Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 10

Radiation Detection & Interactions II

Spiritual Thought

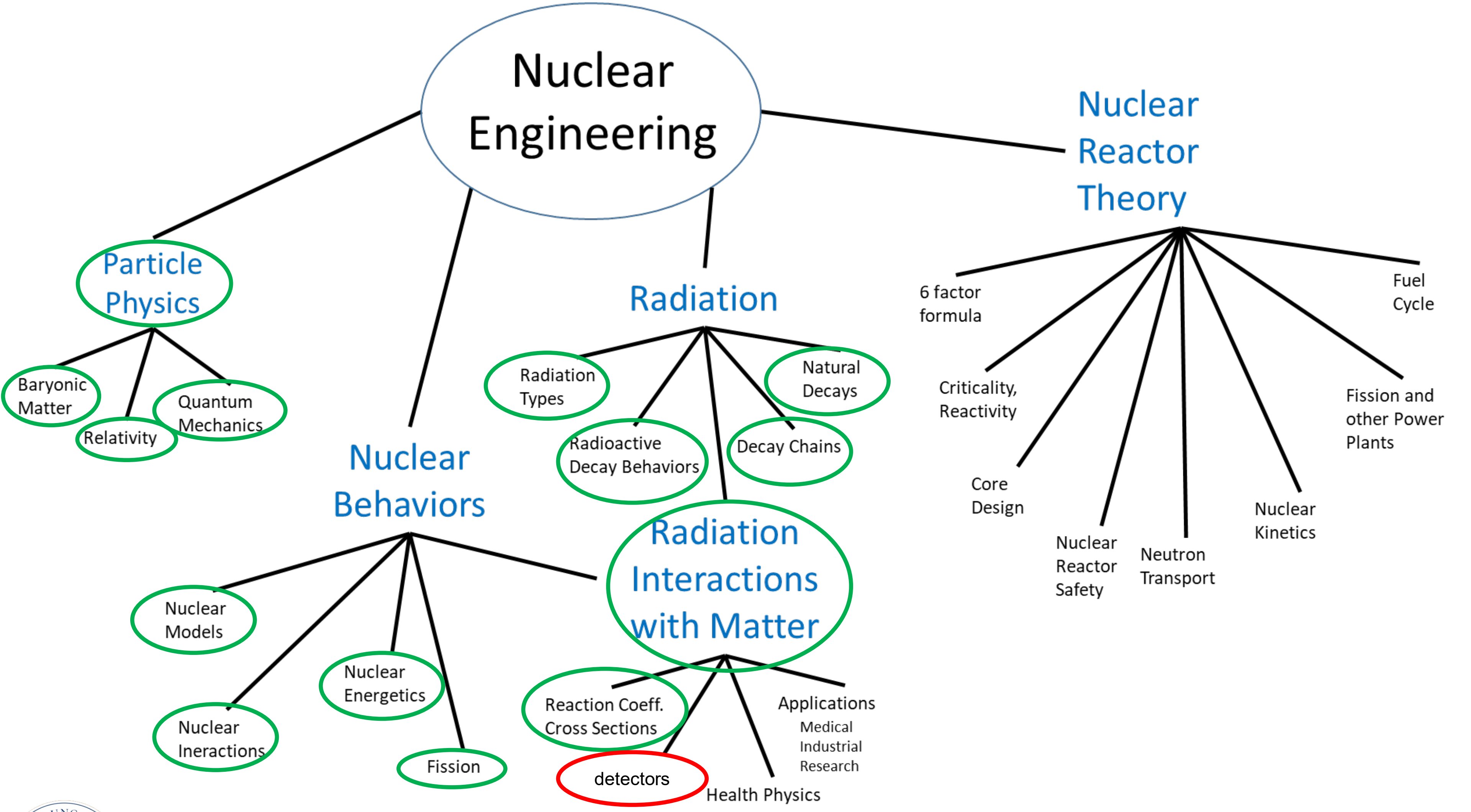
I realize that there are some, perhaps many, [who] feel overwhelmed by the lack of time. You have left unfinished tasks in your Church calling. You've carried your scriptures all day but still have not found a moment to open them. There is someone in your family who would be blessed by your thoughtful attention, but you haven't gotten to them yet…Rather than finding ways to capture leisure time for learning, you are trying to decide what to leave undone.

There is another way to look at your problem of crowded time. You can see it as an opportunity to test your faith. The Lord loves you and watches over you. He is all-powerful, and He promised you this: "But seek ye first the kingdom of God, and his righteousness; and all these things shall be added unto you"

That is a true promise. When we put God's purposes first, He will give us miracles. If we pray to know what He would have us do next, He will multiply the effects of what we do in such a way that time seems to be expanded. He may do it in different ways for each individual, but I know from long experience that He is faithful to His word.

