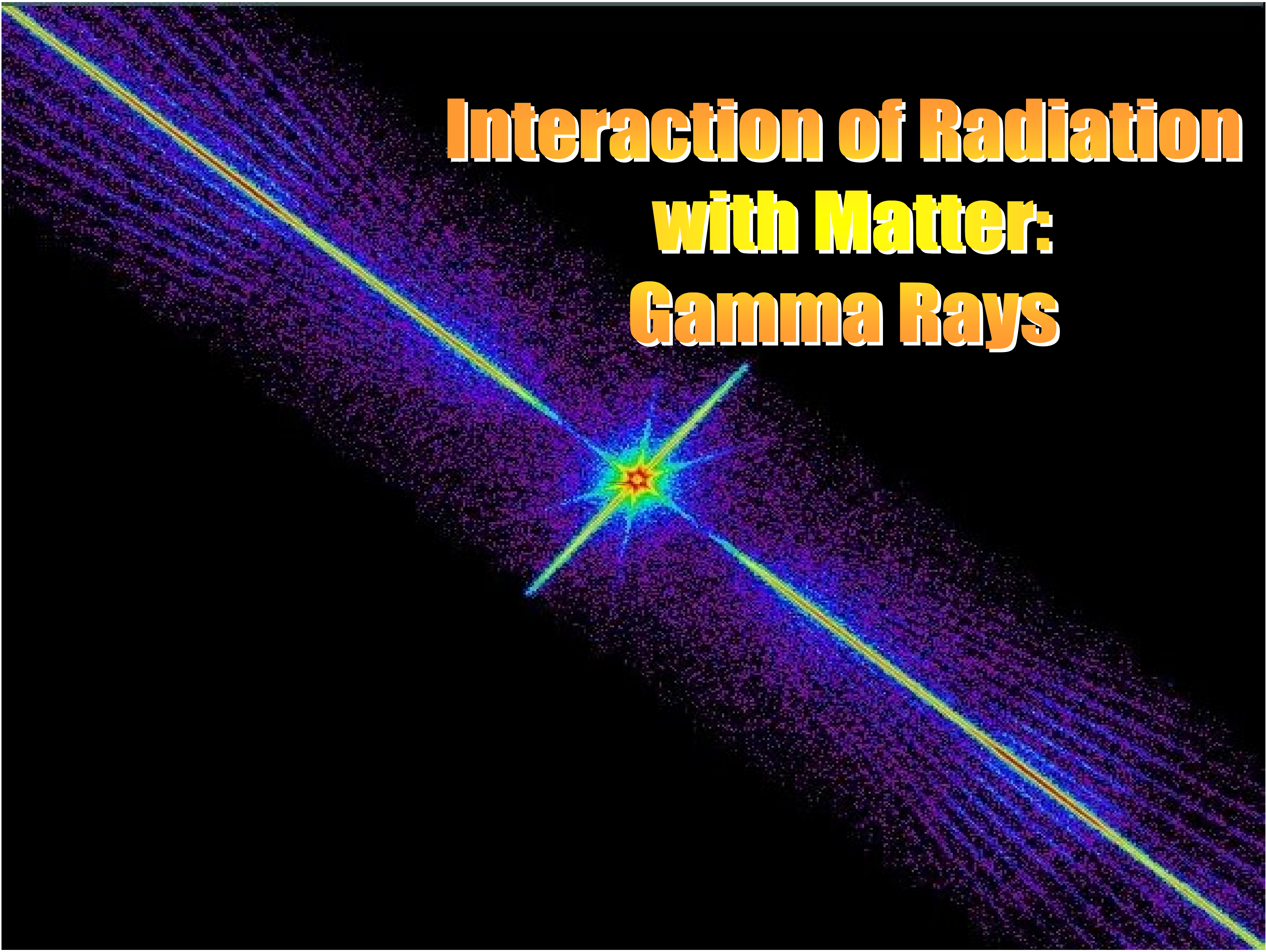
Interaction of Radiation with Matter: Gamma Rays



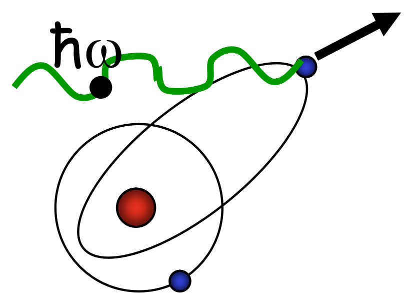
γ- Induced Processes

γ-rays (photons) come from electromagnetic transitions between different energy states of a system → important structural information

Detection principles are based on:

- Photo-electric absorption
- Compton scattering
- Pair production
- γ-induced reactions

1. Photo-electric absorption (Photo-effect)



photon is completely absorbed by e^-, which is kicked out of atom

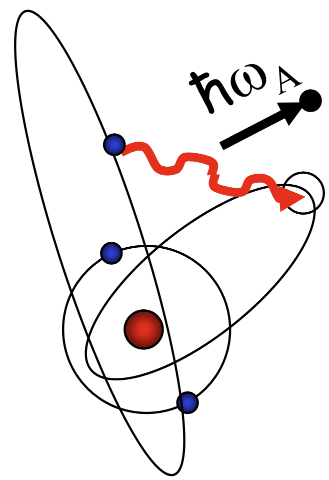
$$E_{kin} = \hbar\varpi - E_n; \quad E_n = binding\ \ energy$$

$$E_n = Rhc \cdot \frac{(Z-\sigma)^2}{n^2} \quad Moseley's\ \ Law$$

$$Rhc = 13.6\,eV \quad Rydberg\ \ constant$$

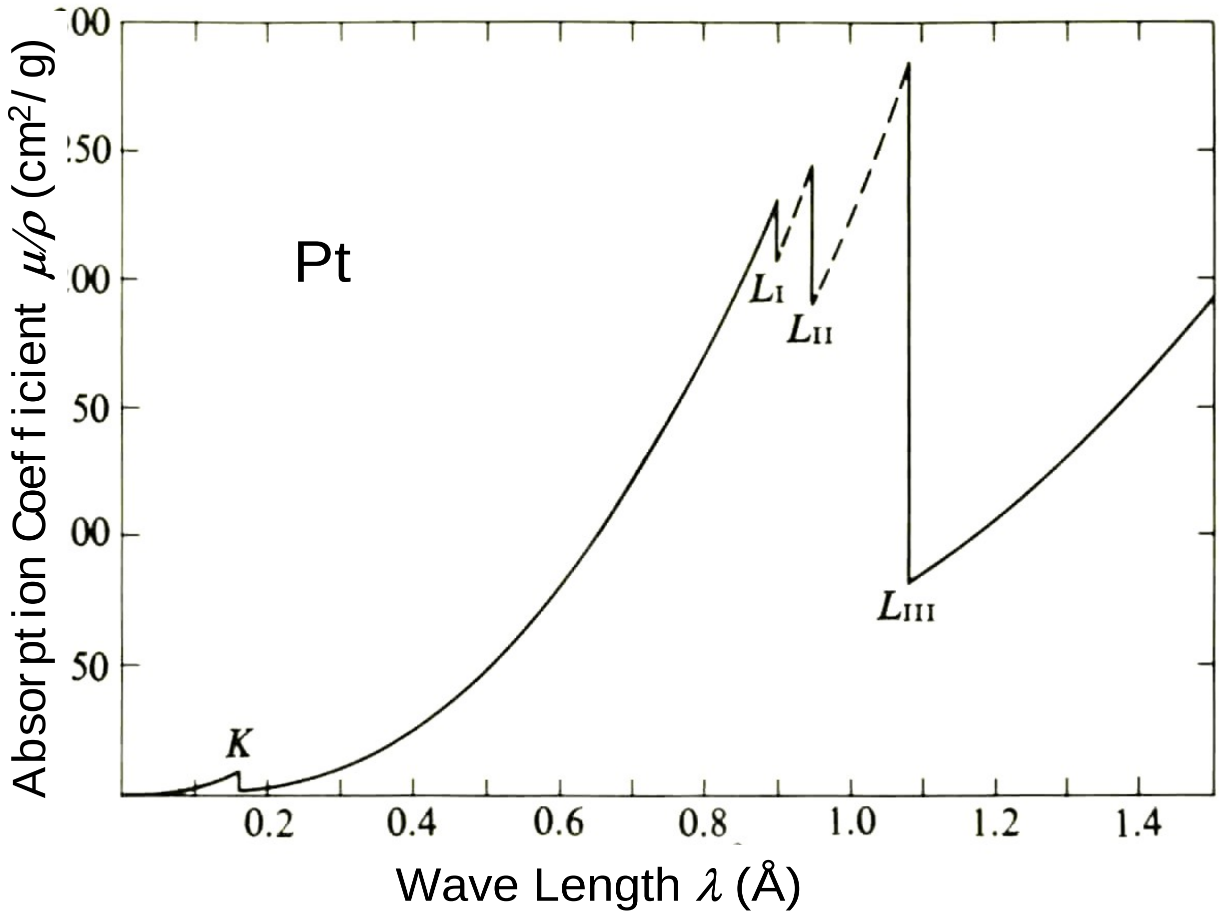
$$screening\ \ constants$$

$$\sigma_K \approx 3,\ \ \sigma_L \approx 5,\ \ different\ \ subshells$$



Electronic vacancies are filled by low-energy "Auger" transitions of electrons from higher orbits

Photo-Absorption Coefficient



Absorption coefficient
→ μ (1/cm)

"Mass absorption" is measured per density ρ

→ μ/ρ (cm^2/g)

"Cross section" is measured per atom

→ σ (cm^2/atom)

Absorption of light is quantal resonance phenomenon: Strongest when photon energy coincides with transition energy (at K,L,... "edges")

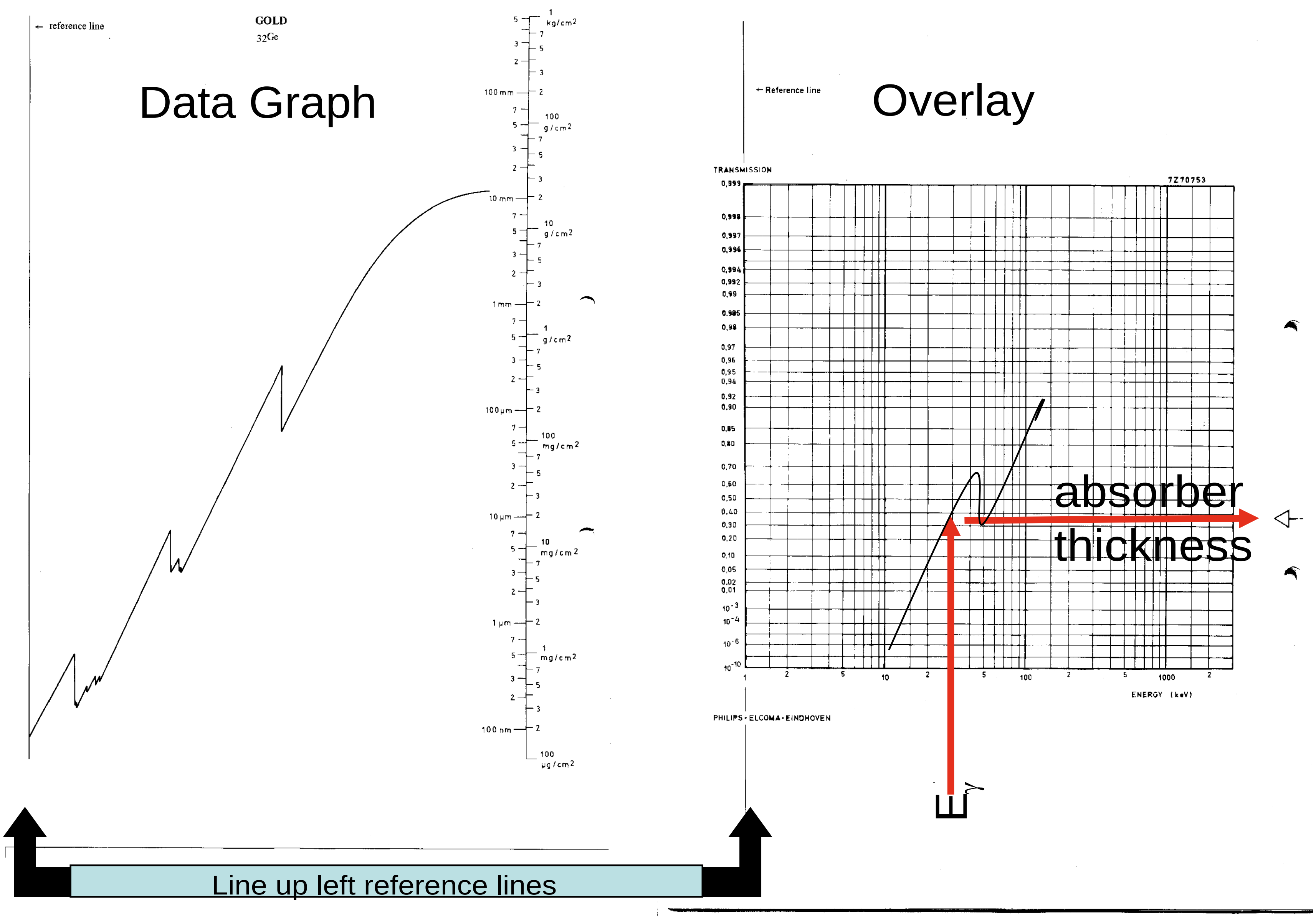
Probabilities for independent processes are additive:

$\mu_{PE} = \mu_{PE}(K) + \mu_{PE}(L) + \ldots$

$$\sigma_{PE}(E_\gamma, Z) \propto Z^5 \cdot E_\gamma^{-7/4} \quad low\ E_\gamma$$

$$\sigma_{PE}(E_\gamma, Z) \propto Z^5 \cdot E_\gamma^{-1/2} \quad high\ E_\gamma$$

