BERKELEY LAB

NUCLEAR SCIENCE DIVISION

Next Generation Gamma-Ray Spectrometers

Heather Crawford

Nuclear Science Division, Lawrence Berkeley National Laboratory

Who Am I? (Very briefly)

B.Sc. with Honors in Chemistry **Simon Fraser University** Burnaby, BC, Canada

Ph.D. in Nuclear Chemistry
Michigan State University
East Lansing, MI

Postdoc
Lawrence Berkeley National Laboratory

Assistant Professor of Physics Ohio University
Athens, OH

BERKELEY LAB

Career Track Staff / Staff / Senior Staff Scientist
Lawrence Berkeley National Laboratory

Who Am I? (Very briefly)

PhD at Michigan State University

- Beta-decay of neutron-rich Ca/Sc/Ti isotopes

Postdoc at LBNL

- Switch to in-beam spectroscopy
- Coulomb excitation of neutron-rich Fe/Cr
- First spectroscopy in ^{40}Mg
- Involvement with early running of GRETINA

Staff/Senior Staff Scientist at LBNL

- Physics programs at FRIB and ATLAS (ANL)
- Deputy Director for the GRETA project
- Program head for low-energy nuclear physics program

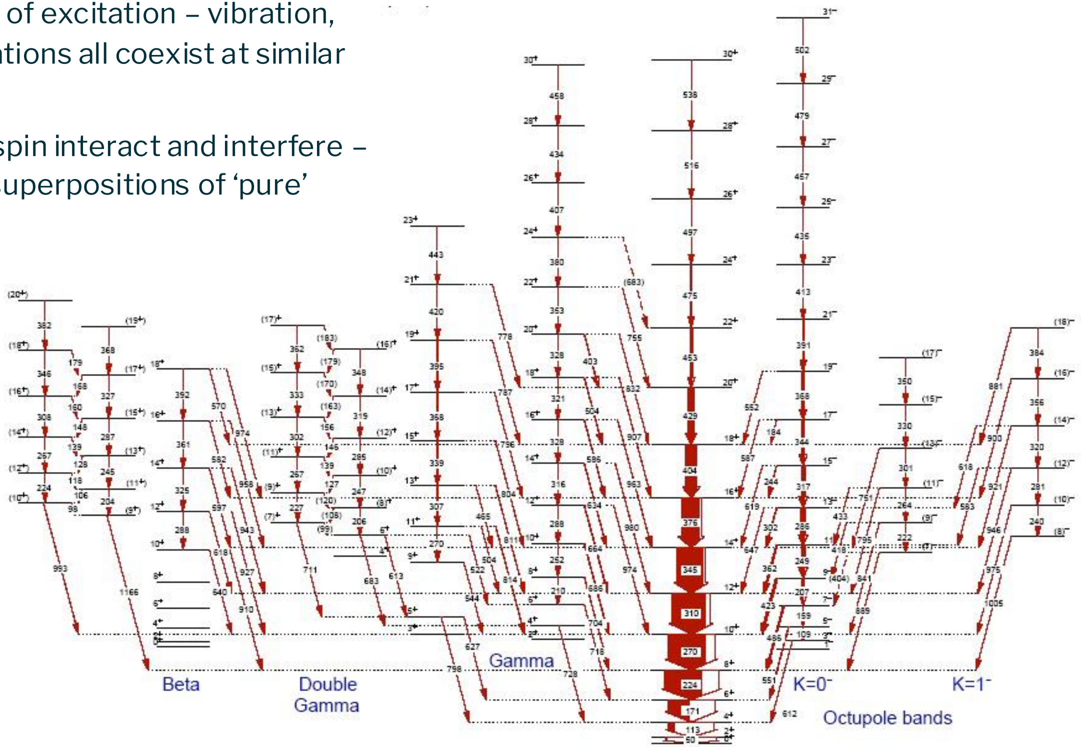
Topics

- **Lecture 1 – Gamma-Ray Detection Considerations**
  - Types of gamma-ray detectors – pros and cons, limitations
  - Evolution of spectrometers for nuclear structure & reactions
  - Resolving Power and Array Performance
- **Lecture 2 – Advanced Gamma-Ray Spectrometers and Nuclear Structure**
  - Gamma-ray tracking detector ingredients
  - The Gamma-Ray Energy Tracking Array (GRETA)
  - Physics beyond energies - angular distributions and linear polarization

Nuclear excitations

Nuclei are not limited to a single type of excitation – vibration, rotation and single-particle configurations all coexist at similar excitation energies.

States near in energy with the same spin interact and interfere – nuclear wavefunctions are complex superpositions of ‘pure’ configurations.



Nuclear 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

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

Nuclear properties from gamma-ray studies

- Coincidence relation ⇒ Level schemes
- Angular distribution/correlation ⇒ Multipolarity, spin
- Doppler shifts ⇒ excited state lifetimes
- Linear polarization ⇒ E/M, parity
- Intensity of transitions ⇒ B(E2)

Gamma-Ray Detection

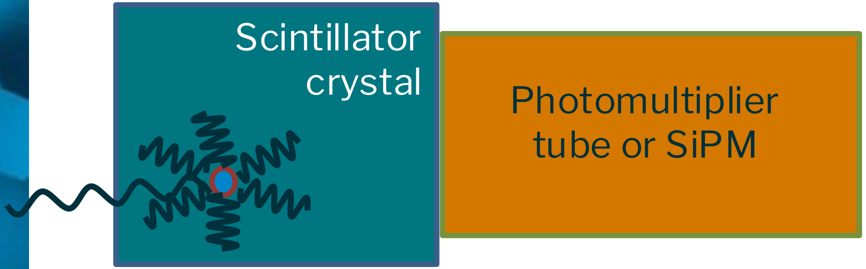
Basic Principles

- 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 as high *Z* (most electrons) as possible
- Methods for measuring energy transferred to electrons vary… but we worry about 3 basic performance parameters:

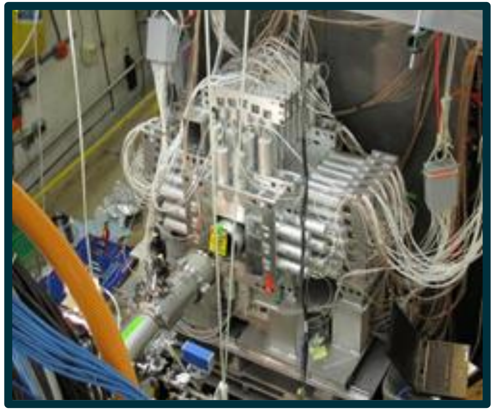
- Energy resolution
- Efficiency
- Peak-to-total (P/T) – probability that a *detected* gamma-ray actually makes it into the peak

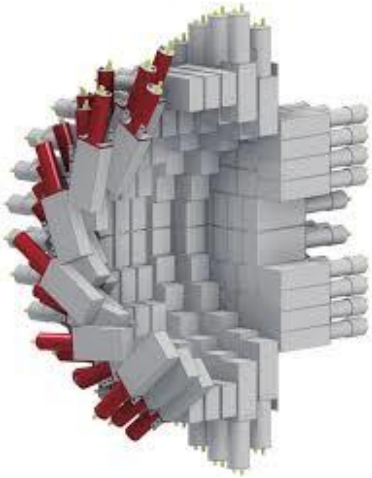
Energy Resolution

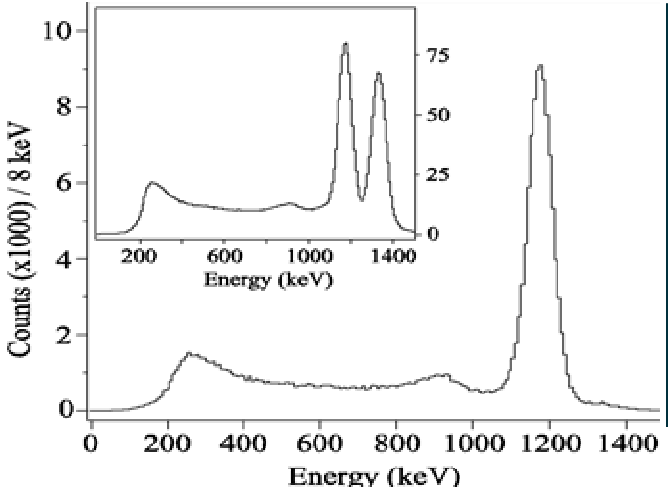
Scintillators



- Materials like ${}_{10}\text{Na}_{53}\text{I}$; ${}_{55}\text{Cs}_{53}\text{I}$, ${}_{56}\text{Ba}_{9}\text{F}$
- High efficiency up to ≃ 40% or even higher
- Intrinsic energy resolution dominated by statistics of photoelectrons in the PMT – for scintillators, resolutions ≃ 5-7%







