# ANSEL EXPERIMENT 1

## PHOTON SPECTROSCOPY

# Today's Agenda

Scientific background to ANSEL Experiment 1
(Photon Spectroscopy): interaction of $\gamma$-rays with matter

Reading Assignments Weeks Feb 2-23
Text book G. F. Knoll:

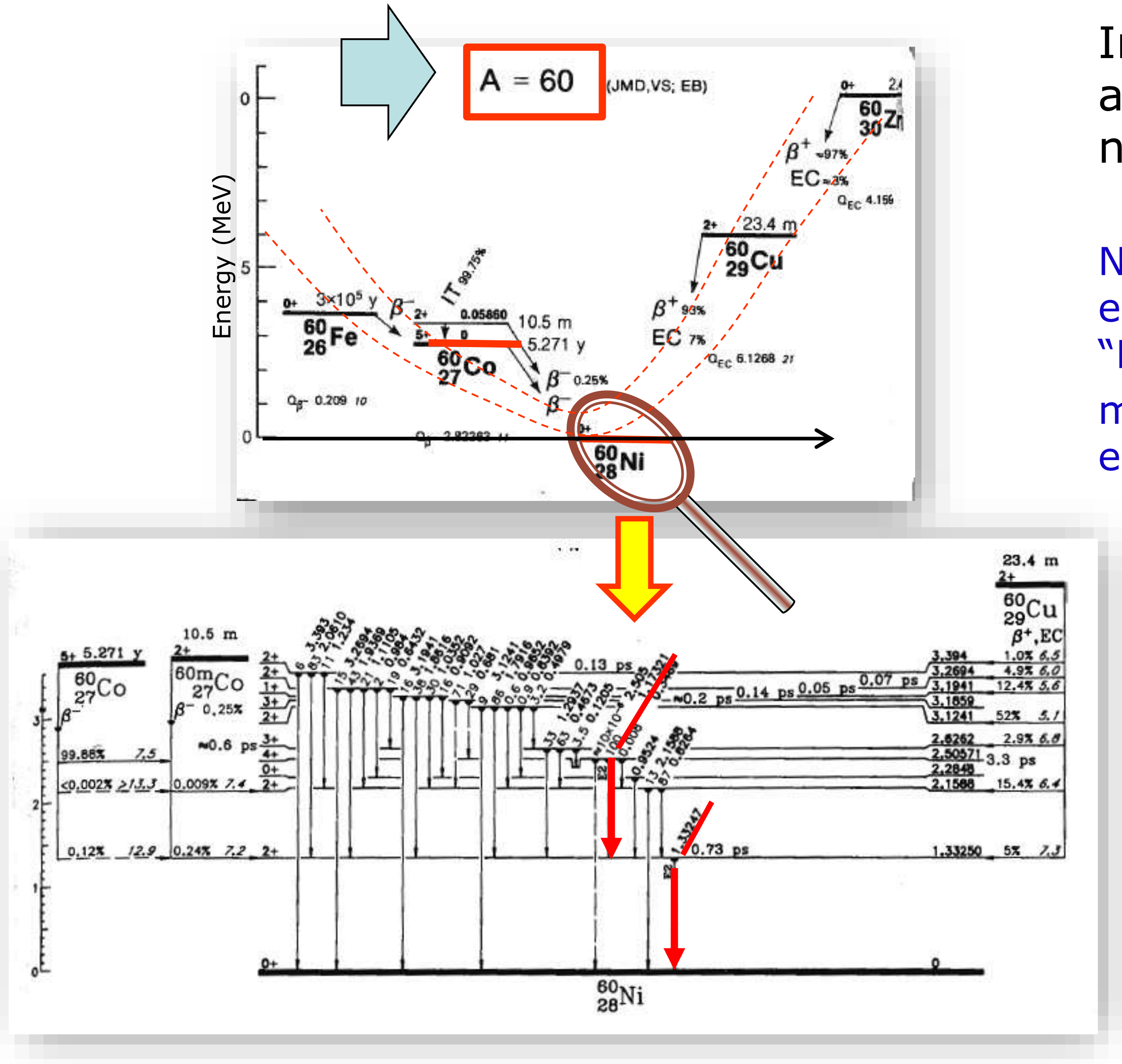
| | |
|---|---|
| • Ch. 2. III A 1-3, B 1-3 | Interaction of $\gamma$-rays |
| • Ch 10. I-III | $\gamma$-ray spectroscopy |
| • Ch 8. I-III | Scintillation Detectors |
| • Ch 9. I-V,VII | Photomultipliers, signal analysis |

**Next:** Writing a good ANSEL lab report

# Scope of ANSEL Experiment: Photon Spectroscopy

- Ubiquitous presence of radiation on Earth, e.g., $\gamma$-ray photons
- Concepts of absorption coefficient and cross section
- Introduction to $\gamma$-interactions with matter
  - Photo electric effect
  - Compton scattering
  - Pair production
- 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




Information ordered according to mass number A. (Lederer)

Nuclear ground state energies E(Z|A) form a “Mass Parabola”