Templates and Nomograms



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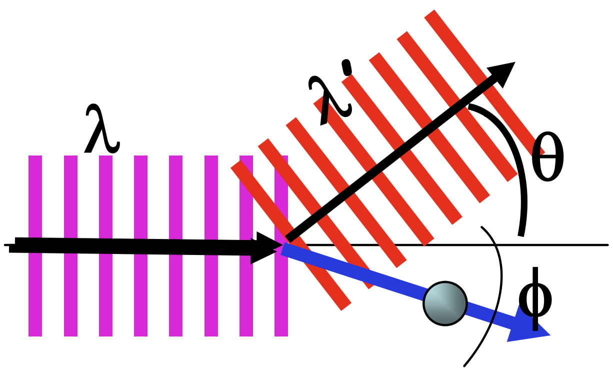
Photon Scattering (Compton Effect)

$$Relativistic\ \ E^2 = (pc)^2 + (m_0c^2)^2 \quad photons: m_0 = m_\gamma = 0$$

$$\rightarrow\ E_\gamma = \hbar\varpi_\gamma = p_\gamma c$$



$$\lambda' - \lambda = \lambda_C \cdot \left(1 - \cos\theta\right)$$

$$"Compton\ \ wave\ length\ \lambda_C\ "$$

$$\lambda_C = \frac{2\pi}{m_e c} = 2.426\,pm$$

Momentum balance:

$$\vec{p}_e = \vec{p}_\gamma - \vec{p}'_\gamma \quad \rightarrow \quad \left|\vec{p}_e c\right|^2 = \left|\left(\vec{p}_\gamma - \vec{p}'_\gamma\right)c\right|^2$$

$$p_e^2c^2 = E_\gamma^2 + E_{\gamma'}^2 - 2E_\gamma E_{\gamma'} \cdot \cos\theta$$

Energy balance:

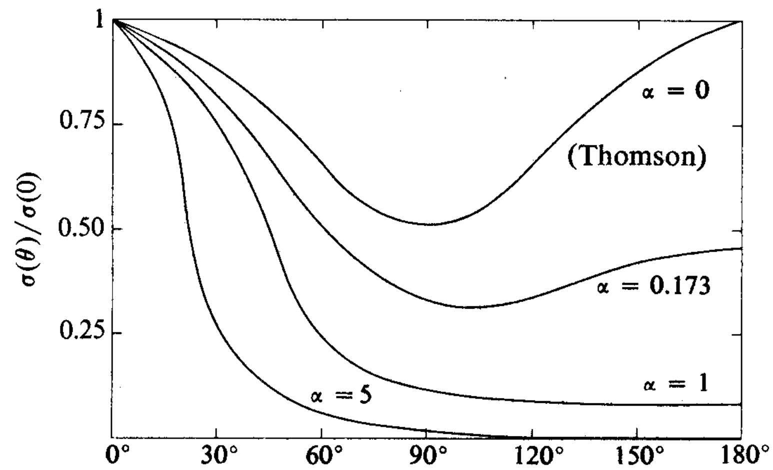
$$E_\gamma + m_ec^2 = E_{\gamma'} + \sqrt{\left(p_ec\right)^2 + \left(m_ec^2\right)^2}$$

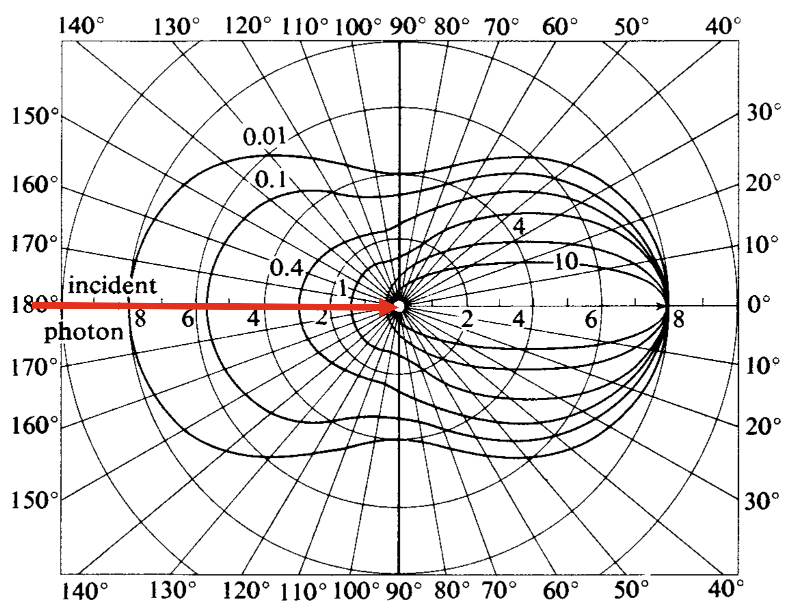
$$\boxed{E_{\gamma'} = \frac{E_\gamma}{1 + \left(E_\gamma / m_ec^2\right)\left(1 - \cos\theta\right)}}$$

$$m_ec^2 = 0.511 MeV$$

Compton Angular Distributions

Intensity as function of θ





Klein-Nishina-Formula ($\alpha = E_\gamma / m_e c^2$)

Forward scattering for high-energy photons, symmetric about 90^0 for low-energy

$$\frac{d\sigma_C}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2 \left\{\frac{E_\gamma}{E_{\gamma'}} + \frac{E_{\gamma'}}{E_\gamma} - \sin^2\theta\right\}$$

"Classical e^- radius" $r_0 = 2.818$ fm.
Alternative formulation:

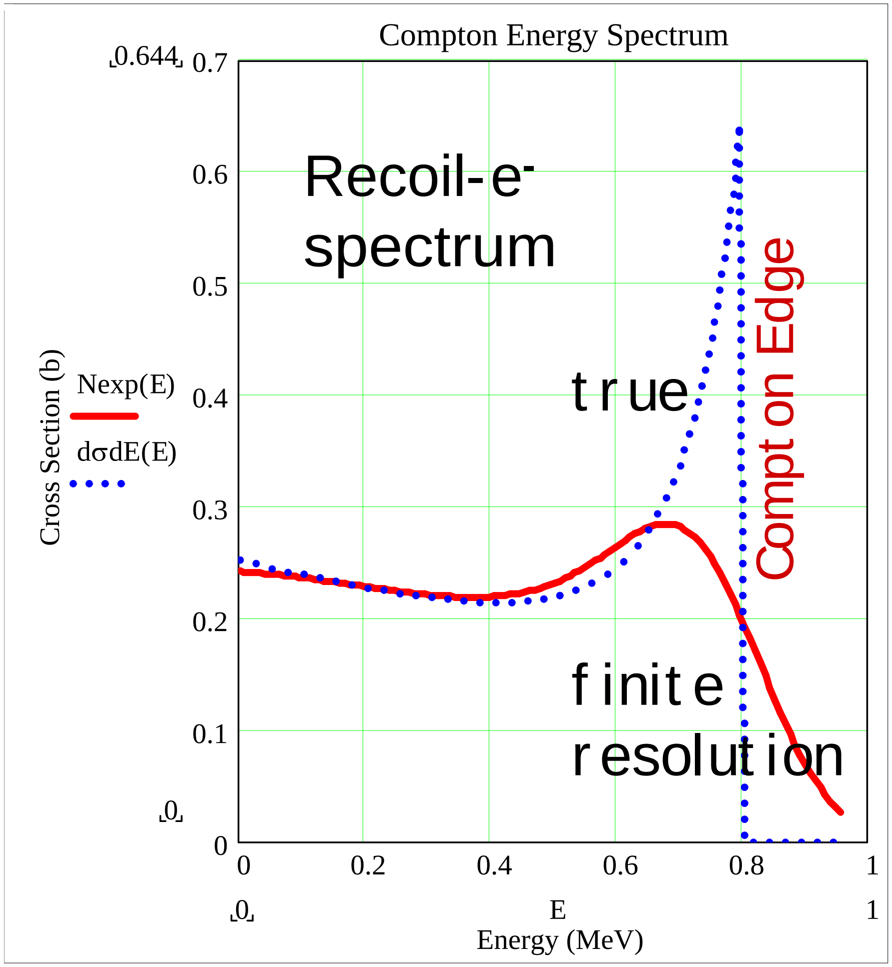
$$\frac{d\sigma_C}{d\Omega} = \frac{r_0^2}{2}\left[1+\cos\theta\right]\left\{\frac{1}{1+\alpha(1-\cos\theta)}\right\}^3 \times$$

$$\times\left\{1+\frac{\alpha^2(1-\cos\theta)^2}{\left(1+\cos^2\theta\right)\left[1+\alpha(1-\cos\theta)\right]}\right\}$$

Total scattering probability: $\sigma_C \propto Z$ (number of e^-)

Compton Electron Spectrum

Actually, not photons but recoil-electrons are detected



$$Scattered - photon\ energy$$

$$E_{\gamma'} = \frac{E_\gamma}{1 + \left(E_\gamma / m_e c^2\right)\left(1 - \cos\theta\right)}$$

$$Scattered\ recoil - electron\ energy:$$

$$E_{kin} = E_\gamma - E_{\gamma'} = \frac{E_\gamma \left(E_\gamma / m_e c^2\right)\left(1 - \cos\theta\right)}{1 + \left(E_\gamma / m_e c^2\right)\left(1 - \cos\theta\right)}$$

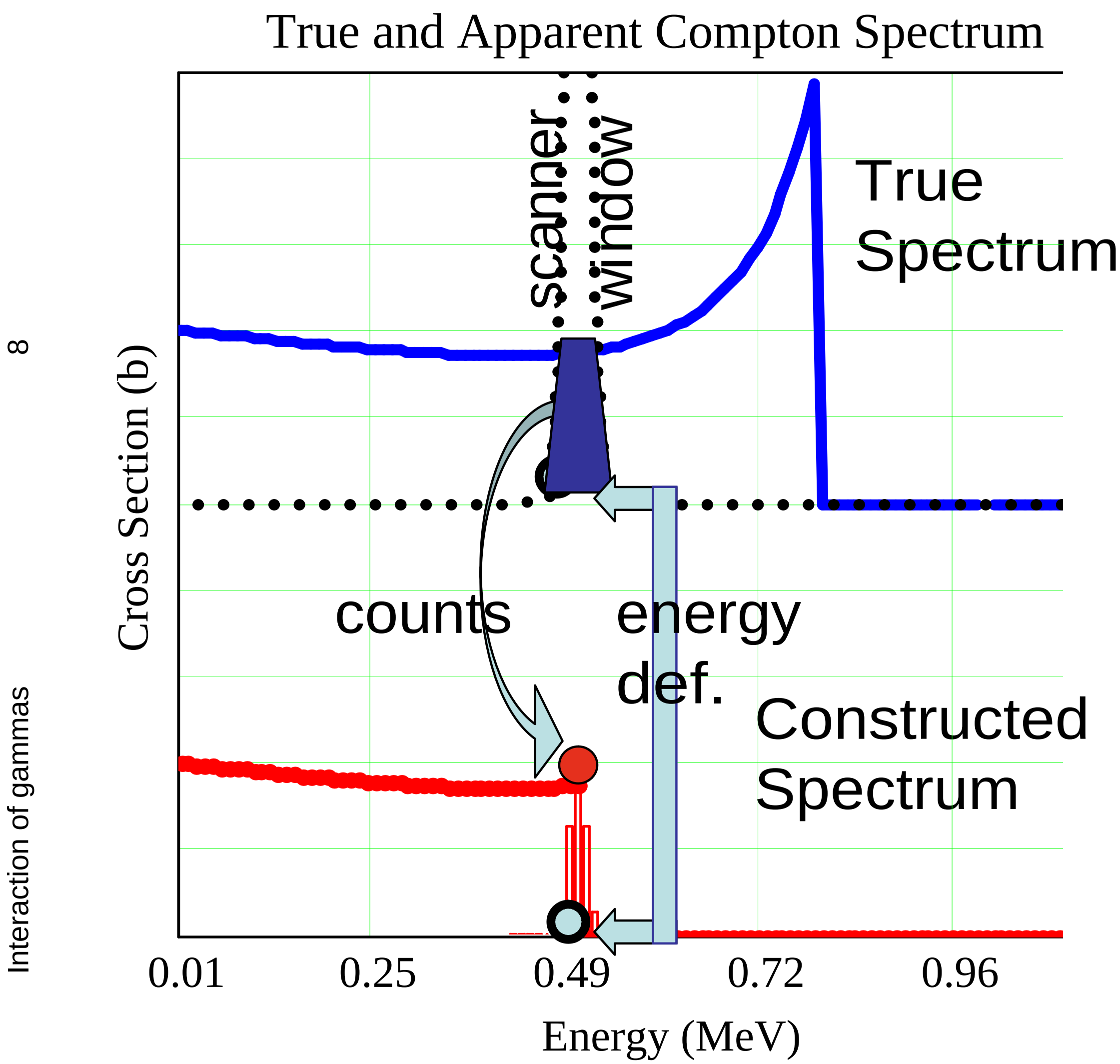
$$Minimum\ photon\ energy: \theta = 180^0$$

$$E_{\gamma'} = \frac{E_\gamma}{1 + 2 E_\gamma / m_e c^2}$$

$$Maximum\ electron\ energy\ (Compton\ Edge):$$

$$E_{kin} \le E_{CE} = E_\gamma \frac{2\left(E_\gamma / m_e c^2\right)}{1 + 2\left(E_\gamma / m_e c^2\right)}$$

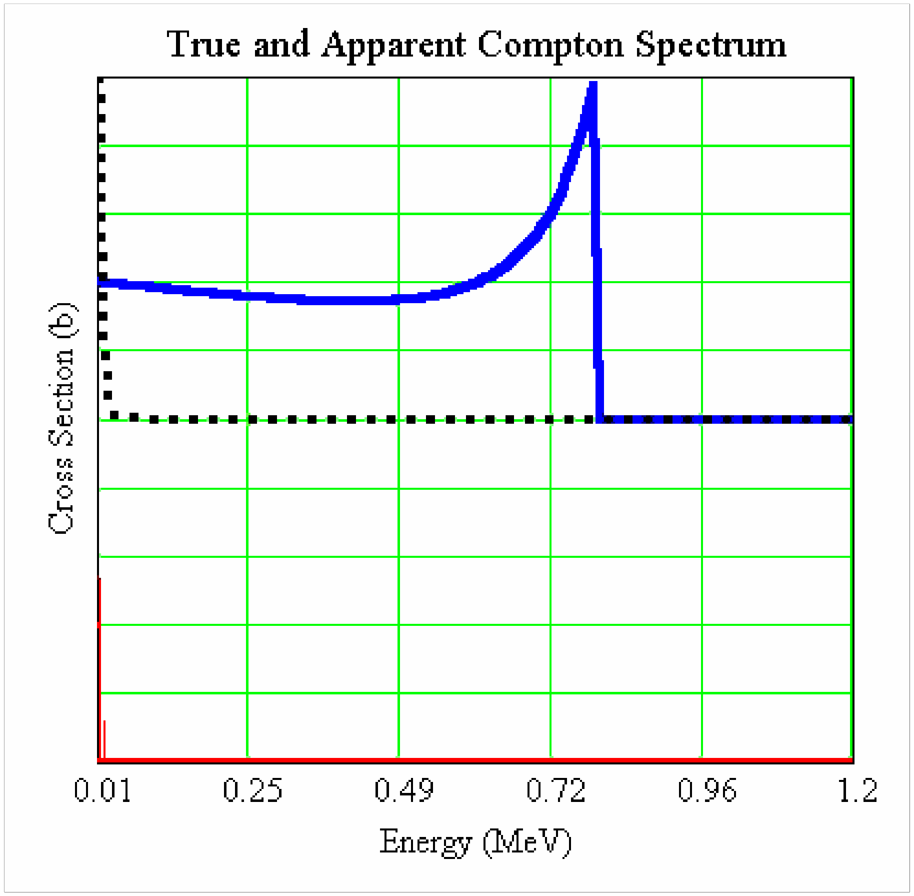
Scanning Spectral Data



A spectrum (e.g., probability vs. energy) is generated by scanning physical data, sorting events according to the values of a variable of interest (energy). The values are determined by scanning an actual (**true**) data set and grouping events according to their (energy) values.