Resolution in Scintillators

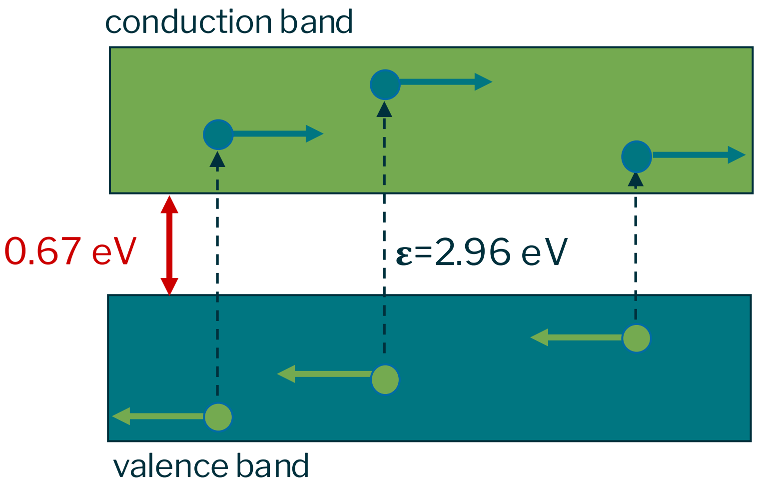
Counting Statistics for Scintillation

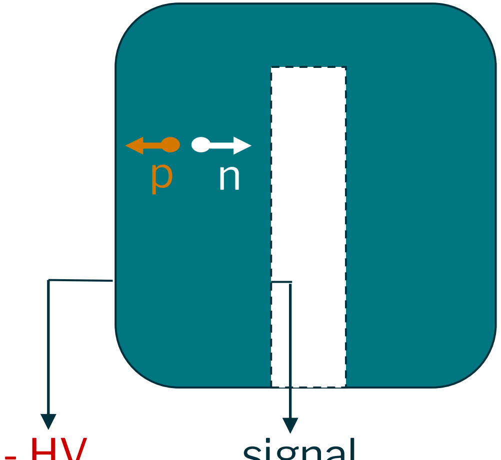
- Energetic particle traveling through a detector (i.e. electron from gamma-ray interaction). Per length traveled dx, this particle may produce scintillation photon, which may make it to the photo-cathode, be converted to a photo-electron and contribute to a signal
    - CsI(Na) yields 38,000 photons / 1 MeV gamma†
    - Light collection + PMT efficiency = 15%
    - 5700 photons collected on average -- $\sigma = \sqrt{5700} = 76$
    - FWHM = 178 → dE/E = 3%

†I. Holl, E. Lorenz and G. Mageras. "A Measurement of the Light Yield of Common Inorganic Scintillators". *IEEE Transactions on Nuclear Science* **35**, 105-109 (1988).

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, for HPGe so many more electron-hole pairs than photons for a scintillator (compare to effectively ~175 eV per detected scintillation photon)
- Compare to band gap in Si is 1.1eV, requires ~3.6 eV to excite electron-hole pair





Thermal Excitations in Semiconductors

- Thermal energy is shared by electrons in a semi-conductor crystal – it is possible for a valence electron to gain enough energy to move into the conduction band
- Probability per unit time for a thermal electron-hole pair to be created:

$$p(T) = CT^{3/2}exp(-\frac{E_g}{2kT})$$

Thermal Excitations in Semiconductors

- Thermal energy is shared by electrons in a semi-conductor crystal – it is possible for a valence electron to gain enough energy to move into the conduction band
- Probability per unit time for a thermal electron-hole pair to be created:

$$p(T) = CT^{3/2} exp(-\frac{E_g}{2kT})$$

- At room temperature semiconductors have sufficient thermal excitations to be conductive – *not ideal for a detector*

Thermal Excitations in Semiconductors

- Thermal energy is shared by electrons in a semi-conductor crystal – it is possible for a valence electron to gain enough energy to move into the conduction band
- Probability per unit time for a thermal electron-hole pair to be created:

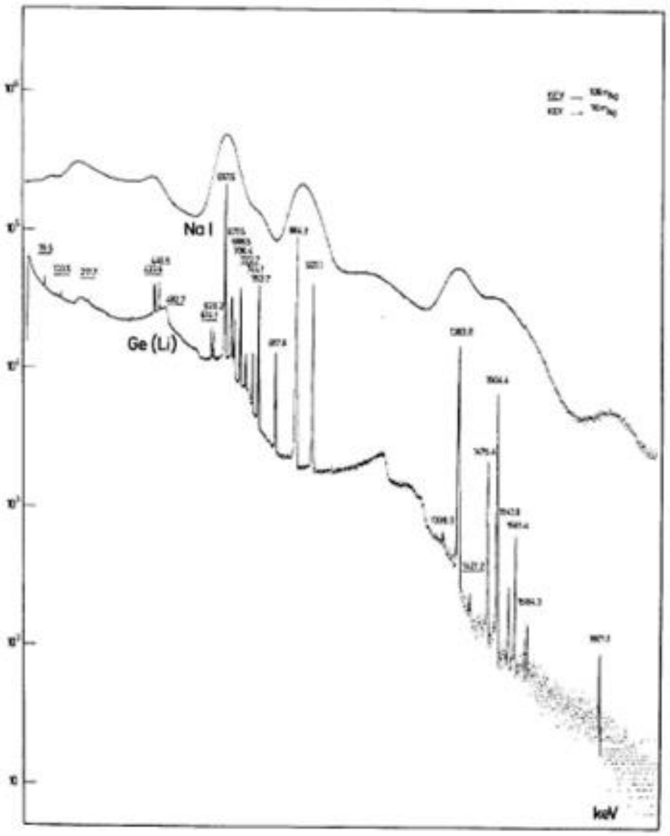
$$p(T) = CT^{3/2} exp(-\frac{E_g}{2kT})$$

- At room temperature semiconductors have sufficient thermal excitations to be conductive – *not ideal for a detector*
- Semiconductors like HPGe must be operated cooled – HPGe typically operated at 77 K (LN_2 temperature)

Energy Resolution in HPGe

Pros and Cons

- 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 can be << 1 ns)



Detector Resolution

Multiple Contributions to Resolution

- Intrinsic resolution ∝ $N^{1/2}$ must be adjusted by the Fano factor (F), which is introduced to quantify deviation of observed statistical fluctuations from Poisson statistics - results from the fact that the processes that give rise to formation of individual charge carriers are not independent (further deviation from Poisson statistics)

- Observed detector resolution folds in contributions from intrinsic resolution, and electronic noise, the two largest contributors:

$$\rightarrow \quad \mathrm{FWHM_{total}} = \sqrt{\mathrm{FWHM^2_{intrinsic}} + \mathrm{FWHM^2_{electronic}}}$$

Detector Resolution

Multiple Contributions to Resolution

- Intrinsic resolution ∝ $N^{1/2}$ must be adjusted by the Fano factor (F), which is introduced to quantify deviation of observed statistical fluctuations from Poisson statistics - results from the fact that the processes that give rise to formation of individual charge carriers are not independent (further deviation from Poisson statistics)

- Observed detector resolution folds in contributions from intrinsic resolution, and electronic noise, the two largest contributors:

$$\rightarrow \quad \mathrm{FWHM}_{\mathrm{total}} = \sqrt{\mathrm{FWHM}^2_{\mathrm{intrinsic}} + \mathrm{FWHM}^2_{\mathrm{electronic}}}$$

Is there anything else that can affect energy resolution?

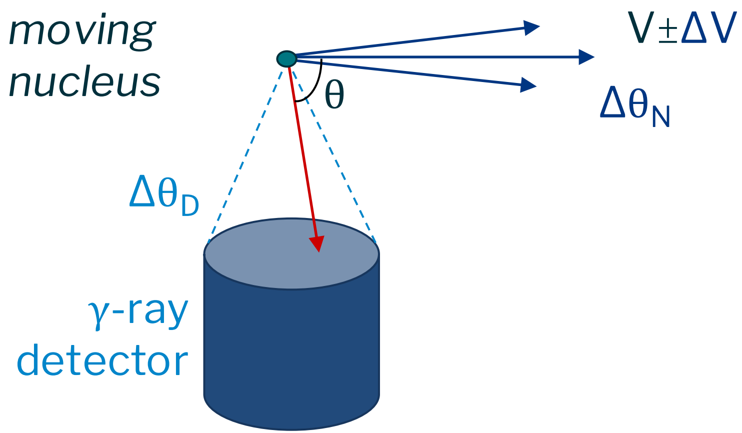
Doppler Correction

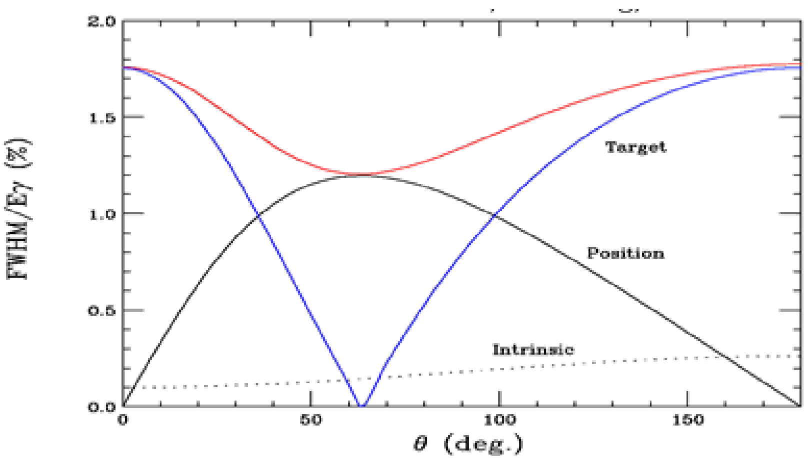
Doppler shift

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

Broadening of detected gamma-ray energy due to:

