

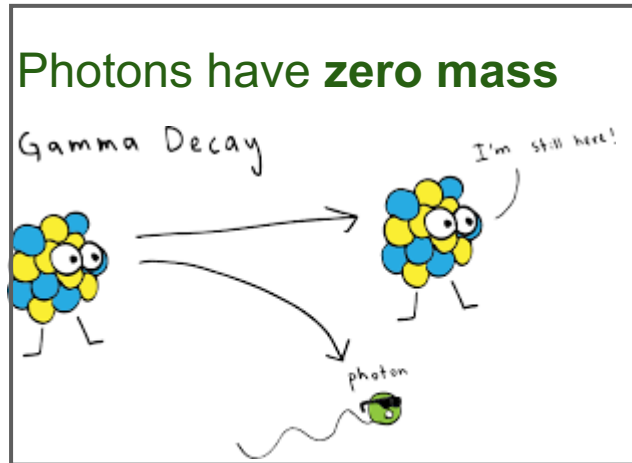
Lecture:

Interaction of radiation with matter-II

Chapter 2 in Leo:

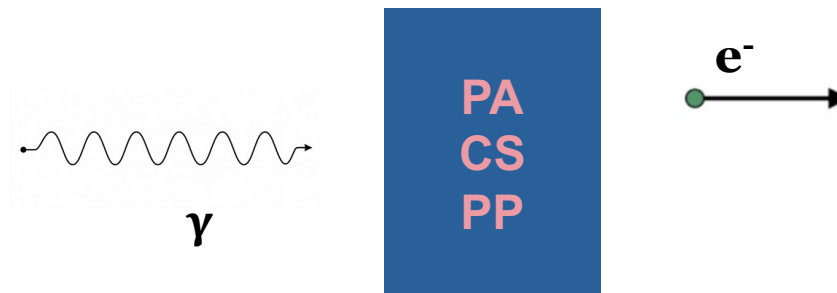
2.7, 2.8

Photons (**γ rays** and X rays)

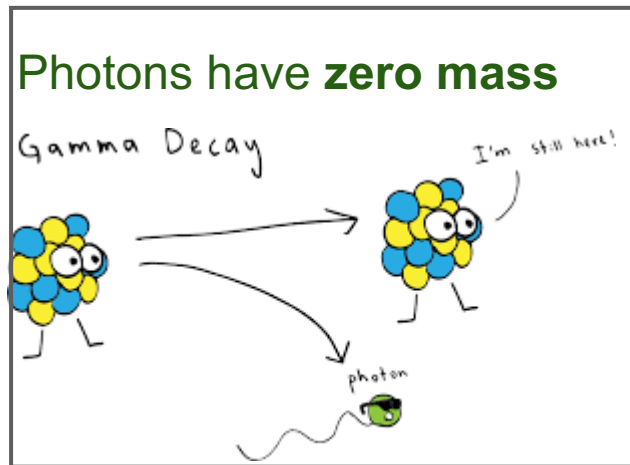


Photons interact with matter in three main processes:

- 1) **Photoelectric Effect (Absorption)**
- 2) **Compton Scattering**
- 3) **Pair production**

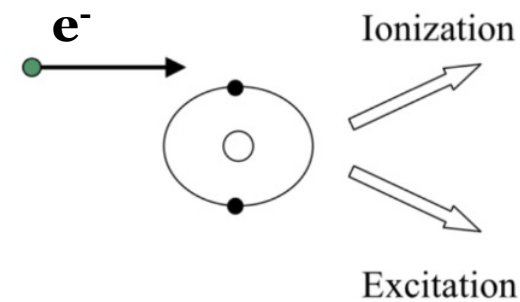
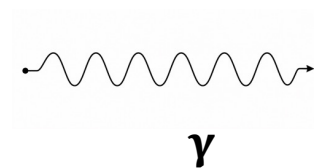


Photons (**γ rays** and X rays)



Photons interact with matter in three main processes:

- 1) **Photoelectric Effect (Absorption)**
- 2) **Compton Scattering**
- 3) **Pair production**



Important features of photons:

- Photons are more penetrating than heavy-charged particles

Because of much smaller cross section of PA, CS, and PP than the inelastic electron collision cross section, only a fraction of them will interact with the matter.

- A beam of photons is not degraded in energy but only attenuated in intensity when passing through the material.

Some fraction of photons will undergo PA, CS, or PP and convert into electrons and the remaining ones (a bigger fraction) will pass through the detector or absorber material causing an attenuation of the beam.



Neutrons are neutral and uncharged and thus more penetrating than heavy charged particles, electrons. Indirect ionizing radiation.

Neutrons interact with matter by bypassing atomic electron clouds to collide directly with atomic nuclei (strong force).

Like photons, a beam of neutrons is not degraded in energy but only attenuated in intensity when passing through the material.

Who is more penetrating, neutrons or photos?

In Water

In Led (^{208}Pb)

Who is more penetrating, neutrons or photons?

In Water

Photons are more penetrating.

A neutron weighs almost exactly the same as a hydrogen nucleus (a single proton), it transfers maximum energy during a collision. They get slowed down and absorbed very quickly. This is why water tanks and concrete are used to shield against neutrons.

Photons need more electrons to undergo PA, CS, PP.

In Lead (^{208}Pb)

Neutrons are more penetrating:

Photons interact heavily with the dense electron clouds of heavy metals, which easily absorb or scatter them (PA, CS, PP). Neutrons, however, don't care about electrons. They easily pass right through heavy atoms until they hit a rare nucleus. This is why a block of lead stops X-rays completely but lets neutrons pass through relatively easily.

Today

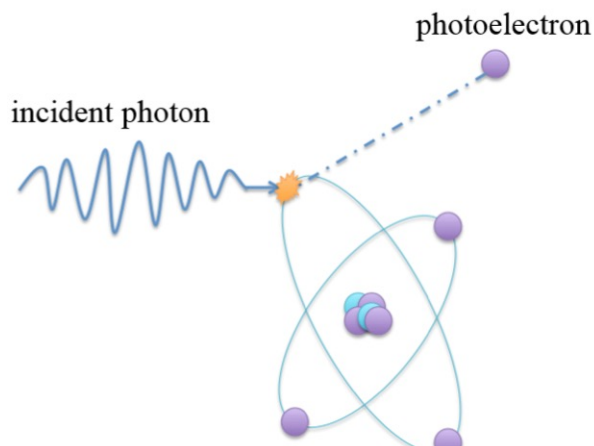
- Gamma rays
 - PA, CS, PP
 - Attenuation coefficient
 - Photons in NP, HEP
- Neutrons
 - Energy loss mechanism
 - Energy dependence
 - Slow and fast neutrons