Finite resolution of variable → **apparent** spectrum deviates from **true** spectrum.

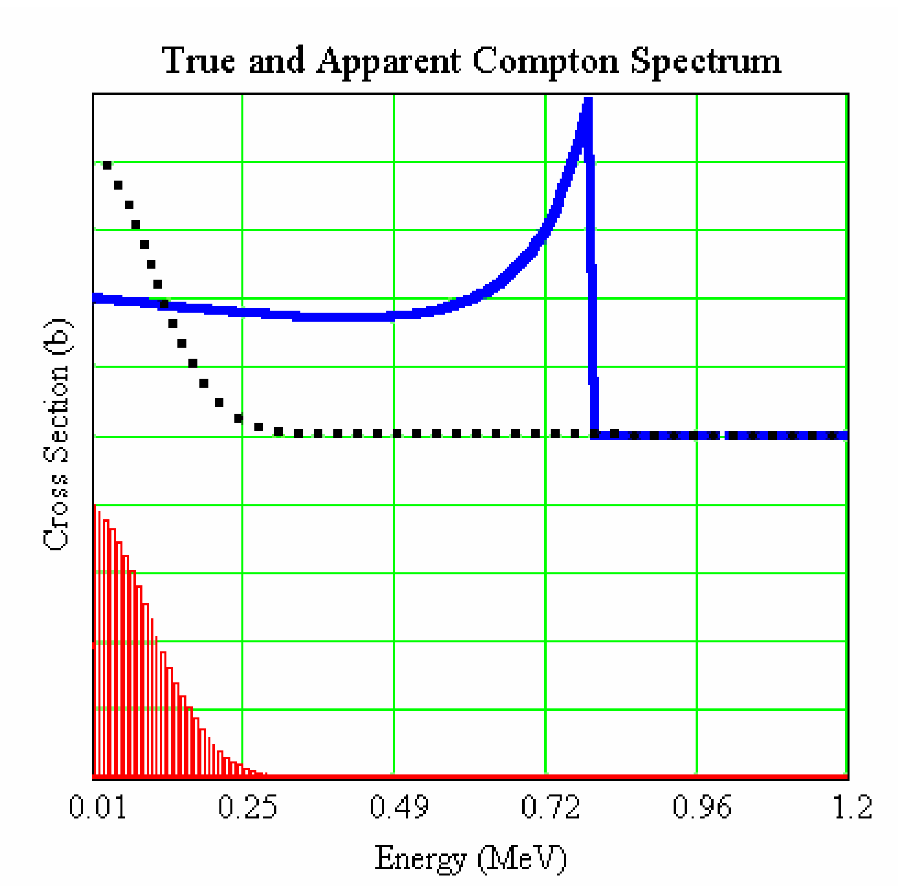
High- Resolution Scan



The number of true events (top) within a well-defined scanning acceptance bin (or within view) is plotted below at the nominal bin position.

A detector with high resolution provides an apparent spectrum very similar to true spectrum, with minimum distortions

Low- Resolution Scan

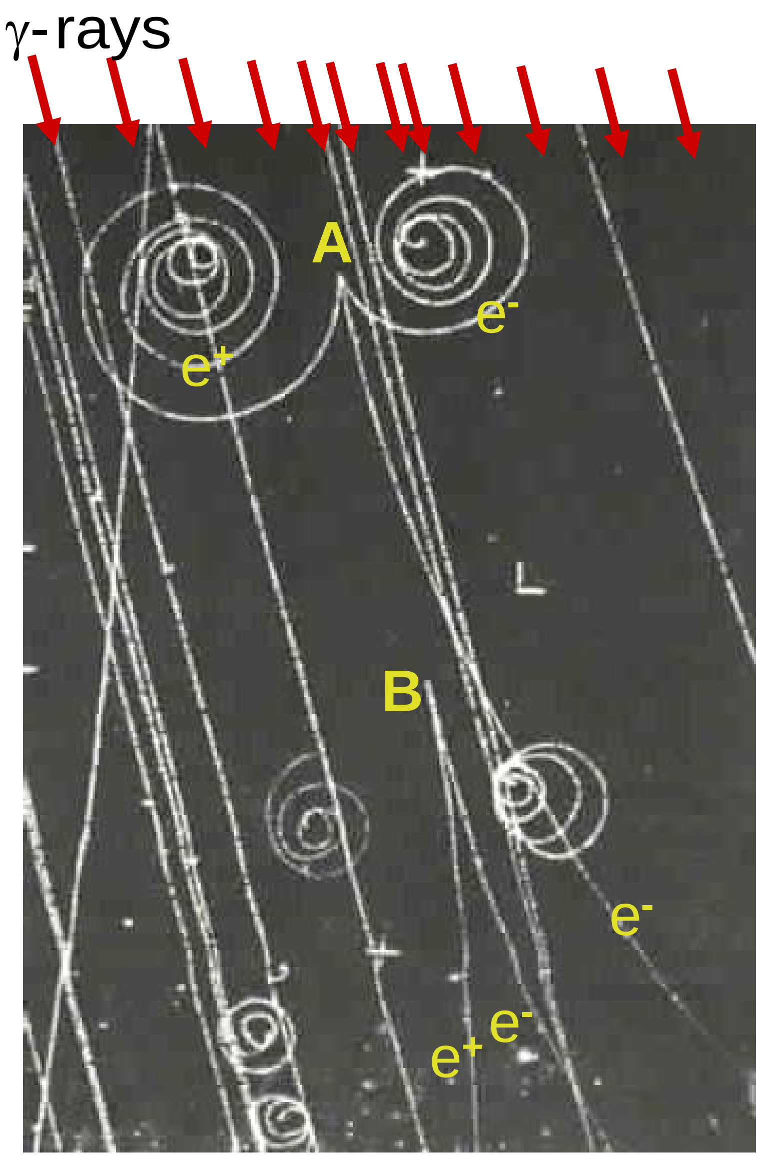


As in previous case, but now the scan is “fuzzy”, the bin is not well defined. True events far away from the center of the scanning bin are seen with some finite probability. The total number of true events (top) within a large range the finite scanning acceptance bin is plotted below at the nominal bin position.

The apparent spectrum has events in unphysical regions, e.g., above the maximum true energy.

A detector with low resolution provides an apparent spectrum very different from true spectrum, with maximum distortions at sharp structures.

Pair Creation by High-Energy γ-rays



Magnetic field

$\{e^+, e^-, e^-\}$ triplet and one doublet in H bubble chamber

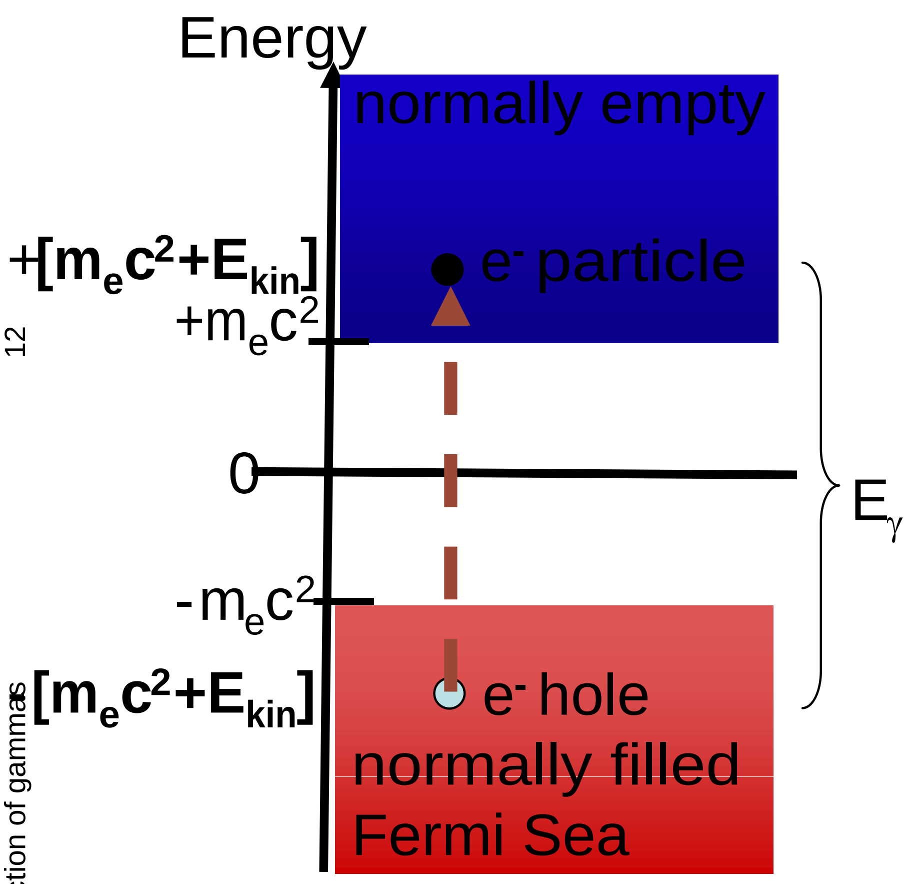
Magnetic field provides momentum/charge analysis

Event A) γ-ray (photon) hits atomic electron and produces $\{e^-, e^+\}$ pair

Event B) one photon converts into a $\{e^-, e^+\}$ pair

In each case, the photon leaves no trace in the bubble chamber, before a first interaction with a charged particle (electron or nucleus).

Dipping into the Fermi Sea: Pair Production



Dirac theory of electrons and holes:

World of normal particles has positive energies, $E \geq +mc^2 > 0$

Fermi Sea is normally filled with particles of negative energy, $E \leq -mc^2 < 0$

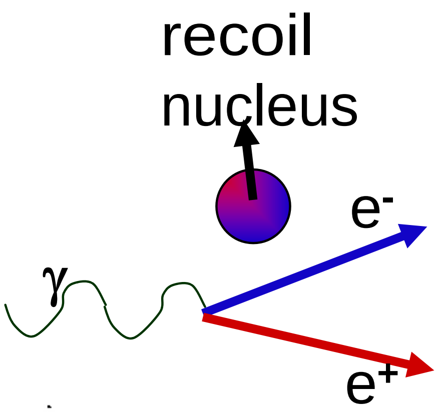
Electromagnetic interactions can lift a particle from the Fermi Sea across the energy gap **$\Delta E = 2\ mc^2$** into the normal world → particle-antiparticle pair

Holes in Fermi Sea: Antiparticles

Minimum energy needed for pair production (for electron/positron)

$$E_\gamma > E_{Threshold} = 2m_ec^2 = 1.022MeV$$

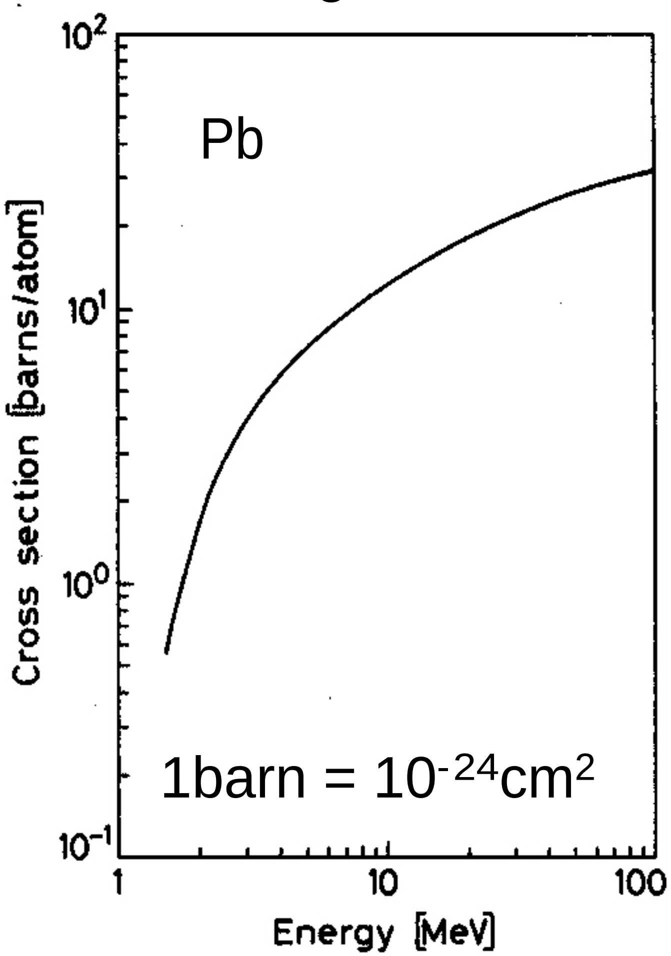
The Nucleus as Collision Partner



$$E_\gamma > E_{Threshold} = 2m_e c^2$$

$$Actually\ converted: \quad E_\gamma = 2m_e c^2 + E^+_{kin} + E^-_{kin} + \ldots.$$

