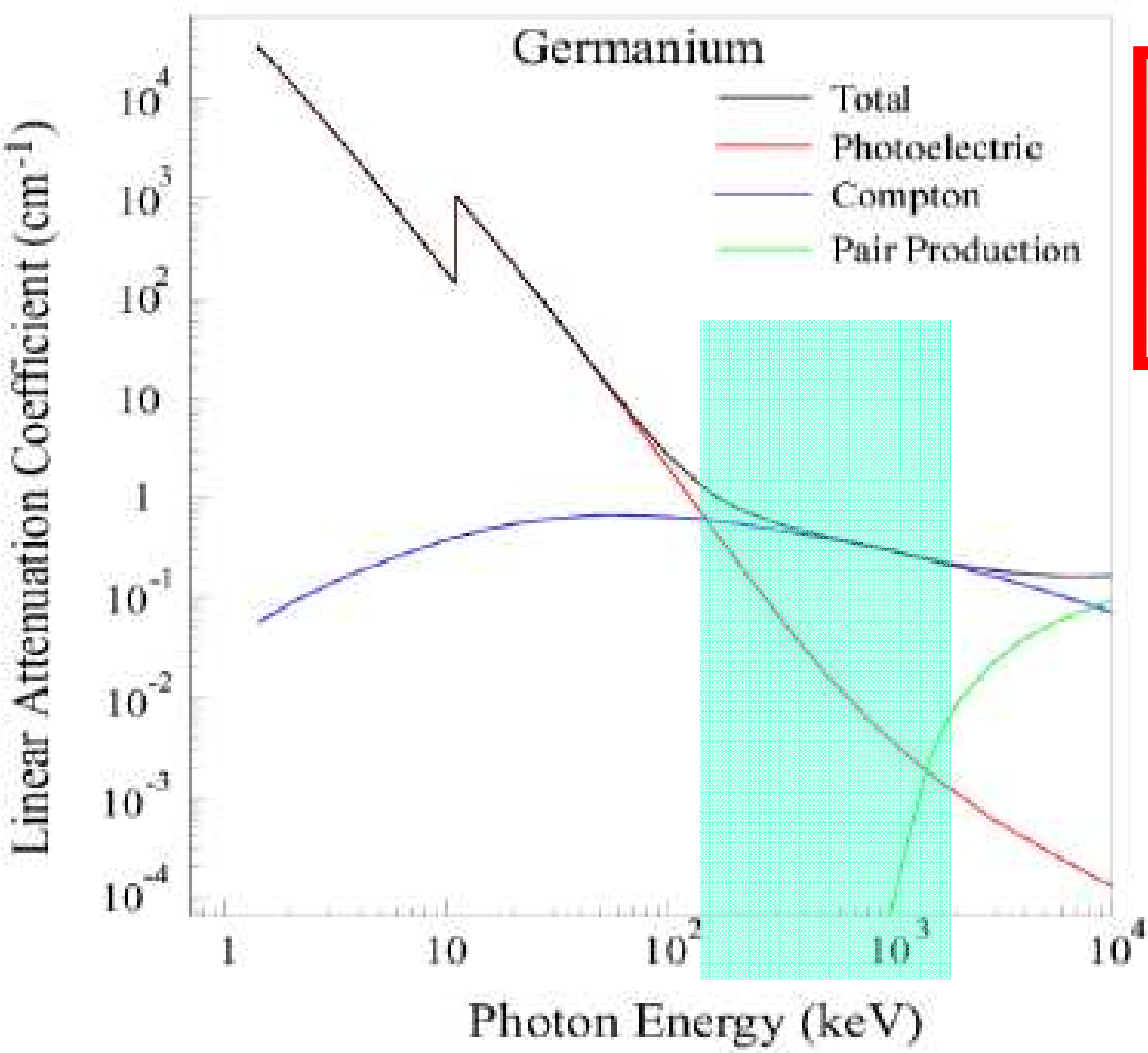
Elastic scattering of a gamma ray off a free electron. A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



If gamma-ray energy is >> 2 m_oc^2 (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 m_oc^2 .

Gamma-ray interaction cross section



300keV-2MeV is typical gamma-ray energy range in nuclear science. Compton scattering is dominant (in Ge)!

Photo effect: ~Z^{4-5}, $E_\gamma^{-3.5}$

Compton: ~Z, E_γ^{-1}

Pair: ~Z^2, increases with E_γ

Compton scattering: More Details

Compton formula:

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}(1 - \cos\theta)}$$

Special case for $E >> m_0 c^2$:
gamma-ray energy after 180° scatter is approximately

$$E' = \frac{m_0 c^2}{2} = 256 \text{ keV}$$

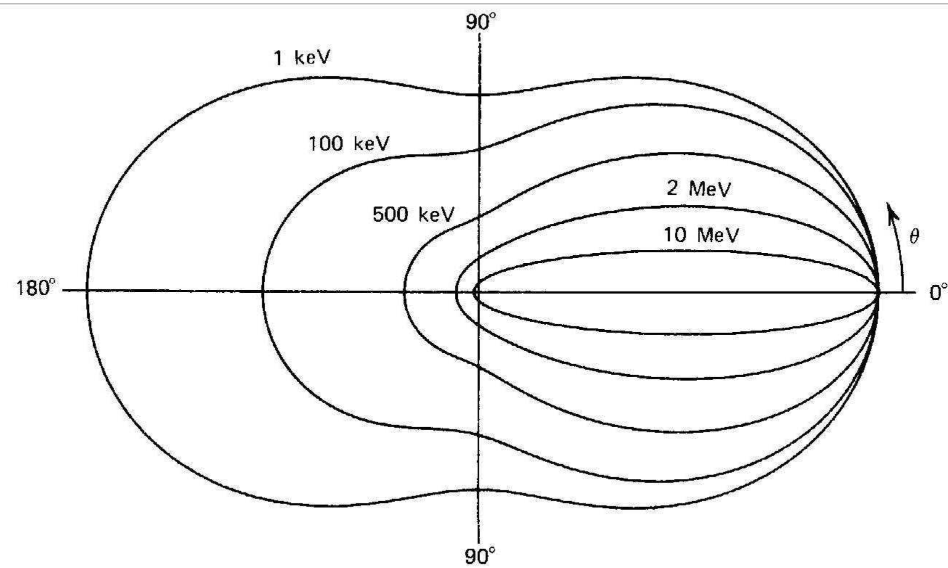


Figure 2-19 A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle θ. The curves are shown for the indicated initial energies.

[KNO]

The angle dependence of Compton scattering is expressed by the

Klein-Nishina Formula

As shown in the plot **forward scattering** (θ small) is dominant for E>100keV

Structure of a gamma-ray spectrum

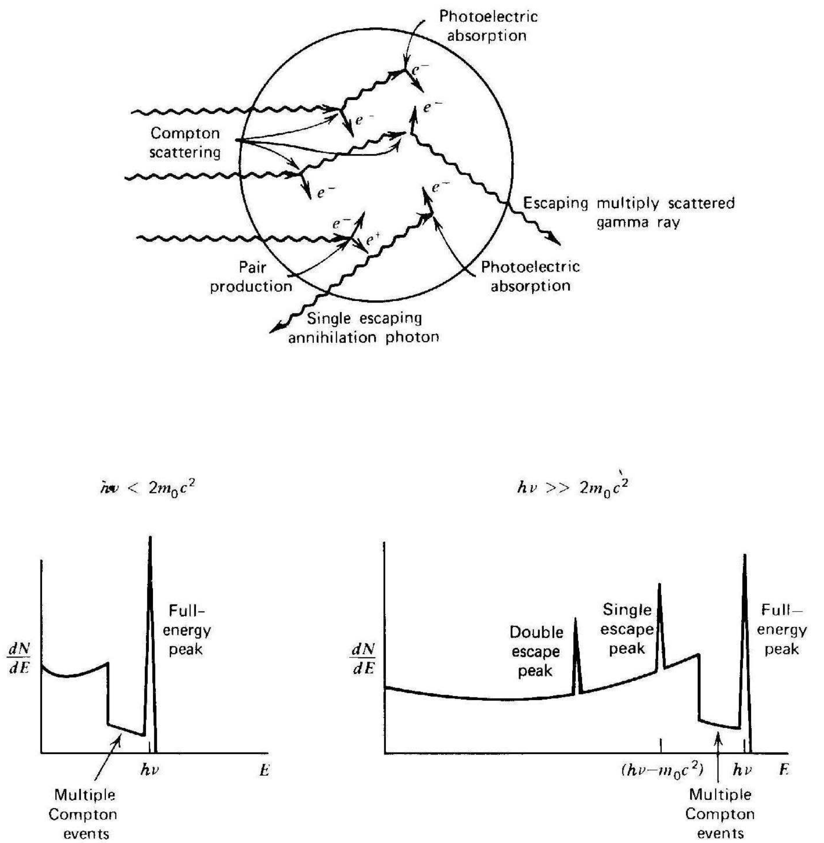


Figure 10-4 The case of intermediate detector size in gamma-ray spectroscopy. In addition to the continuum from single Compton scattering and the full-energy peak, the spectrum at the left shows the influence of multiple Compton events followed by photon escape. The full-energy peak also contains some histories that began with Compton scattering. At the right, the single escape peak corresponds to initial pair production interactions in which only one annihilation photon leaves the detector without further interaction. A double escape peak as illustrated in Fig. 10-2 will also be present due to those pair production events in which both annihilation photons escape.

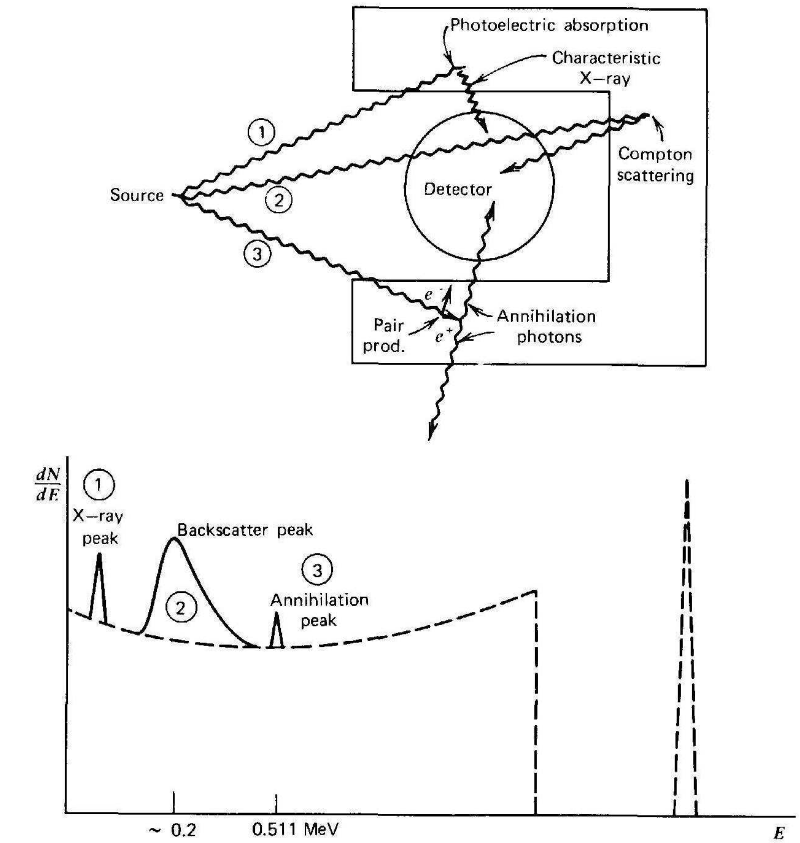


Figure 10-6 Influence of surrounding materials on detector response. In addition to the expected spectrum (shown as a dashed line), the representative histories shown at the top lead to the indicated corresponding features in the response function.

[KNO]

Scintillator

Scintillators are materials that produce ‘small flashes of light’ when struck by ionizing radiation (e.g. particle, gamma, neutron). This process is called ‘**Scintillation**’.

Scintillators may appear as solids, liquids, or gases.

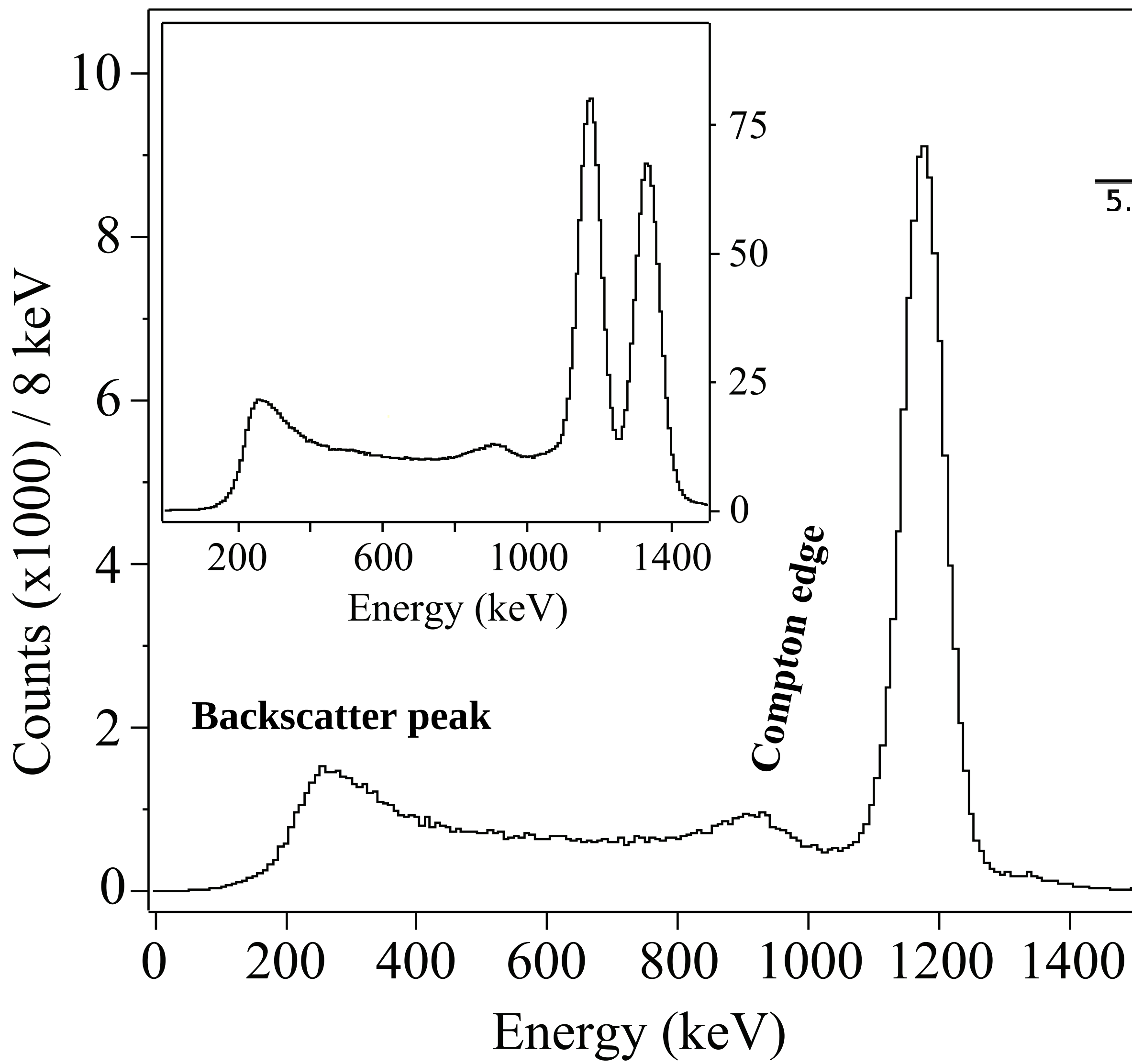
Major properties for different scintillating materials are:

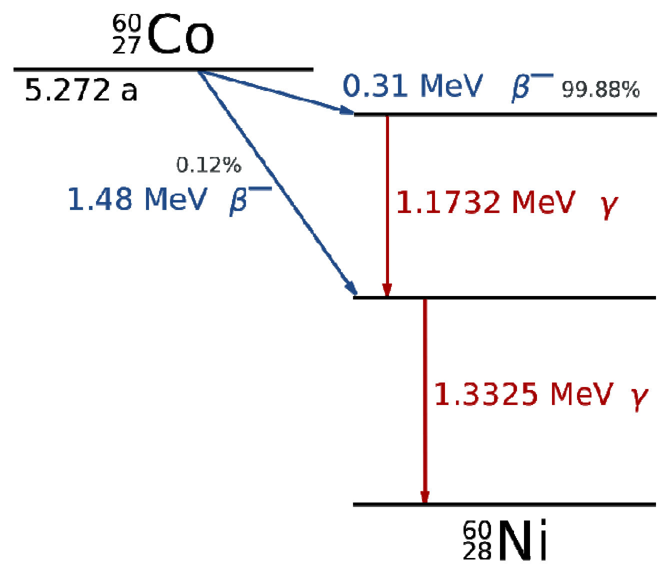
- ➢Light yield and linearity **(energy resolution)**
- ➢How fast the light is produced **(timing)**
- ➢Detection efficiency

Organic Scintillators (“plastics”):
Light is generated by fluorescence of molecules; usually fast, but low light yield

Inorganic Scintillators:
Light generated by electron transitions within the crystalline structure of detector; usually good light yield, but slow

Scintillator spectrum (here CsI(Na))



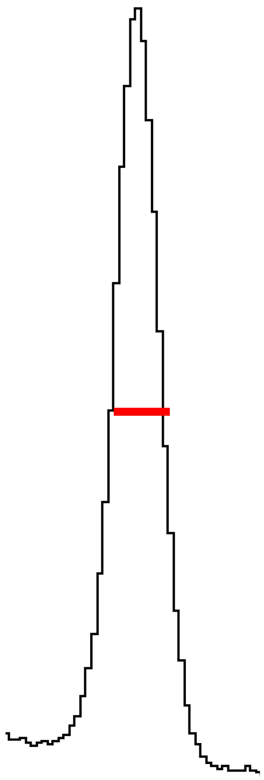


Detector characteristics:

- ❖Energy resolution
- ❖Efficiency
- ❖Peak-to-Total

  (i.e. "Probability that a *detected* γ ray actually makes it into the peak")

Resolution



Our peak has a Gaussian shape with a FULL-WIDTH-HALF-MAXIMUM of 5% (dE/E).

Usually a (Gaussian) distribution is parameterized by its standard deviation σ.

Standard deviation σ and FWHM for a Gaussian have the relationship:

$$FWHM = 2.35\ \sigma$$

but can we understand the value of 5%.......?

Let's roll a dice: Binomial Distribution

What is the probability P(x) to roll x times a 'six' if you try n times?
Answer: The binomial distribution (with $p = 1/6$)

$$P(x) = \frac{n!}{(n-x)!\,x!}\, p^x (1-p)^{n-x}$$

The mean value

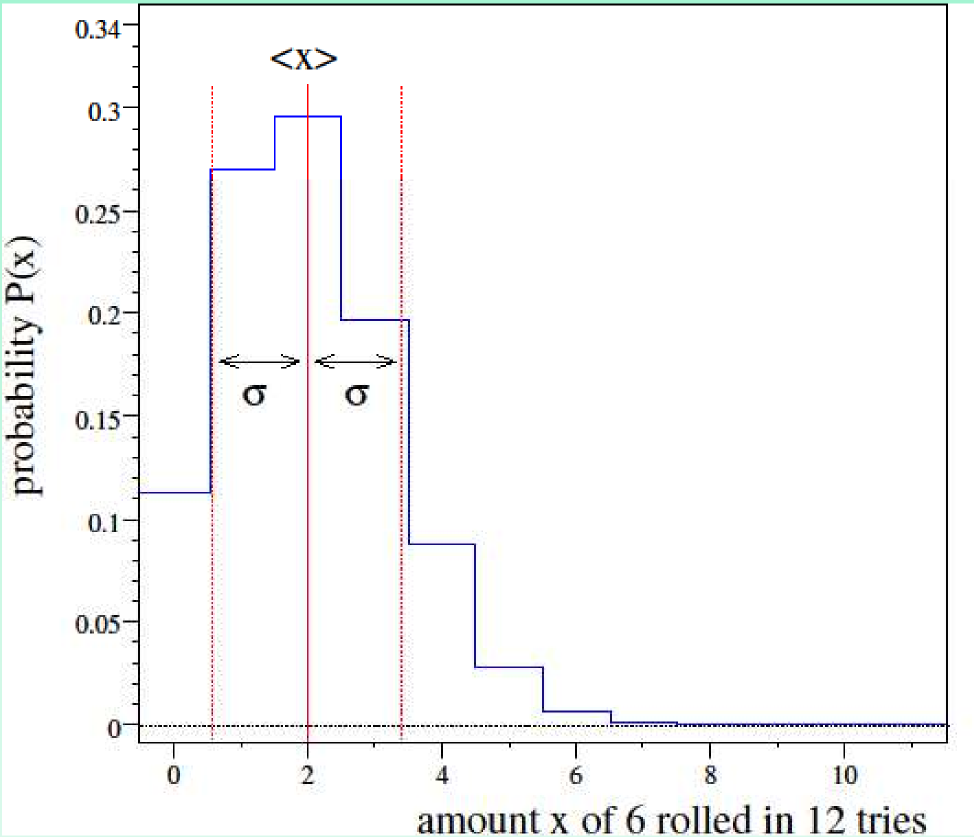
$$< x > = \sum_{x=0}^{n} P(x)\, x$$

for the bin. dist. is np

And the variance

$$\sigma^2 = \sum_{x=0}^{n} (x - < x >)^2 P(x)$$

is np(1-p).



