Nuclear Structure with Gamma-Rays Part I

Heather Crawford
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Why Gamma Rays Are the Best Kind of Radiation

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The Plan

- Today (Tuesday – July 29)
  - Basics of Gamma-Rays
  - Practical Aspects – detection etc.
    - Types of detectors
    - Characterizing detectors
    - Tracking detectors
- Wednesday – July 30
  - Experiments with gamma-rays
    - Fast beams (Knockout, Coulex, etc.)
    - Low-energy beams (Coulex, g-factors, etc.)

Overview (I)

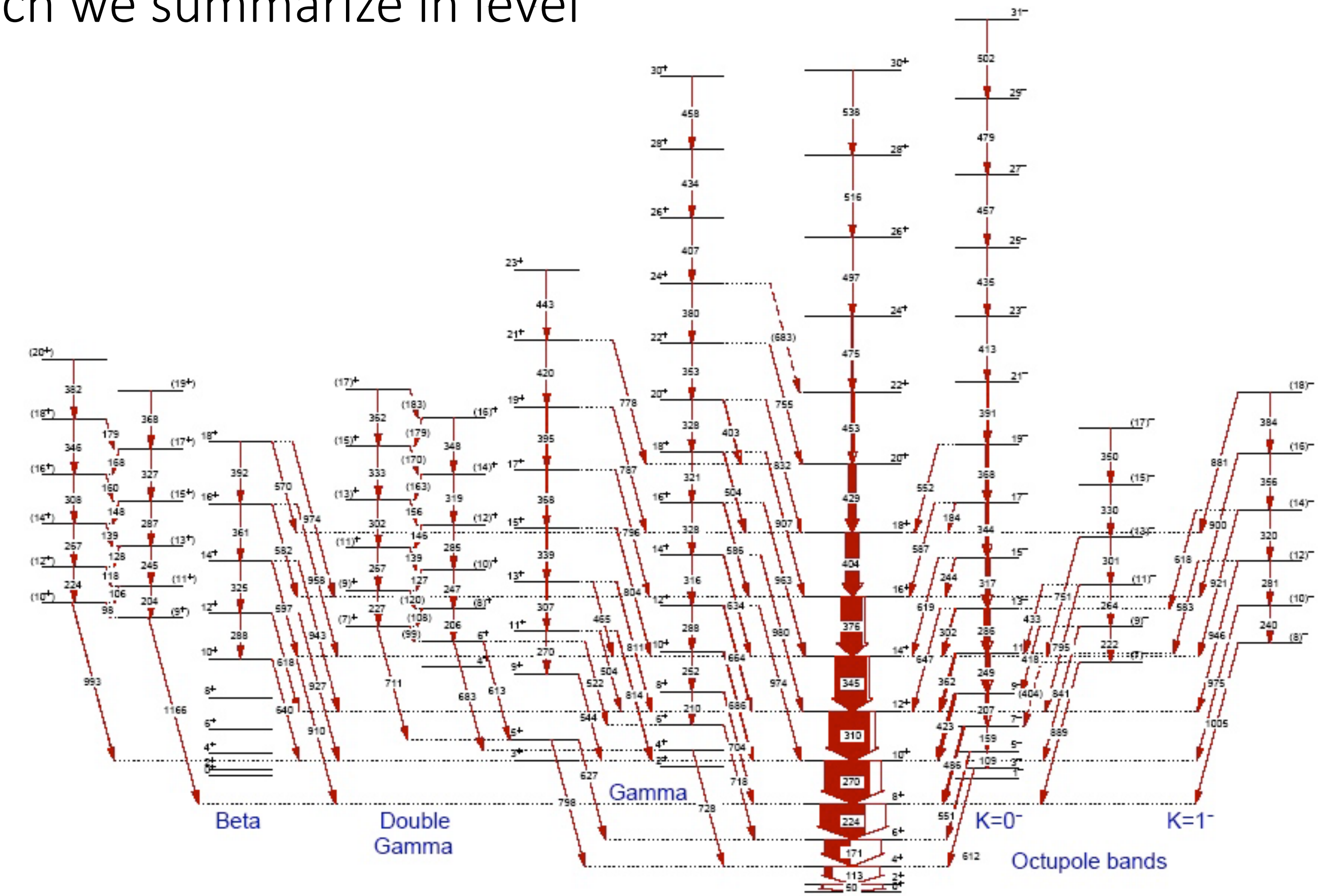
- Gamma rays and nuclear structure – the big picture
- Gamma radiation
  - Characteristics properties – what we measure
  - Selection rules
    - Multipolarity, lifetimes and isomerism…
  - Learning more
    - Angular distributions, polarization, etc…
- Gamma-Ray Detection
  - Basic principles: scintillators and semi-conductors
  - Performance parameters
  - Advanced gamma-ray detectors systems

Question We Forgot...

- Have you had a nuclear structure graduate course?
  (A) Yes
  (B) No

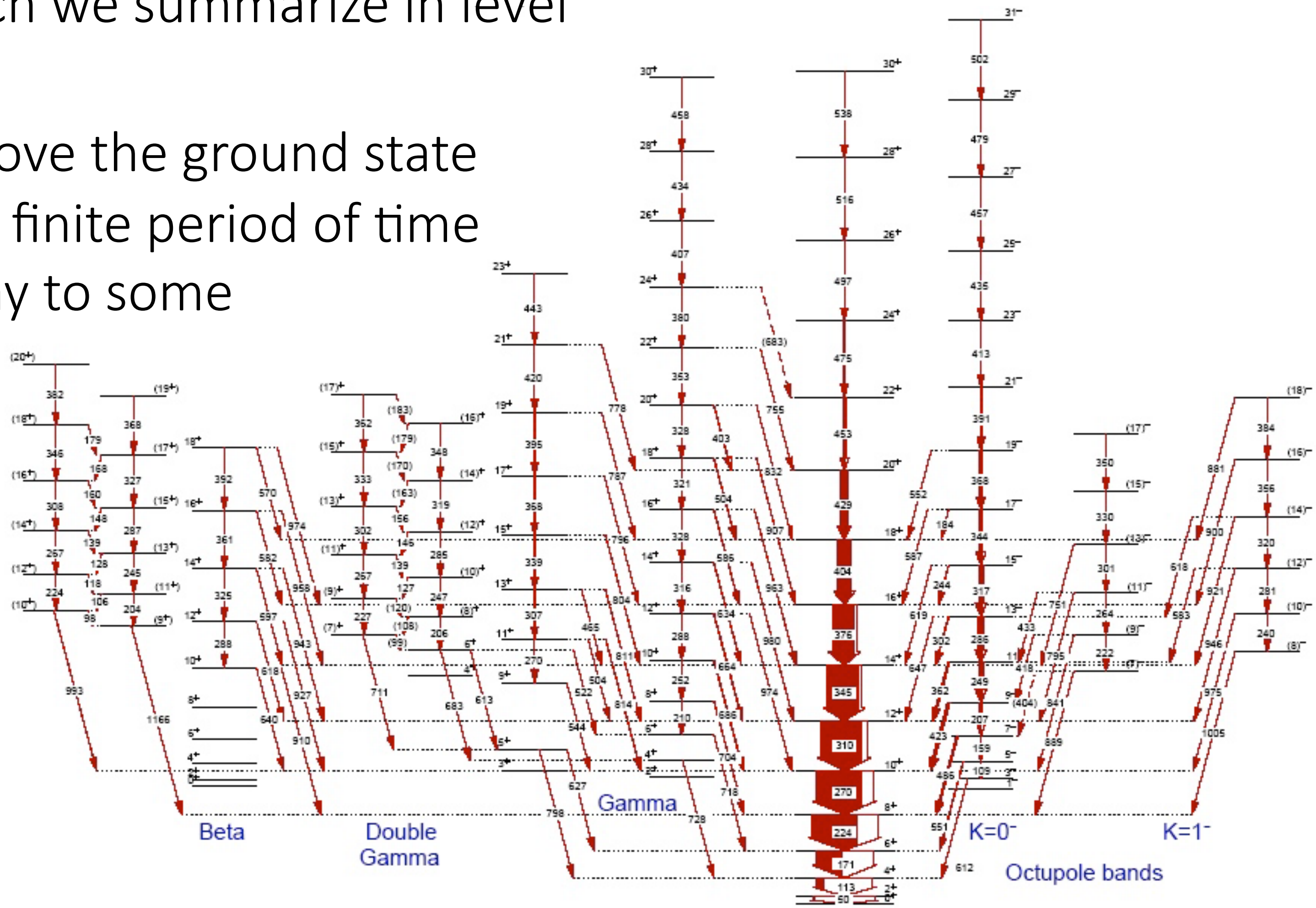
Nuclear Excitations

- Nuclear structure refers, predominantly, to the excitation modes of a nucleus – the details of which we summarize in level schemes



Nuclear Excitations

- Nuclear structure refers, predominantly, to the excitation modes of a nucleus – the details of which we summarize in level schemes
- Excitations above the ground state exist for some finite period of time and then decay to some lower energy configuration



Dominant Excited State Decay

- Excited states in nuclei can decay in a number of ways:
  - β^+, β^-, electron capture (EC) -- $^{177}Lu^m$
  - Particle emission -- $^{53}Co^m$, $^{211}Po^m$
  - Fission $^{239}Pu^m$
  - Internal conversion
  - Gamma-ray emission

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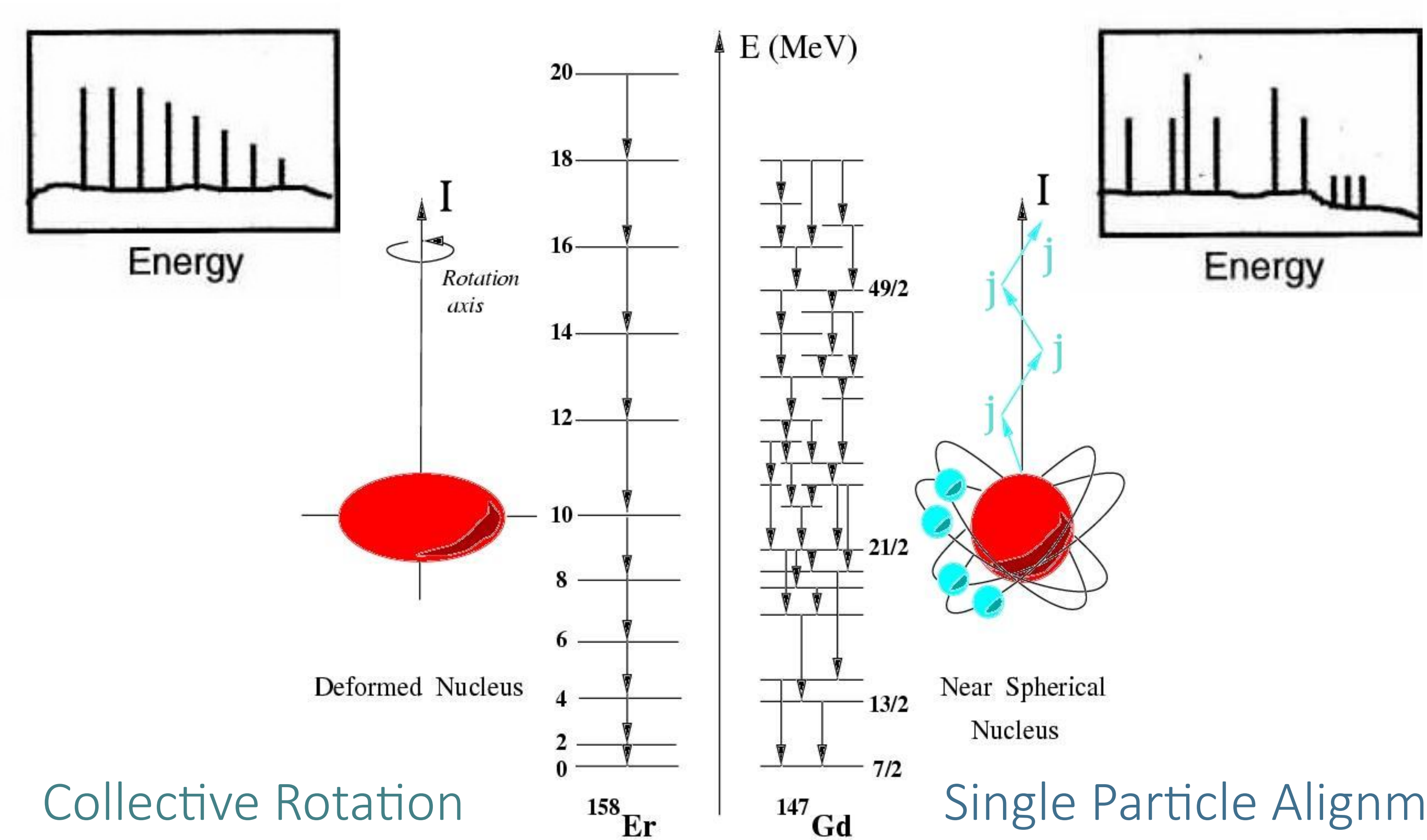
  - **Gamma-ray emission**

→ Nuclear properties from gamma-ray studies
  - Coincidence relation $\rightarrow$ Level schemes
  - Angular distribution/correlation $\rightarrow$ Multipolarity, spin
  - Doppler shifts $\rightarrow$ excited state lifetimes
  - Linear polarization $\rightarrow$ E/M, parity
  - Intensity of transitions $\rightarrow$ B(Eλ)

So Nuclear Structure Studies….

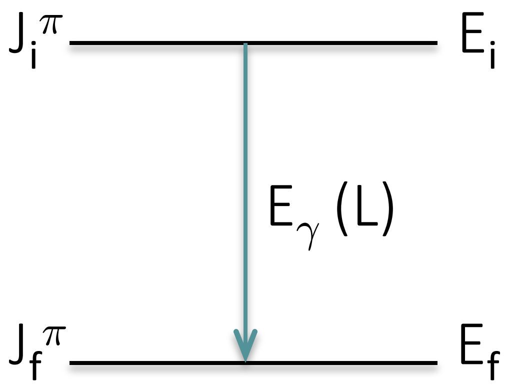
Level Schemes Contain Structural Information



Collective Rotation

Single Particle Alignment

Selection Rules



$$E_\gamma = E_i - E_f$$

$$|J_i - J_f| \leq L \leq J_i + J_f$$

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

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

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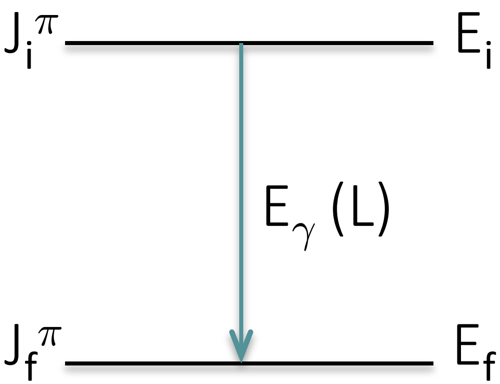

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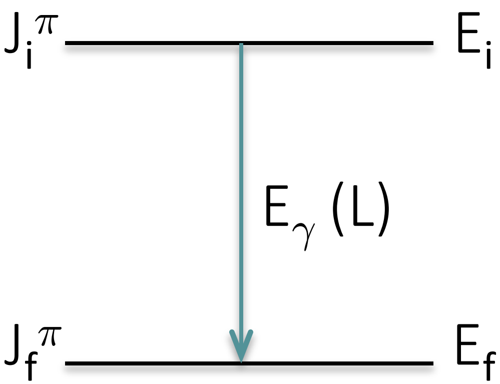
$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)$$

SELECTION RULES



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Reduced matrix element – i.e.

$$B(E2 : J_i \rightarrow J_f) = \frac{1}{2J_i + 1} \langle \psi_f || E2 || \psi_i \rangle^2$$

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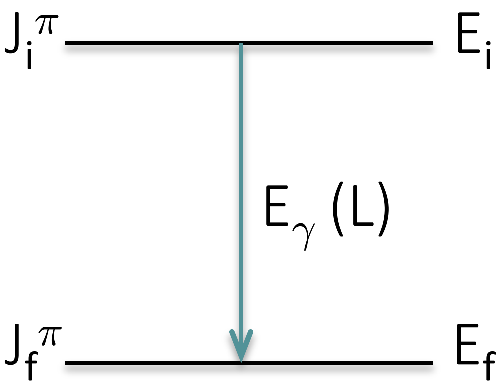

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Weisskopf estimates

$$T(E1) = 1.03 \times 10^{24} A^{2/3} E_\gamma^3$$
$$T(E2) = 7.28 \times 10^{7} A^{4/3} E_\gamma^5$$

…

$$T(M1) = 3.15 \times 10^{13} E_\gamma^3$$
$$T(M2) = 2.24 \times 10^{7} A^{4/3} E_\gamma^5$$

…

Lifetimes and Gamma Decay

- The bulk of electromagnetic (gamma) transitions have lifetimes of $10^{-15} - 10^{-13}$ s
  - Explains why excited states primarily undergo gamma decay (compare to beta-decay lifetimes $\sim$ ms, or alpha decay $\sim$ s)

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  - Isomers arise for many reasons

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QUESTION!

- What would you expect to be the dominant character of the gamma-ray transition linking the second 0^+ excited state at 1.06 MeV in ^{32}Mg with the ground state (0^+)?
  (A) E1
  (B) M2
  (C) E2
  (D) No gamma transition
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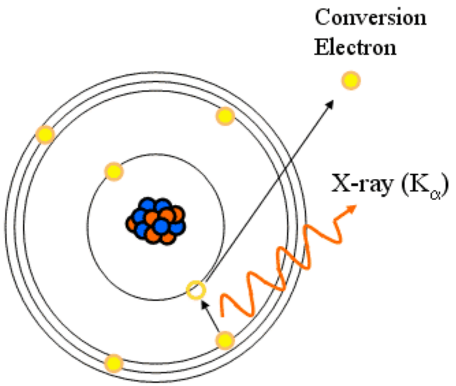

Gamma rays must carry at least one $\hbar$ of angular momentum – cannot link two 0+ states
When gamma transition is not possible, internal conversion is an alternative electromagnetic transition.