Excess momentum requires presence of additional charged body, the nucleus



$$\frac{d\sigma_{PP}}{dE^+_{kin}} = Z^2 \underbrace{\frac{1}{137}\left(\frac{e^2}{m_e c^2}\right)^2}_{5.8\cdot 10^{-28}\,cm^2} \underbrace{\frac{P(Z,E_\gamma)}{E_\gamma - 2m_e c^2}}_{E_\gamma > 2m_e c^2}$$

P *slowly varying*

Increase with E_γ because interaction sufficient at larger distance from nucleus

Eventual saturation because of screening of charge at larger distances

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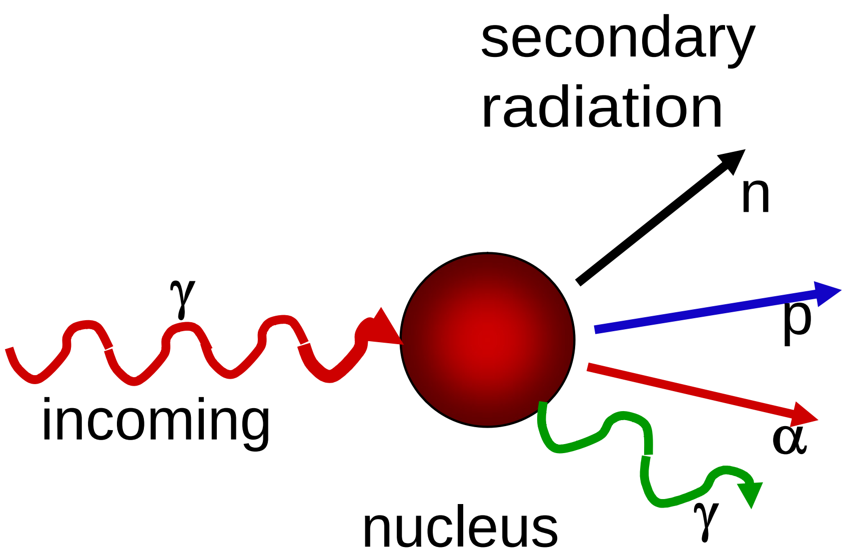
γ- Induced Nuclear Reactions



Real photons or "virtual" elm field quanta of high energies can induce reactions in a nucleus:

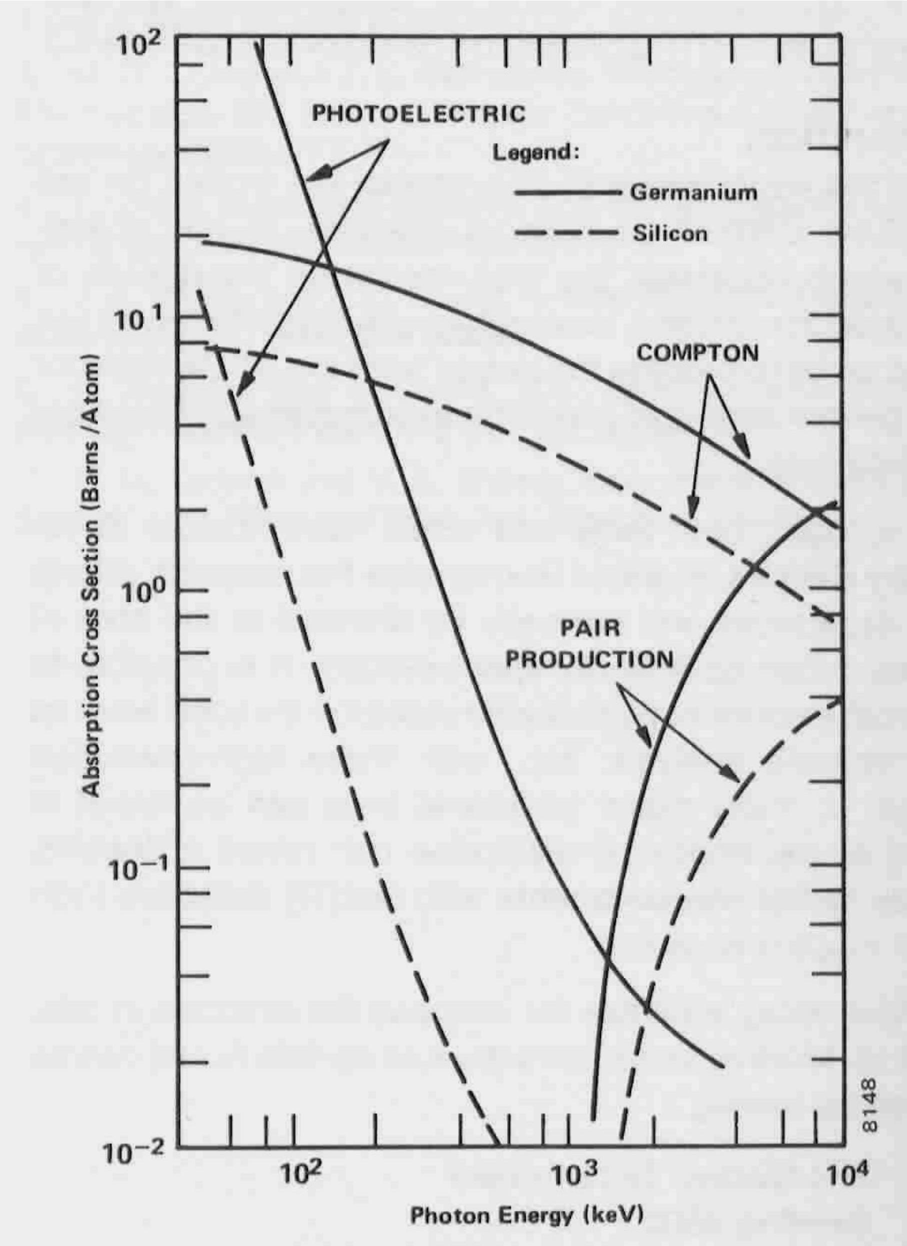
(γ, γ'), (γ, n), (γ, p), (γ, α), (γ, f)

Nucleus can emit directly a high-energy secondary particle or, usually sequentially, several low-energy particles or γ-rays.

Can heat nucleus with (one) γ-ray to boiling point, nucleus thermalizes, then "evaporates" particles and γ-rays.

γ-induced nuclear reactions are most important for high energies, $E_\gamma \gtrsim (5 - 8)\mathrm{MeV}$

Efficiencies of γ-Induced Processes



Different processes are dominant at different γ energies:

Photo absorption at low E_γ

Pair production at high E_γ

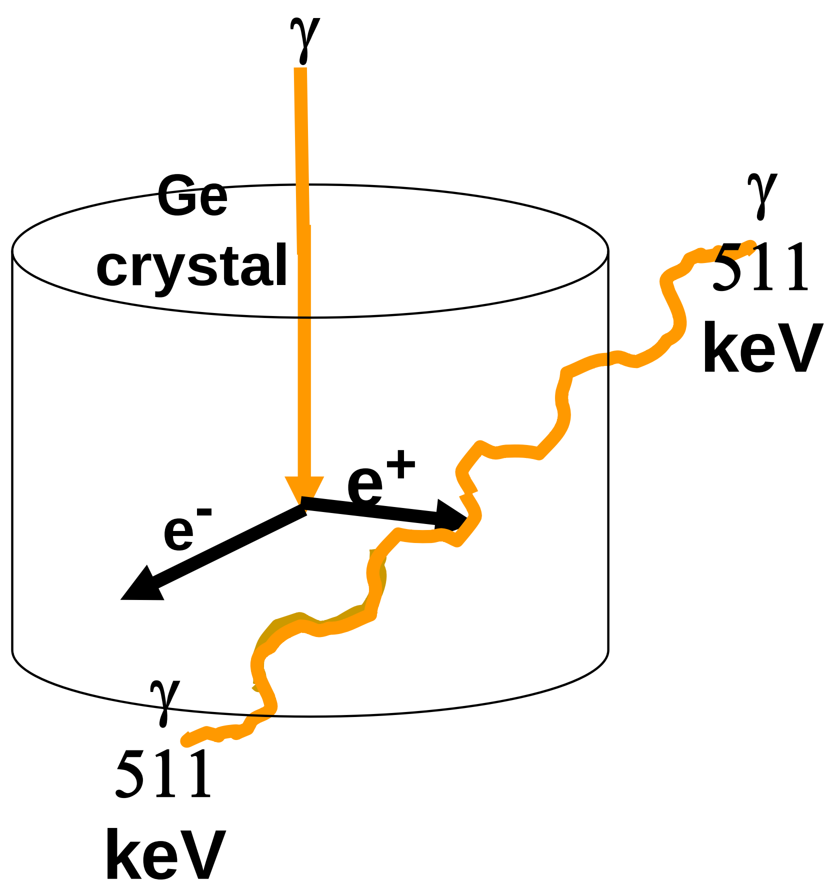
Compton scattering at intermediate E_γ.

Z dependence important: Ge(Z=32) has higher efficiency for all processes than Si(Z=14). Take high-Z for large photo-absorption coefficient

Response of detector depends on

- detector material
- detector shape
- E_γ

Escape Geometries



High-energy γ-ray leading to e^+/e^- pair production, with e^- stopped in the detector.

e^+ is also stopped in the detector and annihilates with another e^- producing 2 γ-rays of E_γ = 511 keV each. If both γ-rays are absorbed → full energy E_γ is absorbed by detector → event is in FE peak.

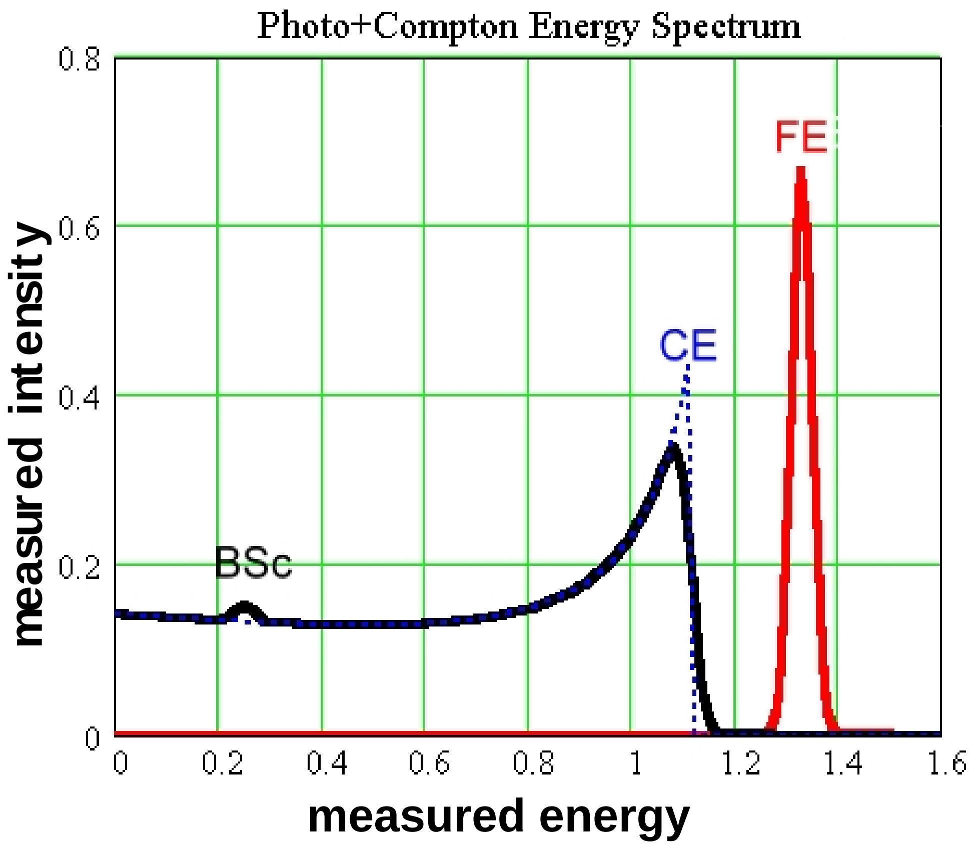
If one γ-ray escapes detector → event is in SE peak at FE-511 keV

If both of them escape → event is in detector → DE peak at FE-1.022 MeV.

Relative probabilities depend on detector size!

Shapes of Low-Energy γ Spectra

Photons/γ-rays are measured only via their interactions with charged particles, mainly with the electrons of the detector material. The energies of these e^- are measured by a detector.