President Henry B. Eyring

Roadmap



Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
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Decay Chains
Radiation Interactions with Matter
Reaction Coeff. Cross Sections
detectors
Health Physics
Applications
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Nuclear Reactor Theory
6 factor formula
Criticality, Reactivity
Core Design
Nuclear Reactor Safety
Neutron Transport
Nuclear Kinetics
Fission and other Power Plants
Fuel Cycle

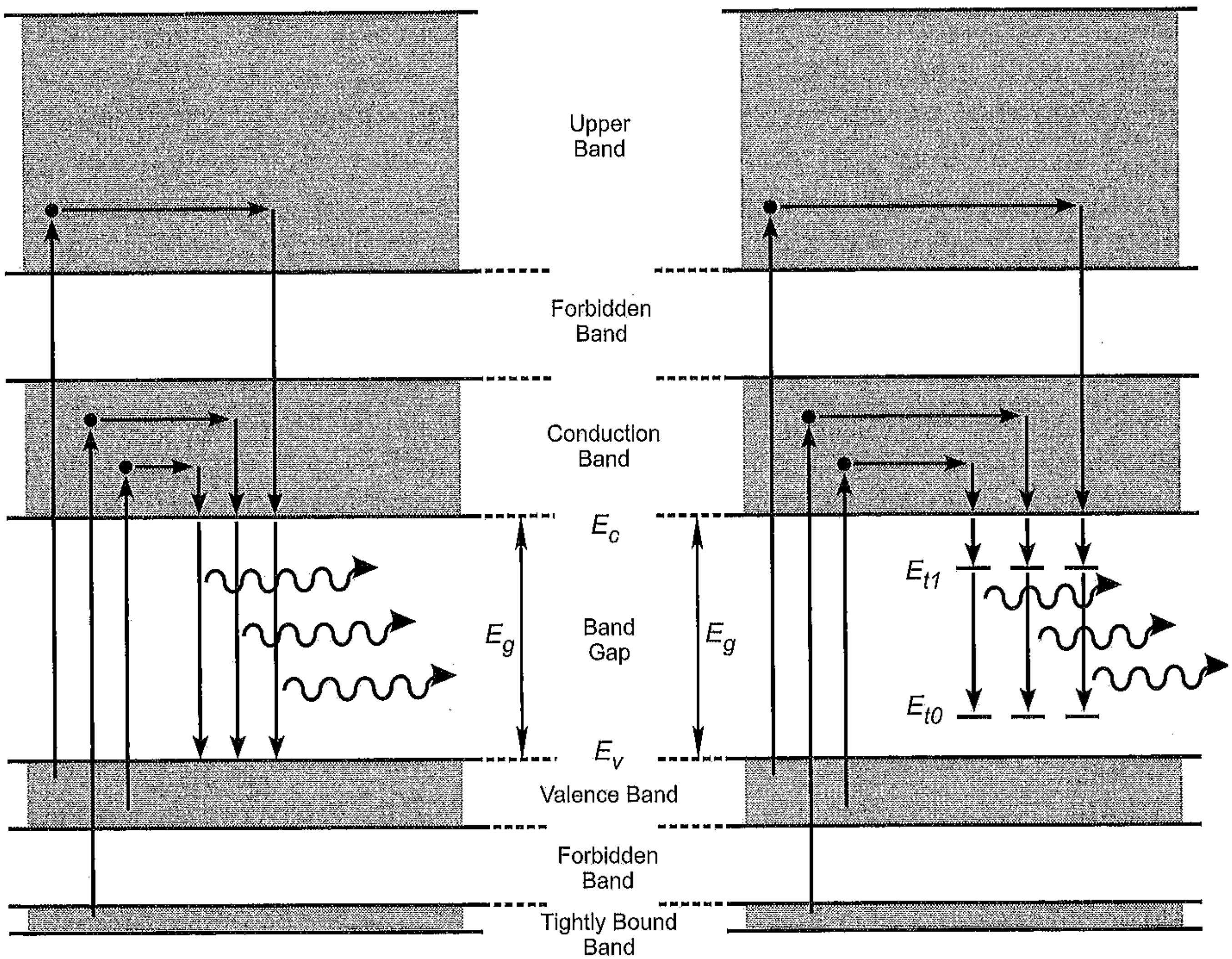
Objectives

- Know the principles behind detecting radiation
- Understand the influence of voltage and design on detection
- Understand Scintillation detection (spectroscopy)
- Be prepared to build your own detector!