Poisson statistics

Imagine a dice with 100 sides. And you try it 1000 times and ask again how often a six shows up.
In this case p << 1 and n large the binomial distribution reduces to the **Poisson distribution**:

$$P(x) = \frac{(pn)^x \, e^{-pn}}{x!}$$

For the Poisson distribution still holds <x> = np and the variance is $\sigma^2 = np$ (= <x>)!!

The **standard deviation** of a **Poisson distribution** is:

$$\sigma = \sqrt{< x >}$$

Poisson statistic and nuclear science

Mostly counting experiments are done like “How many events C do I count if a beam of nuclei B hit a target A ?” The cross section for producing event C is low, beam means many nuclei B are shot on target nuclei A. So the counting statistics will follow the **Poisson Distribution** and **if we count N events C, its error is $\sqrt{N}$.**

Same applies for our scintillation detector:
An energetic particle is traveling through the detector (e.g. electron from gamma ray interaction). Per travelling length dx this particle may produce a scintillation photon, which may make it to the photo-cathode, which may be converted into a photo-electron in the PMT and contribute to the signal.

Example: CsI(Tl) does 39.000 photons per 1 MeV gamma. Light collection and PMT quantum efficiency ~15% → ~6000 photons are collected in average. $\sigma = \sqrt{6000} = 77$. FWHM=2.35 * 77 = 180. →dE/E = 180/6000 = 3%.

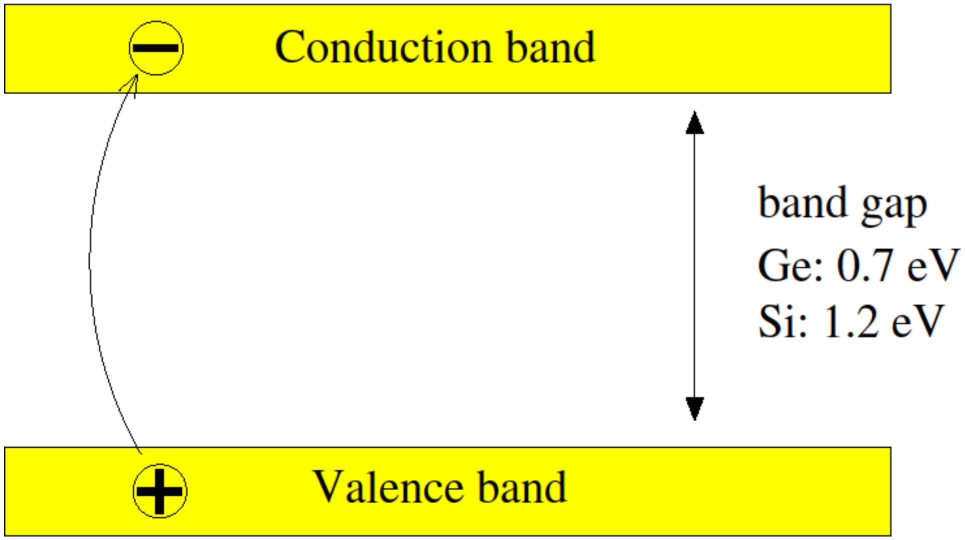
Semiconductor detectors

For **better energy resolution** Poisson distribution tells us:

We need a lot more (charge) carriers!

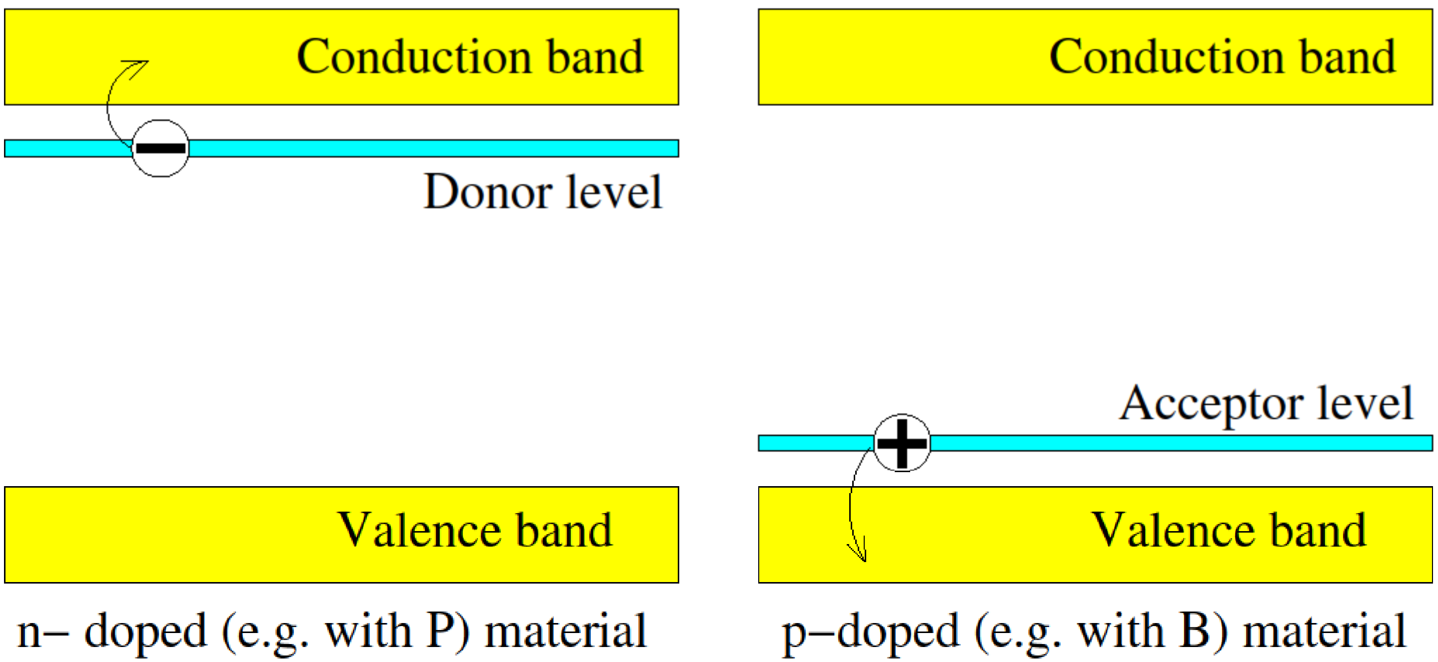
In a scintillator 1 carrier (photoelectron) cost us more than 150eV of incident energy.

Basic idea for using a semiconducter:
Because of the narrow band structure (~eV) it does cost us only a few eV to create an electron-hole pair!



Real-life problems:
Lifetime of electron-hole pair has to be long enough so we can collect them
and
How do we collect them anyway?

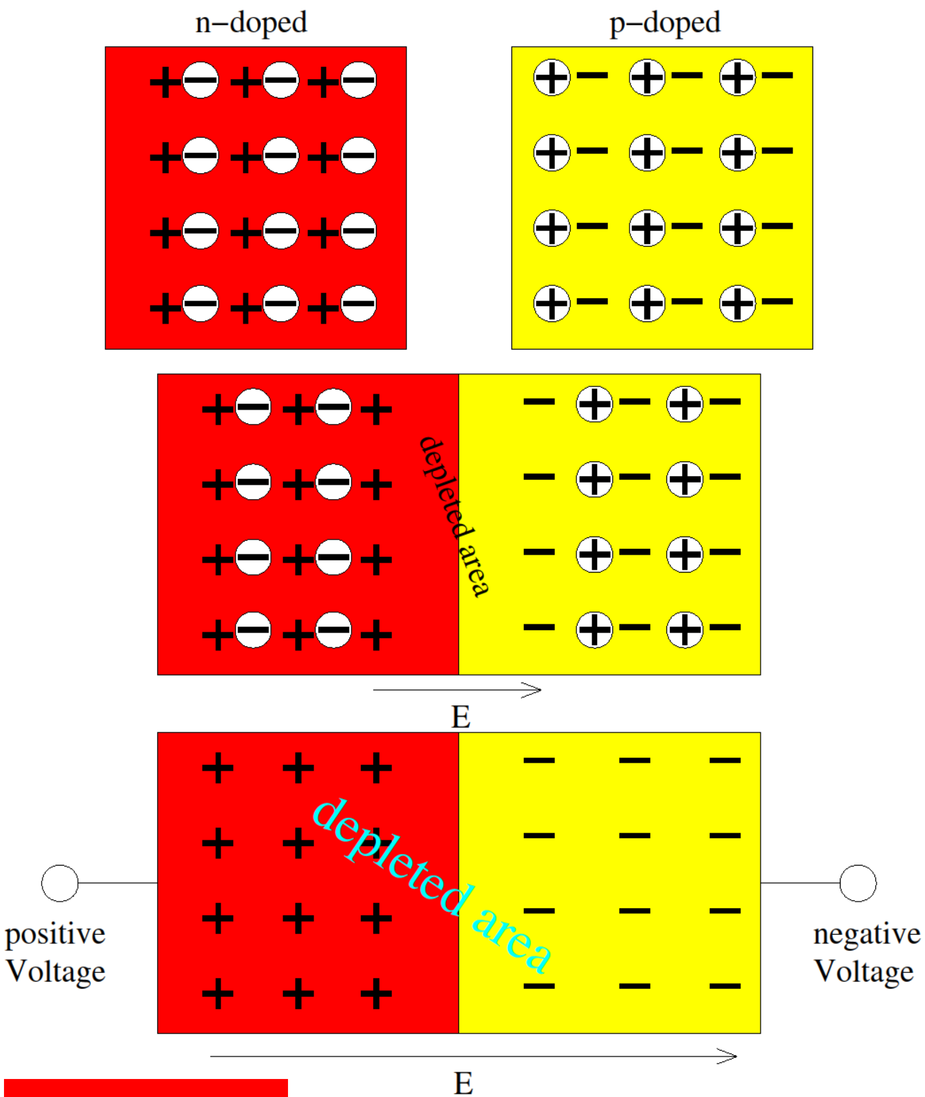
n- and p-doped semiconductor material



Even the purest materials contain impurities which make them n- or p-doped.
Purest materials obtained are germanium ($<10^{10}$ impurities per cm^3) and silicon (10^{12} impurities per cm^3). For comparison 1 cm^3 Ge or Si contains 10^{22} atoms!

(not shown)

Depletion and reverse biasing



(not shown)

Doped material is electrical neutral.

If n- and p-doped material are brought in contact, diffusion of the mobile charge carriers starts. The ionized atoms remain and create an electric field E stopping further diffusion. A **depleted** area is formed (no free, mobile charges here)

Reverse biasing increases the depleted area. Charges created here (e.g. by radiation) will travel along electric field lines towards the electrodes. The achievable width **d** depends on doping concentration **N** and bias voltage **V: $d^2 \sim V/N$** [KNO]

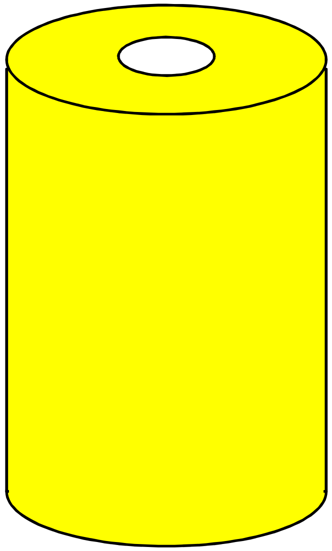
For large(r) d:

→low doping concentration N, i.e. pure material

→high bias voltage, i.e. high resistivity (=small N)

Making a **H**igh **P**urity **Ge**rmanium detector

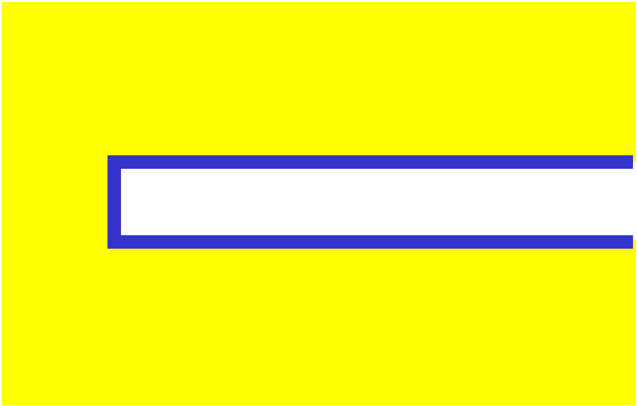
1) Start with high-purity, n-type Ge crystal ($4000-$40.000 depending on size)



(not shown)

Making a High Purity Germanium detector

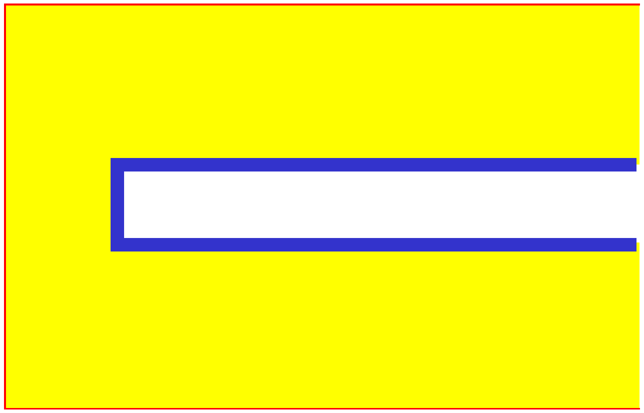
1) Start with high-purity, n-type Ge crystal ($4000-$40.000 depending on size)
2) Li-diffused n+ contact, thickness ≥0.6mm



(not shown)

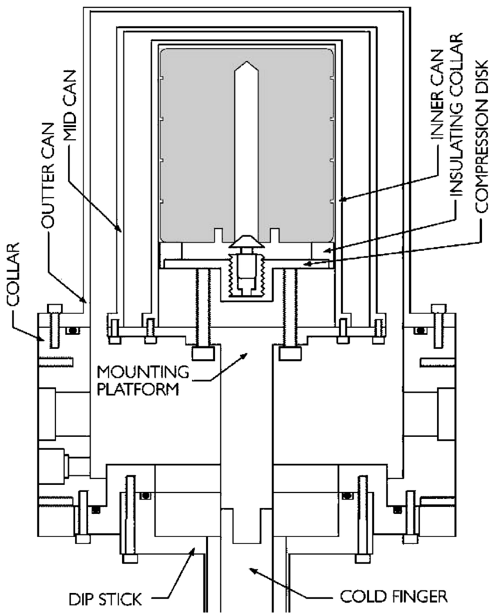
Making a **High Purity Germanium** detector

1) Start with high-purity, n-type Ge crystal ($4000-$40.000 depending on size)
2) Li-diffused n+ contact, thickness ≥0.6mm
3) Ion-implanted (B) p+ contact (pn junction), thickness ~0.3µm

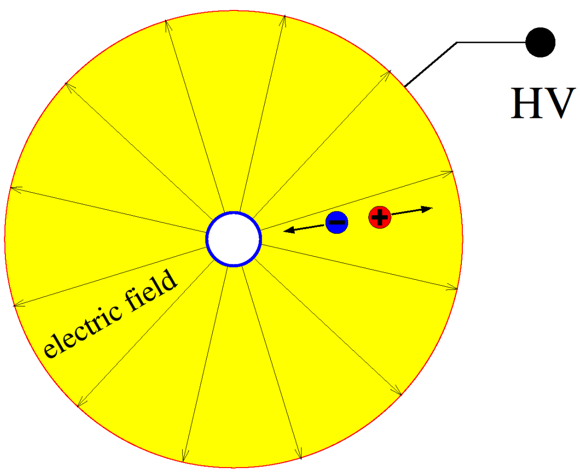


(not shown)

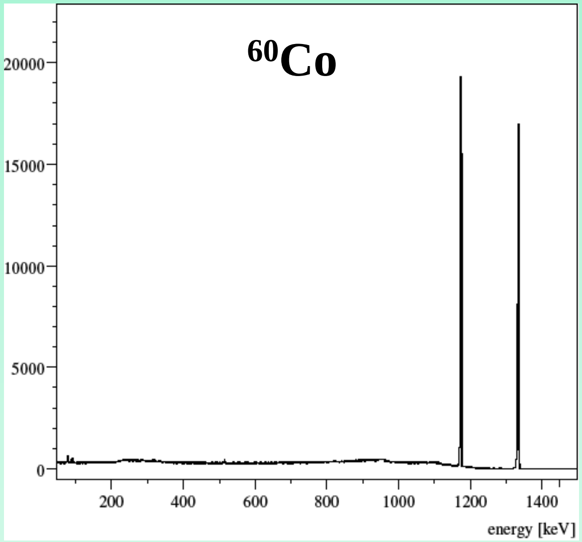
Making a High Purity Germanium detector



G.S. King et al.,NIM A595 (2008) 599-



1) Start with high-purity, n-type Ge crystal ($4000-$40.000 depending on size)
2) Li-diffused n+ contact, thickness ≥0.6mm
3) Ion-implanted (B) p+ contact (pn junction), thickness ~0.3μm
4) Mount into cryostat, cool down to 100K, apply bias voltage, enjoy your detector:



The hard part: **Don't spoil purity of the Ge crystal** (HPGe 10^{10} imp./cm^3; e.g. 1ng Cu = 10^{13} atoms and 10^9 Cu atoms per cm^3 already deteriorates FWHM [L. Van Goethem et al., NIM A240 (1985) 365-])

Energy resolution Ge vs NaI(Tl) scintillator

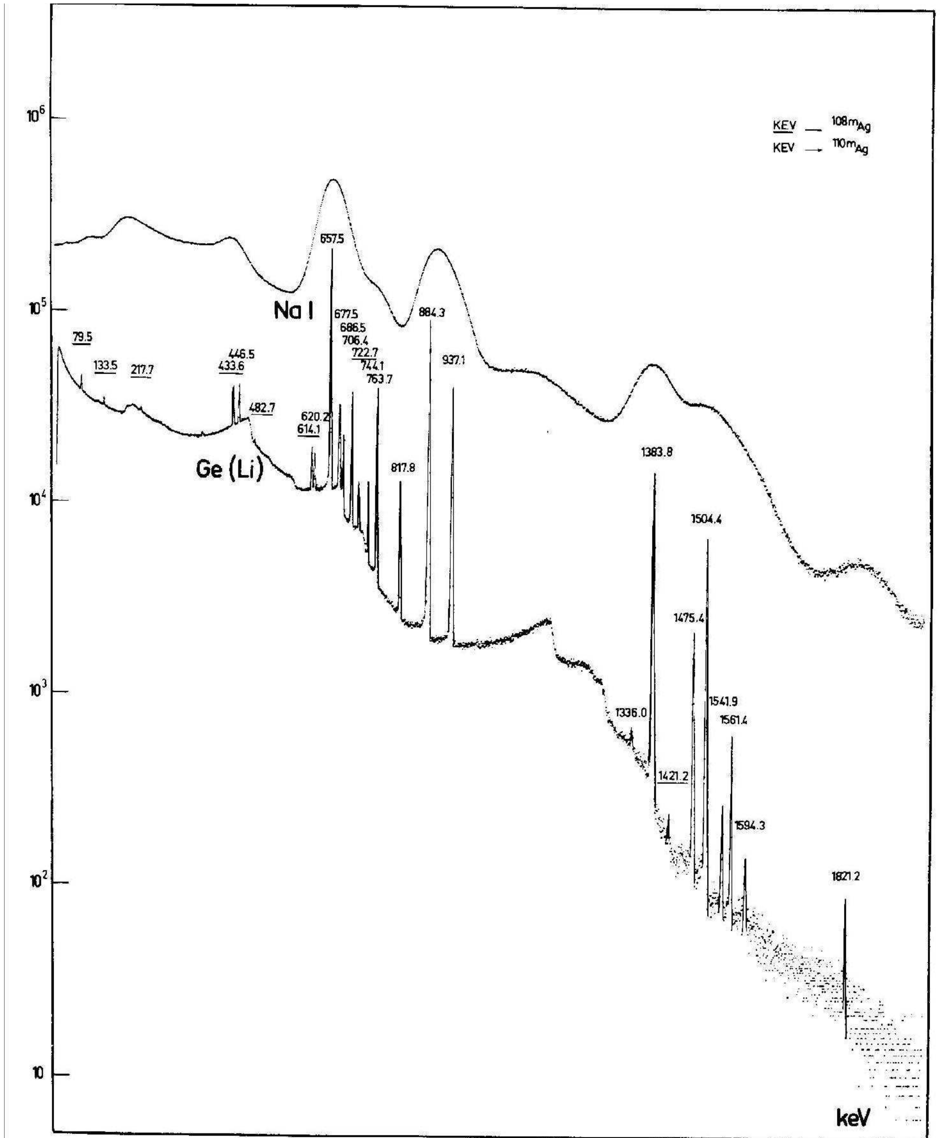


Figure 12-6 Comparative pulse height spectra recorded using a sodium iodide scintil-

Energy resolution for Ge is one order of magnitude better than scintillators.