Properties of Gamma Decay

- Energies $\rightarrow$ spacing between nuclear levels

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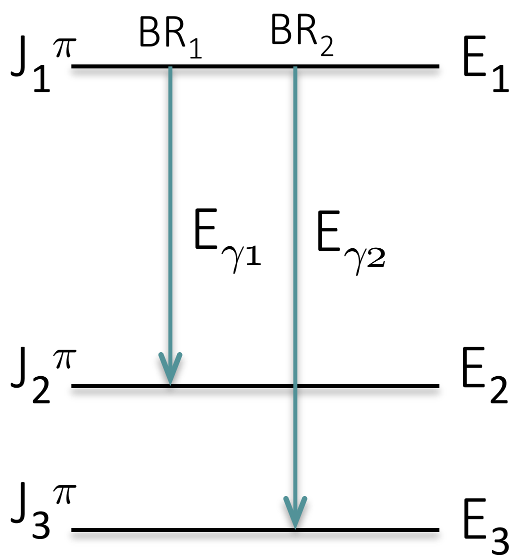

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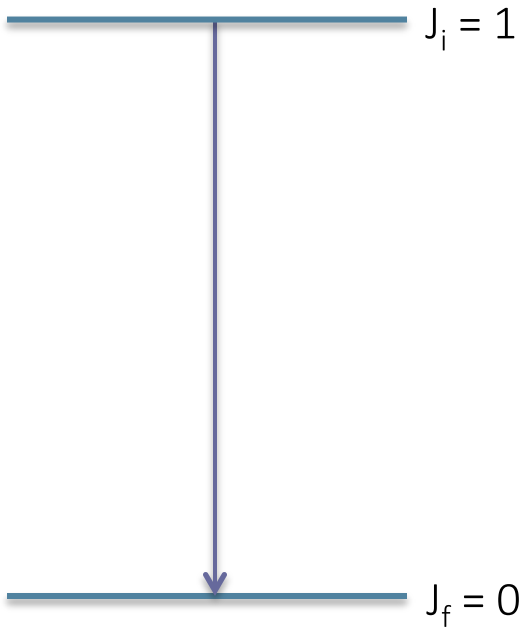
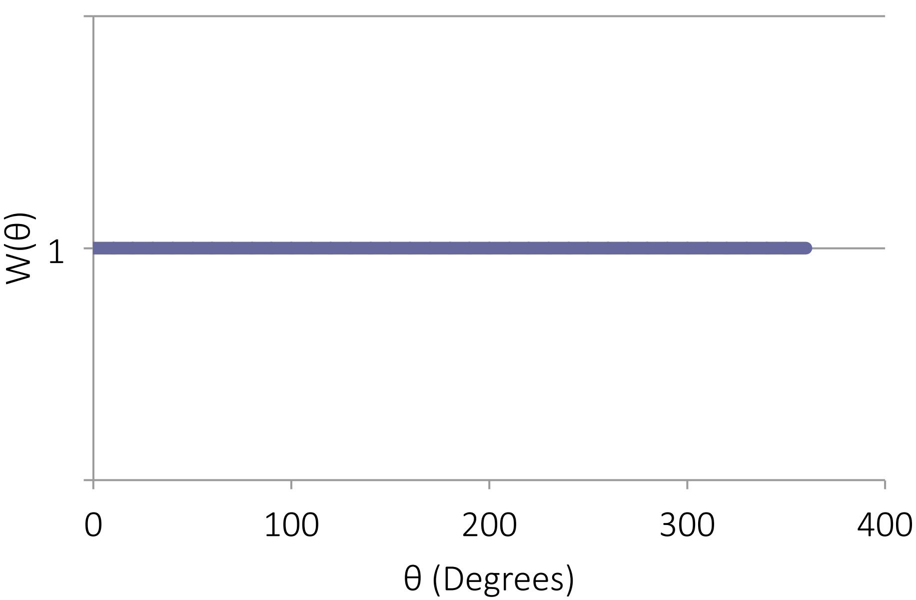
- Knowledge of J_i and J_f limit the multipolarity (L) of gamma-ray transitions
- To measure multipole order (L) we can measure angular distributions
- To determine E vs. M we need to measure polarization of the transition

Gamma-Ray Angular Distributions

- Angular distribution of a gamma-ray depends on the values of m_i and m_f





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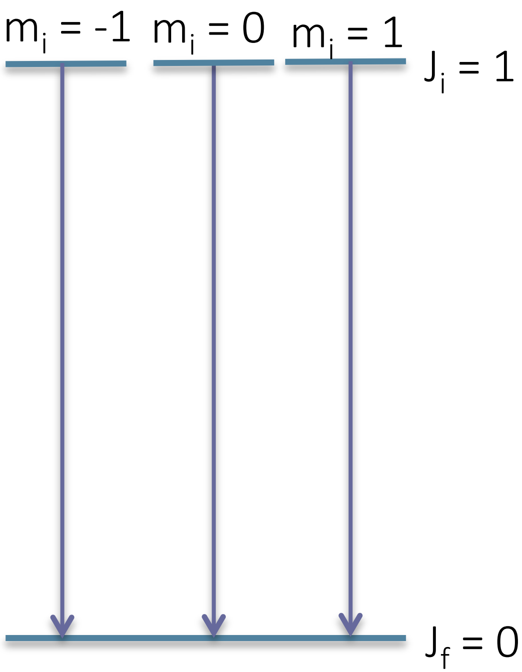
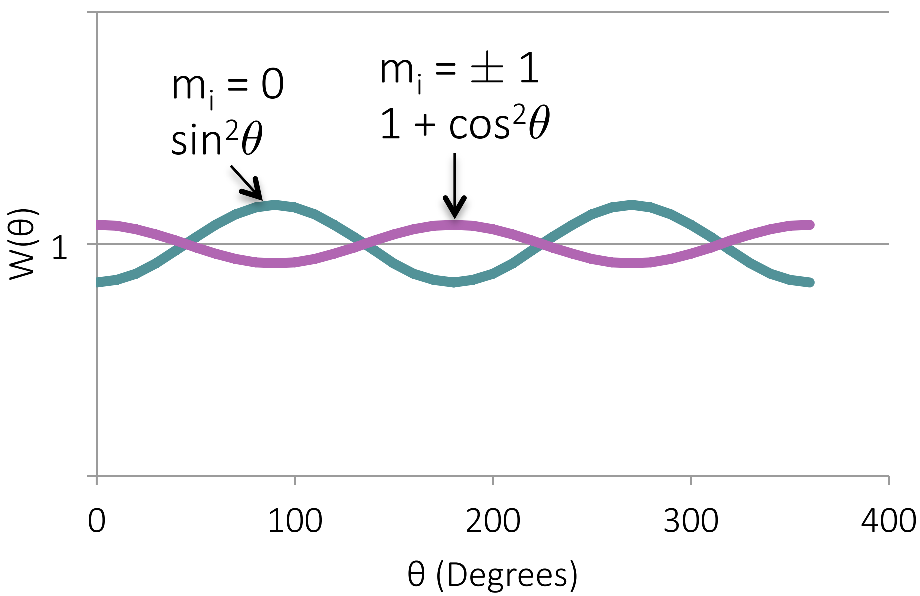
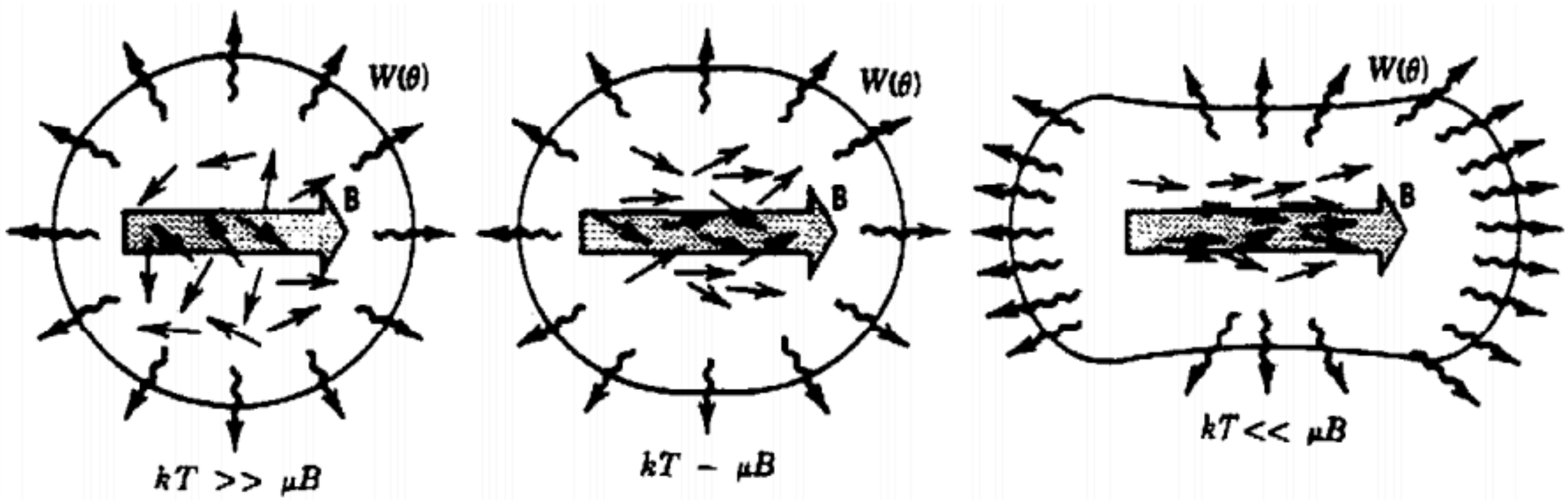




Gamma-Ray Angular Distributions

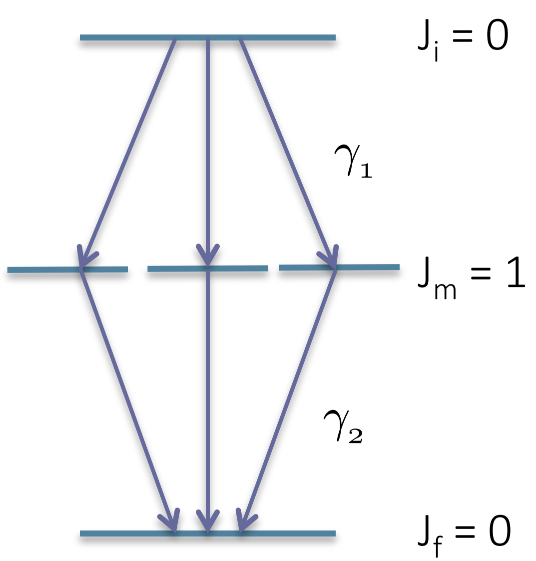
- If we produce unequal populations $p(m_i)$ angular distributions $W(\theta)$ will be non-constant

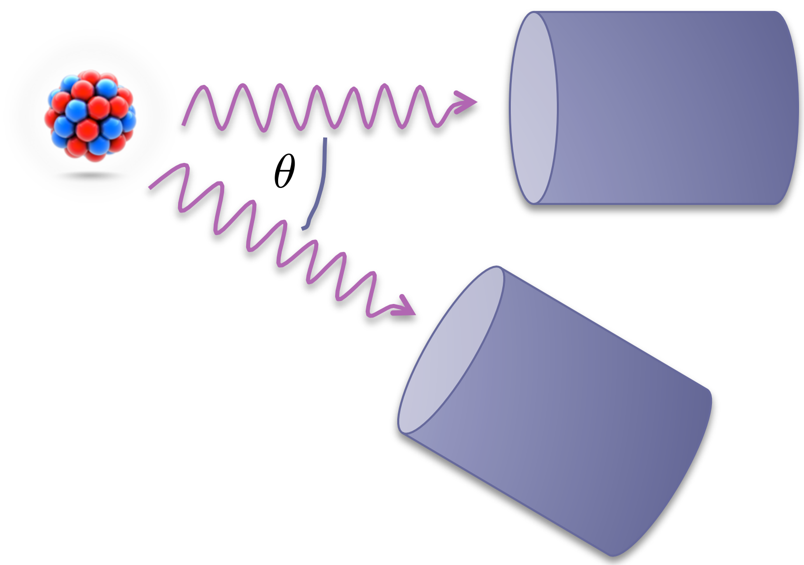
Nuclear Orientation



GAMMA-RAY ANGULAR CORRELATIONS

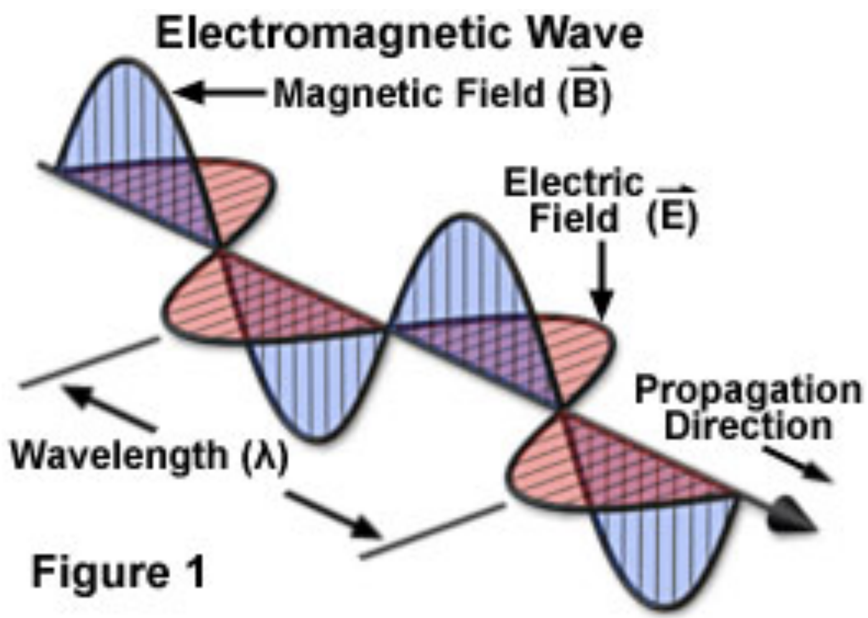
- Observation of a previous radiation selects an unequal mixture of populations $p(m_i)$





- First gamma defines z-axis -- $\theta_1 = 0$
  - $p(m_m) = 0$ for $m_m = 0$
- Distribution of γ_2 relative to γ_1 is $m = \pm 1 \rightarrow m = 0$
  - $W(\theta) \propto 1 + \cos^2\theta$

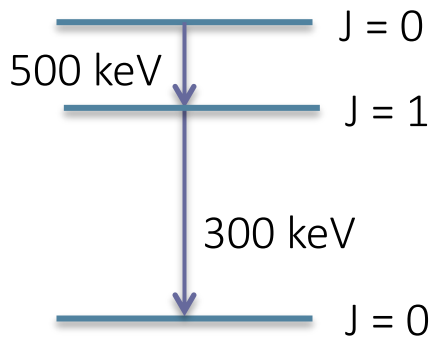
Polarization



- Remember – gamma rays are light, and have electric and magnetic components
- Gamma-rays can be emitted with a specific orientation of their electric field vector with respect to some axis – this alignment can give us insight into the E vs. M nature of the transition
- The scattering of a gamma-ray via the Compton interaction is sensitive to the polarization of gammas…

QUESTION!

- We set up an angular correlation measurement to study the cascade of gamma-rays shown below with two detectors at 90° with respect to each other. What will see in detector 1 if we require
  - (i) 300 keV transition in detector 2, or
  - (ii) no requirement for detector 2?



(A) (i) 500 keV peak, (ii) 300 & 500 keV peaks
(B) (i) 500 keV peak, (ii) 300 & 500 keV peaks
(C) (i) No peaks, (ii) 500 keV peak
(D) (i) 500 keV peak, (ii) 500 keV peak
(E) (i) No peaks, (ii) 300 and 500 keV peaks

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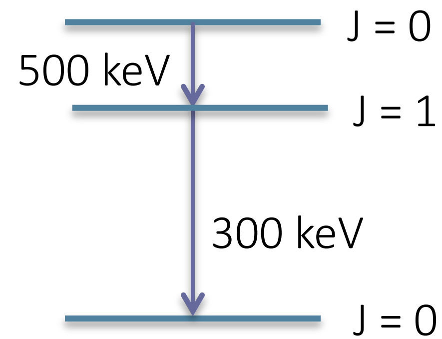


(A) (i) 300 & 500 keV peaks, (ii) 300 & 500 keV peaks

(B) (i) 500 keV peak, (ii) 300 & 500 keV peaks

(C) (i) No peaks, (ii) 500 keV peak

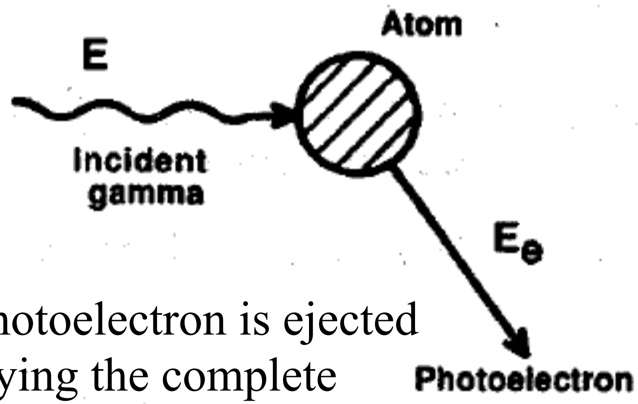
(D) (i) 500 keV peak, (ii) 500 keV peak

(E) (i) No peaks, (ii) 300 and 500 keV peaks

The 500 keV peak will be at it's lowest intensity, but $1+\cos^2\theta$ does not vanish completely anywhere.

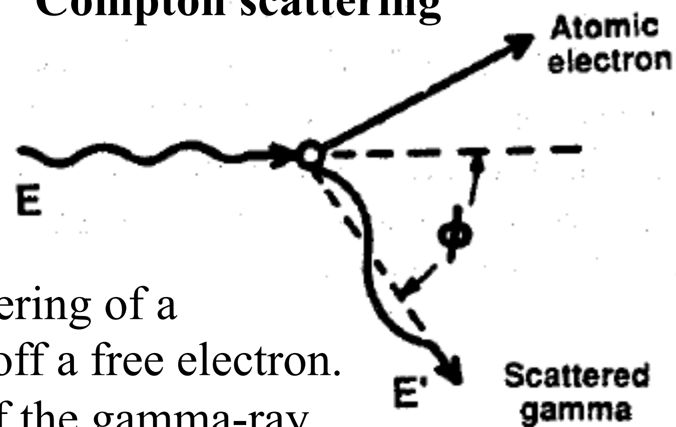
Interaction of Gamma-Rays with Matter

Photo effect



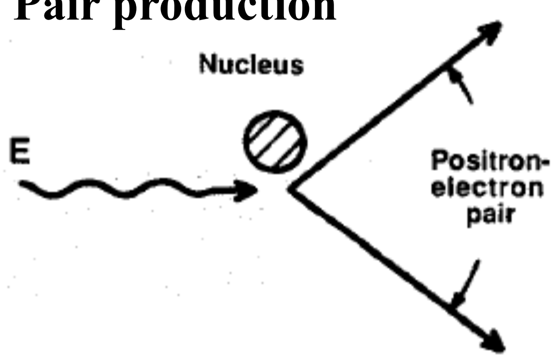
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering



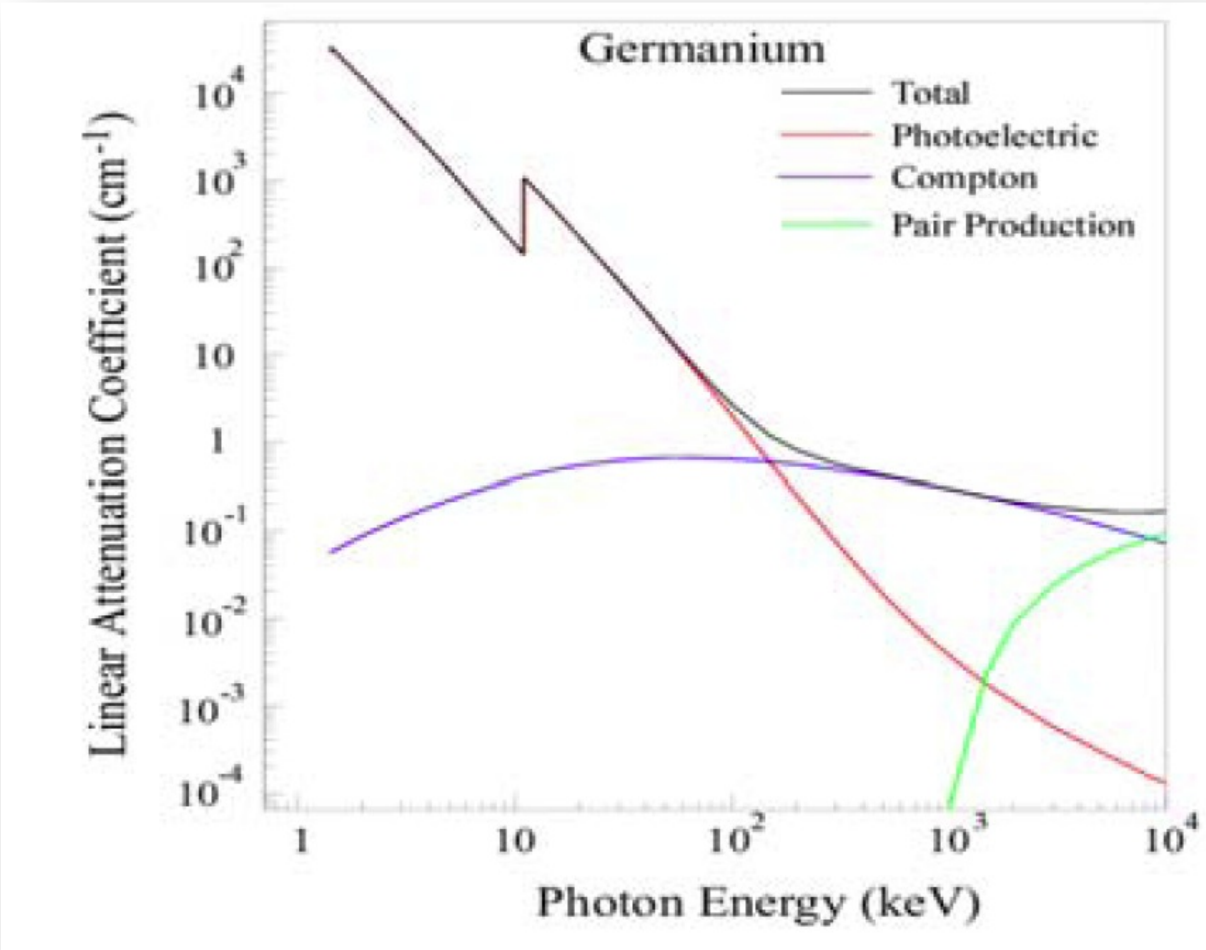
Elastic scattering of a gamma ray off a free electron. A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