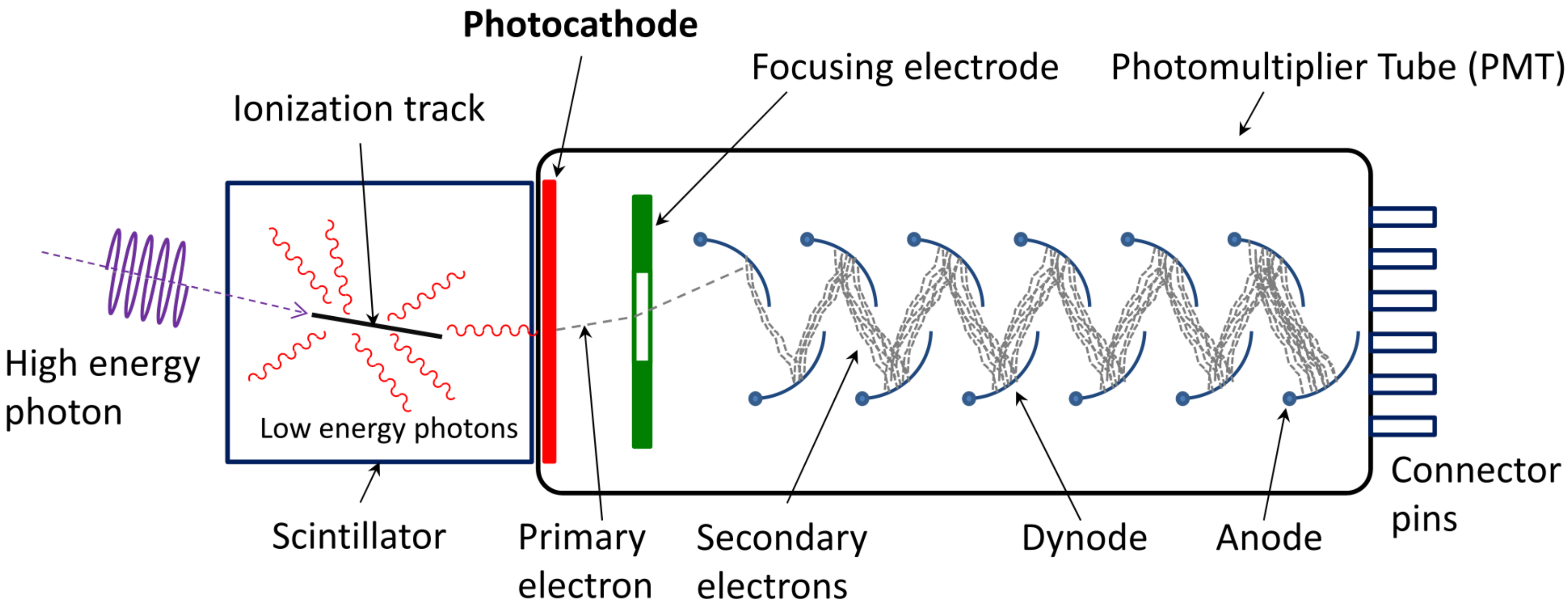
Scintillation detectors

- Scintillators are used in conventional film-screen radiography, many digital radiographic receptors, fluoroscopy, scintillation cameras, most CT scanners, and PET scanners
- Scintillation detectors consist of a scintillator and a device, such as a PMT, that converts the light into an electrical signal

Scintillation Mechanism - Inorganic



Interaction to Signal



Fluorescence Decay Signal

$$N(t) = N_0\, exp(-\lambda t) \qquad \lambda = \frac{1}{\bar{t}}$$

$$n(t) = total\ decays\ up\ to\ time\ t$$

$A(0) = \lambda N(0)$ - decays per time

$$n(t) = \int_0^t A(t')dt' = \int_0^t \lambda N(t')dt'$$

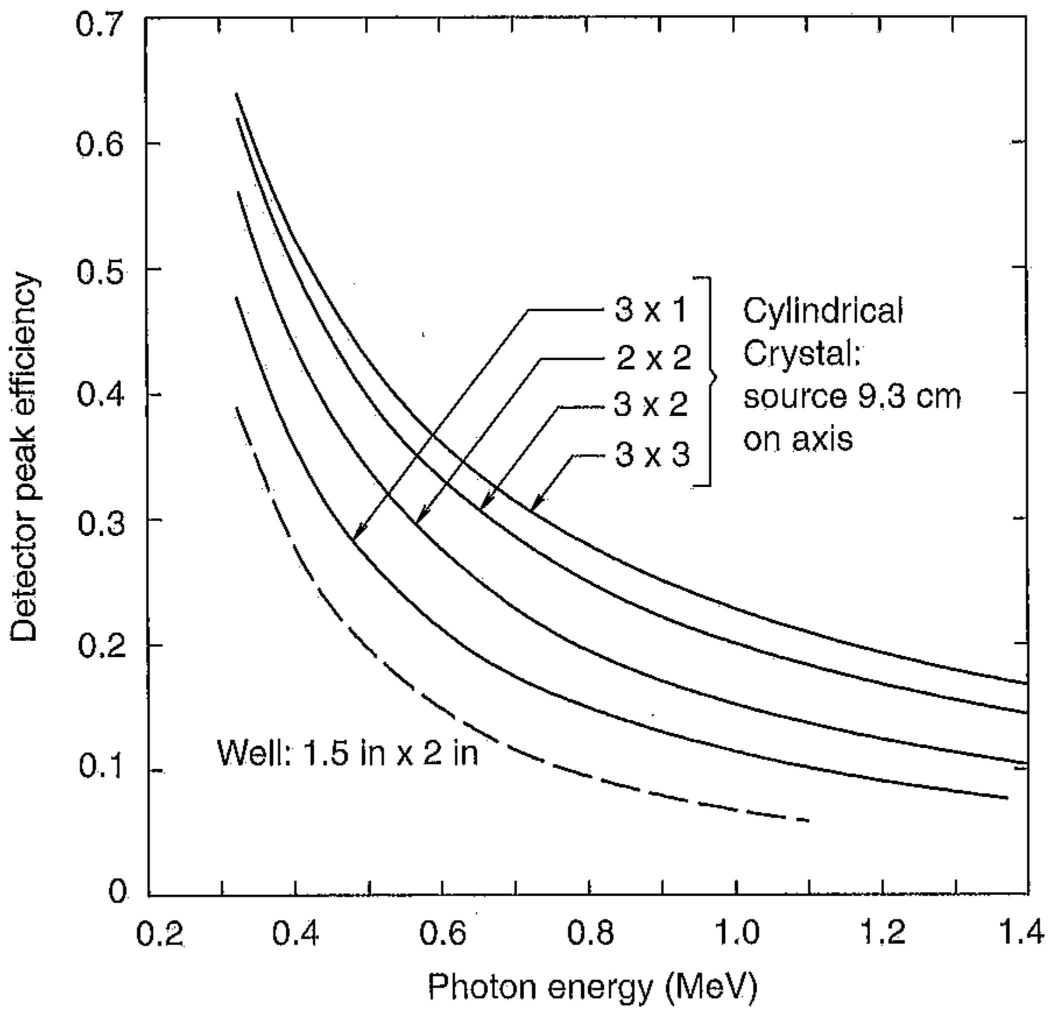
$$n(t) = N(0)\left[1 - e^{-\lambda t}\right]$$