Today

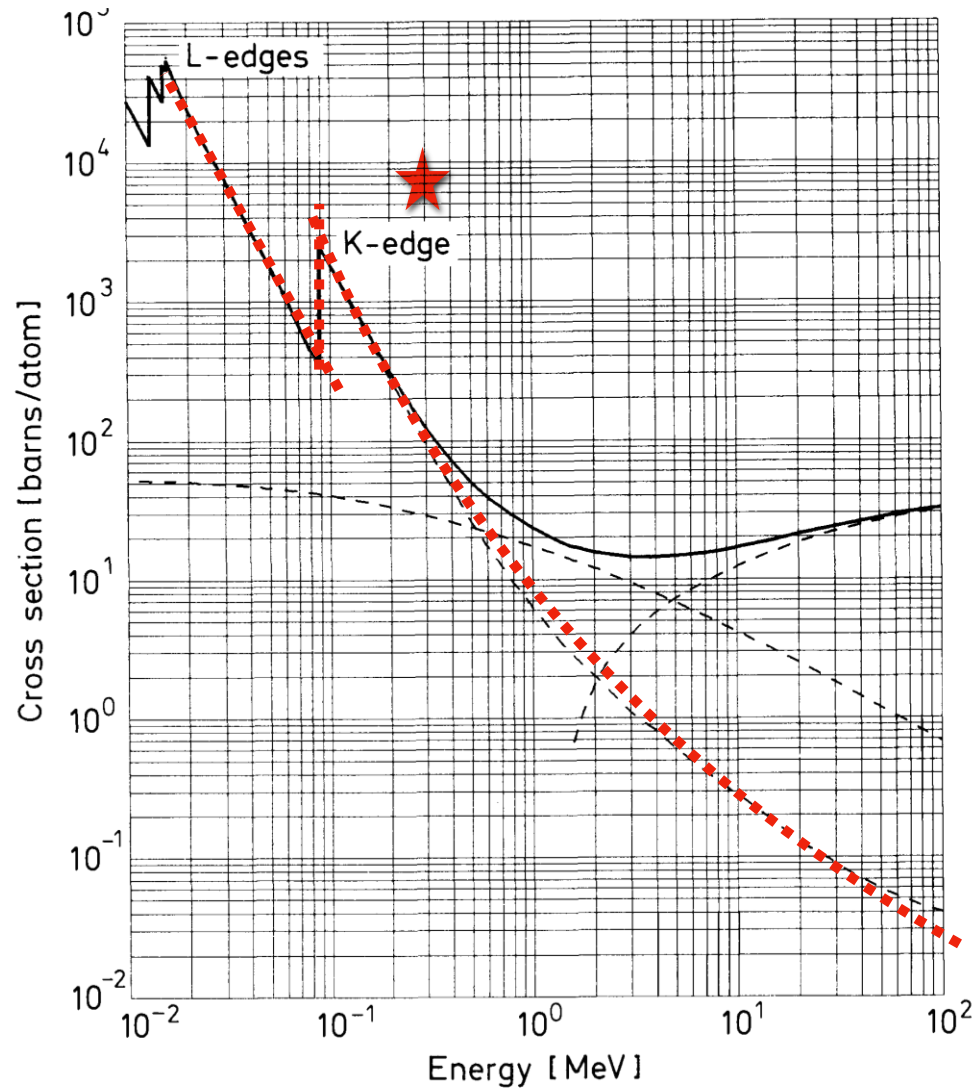
- Gamma rays
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1. Photoelectric effect (absorption)

- A photon interacts with a **bound electron** of the atom and this electron is emitted while the photon is absorbed. The emitted electron is called photoelectron.
- Process correctly explained by Einstein in 1905
- Electrons in K-shell are more bound. PA will be higher for K-shell electrons than L-shell ones.
- The smaller the incoming photon energy, the higher probability of PA.



Photoelectron is the one causes ionization of the atoms of the detector material. (energy loss of electron with the matter.)



Probability for photoelectric absorption

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

n=4 or 5

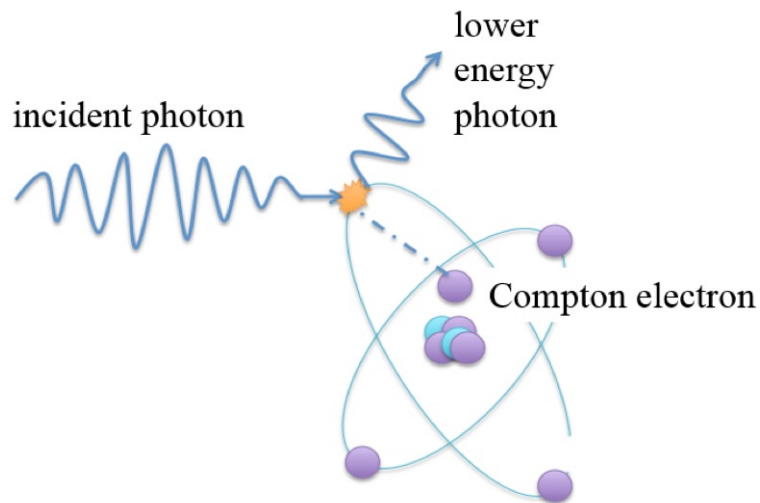
- Strong energy dependence
- High Z detector materials higher PA

2. Compton scattering

- The scattering of photons occurs on free electrons:

In matter, the electrons are bound; however, if the photon energy is high with respect to the binding energy, this latter energy can be ignored and the electrons can be considered as essentially free.

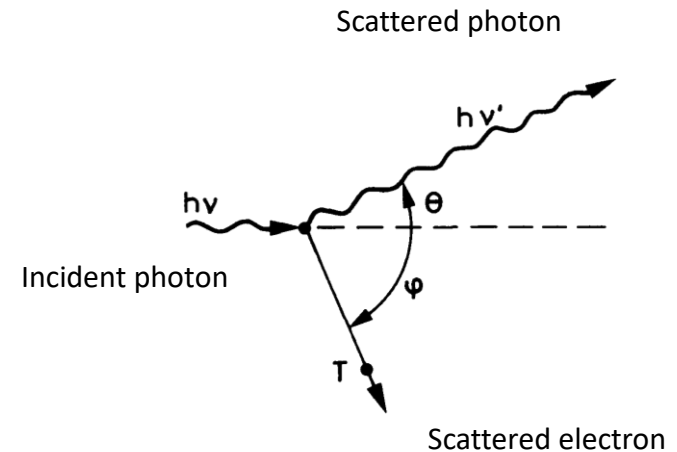
- The photon gives a part of its energy to an electron and is scattered with lower energy.
- Note that once the energy of the photon increases around 1 MeV, the probability for CS increases and competes largely with PA.



2. Compton scattering

(Scattered photon energy)

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1 - \cos \theta)}$$



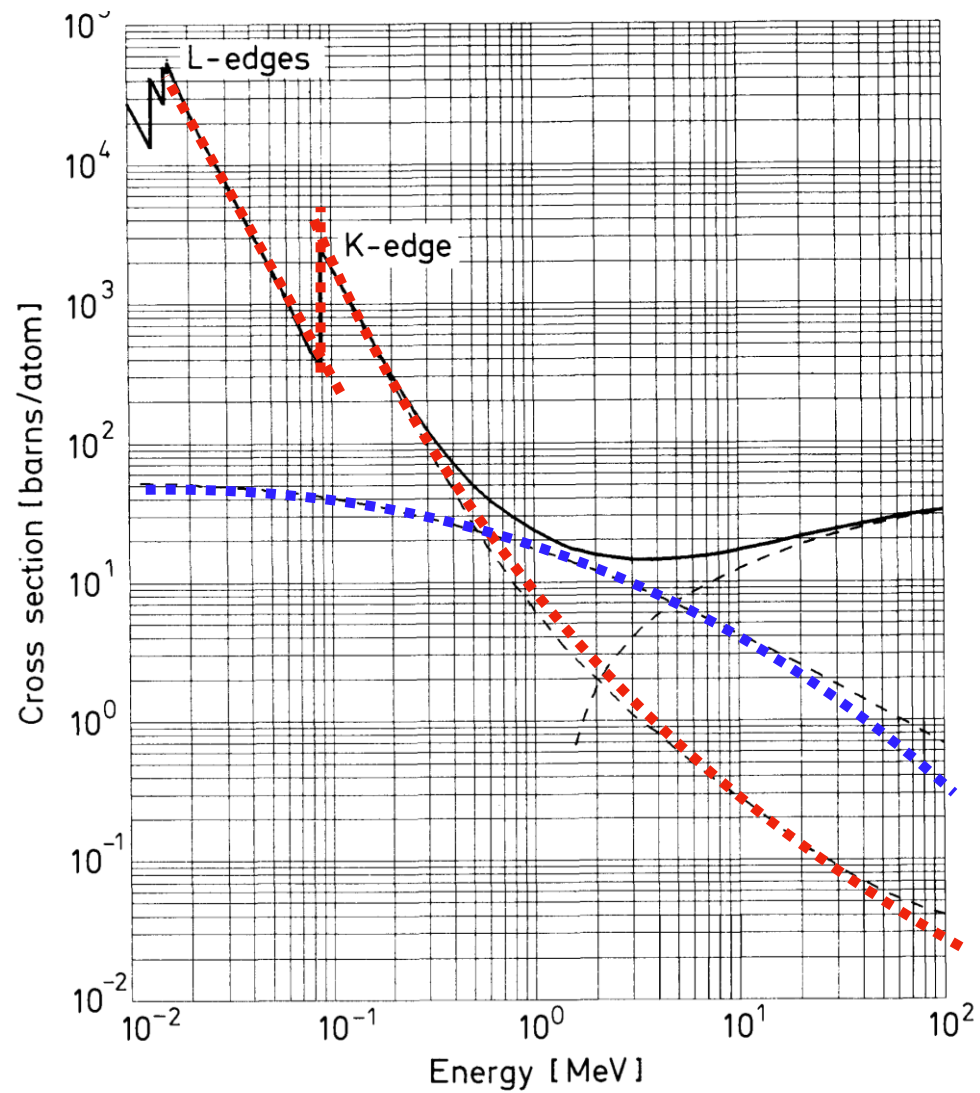
What happens to the scattered photon and electron inside the material?

