ANSEL EXPERIMENT

PHOTON SPECTROSCOPY

ANSEL Experiment: γ/Photon Spectroscopy

- Ubiquitous presence of radiation on Earth, e.g., γ-ray photons
- Concepts of absorption coefficient and cross section
- Intro: γ-interactions with matter
  - Photo electric effect
  - Compton scattering
  - Pair production

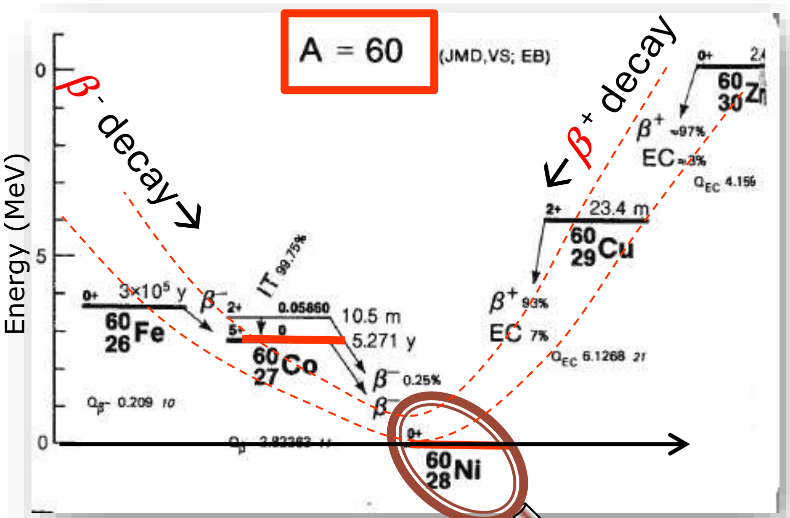
Reading Assignments Weeks Feb 1 & 8, 2026
Textbook G. F. Knoll:

Ch. 2.	III A 1-3, B 1-3	Interaction of γ-rays
Ch 10.	I-III	γ-ray spectroscopy
Ch 8.	I-III	Scintillation Detectors
Ch 9.	I-V,VII	PMTs, signal analysis

- Operational principles of inorganic scintillation detectors
- Examples of energy spectra with NaI(*Tl*) detectors
- Experimental setup with a 3″x3″ NaI(*Tl*) detector
- Lab measurements in Expt. 1, tasks
- Simple electronic signal processing

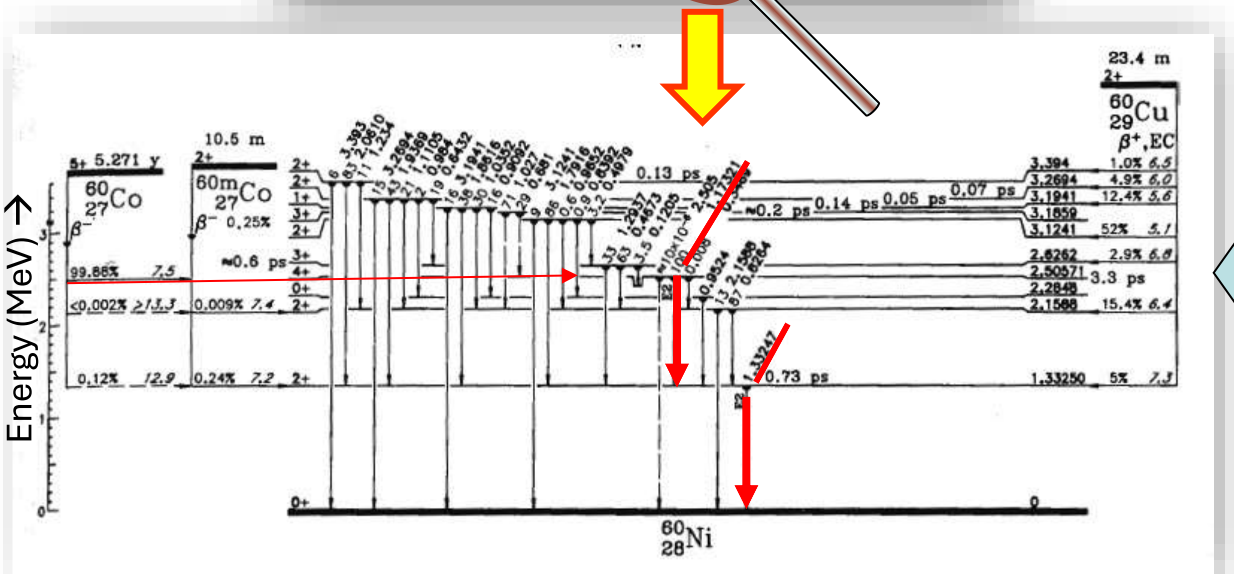
Table of Isotope Information: (Given A=N+Z)

Cobalt-60 source



Information ordered according to mass number A. (Lederer)

Nuclear ground state energies E(Z|A) form a "Mass Parabola" modified by structure effects.



^{60}Ni Level Scheme

γ-Induced Processes in Matter

γ-rays (photons): from electromagnetic transitions between different energy states → detect indirectly via effects in detector (**charged particles, e^-, e^+**)

Detection via secondary particles (e^-,e^+) from:

1. Photo-electric absorption
2. Compton scattering
3. Pair production
4. γ-induced nuclear reactions

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

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

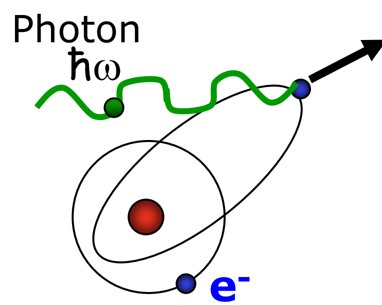
$$Rhc = 13.6\,eV \quad Rydberg\ constant$$

$$screening\ constants$$

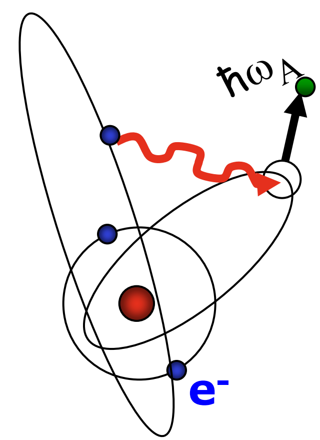
$$\sigma_K \approx 3,\ \sigma_L \approx 5,\ different\ subshells$$