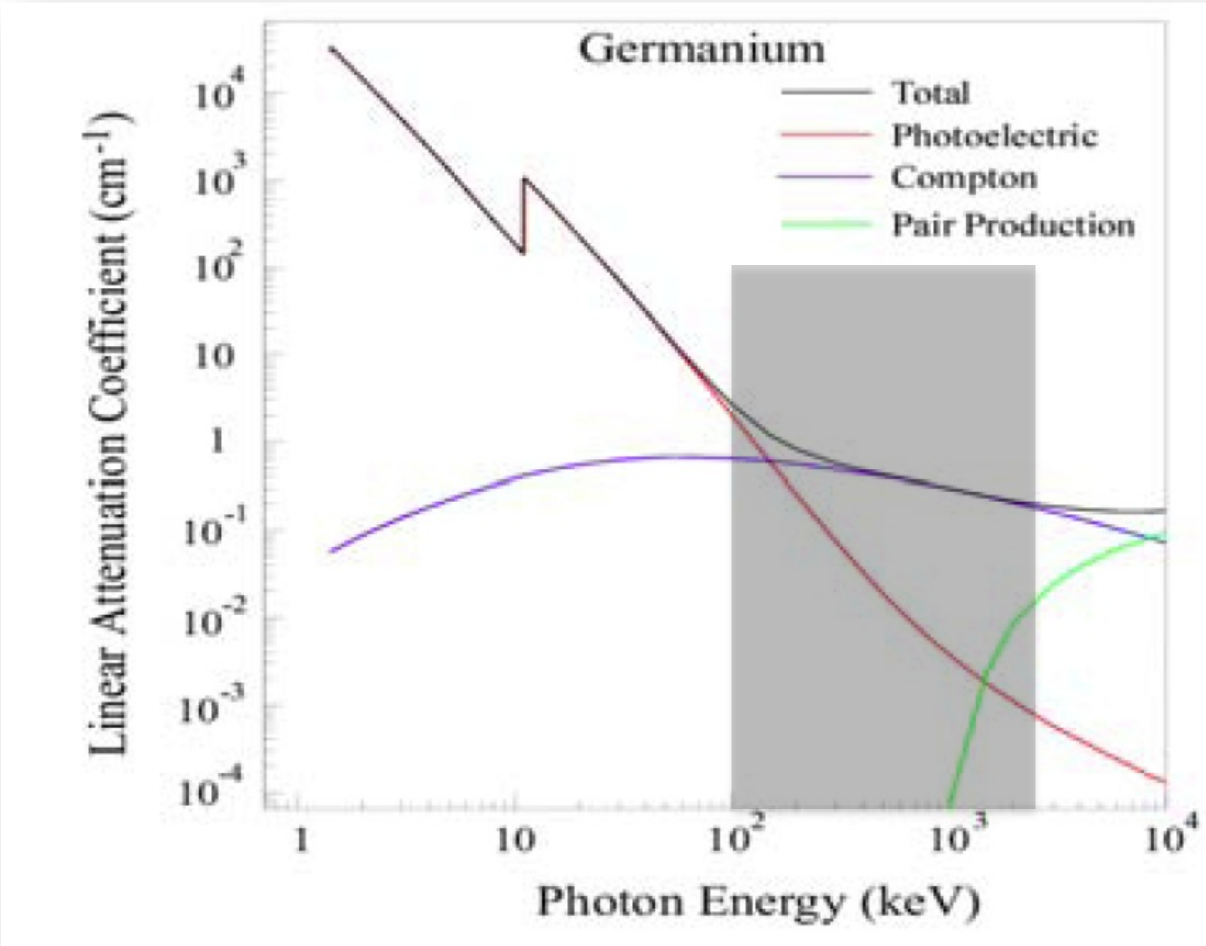
If gamma-ray energy is >> 2 $m_o c^2$ (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 $m_o c^2$.

GAMMA-RAY INTERACTIONS WITH MATTER



Photoelectric: $\sim Z^{4-5}$, $E_\gamma^{-3.5}$
Compton: $\sim Z$, E_γ^{-1}
Pair production: $\sim Z^2$, increase with E_γ

Gamma-Ray Interactions with Matter

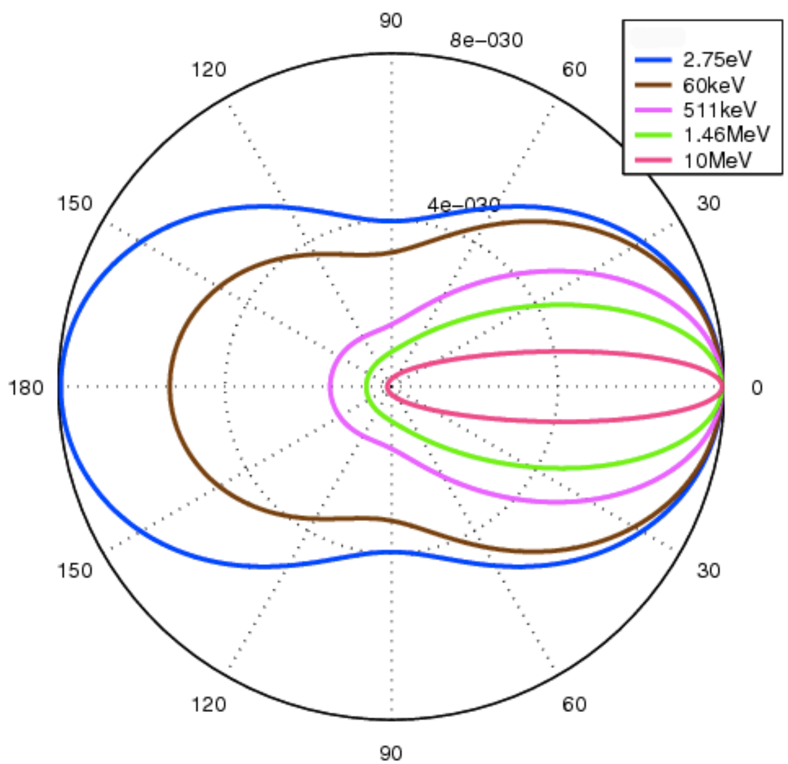


100 keV – 3 MeV gamma-ray energies are typical in nuclear structure studies → Compton scattering dominates!

Photoelectric: $\sim Z^{4-5}$, $E_\gamma^{-3.5}$
Compton: $\sim Z$, E_γ^{-1}
Pair production: $\sim Z^2$, increase with E_γ

COMPTON SCATTERING: MORE DETAILS

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



The angle dependence of Compton scattering is expressed by the

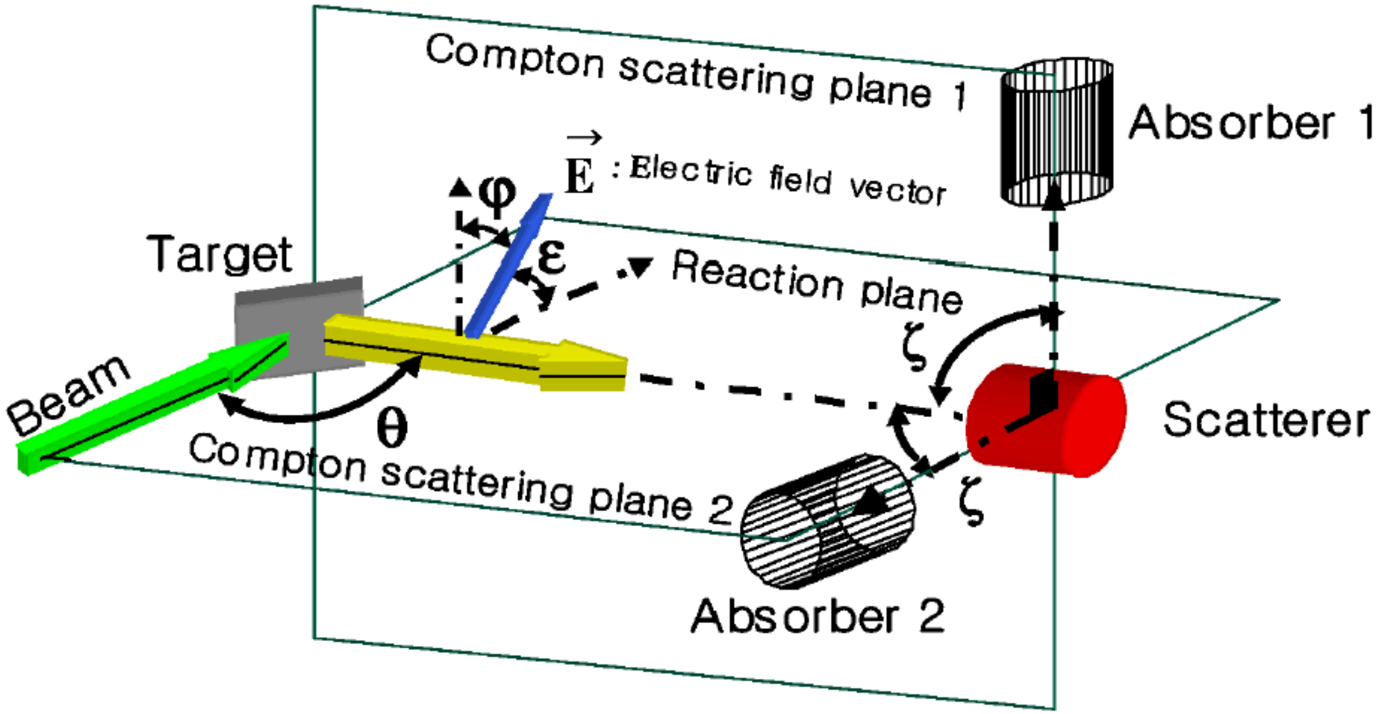
Klein-Nishina Formula

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

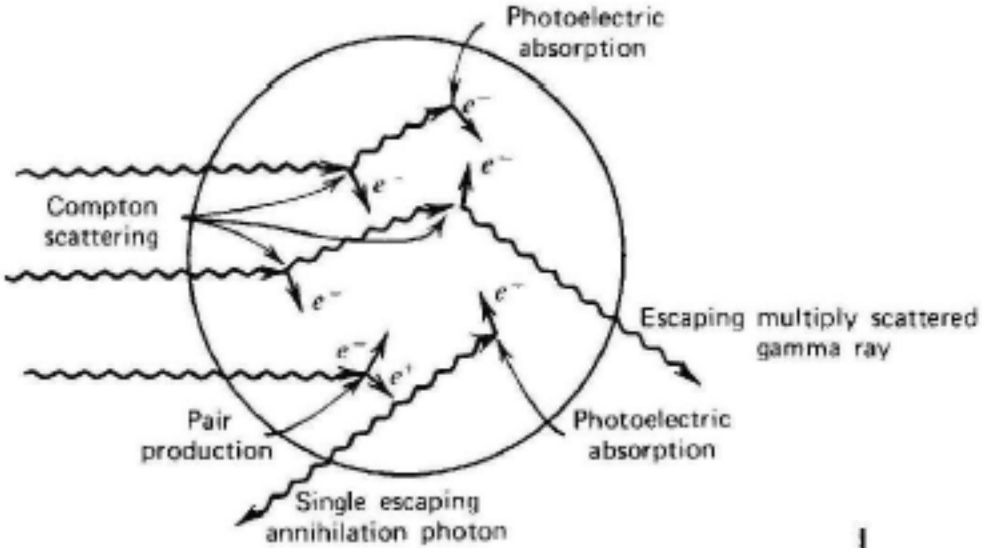
$$\frac{d\sigma_c^{KN}}{d\Omega}(\theta) = r_0^2 \frac{1+\cos^2\theta}{2} \frac{1}{[1+h\nu(1-\cos\theta)]^2} \left\{ 1 + \frac{h\nu^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+h\nu(1-\cos\theta)]} \right\}$$

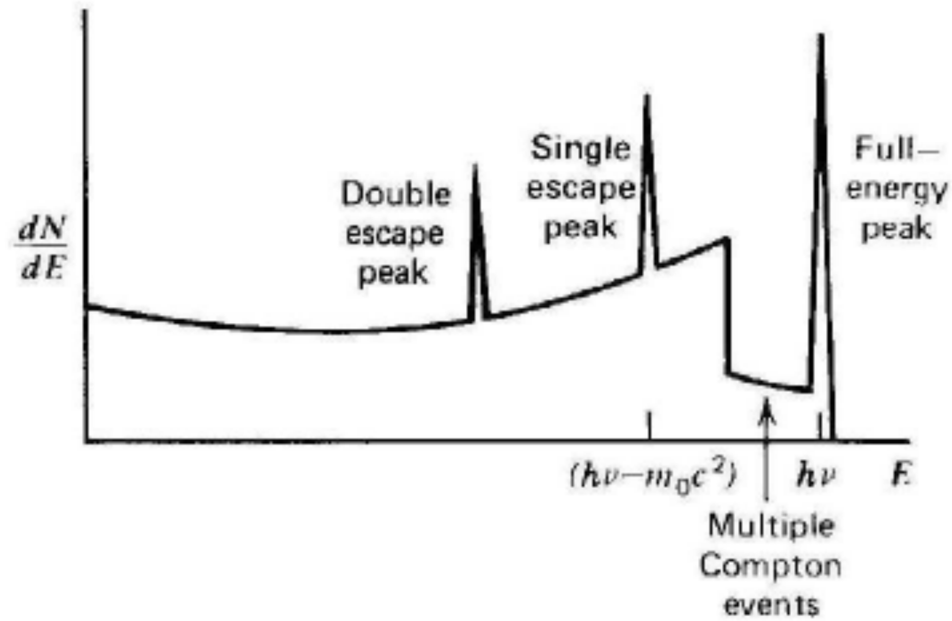
Compton Scattering and Polarization

$$\frac{d\sigma}{d\Omega} = \frac{r_\circ^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2\left(\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2\sin^2\zeta\cos^2\phi\right)$$



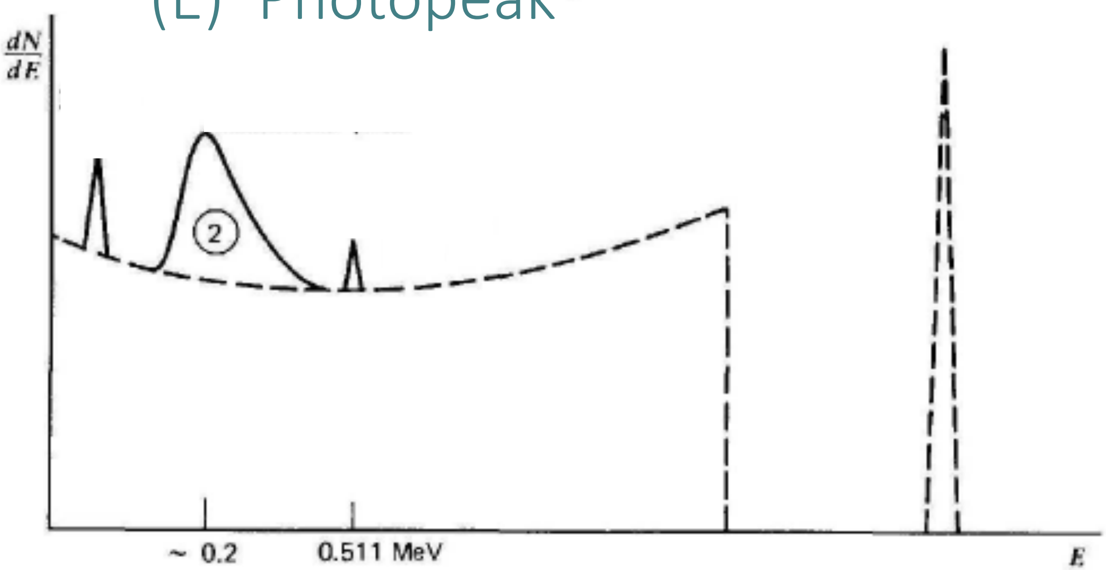
Gamma-Ray Spectra – General Features





QUESTION!

- What does peak (2) in the cartoon gamma-ray spectrum correspond to?
  - (A) Backscatter peak
  - (B) (n,γ) reaction on detector nuclei
  - (C) x-ray peak from internal conversion
  - (D) Second escape peak
  - (E) Photopeak



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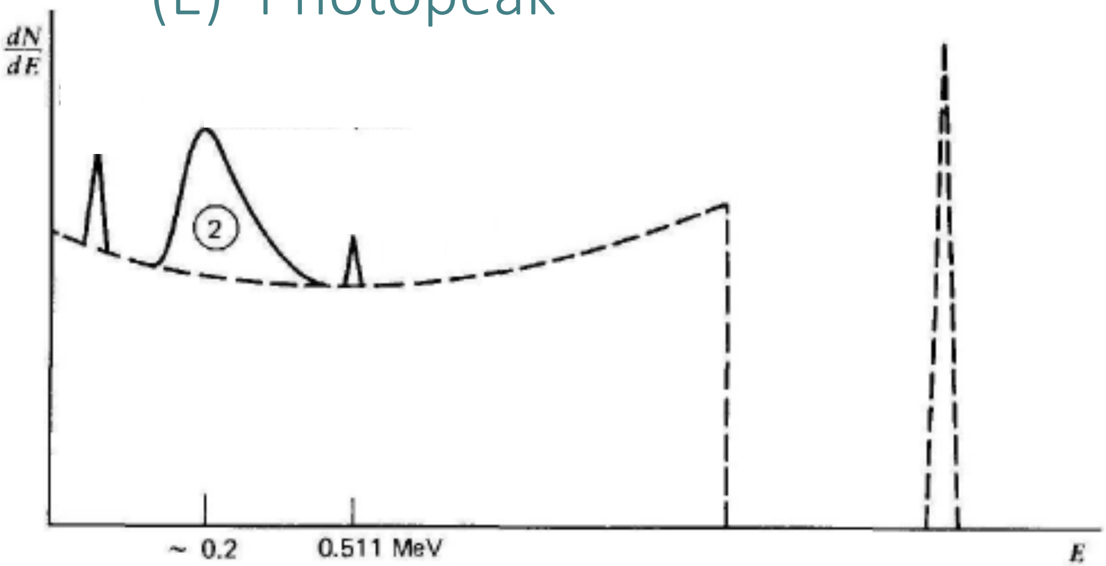
$\theta = 180°$