- Scattered electron leaves its atom, ionizing it and loses its energy via collision with the electrons in the medium.
- Energy loss via Bremsstrahlung will not occur at energies of a few MeV or less, which is the energy regime for NP experiments.
- Scattered photon will continue on its new path, causing further ionization and often exiting the detector material.

(Scattered electron energy)

$$T = h\nu - h\nu' = h\nu \frac{\gamma(1 - \cos \theta)}{1 + \gamma(1 - \cos \theta)}$$

Experiment IV for FYS4505/9505:
Derivation of the CS formulas for
scattered photon and electron



Probability for PA

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

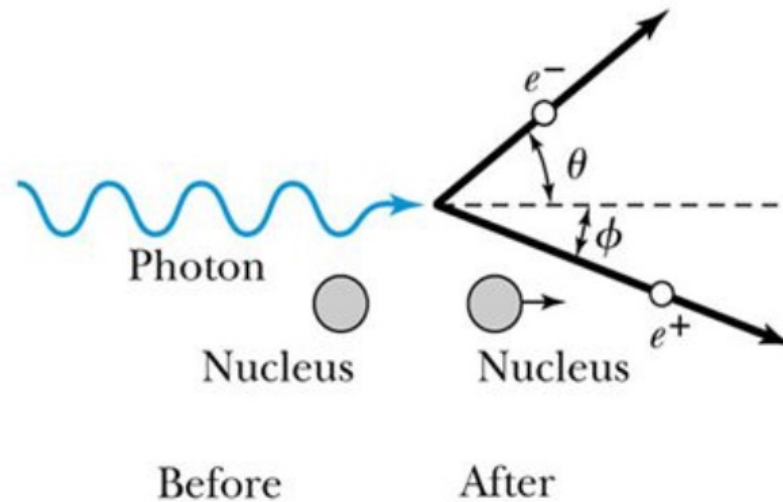
$n=4 \text{ or } 5$

Probability of CS

$$\sigma_C \approx \text{const.} Z$$

3. Pair Production

A photon of at least 1.02 MeV or the equivalent of two electrons masses ($2m_0c^2$) can create an electron positron pair. In empty space, momentum and energy cannot be conserved. In the vicinity of a nucleus, the process is possible since the nucleus can carry some momentum and energy.