1. Photo-electric absorption

(Photo-effect)

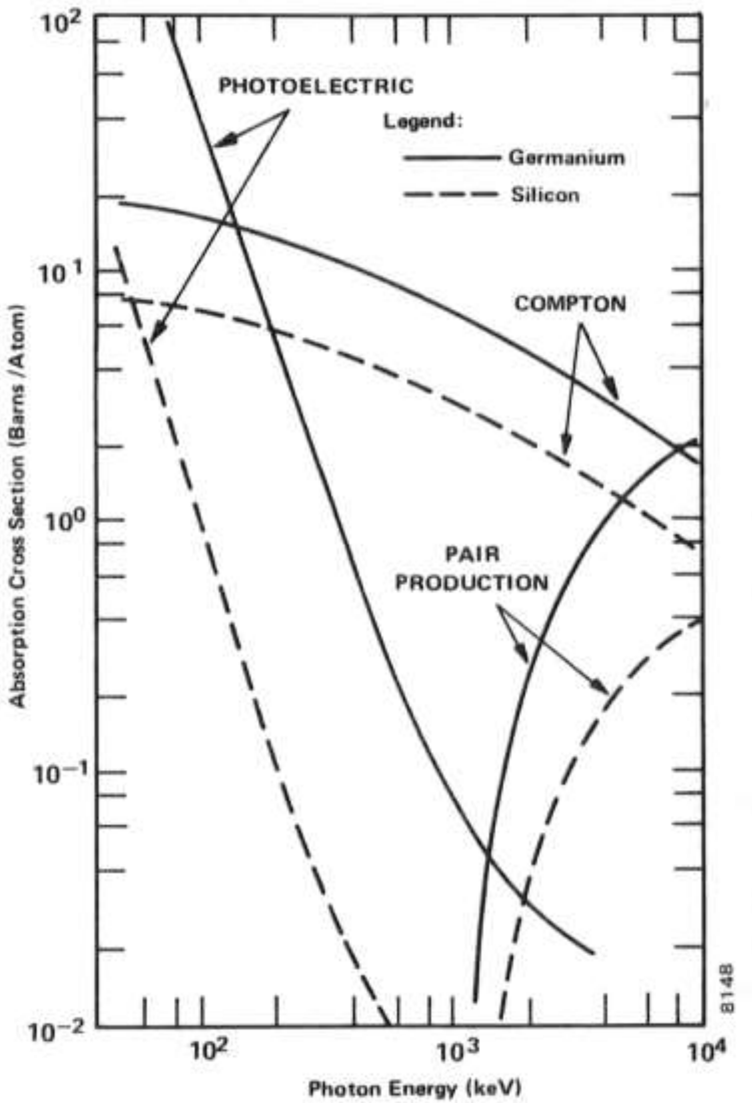


photon is completely absorbed by e^-, which is ejected from atom, creating vacant orbits



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

Efficiencies of γ-Induced Processes



Different processes are dominant at different γ energies and for different materials: ($1b = 10^{-24}$ cm^2)

Photo absorption at low E_γ

Pair production at high $E_\gamma > 5$ MeV

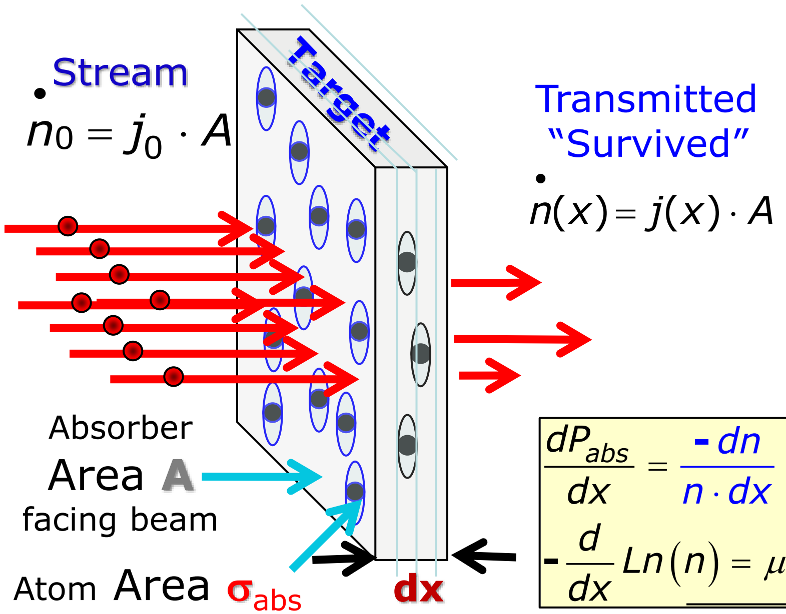
Compton scattering at intermediate E_γ.

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

Interaction Probability/Atom (=*Cross Section*)



$$\frac{dP_{abs}}{dx} = \frac{-dn}{n \cdot dx} = -\frac{d}{dx} Ln(n) = \mu(\cdots)$$

Assumption: absorption coefficient $\mu(x) \approx$ const.