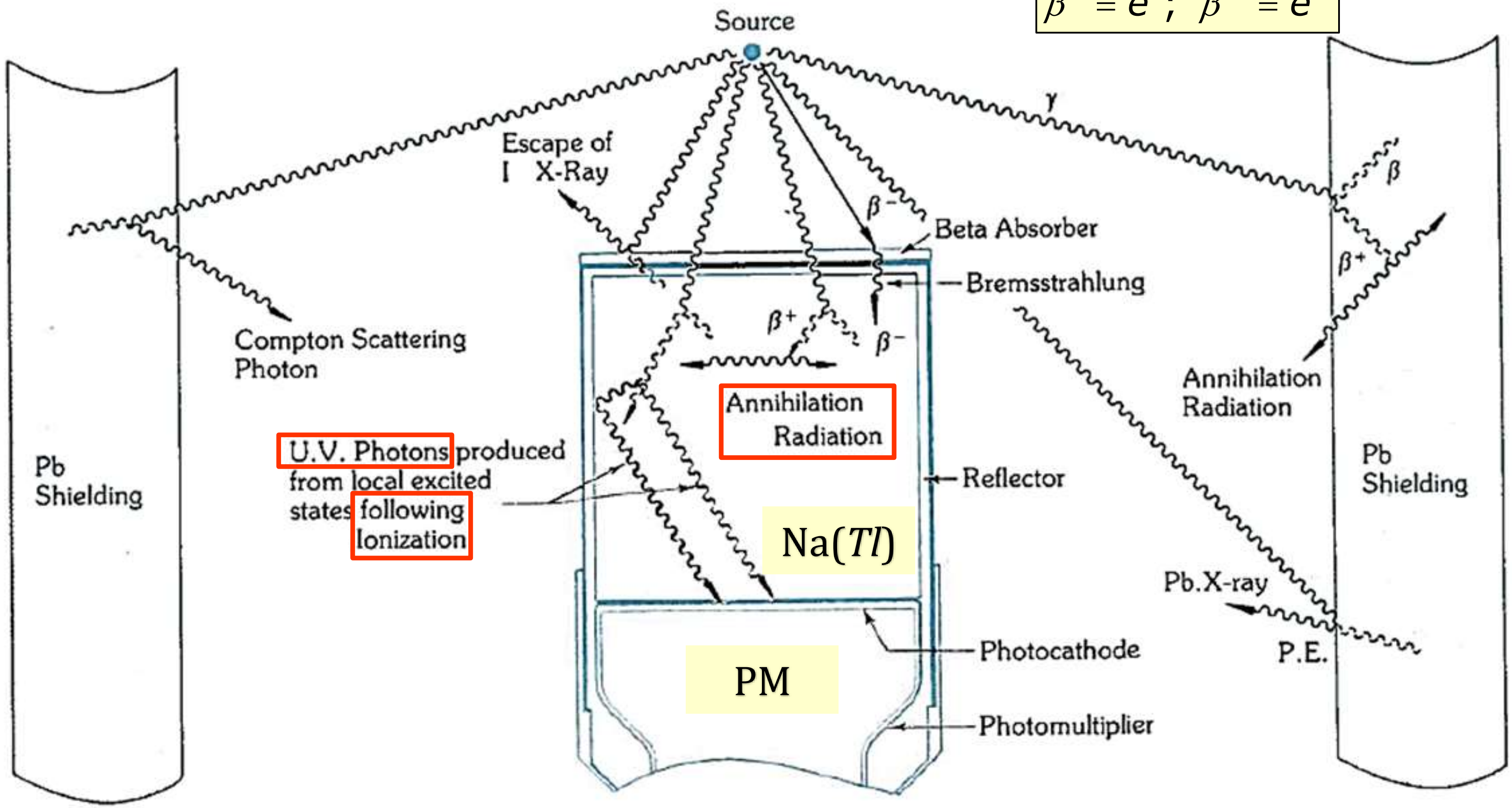
modified by structure effects.

$^{60}$Ni
Level Scheme

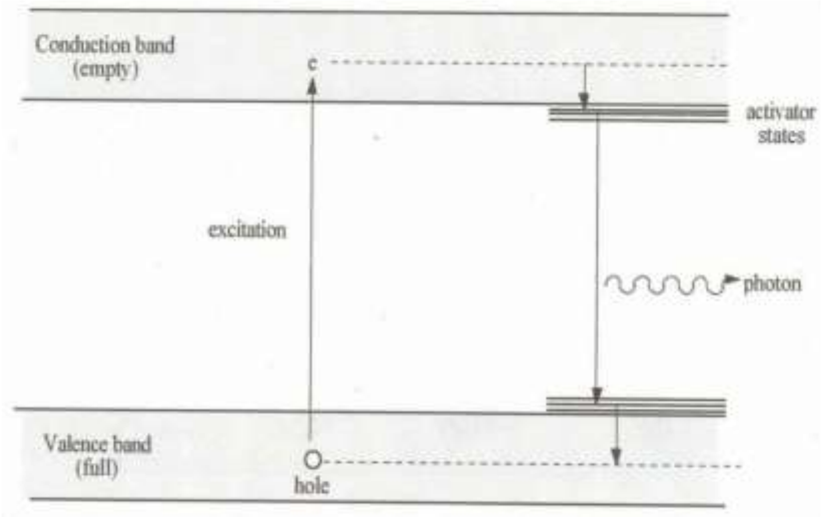
W. Udo Schröder 2020

# High-Energy γ Spectral Components

$\beta^- = e^-;\ \beta^+ = e^+$



# Scintillation Mechanism: Inorganic Scintillators




Primary ionization and excitations of solid-state **crystal lattice**:
NaI (Tl) = single crystals with well defined periodic lattice $N \sim 10^{23}$

2 types of $e^-$: bound and free → 2 bands (valence, conduction)

→ free (CB) $e^-$ or excitons ($e^-$,$h^+$) sequential de-excitation with different $E_{ph}$ and time constant.

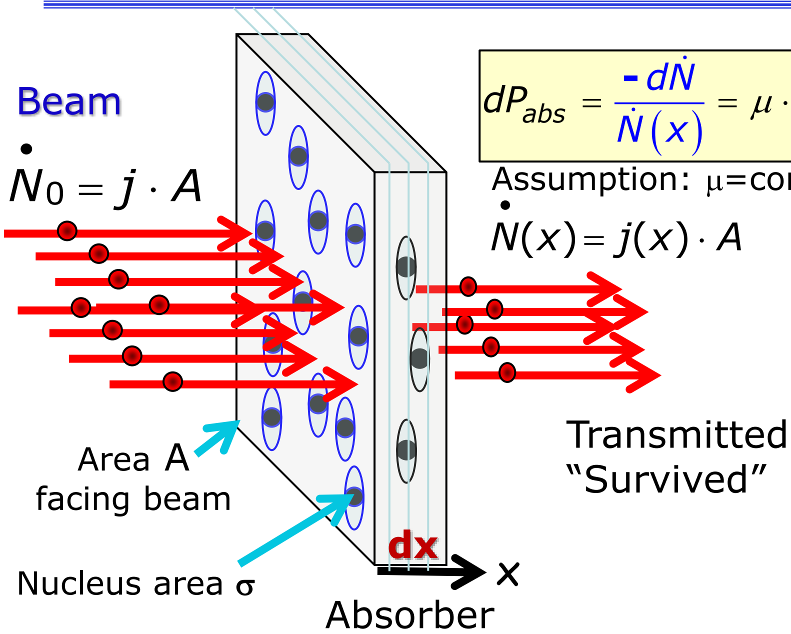
Electronic excitation:

VB → CB (or below)
Trapping of e- in activator states (Tl) doping material, in gs of activator band e **transition emits lower Eγ, not absorbed**.