Probability for PA

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

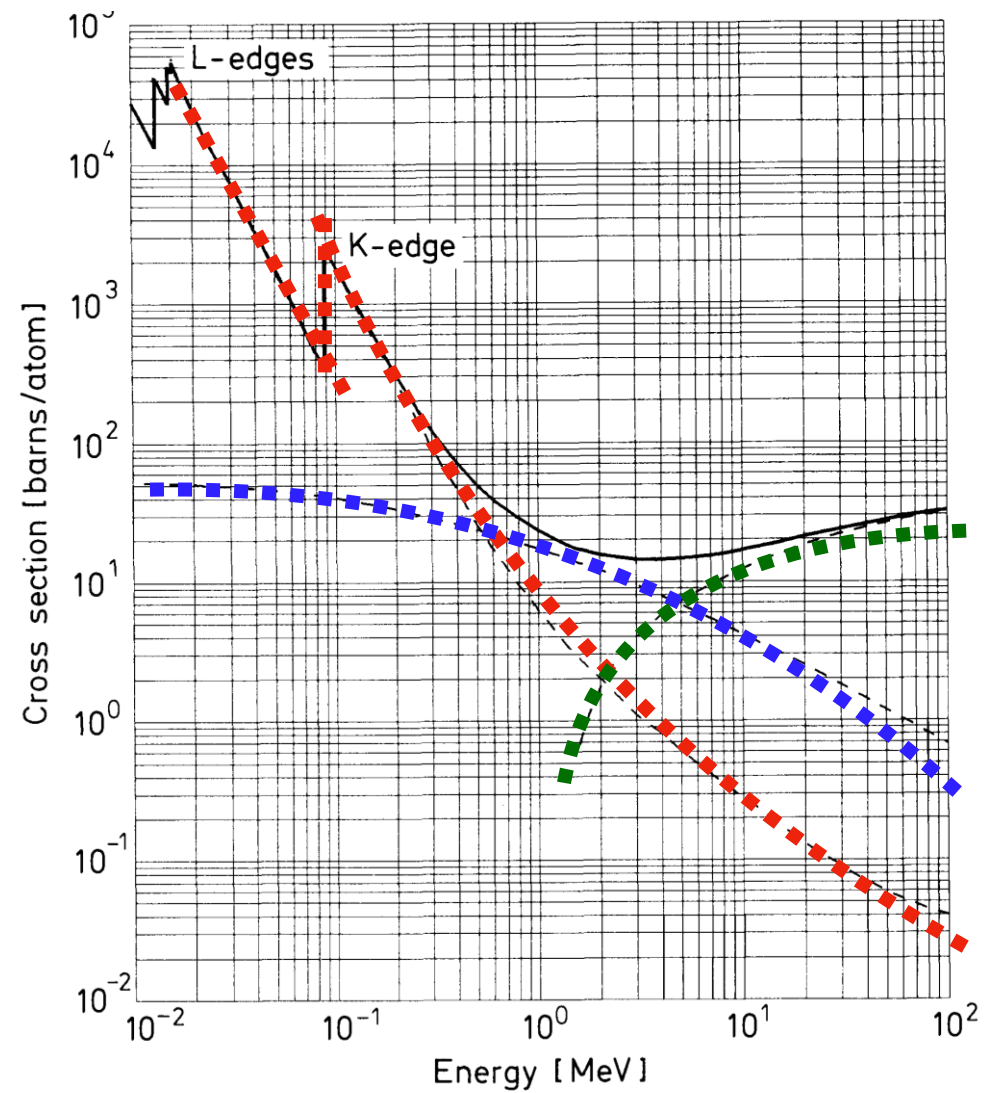
$n=4 \text{ or } 5$

Probability of CS

$$\sigma_C \approx \text{const.} Z$$

Probability of PP

$$\sigma_{pp} \approx \text{const.} Z^2$$



$$\sigma_T = \tau + \sigma_C + \sigma_{PP}$$

Probability for PA

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

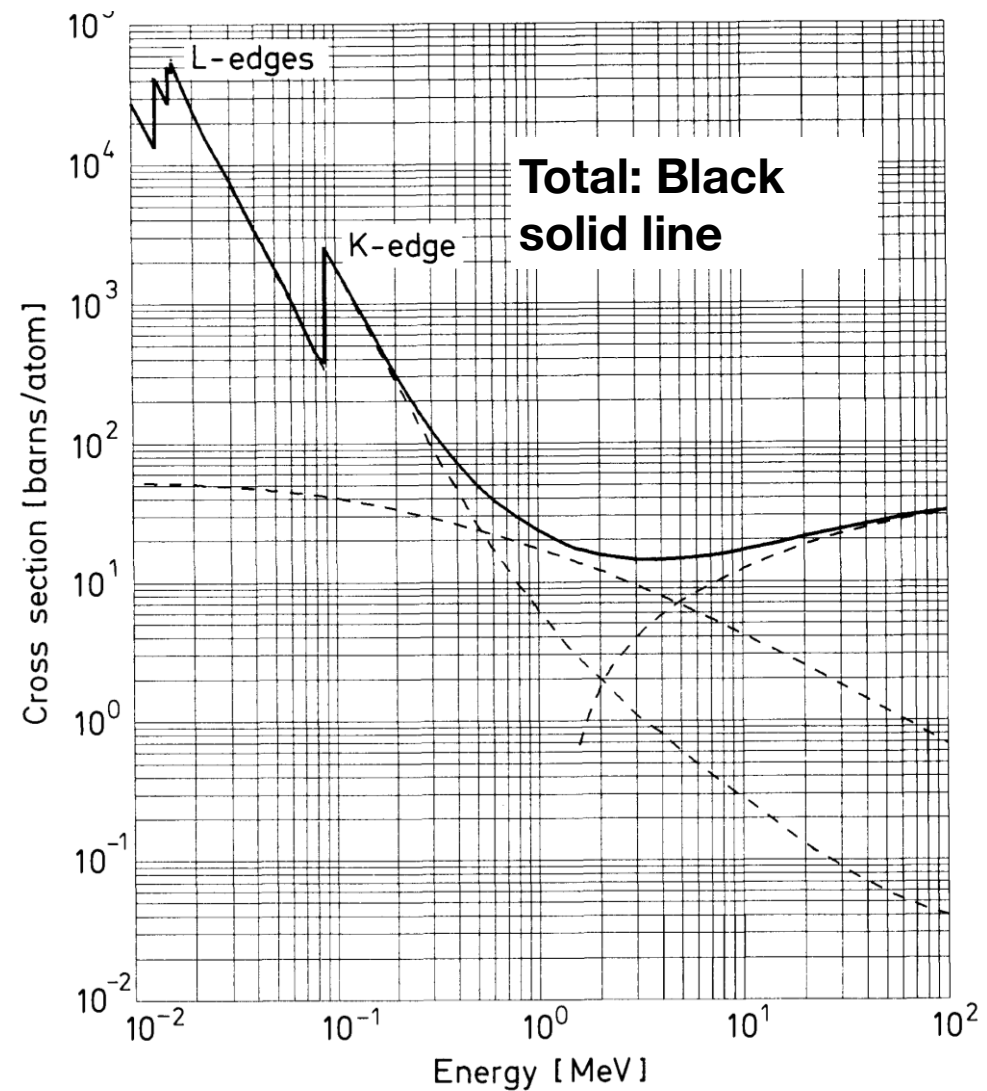
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Probability of CS

$$\sigma_C \approx \text{const.} Z$$

Probability of PP

$$\sigma_{pp} \approx \text{const.} Z^2$$



$$\sigma_T = \tau + \sigma_C + \sigma_{PP}$$

Probability for PA

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

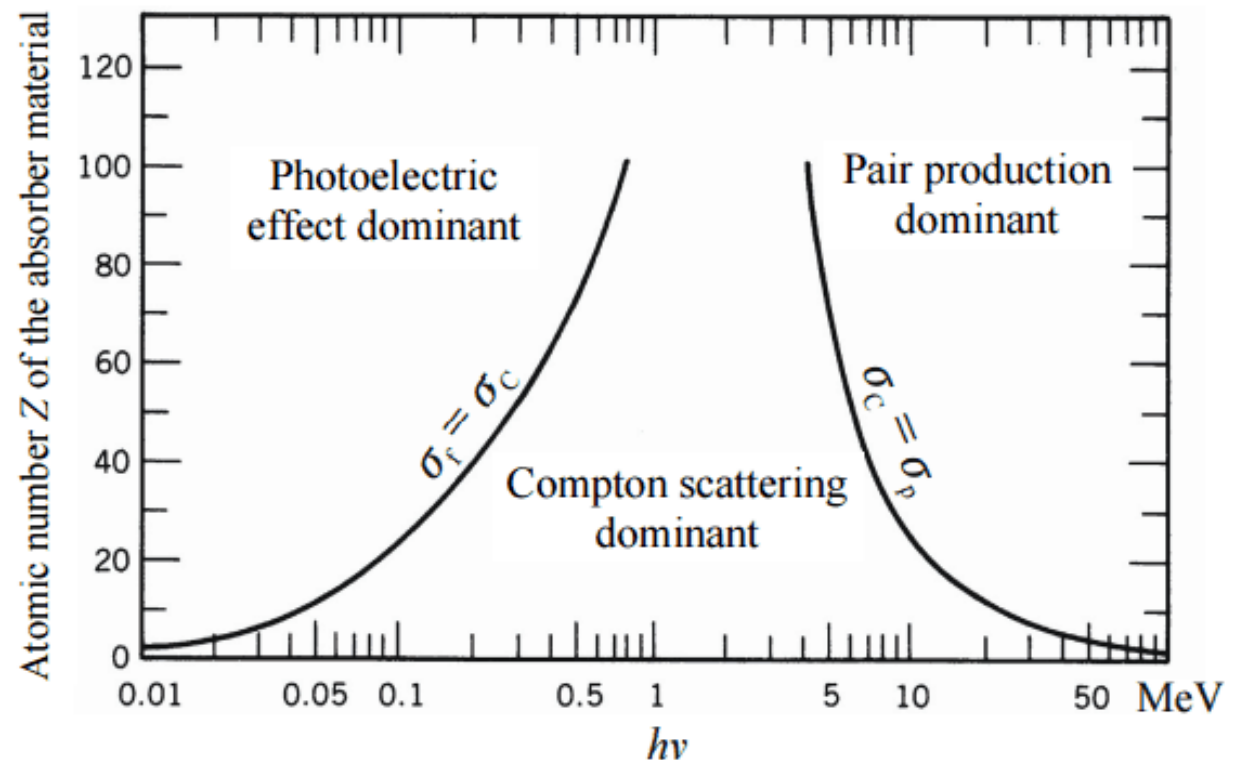
n=4 or 5

Probability of CS

$$\sigma_C \approx \text{const.} \cdot Z$$

Probability of PP

$$\sigma_{pp} \approx \text{const.} \cdot Z^2$$



Q: If we want to detect the whole energy of an incoming photon, what formula you would choose among these three?

$$\sigma_T = \tau + \sigma_C + \sigma_{PP}$$

Probability for PA

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

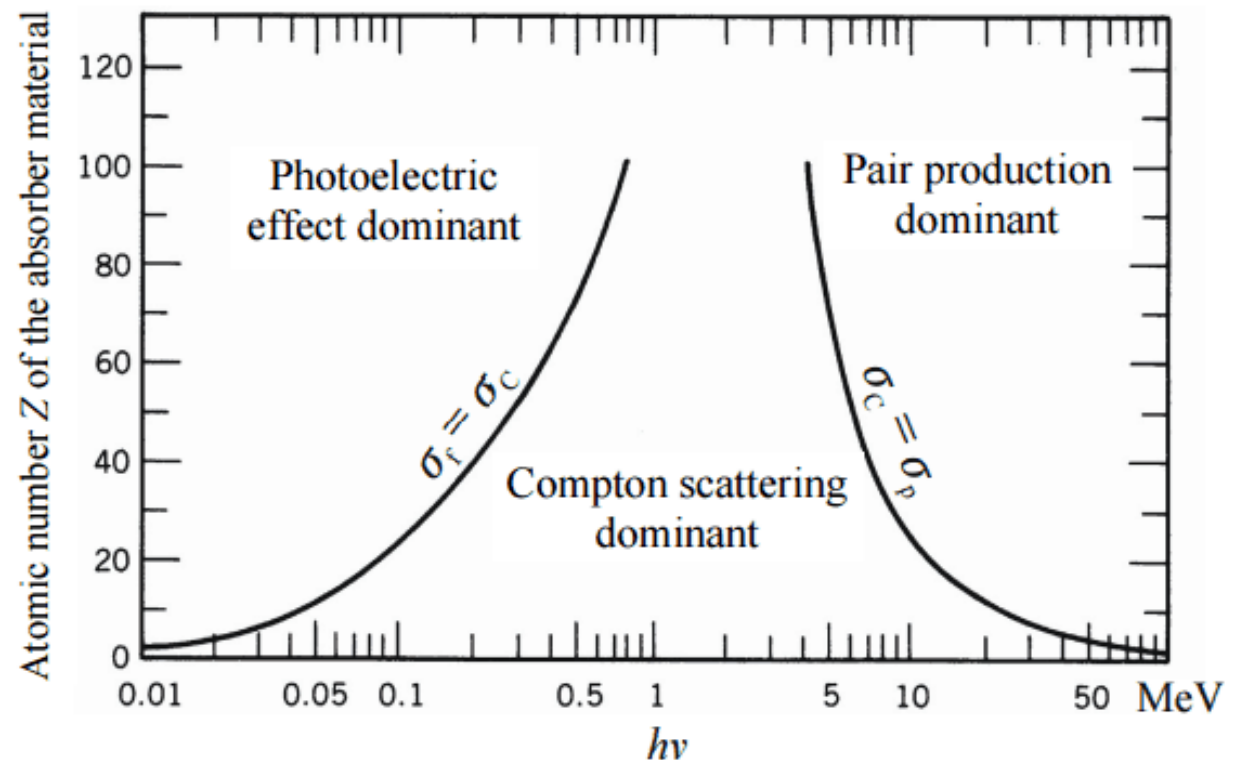
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Probability of CS