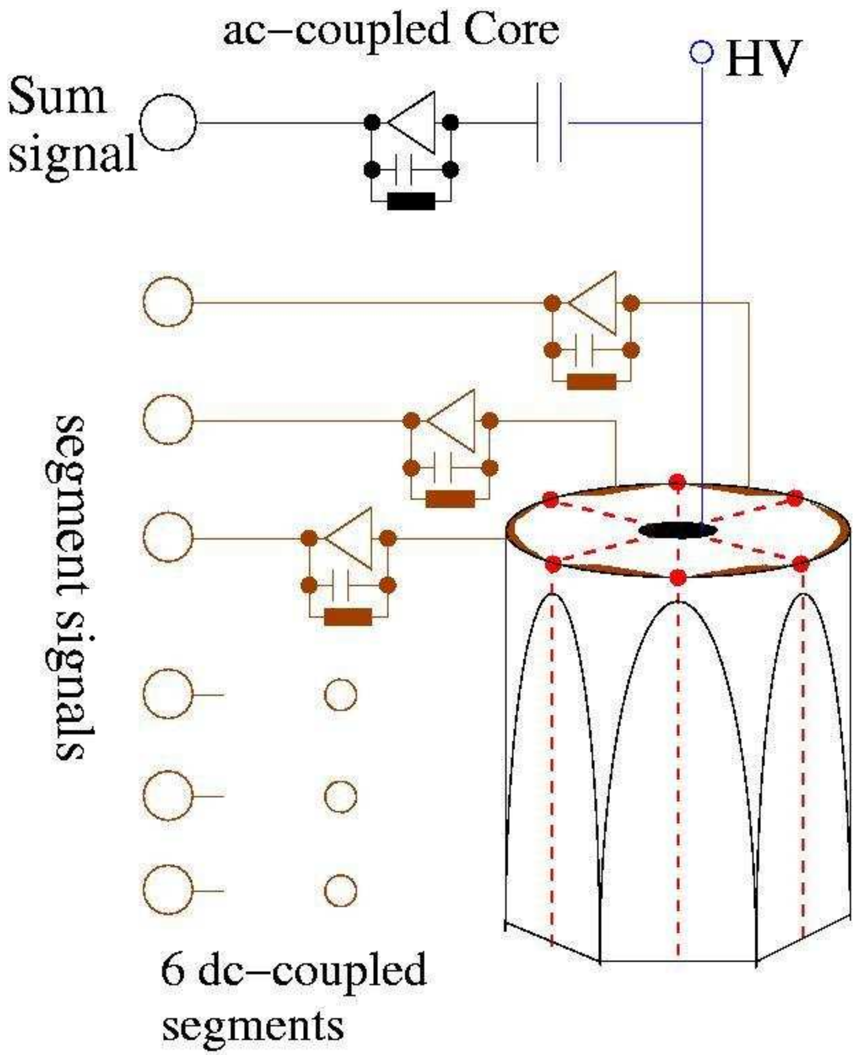
Why did we even talk about scintillators?

a) Ge detectors are VERY expensive and fragile devices (>> $10.000)
b) Ge detector crystals can't be made as big as scintillators. Scintillators offer higher Z materials.
c) Ge detectors need complex infrastructure (cooling).
d) Scintillators offer better timing (<<1ns). Ge: 5-10ns

Energy resolution of a germanium detector is 2keV at 1MeV (0.2%)

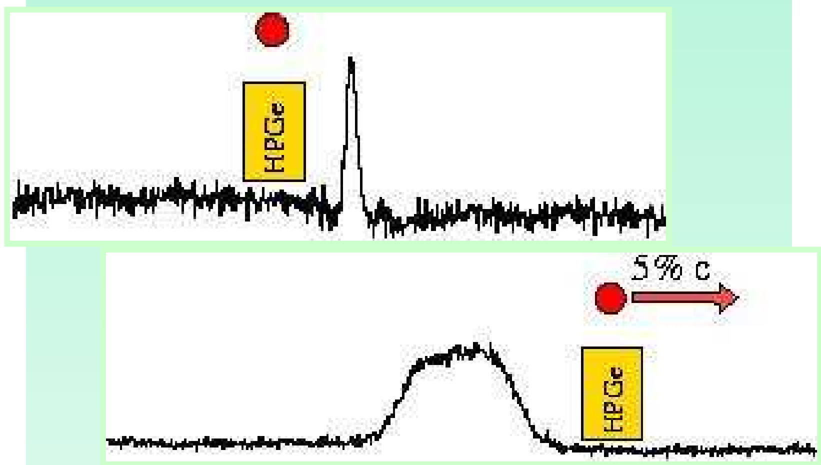
[KNO]

Position-sensitive Ge-detectors



Task:
Find out where within the Ge volume the γ-ray interaction(s) happened.
Technical:
Leave "small" gaps in the outer p^+ contact (e.g. using masks) and tag the contact collecting the charges.

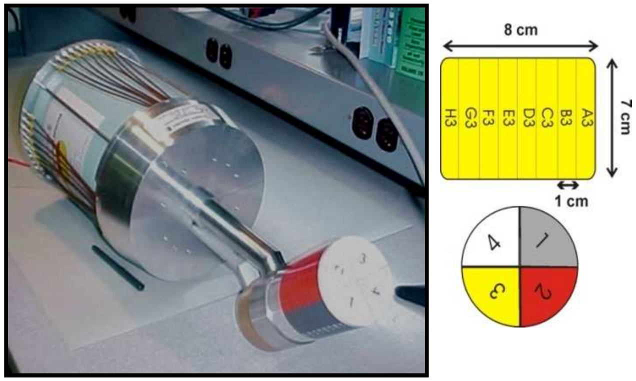
What is it good for?
→Smaller effective opening angel.
Doppler broadening!



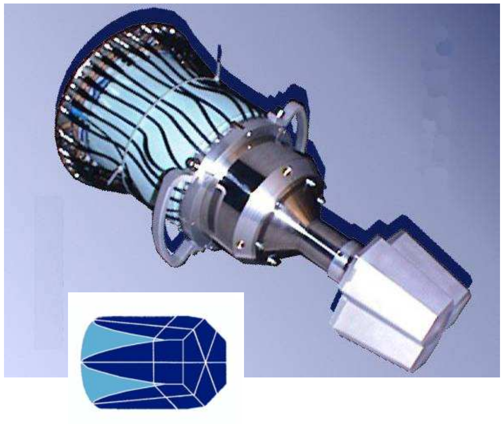
(More details on Doppler later…)

Segmented HPGe detetctors

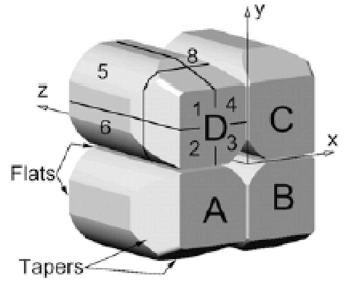
SeGA (NSCL)



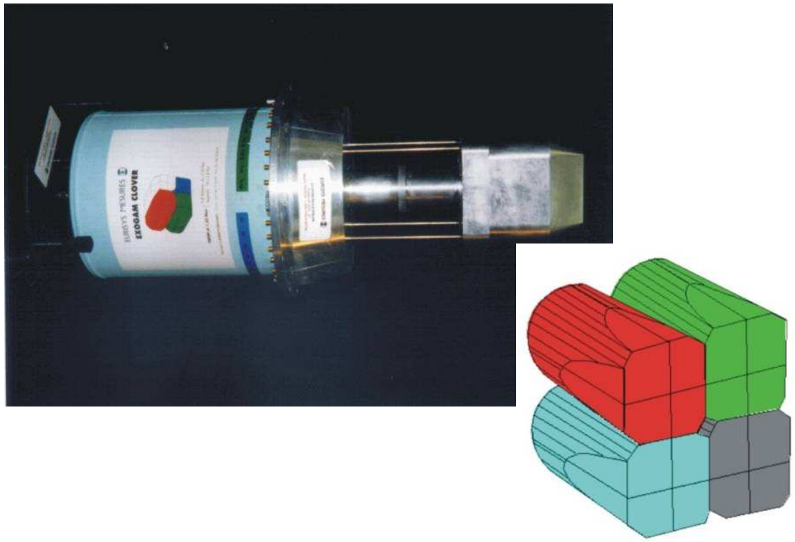
MINIBALL (CERN)



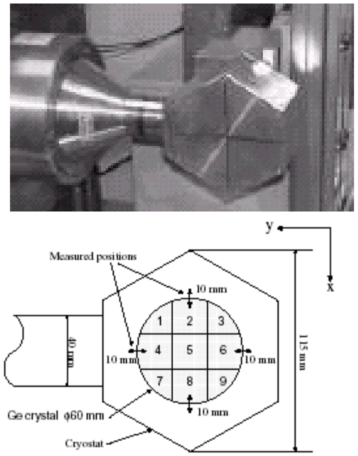
TIGRESS (TRIUMF)



EXOGAM (GANIL)

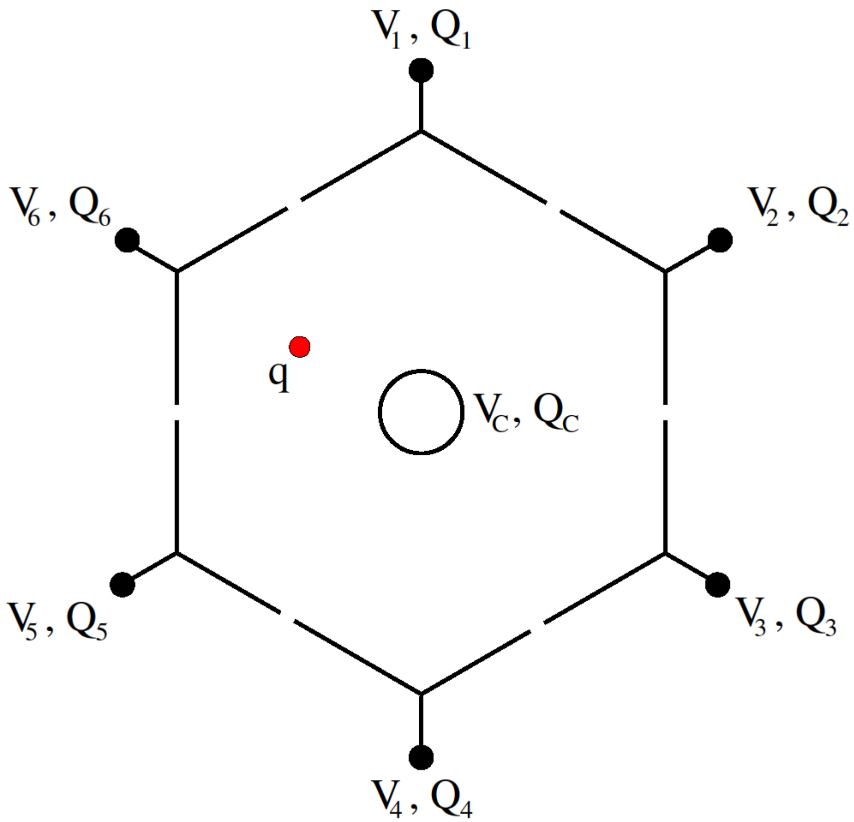


GRAPE (RIKEN)



Detector signal generation

Step 1:
Describe the detector as a network of electrodes.
Step 2:
Place a charge q in the detector volume.
Step 3:
Charge q induces mirror charges Q_x on each electrode depending on the geometry and its location.
Step 4:
Charge q travels along the electric field lines (HV), changes therefore its location.
Step5:
Go to Step 3, until charge q got collected on an electrode.



Steps 3, 4, 5 can be computed using Ramo's Theorem*. I'll skip in this presentation a detailed description how to do that quantitatively (lack of time), but move on with 'hand-waving' qualitative explanation .

*[S. Ramo, Proc. IRE 27(1939)584]

Computing Mirror Charges (1)

(not shown)

We need from electrostatics 101 (J. D. Jackson, "*Classical Electrodynamics*")
Green's 2nd identity for two scalar functions Φ and Φ':

$$\int_V \Phi\Delta\Phi' - \Phi'\Delta\Phi = \int_{\partial V} \Phi \frac{\partial \Phi'}{\partial n} - \Phi' \frac{\partial \Phi}{\partial n}$$

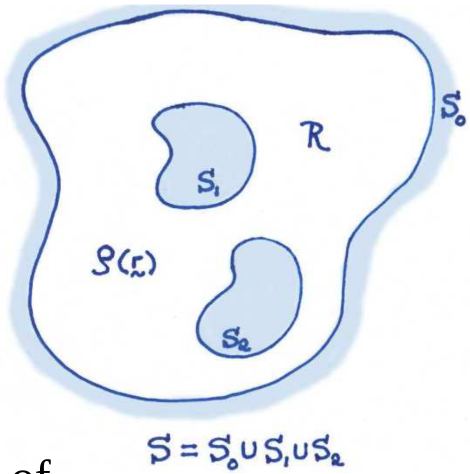
Poisson equation; ρ, ρ':charge distribution σ, σ': surface charge

$$\Delta\Phi = -4\pi\varrho \quad \Delta\Phi' = -4\pi\varrho' \qquad \frac{\partial\Phi}{\partial n} = 4\pi\sigma \quad \frac{\partial\Phi'}{\partial n} = 4\pi\sigma'$$

leads to

Green's reciprocity theorem:

$$\int_V \rho\Phi' + \int_{\partial V} \sigma\Phi' = \int_V \rho'\Phi + \int_{\partial V} \sigma'\Phi$$



In words: "If (Φ,ρ,σ) and (Φ',ρ',σ') are both solutions for a system of same geometry (V, ∂V), they are connected according this relationship."

Computing Mirror Charges (2)

(not shown)

That's quite powerful for us! For our 'hexagon'-system choose following solutions:
(Φ,ρ,σ): ground all electrodes ($V_{1\text{-}6},V_C = 0$), leave charge q
V_x corresponds Φ on ∂V, $\rho(r)=q\,\delta(r-r_q)$ with r_q position of q, σ is Q_x on ∂V
(Φ',ρ',σ')): set one electrode on $V_x=1$, leave others grounded, remove charge q.

Taking the reciprocity relationship:

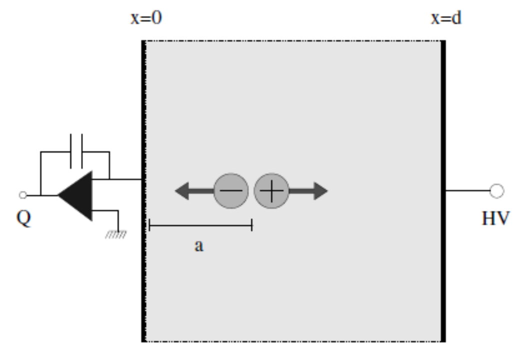
$$\underbrace{\int_V q\,\delta(r-r_q)\,\Phi'(r)}_{=q\,\Phi(r_q)} + \underbrace{\int_{\partial V} \sigma\Phi'}_{=Q_x} = \underbrace{\int_V (\rho' \equiv 0)\Phi + \int_{\partial V} \sigma'\,(\Phi \equiv 0)|_{\partial V}}_{=0}$$

→ Mirror charge on electrode x is $Q_x = -q\,\Phi(r_q)$

What we need to do is solving the potential $\Phi(r)$ for electrode x on $\Phi|_x=1$ and $\Phi|_{\text{other electrodes}}=0$

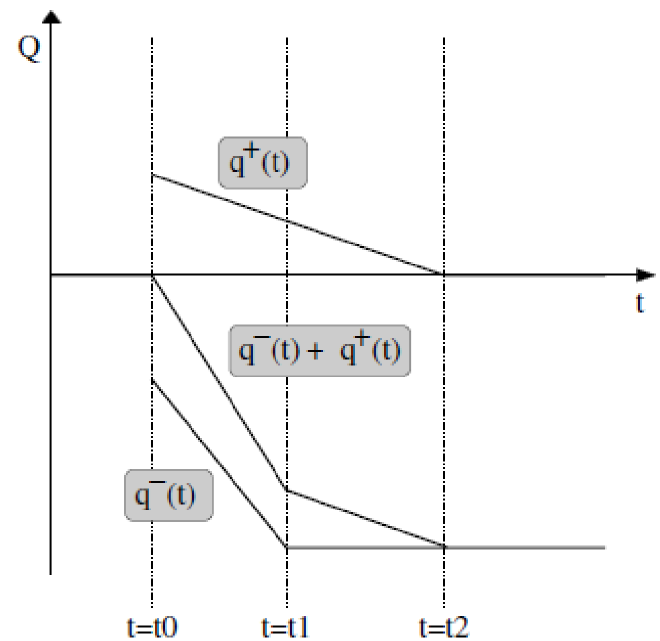
Computing Mirror Charges (3)

(not shown)



Example planar detector:
Compute mirror charge Q on electrode at x=0 for a charge q at distance a (see figure).

Apply recipe: Set electrode x=0 on V=1, the other V=0.
→ $\Phi(x) = (1-x/d)$
→ mirror charge $Q = -q\,(1-a/d)$



Actually, in a real detector radiation produces electrons q^- and holes q^+. q^- travels with velocity **v** towards electrode x=0 and q^+ towards other one. We solve both contributions separately and add them (superposition!).
$q^-(t) = -q\,(1-(a-vt)/d)$ and $q^+(t) = q(1-(a+vt)/d)$
At t=t0 q^- and q^+ are at same position x and their mirror charge contribution cancel. At t=t1 $q^-(t)$ arrives at electrode x=0, $q^+(t)$ still travels. At t=t2 $q^+(t)$ gets collected on other electrode. In total we see sum $q^-(t)+q^+(t)$ as detector signal.