Transmitted (survived)

$$n(x) = n_0 \cdot e^{-\mu \cdot x} \rightarrow \dot{n}(x) = \dot{n}_0 \cdot e^{-\mu \cdot x}$$

$$P_{abs}(x) = \mu x = \left[\frac{\#\,atoms/x}{in\,absorber}\right] \bullet \left(\frac{P_{absorption}\,/}{abs\ atom}\right) \bullet \begin{pmatrix} Random \\ medium \\ depth\ x \end{pmatrix}$$

$$\mu x = \left[\left(\frac{L}{M_{abs}}\right) \cdot (\rho_{abs} \cdot A \cdot x)\right] \bullet \left(\frac{\sigma_{abs}}{A}\right)$$ ← Atomic cross section "area"

$$\boldsymbol{\mu} = (L/M_{abs})\rho_{abs} \cdot \boldsymbol{\sigma}_{abs}$$ abs. coeff. =#atoms·σ/Vol

Thin-absorber approximation: $(\mu \cdot x \ll 1)$

$$\dot{n}(x)_{absorbed} = \dot{n}_0 - \dot{n} = \dot{n}_0 \cdot \left(1 - e^{-\mu \cdot x}\right)$$

$$\dot{n}_{absorbed} \approx \dot{n}_0 \cdot (\mu \cdot x) = \frac{\dot{n}_0}{A} \cdot \left(\left(\frac{L\rho_{abs}}{M_{abs}}\right) A \cdot x\right) \sigma_{abs}$$

$$\approx j_0 \cdot N_{abs} \cdot \sigma_{abs}$$ *stream current density j*

Absorption occurs upon photon "hit" atom within cross section area σ_{abs}

- j_0, j stream current density (#part/time·area)
- A area illuminated by stream
- L = 6.022 10^{23}/mol Loschmidt#(Avogadro)
- N_{abs} # absorber nuclei in stream
- M_{abs} absorber molar weight
- ρ_{abs} absorber mass density (g/cm^3)
- x absorber linear thickness

[σ]=***1barn = 10^{-24}cm^2***

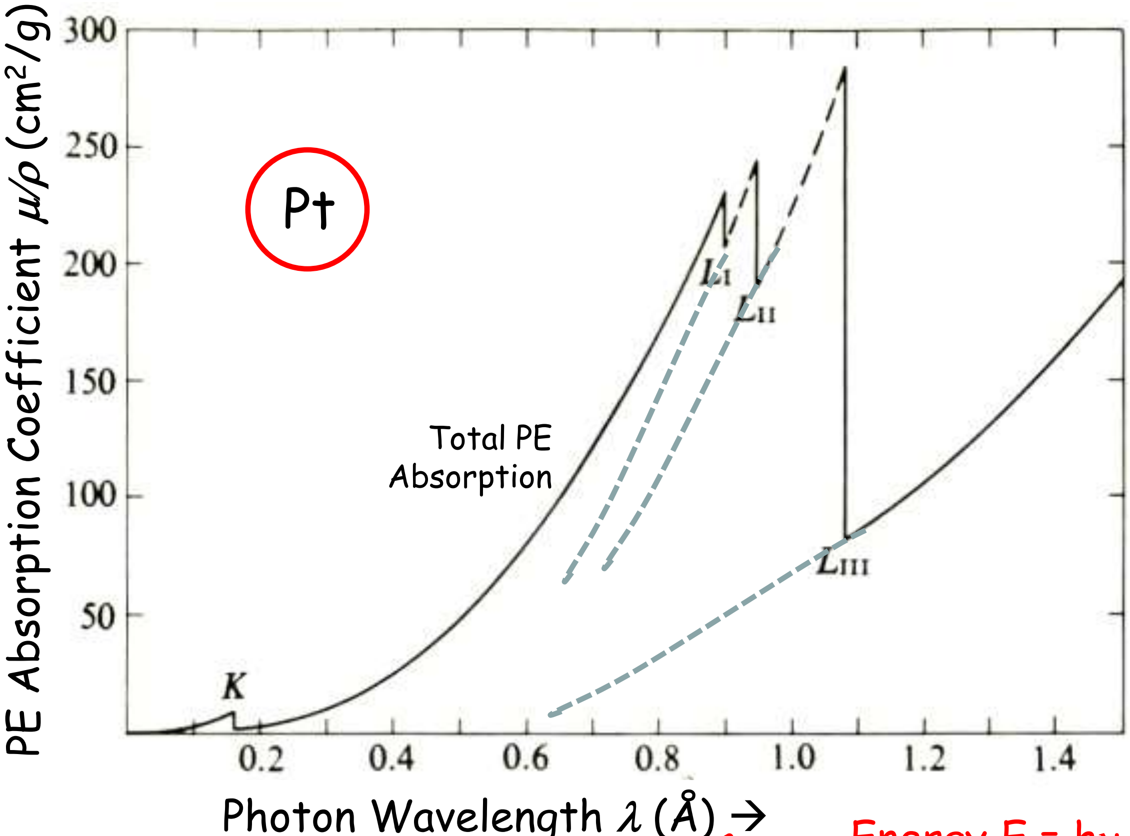
Elementary absorption cross section of one atom

$$\sigma_{abs} = \frac{\dot{n}_{absorbed}}{N_{abs} \bullet j_0}$$

observe sum effect → $\sigma_{abs} = \sum_i \sigma_{abs}(i)$ (*process i*)

1. Photo-Absorption Coefficient

Absorbance $A := Ln(n_0/n) = \mu(E)\cdot x = (\mu(E)/\rho)\cdot(\rho x)$ *Areal mass density* $\rho \cdot x$, $\mu(x) = const.$



Energy $E_\gamma = h\nu$

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:

$$\mu^{PE}(E_\gamma) = \mu_K^{PE}(E_\gamma) + \mu_L^{PE}(E_\gamma) + \dots.$$

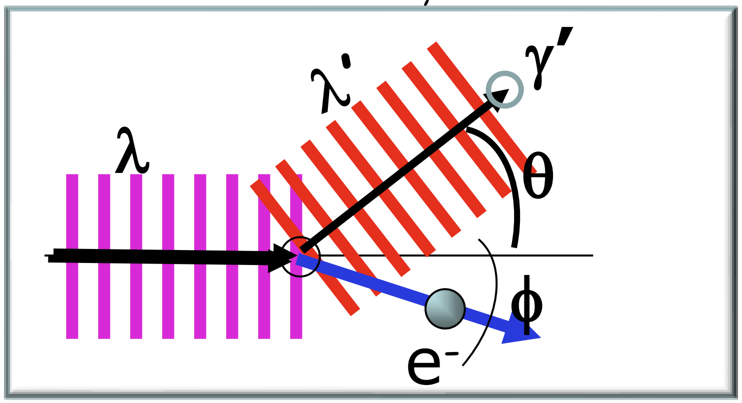
$$\sigma_{PE}(E_\gamma, Z) \propto Z^5 \cdot E_\gamma^{-7/4} \quad low\ E_\gamma$$