Advantage of inorganic scintillator: high density, stopping power
→ good efficiency

Disadvantage: slow response – μs decay time, "after glow",
Hygroscopic → encapsulate

# Interaction Probability per Nucleus (Cross Section)




$$dP_{abs} = \frac{-d\dot{N}}{\dot{N}(x)} = \mu \cdot dx$$

Assumption: μ=const.

$$\dot{N}(x) = j(x) \cdot A$$

$$P_{abs}(x) = \mu x = \left[\begin{matrix}\#\, nuclei \\ in\, target\end{matrix}\right] \bullet \left(\begin{matrix}P_{absorption} \\ per\ nucleus\end{matrix}\right)$$

Random medium depth x

$$\mu x = \left[\left(\frac{L}{M_T}\right) \cdot (\rho_T \cdot A \cdot x)\right] \bullet \left(\frac{\sigma}{A}\right)$$

Cross section "area" σ

$$\boldsymbol{\mu} = (L/M_T)\rho_T \cdot \boldsymbol{\sigma}$$

Linear abs. coeff. = #nuclei·σ/Volume

$$N(x) = N_0 \cdot e^{-\mu \cdot x} \rightarrow \dot{N}(x) = \dot{N}_0 \cdot e^{-\mu \cdot x}$$

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

**Absorption upon intersection of nuclear cross section area σ**

***j*** beam current density (#part/time x area)
***A*** area illuminated by beam
***L***= 6.022 $10^{23}$/mol Loschmidt#
$N_T$ # target nuclei in beam
$M_T$ target molar weight
$\rho_T$ target mass density (g/cm$^3$)
***x*** target thickness
[σ]=***1barn = $10^{-24}$cm$^2$***

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

$$\dot{N}_{abs} \approx \dot{N}_0 \cdot (\mu \cdot x) = \frac{\dot{N}_0}{A} \cdot \left(\left(\frac{L\rho_T}{M_T}\right) A \cdot x\right)\sigma$$

$$\approx j \cdot N_T \cdot \sigma \qquad \textit{beam current density } j$$

$$\sigma = \frac{\dot{N}_{abs}}{N_T \bullet j}$$

Elementary absorption cross section of one nucleus=

$$\sigma = \sum_i \sigma_i \quad (process\ i)$$

→ observe sum effect

# $\gamma$-Induced Processes in Matter

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

**Detection of secondary particles from:**

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

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

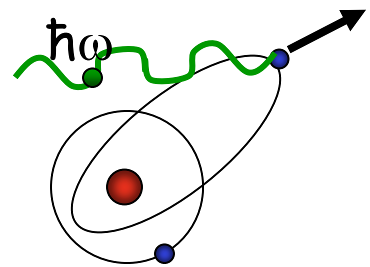
$$E_n = Rhc \cdot \frac{(Z-\sigma)^2}{n^2} \quad Moseley's\ Law$$

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

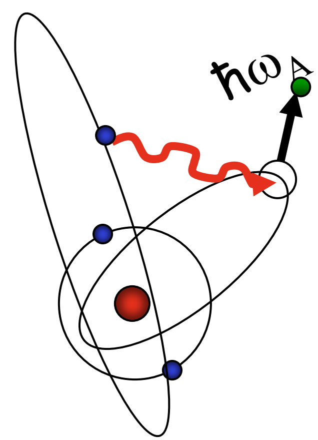
*screening constants*

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

1. Photo-electric absorption (Photo-effect)




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

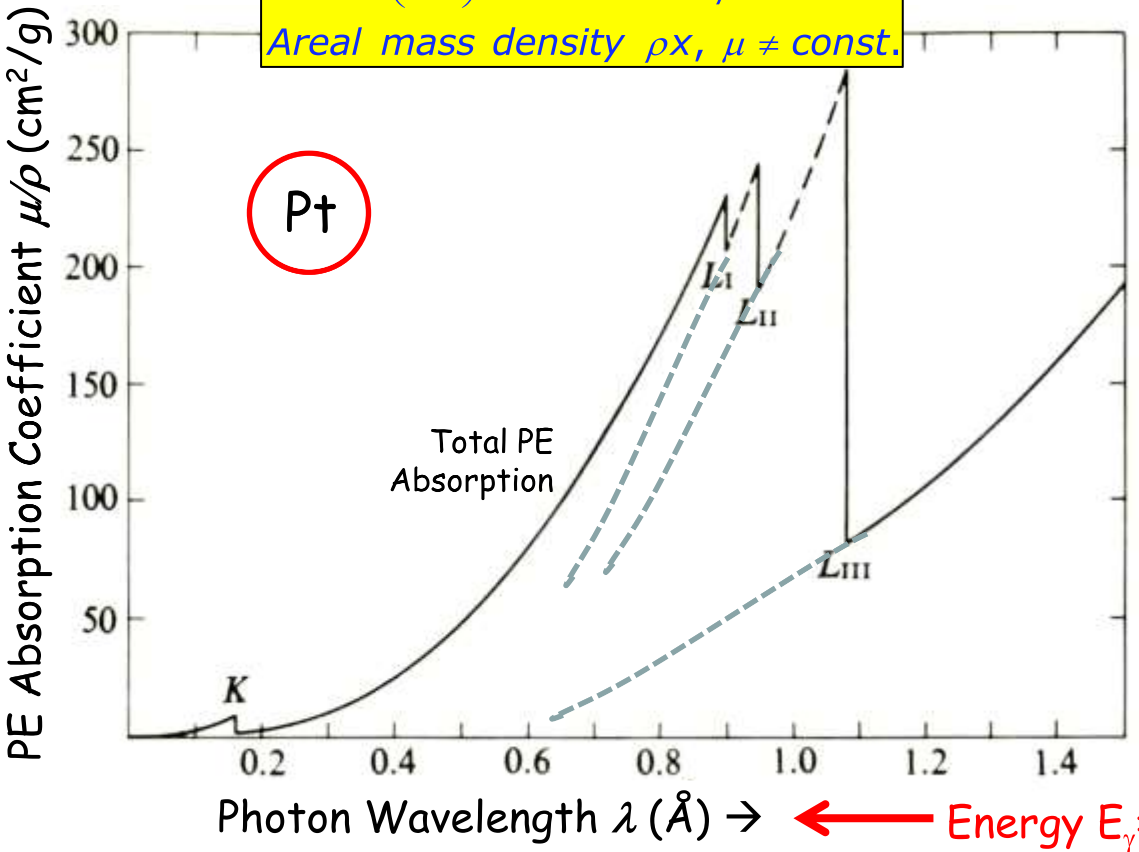



Electronic vacancies are filled by low-energy "Auger" transitions of electrons from higher orbits

# 1. Photo-Absorption Coefficient

Absorbance $A := \ell n\left(\frac{N_0}{N}\right) = \mu(E)\cdot x = \frac{\mu(E)}{\rho}\cdot(\rho x)$

*Areal mass density* $\rho x$, $\mu \neq const.$




← Energy $E_\gamma = h\nu$

**Absorption coefficient**

→ $\mu$ (1/cm)

"Mass absorption" is measured per density $\rho$

→ $\mu/\rho$ (cm²/g)

"Cross section" is measured per atom

→ $\sigma$ (cm²/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:

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

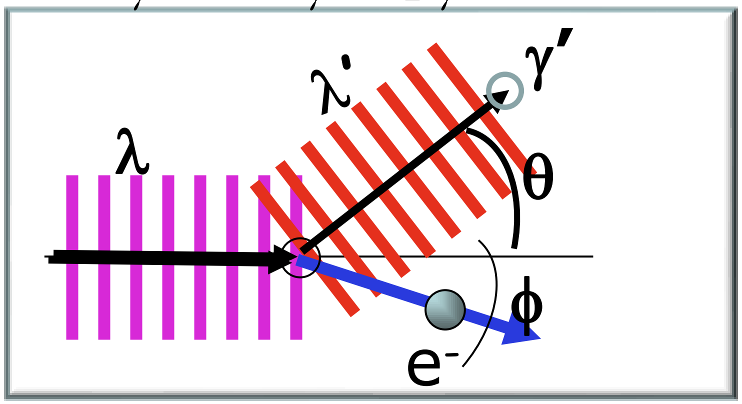
$$\sigma_{PE}(E_\gamma, Z) \propto Z^5 \cdot E_\gamma^{-7/4} \quad low\ E_\gamma$$