$$\sigma_C \approx \text{const.} \cdot Z$$

Probability of PP

$$\sigma_{pp} \approx \text{const.} \cdot Z^2$$



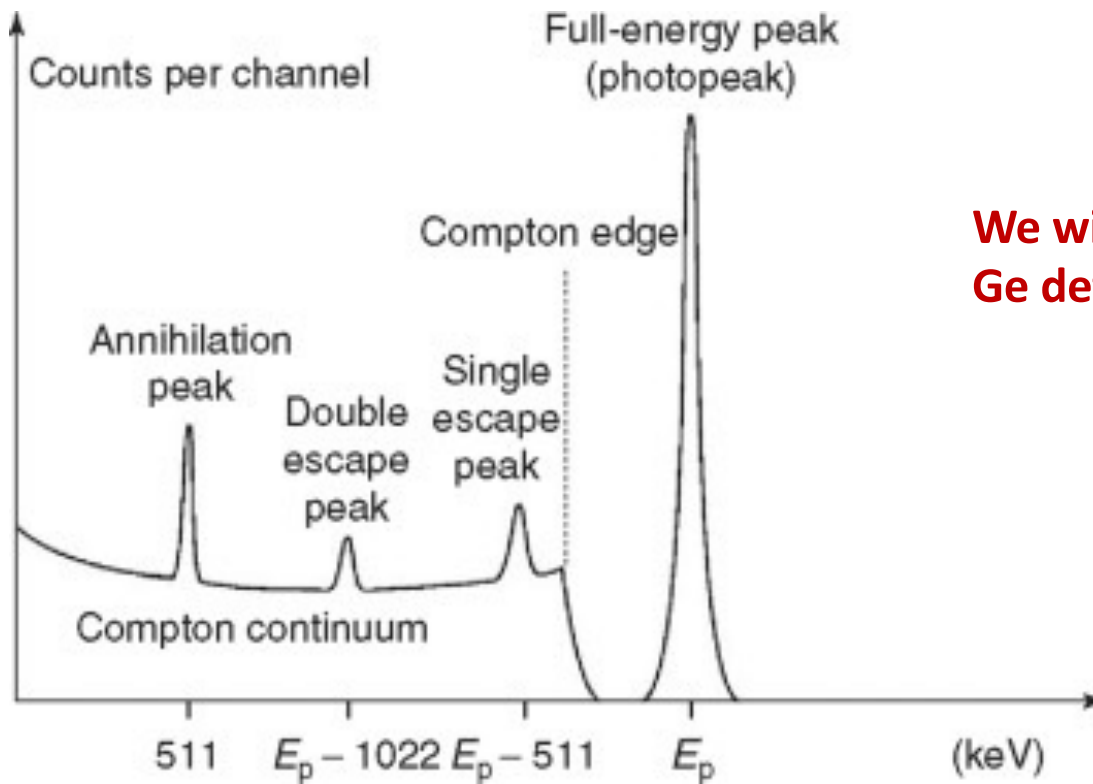
A: Photo electric absorption formula

High Z materials for gamma-ray detection!

We can design best gamma-ray detectors if we know how they interact with matter.

One important note:

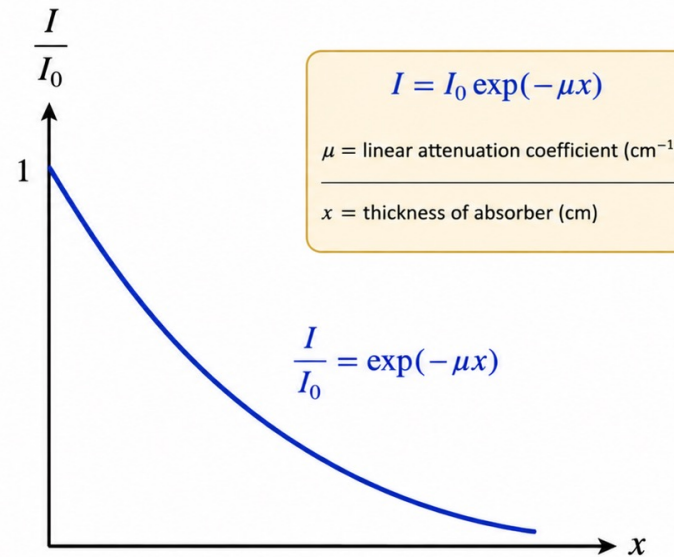
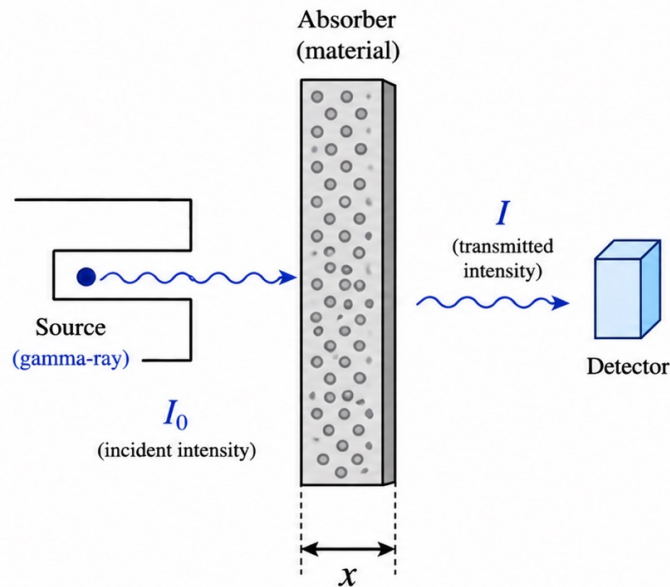
One energetic gamma ray (Depending on its energy) can cause an energy spectrum like below. We therefore, should know how a gamma ray interact with matter.



We will do experiments using NaI(Tl) and Ge detectors and detect gamma rays.

Attenuation coefficient

Photon (gamma-ray) attenuation



$$\mu = N\sigma_T$$

$$N = \frac{\rho N_A}{A}$$

$$\sigma_T = \tau + \sigma_C + \sigma_{PP}$$

N : density of atoms

N_A : Avagadro number: $6.02 \times 10^{23} [\text{mol}^{-1}]$

ρ : density of the material [g/cm^3]

A : molecular weight [g/mol] $\rightarrow A(^{27}\text{Al})=27 \text{ g}/\text{mol}$

$\sigma_T = [\text{cm}^2]$

τ : Photoelectric absorption cross section

σ_C : Compton scattering cross section

σ_{PP} : Pair production cross section

Photons interact with matter in three main processes:

- 1) **Photoelectric Effect (Absorption)**
- 2) **Compton Scattering**
- 3) **Pair production**

1) Rayleigh scattering (coherent scattering)