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

2. Photon-e$^-$ Scattering (Compton Effect)

$Relativistic\ E^2 = (pc)^2 + (m_0c^2)^2 \rightarrow E_\gamma = \hbar\varpi_\gamma = p_\gamma c$

$photons: m_0 = m_\gamma = 0$



Momentum conservation:

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

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

Energy conservation (initial = final):

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

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

"Compton wave length λ_C"

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

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

$Electron\ rest\ mass\ m_ec^2 = 0.511 MeV$

Compton cross section $\sigma \propto Z$ (# of e$^-$ per atom)

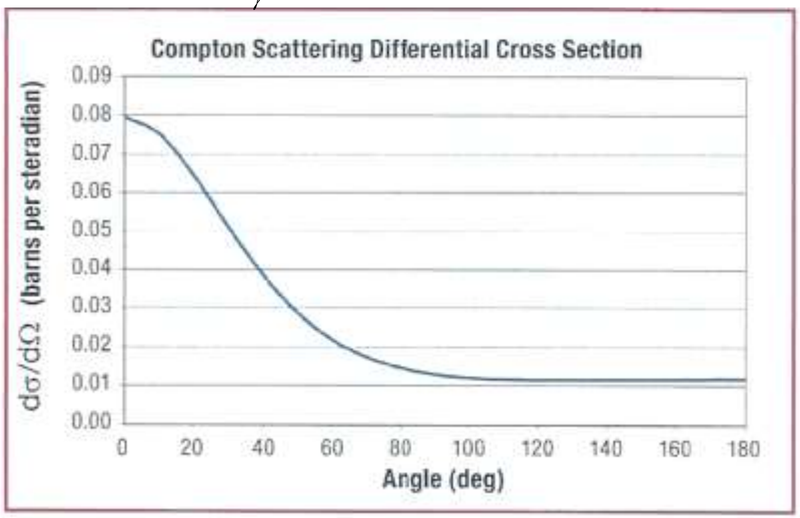
Compton Scattering Distributions

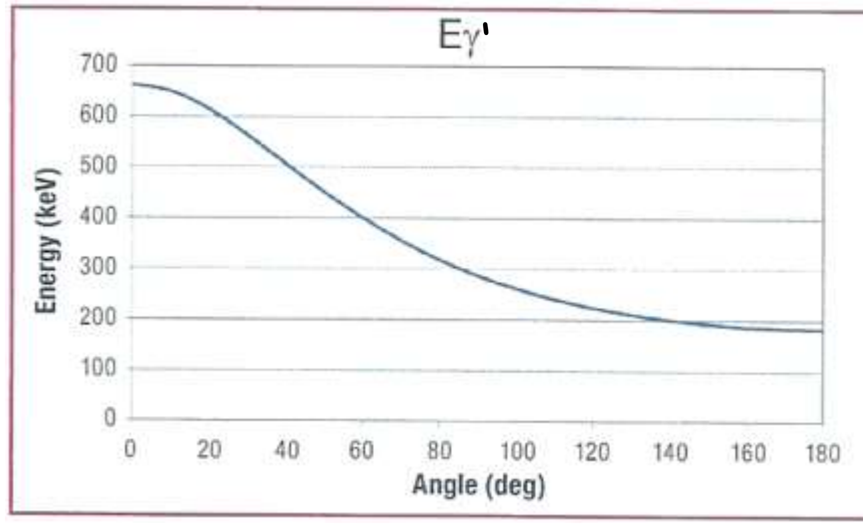
Klein-Nishina Formula

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{r_0^2}{2}\left\{\frac{1+cos^2\theta}{[1+\alpha(1-cos\theta)]^2}\right\}\left\{1+\frac{\alpha^2(1-cos\theta)^2}{[1+cos^2\theta][1+\alpha(1-cos\theta)]}\right\}\left[\frac{m^2}{sr}\right]$$

$r_0 = 2.82 \times 10^{-15}$ m, the classical electron radius, and for ^{137}Cs $\Rightarrow \alpha = \frac{E_\gamma}{m_e c^2} = \frac{662\ keV}{511\ keV} = 1.29$

$Cs-137:\ E_\gamma = 662\,keV$



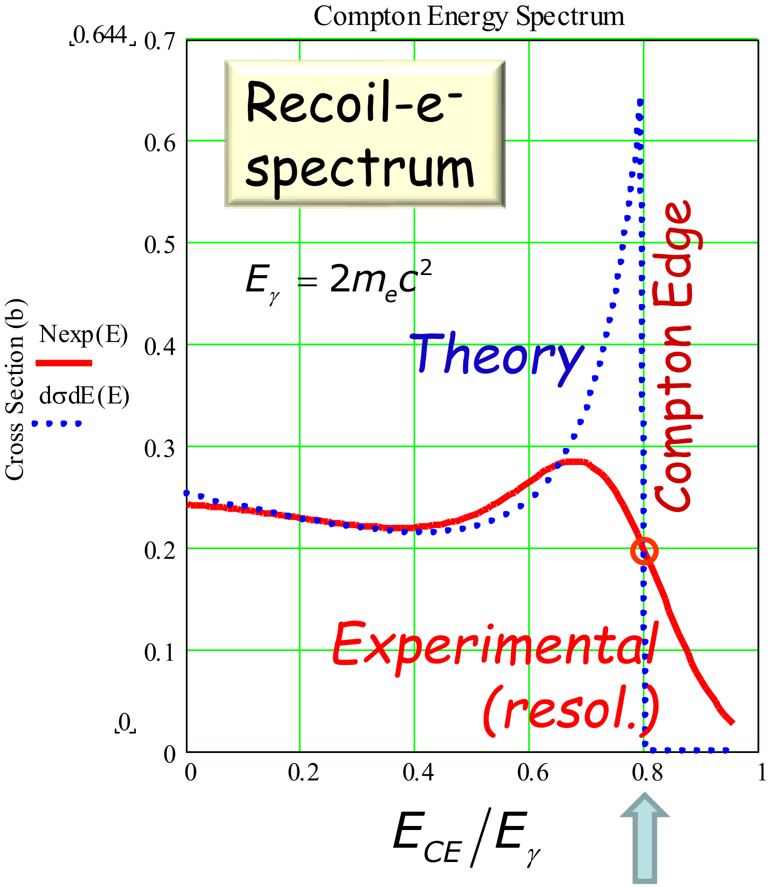


Unit of differential cross section

$[\,] = 10^{-28}\,m^2/sr = b/sr$ *(barn per steradian)*

Compton Recoil Electron Spectrum

Detected are **not** photons but recoil-electrons !