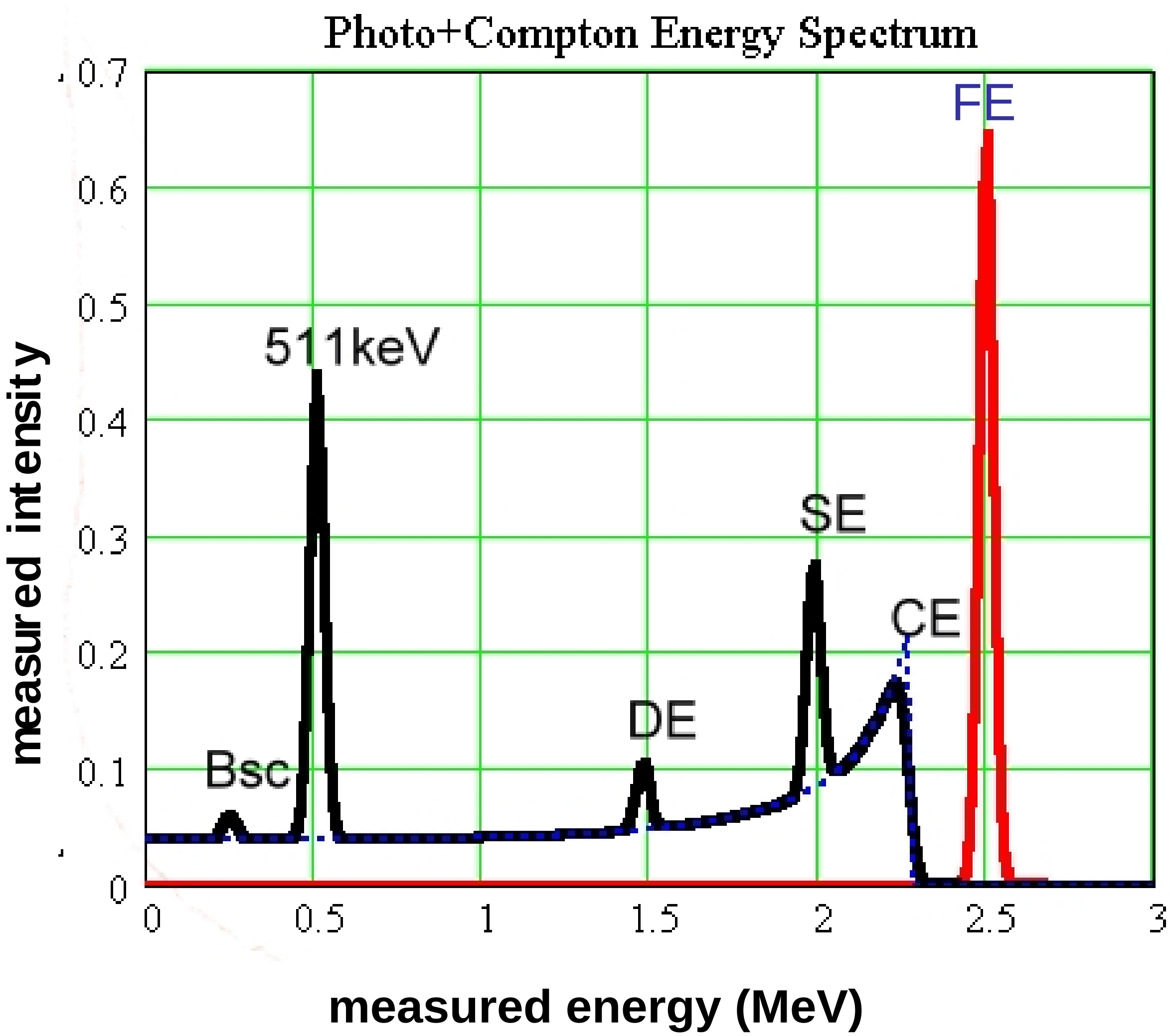
The energy E_γ of an incoming photon can be completely converted into charged particles which are all absorbed by the detector, → measured energy spectrum shows only the full-energy peak (FE, red)
Example: photo effect with absorption of struck e^-

The incoming photon may only scatter off an atomic e^- and then leave the detector → Compton-e^- energy spectrum (CE, dark blue)

An incoming γ-ray may come from back-scattering off materials outside the detector → backscatter bump (BSc)

Shapes of High-Energy γ Spectra

The energy spectra of high-energy g-rays have all of the features of low-energy γ-ray spectra



High-Eγ can lead to e^+/e^- pair production,

e^- : stopped in the detector

e^+: annihilates with another e^- producing 2 γ-rays, each with E_γ = 511 keV.

One of them can escape detector → single escape peak (SE) at FE-511 keV

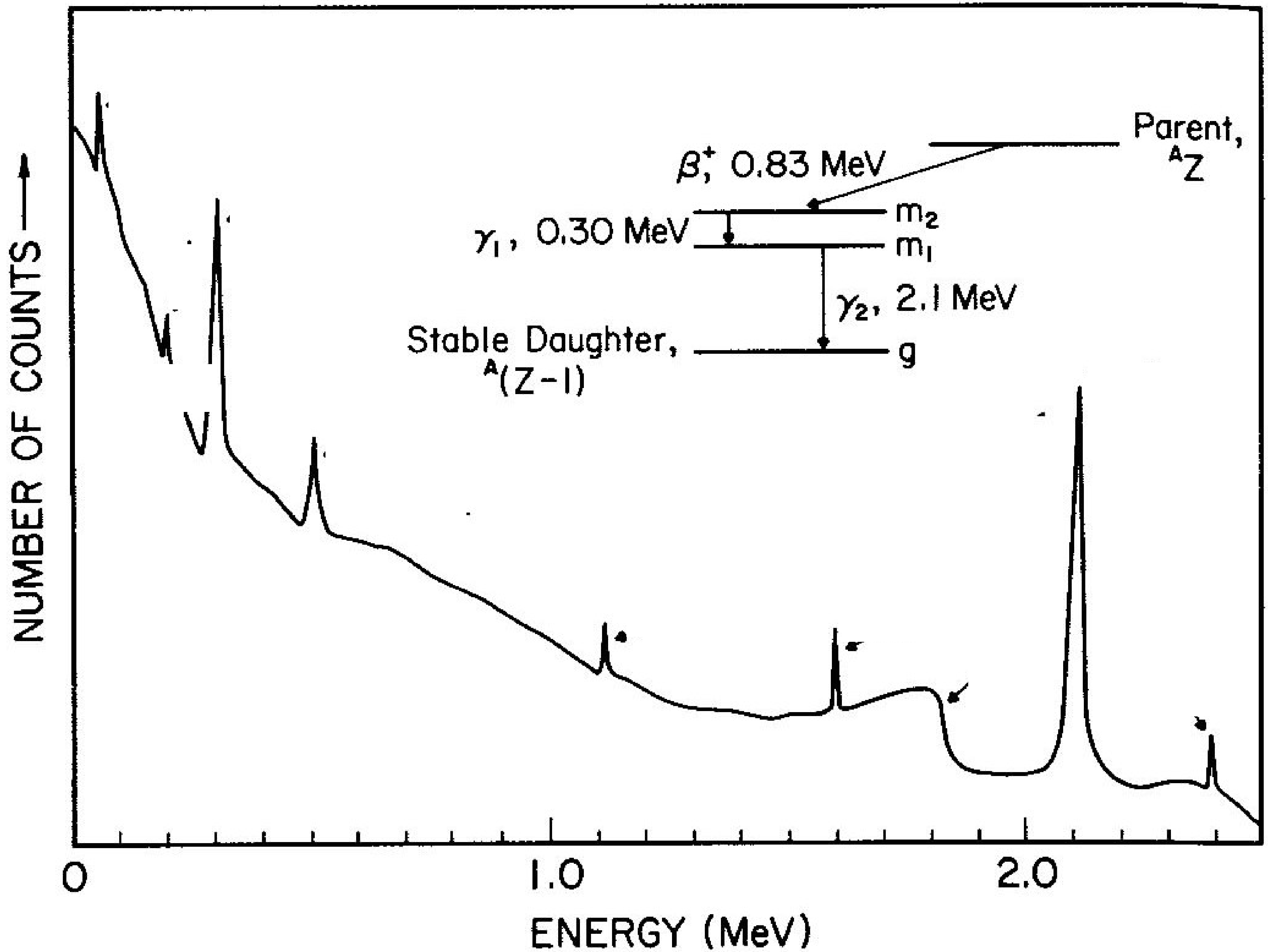
Both of them can escape detector → double escape peak (DE) at FE-1.022 MeV

e^+/e^- annihilation in detector or its vicinity produces 511keV γ-rays

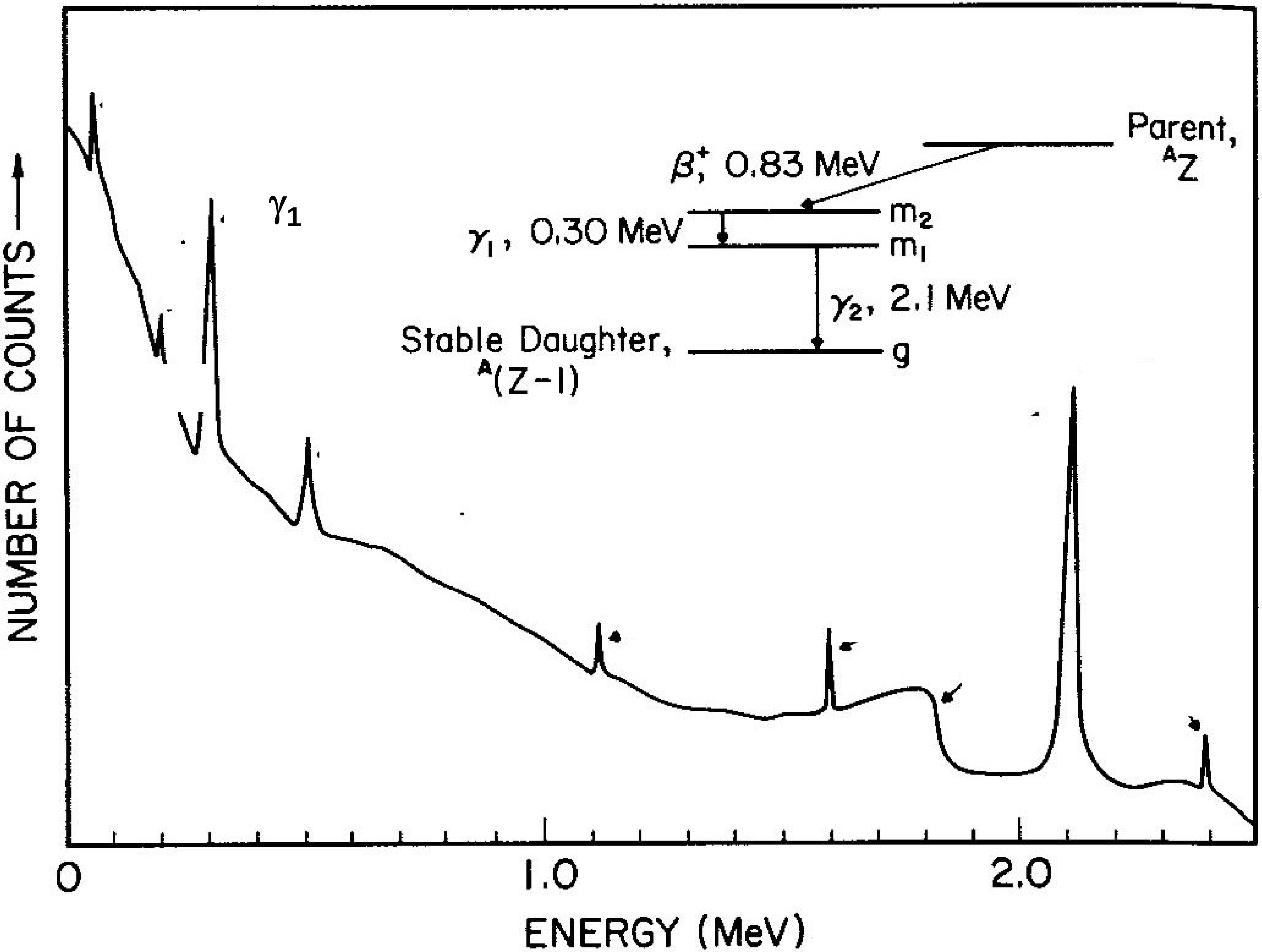
Quiz

- Try to identify the various features of the γ spectrum shown next (well, it is really the spectrum of electrons hit or created by the incoming or secondary photons), as measured with a highly efficient detector and a radio-active ^{A}Z source in a Pb housing.
- The γ spectrum is the result of a decay in cascade of the radio-active daughter isotope $^{A}(Z-1)$ with the photons γ_1 and γ_2 emitted (practically) together
- Start looking for the full-energy peaks for γ_1, γ_2,...; then identify Compton edges, single- and double-escape peaks, followed by other spectral features to be expected.
- The individual answers are given in sequence on the following slides.