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

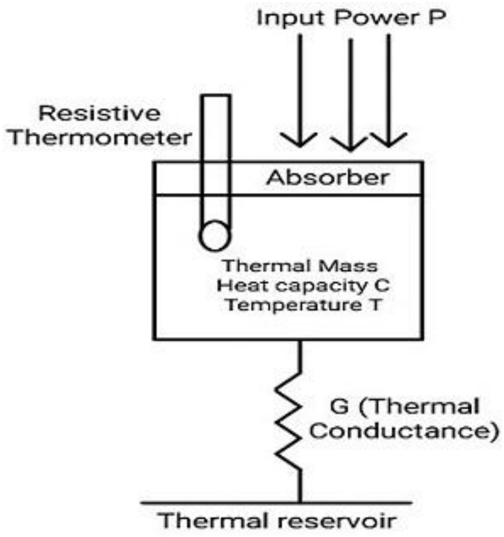




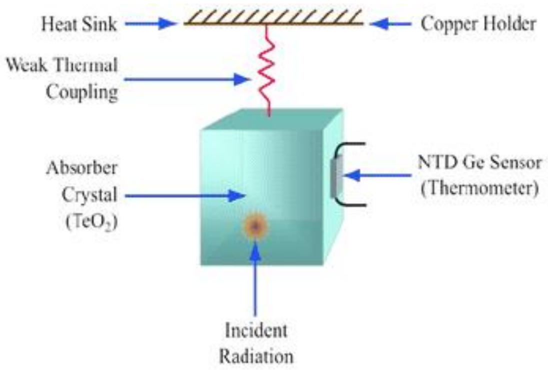
BERKELEY LAB

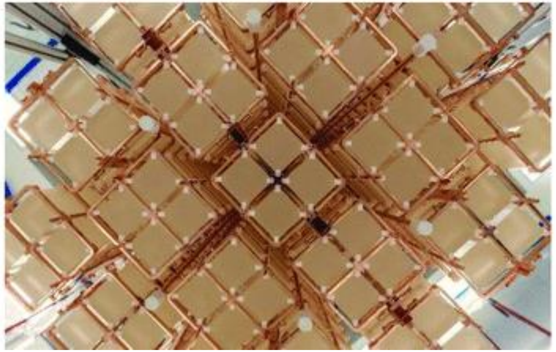
Bolometers

- Bolometers operate under a completely different principle as compared to scintillators and semiconductors
- Incident radiation is absorbed by a thin film layer and causes a slight change in the temperature above the baseline temperature
- This change in temperature alters the electrical resistance of the thermometer element – this is measured by detecting voltage changes based on a constant electrical bias current
- This change can be measured very accurately, enabling resolutions on the order of a few hundred eV



Bolometers – CUORE





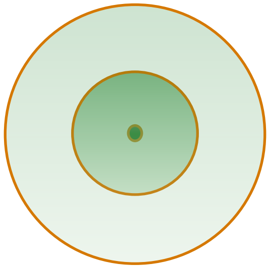
- One example of bolometers deployed in (near) nuclear physics experiment is the CUORE $0\nu\beta\beta$ experiment
- In this case the thermal mass and absorber are one and the same (and also the source of radiation!) – namely a TeO_2 crystal (^{130}Te is a $0\nu\beta\beta$ candidate)
- Detector is operated at roughly 10 mK, using a custom dilution refrigerator

Efficiency & Peak to Total

Efficiency

Two contributions to the efficiency of an array

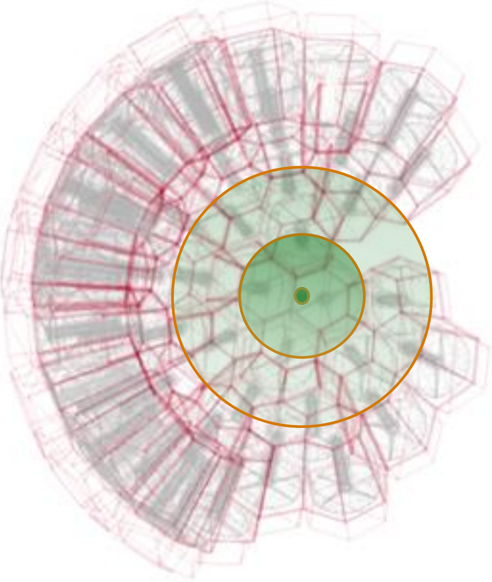
- Efficiency is typically discussed as photopeak efficiency -- defined as the fraction of emitted gamma-rays that are detected with their full energy
- Two components – geometric and intrinsic

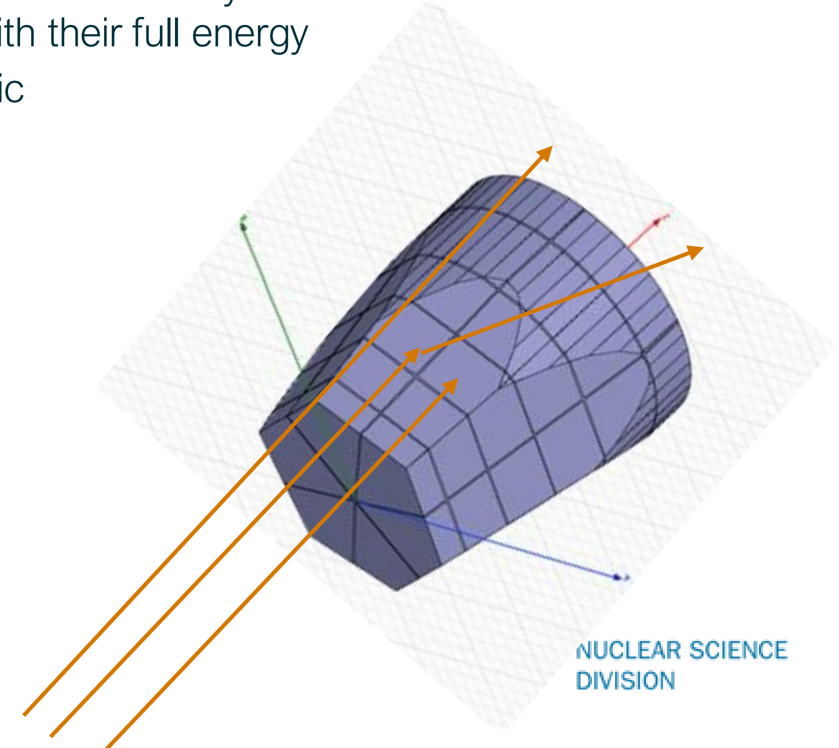


Efficiency

Two contributions to the efficiency of an array

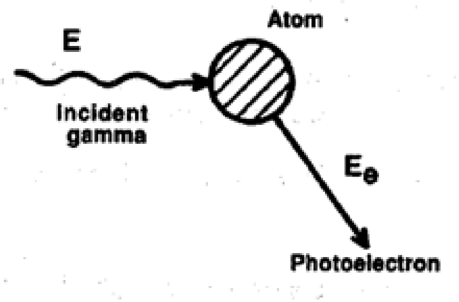
- Efficiency is typically discussed as photopeak efficiency -- defined as the fraction of emitted gamma-rays that are detected with their full energy
- Two components – geometric and intrinsic