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

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

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

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




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

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

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

*Momentum conservation:*

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

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

*Energy conservation* (*initial* = *final*):

$$E_\gamma + m_e c^2 = E_{\gamma'} + \sqrt{(p_e c)^2 + (m_e c^2)^2}$$

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

$$Electron\ rest\ mass\ m_e c^2 = 0.511 MeV$$

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

# Compton Scattering Distributions

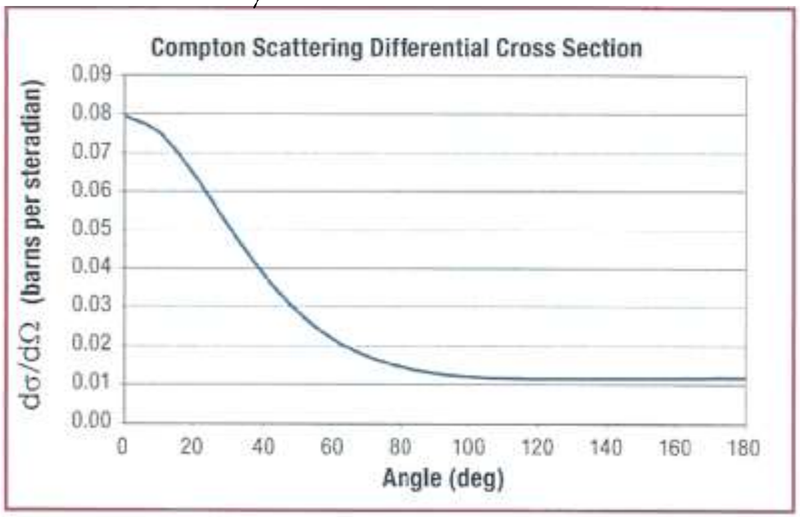
## Klein-Nishina Formula

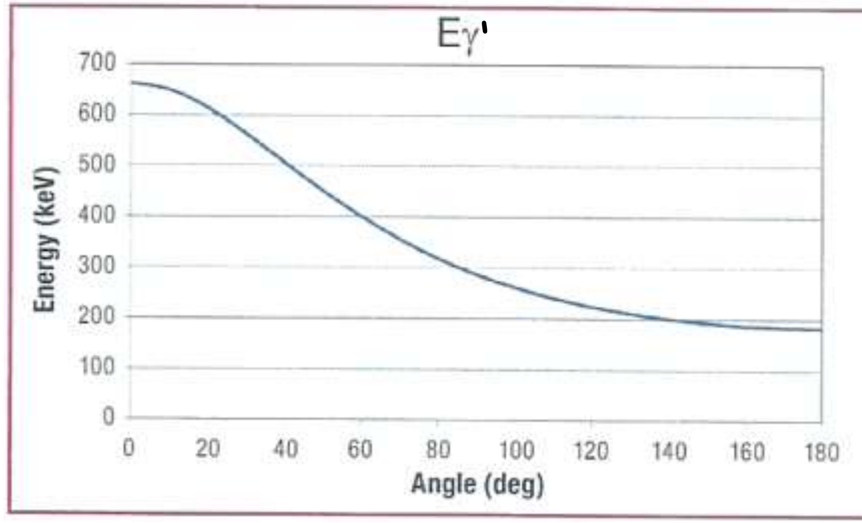
$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{r_0^2}{2}\left\{\frac{1+cos^2\theta}{[1+\alpha(1-cos\theta)]^2}\right\}\left\{1+\frac{\alpha^2(1-cos\theta)^2}{[1+cos^2\theta][1+\alpha(1-cos\theta)]}\right\}\left[\frac{m^2}{sr}\right]$$

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



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



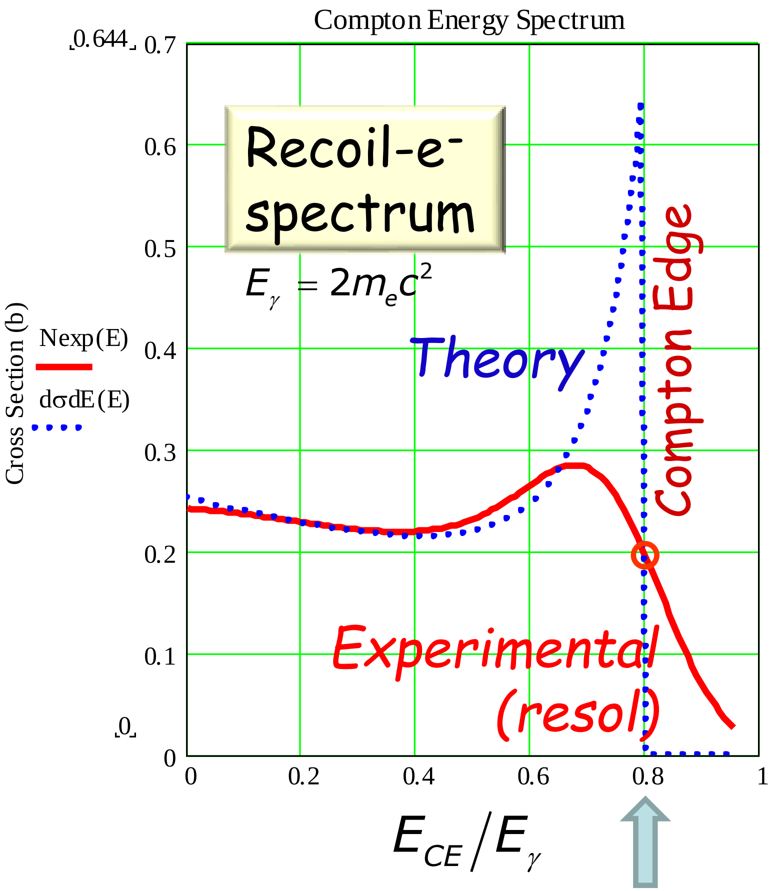




*Unit of differential cross section*

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

# Compton Recoil Electron Spectrum

Actually, not photons but recoil-electrons are detected !