Spectrum of γ Rays from Nuclear Decay



Spectrum of γ Rays from Nuclear Decay



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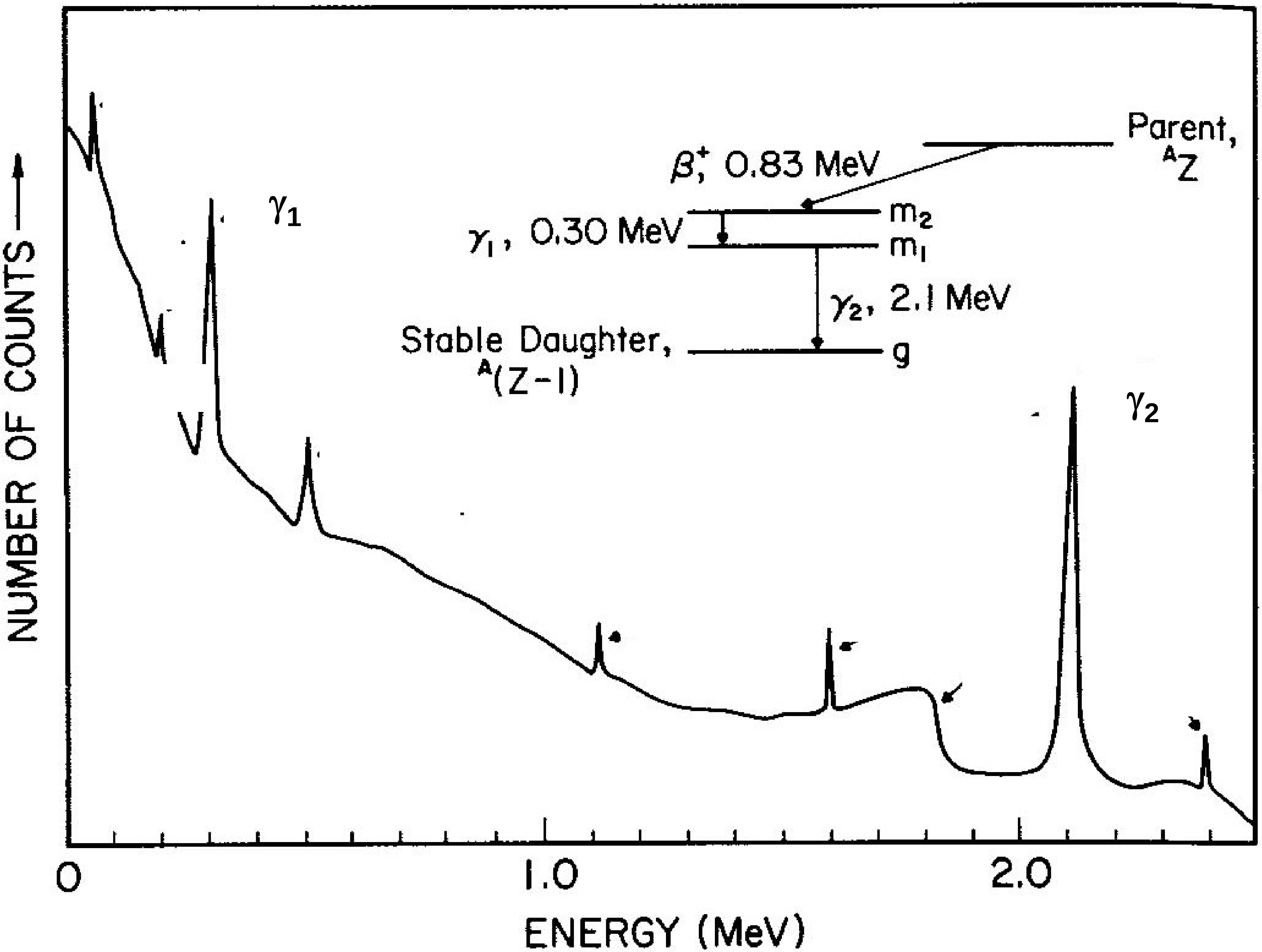
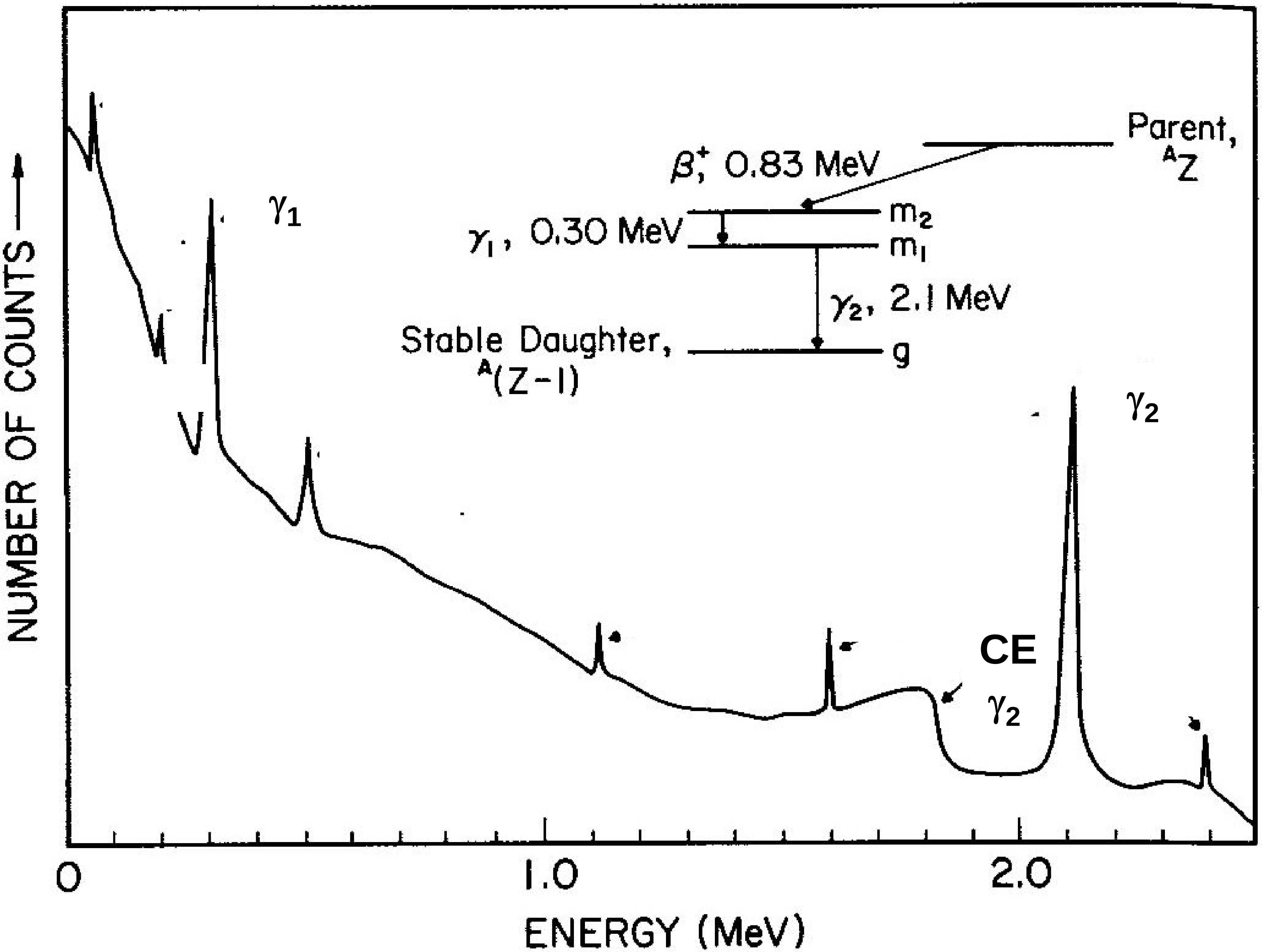
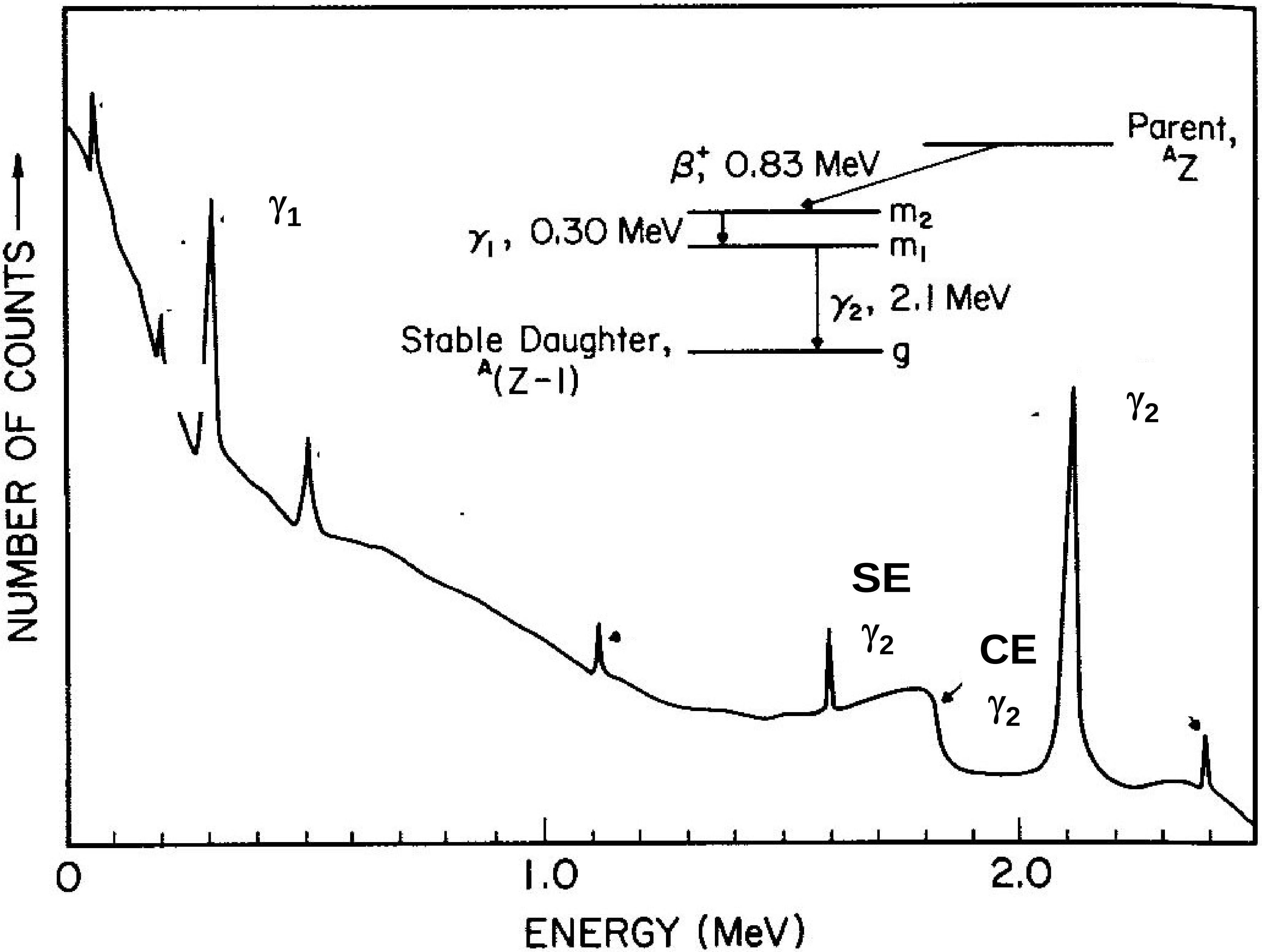