Gamma-Ray Interactions in Matter

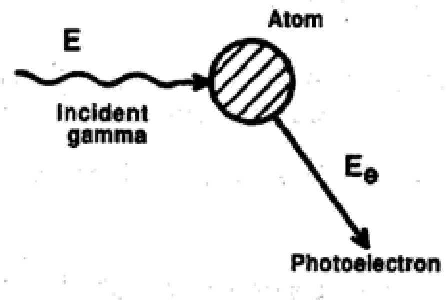
Photoelectric effect



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

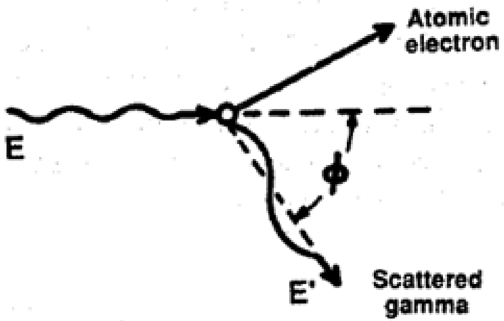
Gamma-Ray Interactions in Matter

Photoelectric effect



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

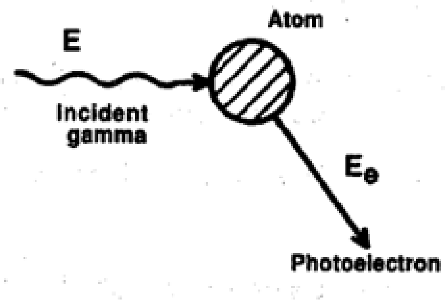
Compton scattering



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

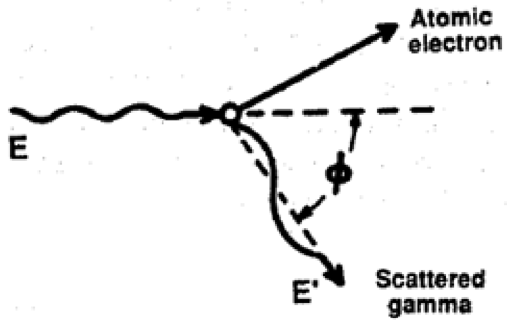
Gamma-Ray Interactions in Matter

Photoelectric effect



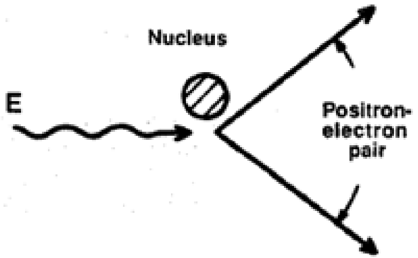
A photoelectron is ejected carrying the complete gamma-ray energy (less the electron binding energy)

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.

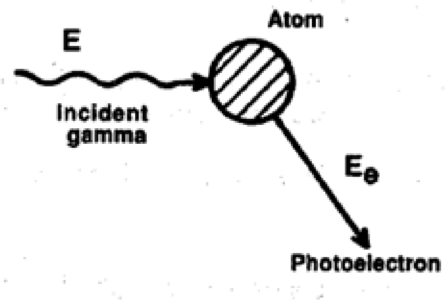
Pair production



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.

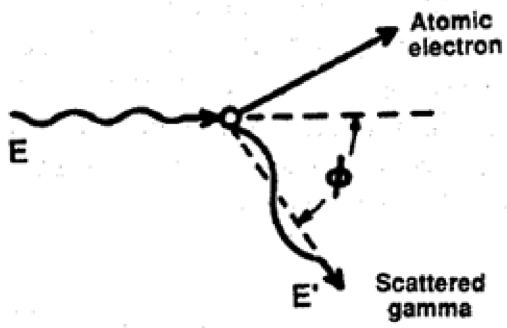
Gamma-Ray Interactions in Matter

Photoelectric effect



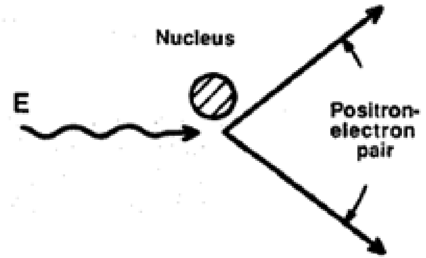
A photoelectron is ejected
carrying the complete gamma-ray energy (less the electron binding energy)

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.

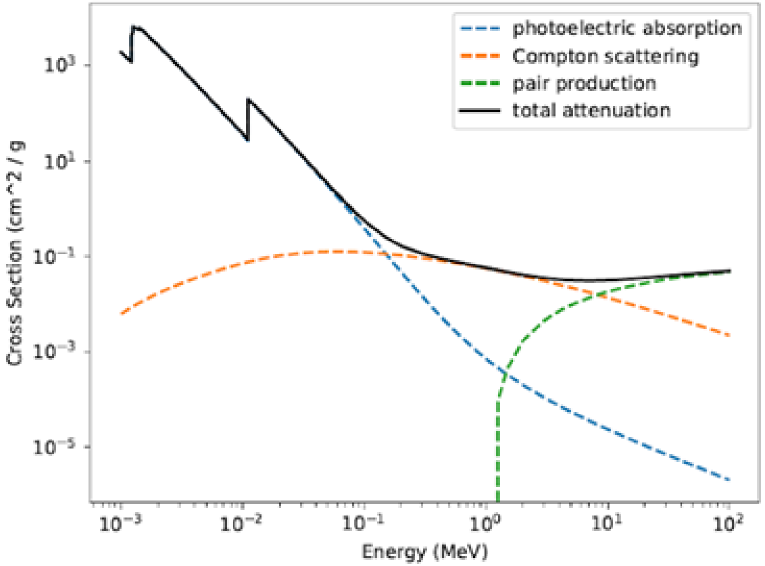
Pair production



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 $m_o c^2$.

In all cases gammas interact with atoms and generate free electrons/ion pairs.
→ They interact with the electrons in the atom, so they'll interact more in materials with lots of electrons – heavy nuclei (high Z).

Gamma-Ray Interactions in Matter



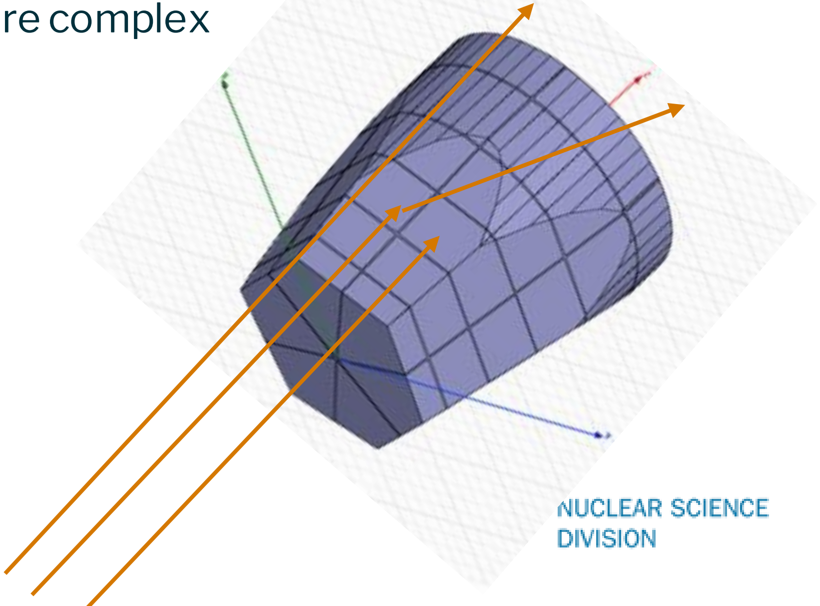
100 keV – 3 MeV gamma-ray energies are typical in nuclear structure studies

⟹ Compton scattering dominates, with a scatter sequence always eventually terminating in photoelectric energy deposition

Peak-To-Total (P/T)

P/T and efficiency

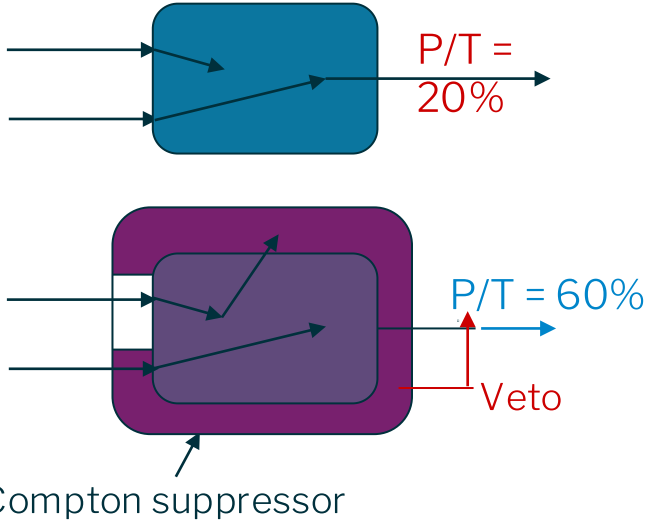
- Efficiency was defined as the photo-peak efficiency; can also consider the total efficiency for a given detector (size, material etc.) as the fraction of emitted gamma-ray which deposit any measurable energy
- For a single detector, this is a function of the material and geometry of the detector; for an array this becomes more complex