*Scattered – photon energy.* $\theta$ = *photon angle*

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

*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 :* $\theta = 180^0$

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

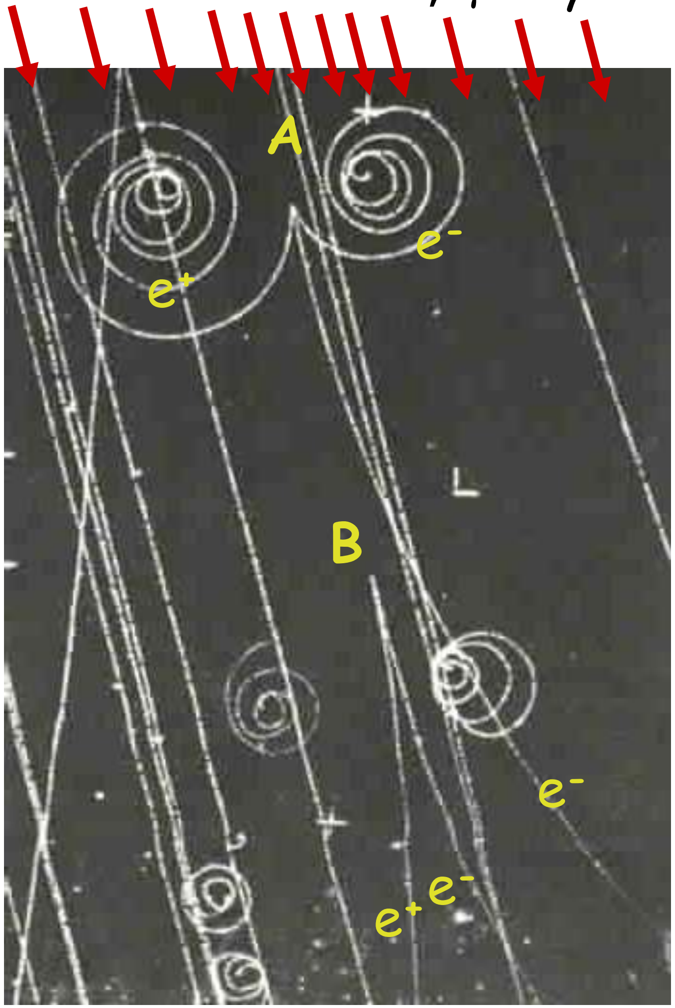
*Maximum electron energy (Compton Edge) :*

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

*Compton electron energy distribution.*

# 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

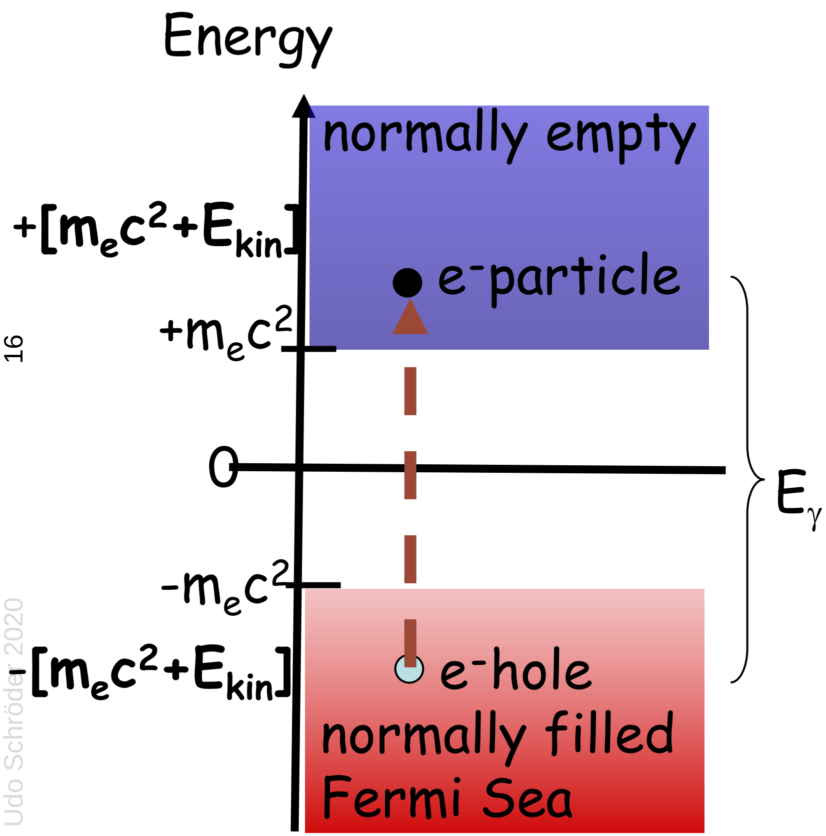
Magnetic field provides momentum/charge analysis

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

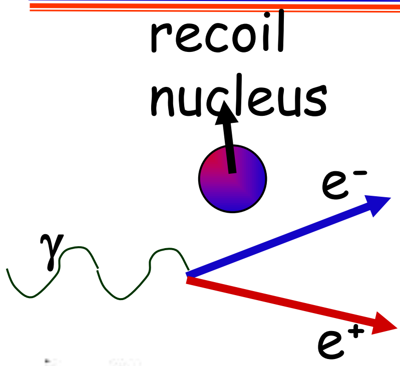
Electromagnetic interactions can lift a particle from the Fermi Sea across the energy gap **$\Delta E=2\ mc^2$** into the normal world → particle-antiparticle pair