Computing Mirror Charges (1)

(not shown)

One more step:
Charge q runs with velocity **v**(t) (vector) along electric field lines defined by detector material, geometry and applied high voltage. It is worthwhile switching from mirror charge Q(t) to current i(t) induced on an electrode:

$$i(t) = \dot{Q}(t) = -\frac{d}{dt}\, q\, \Phi\big(x(t)\big) = -q\, \nabla\Phi\big(x(t)\big)\, \vec{v}(t) = -q\, \vec{E}_{geo}\big(x(t)\big)\, \vec{v}(t)$$

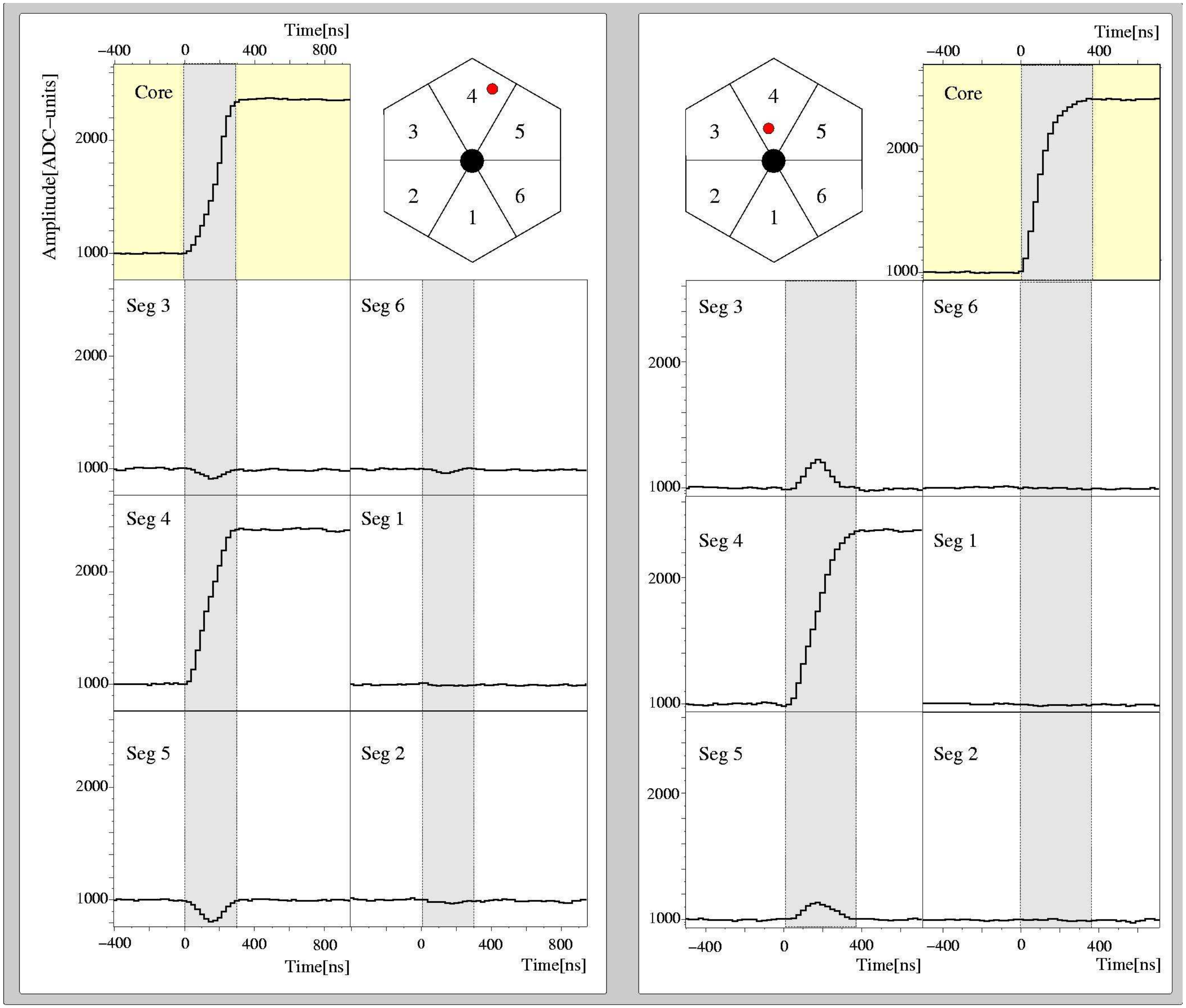
$E_{geo}(x(t))$ is called 'geometric' or 'weighting field' of dimension [1/m] and describes the electrostatic coupling. Don't mistake it with the 'real' electric field in a detector which determines value and direction of **v**(t).
This relationship

$$i(t) = -q\, \vec{E}_{geo}\big(x(t)\big)\, \vec{v}(t)$$

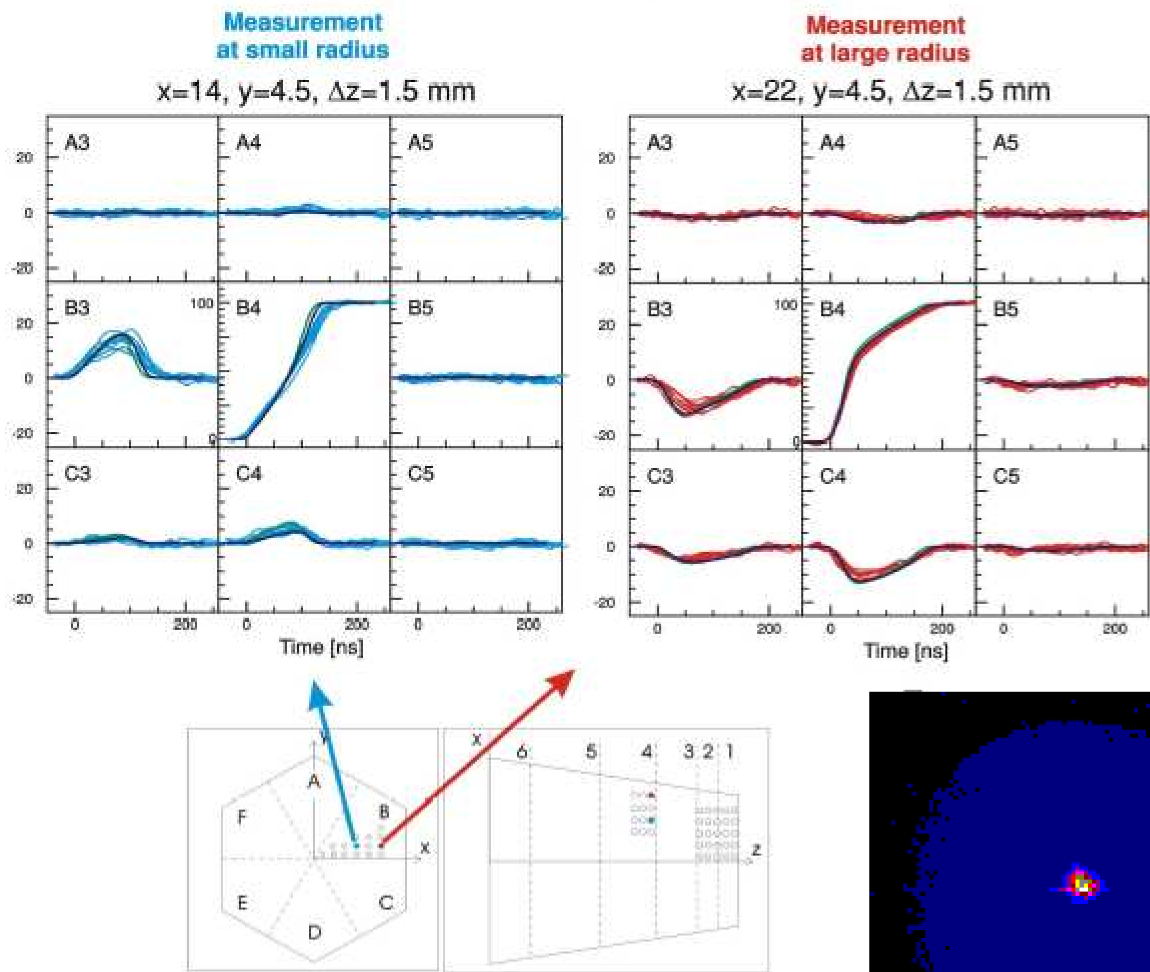
is called **Ramo's theorem** [S. Ramo, Proc. IRE (1939) 584] and is usually used for computing of detector signals.

Exercise: Use Ramo's theorem for solving planar and cylindrical detector geometry!

MINIBALL signals

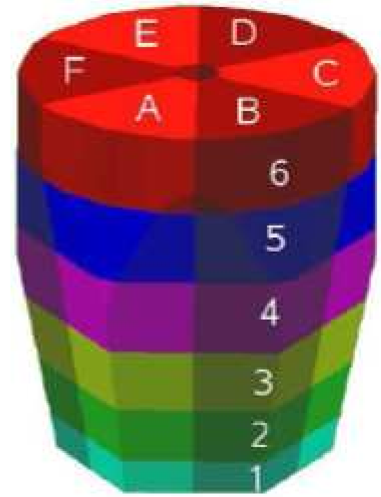


Highly segmented HPGe

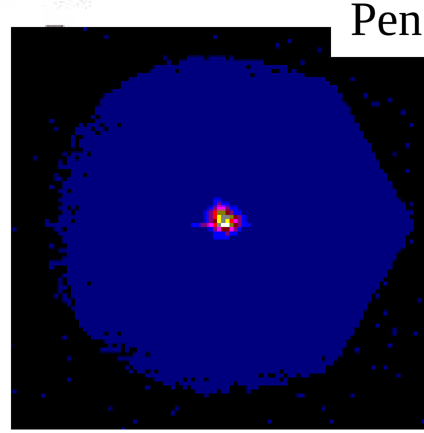


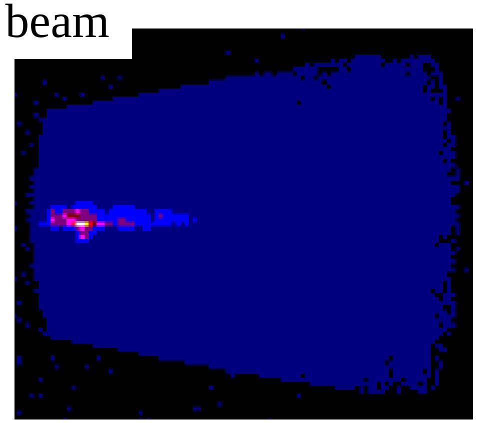
K. Vetter et al., NIM A452 (2000) 223-

36 segments



Pencil beam



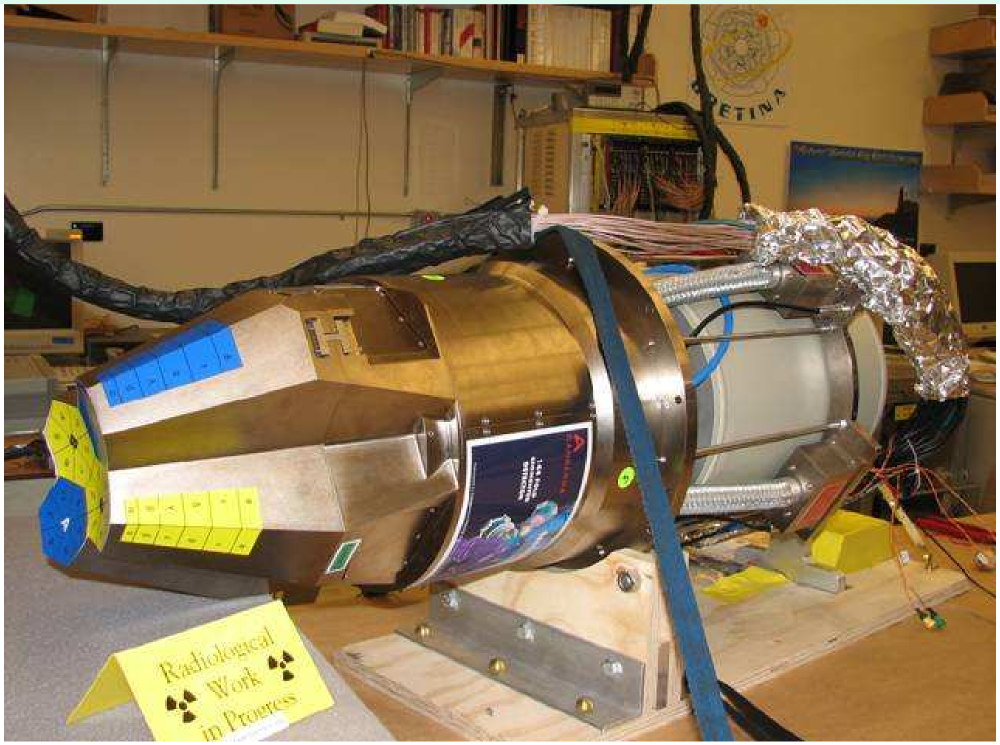


Capable to resolve multiple interaction points (E_x,x_x,y_x,z_x) in crystal!!

Position resolution better then 2mm (rms)!

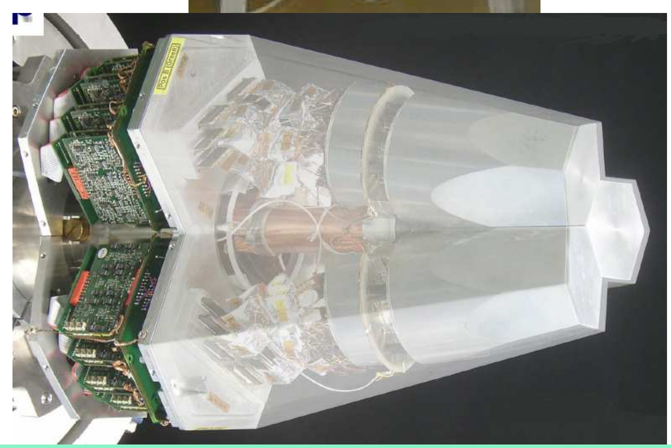
36-fold segmented detectors

Gamma-**R**ay **E**nergy **T**racking **I**n-Beam **N**uclear **A**rray detector module (USA)



GRETINA: Four 36-fold segmented HPGe in a cryostat
AGATA: Three 36-fold segmented HPGe in a cryostat

What it's really good for….later



Advanced **GA**mma-ray **T**racking **A**rray detector module (Europe)

QUIZ

Statement:

"HPGe detectors provide BEST energy resolution for gamma rays"

a) I agree.
b) I don't agree!

QUIZ

Statement:

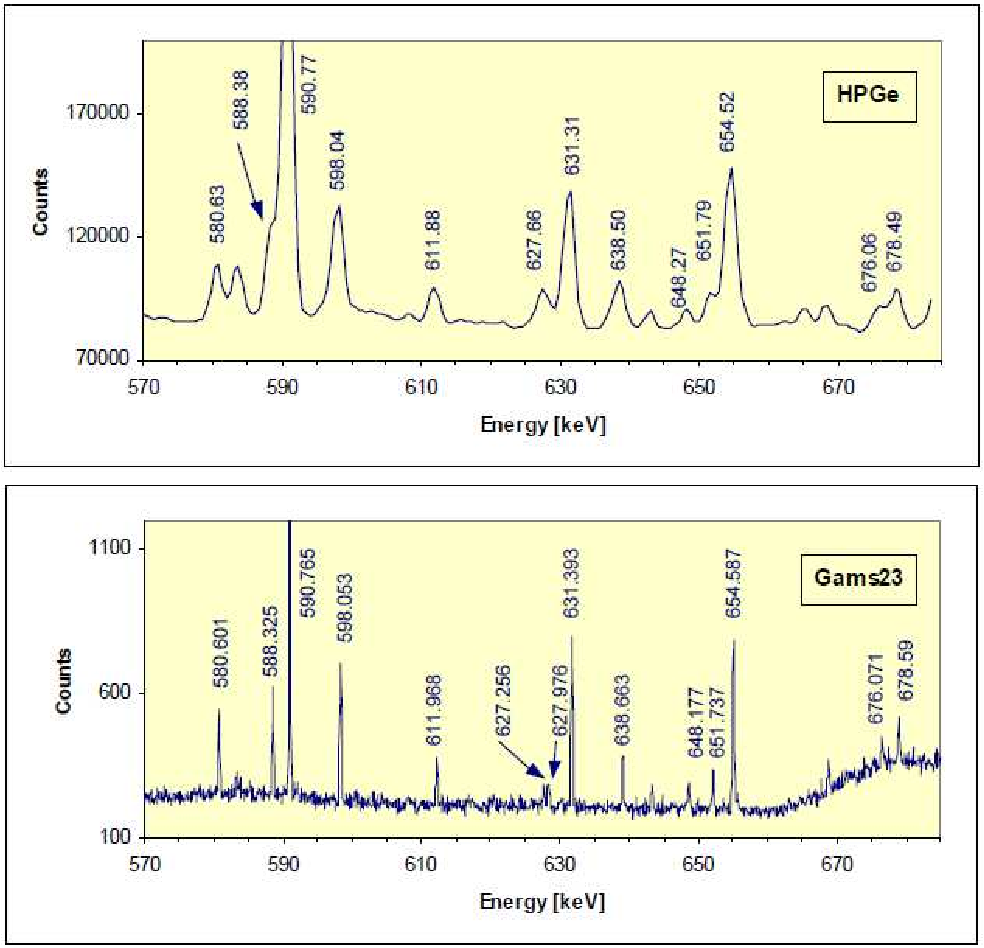
"HPGe detectors provide BEST energy resolution for gamma rays"

a) I agree. (i.e "I believe in Poisson statistics")
b) I don't agree! (i.e. "I believe I-Yang")

Look beyond the rim of …

…your own tea cup: other gamma-ray detectors (which are usually not mentioned in our field)

Figure 2: Part of the spectrum from the $^{99}Ru(n,\gamma)^{100}Ru$ reaction measured with an HPGe detector and the GAMS23 crystal spectrometer



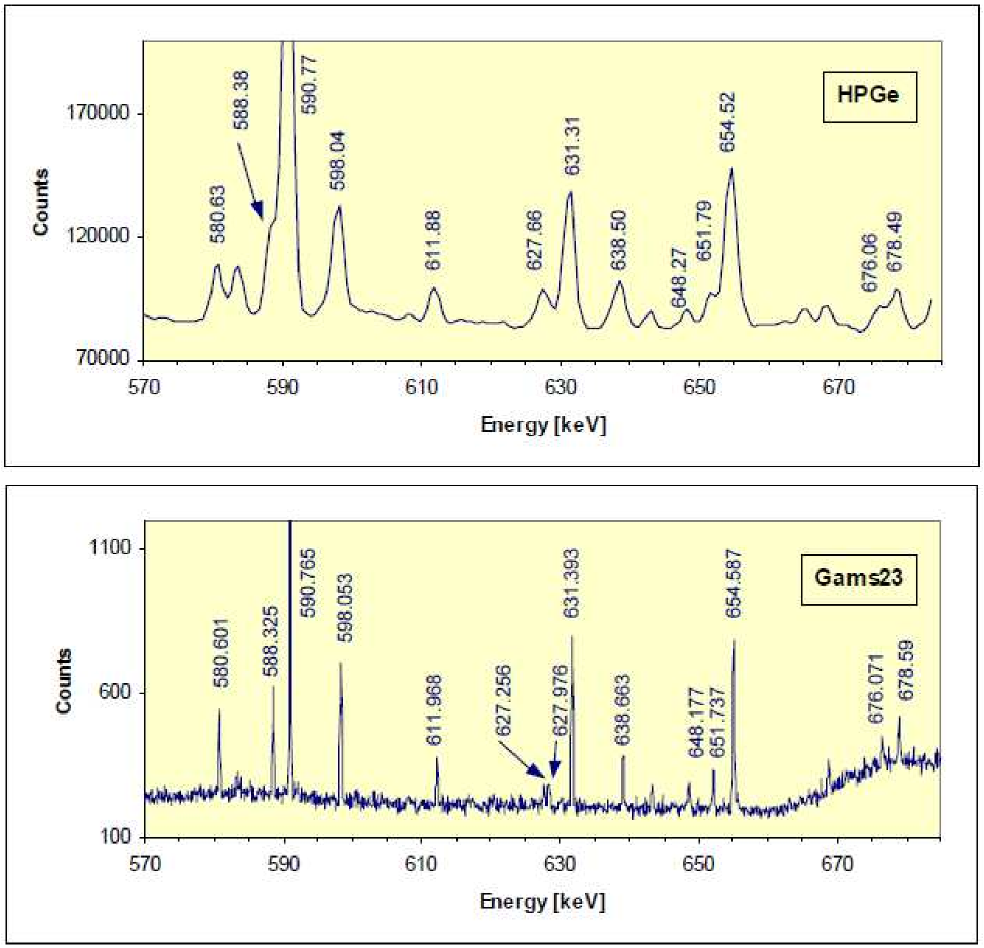
FWHM < 500eV !
How is that possible !?!