Elastic scattering of the photon from the atom

1) Thompson scattering

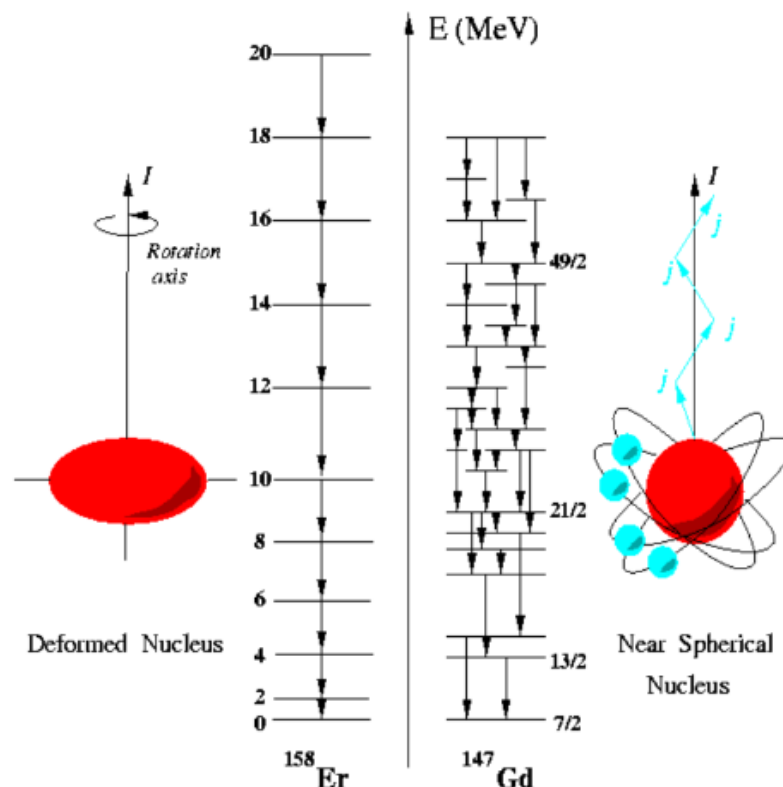
Elastic scattering of the photon from the free electron

Photon does not lose energy in these two processes.

Photons in Nuclear Physics

Gamma-rays and their detection mean a lot for Nuclear Physics

Nuclear Structure!!

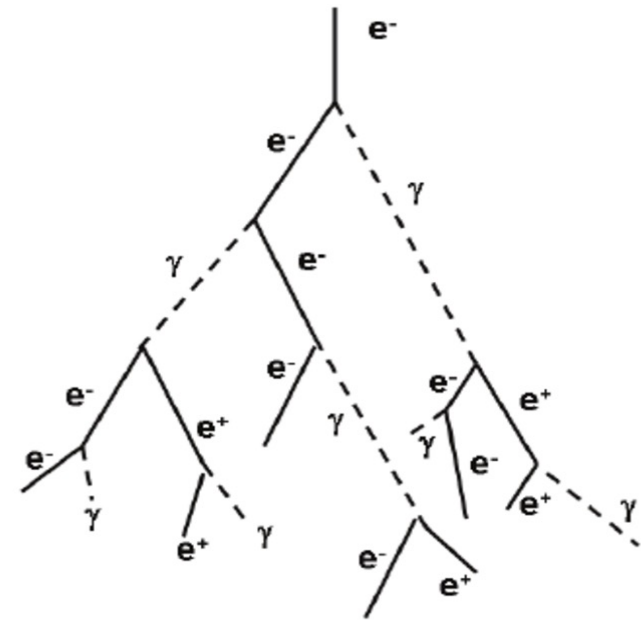
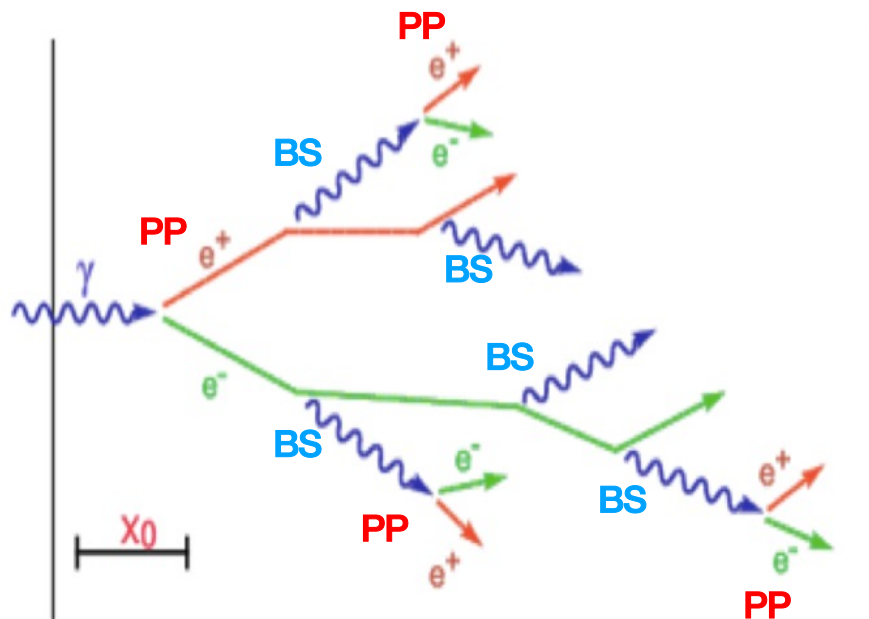


- There are two basic ways of generating high-spin states in a nucleus
 - Collective** (in-phase) motions of the nucleons: vibrations, rotations etc
 - Single-particle** effects: pair breaking, particle-hole excitations. The individual spins of a few nucleons j_i generate the total nuclear spin

Photons (and electrons) in High-Energy Physics

What happens when an energetic photon interacts with matter?

EM showers happen



Alex and Trine will go through EM showers in detail.

Today

- Gamma rays
 - PA, CS, PP
 - Attenuation coefficient
 - Photons in NP, HEP
- Neutrons
 - Energy loss mechanism
 - Energy dependence
 - Slow and fast neutrons

- **Neutron interactions are dominated by collisions *with nuclei !!!***
- Electromagnetic interactions involving neutrons are rather weak
- Their interaction differ as a function of energy
- Scattering (elastic, inelastic), capture or fission reactions, etc occur (nuclear reactions)

- Neutrons are neutral and do not ionize matter directly.
- Instead, they produce secondary (heavy) charged particles that create the detectable ionization.
- These charged particles are either:
 - reaction products from neutron-induced nuclear reactions, or
 - recoil nuclei produced by elastic or inelastic neutron scattering.
- The type of interaction depends strongly on the neutron energy.

"If neutrons are neutral, how do we detect them?"

Charged Particulate Radiations		Uncharged Radiations
Heavy charged particles (characteristic distance $\cong 10^{-5}$ m)	⇐	Neutrons (characteristic length $\cong 10^{-1}$ m)
Fast electrons (characteristic distance $\cong 10^{-3}$ m)	⇐	X-rays and gamma rays (characteristic length $\cong 10^{-1}$ m)

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"If neutrons are neutral, how do we detect them?"

Most neutron detectors work by converting neutrons into charged particles, which are then detected via their ionization.

Charged Particulate Radiations		Uncharged Radiations
Heavy charged particles (characteristic distance $\cong 10^{-5}$ m)		Neutrons (characteristic length $\cong 10^{-1}$ m)
Fast electrons (characteristic distance $\cong 10^{-3}$ m)	$\Leftarrow$	X-rays and gamma rays (characteristic length $\cong 10^{-1}$ m)

Classification of neutrons (can be different)

High energy neutrons: $E > 20 \text{ MeV}$
Fast neutrons: $10 \text{ keV} < E < 1 \text{ MeV}$
Epithermal neutrons: $1 \text{ eV} < E < 10 \text{ keV}$
Slow neutrons: $0.025 \text{ eV} < E < 1 \text{ eV}$
Thermal neutrons $E \leq 0.025 \text{ eV}$
Cold neutrons: $E < 0.025 \text{ eV}$