Holes in Fermi Sea: Antiparticles

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

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

# The Nucleus as Collision Partner



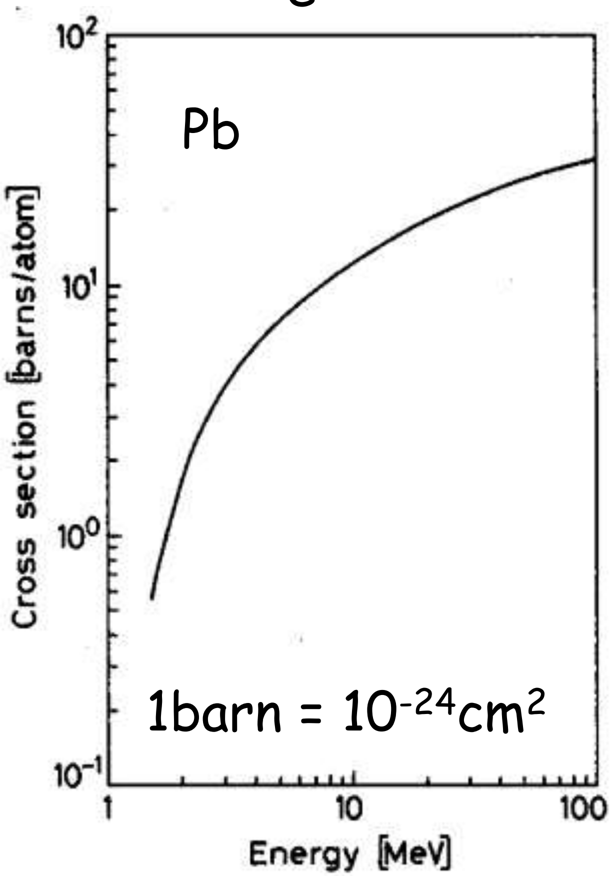

$$E_\gamma > E_{Threshold} = 2m_e c^2$$

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

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

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

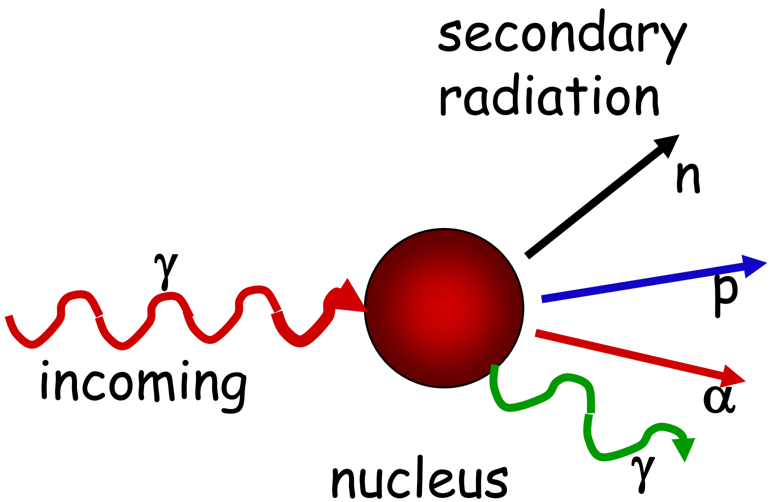
$$P\ slowly\ varying\ with\ energy, Z$$




Increase with $E_\gamma$ because interaction sufficient at larger distance from nucleus

Eventual saturation because of screening of charge at larger distances

# 4. γ-Induced Nuclear Reactions




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

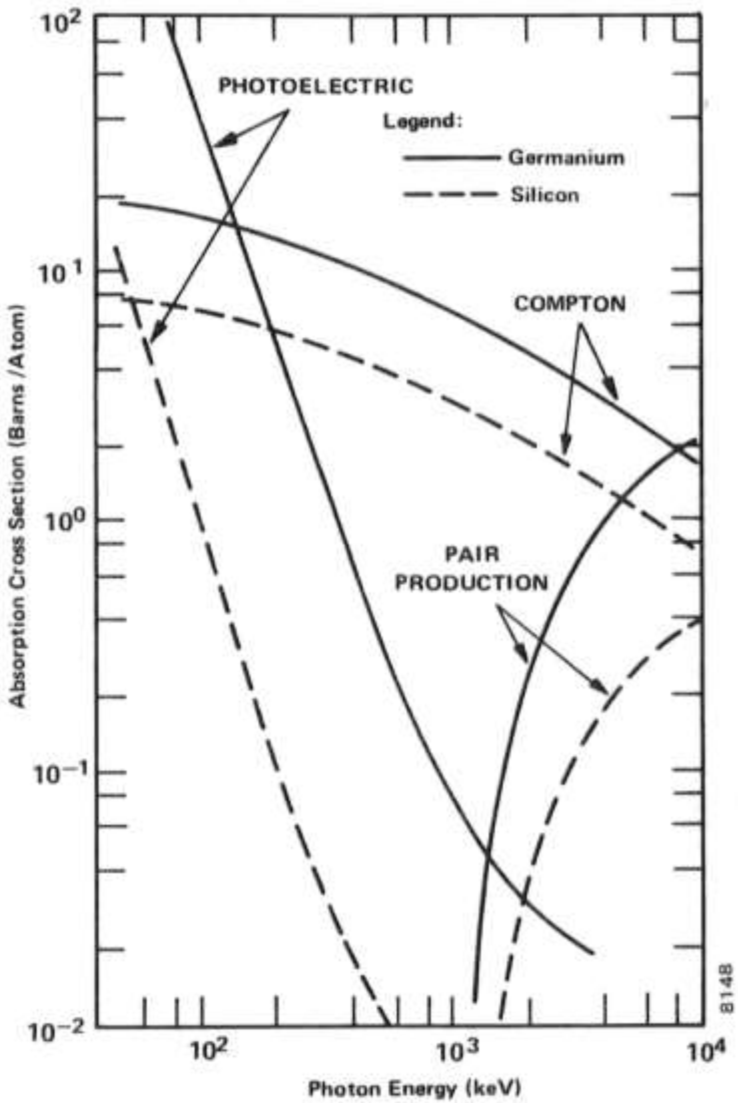
**(γ, γ' ), (γ, n), (γ, p), (γ, α), (γ, f)**

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

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.

# Efficiencies of $\gamma$-Induced Processes




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

Photo absorption at low $E_\gamma$

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

Compton scattering at intermediate $E_\gamma$.

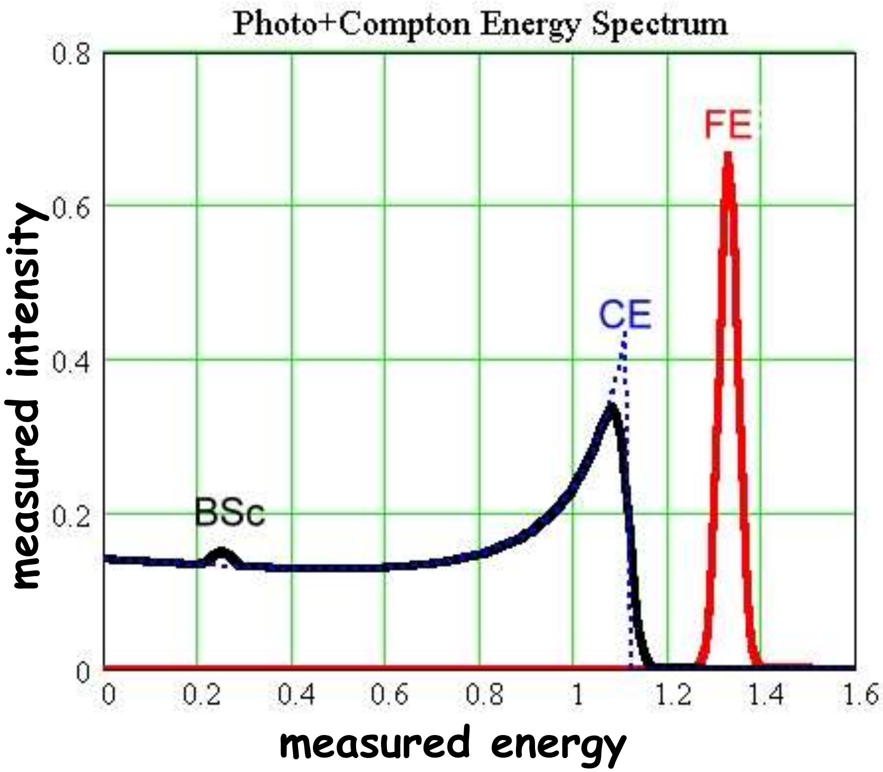
Z dependence important: Ge(Z=32) has higher efficiency for all processes than Si(Z=14). Take high-Z for large photo-absorption coefficient