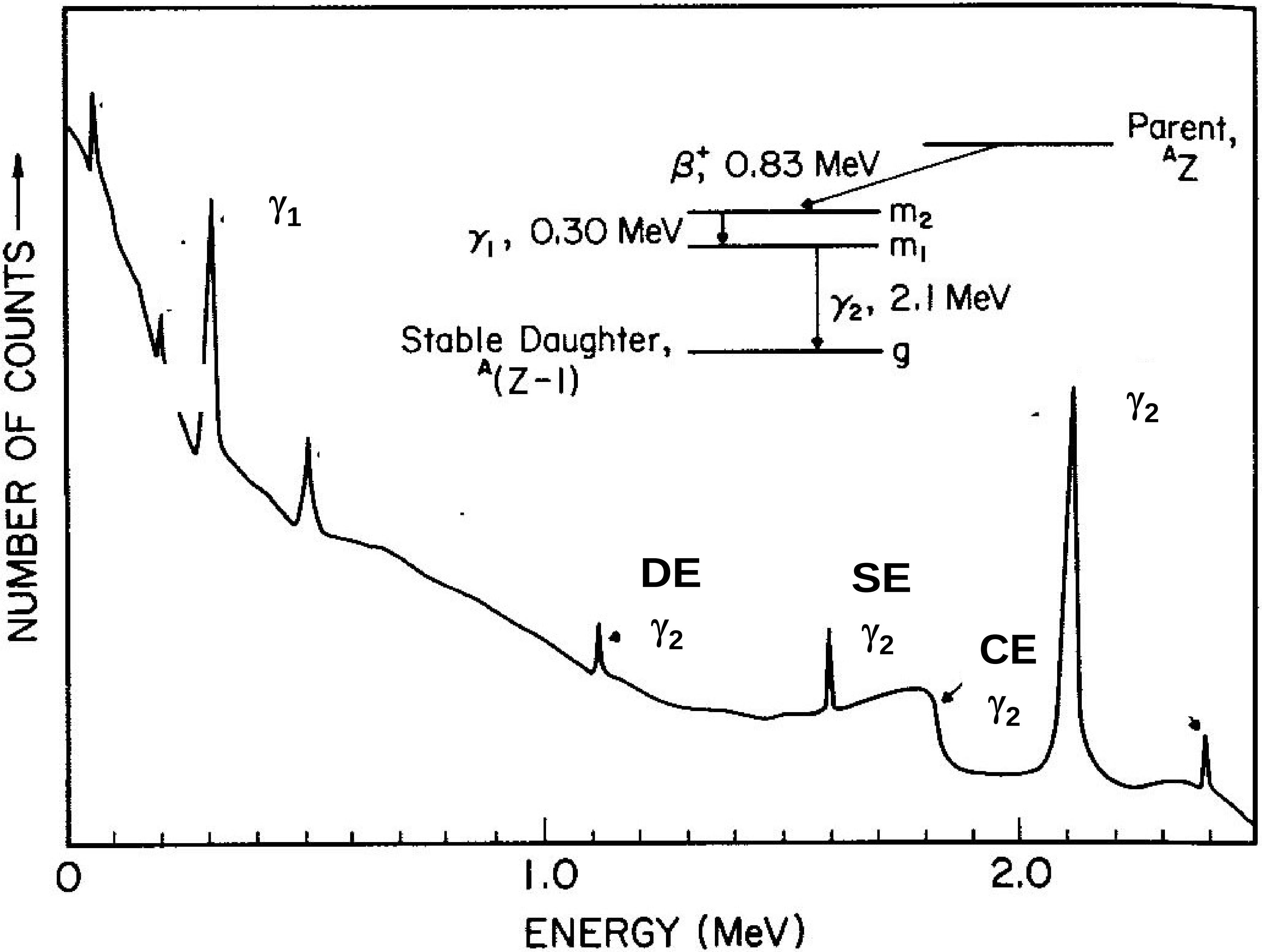
Spectrum of γ Rays from Nuclear Decay



Spectrum of γ Rays from Nuclear Decay



Spectrum of γ Rays from Nuclear Decay



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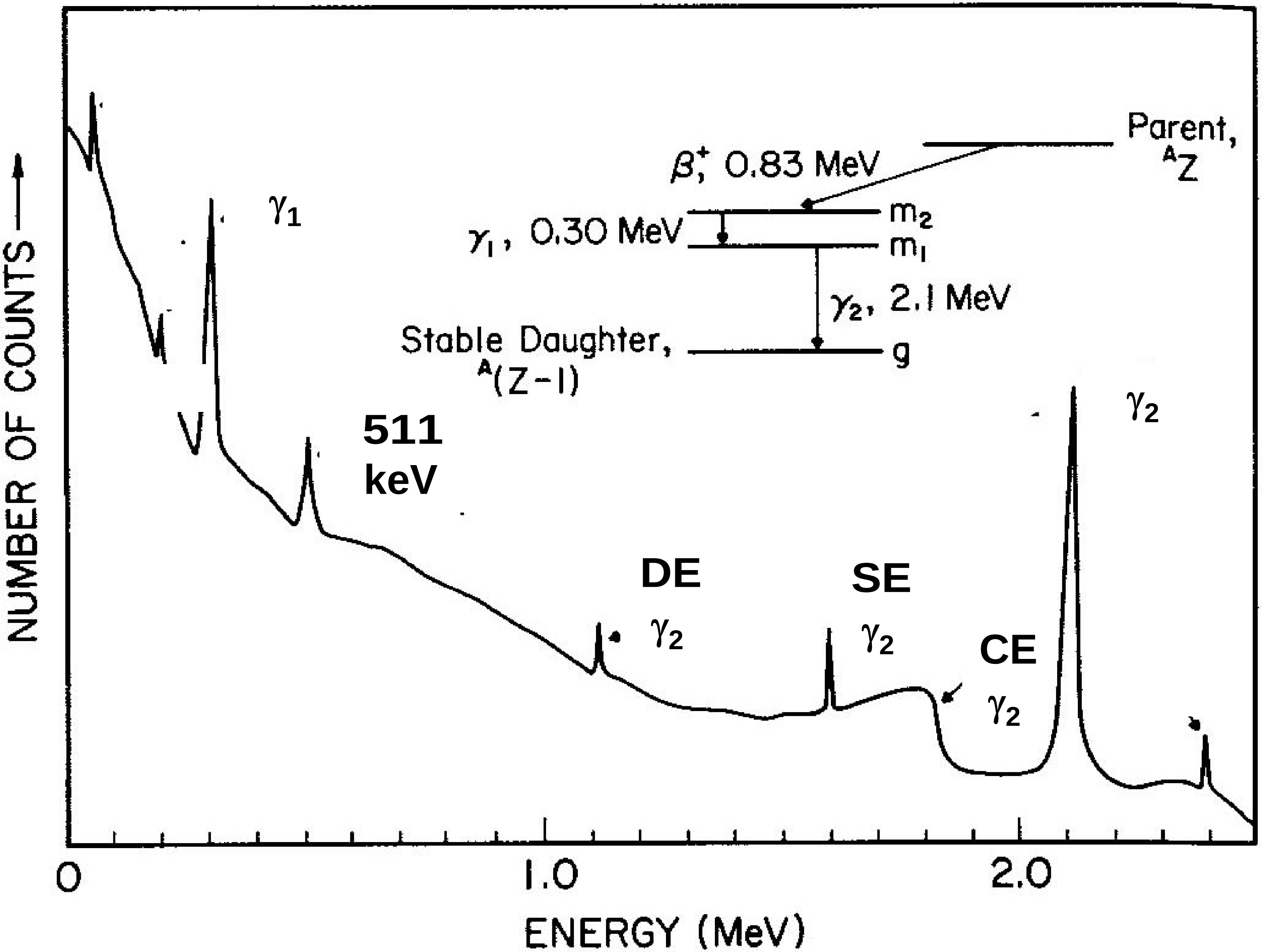

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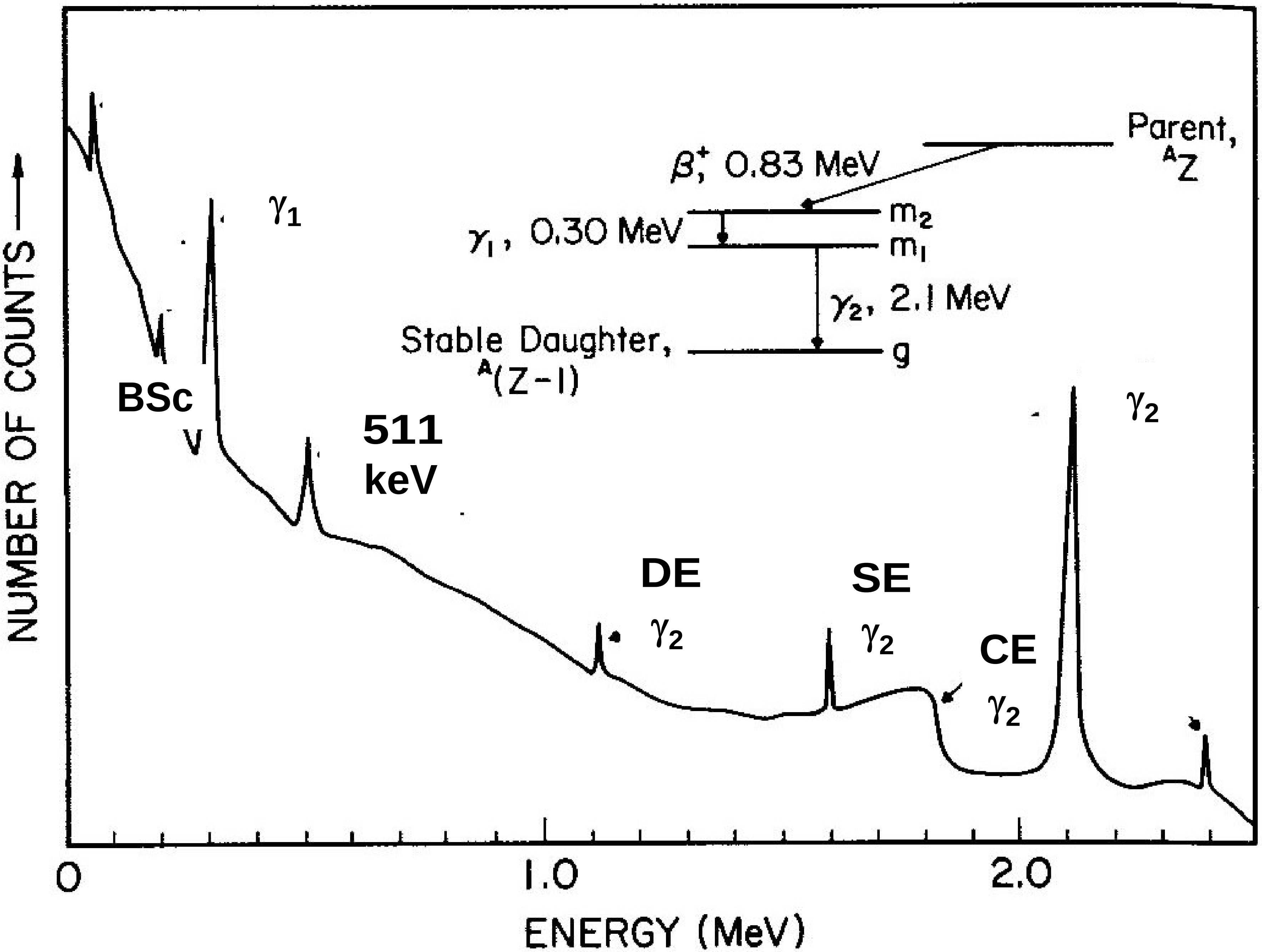
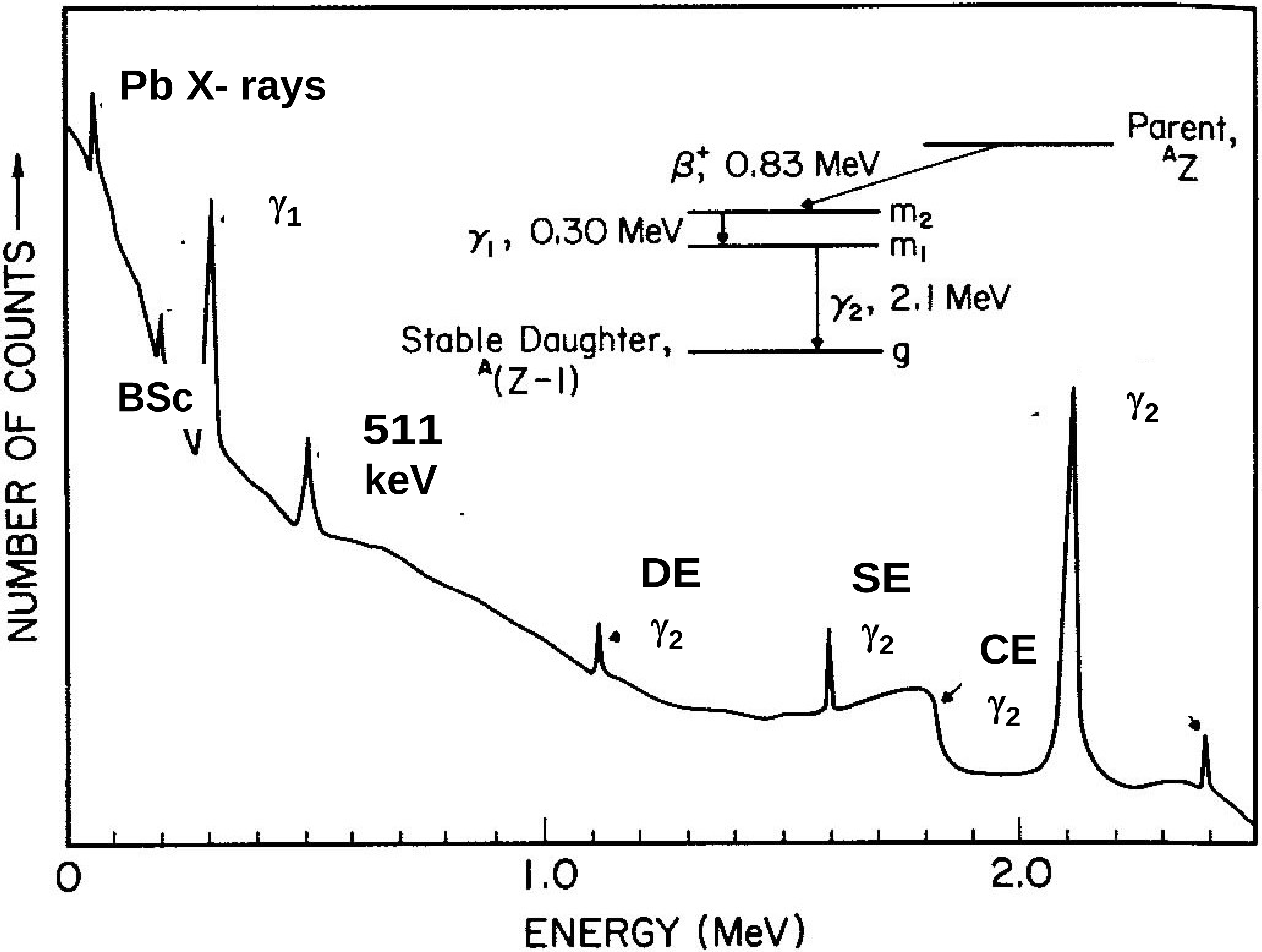
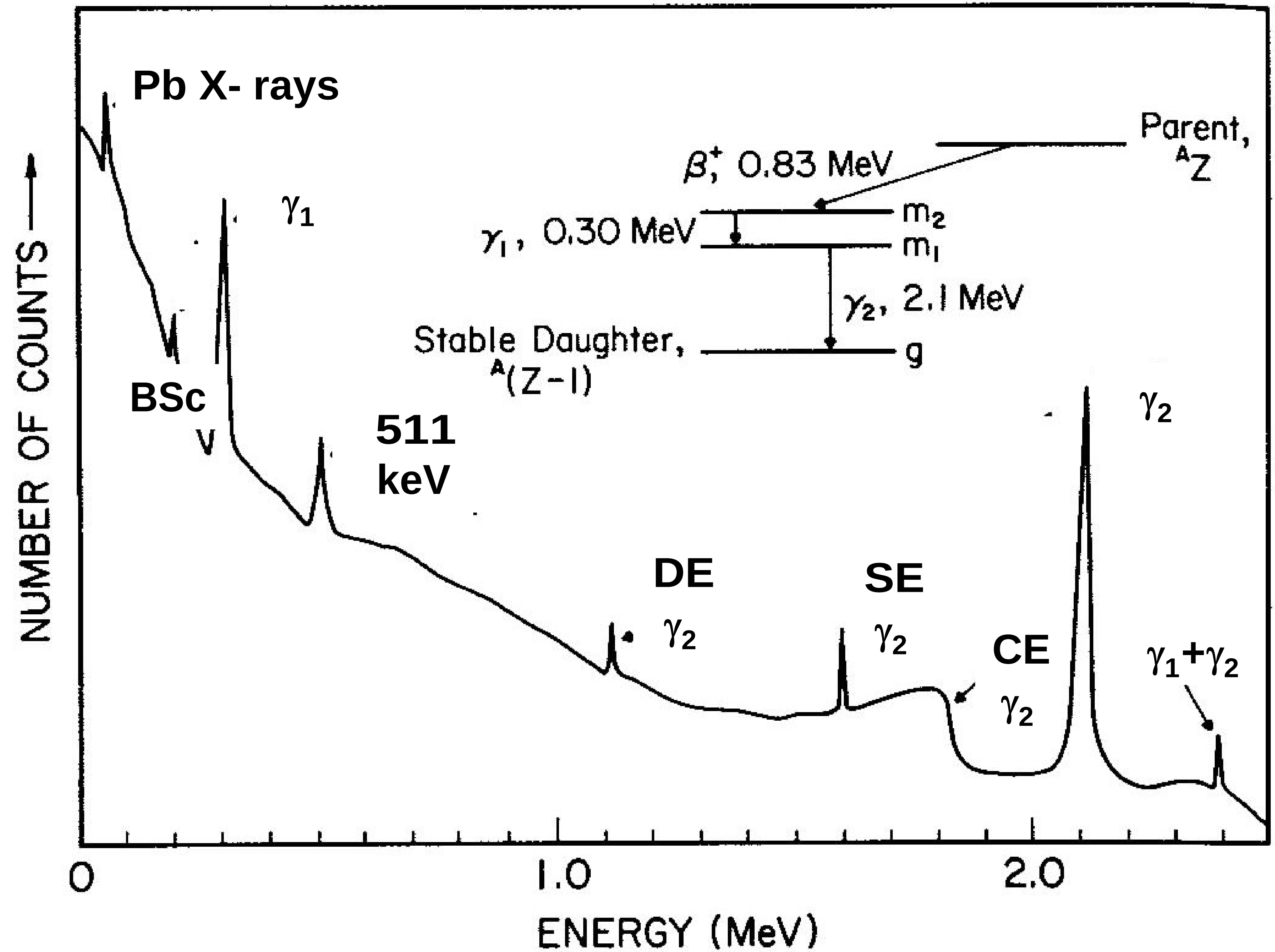