Scattered − photon energy. θ = *photon angle*

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

Scattered recoil − electron energy:

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

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

("*Backscatter*") $$E_{\gamma'} = \frac{E_\gamma}{1+2E_\gamma/m_ec^2}$$

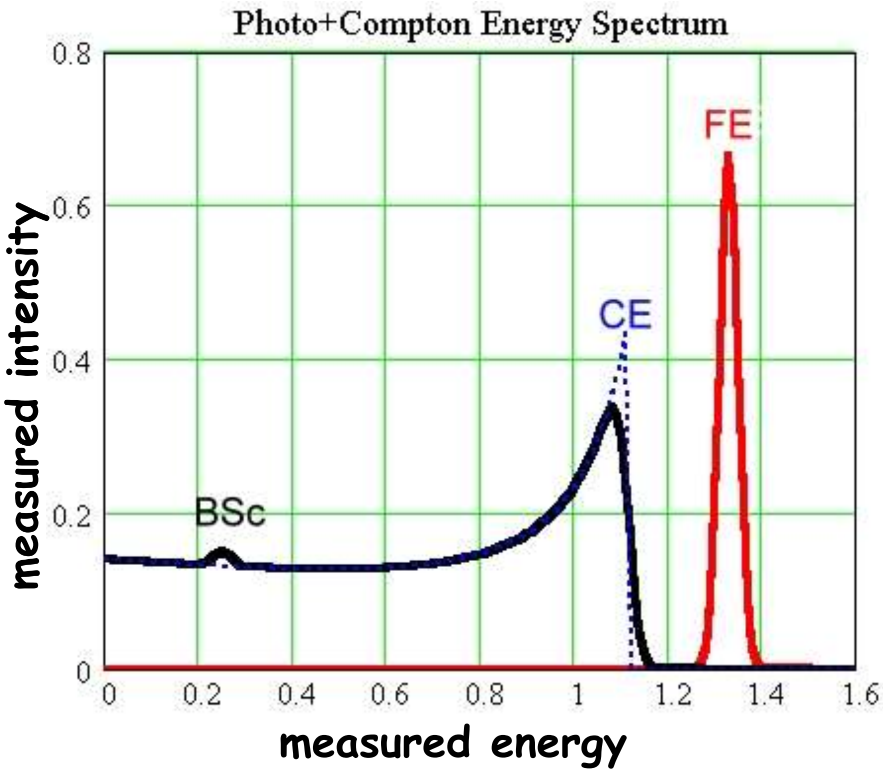
Maximum electron energy (Compton Edge):

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

Compton electron energy distribution.

Shapes of Low-Energy "γ" (e^- Recoil) 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.



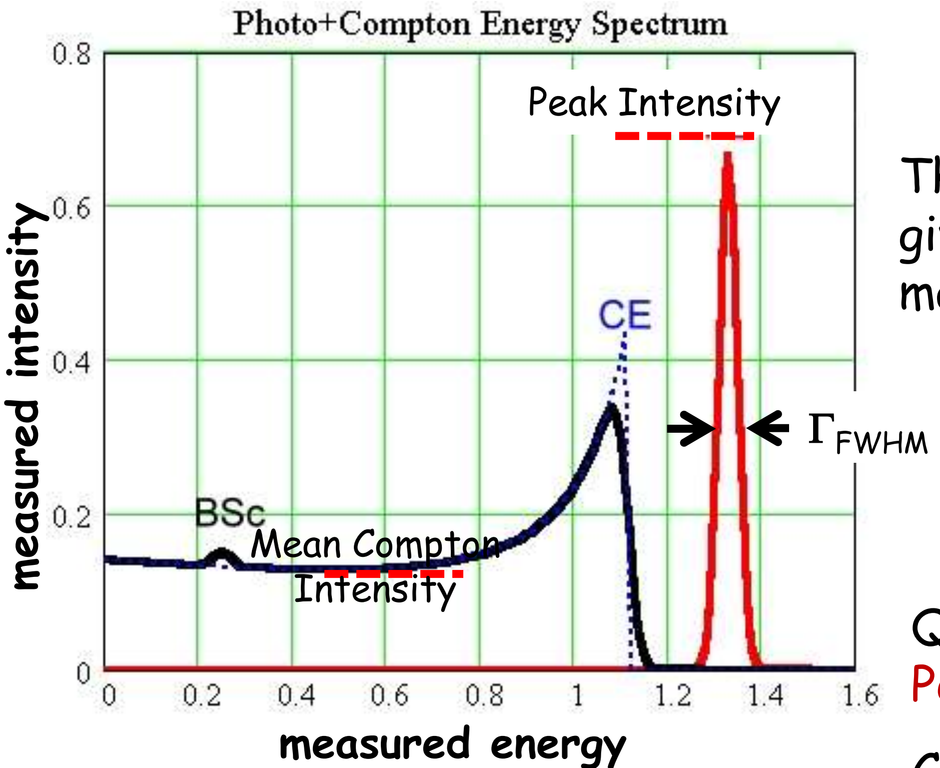
The energy E_γ of an incoming photon can be ≈completely converted into charged particles which are all absorbed by the detector, → measured energy spectrum shows only the full-energy peak (FE, red) *Example*: photo effect with absorption of struck e^-

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 Low-Energy "γ" (e^- Recoil) Spectra

Photons/γ-rays are measured only via their interactions with charged particles, mainly with the electrons of the detector material. Best response of detector is in Full Energy peak, Compton effect distributes response



$$0 \le E_e \le CE$$

The energy resolution of the detector is given by the full width Γ_{FWHM} at half maximum of the measured γ line.