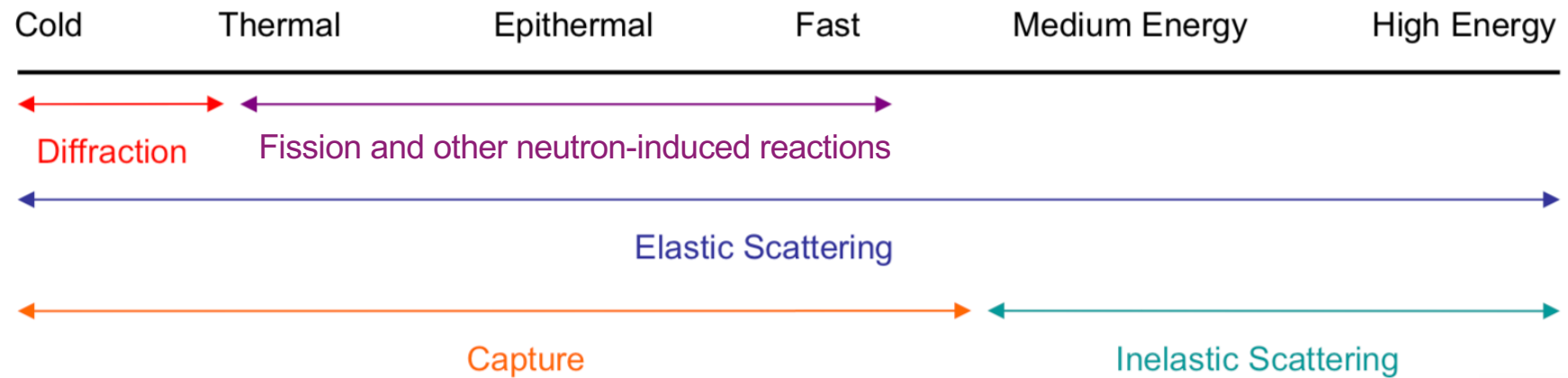
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High energy neutrons: $E > 10 \text{ MeV}$
Medium-energy neutrons: $> 1 \text{ MeV}$
Fast neutrons: $> 50 \text{ keV}$
Epithermal neutrons: $0.5 \text{ eV} < E < 50 \text{ keV}$
Thermal neutrons $E < 0.5 \text{ eV}$
Cold neutrons: $E < 0.001 \text{ eV}$

D. Hamilton et al.
European Commission
Institute for Transuranium Elements, Germany

High energy neutrons: $E > 100 \text{ MeV}$
Fast neutrons: $100 \text{ keV} < E < 10 \text{ MeV}$
Epithermal neutrons: $0.1 \text{ eV} < E < 100 \text{ keV}$
Thermal/slow neutrons $E \cong 0.025 \text{ eV}$
Cold neutrons: $E < 0.001 \text{ eV}$

Book: W.Leo



Total probability for a neutron to interact with matter

$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{capture}} + \dots$$

Neutrons are attenuated like gamma rays

Transmitted intensity (neutron flux) I

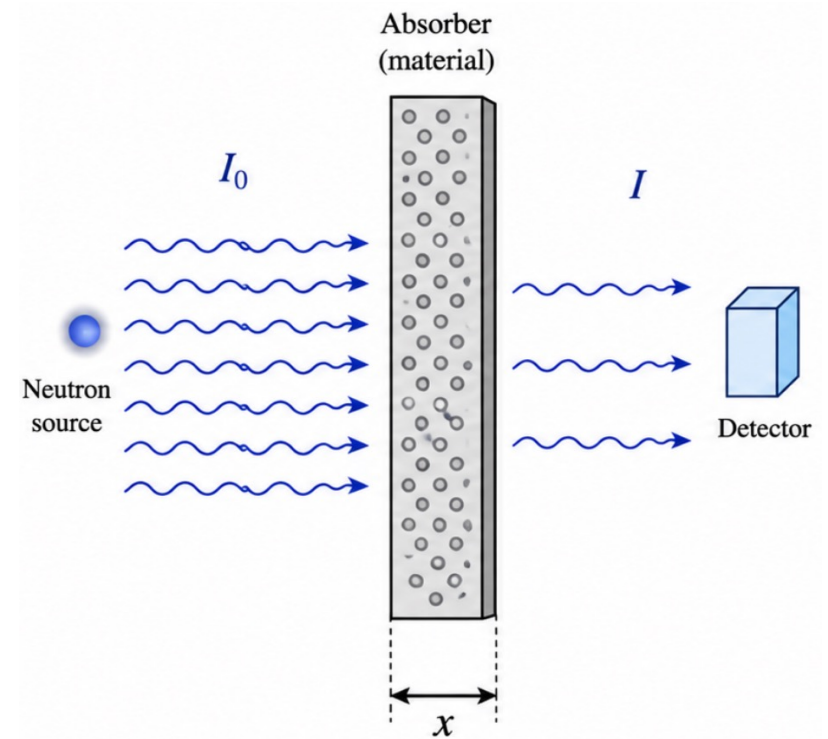
Initial intensity (neutron flux) I_0

Number of nuclei N

Total cross section σ_t

Thickness of the absorber material x

$$I = I_0 \exp(-N\sigma_t x)$$



$$N = \frac{\rho N_A}{A}$$

N : density of atoms

N_A : Avagadro number: $6.02 \times 10^{23} [\text{mol}^{-1}]$

ρ : density of the material $[\text{g}/\text{cm}^3]$

A : molecular weight $[\text{g}/\text{mol}] \rightarrow A(^{27}\text{Al})=27 \text{ g}/\text{mol}$

$$\sigma_t = \sigma_s + \sigma_a$$

σ_s : scattering cross section

σ_a : absorption cross section

Unit: barn ($1 \text{ barn} = 10^{-24} \text{ cm}^2$)

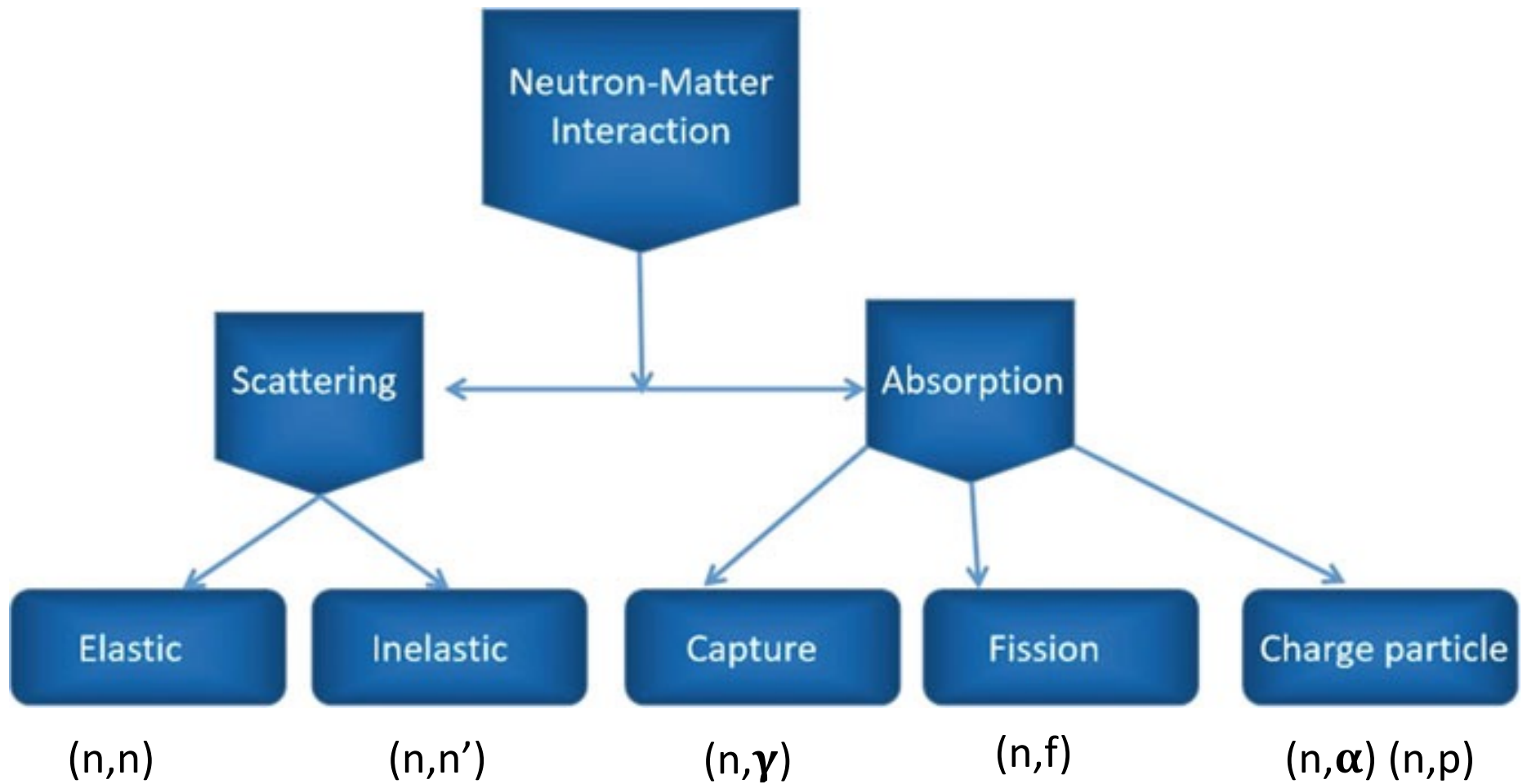
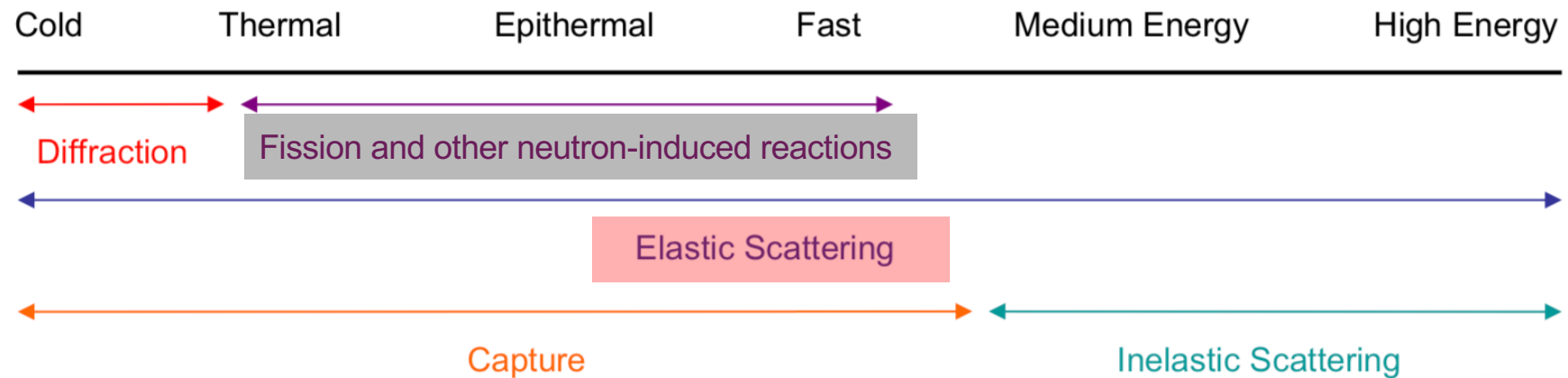