Example

- The half-life for NaI(TI) fluorescence radiation is about 230 ns. How long must one wait to collect 90% of the scintillation photons?

- λ=4.35E6/sec
- n/N=$\frac{n}{N} = \lambda \int_0^{t_o} e^{-\lambda t}$
- $t_o = -\frac{1}{\lambda} ln\left(1 - \frac{n}{N}\right)$ =0.53μs

Absorption Efficiency



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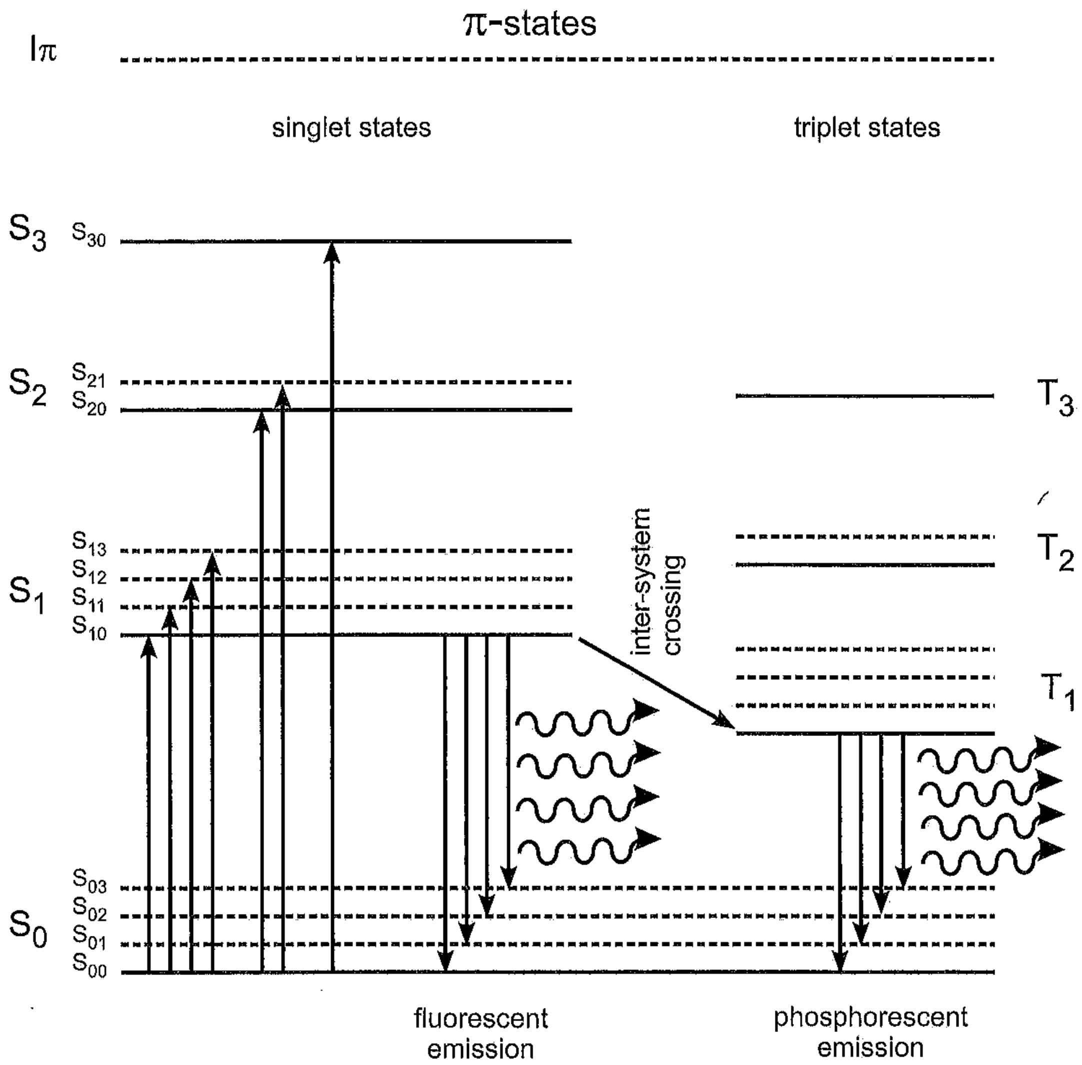
Scintillation Mechanism - Organic