$$\Gamma_{FWHM} = 2.35 \cdot \sigma$$

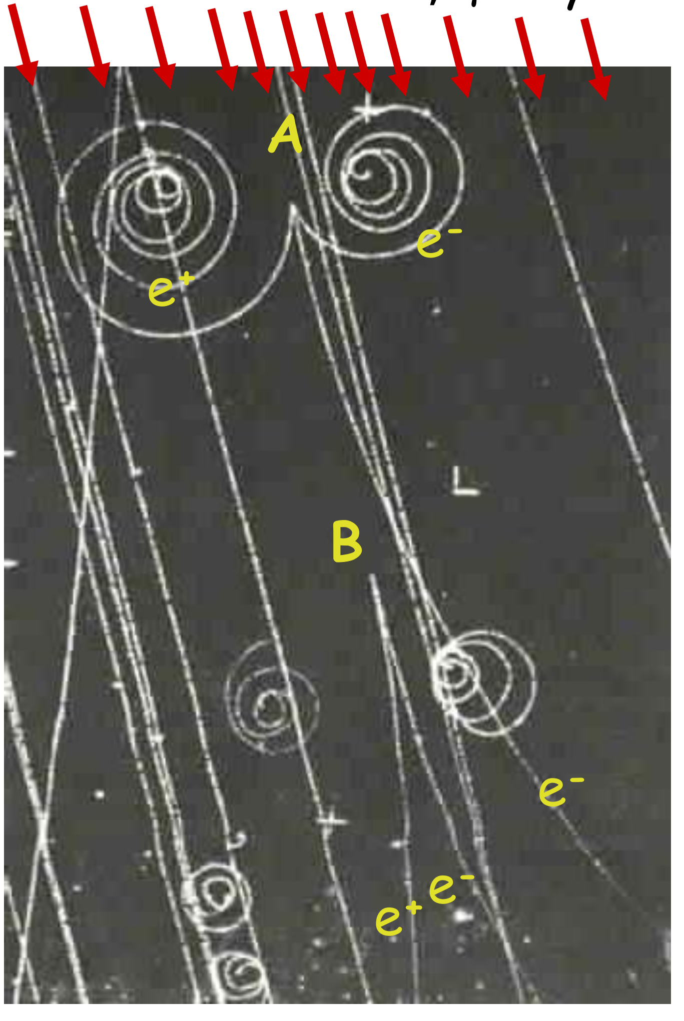
σ = standard deviation, width of Gaussian fit

Quality measure of practical use: Peak-to-Compton Ratio P/C.

C defined by flat region in spectrum

3. Pair Creation by High-Energy γ-rays

Neutral radiation, γ-rays



Magnetic field

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

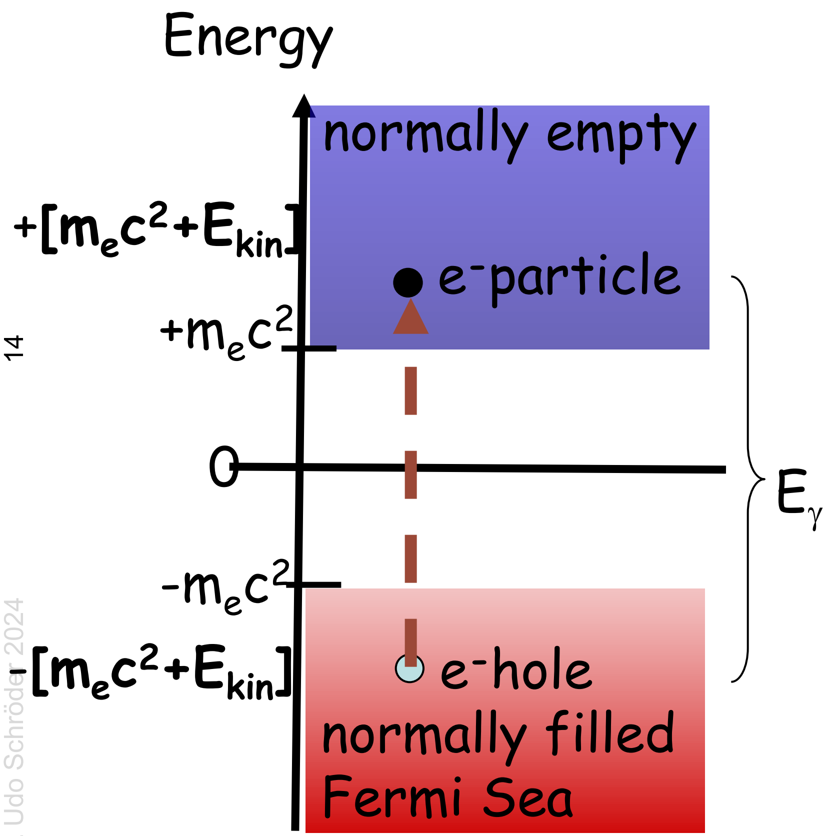
Magnetic field provides momentum/charge analysis

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, $E \leq -mc^2 < 0$

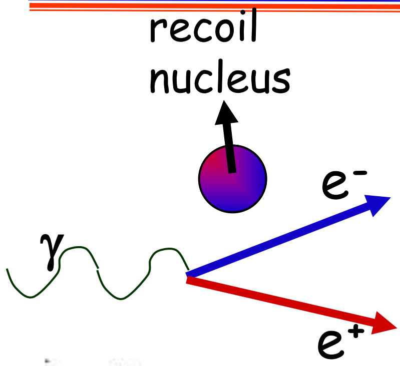
Electromagnetic interactions can lift a particle from the Fermi Sea across the energy gap **$\Delta E=2\ mc^2$** into the normal world → particle-antiparticle pair