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



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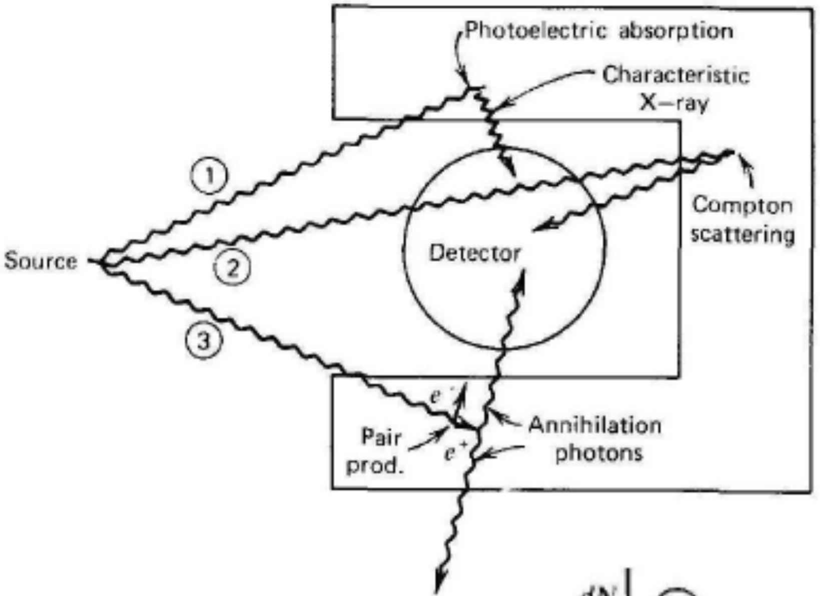
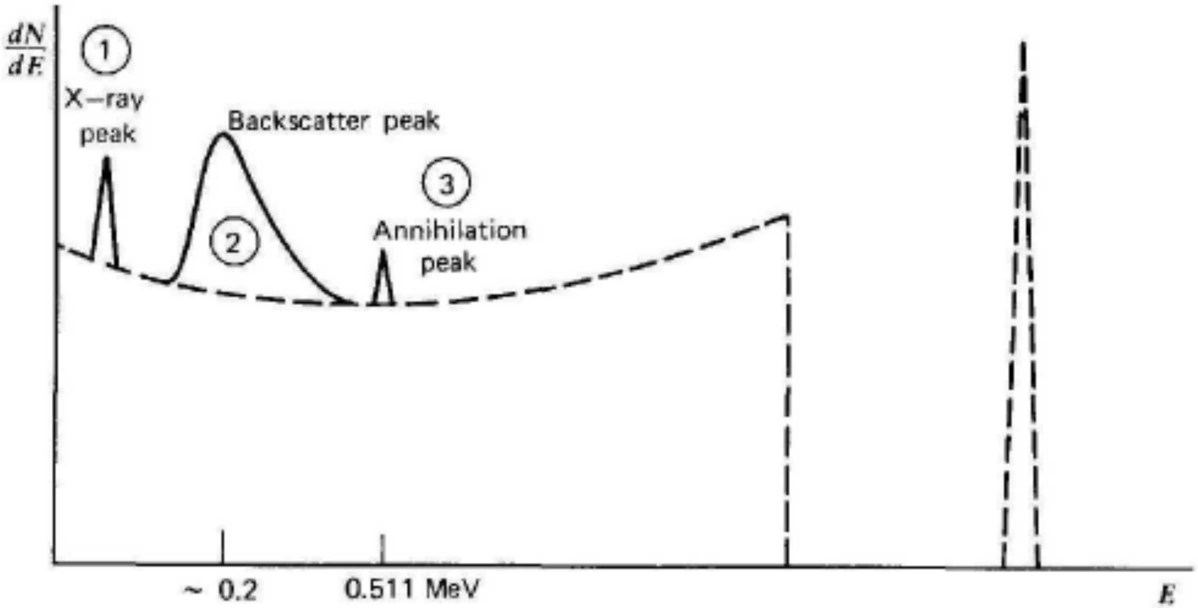


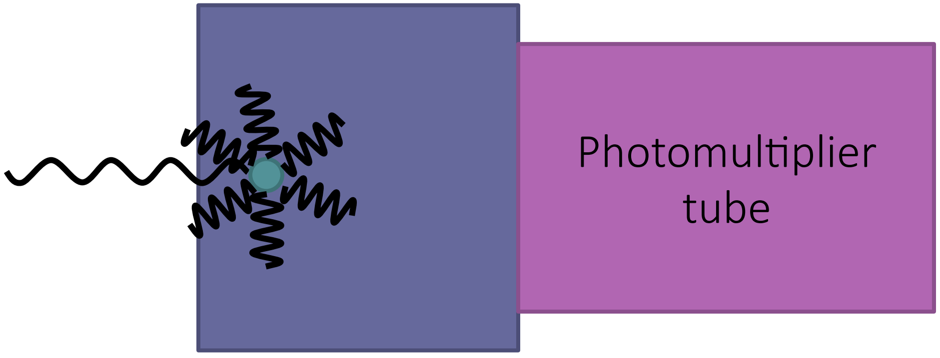


Gamma-Ray Detection: Basic Principles

- Fundamentally, we can detect a gamma-ray if it can leave energy in our detector that we can collect
- Gamma-rays primarily interact with electrons – most detectors therefore high Z
- Methods for measuring energy transferred to electrons vary… but we worry about 3 basic performance parameters:

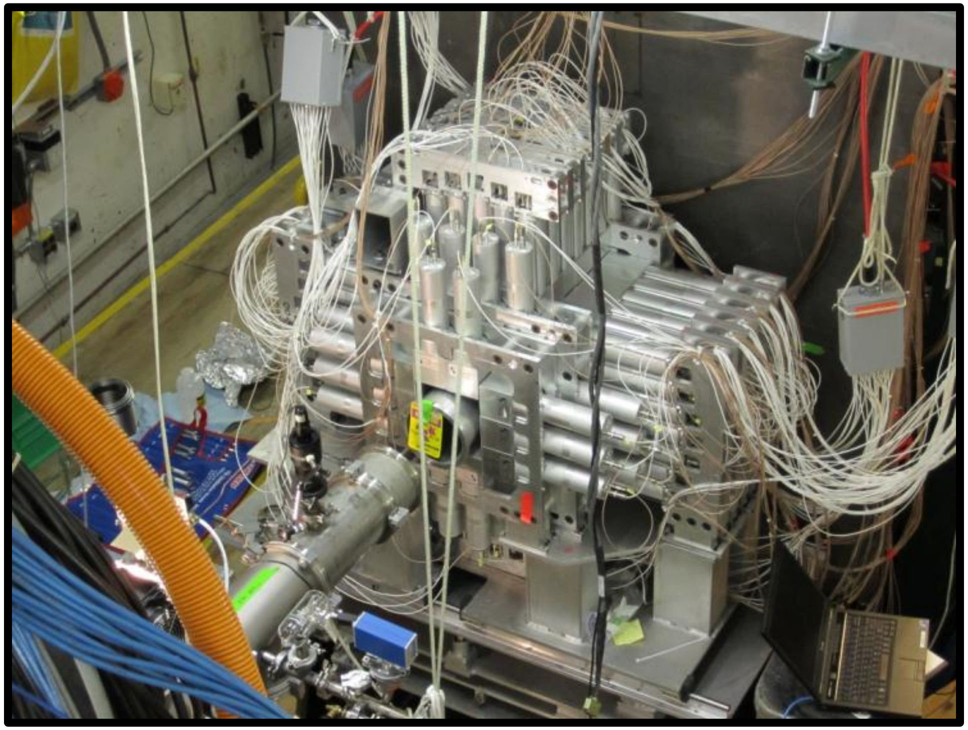
> - Energy resolution
> - Efficiency
> - Peak-to-total (P/T) – probability that a *detected* gamma-ray actually makes it into the peak

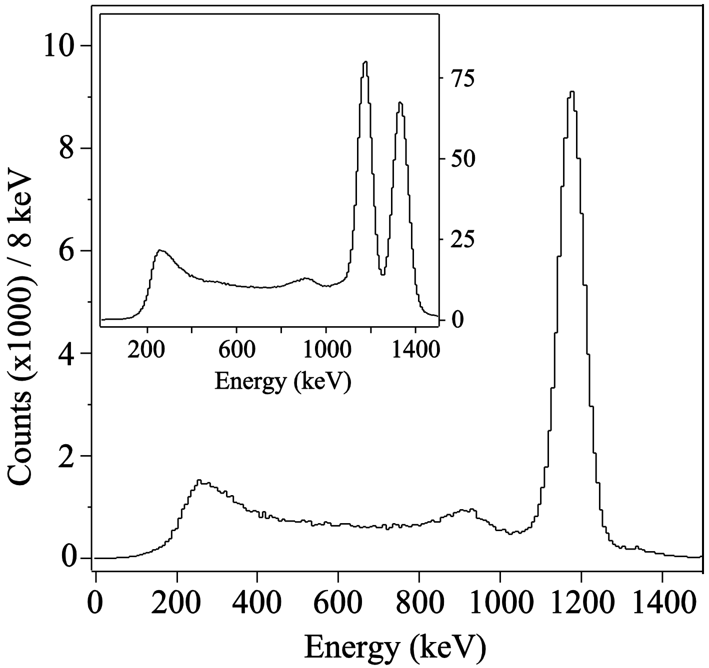
Scintillators



High efficiency ~ 40%

Intrinsic energy resolution determined by statistics of photoelectrons in the PMT – for scintillators, resolutions ~ 6-7%





Poisson (Counting) Statistics

- Binomial distribution – Roll a dice n times, what is the probability for rolling a 6 x times?

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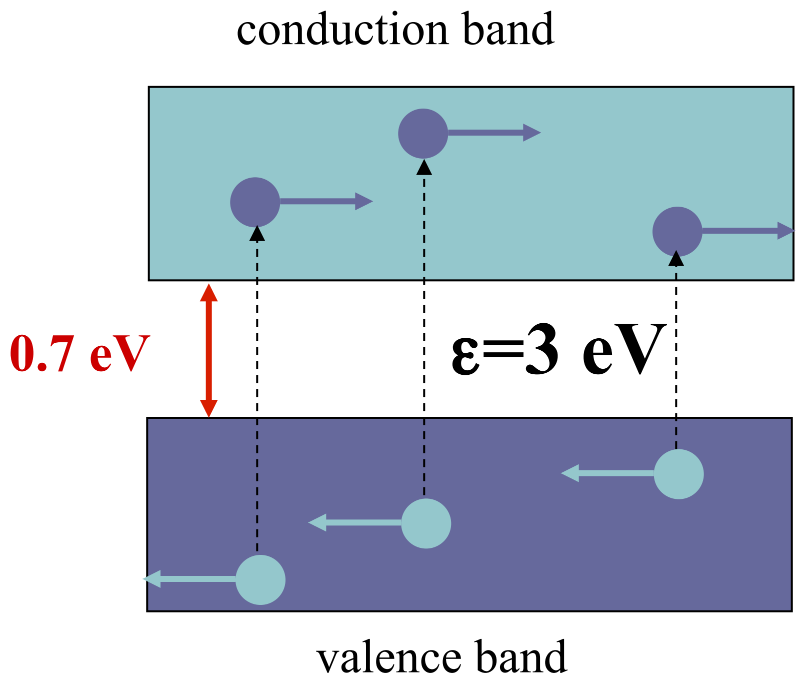
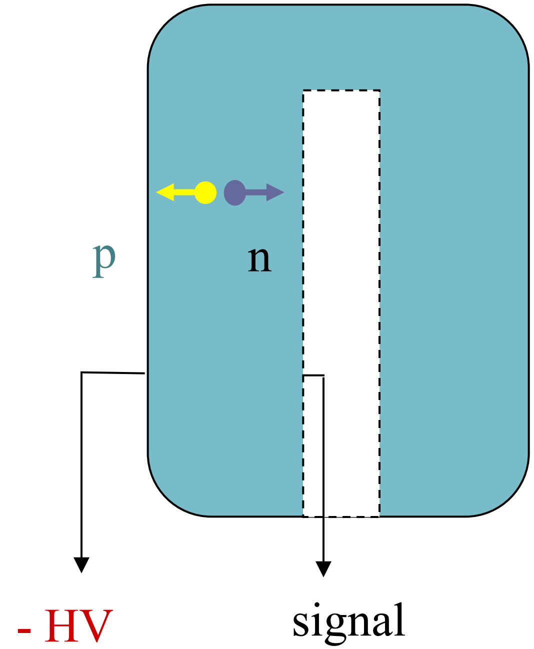
Resolution in Scintillators

- Energetic particle traveling through a detector (i.e. electron from gamma-ray interaction). Per length traveled dx, this particle may produce scintillation photon, which may make it to the photo-cathode, be converted to a photo-electron and contribute to a signal
  - CsI(Tl) yields 39,000 photons / 1 MeV gamma
  - Light collection + PMT efficiency = 15%
  - 6000 photons collected on average -- $\sigma = \sqrt{6000} = 77$
  - FWHM = 180 $\rightarrow$ dE/E = 3%

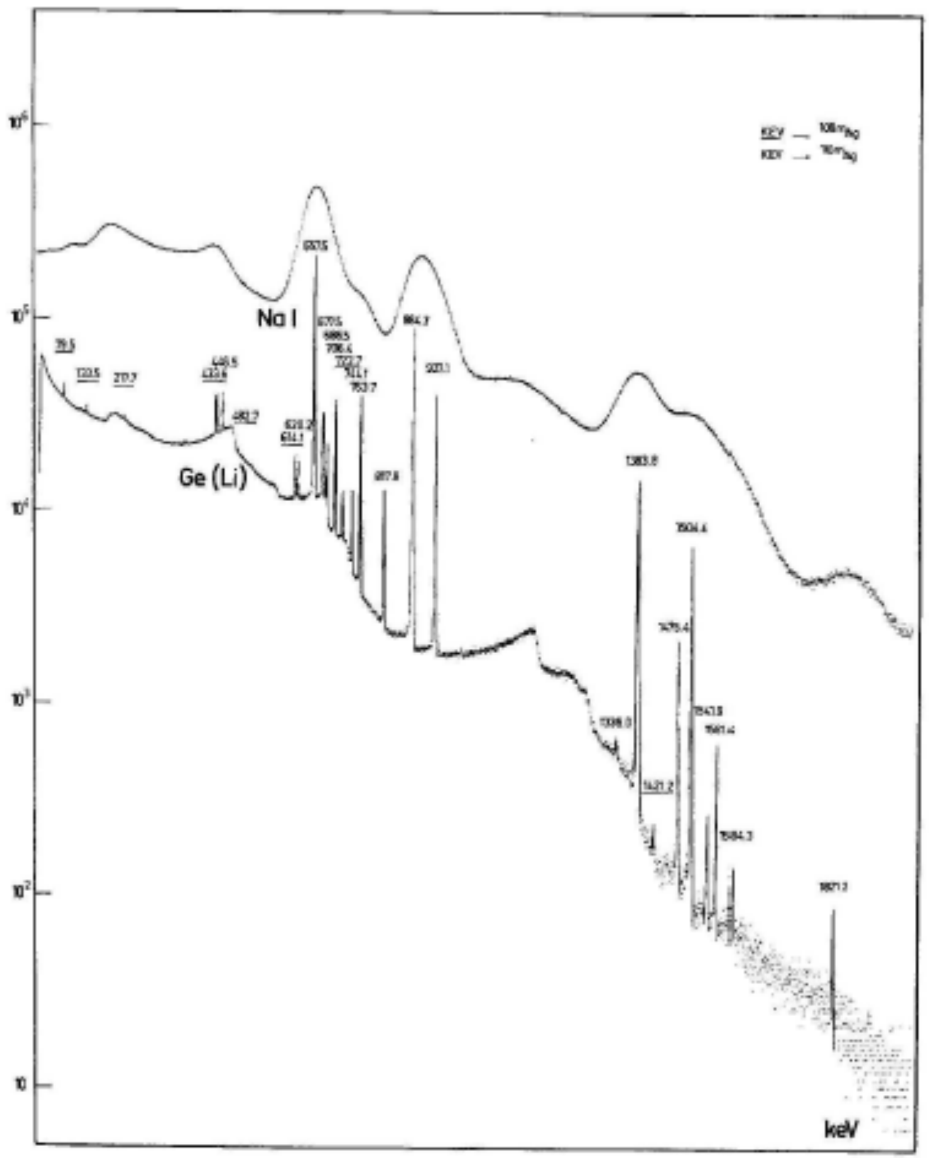
SEMI-CONDUCTORS

- Semiconductors like HPGe provide a gold standard for gamma-ray energy resolution
- Energy required to excite electron into the conduction band ~ 3 eV, many more electron-hole pairs than photons for a scintillator



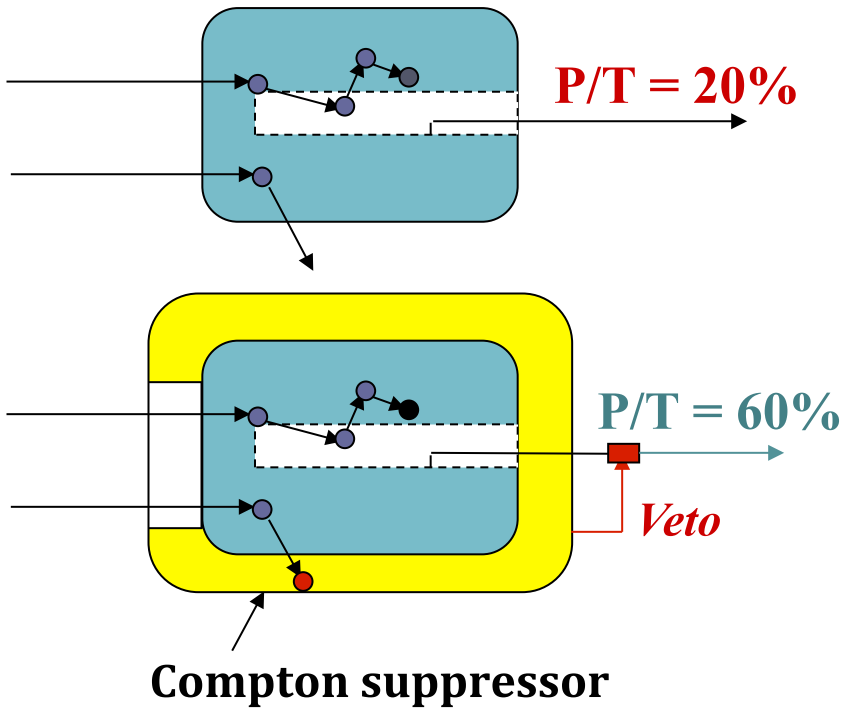


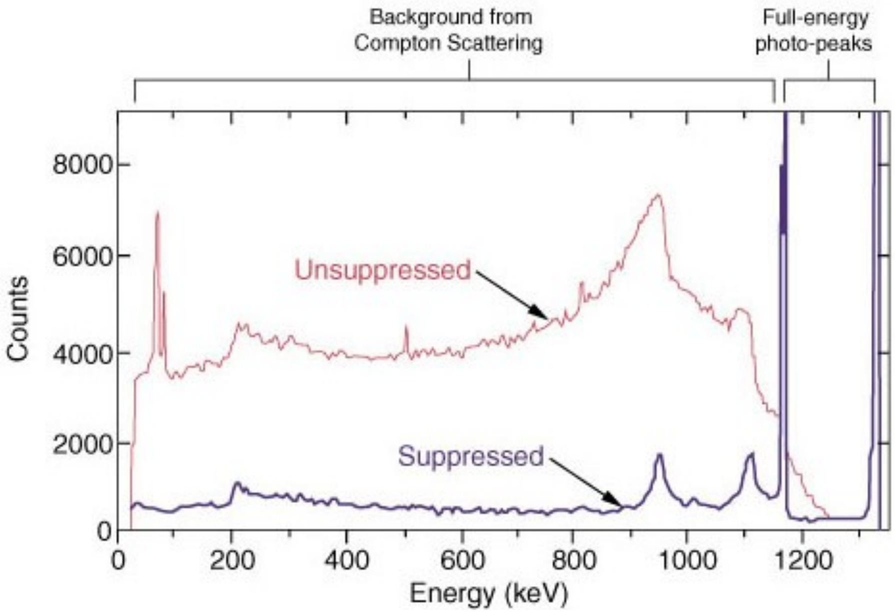
Energy Resolution in HPGe

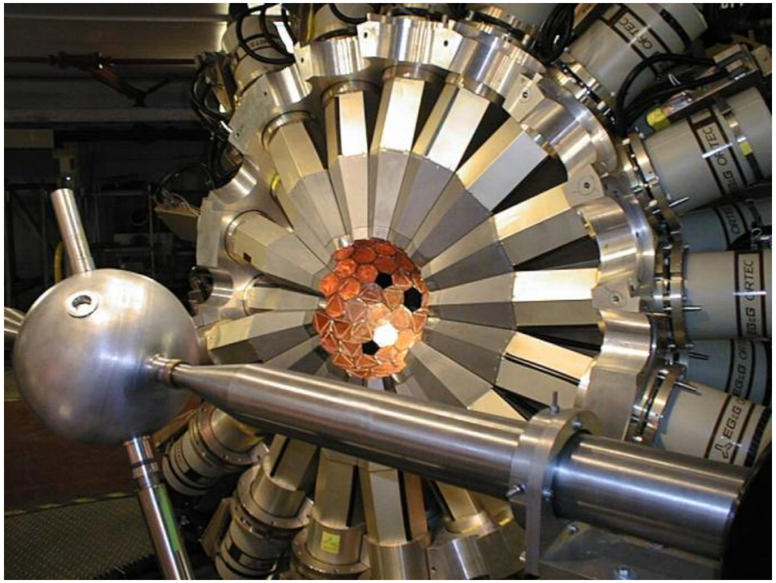


- Energy resolution for Ge is ~ order of magnitude better than scintillators
- So what are the downsides?
  - Very expensive (> $10K)
  - Smaller than scintillator crystals usually
  - Require cooling (LN_2)
  - Slower response (timing Ge 5-10ns; scintillator << 1 ns)