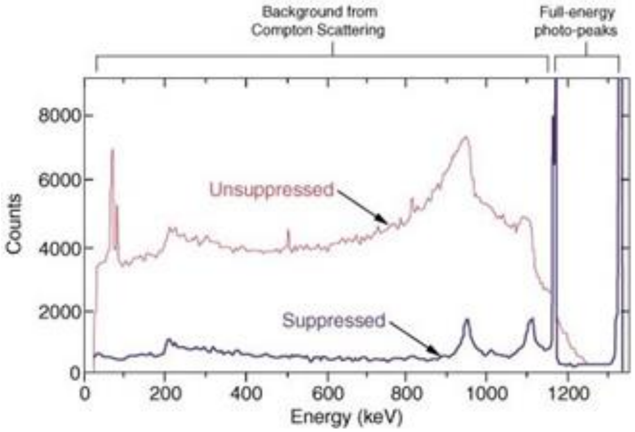


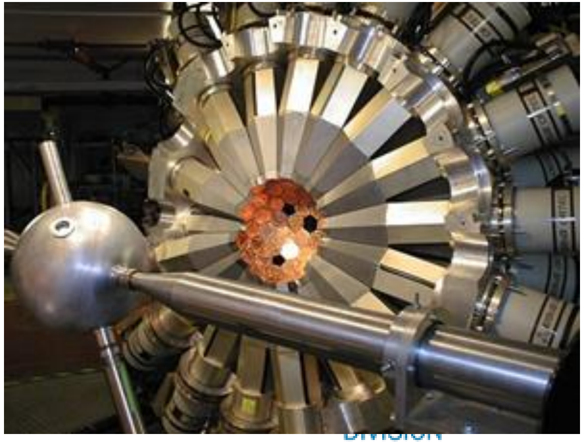
Compton Scattering & Suppression

Improving Peak to Total

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







Resolving Power

Gamma-Ray Detection

Basic Principles

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

The performance of a gamma-ray detector array can be expressed in terms of the **effective resolving power (RP)**, which depends on these three quantities.

$$RP = \left(\left(\frac{\Delta E_\gamma}{\delta E}\right)\left(\frac{P}{T}\right)\right)^{F_{opt}}$$

Gamma-Ray Detection

Basic Principles

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

The performance of a gamma-ray detector array can be expressed in terms of the **effective resolving power (RP)**, which depends on these three quantities.

Averaging spacing between gammas

$$RP = \left(\left(\frac{SE}{\delta E} \right) \left(\frac{P}{T} \right) \right)^{F_{opt}}$$

Optimal fold

Energy Resolution (FWHM)

Photopeak-to-total ratio

Resolving Power

Resolving Power = Ability to find a needle in the haystack

https://www.triz.co.uk/problem-solving---facilitation-workshops

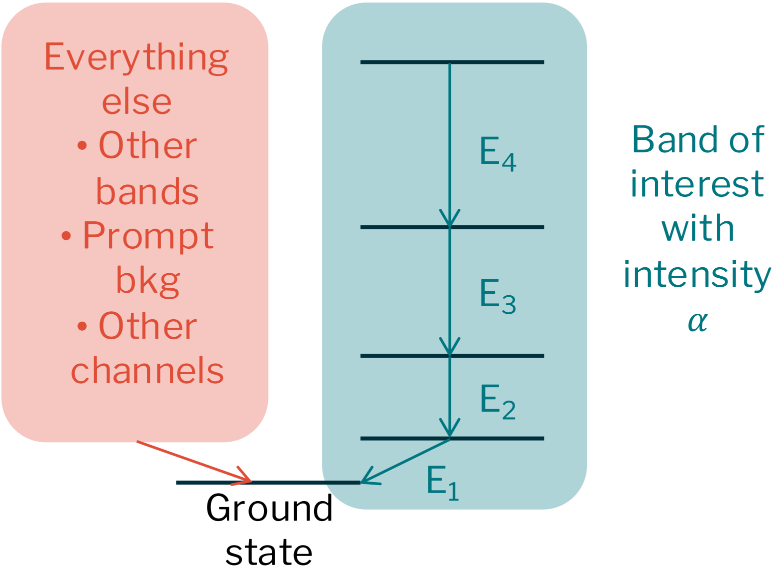
Resolving Power in Gamma-Ray Spectrometry

- In spectroscopic terms, resolving power is the ability to isolate a given sequence of transitions from a complex spectrum

- Sensitivity (resolving power)

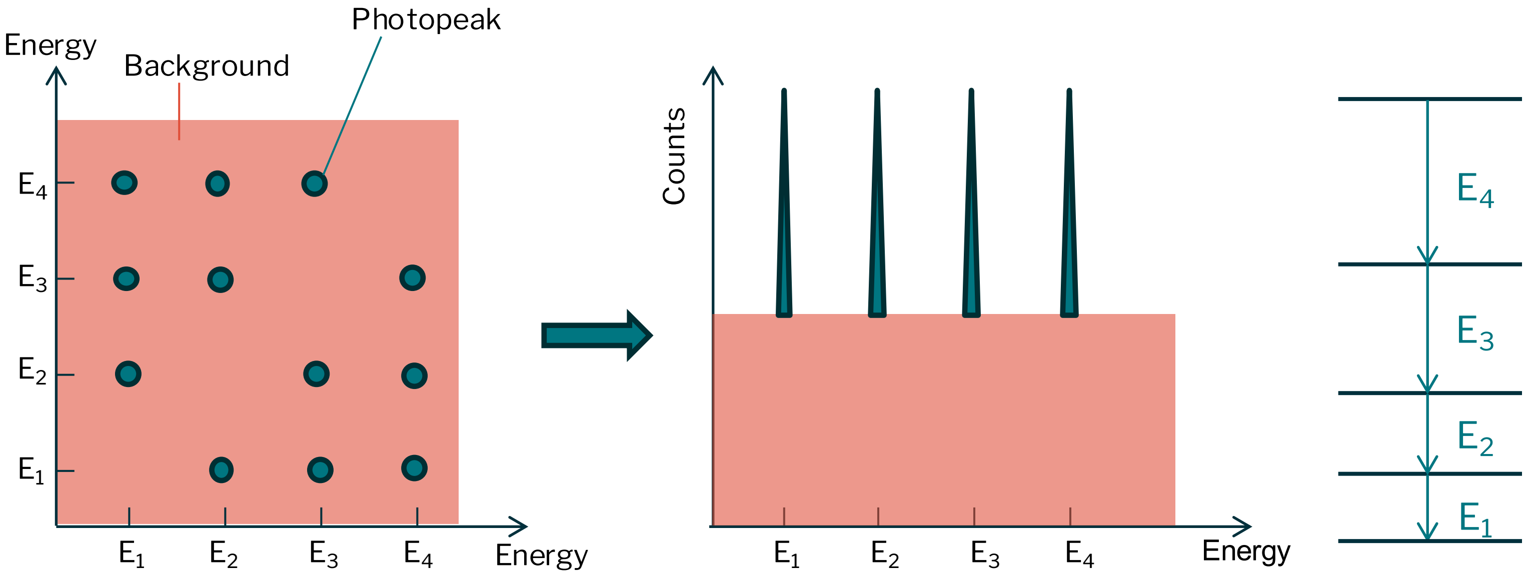
$$\text{Sensitivity} = \frac{1}{\alpha_{min}}$$

α_{min} = branching ratio of weakest branch (cascade) expected to be observable (as a fraction of total)



Improving Peak-to-Background

Using 'F' fold coincidences to improve signal to background (here F=2)

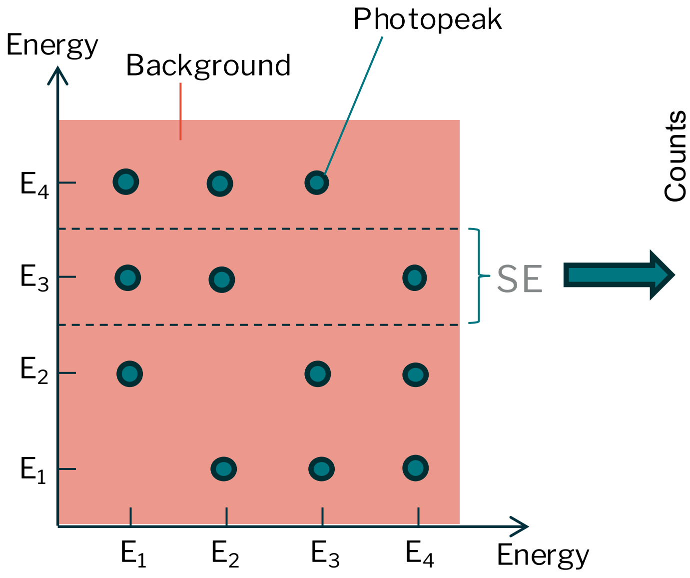


Fold=2 Gamma-gamma coincidences (2D plot)