Holes in Fermi Sea: Antiparticles

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

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

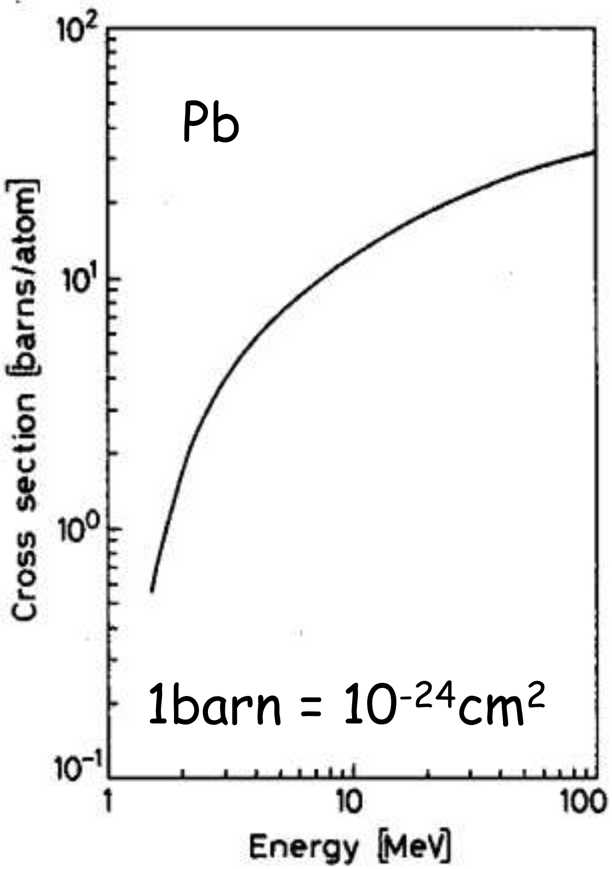
The Nucleus as Collision Partner



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

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

Excess momentum **requires presence of nucleus** as additional charged body.



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

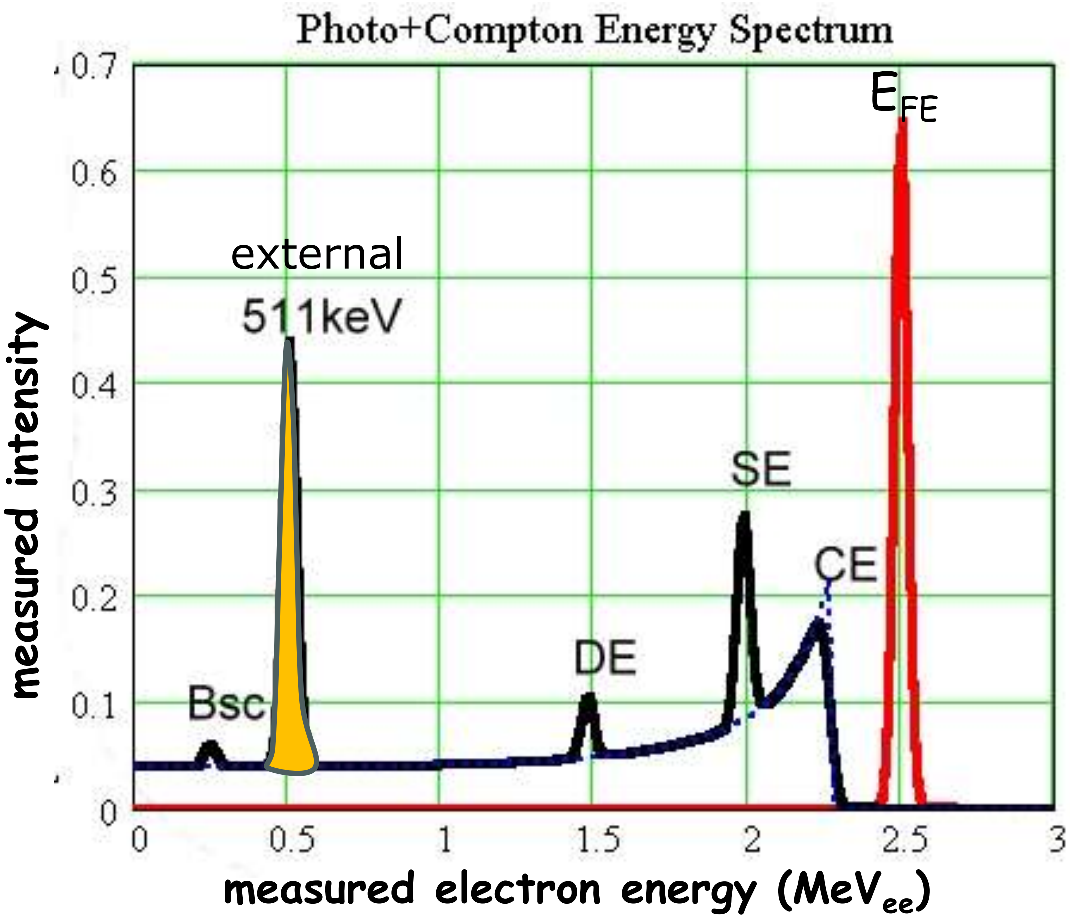
$$P\ slowly\ varying\ with\ energy, Z$$

Increase with E_g because interaction sufficient at larger distance from nucleus

Eventual saturation because of screening of charge at larger distances

Shapes of High-Energy "γ" (e^- Recoil) Spectra

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



High-Eγ can lead to e^+/e^- pair production (inside detector or in surroundings of source),

e^-: stopped in the detector, deposits its energy

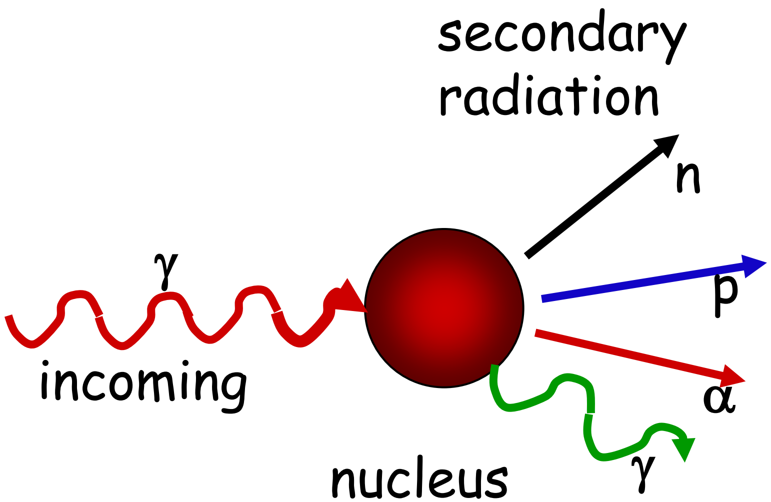
e^+: annihilates with another e^- producing 2 γ-rays, each with E_γ = 511 keV.