Compton Suppression



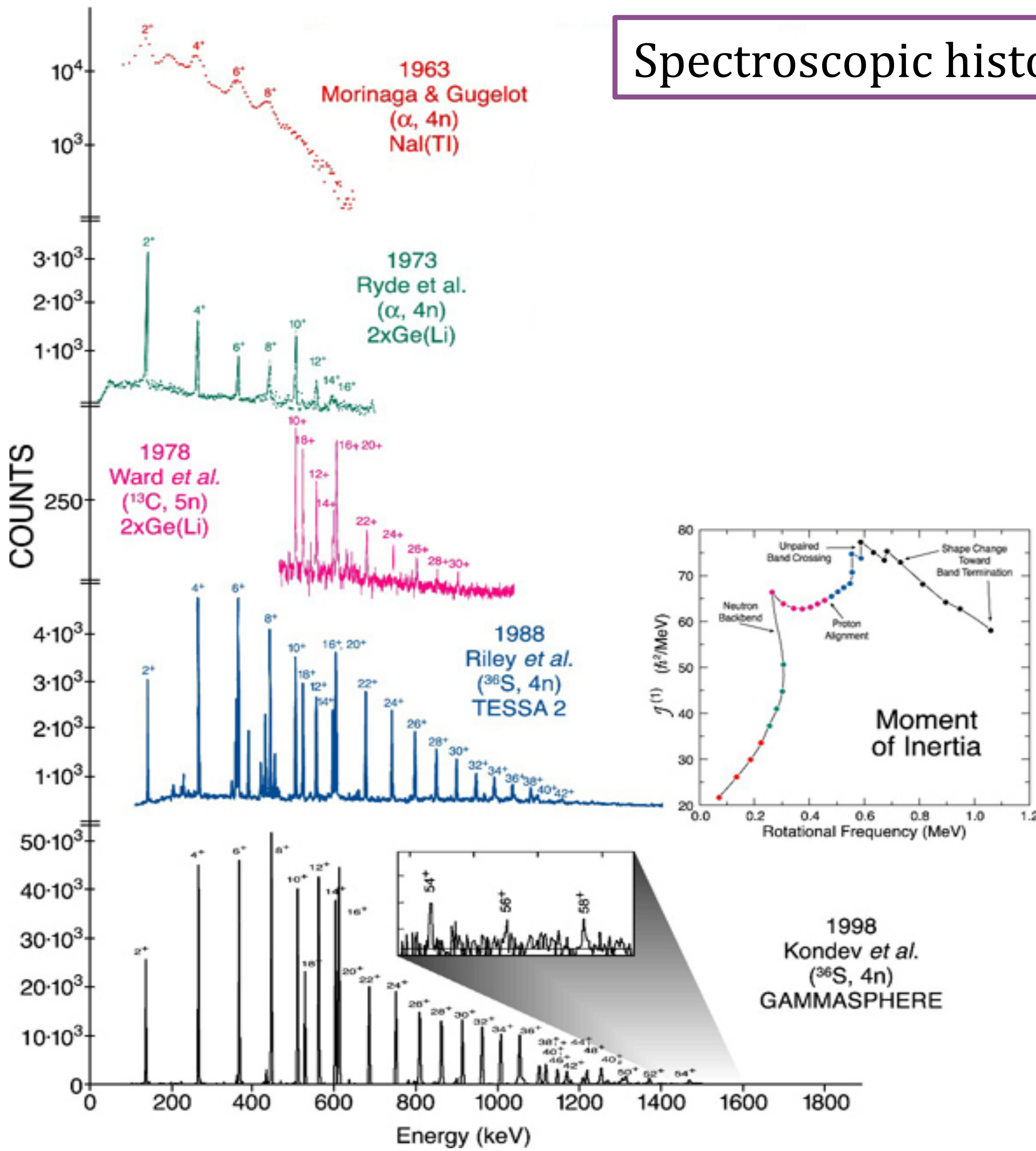




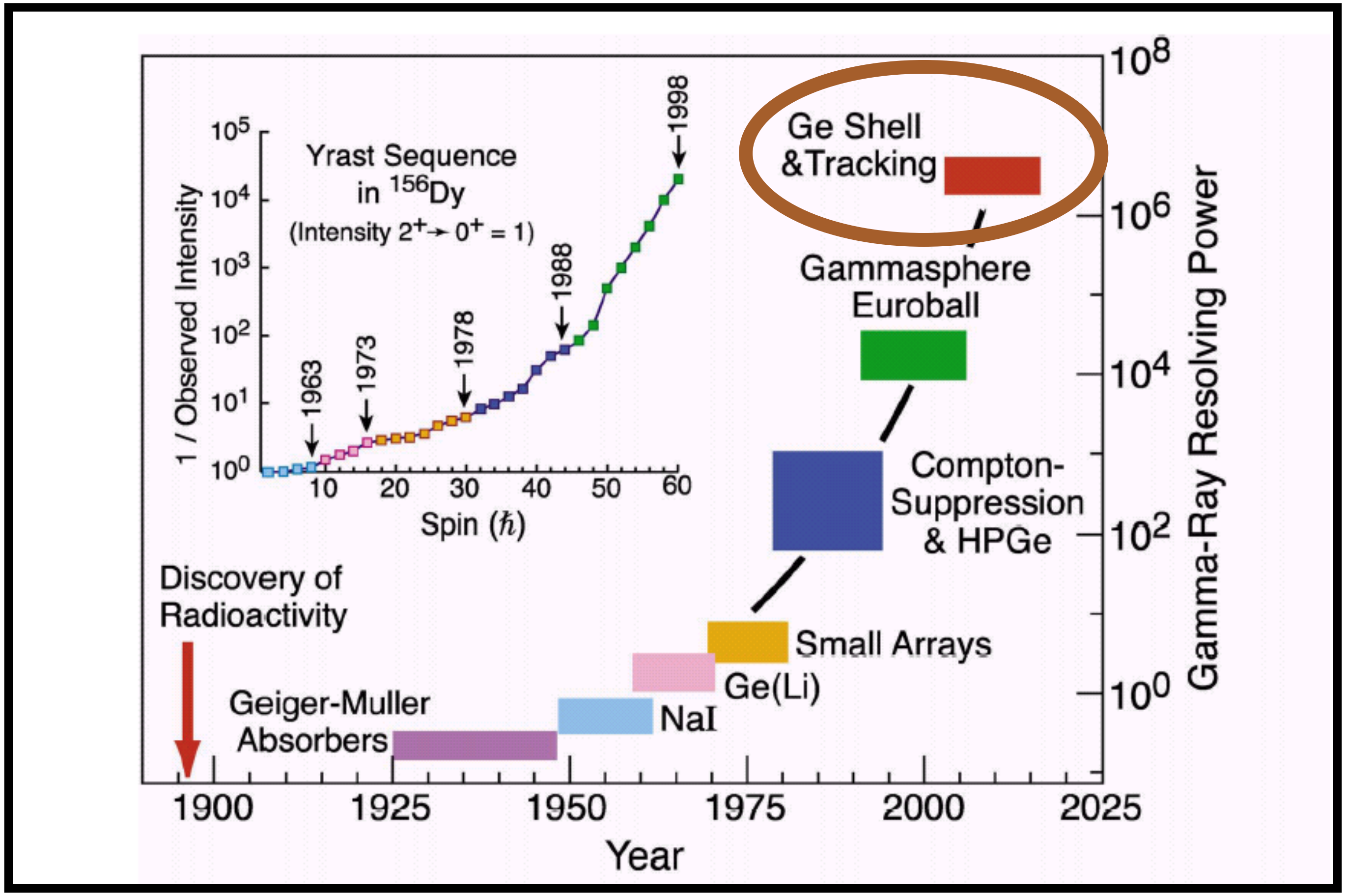
- Eliminate Eliminate contribution from Compton-scattered gamma-rays, which contribute to background, by vetoing these events using a high-efficiency scintillator surrounding the Ge crystal

Timeline of γ-Ray Spectroscopy

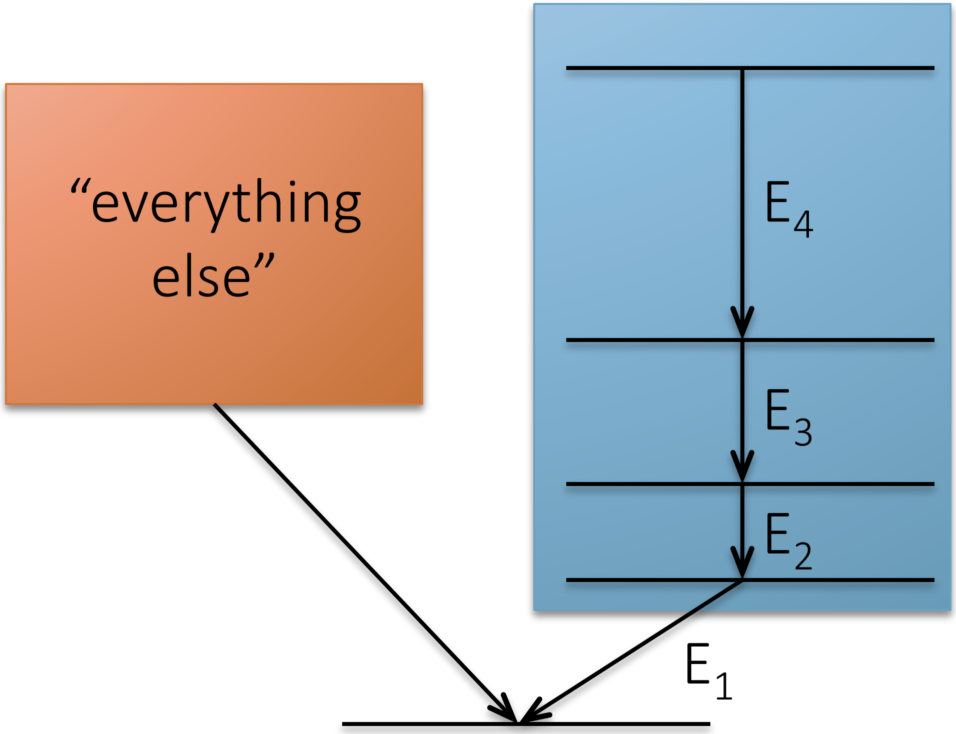
Spectroscopic history of ^{156}Dy



Timeline of γ-Ray Spectroscopy

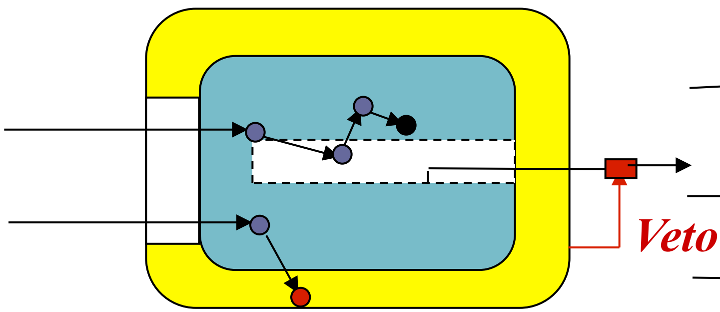


Benchmark: Resolving Power



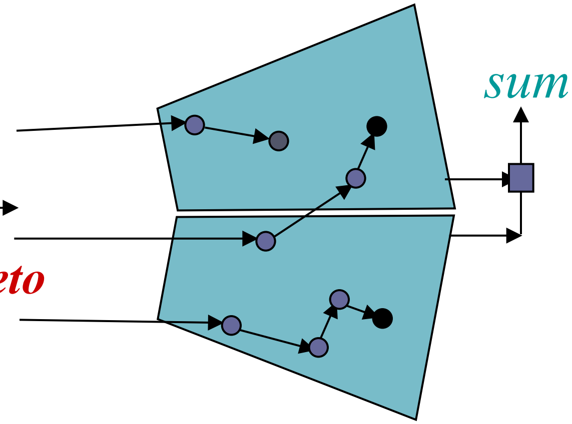
Gamma-Ray Energy Tracking Array

- Compton Suppressed Ge



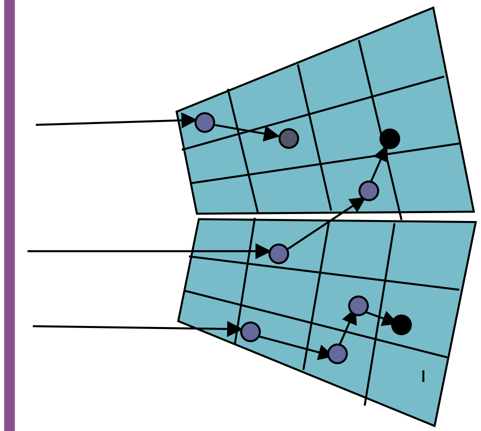
N = 100
NΩ e = 0.1
Efficiency limited

- Ge Sphere



N = 1000 (summing)
NΩ e = 0.6
Too many detectors

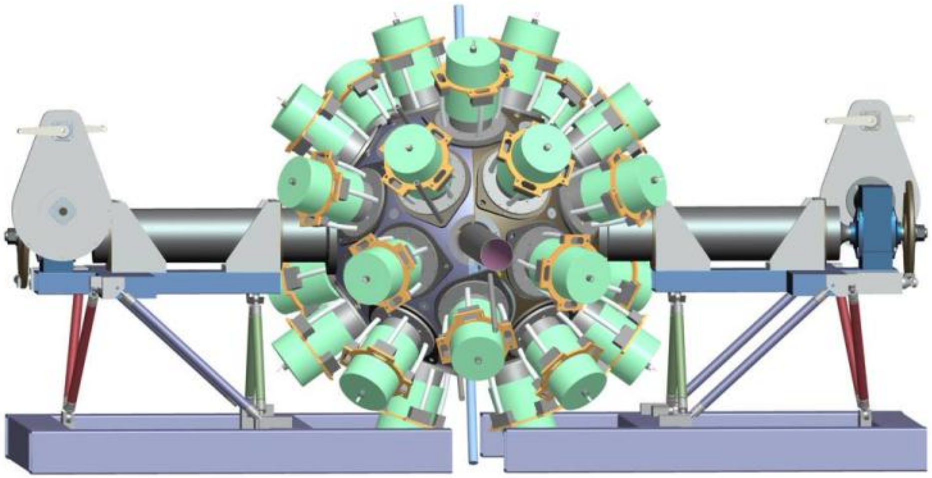
- Gamma Ray Tracking

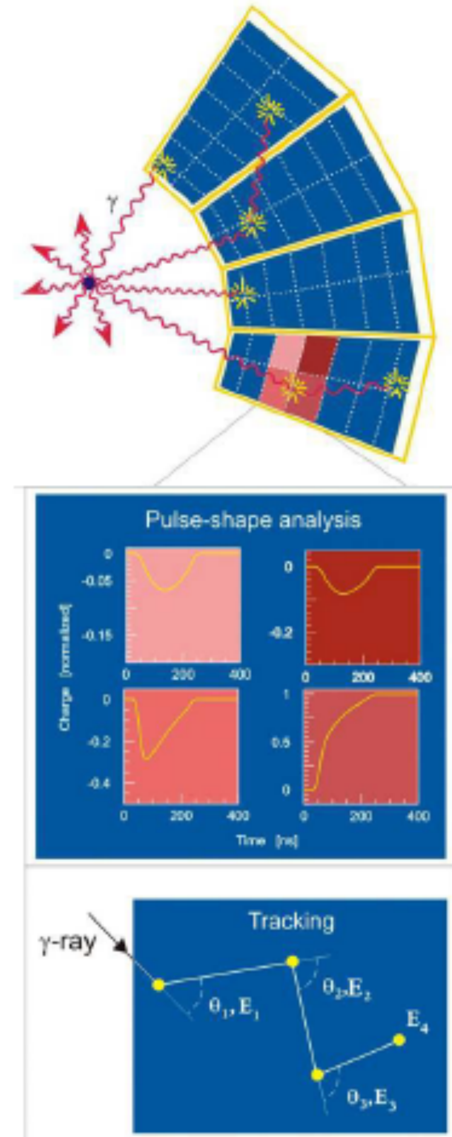


N = 100
NΩ e = 0.6
Segmentation

Build a 4π sphere of Ge, using highly-segmented detectors
Gamma-ray tracking allows rejection of Compton scattering events,
Signal decomposition allows sub-segment position resolution

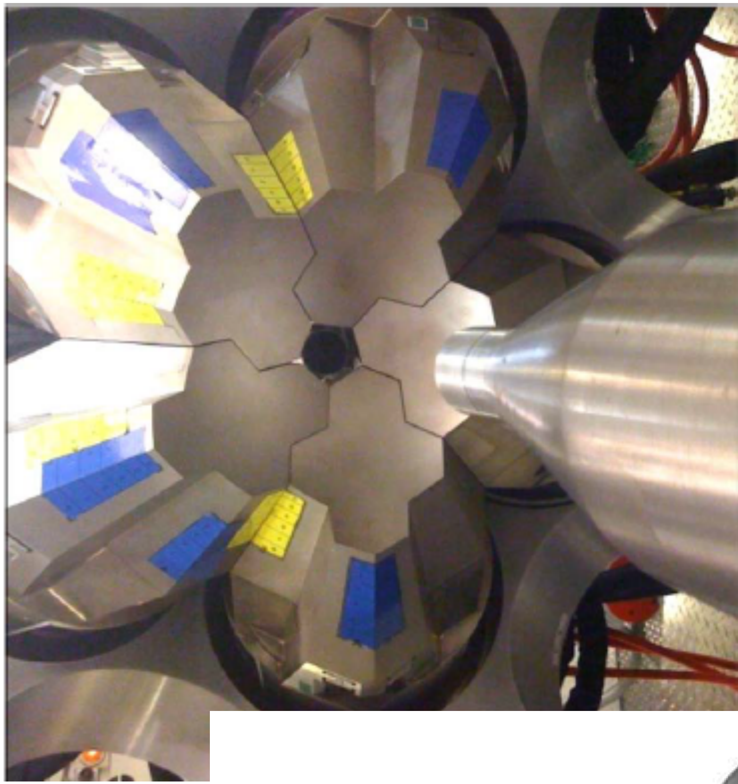
GRETA





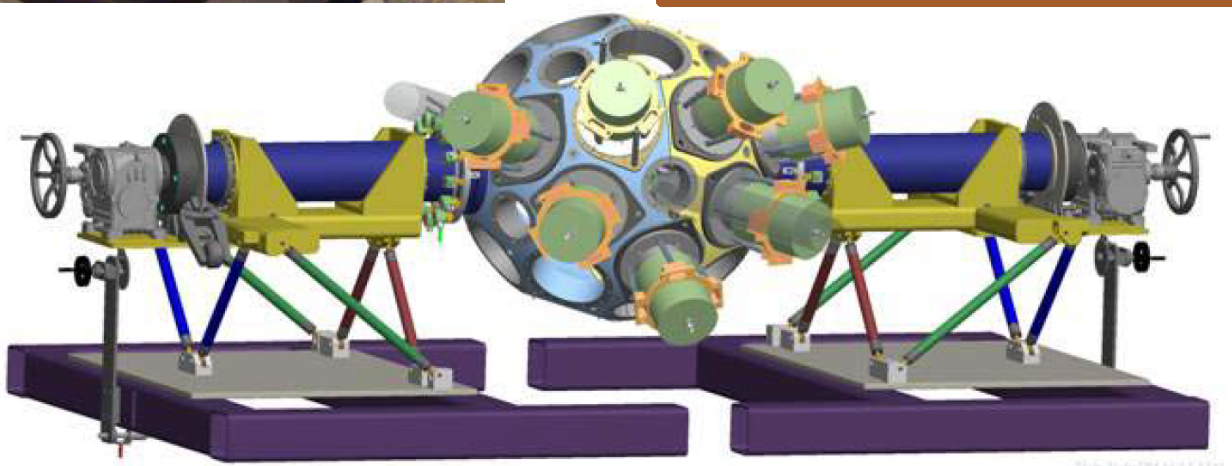
- GRETA will be a 4π solid sphere of HPGe, composed of 120 individual crystals, housed as quads
- Array will be self-shielding, signal decomposition and tracking allows for Compton rejection, and sub-segment first-hit localization for Doppler correction

GRETINA: ¼ of GRETA (sort of)