Response of detector depends on

- detector material
- detector shape
- $E_\gamma$

# 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.



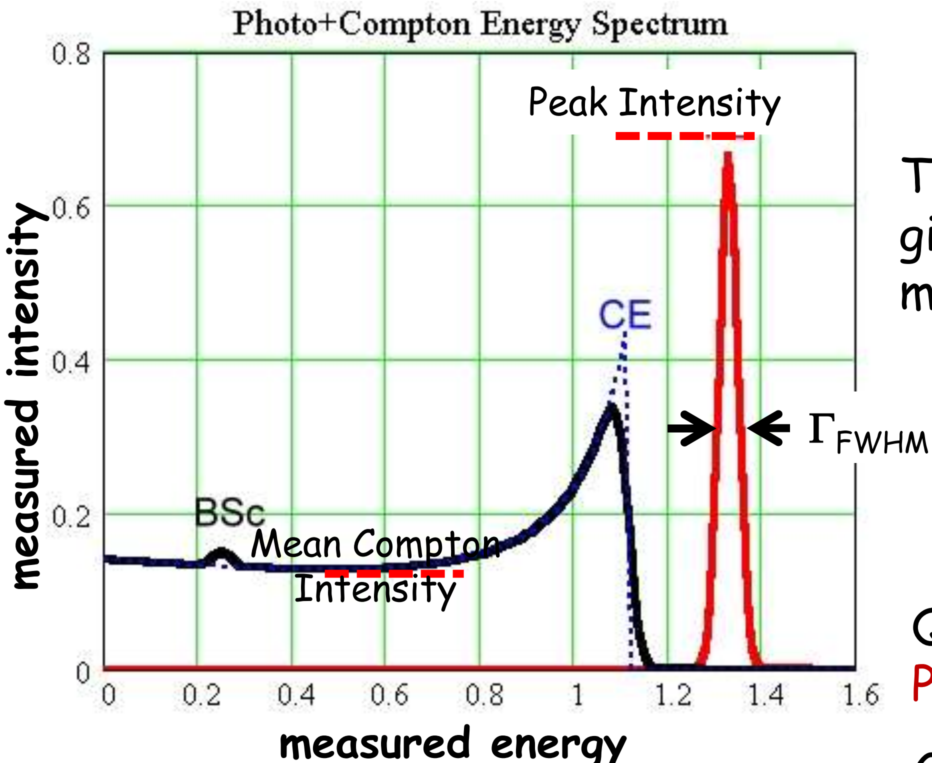

The energy $E_\gamma$ of an incoming photon can be ≈completely converted into charged particles which are all absorbed by the detector, → measured energy spectrum shows only the full-energy peak (FE, red)
*Example*: photo effect with absorption of struck $e^-$

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 $\Gamma_{FWHM}$ at half maximum of the measured γ line.

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

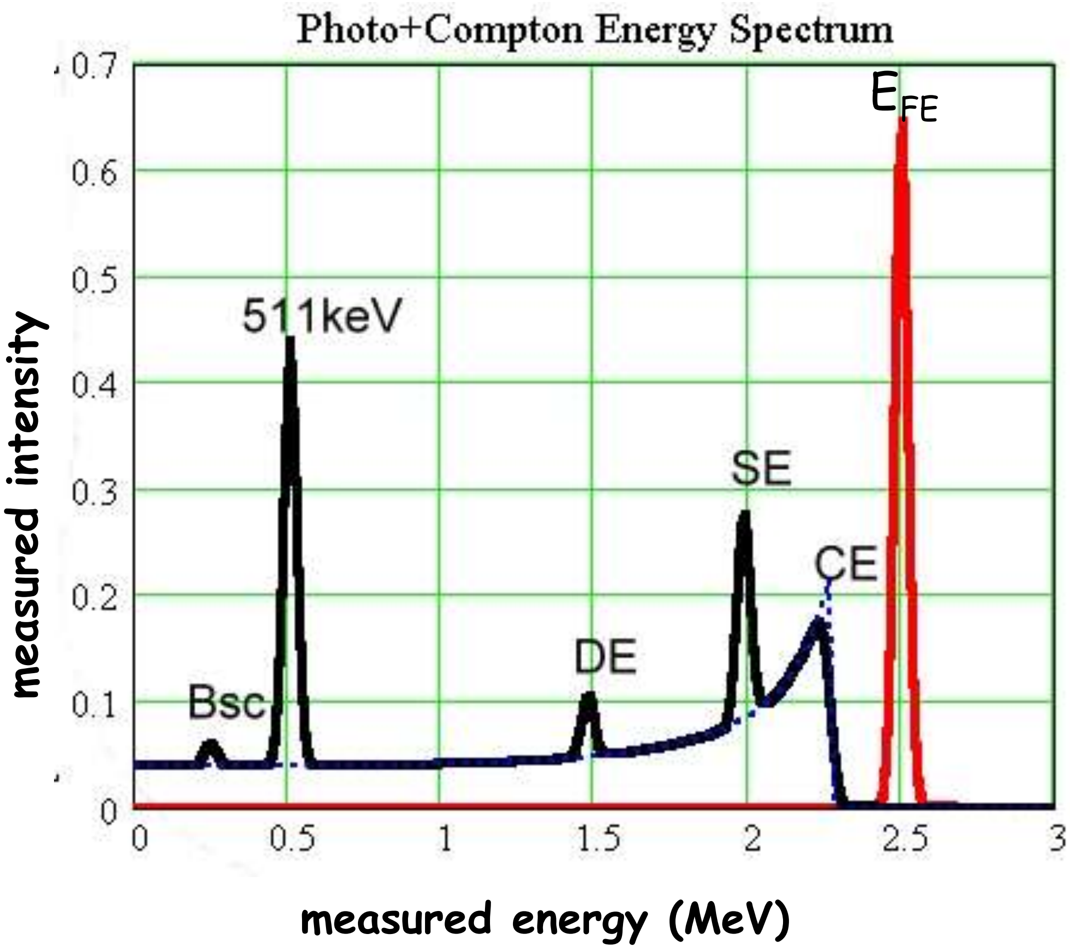
$\sigma$ = standard deviation, width of Gaussian fit