Inorganic vs. Organic

- Inorganic
  - Depends on crystalline structure and hence must be crystalline or poly-crystalline
  - Involve high Z elements (compared to organics), especially as activator/dopants, and are therefore effective gamma absorbers
  - Generally hydroscopic and fragile
- Organic
  - Depend on molecular rather than crystalline structure, and hence more easily fabricated.
  - Less sensitive generally and especially to gamma radiation
  - Low Z-numbers produce less backscatter
  - Good for electron and beta detection and for fast neutron detection (fast neutrons produce fast H and C that ionize as they slow).

Scintillators

- Desirable properties:
  - High conversion efficiency
  - Decay times of excited states should be short
  - Material transparent to its own emissions
  - Color of emitted light should match spectral sensitivity of the light receptor
  - For x-ray and gamma-ray detectors, μ should be large – high detection efficiencies
  - Rugged, unaffected by moisture, and inexpensive to manufacture

Scintillators (cont.)

- Amount of light emitted after an interaction increases with energy deposited by the interaction
- May be operated in pulse mode as spectrometers
- High conversion efficiency produces superior energy resolution

Materials

- Sodium iodide activated with thallium [NaI(Tl)], coupled to PMTs and operated in pulse mode, is used for most nuclear medicine applications
  - Fragile and hygroscopic
- Bismuth germanate (BGO) is coupled to PMTs and used in pulse mode as detectors in most PET scanners