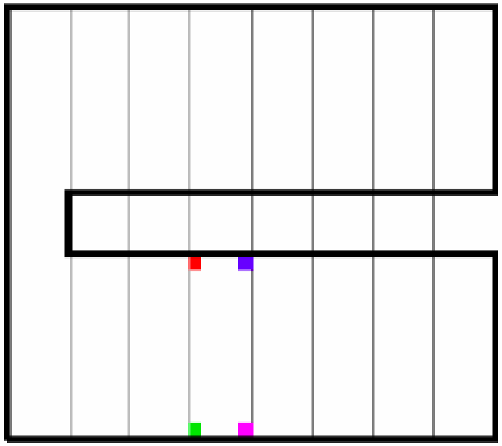


- GRETINA is the first-stage of GRETA, an array covering ¼ of 4π, consisting of 28 individual crystals in 7 quads
- Something to consider: ¼ of a full HPGe sphere is no longer self-shielding

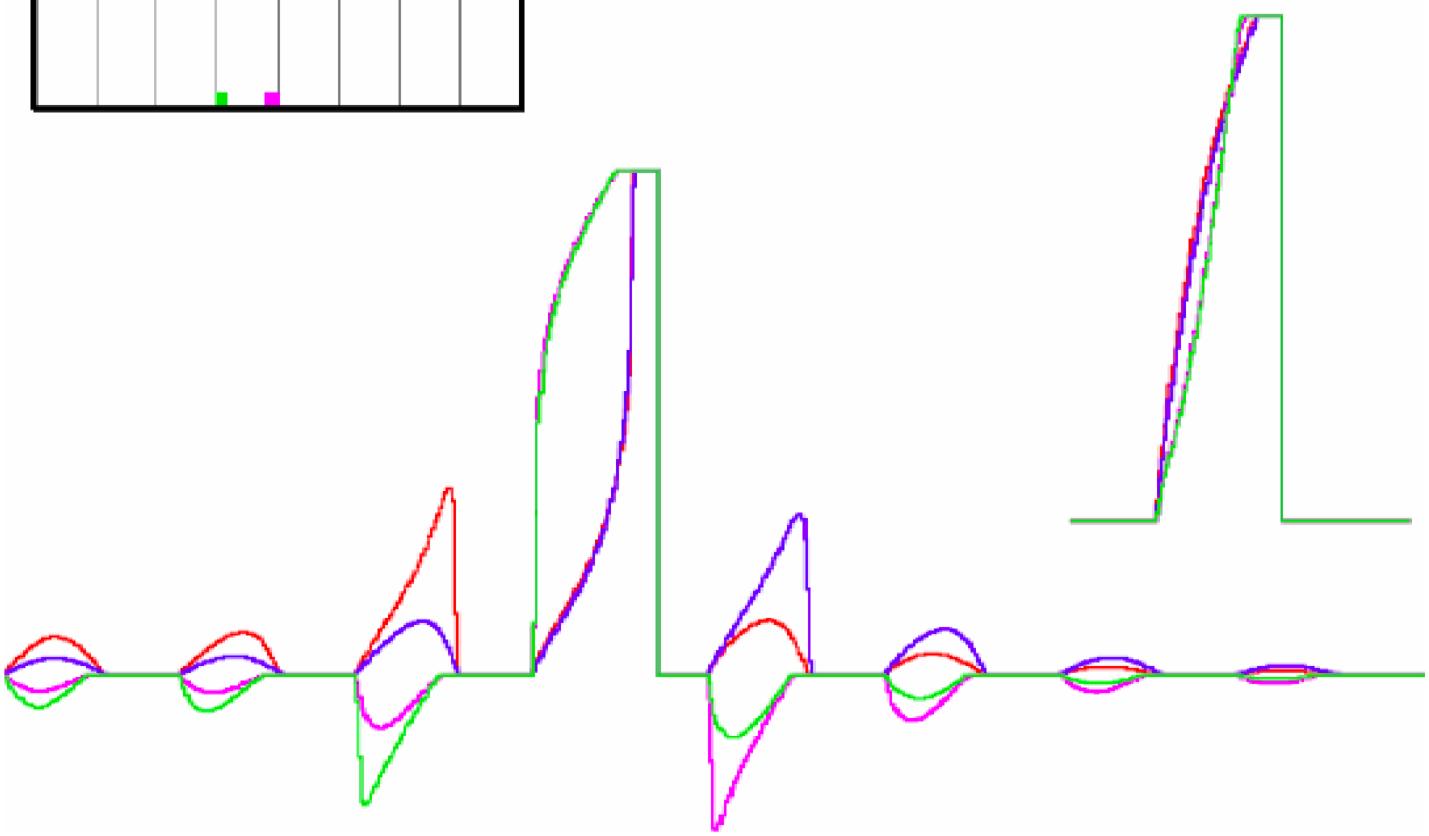
Construction started at LBL in 2005
Commissioning runs at LBL finished in March, 2012



Signal Decomposition



Principle: The movement of charge in a given segment induces a signal on the electrodes of neighbouring segments. The shape of this induced signal is sensitive to the spatial position of the γ-ray interaction point.

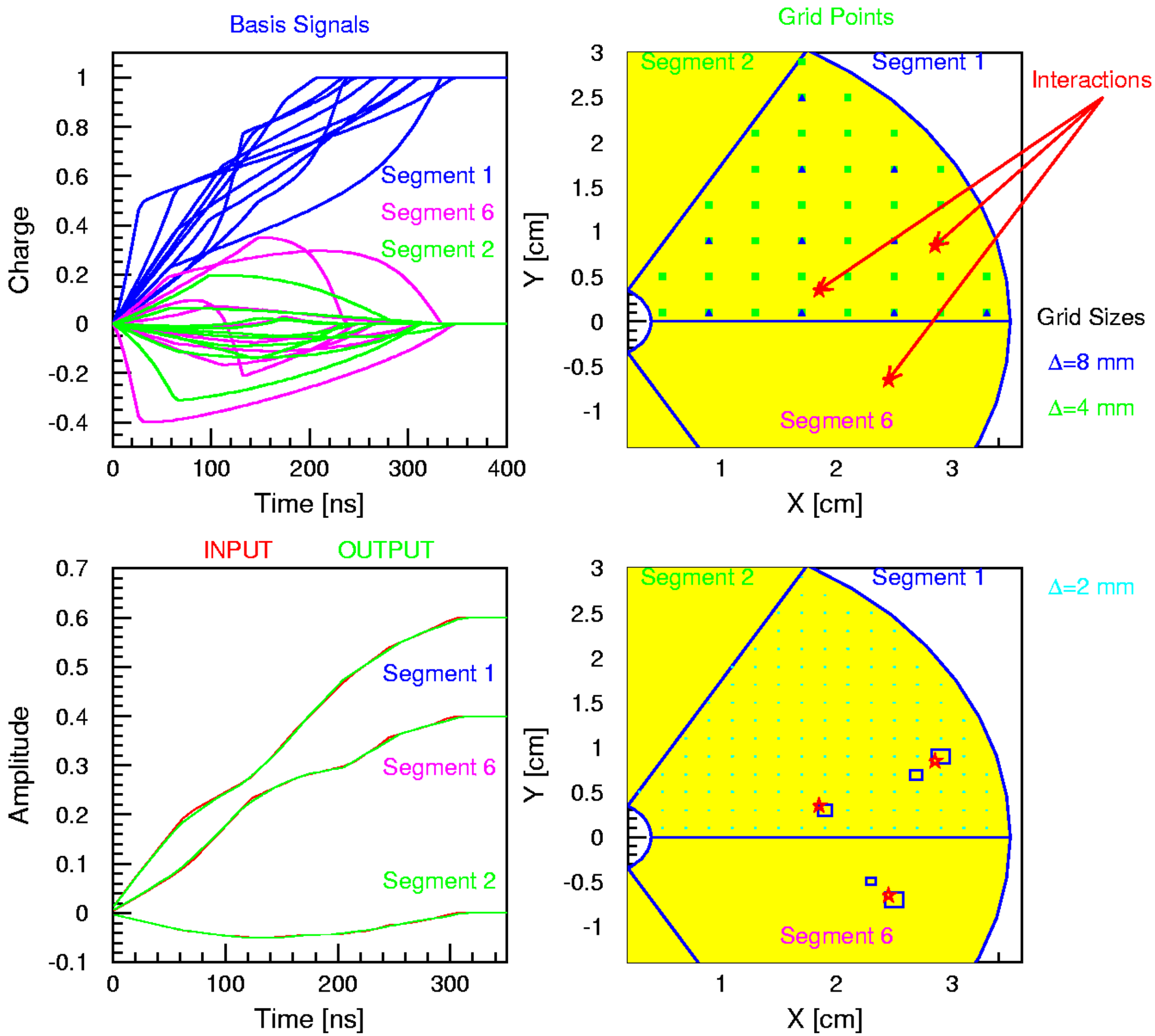


Adaptive Grid Search

Adaptive Grid Search algorithm:

Start on a course grid, to roughly localize the interactions, then refine the grid close by.

Pristine basis (set of signals at grid points) is calculated based on simulation; measurements are made to correct for effects such as segment cross-talk, etc.



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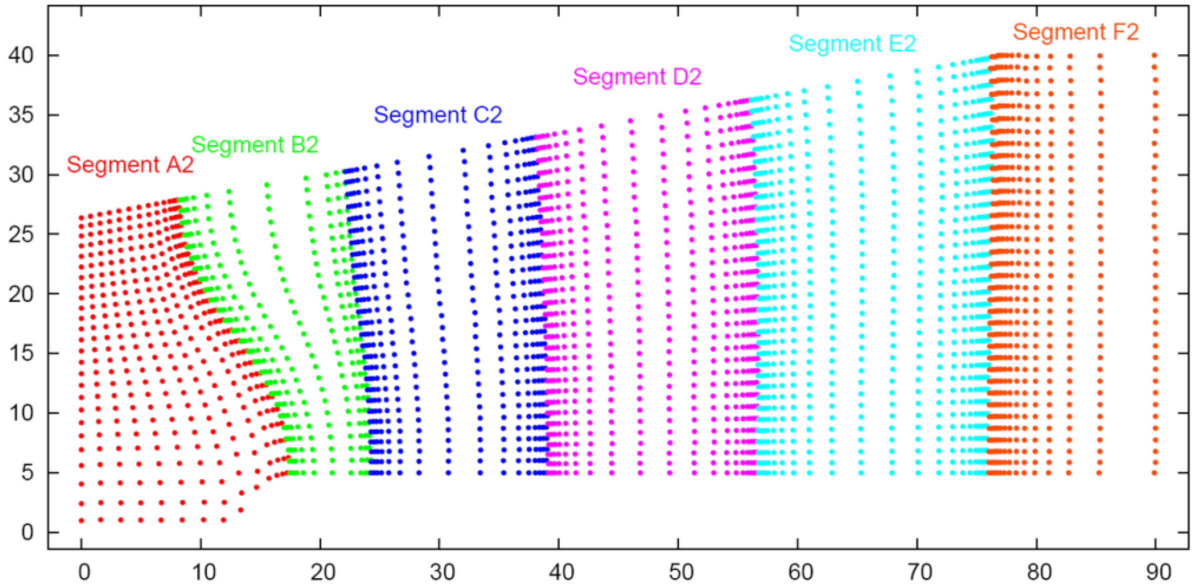
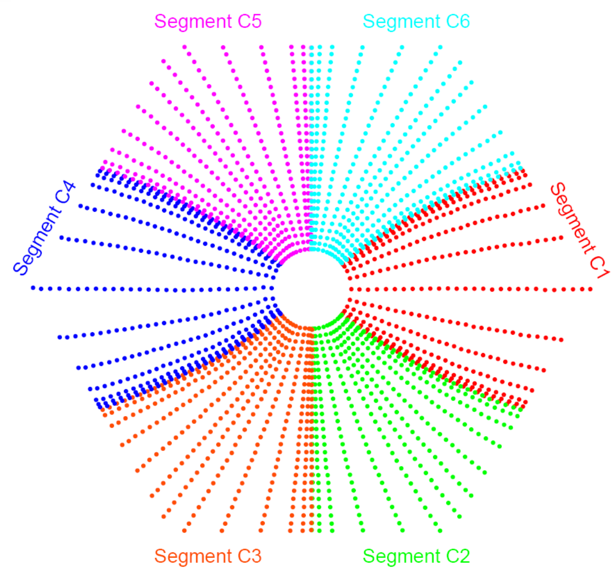
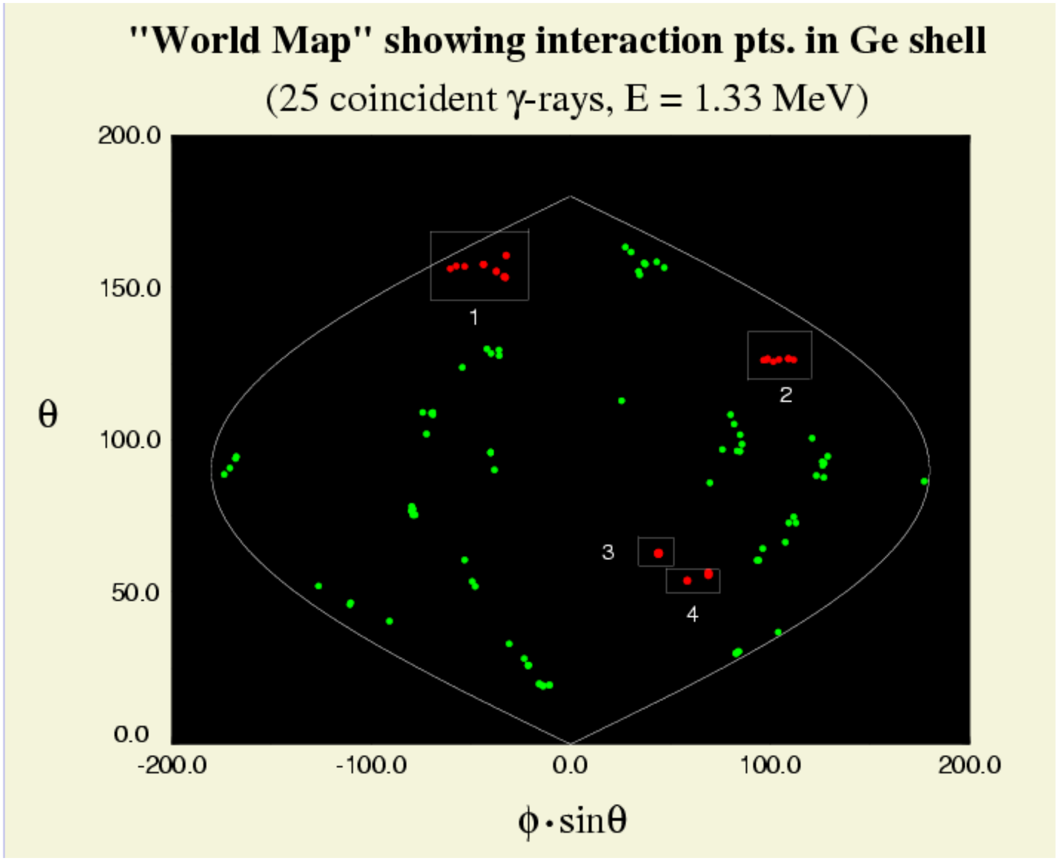
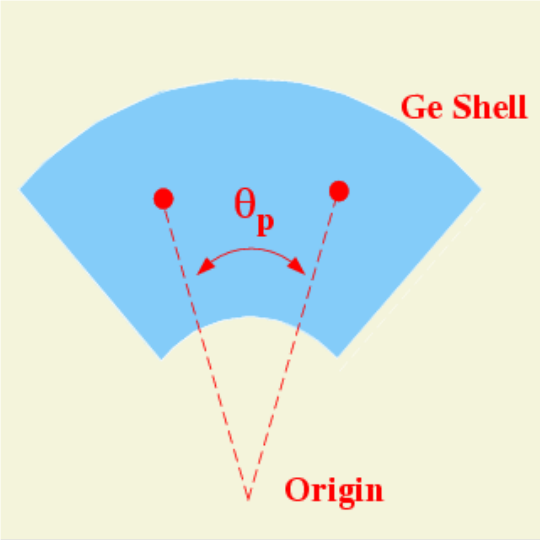




TRACKING: CLUSTERING

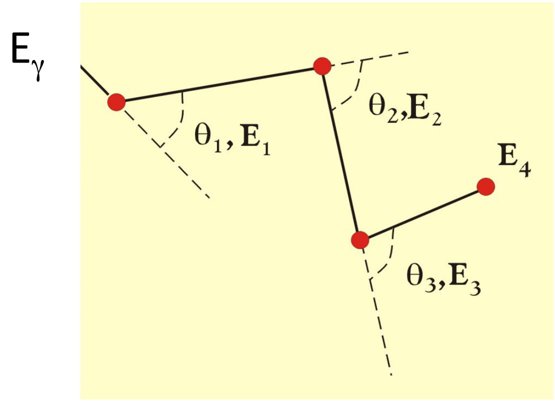
First step in tracking is to find clusters of interaction points which likely belong to a single γ-ray scattering in the detector – based on opening angle into the Ge shell





Any two points with $\theta < \theta p$ are grouped into the same cluster

Compton Tracking

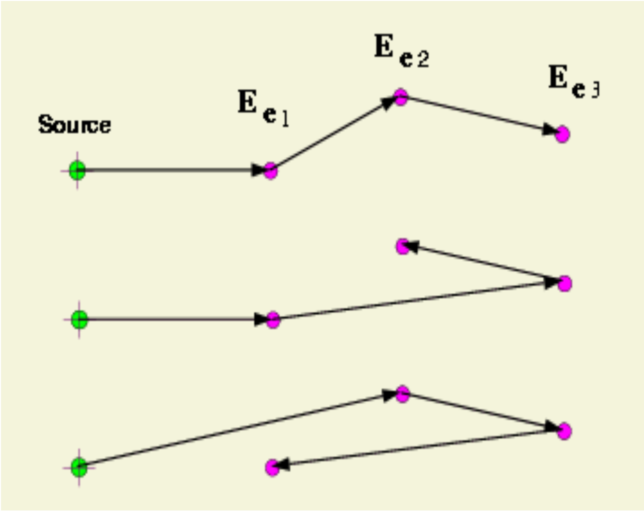


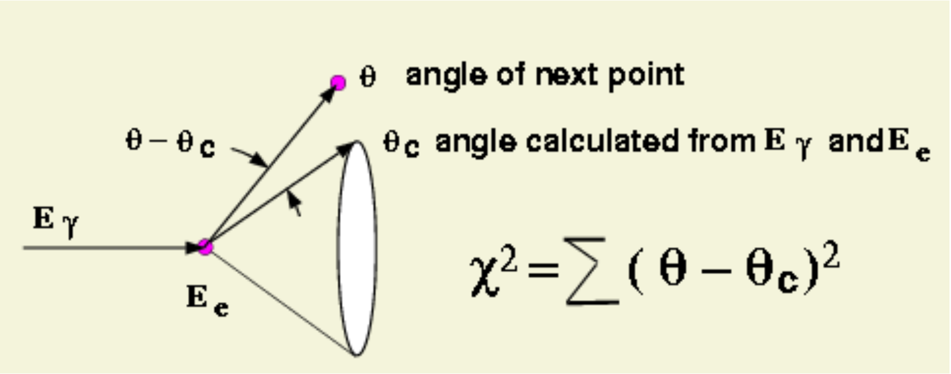
$$E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{E_\gamma}{0.511}(1 - \cos\theta)} \right)$$

Assume:

- $E_g = E_{e1} + E_{e2} + E_{e3}$
- γ-ray from the source

Problem: 3!=6 possible sequences





Sequence with the minimum $\chi^2 < \chi^2_{max}$
→ correct scattering sequence
→ rejects Compton and wrong direction

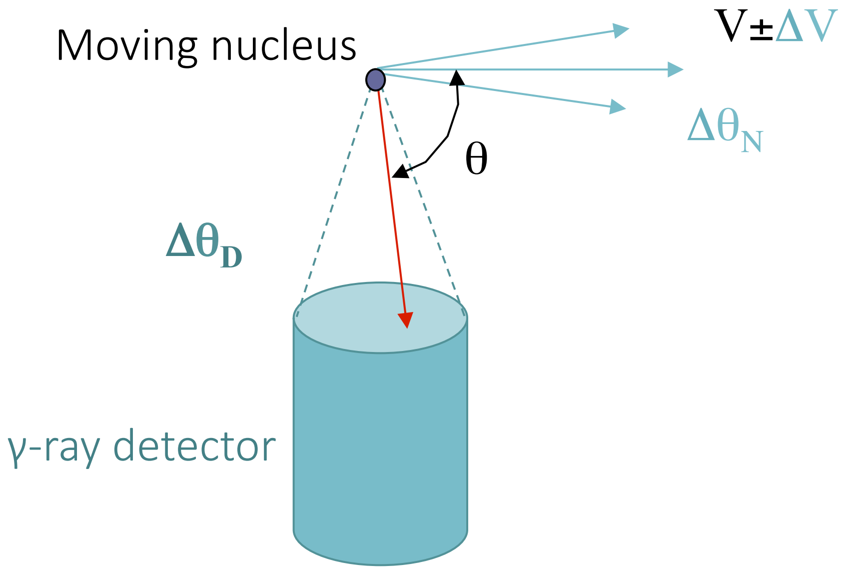
→ Low-energy single interaction point γ-rays don't track

So What Do We Get From GRETINA?