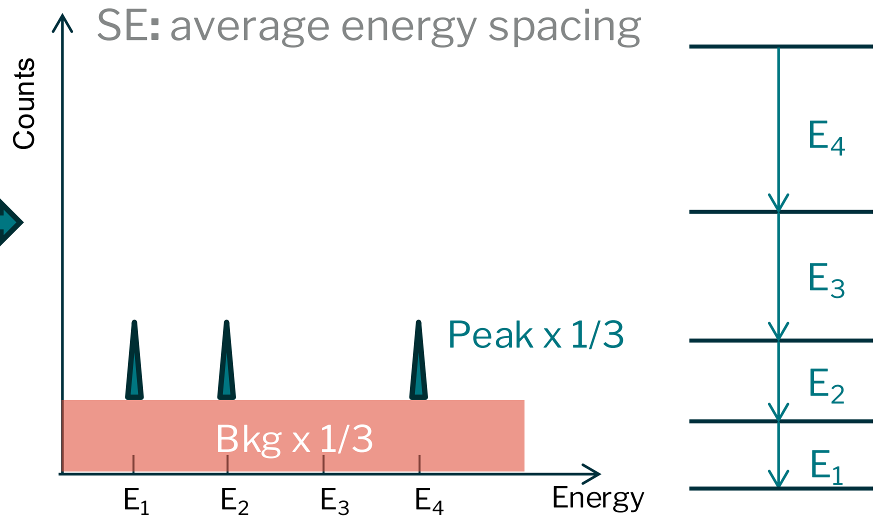
Total projected gamma spectrum

Improving Peak-to-Background

Using 'F' fold coincidences to improve signal to background (here F=2)



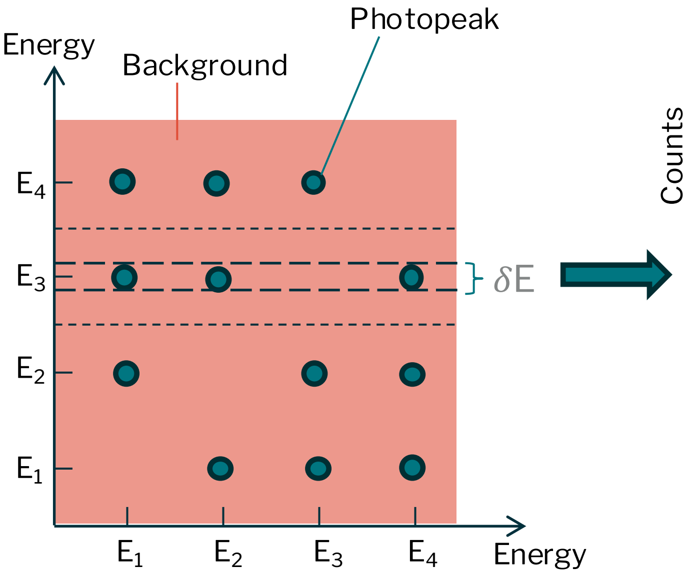
Fold=2 Gamma-gamma coincidences (2D plot)



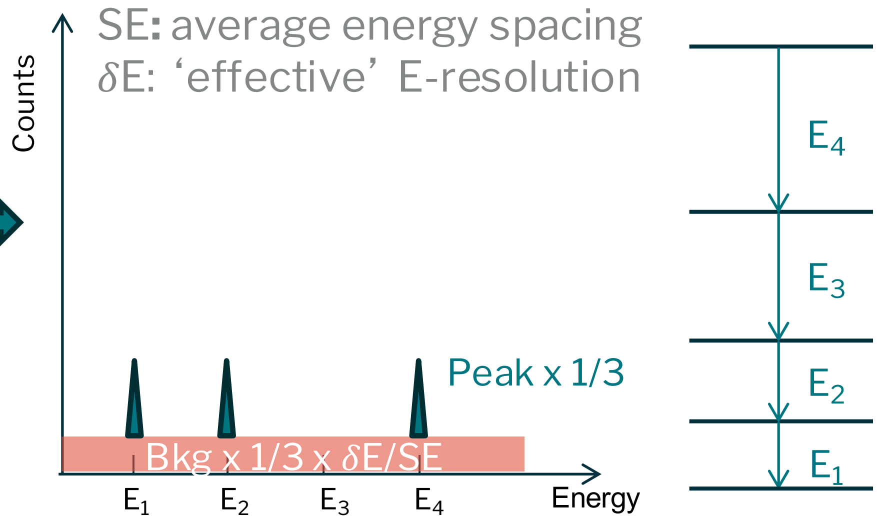
Total projected gamma spectrum

Improving Peak-to-Background

Using 'F' fold coincidences to improve signal to background (here F=2)



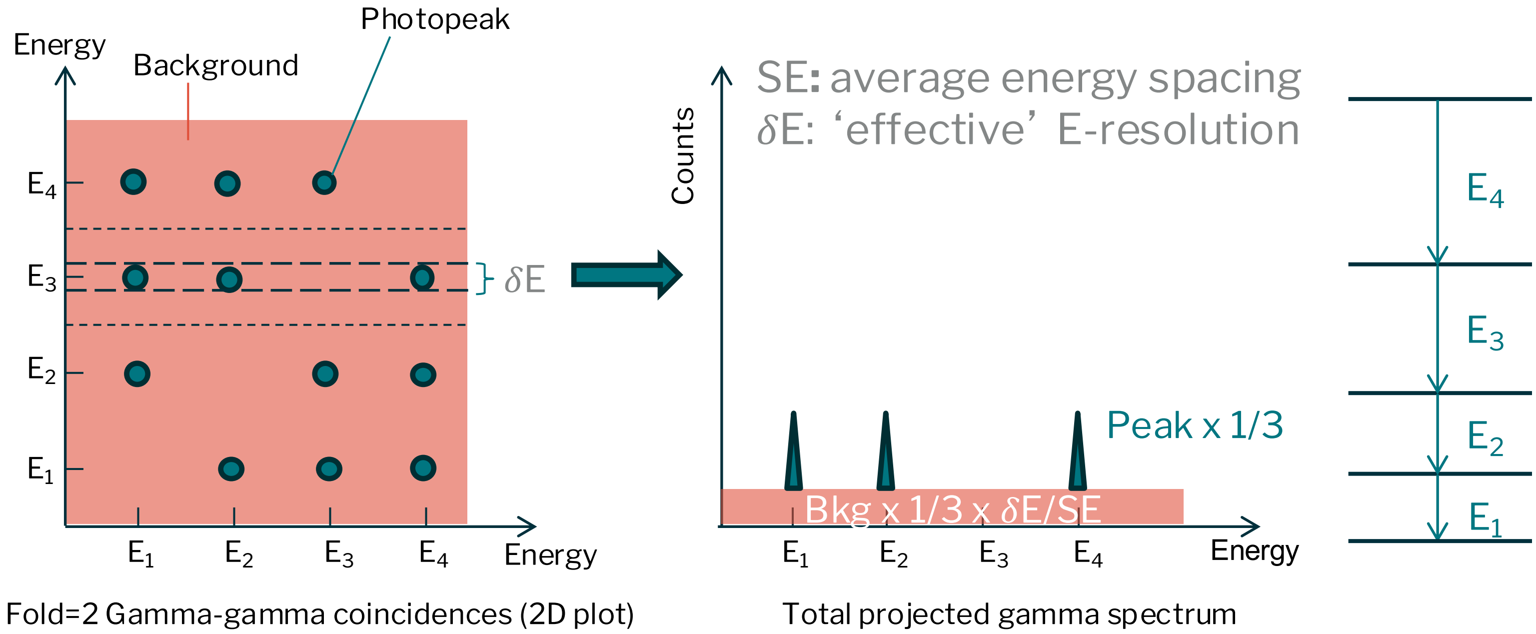
Fold=2 Gamma-gamma coincidences (2D plot)



Total projected gamma spectrum

Improving Peak-to-Background

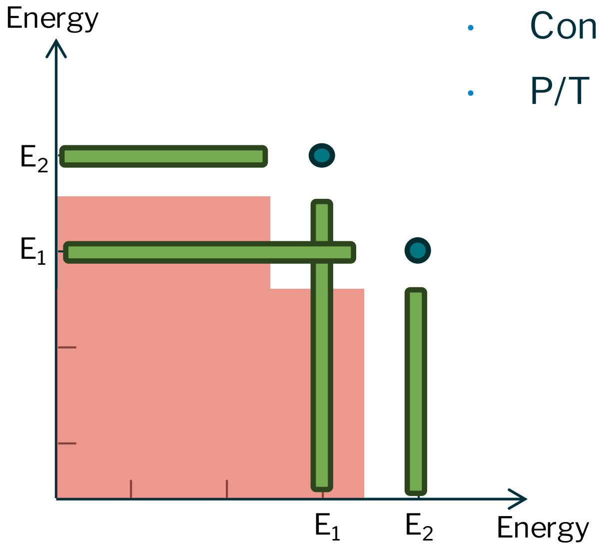
Using 'F' fold coincidences to improve signal to background (here F=2)



⇒ Improves the P/T by a factor of SE/δE

Peak-to-Total and Statistics

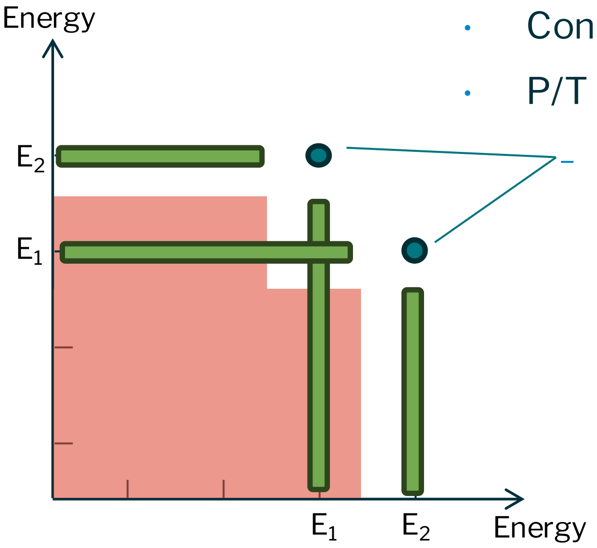
What does it cost us to increase Fold in analysis?