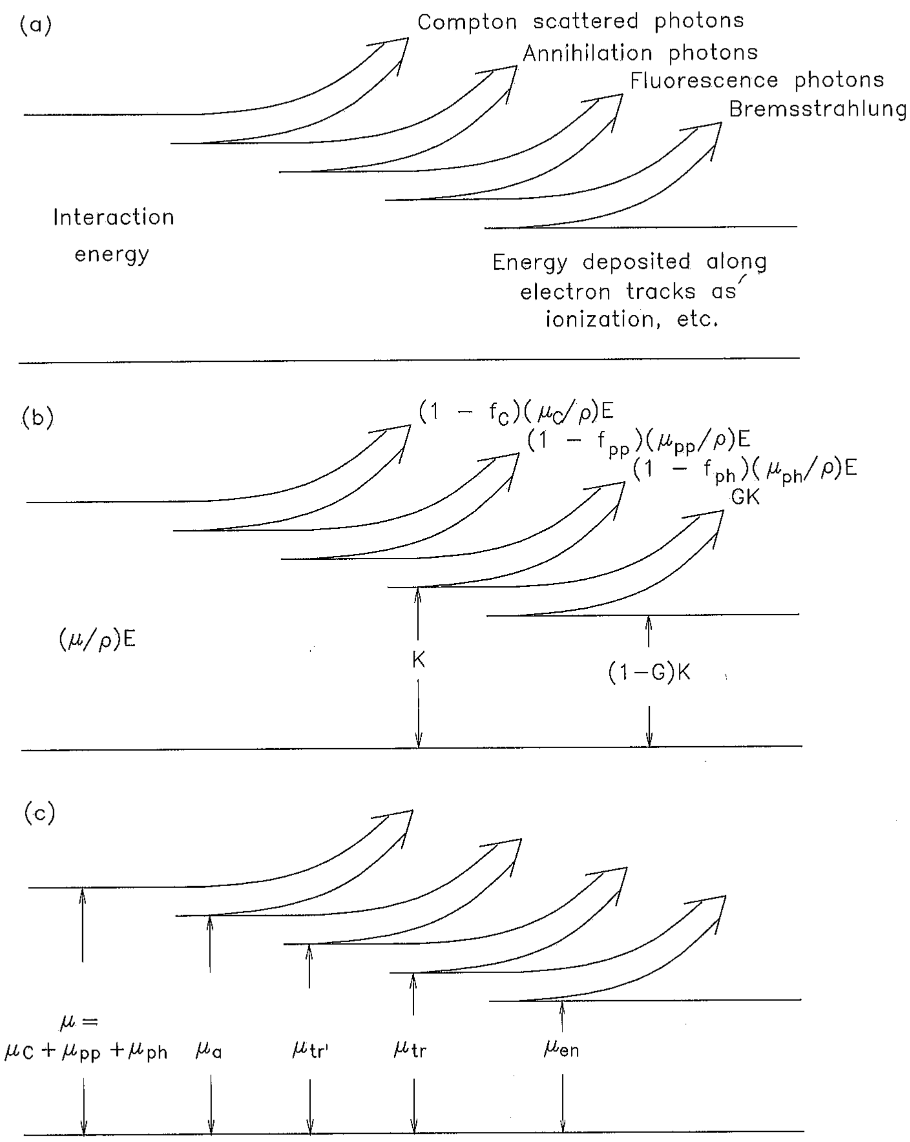
Semi-conductor Detectors

Type	Efficiency (Z)	Density (g/cm^3)	Resolution (Band Gap eV)	Ionization Energy (eV/e-h)	Convenience	Notes
Si(Li)	Very Low (14)	2.33	High 1.12	3.61	Low	LN operation
Ge(Li)	Low (32)	5.33	High 0.72	2.98	Very Low	LN always
GaAs	Low (31/33)	5.32	1.42	4.2	modest	
CdTe	Moderate (48/52)	6.06	1.52	4.43	low	polarizes slowly with time
$Cd_5Zn_{45}Te_{50}$	Moderate (48/52)	6.0	1.6	5.0	high	no cooling necessary, stable
HgI_2	Moderate (80/53)	6.4	2.13	4.3	low	polarizes with time

Photon (γ-ray) Interactions

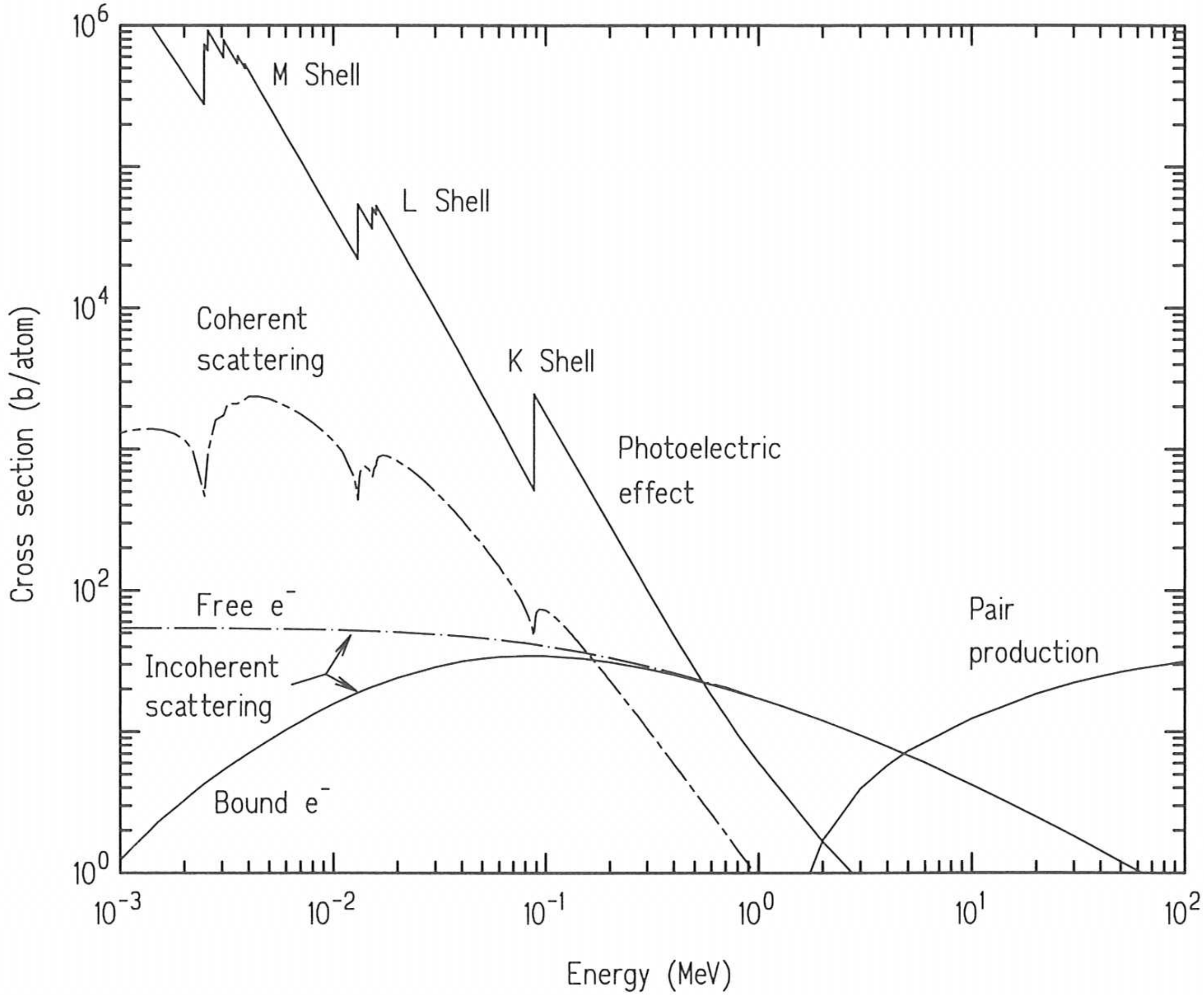
- Photoelectric effect
  - Generally decreasing absorption with increasing energy
  - Indicative of elemental/nuclear structure.
  - γ-ray absorbed
  - Low energy products
- Pair Production
  - Increasing absorption with increasing energy
  - Depends on Z (happens in Coulomb field near nucleus)
  - γ-ray absorbed
  - Low energy products
- Compton Effect
  - Generally decreasing absorption with increasing energy
  - Depends on electron structure and hence Z
  - γ-ray remitted
  - Small energy change

Photon Energy Partitioning



All of these mechanisms cause a photon to loose energy, but those listed here cause radiation that mostly deposits energy elsewhere rather than locally. The local energy deposition is indicated by μ_{en}.