One of the 511 keV escapes detector → single escape peak (SE) at $E_{SE} \backsimeq E_{FE}$-511 keV

Both of them escape detector → double escape peak (DE) at $E_{DE} \backsimeq E_{FE}$-1.022 MeV

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

4. γ-Induced Nuclear Reactions



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

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.

Task

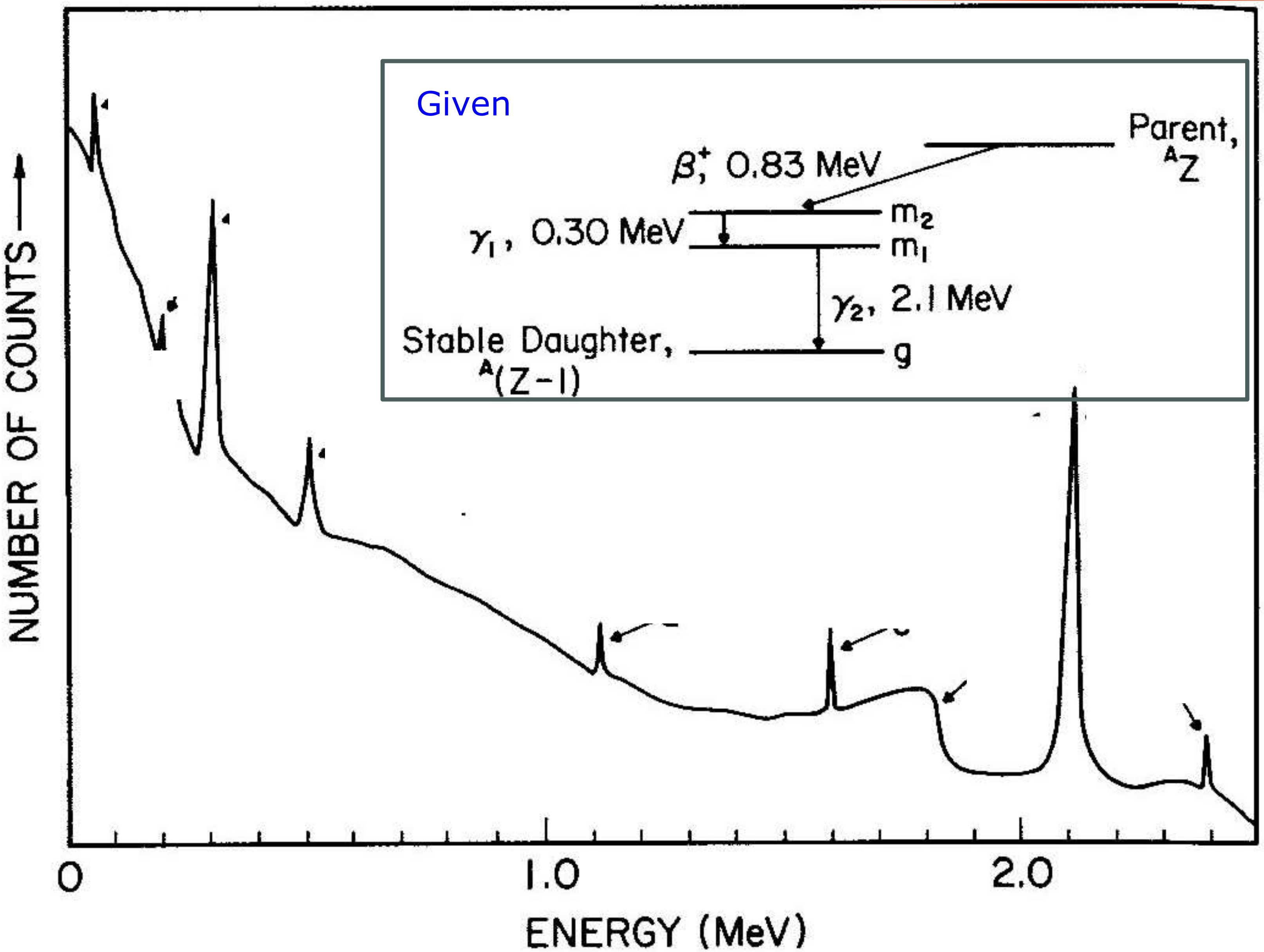
- Try to identify the various features of the γ spectrum shown (it is really the spectrum of electrons hit or created by the incoming or secondary photons), as measured with a highly efficient detector and a radio-active ^{A}Z source in a Pb housing.

- The γ spectrum is the result of a decay in cascade of the radio-active daughter isotope $^{A}(Z\text{-}1)$ 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 a set of slides.

Task: Identify Spectral Components



Data Analysis Expt. Photon Spectroscopy

1. Compare measured count rates with expectations based on source half lives.
2. Identify in the measured spectra for the three known sources the prominent spectral features and correlate their channel positions (ch#) with the known energies (E_γ or E_{CE}). Perform IGOR fits of main γ lines, track experimental errors. Use Gaussians for γ lines and half-Gaussians for Compton edges.
3. Generate a calibration table and a plot of energies of the positively identified prominent spectral features from the three known sources (^{22}Na, ^{60}Co, ^{54}Mn) *vs.* the experimental channel numbers for these features.
4. Perform a least-squares fit for the calibration data E_γ(ch#) and include the best-fit line in the calibration table and plot.
5. Generate plots of all measured energy spectra as Counts/keV *vs.* Energy(keV).
6. Identify the γ-ray energies of prominent features in the spectrum for the unknown source. Based on the γ-ray energy tables (provided in the ANSEL Twiki pages), suggest the identity of the unknown source (or source mix).
7. Identify the γ-ray energies of prominent features in the spectrum for the room background. Based on known γ-ray energies, identify several components.
8. Measure the peak-to-Compton ratio of the detector for a high-energy γ-ray.
9. Determine the energy resolution of the detector as function of E_γ.
10. Determine the attenuation of two γ-rays with different energies and X-rays by Al and Pb absorbers. Compare your results to published data (NIST).