L. Genilloud, PhD thesis (2000) Fribourg

Look beyond the rim of …

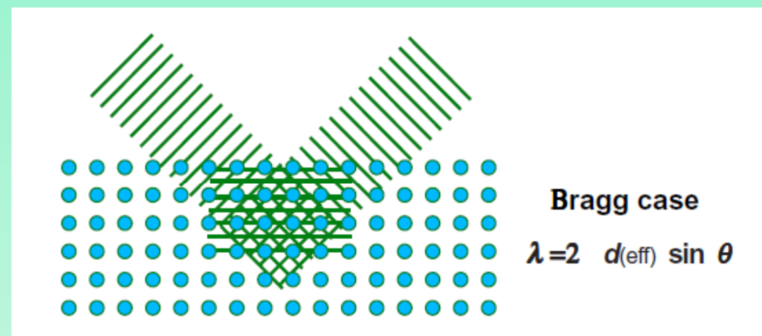
…your own tea cup: other gamma-ray detectors (which are usually not mentioned in our field)

Figure 2: Part of the spectrum from the ^{99}Ru(n,γ)^{100}Ru reaction measured with an HPGe detector and the GAMS23 crystal spectrometer



L. Genilloud, PhD thesis (2000) Fribourg

The trick: **Diffraction spectrometry**
Measure wavelength, not energy, using Bragg diffraction.



More details:
R. D. Deslattes,
J. Res Natl. Inst. Stand. Technol. 105, 1 (2000)
Or google “GAMS5 ILL” or
“DuMond diffractometer gamma”

Energy Resolution: 10^{-3}-10^{-6} (**WOW!**)
Efficiency: 10^{-7} or less (Well, cr*p)
(therefore almost never mentioned in our ‘business’)

Gamma-ray spectrometers

Hulk et al., Univ. Pict. (2003)

…not only good for a daily work-out…

….but also not just many detectors!

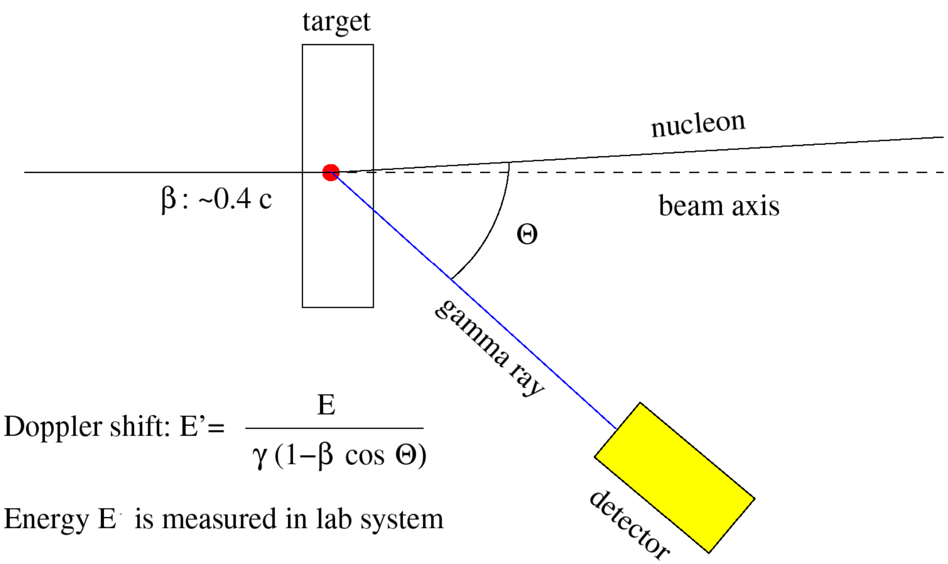
Outline for this section:

1) Design of gamma-ray spectrometers meeting the needs of a particular experiment. Example: Gamma-ray spectroscopy with fast beams (0.4c) at NSCL

2) Resolving Power as a benchmark for gamma-ray spectrometers

Personally I think it's the most important part of this lecture, stay tuned!
(The following you won't find in textbooks…)

Fast beam experiments: Doppler shift



Doppler shift: $E' = \dfrac{E}{\gamma\,(1-\beta\,\cos\,\Theta)}$

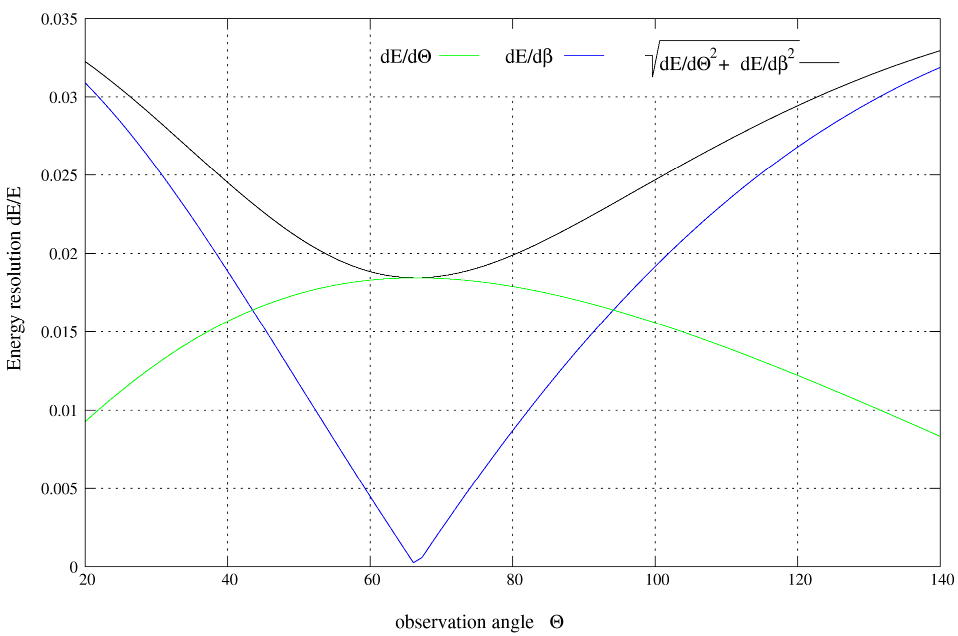
Energy E is measured in lab system

Uncertainties:

ΔΘ: opening angle detector, trajectory of nucleon

Δβ: velocity change in target (unknown interaction depth), momentum spread

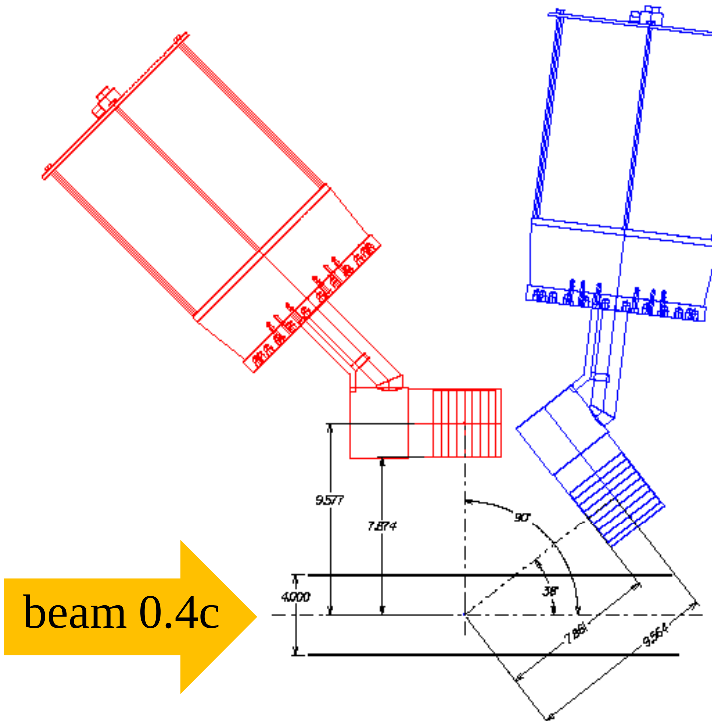
→**Doppler broadening**
(i.e. peak in spectrum becomes wider)



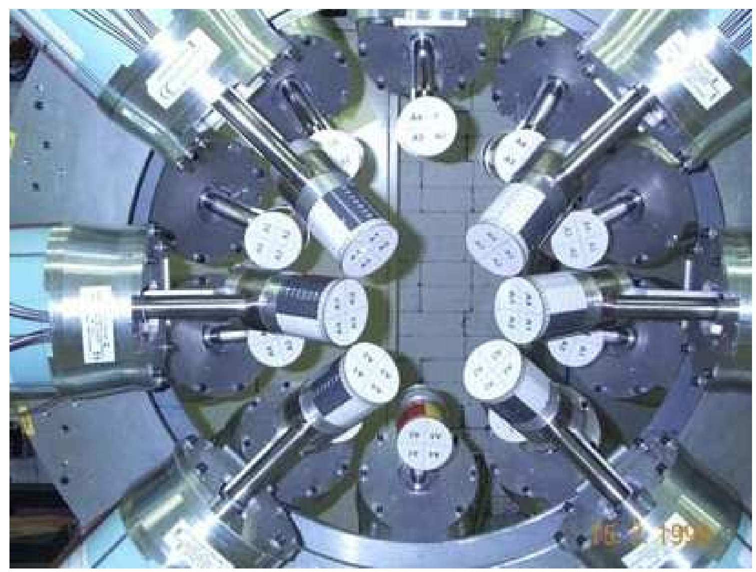
Doppler broadening dE/E at v=0.4c for
$\Delta\Theta = 2.4^{o}$ (SeGA classic)
$\Delta\beta = 0.03$
(recall: HPGe FWHM 0.002)

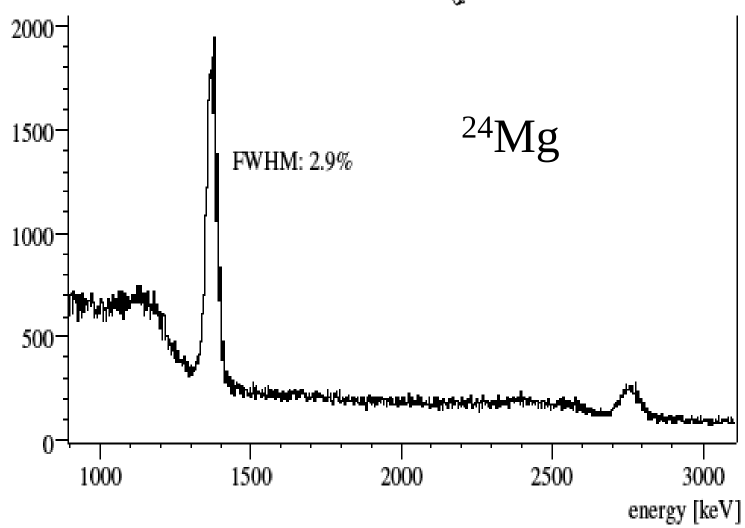
Another important effect: **Lorentz boost**
Forward focusing of gamma-ray distribution in laboratory frame (where the detectors usually are…)

Segmented Germanium Array



SeGA in 'classic' configuration
- o 32-fold segmented HPGe detectors
- o 10 detectors at 90°, 8 at 37°
- o In-beam FWHM 2-3%
- o In-beam ε 2.5% at 1 MeV
- o P/T 0.2

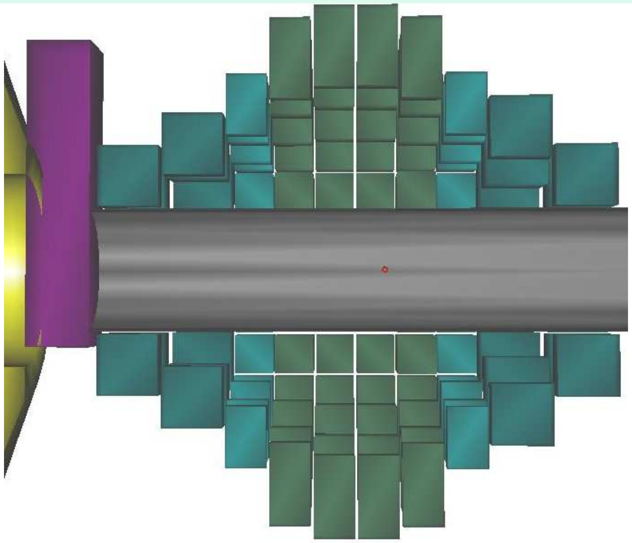


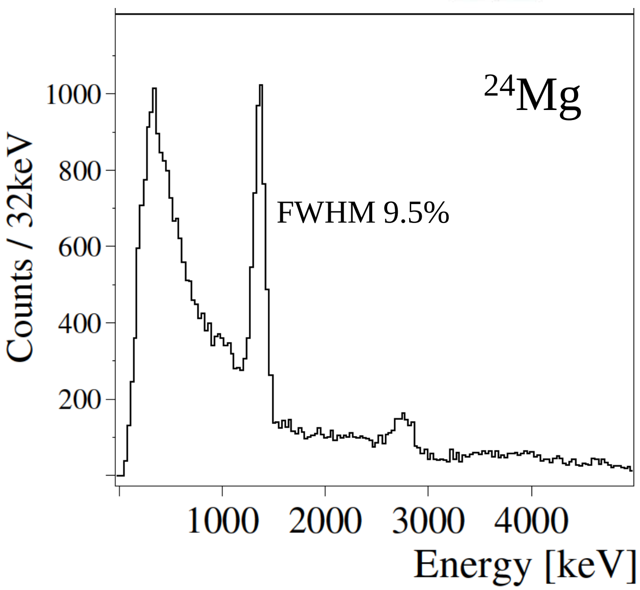


γ spectrum of ^{24}Mg produced in fragmentation reaction of ^{36}Ar on Be. Remember, dE/E=0.2% for Ge

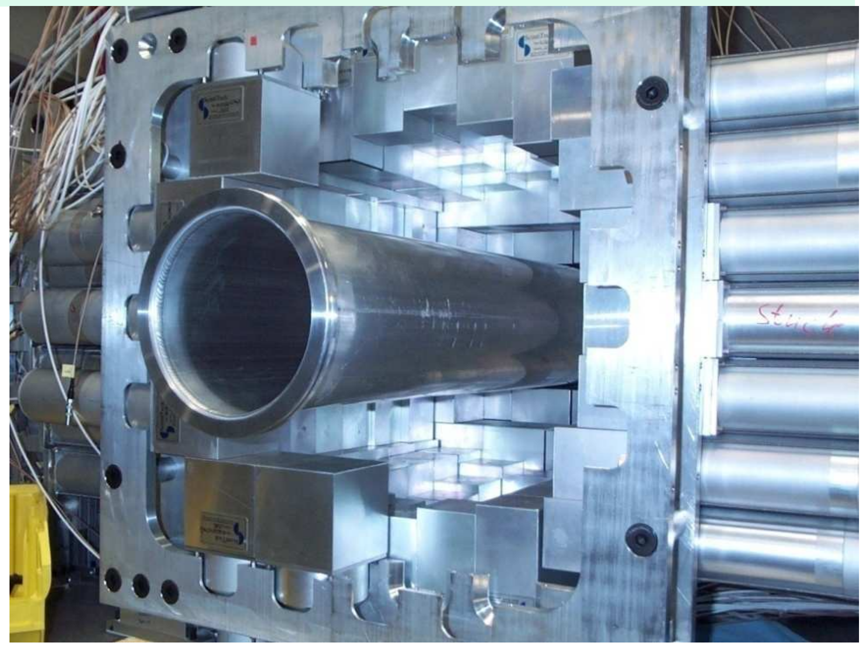
CAESium iodide ARray

"Gain efficiency, pay with resolution"….





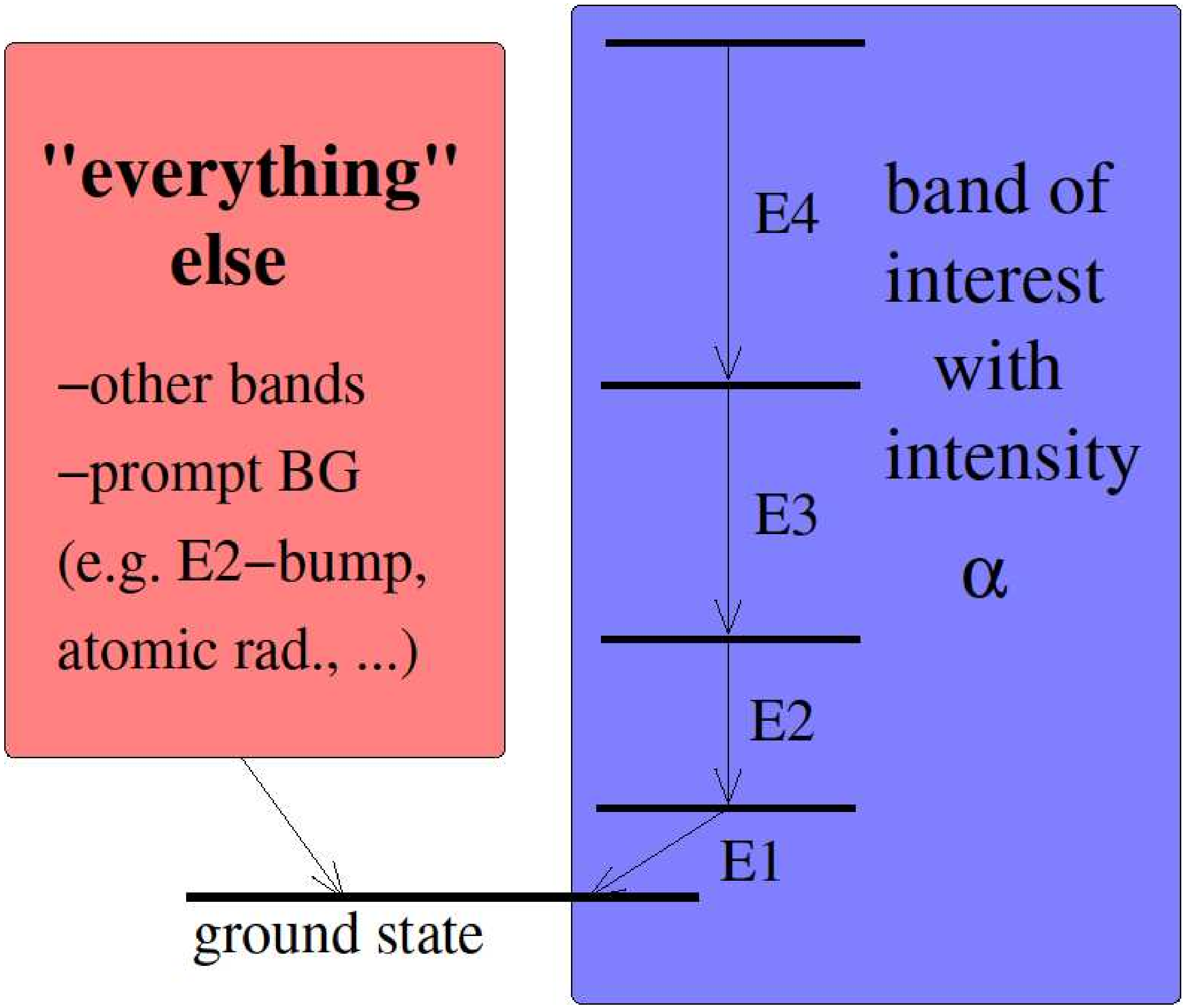
- CsI(Na)
- 48 3"x 3"x 3" crystals
- 144 2"x 2"x 4" crystals
- Solid angle coverage 95%
- In-beam FWHM: 10% (SeGA: 2-3%)
- Efficiency 35% at 1MeV (SeGA: 2.5%)



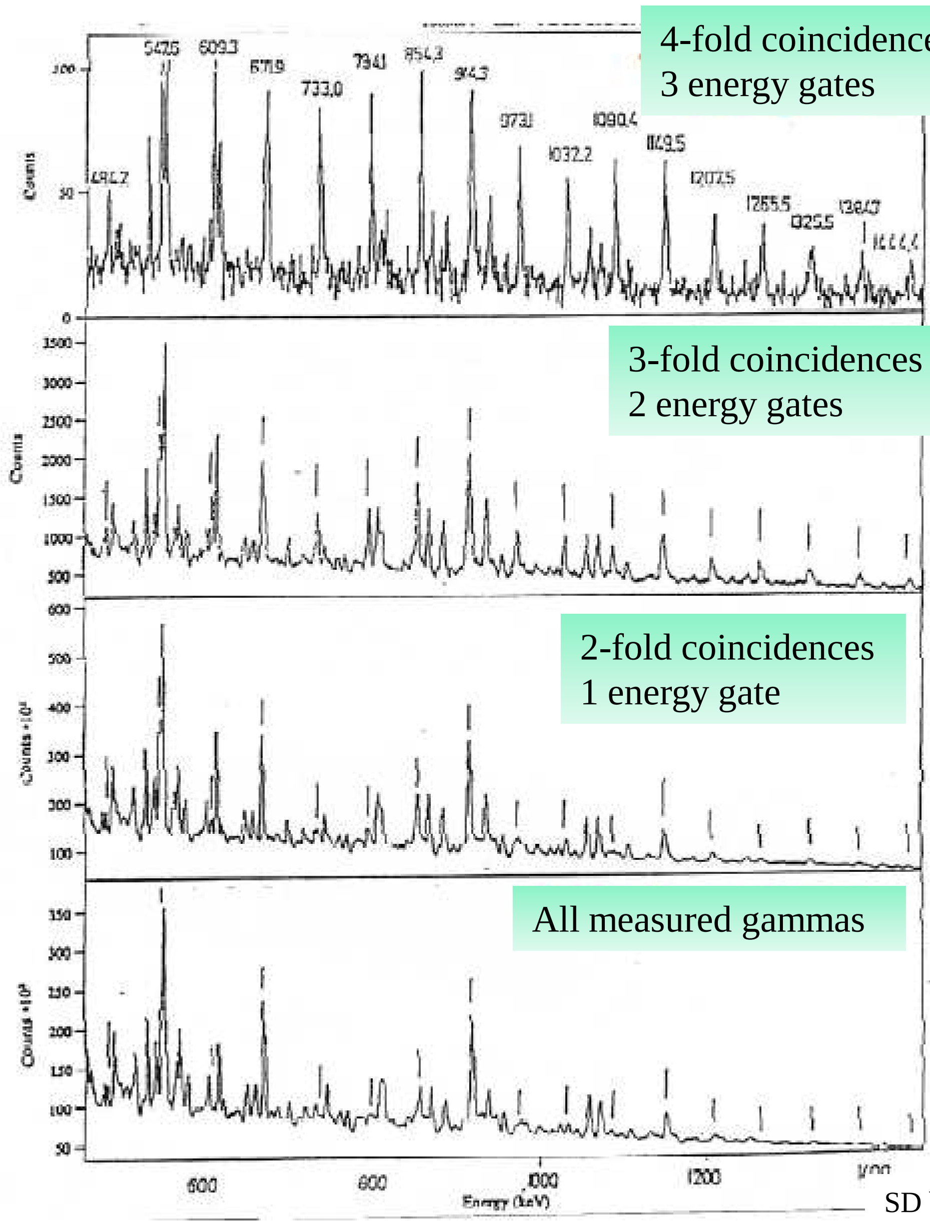
…good deal or not?
How do we benchmark efficiency vs. resolution?