Photon Interactions:



Photoelectric effect

- Photoelectric effect
  - γ-ray is absorbed
  - depends on γ-ray energy and Z
  - electron ejection, generally from the K, L, or M levels
  - X-ray or Auger electron emission follows
  - electron and x-ray/Auger emission generally low energy compared to γ-ray
  - cross section designated as σ_{pe} with interactions/volume given by $IN\sigma_{pe}$ as usual
  - Cross section depends on Z^n where n is ~ 4

Compton Effect

- Elastic scattering of photon by an electron
- Scattered photon has nearly same energy as initial photon (same except for rebound energy of electron)
- In terms of energy

$$E' = \frac{E E_e}{E(1 - \cos\vartheta) + E_e}$$

- In wavelength

$$\lambda' - \lambda = \lambda_C (1 - \cos\vartheta)$$

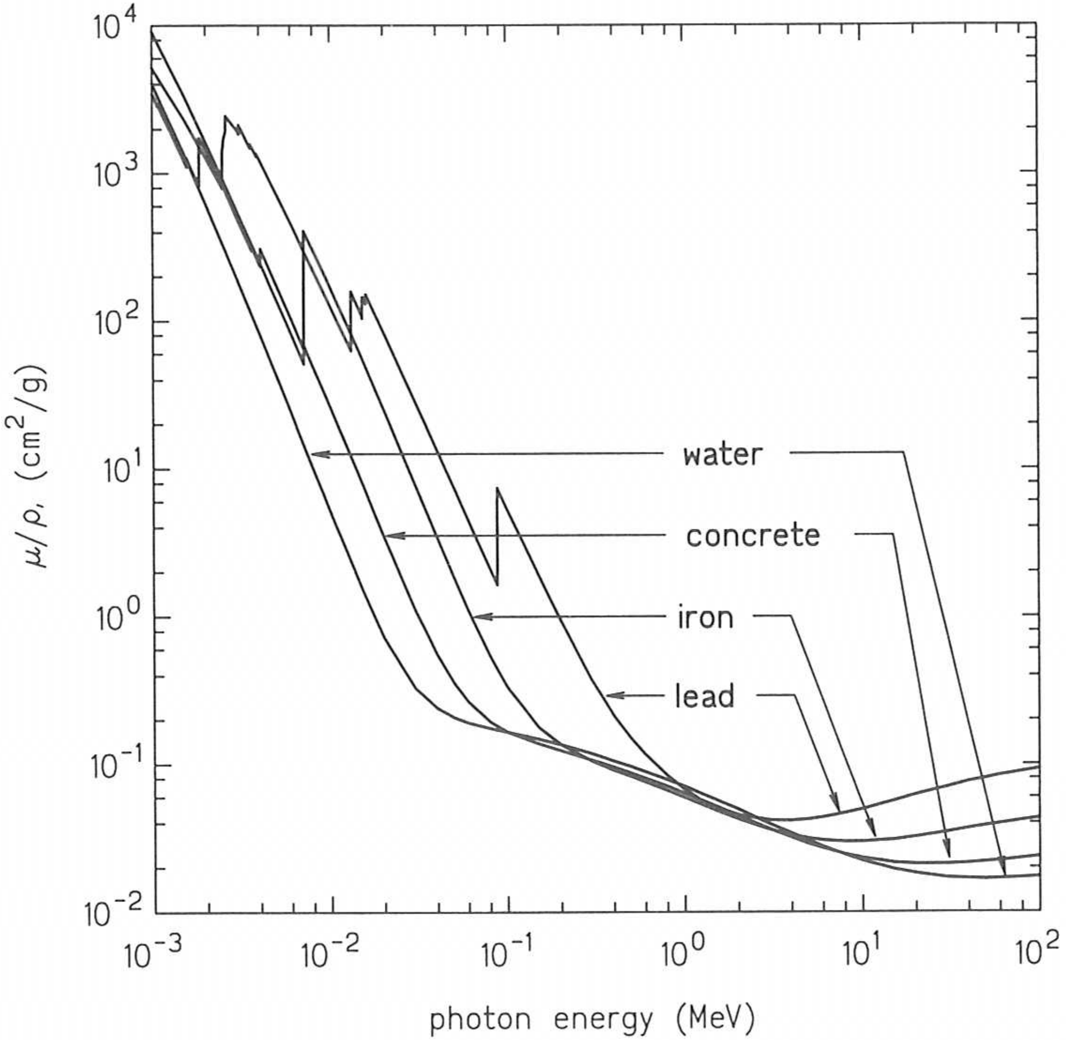
$$\lambda_C = \frac{h}{m_e c} = 2.426 x 10^{-10} cm$$