- Consider P/T as probability to count a gamma in the photopeak and not the Compton plateau
- Consider P/T with background ONLY from the Compton
- P/T = 0.2, and two gammas, 100 events in total

Peak-to-Total and Statistics

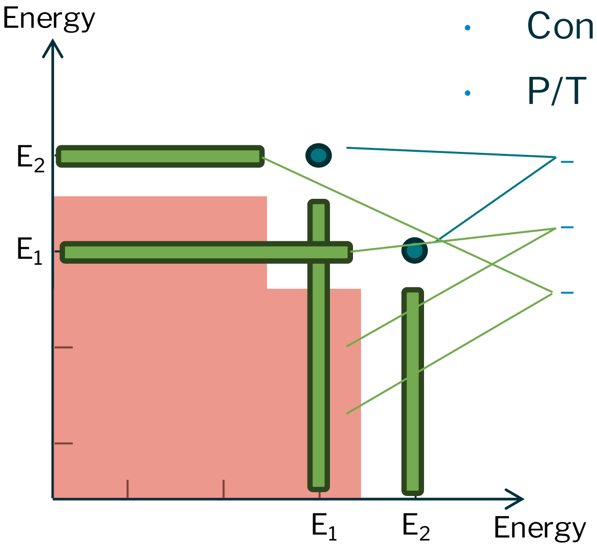
What does it cost us to increase Fold in analysis?



- Consider P/T as probability to count a gamma in the photopeak and not the Compton plateau
- Consider P/T with background ONLY from the Compton
- P/T = 0.2, and two gammas, 100 events in total
  - Detection of both gamma as peak = PxP = 4%

Peak-to-Total and Statistics

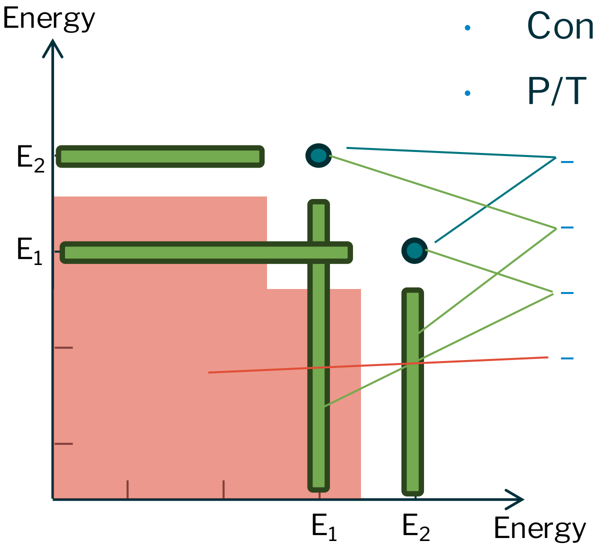
What does it cost us to increase Fold in analysis?



- Consider P/T as probability to count a gamma in the photopeak and not the Compton plateau
- Consider P/T with background ONLY from the Compton
- P/T = 0.2, and two gammas, 100 events in total
  - Detection of both gamma as peak = PxP = 4%
  - E_1 in peak, E_2 in Compton = PxC = 16%
  - E_1 in Compton, E_2 in peak = CxP = 16%

Peak-to-Total and Statistics

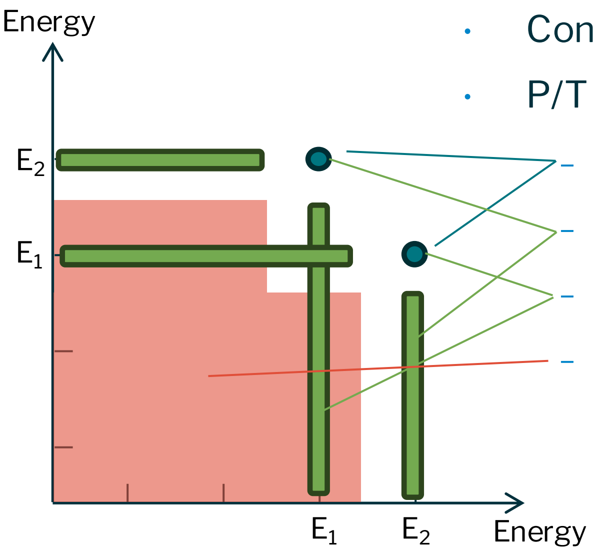
What does it cost us to increase Fold in analysis?



- Consider P/T as probability to count a gamma in the photopeak and not the Compton plateau
- Consider P/T with background ONLY from the Compton
- P/T = 0.2, and two gammas, 100 events in total
  - Detection of both gamma as peak = PxP = 4%
  - E_1 in peak, E_2 in Compton = PxC = 16%
  - E_1 in Compton, E_2 in peak = CxP = 16%
  - Both as Compton = CxC = 64%

Peak-to-Total and Statistics

What does it cost us to increase Fold in analysis?



- Consider P/T as probability to count a gamma in the photopeak and not the Compton plateau
- Consider P/T with background ONLY from the Compton
- P/T = 0.2, and two gammas, 100 events in total
  - Detection of both gamma as peak = PxP = 4%
  - E_1 in peak, E_2 in Compton = PxC = 16%
  - E_1 in Compton, E_2 in peak = CxP = 16%
  - Both as Compton = CxC = 64%

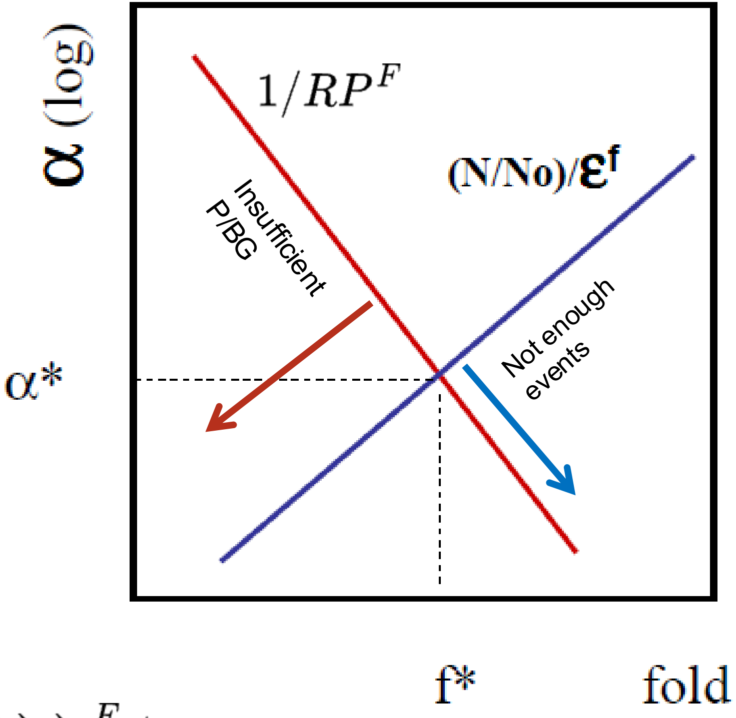
In total projection we have 10 events in the peak.
If we cut with δE, we only have 2 (10 x P/T).
⇒ We lose a factor of P/T in efficiency with each unit increase in fold (F).