Resolving Power…

…or how to benchmark a gamma-ray spectrometer.



Carving out tiny intensities α



SD band in ^{143}Eu in NORDBALL (A. Ataç et al., Nucl. Phys. A557 (1993) 109c-)

A practitioner’s example

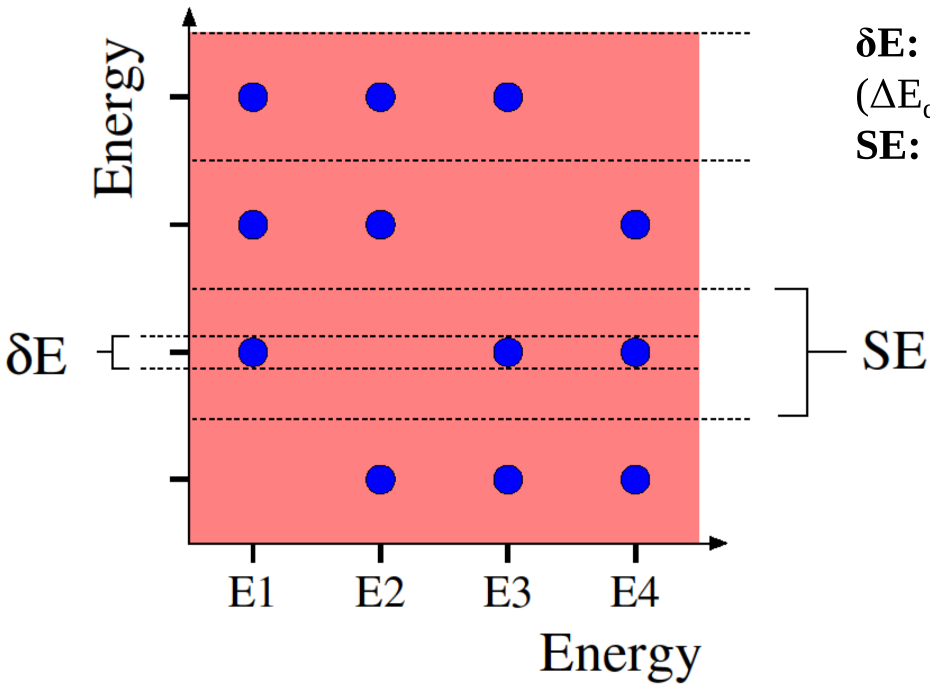
Recipe:
Measure high-fold coincidences (F)
and apply (F-1) gates on energies $E_1..E_{F-1}$

Obvious:
Energy resolution helps (narrower gates)
Efficiency helps (more F-Fold coincidences)

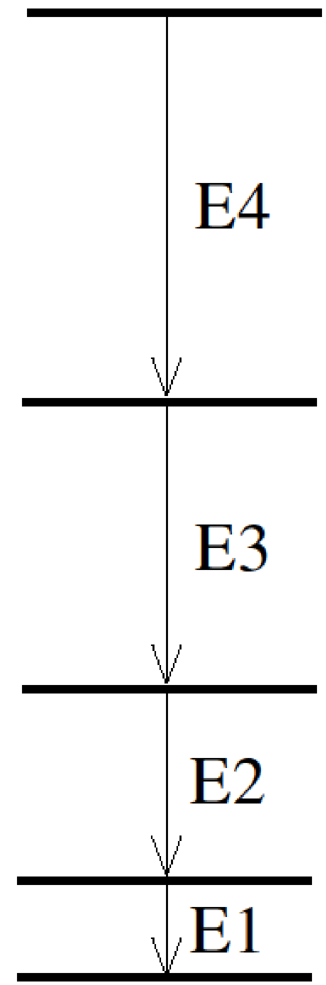
Question(s):
How important is resolution compared to efficiency?
Maybe something else important?
Why does the gating improve peak-to-background (P/BG)?

Improving Peak-to-Background…

…using F-fold coincidences (here ‘matrix’: F=2)



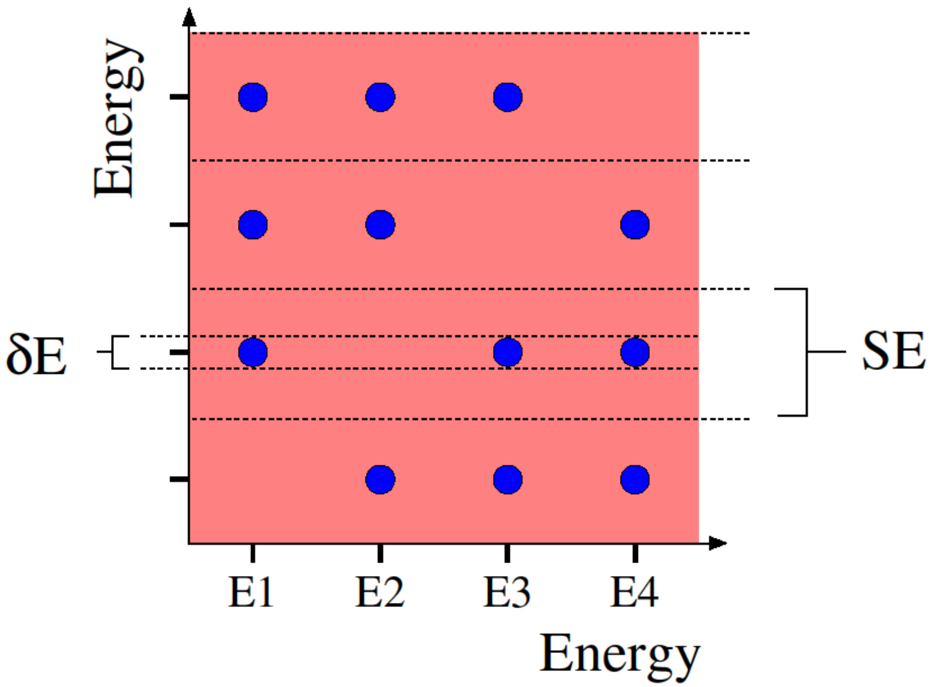
δE: ‘effective’ E-resolution (ΔE_{det} and $\Delta E_{Doppler}$)
SE: average energy spacing

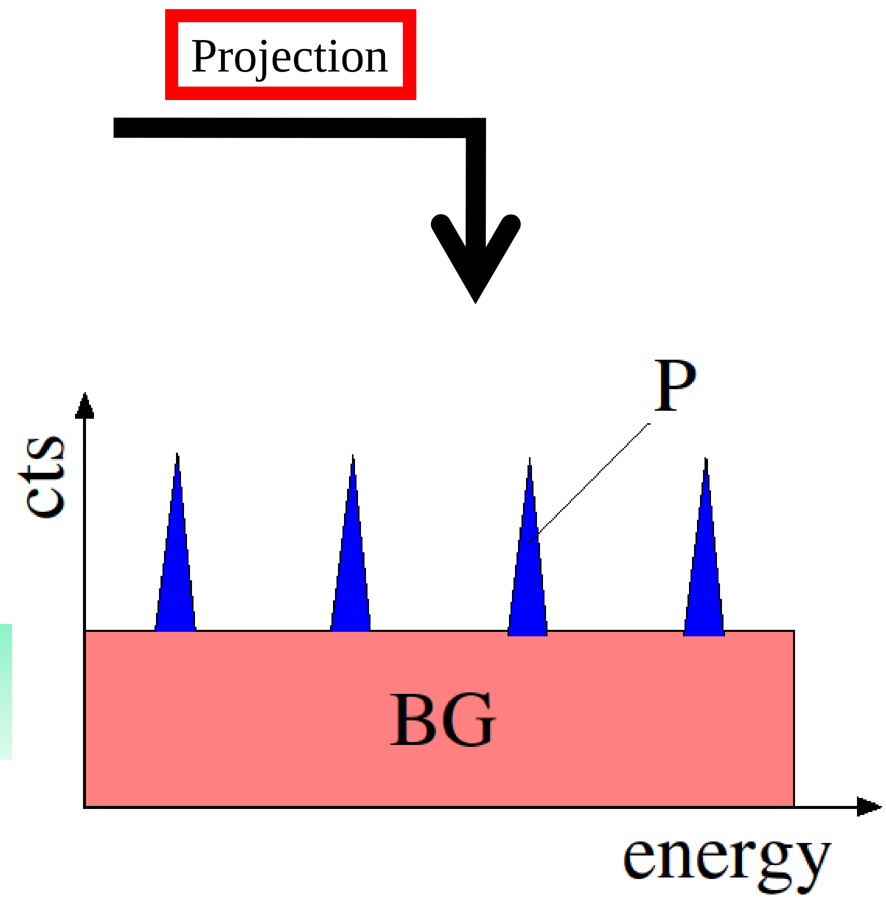


→ E_x-E_y coincidences go into peak (blue)
→ “everything else” spread over red area, as it isn’t coincident with any E_x

Improving Peak-to-Background…

…using F-fold coincidences (here ‘matrix’: F=2)

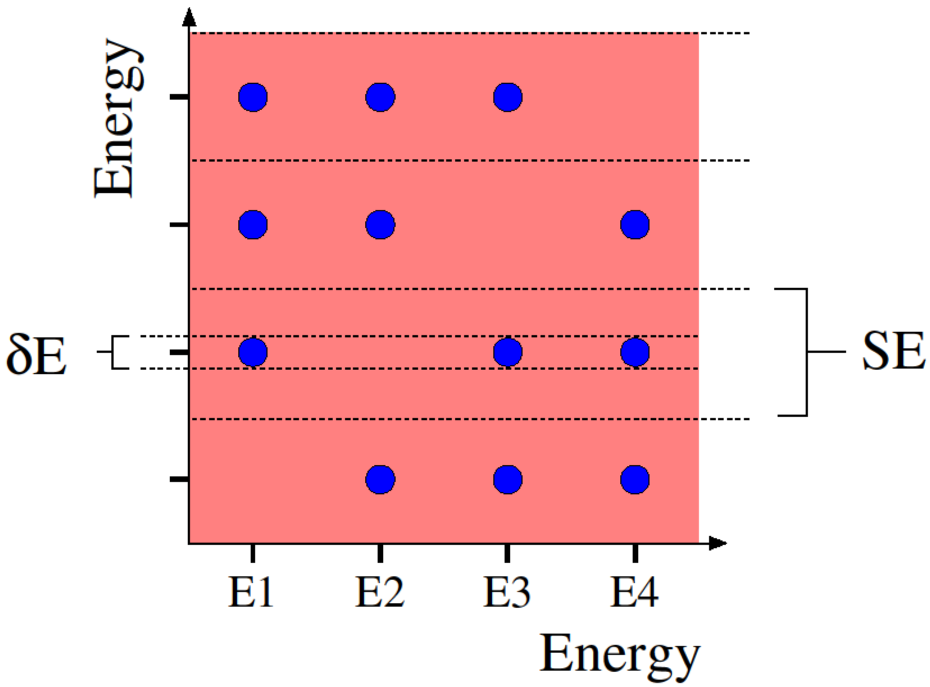


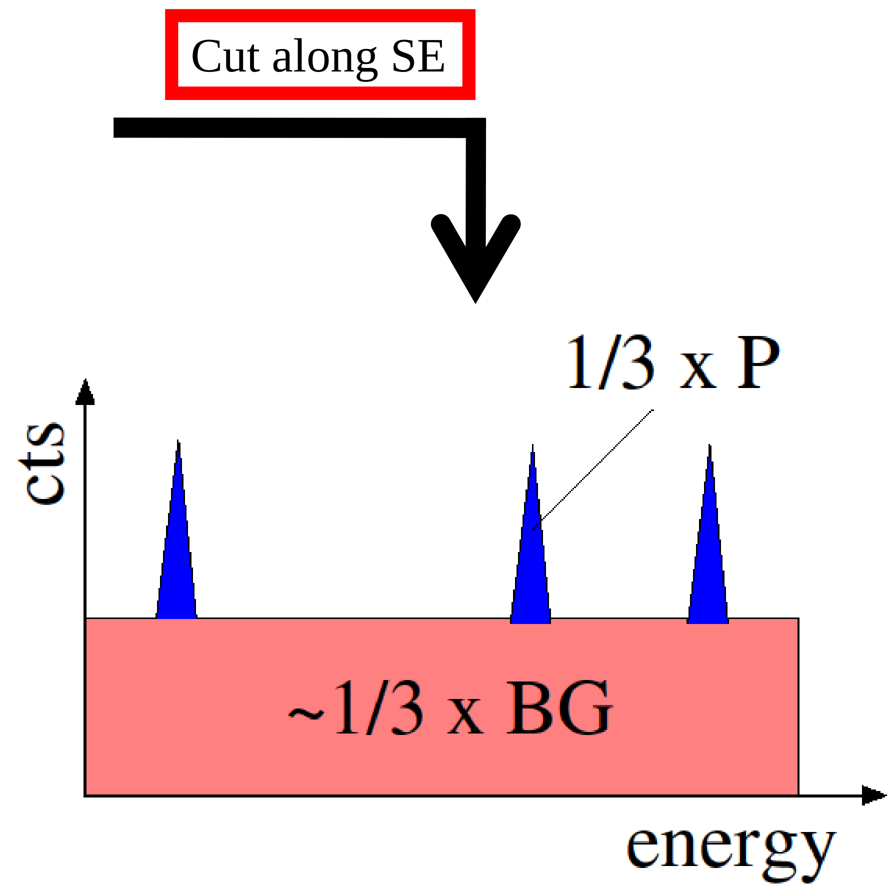


This corresponds to “all measured gammas” in the example “carving out tiny α”.

Improving Peak-to-Background…

…using F-fold coincidences (‘matrix’: F=2)

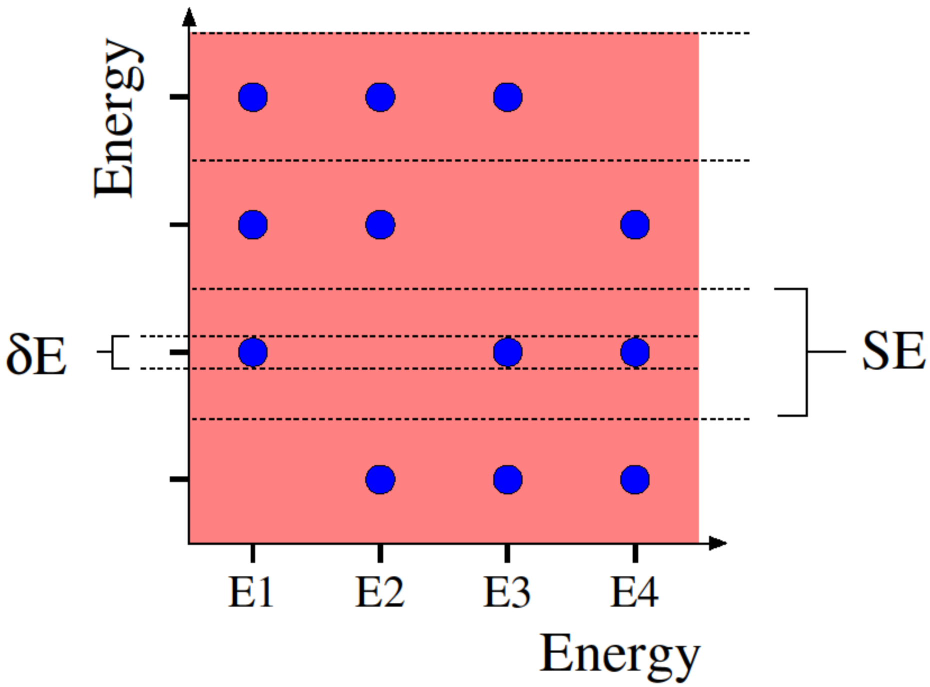




No improvement in P/BG as peak and BG intensities are reduced equally!

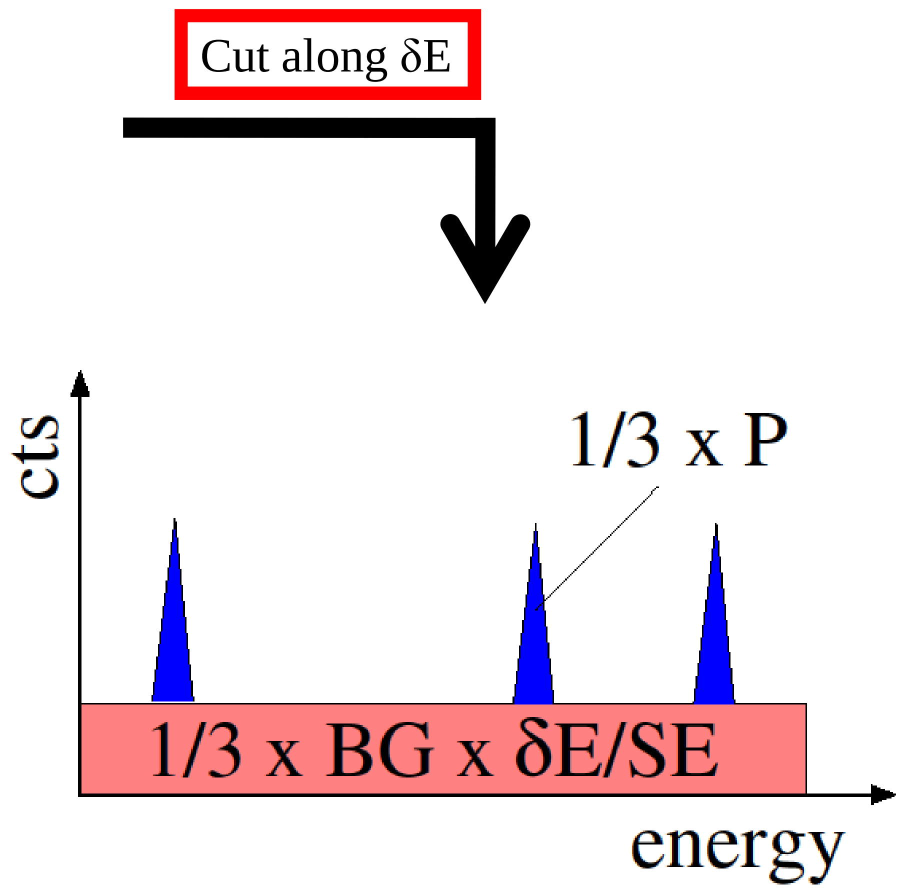
Improving Peak-to-Background…

…using F-fold coincidences ('matrix': F=2)



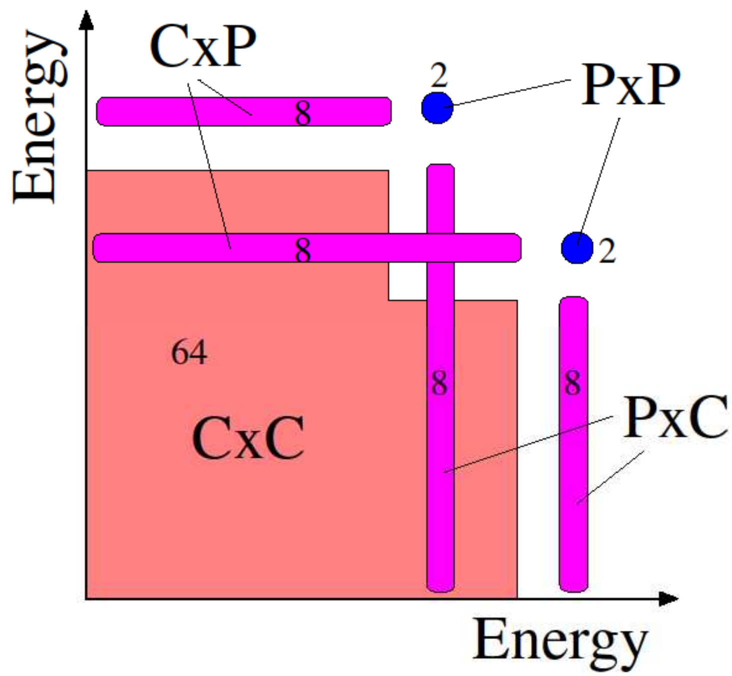
Improvement of P/BG by factor **SE/δE** !!!