- Serious shielding problem

Pair Production

- Creates negatron (electron) and positron from the photon/ γ-ray
- Minimum energy threshold of 1.02 MeV
  $E_{min} = 2m_e c^2$
- Product particles lose kinetic energy (thermally) prior to recombining in annihilation radiation
- Cross section approximately proportional to Z^2

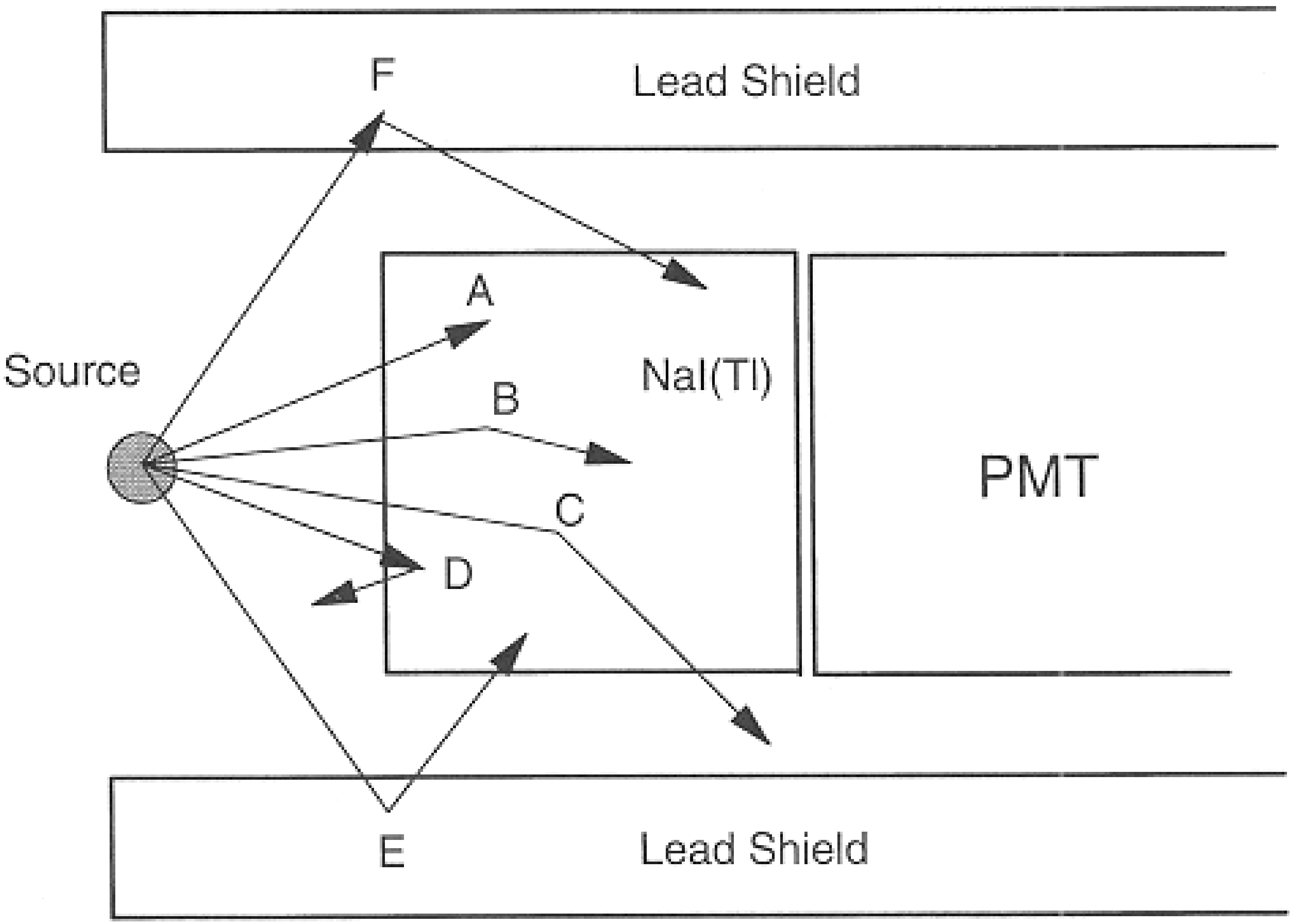
Total Mass Interaction Coefficients



Photons Spectrometer

- An incident photon can deposit its full energy by:
  - A photoelectric interaction (A)
  - One or more Compton scatters followed by a photoelectric interaction (B)
- A photon will deposit only a fraction of its energy if it interacts by Compton scattering and the scattered photon escapes the detector (C)
  - Energy deposited depends on scattering angle, with larger angle scatters depositing larger energies

Possible Interactions



Interactions (cont.)

- Detectors normally shielded to reduce effects of natural background radiation and nearby radiation sources
- An x-ray or gamma-ray may interact in the shield of the detector and deposit energy in the detector:
  - Compton scatter in the shield, with the scattered photon striking the detector (E)
  - A characteristic x-ray from the shield may interact with the detector (F)