- GRETINA (GRETA) provides us the benefits of Ge resolution, the background reduction of suppression and the maximum efficiency by allowing the most detector material to be in place
  - More resolving power than any previous array

- Do we gain anything else?

Doppler Correction

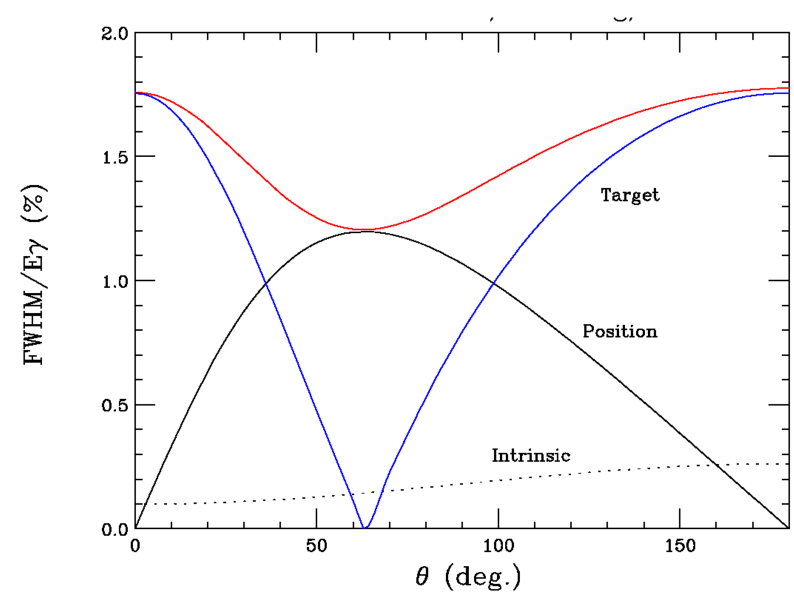


Doppler shift

$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\frac{V^2}{c^2}}}{1-\frac{V}{c}\cos\theta}$$

Broadening of detected gamma-ray energy due to:

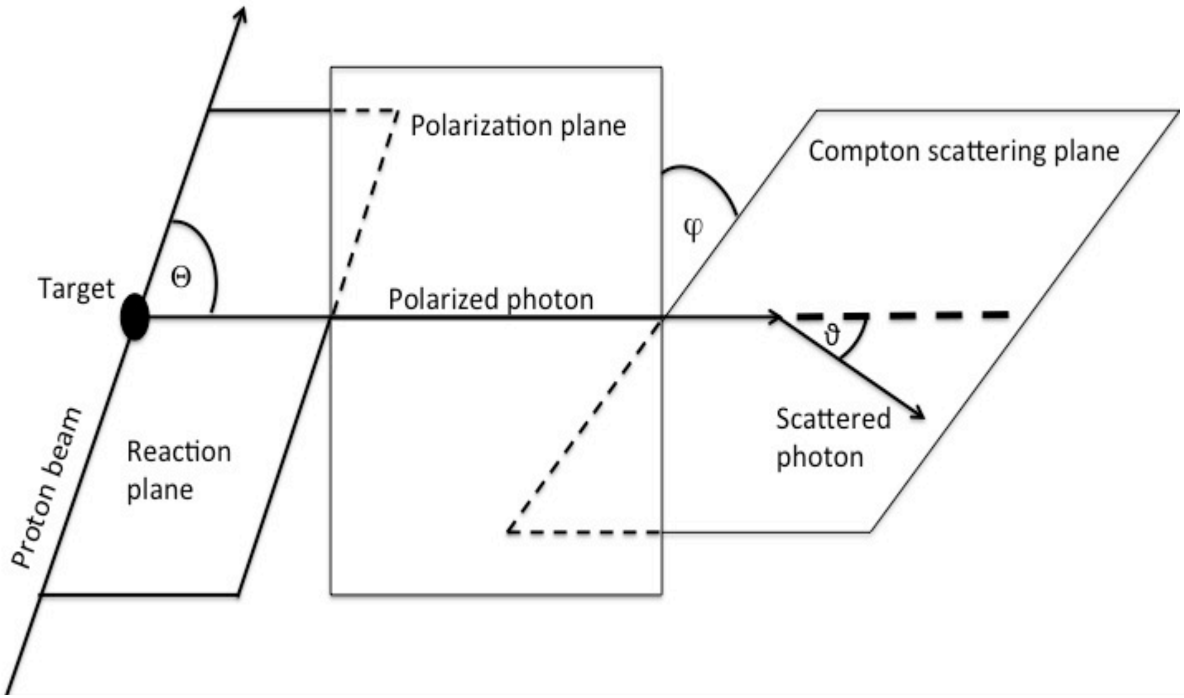
- Spread in speed ΔV
- Distribution in direction of velocity $\Delta \theta_N$
- Detector opening angle $\Delta \theta_D$



POLARIZATION IN GRETINA

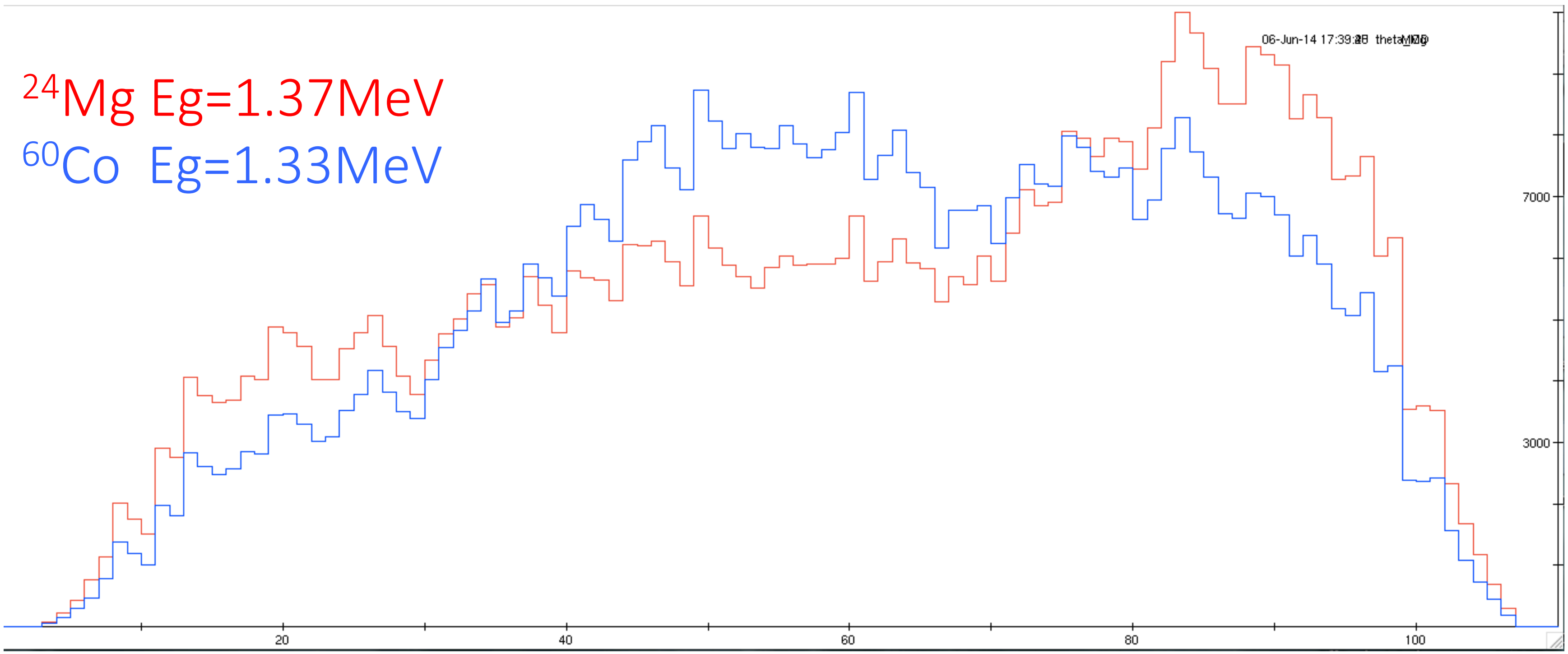
^{24}Mg(p,p'g)^{24}Mg, $E_p = 2.6$ and 6 MeV

P(2^+,M=0) $\sim$ 100% P(M=1) $\sim$ few %



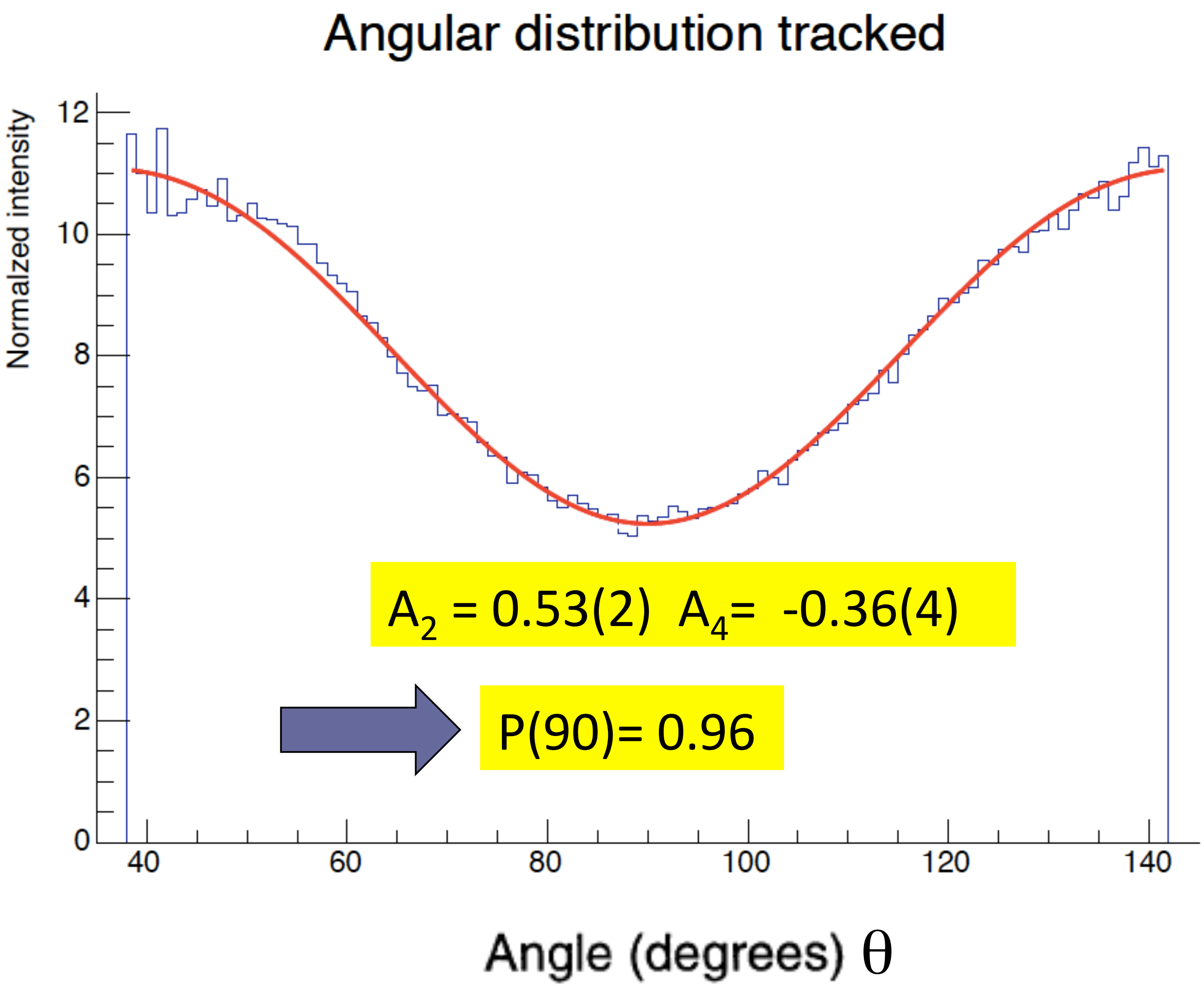
$$\frac{d\sigma}{d\Omega}(\vartheta,\varphi) = \frac{r_0^2}{2}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2\left[\frac{E_{\gamma'}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma'}} - 2\sin^2\vartheta\cos^2\varphi\right]$$

POLARIZATION IN GRETINA

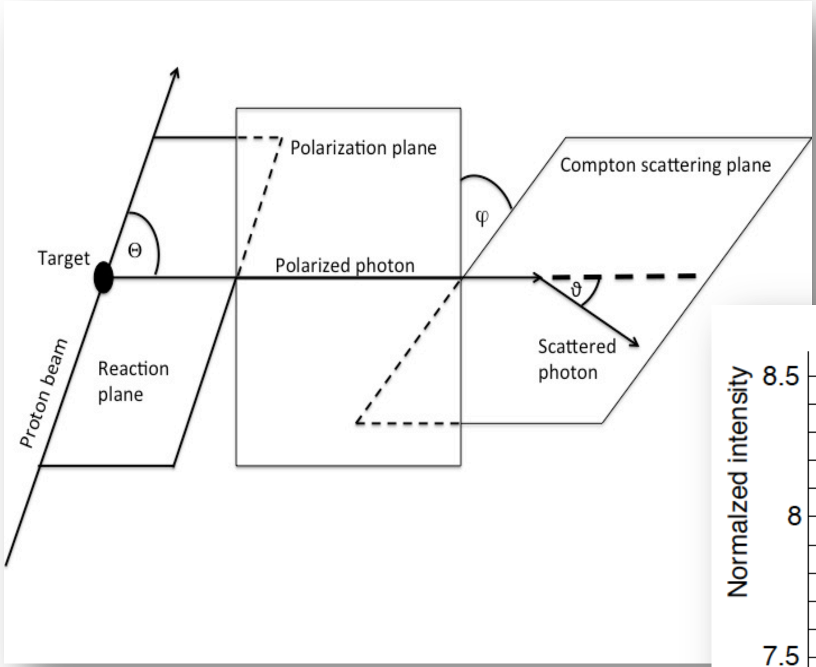


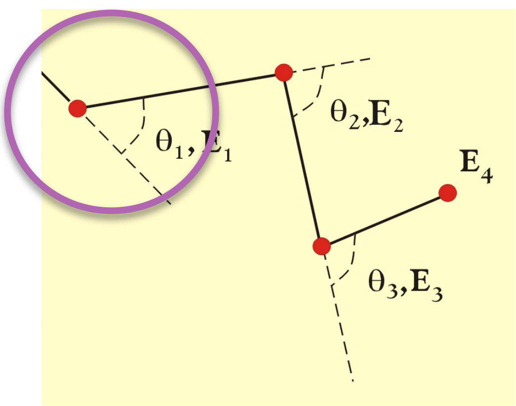
θ Angle (Channels)

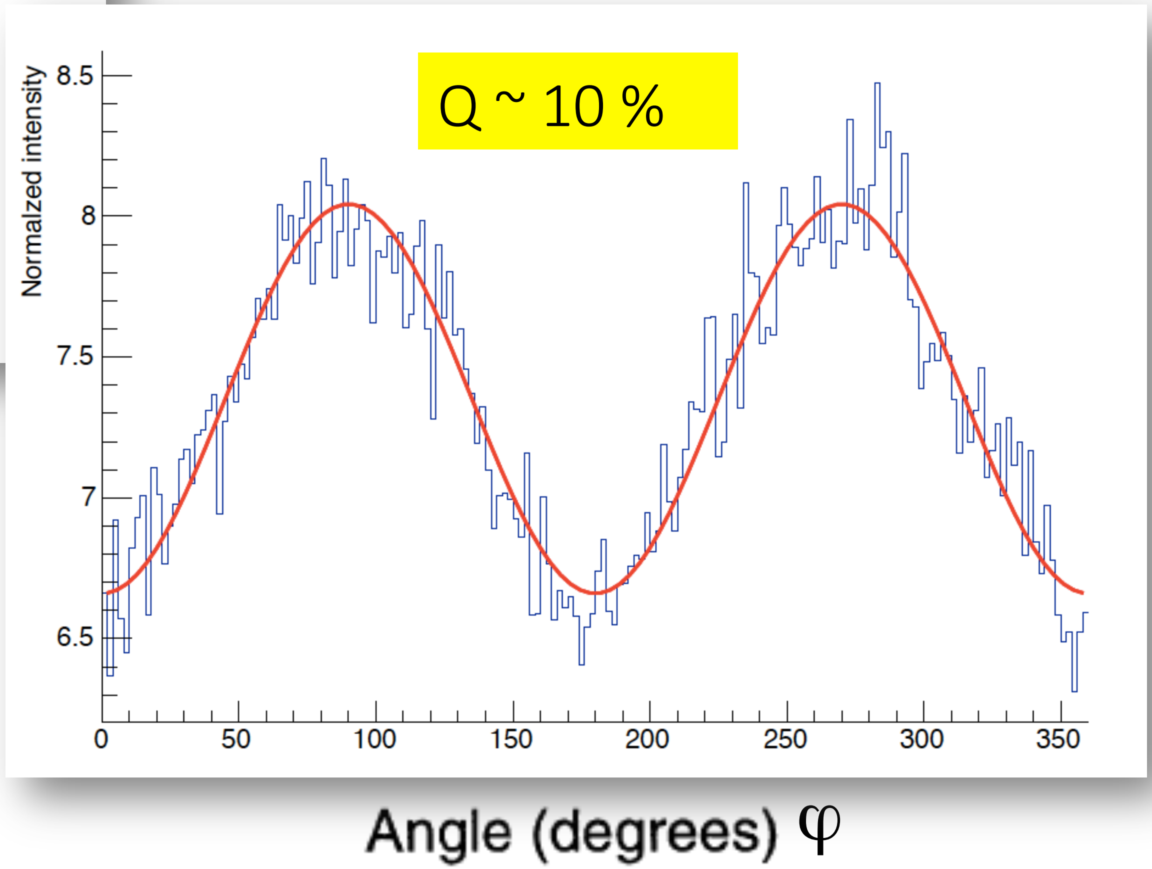
Polarization in GRETINA



POLARIZATION IN GRETINA







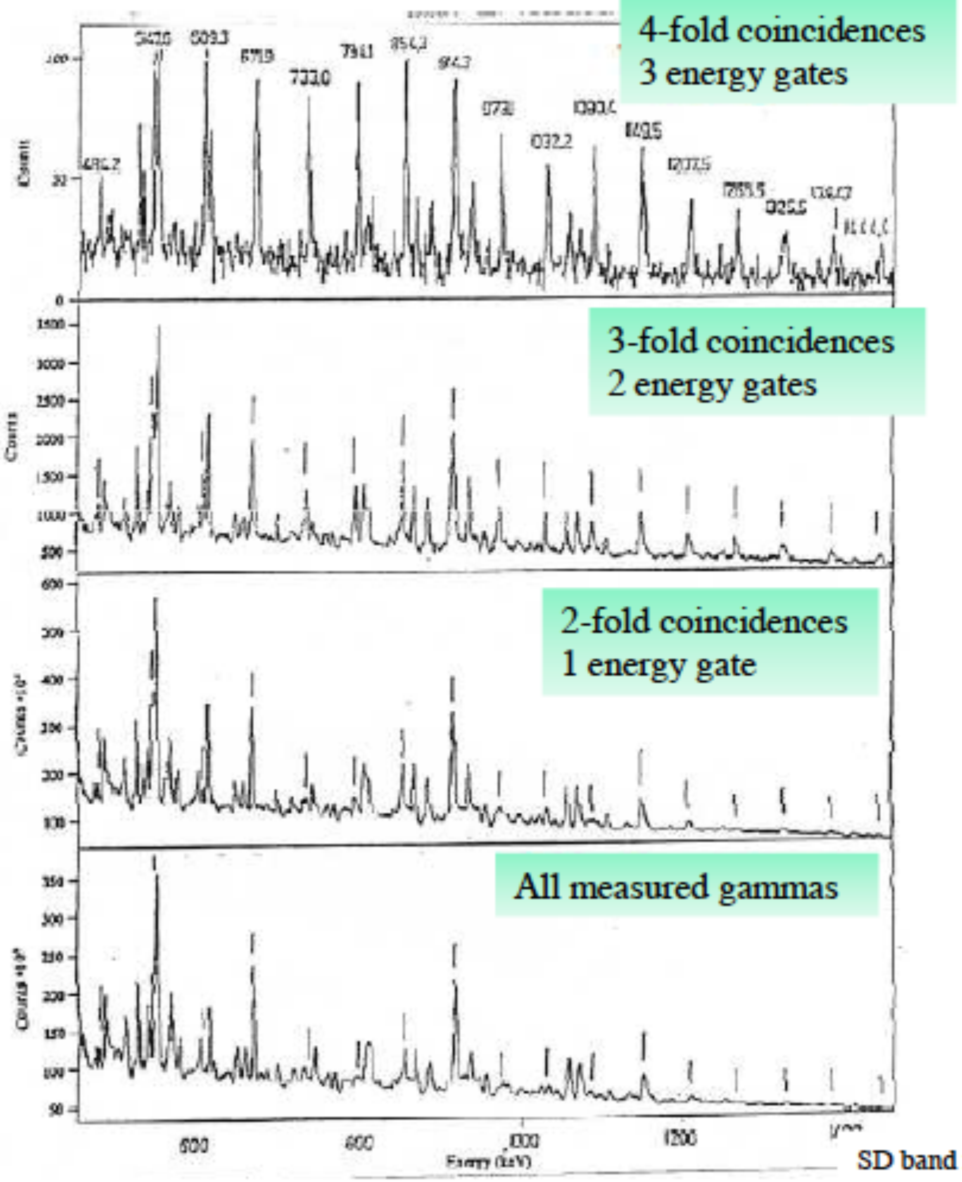
Summary (of Part I)

- What should you take home:
  - Gamma spectroscopy can provide important details about nuclear levels – energy separations, spin information, etc.
  - Detectors for gamma spectroscopy are of two main types – scintillators and Ge
  - Counting statistics largely determine the resolution of gamma-spectrometers
  - Next generation spectrometers (GRETA) provide unparalleled performance (resolving power) and may open new experimental opportunities

THANK YOU TO A.O. MACCHIAVELLI, I.Y. LEE AND D. WEISSHAAR FOR SLIDE MATERIAL!