BERKELEY LAB

Resolving Power

$$RP \simeq \left(\left(\frac{SE}{\delta E}\right)\left(\frac{P}{T}\right)\right)$$

- Ignoring statistics, the weakest branch we can observe $\alpha = 1/RP^F$
- The counts in the peak of interest goes as $N = \alpha N_0 \varepsilon^F$
- For a given gamma-ray array, there is an optimal fold where the efficiency and P/T balance for optimized spectroscopic sensitivity
- Combine at optimal fold



$$RP = \left(\left(\frac{SE}{\delta E}\right)\left(\frac{P}{T}\right)\right)^{F_{opt}}$$

Resolving Power

$$RP = \left(\left(\frac{SE}{\delta E}\right)\left(\frac{P}{T}\right)\right)^{F_{opt}}$$

- For low-multiplicity spectroscopy (F_{opt} = 1-2) and large energy spacing (SE), the P/T of an array will dominate the resolving power – a scintillator with poorer resolution but superior P/T compared to the average HPGe array is better suited
- As soon as SE becomes smaller, or higher gamma multiplicities are required, superior energy resolution becomes more critical

Resolving Power

$$RP = \left(\left(\frac{SE}{\delta E} \right) \left(\frac{P}{T} \right) \right)^{F_{opt}}$$

- For low-multiplicity spectroscopy (F_{opt} = 1-2) and large energy spacing (SE), the P/T of an array will dominate the resolving power – a scintillator with poorer resolution but superior P/T compared to the average HPGe array is better suited
- As soon as SE becomes smaller, or higher gamma multiplicities are required, superior energy resolution becomes more critical

Array	δE (keV)	Efficiency @ 1 MeV	P/T
CAESAR (CsI(Na))	10% (in-beam, β~0.3)	35%	0.24
DALI2 (NaI(Tl))	10-12% (in-beam, β~0.4/0.5)	24%	> 0.2
SeGA (HPGe)	2-3% (in-beam, β~0.3)	2.5%	0.22
Gammasphere	0.5-1% (in-beam, β~0.1)	9%	0.55
GRETA (HPGe; tracking)	0.5-1% (in-beam, , β~0.3-0.5)	>30%	>0.5

Resolving Power

$$RP = \left(\left(\frac{SE}{\delta E}\right)\left(\frac{P}{T}\right)\right)^{F_{opt}}$$

- For low-multiplicity spectroscopy (F_{opt} = 1-2) and large energy spacing (SE), the P/T of an array will dominate the resolving power – a scintillator with poorer resolution but superior P/T compared to the average HPGe array is better suited
- As soon as SE becomes smaller, or higher gamma multiplicities are required, superior energy resolution becomes more critical

Array	δE (keV)	Efficiency @ 1 MeV	P/T
CAESAR (CsI(Na))	10% (in-beam, β~0.3)	35%	0.24
DALI2 (NaI(Tl))	10-12% (in-beam, β~0.4/0.5)	24%	> 0.2
SeGA (HPGe)	2-3% (in-beam, β~0.3)	2.5%	0.22
Gammasphere	0.5-1% (in-beam, β~0.1)	9%	0.55
GRETA (HPGe; tracking)	0.5-1% (in-beam, , β~0.3-0.5)	>30%	>0.5

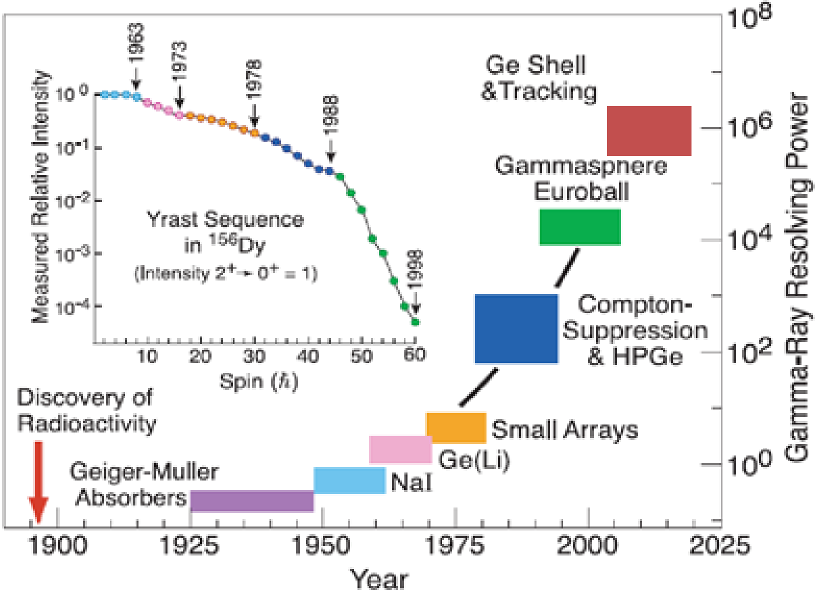
Resolving Power and Array Performance

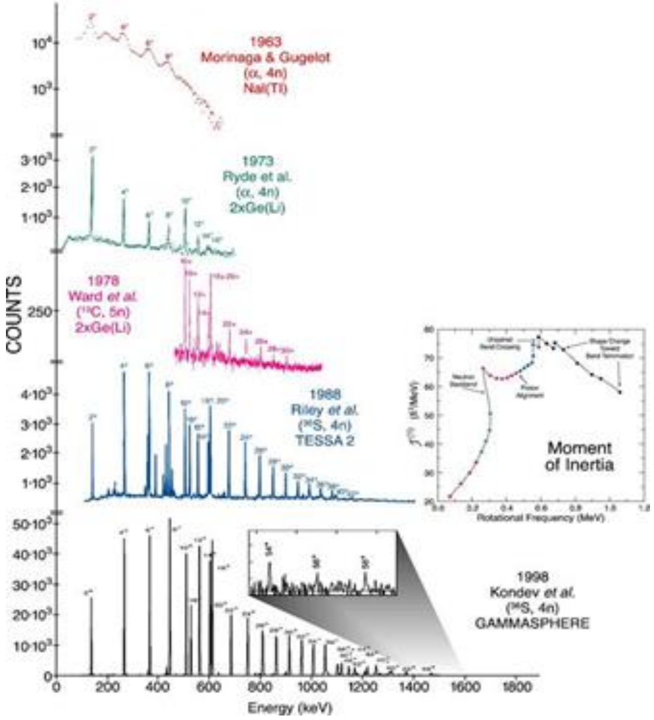
Optimized resolution, peak-to-total and efficiency **at the same time**

The science reach of a γ-ray tracking array can be expressed in terms of the effective resolving power (RP)

Depends on Efficiency (ε); Peak-to-Total (P/T); Resolution (δE)

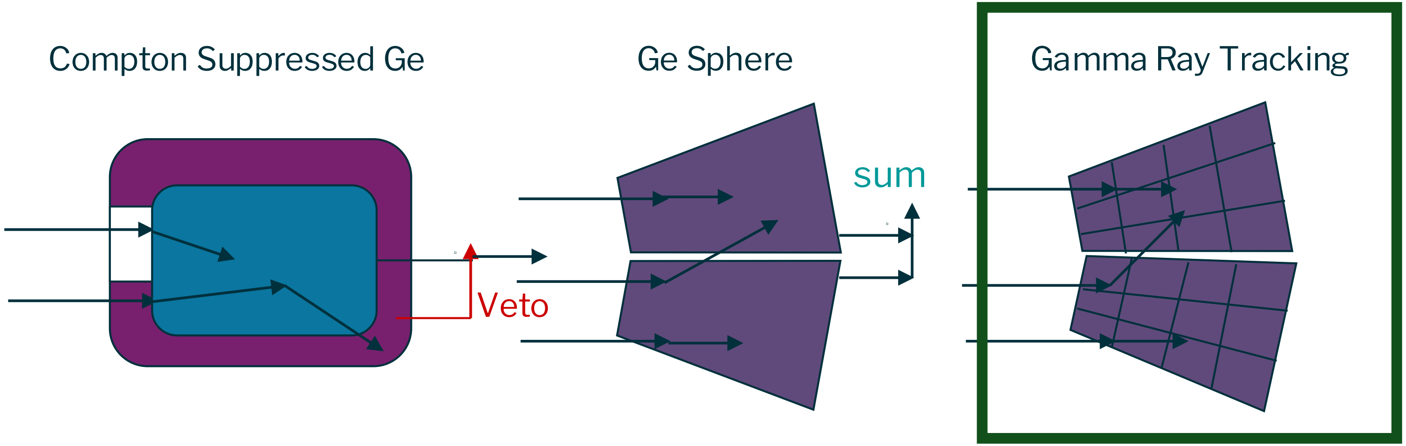
Resolving Power = Science





Compton Suppression and Gamma-Ray Tracking

Optimized resolution, peak-to-total and efficiency **at the same time**



Compton Suppressed Ge	Ge Sphere	Gamma Ray Tracking
N = 100	N = 1000 (summing)	N = 100
$N\Omega e = 0.1$	$N\Omega e = 0.6$	$N\Omega e = 0.6$
Efficiency limited	Too many detectors	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

BERKELEY LAB

Discussion – Pros and Cons in Spectrometers

- I've been building the case for why a HPGe gamma-ray tracking array is so powerful – so if we have one, should we get rid of our other spectroscopic systems?
  - Can you think of reasons / experiments where you would want to use a scintillator array over a HPGe tracking array? Why?
  - What about bolometers? They have **much** better resolution than HPGe, why aren't we building arrays of bolometers or using these for nuclear structure? Or have you heard of examples using bolometers?
  - Are there parameters to optimize or capabilities that you think are missing in terms of gamma-ray spectroscopy?

Questions?