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

C defined by flat region in spectrum

# 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 $E_\gamma$ = 511 keV.

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

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

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

# Quiz

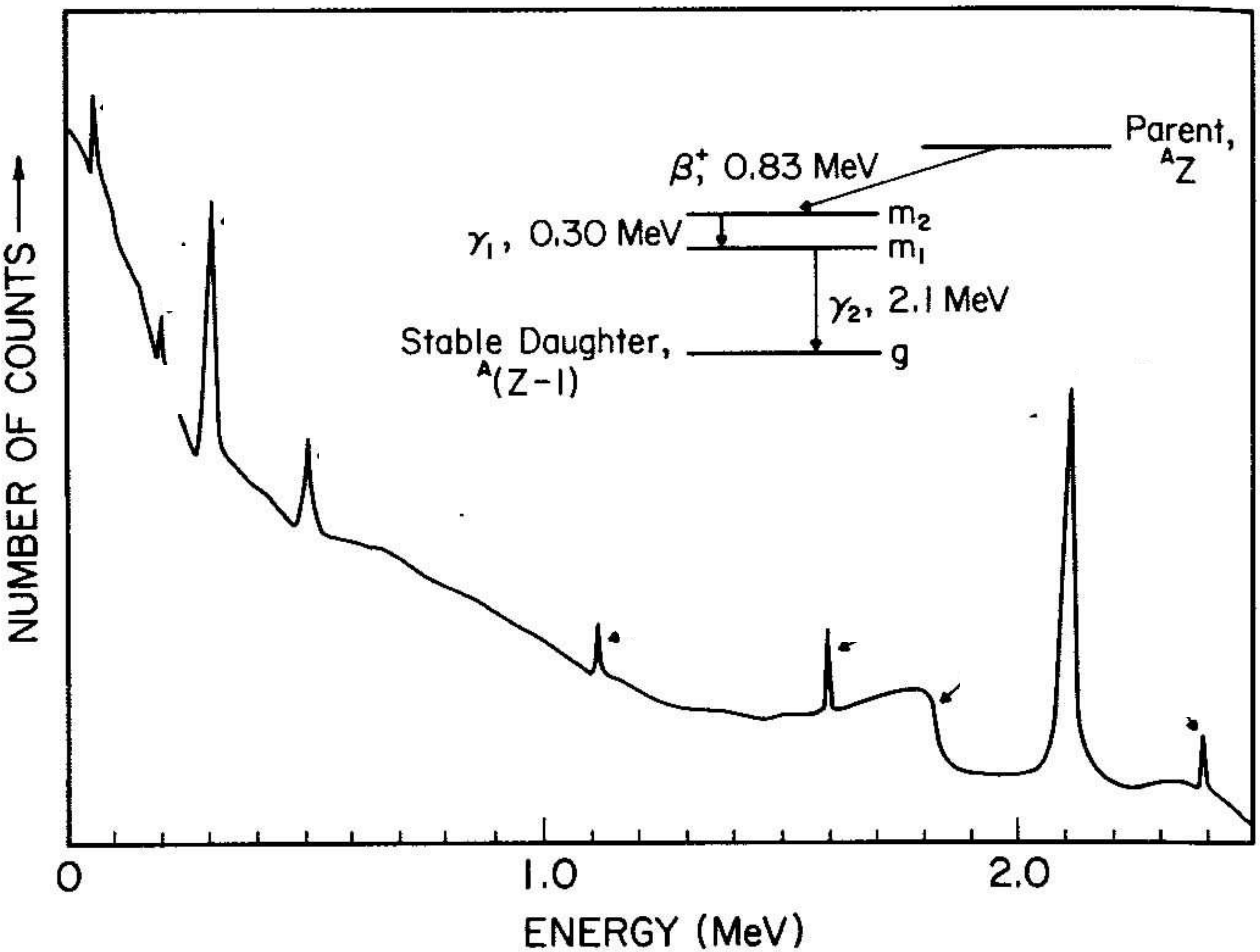
- Try to identify the various features of the $\gamma$ spectrum shown next (it is really the spectrum of electrons hit or created by the incoming or secondary photons), as measured with a highly efficient detector and a radio-active $^{A}Z$ source in a Pb housing.

- The $\gamma$ spectrum is the result of a decay in cascade of the radio-active daughter isotope $^{A}(Z-1)$ with the photons $\gamma_1$ and $\gamma_2$ emitted (practically) together

- Start looking for the full-energy peaks for $\gamma_1$, $\gamma_2$,…; 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.

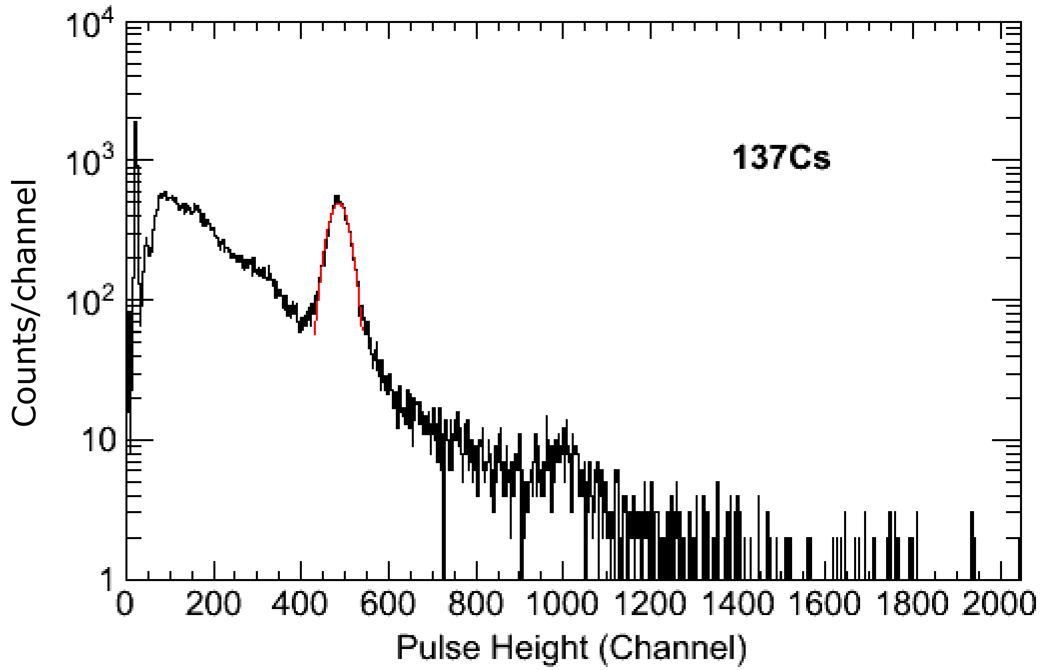
# Identify Spectral Components



# Data Analysis Expt. 1

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 ($E_\gamma$ or $E_{CE}$). Perform IGOR fits of main $\gamma$ lines, keeping track of experimental errors. Use Gaussians for $\gamma$ 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 $E_\gamma$(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 $\gamma$-ray energies of prominent features in the spectrum for the unknown source. Based on the provided search table, suggest the identity of the unknown source (or source mix).
7. Identify the $\gamma$-ray energies of prominent features in the spectrum for the room background. Based on the tables (provided in the ANSEL Twiki pages) of known $\gamma$-rays, suggest the identities of the various spectral components.
8. Measure the peak-to-Compton ratio of the detector for a high-energy $\gamma$-ray.
9. Determine the energy resolution of the detector as function of $E_\gamma$.

# Sample Spectrum

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