Spectrum of γ Rays from Nuclear Decay



Spectrum of γ Rays from Nuclear Decay



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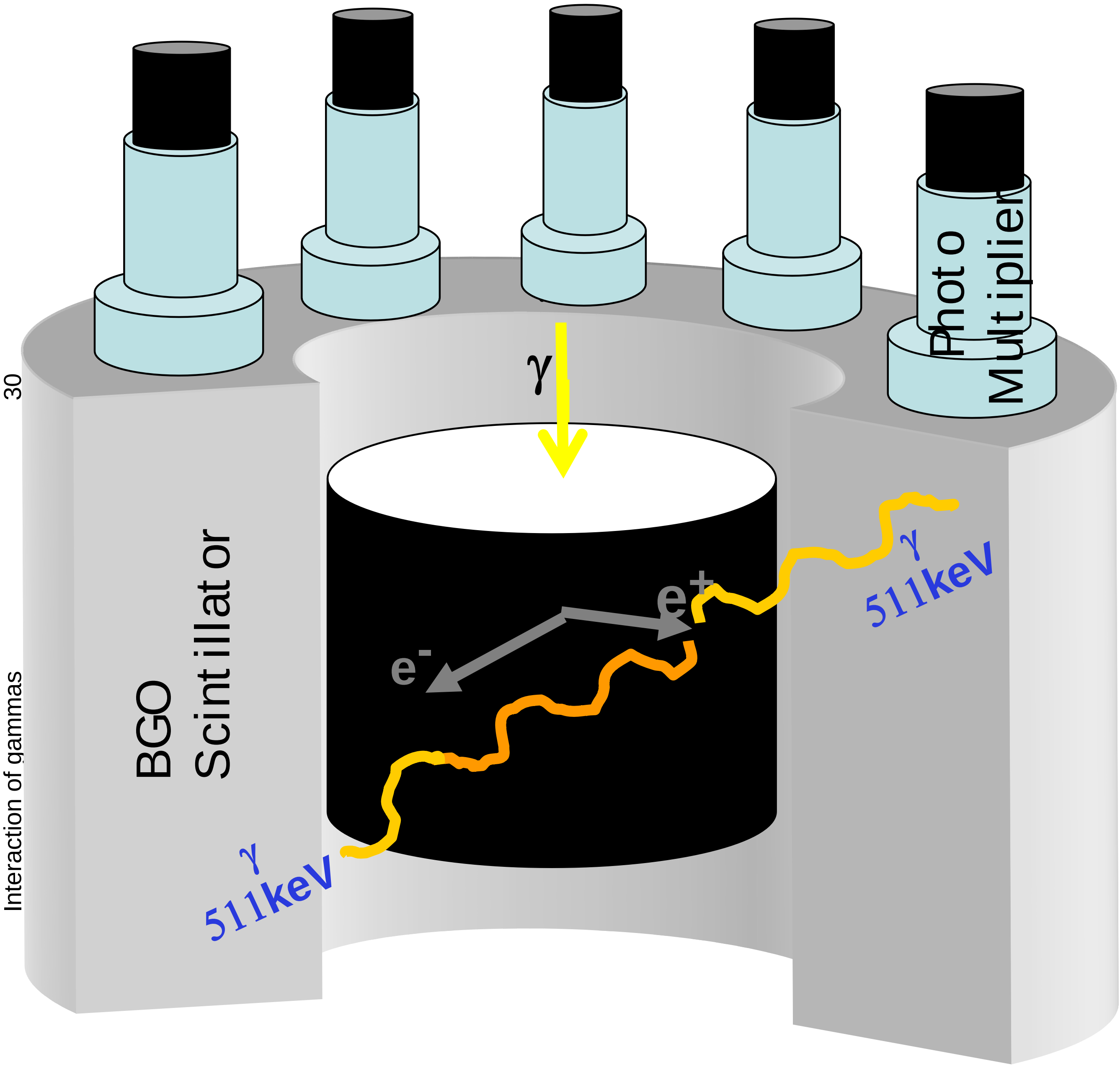
Reducing Background with Anti-Compton "Shields"

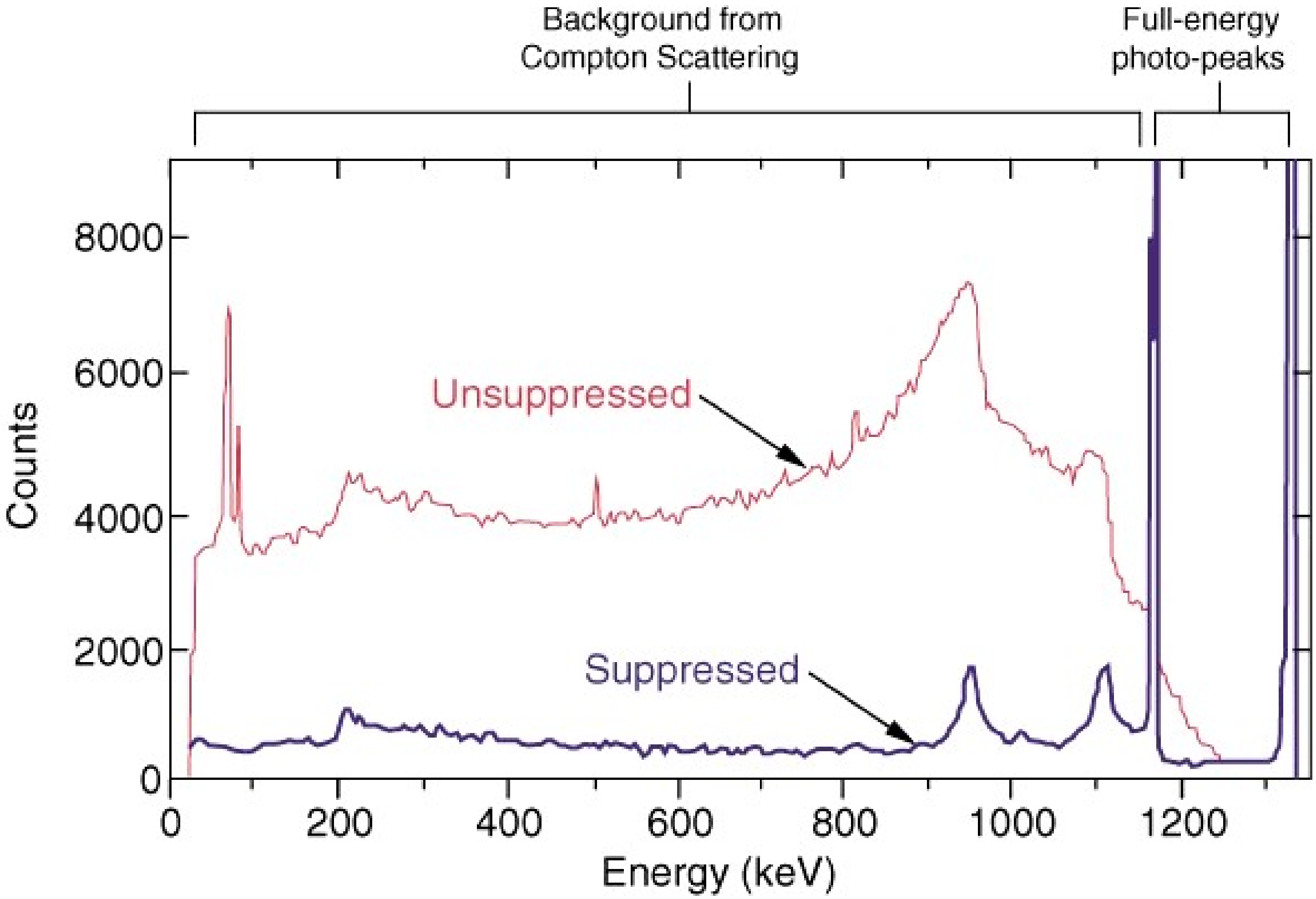


High-energy γ-rays produce e^+/e^- pairs in the primary Ge detector. All e^+ and e^- are stopped in the Ge detector.

e^+ finds an e^- and annihilates with it, producing 2 back-to-back 511-keV photons.

Escaping 511-keV photons are detected by surrounding annular scintillation detector. Escape events are "tagged" and can be rejected.

Compton Suppression Technique



The figure shows a comparison between the "raw" ^{60}Co γ-ray spectrum (in pink) and one (blue) where Compton contributions have been removed.

The disturbing Compton background has been reduced by app. a factor 8 by eliminating all events, where a photon has been detected by the BGO scintillation shield counter in coincidence with a γ-ray in the corresponding inner Ge detector.

γ- Ray/Photon Detectors

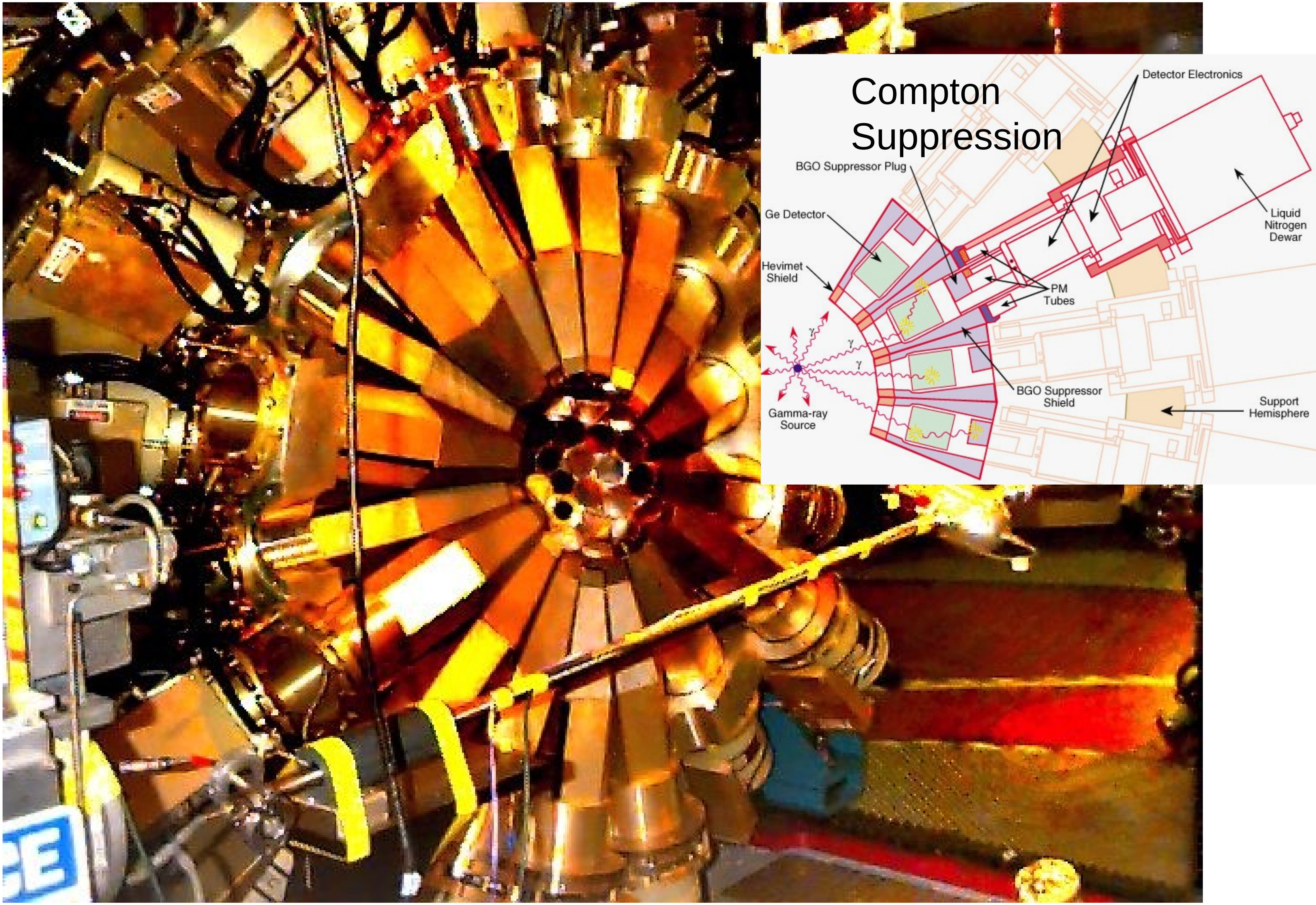
There is a variety of detectors for nuclear radiation, including γ-rays. A special presentation is dedicated to the main detector principles.

The next image shows a section of one of the currently modern γ detector arrays, the "Gamma-Sphere."

The sphere surrounds the reaction chamber on all sides and leaves only small holes for the beam and target mechanisms.

Each element of the array consists of two different detector types, a high-resolution Ge-solid-state detector encapsulated in a low-resolution BGO scintillation counter detecting Compton-scattered photons escaping from the Ge detectors

Modern γ Detectors: "Gammasphere"



The End