BTW: Of course we would create a cut spectrum for each E_x and sum them up. This improves statistics, BUT NOT P/BG.



Drop of bitterness – P/T and F-fold ….

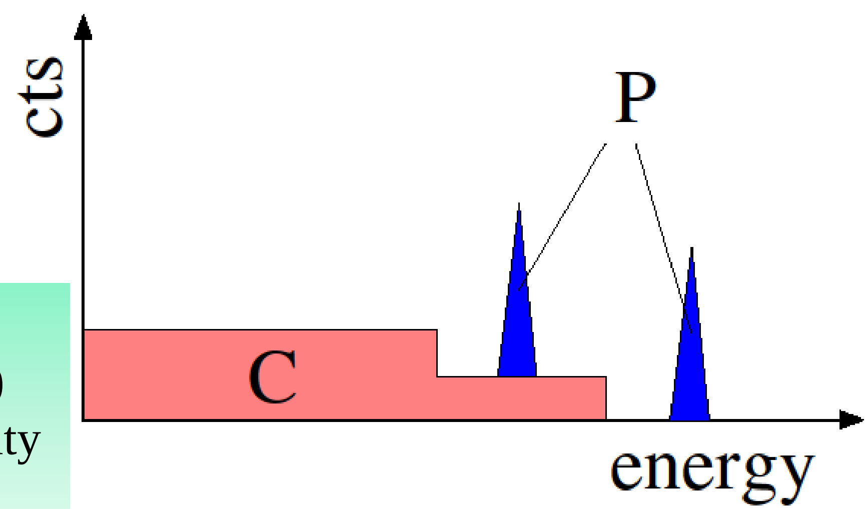
….what we have to pay:



P/T: Probability to count a detected gamma in the Peak and NOT in the Compton plateau

Example: P/T=0.2, two gammas, 100 events

Detecting both in peak	PxP: 4%
1 in Peak, 1 as Compton	PxC:16%
1 as Compton, 1 in Peak	CxP:16%
Both as Compton	CxC:64%



In projection we have 10 events in peak,
but in a corresponding δE cut only 2 (10 x P/T)
Conclusion: We **lose factor P/T** in peak intensity each time we increase Fold F.

The background reduction factor R

We conclude:
Each time we increase our Fold F we IMPROVE the **Peak-to-Background ratio** by

$$\mathbf{SE/\delta E \times P/T}$$

This is called the **background reduction** factor R usually defined as

$$\mathbf{R = 0.76 \times SE/\delta E \times P/T}$$

(0.76: δE is FWHM of peak consisting 76% of peak intensity. Like for P/T we reduce the peak intensity by factor 0.76 with each cut window of width δE).

NOTE: A good (high value for) P/T is as important as good (small value of) δE.

Reference: M.A. Deleplanque et al., NIM A430 (1999) 292-

Back to **Resolving Power**

For fold **F=1** the **Peak-to-Background ratio** for a branch with intensity α is $\boldsymbol{\alpha}$**R**.
(here, background means the background under the peak)

If we go to a higher fold F the **Peak-to-Background ratio** changes to $\boldsymbol{\alpha R^F}$.

If N_0 is the total number of events, the amount of detected counts N in the peak is

$$\mathbf{N = \alpha\, N_0\, \varepsilon^F} \quad (1)$$

(ε: full-energy-peak efficiency of spectrometer)

Now, a minimum intensity $\boldsymbol{\alpha_0}$ is resolvable if

$$\mathbf{\alpha_0 R^F = 1} \ (2) \ \text{ and } \mathbf{N=100}$$

The **RESOLVING POWER** is defined as

$$\mathbf{RP=1/\alpha_0} \ (3)$$

Taking (1), (2), and (3) leads to

$$\mathbf{RP = \exp[\ln(N_0/N)/(1-\ln(\varepsilon)/\ln(R))]}$$

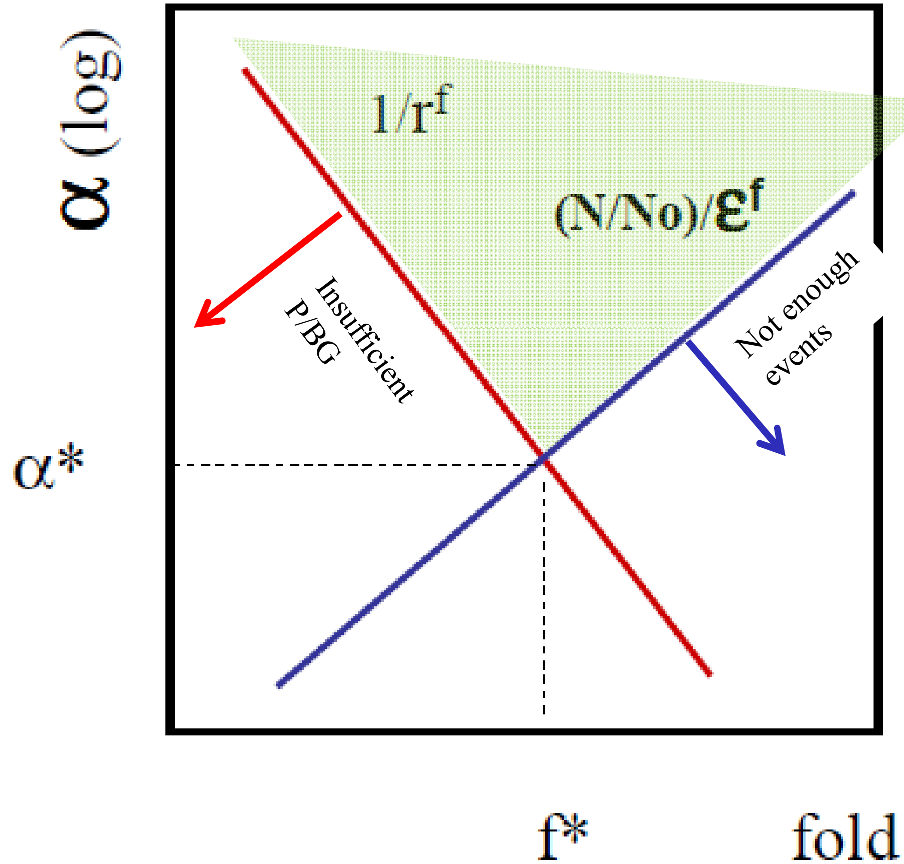
Resolving Power….

…adding some 'more' understanding

<u>On one hand:</u>
As **α = 1/R^{F}** , we can reach any small α by making F large enough, i.e. measure sufficient high F-fold coincidences.
(red line in the plot)

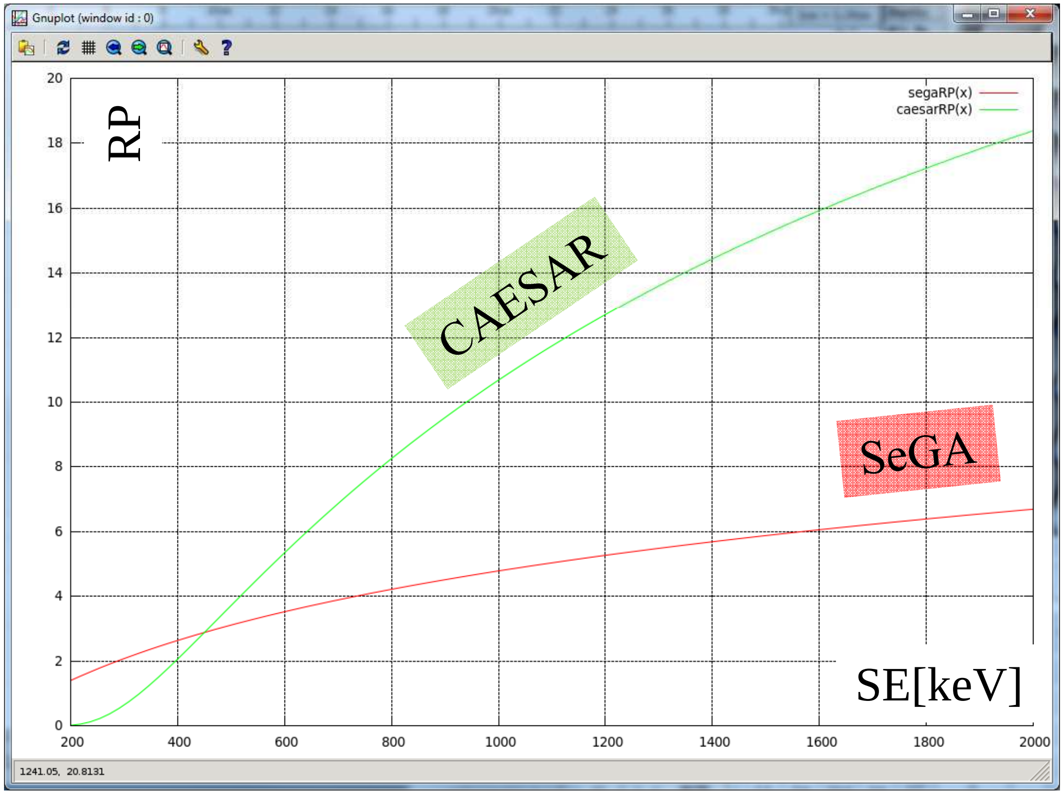
<u>On the other hand:</u>
We have to measure the F-Fold coincidences in reality. This imposes some constraints, expressed by **α=(N/N$_0$)/ε^F** or in words:
"Can you acquire enough F-fold coincidence events in a reasonable time?"

Note: R>1, ε<1



RP applied to SeGA and CAESAR

1MeV gamma ray: SeGA: δE= 25keV, P/T=0.22, ε=0.025
CAESAR: δE=100keV, P/T=0.40, ε=0.35
Average line separation SE vs. Resolving Power RP for N_0=10.000



Conclusion from RP: For low line density (SE large) CAESAR is superior to SeGA. If line density increases (SE small) SeGA beats CAESAR.
[Don’t believe actually the quantitative value of SE = 450keV (!)]

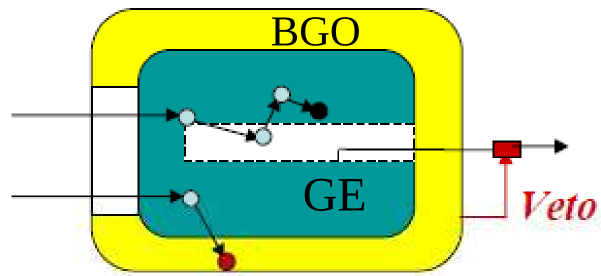
Back to the Future….the nineties

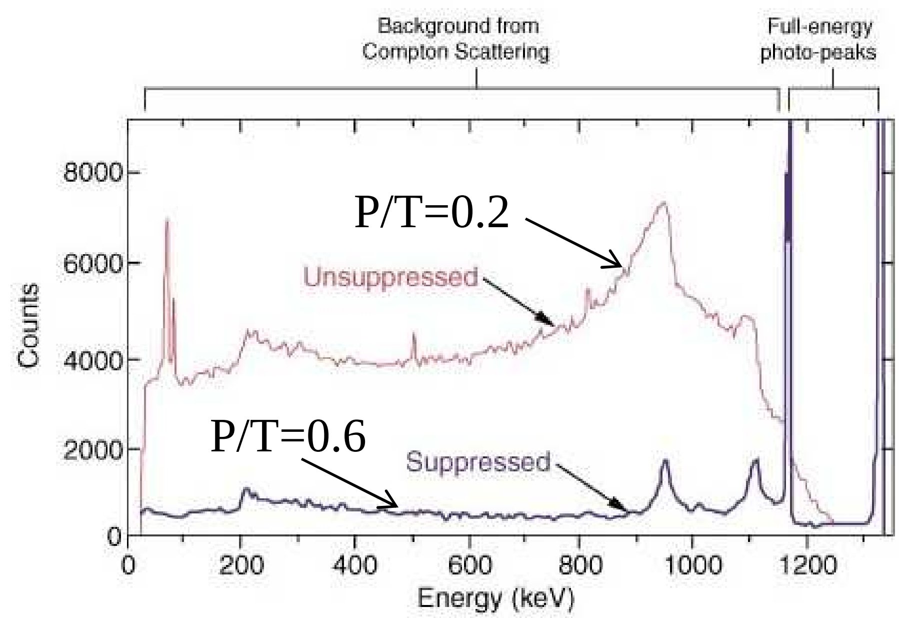
From RP: optimize δE (HPGe), P/T (Compton suppression), and ε (4π coverage)!

→Gammasphere

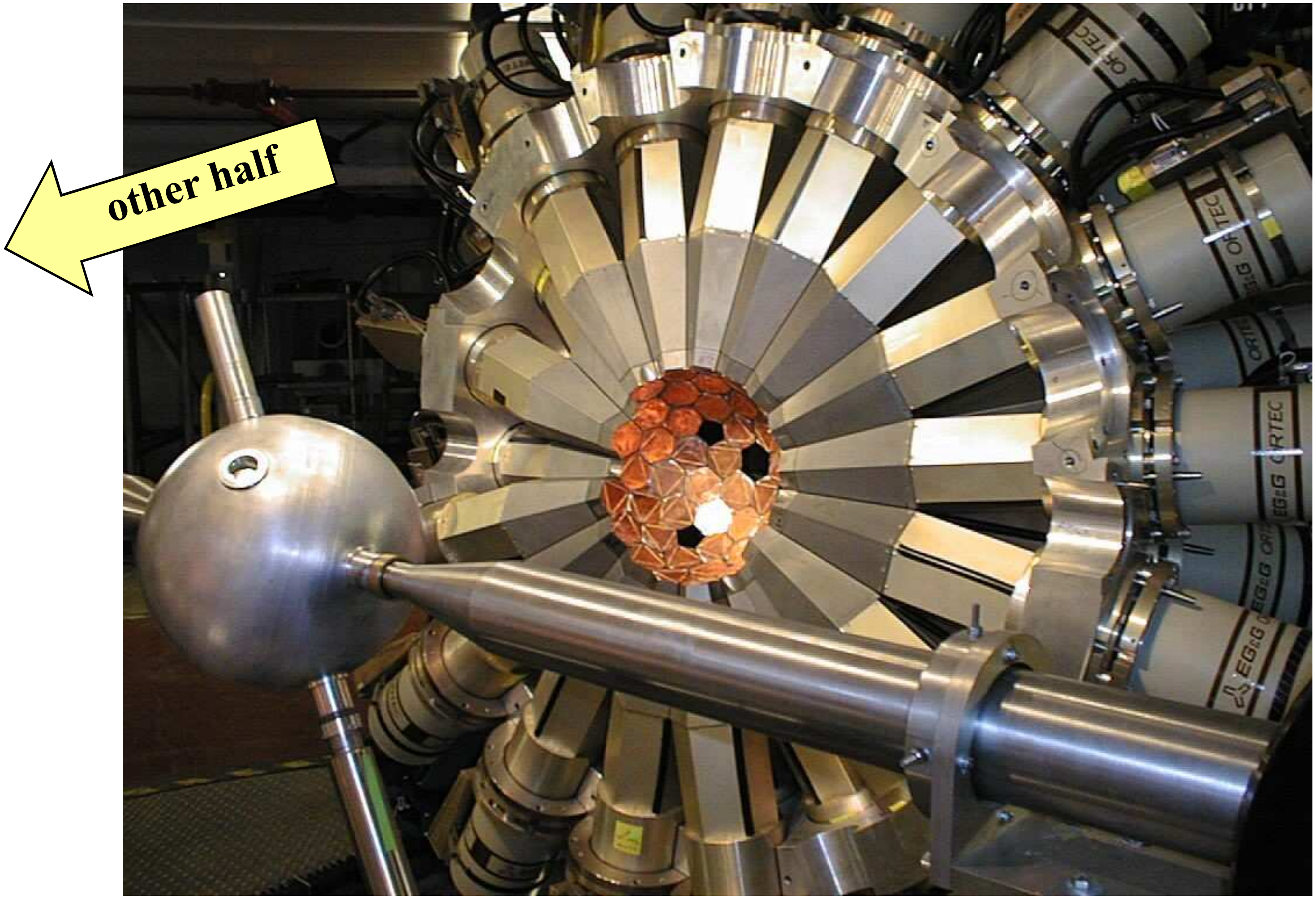
(proposed 1988, funded 1991, commissioned 1995)

Compton suppression:





GAMMASPHERE

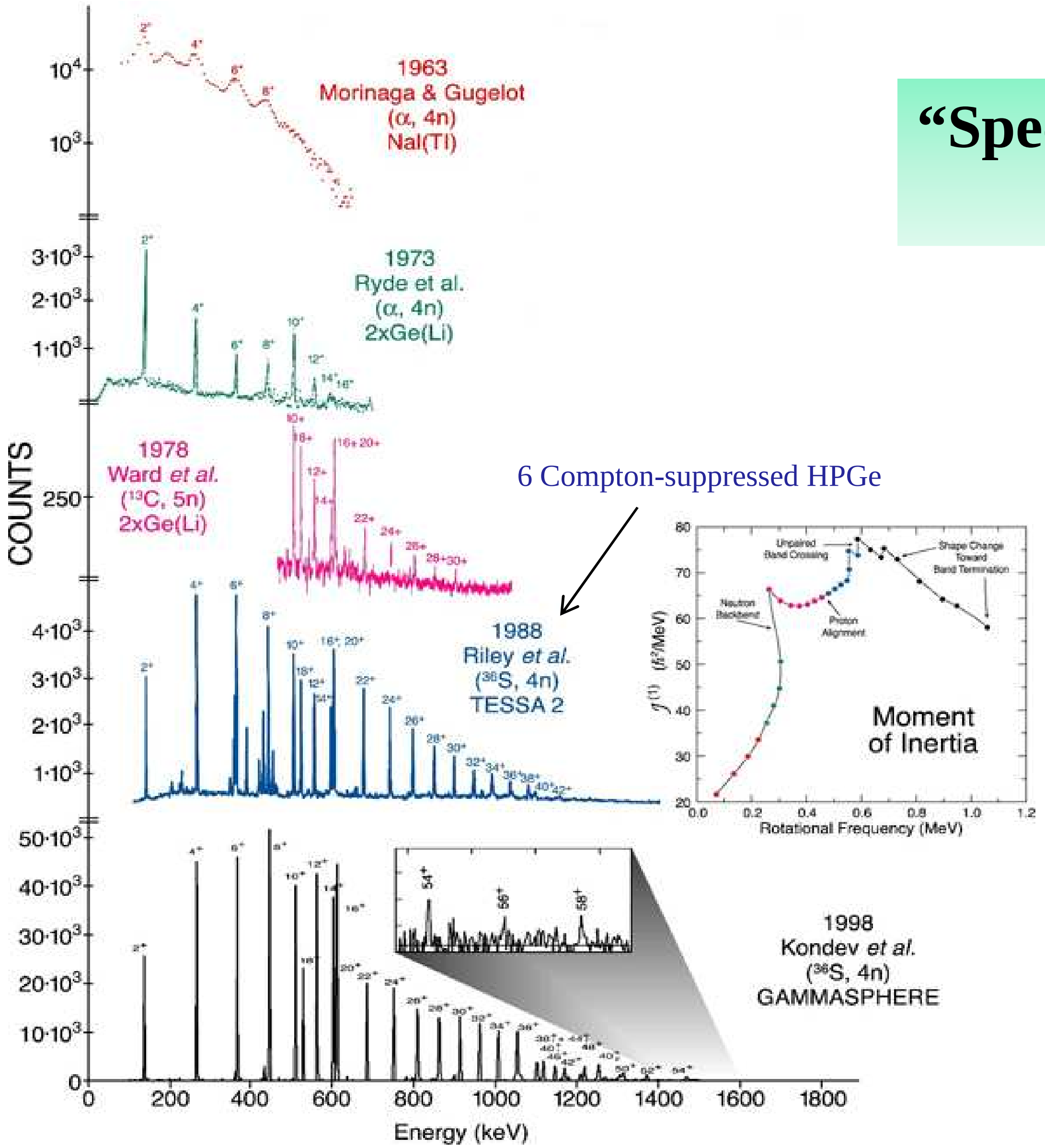


Number of modules	110
Ge Size	7cm (D) × 7.5cm (L)
Distance to Ge	25 cm

Peak efficiency	9% (1.33 MeV)
Peak/Total	55% (1.33 MeV)
Resolving power	10,000

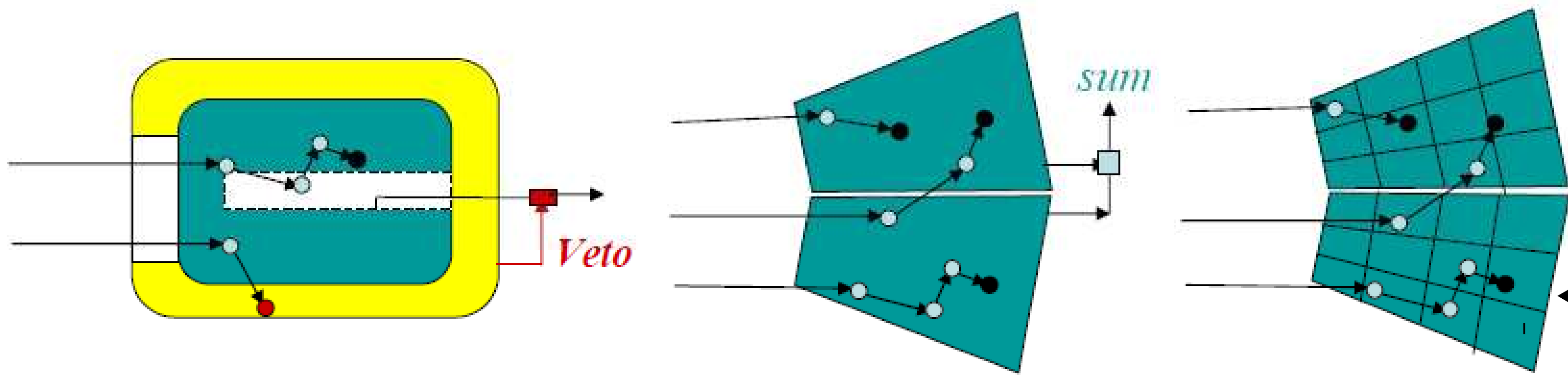
Better instruments – better results

"Spectroscopic history" of ^{156}Dy



Spectrometers beyond GAMMASPHERE

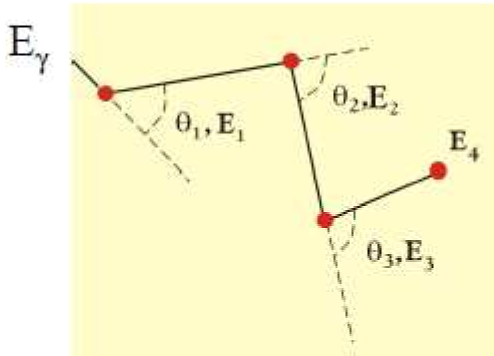
- Compton Suppressed Ge
- Ge Sphere
- Gamma Ray Tracking



Compton Suppressed Ge	Ge Sphere	Gamma Ray Tracking
N = 100	N = 1000 (summing)	N = 100
NΩ ε = 0.1	NΩ ε = 0.6	NΩ ε = 0.6
Efficiency limited	**Too many detectors**	**Segmentation**

As the 36-fold segmented GRETINA/AGATA detectors do!

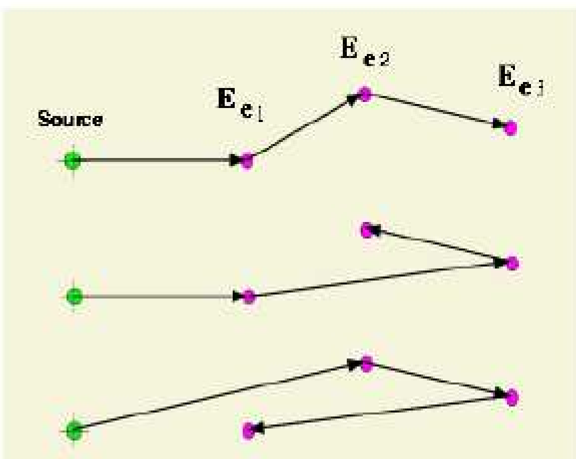
Gamma-ray tracking

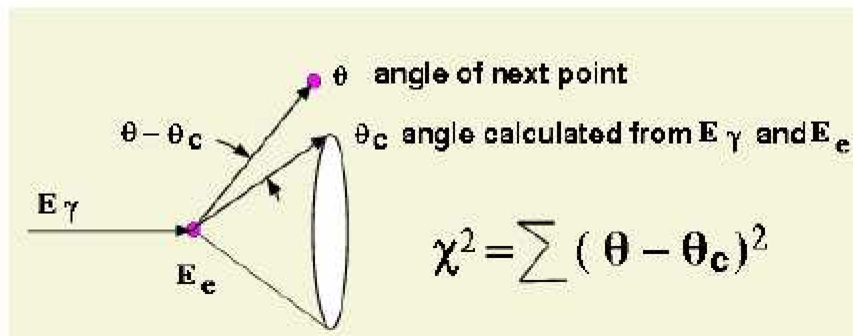


$$E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{E_\gamma}{0.511}(1-\cos\theta)} \right)$$

Problem: 3!=6 possible sequences

Assume: $E_\gamma = E_{e1} + E_{e2} + E_{e3}$;γ-ray from the source





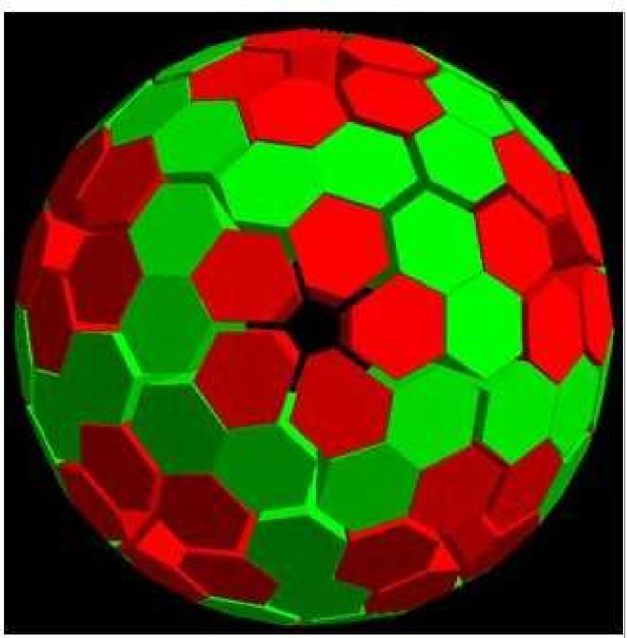
Sequence with the minimum $\chi^2 < \chi^2_{max}$

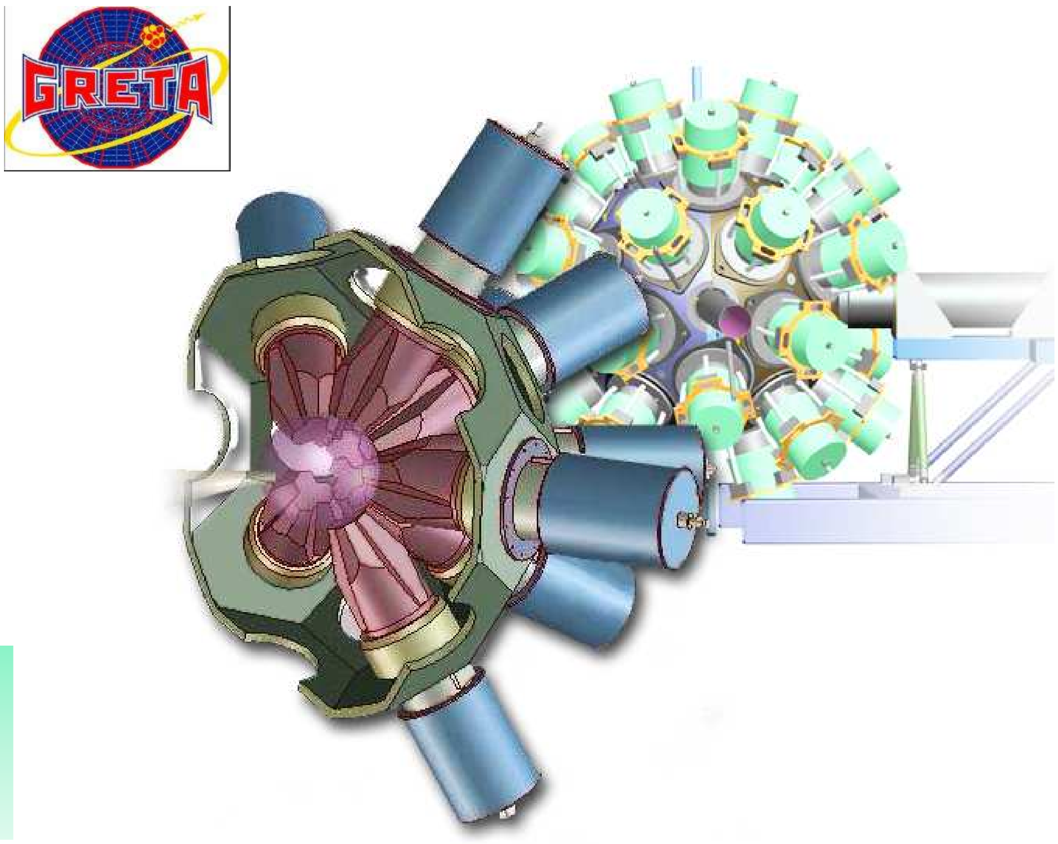
➔correct scattering sequence

➔rejects Compton and wrong direction

GRETA

RP again:
→ Optimize efficiency, now by getting rid of Compton-suppression shields
→ Recover good P/T using gamma-ray tracking
→ Use position sensitivity for better Doppler-shift correction





4π shell covered by 120 HPGe crystals
4 HPGe crystals in one cryostat.
→ 30 modules

GRETINA = ¼ GRETA

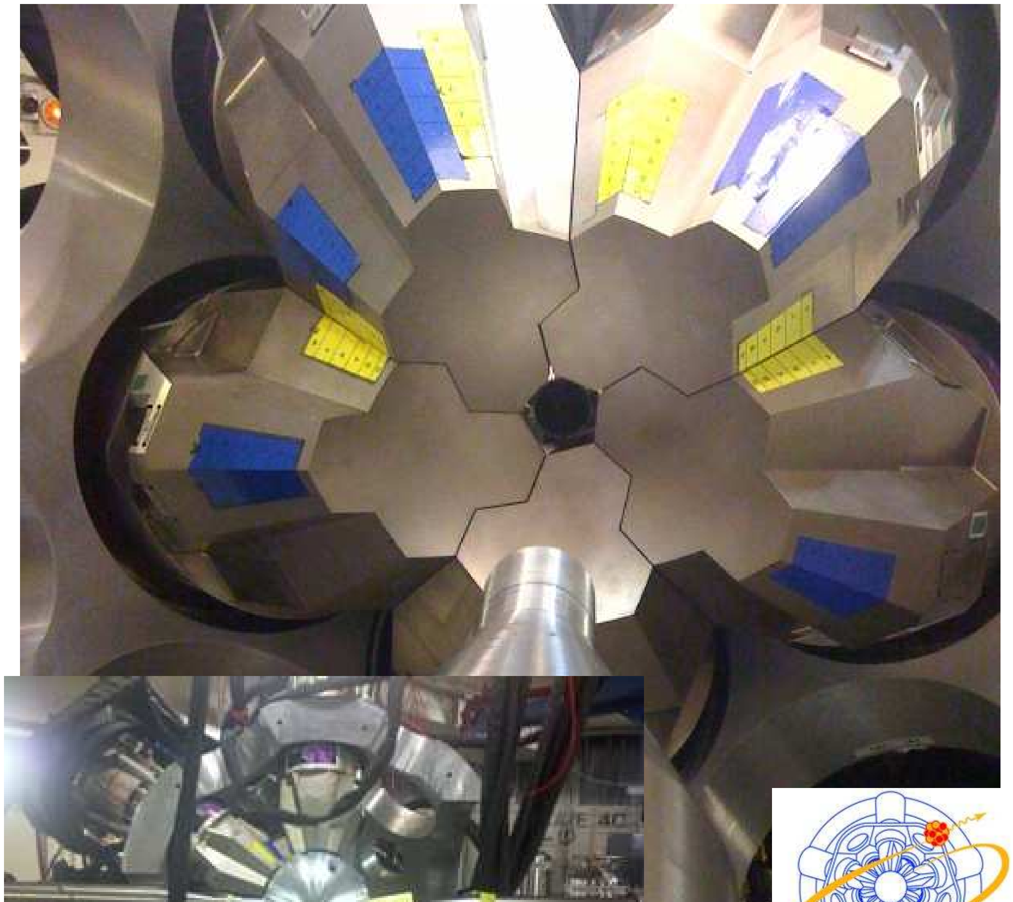
But NOT ‘little GRETA’ !

Collaborating Institutions

- **Argonne National Laboratory**
  - Trigger system
  - Calibration and online monitoring software
- **Michigan State University**
  - Detector testing
- **Oak Ridge National Laboratory**
  - Liquid nitrogen supply system
  - Data processing software
- **Washington University**
  - Target chamber

And, of course:
Lawrence Berkley Nat’l Lab

GRETINA



28 36-fold segmented HPGe detectors in 7 cryostats.

GRETINA is operational!
(CD-4 approval in March 2011)

Currently commissioned in Berkeley

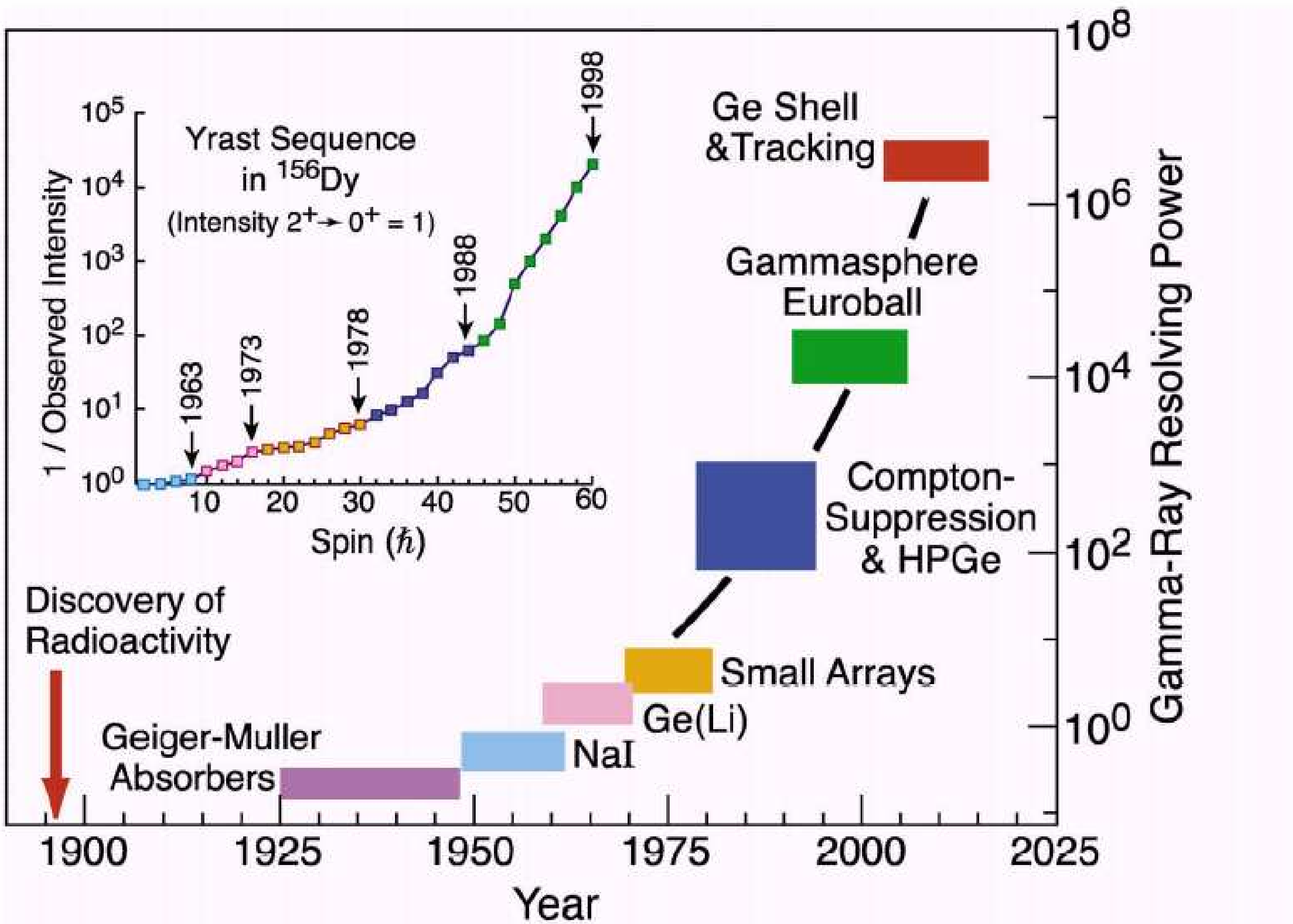
Physics campaign, 6 months each
MSU, NSCL (2012)
ORNL, HRIBF (2012/13)
ANL, ATLAS (2013)

I didn't (and won't)[*] talk about:
Electronics, Data acquisition, Signal processing, Mechanics, Infrastructure, Signal decomposition, Tracking algorithms, ….

[*]or just give me more time

Resolving Power again….

…but that's why we built GRETINA, go for GRETA, and Europe does AGATA.



Summary

You should take home from this lecture:

- Two detector types are usually used in gamma spectroscopy: Semiconducters made from Ge and scintillators (seldom)
- Importance of Poisson statistics for counting experiments: $\sigma^2=N$
- HPGe detectors provide intrinsic energy resolution of 2keV for 1MeV gamma rays
- Modern HPGe detectors can resolve the spatial coordinates of each interaction point of a gamma ray in the detector (GRETINA/AGATA detectors).

- Gamma-ray spectrometers are carefully designed for certain experimental conditions in terms of δE (effective resolution, Doppler!), P/T, and ε.
- Resolving Power benchmarks gamma-ray spectrometer and is a rather complicated thing.
- GAMMASPHERE, GRETINA, GRETA, and AGATA are present/planned gamma-ray spectrometers.

Thanks for your attention!

And don't hesitate to ask, now or later!

Acknowledgement:
I.Y. Lee, A. Macchiavelli, D. Radford, M. Riley contributing figures/material. Thanks!