Questions?

Carving Out Tiny Intensities



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

A practitioner's example

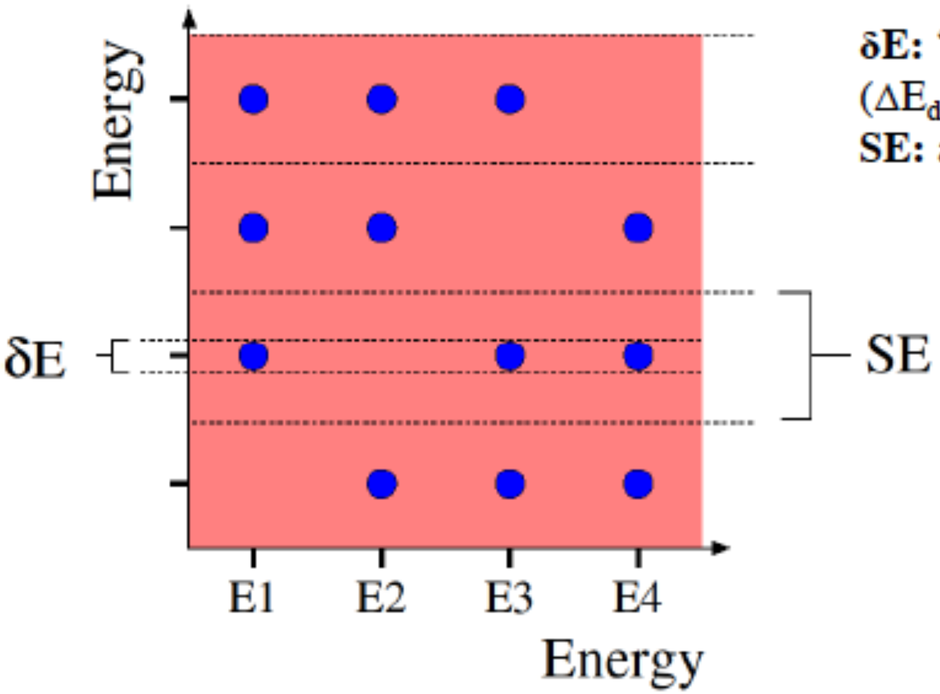
Recipe:
Measure high-fold coincidences (F) and apply (F-1) gates on energies $E_1..E_{F-1}$

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

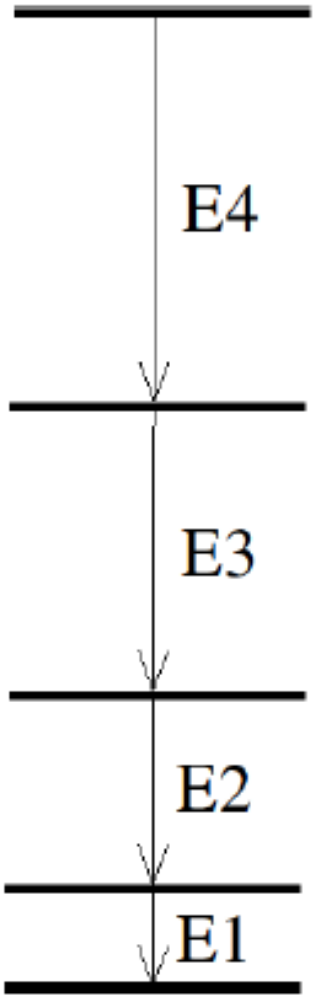
Question(s):
How important is resolution compared to efficiency?
Maybe something else important?
Why does the gating improve peak-to-background (P/BG)?

IMPROVING PEAK TO BACKGROUND

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



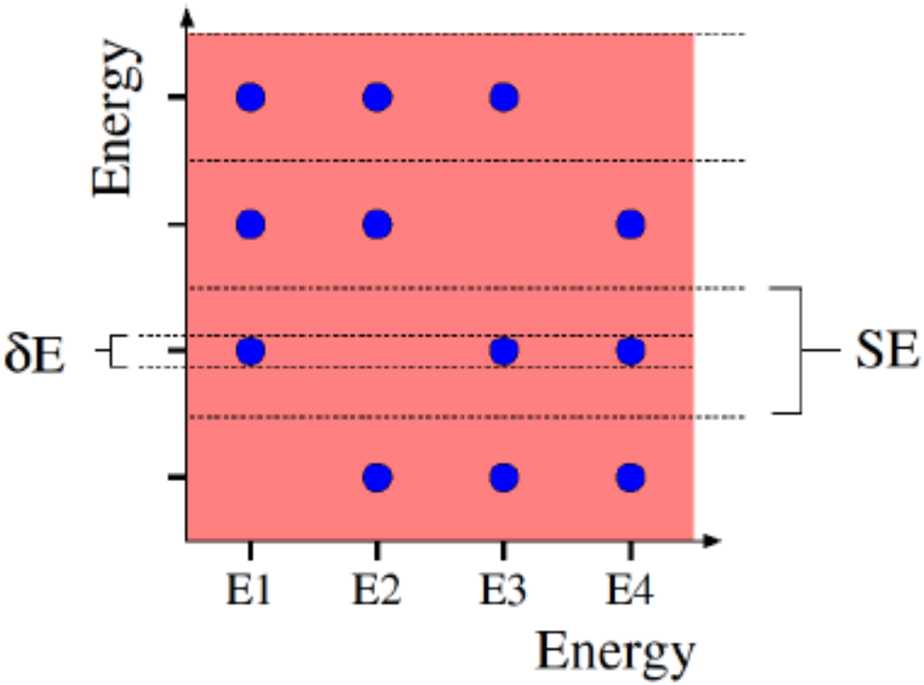
δE: 'effective' E-resolution (ΔE_{det} and $\Delta E_{Doppler}$)
SE: average energy spacing

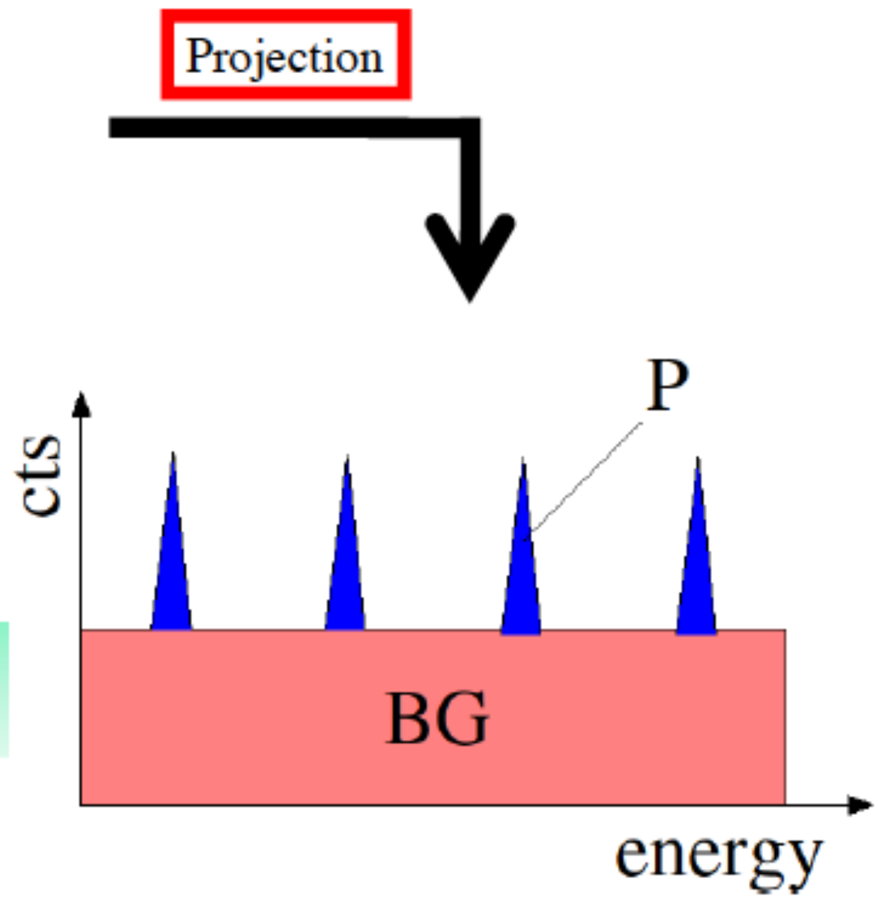


→ E_x-E_y coincidences go into peak (blue)
→ "everything else" spread over red area, as it isn't coincident with any E_x

Improving Peak To Background

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

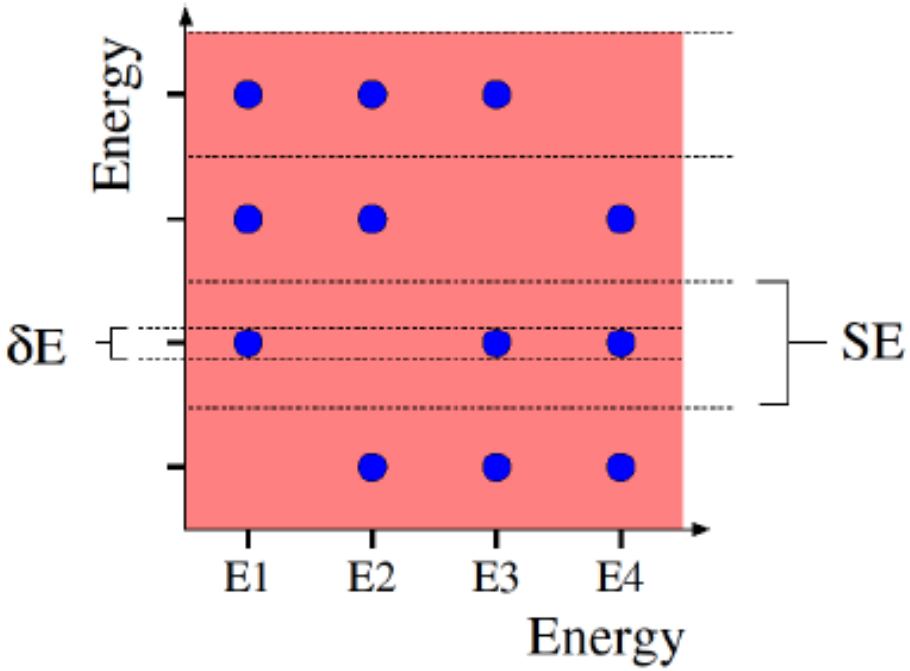




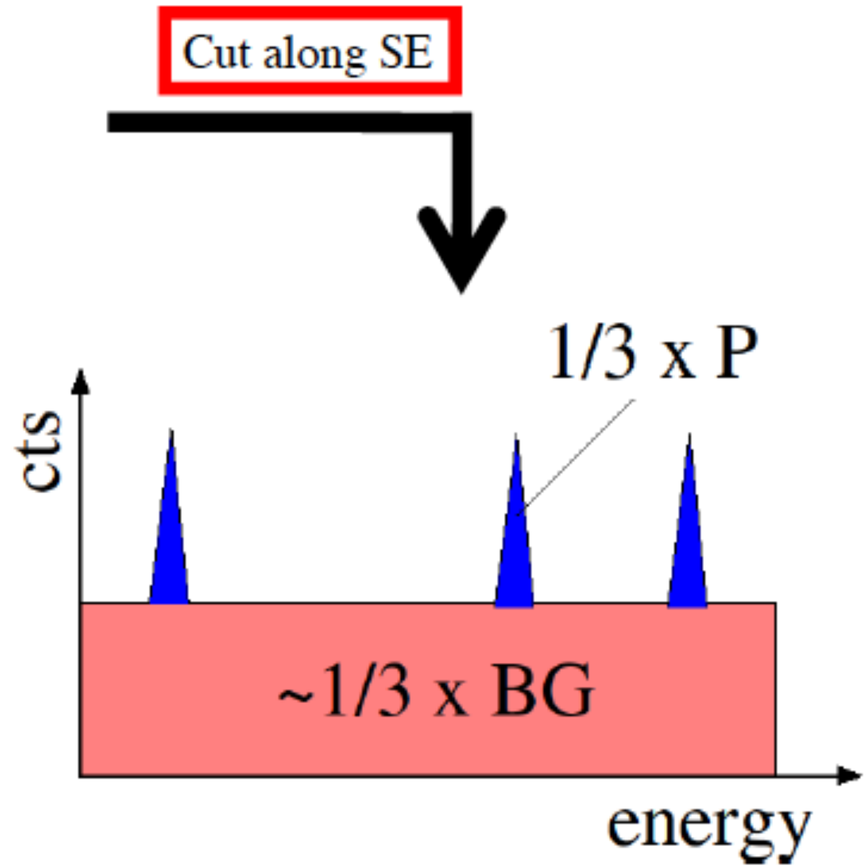
This corresponds to “all measured gammas” in the example “carving out tiny α”.

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

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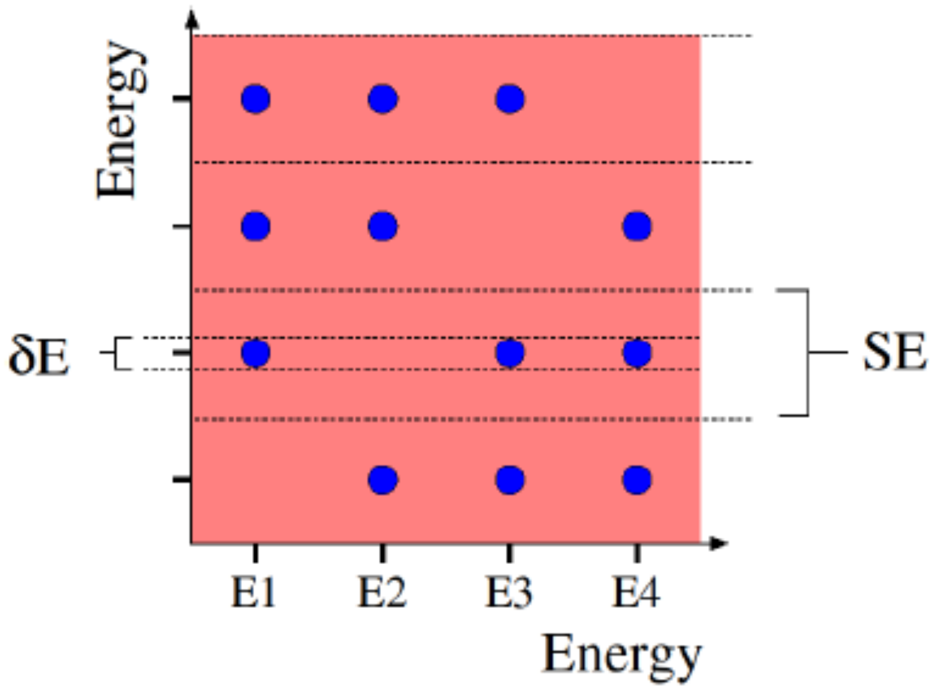

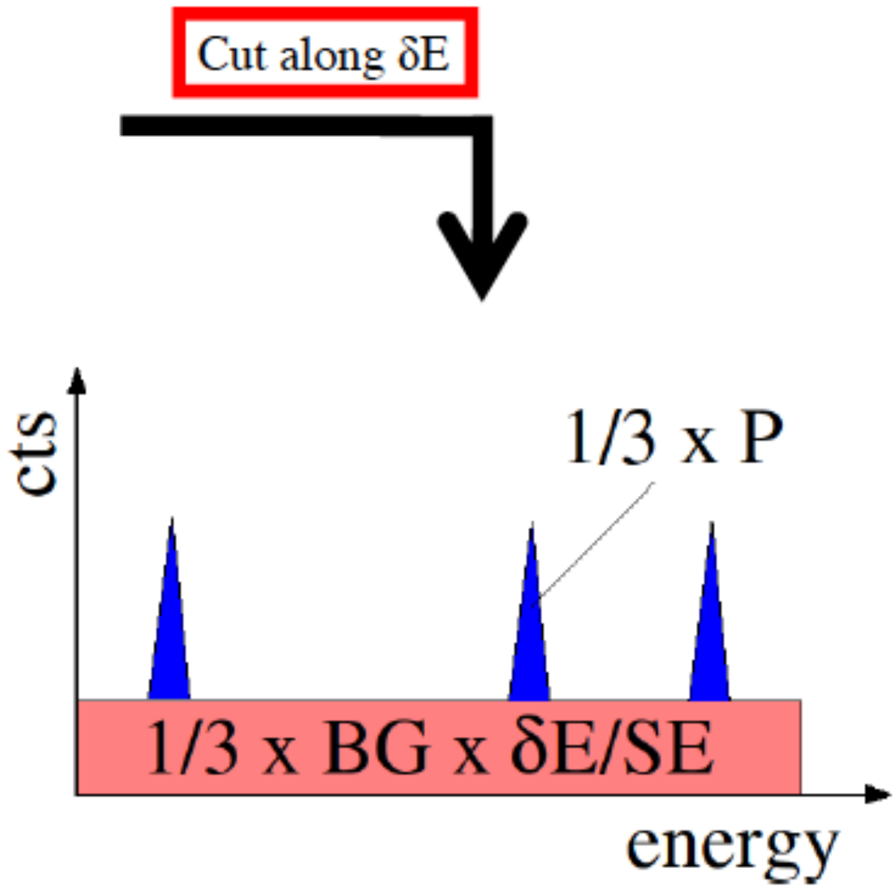

Improvement of P/BG by factor **SE/δE** !!!

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

RESOLVING POWER

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

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

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

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

The **RESOLVING POWER** is defined as

$$\mathbf{RP=1/\boldsymbol{\alpha}_0} \ (3)$$

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

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

Resolving Power

...adding some 'more' understanding

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

On the other hand:
We have to measure the F-Fold coincidences in reality. This imposes some constraints, expressed by $\boldsymbol{\alpha}=(N/N_0)/\varepsilon^F$ or in words: "Can you acquire enough F-fold coincidence events in a reasonable time?"