Figure from: https://link.springer.com/chapter/10.1007/978-981-16-6273-7_1

Slow neutrons



1- Elastic scattering with the nuclei of the absorber material

most probable

not desired for slow neutron detection since little energy is transferred

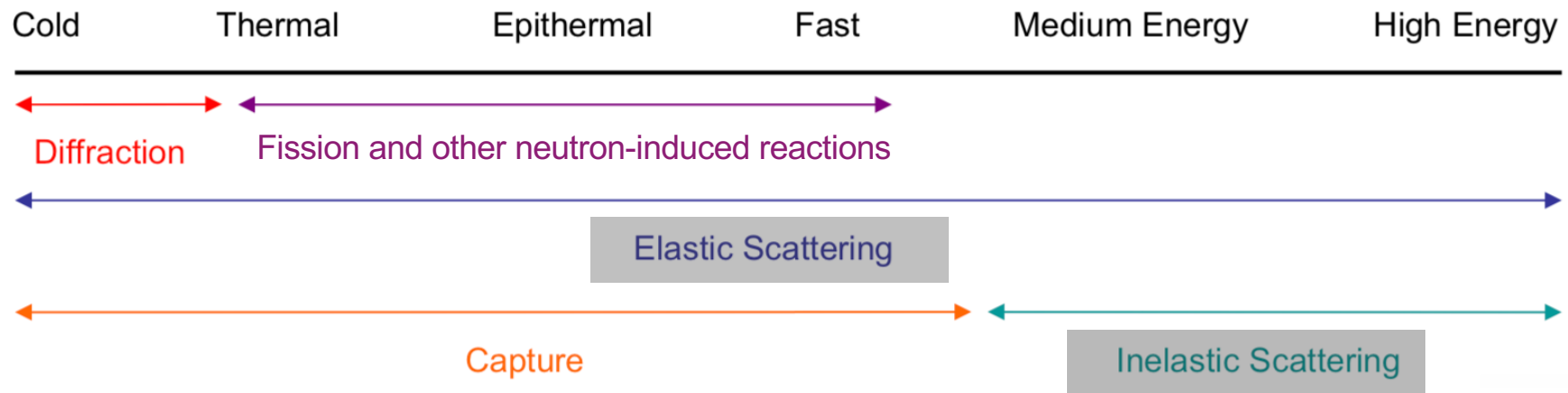
2- neutron-induced nuclear reactions

Thermal/slow neutrons have low energy $\rightarrow$ Q reaction energy must be positive

(n, γ) radiative capture reaction, not very desired since γ rays are difficult to detect

(n, p) , (n, α) , $(n, \text{fission})$ are better welcomed since the detection of charged particles is easier and more efficient.

Fast neutrons



1- neutron-induced nuclear reactions are less probable with increasing neutron energy

Instead, scattering becomes greater

Neutron transfers sufficient energy in each collision to the recoiling nucleus

Neutrons are then moderated and slowed down. The best moderator is hydrogen (protons)

Elastic scattering will happen for fast neutrons too. Energy loss will be significant.

2- inelastic scattering happens when fast neutrons have enough high energy

Recoiled nucleus is now elevated to one of its excited state

As a result of this excitation, the recoiling nucleus will de-excite gamma rays.

Neutron will lose more energy with inelastic scattering compared to elastic scattering.

Inelastic scattering and the subsequent secondary gamma rays play an important role in the shielding of high energy

neutrons but are an unwanted complication in the response of most fast neutron detectors

B. Slow Neutron Interactions

For slow neutrons, the significant interactions include elastic scattering with absorber nuclei and a large set of neutron-induced nuclear reactions. Because of the small kinetic energy of slow neutrons, very little energy can be transferred to the nucleus in elastic scattering. Consequently, this is not an interaction on which detectors of slow neutrons can be based. Elastic collisions tend to be very probable, however, and often serve to bring the slow neutron into thermal equilibrium with the absorber medium before a different type of interaction takes place. Much of the population in the slow neutron energy range will therefore be found among these *thermal neutrons*, which, at room temperature, have an average energy of about 0.025 eV.

The slow neutron interactions of real importance are neutron-induced reactions that can create secondary radiations of sufficient energy to be detected directly. Because the incoming neutron energy is so low, all such reactions must have a positive Q -value to be energetically possible. In most materials, the radiative capture reaction [or (n, γ) reaction] is the most probable and plays an important part in the attenuation or shielding of neutrons. Radiative capture reactions can be useful in the indirect detection of neutrons using activation foils as described in Chapter 19, but they are not widely applied in active neutron detectors because the secondary radiation takes the form of gamma rays, which are also difficult to detect. Instead, reactions such as (n, α) , (n, p) , and $(n, \text{fission})$ are much more attractive because the secondary radiations are charged particles. A number of specific reactions of this type are detailed in Chapter 14.

C. Fast Neutron Interactions

The probability of most neutron-induced reactions potentially useful in detectors drops off rapidly with increasing neutron energy. The importance of scattering becomes greater, however, because the neutron can transfer an appreciable amount of energy in one collision. The secondary radiations in this case are *recoil nuclei*, which have picked up a detectable amount of energy from neutron collisions. At each scattering site, the neutron loses energy and is thereby *moderated* or slowed to lower energy. The most efficient moderator is hydrogen because the neutron can lose up to all its energy in a single collision with a hydrogen nucleus. For heavier nuclei, only a partial energy transfer is possible [see Eq.(15.4) and the associated discussion].

If the energy of the fast neutron is sufficiently high, *inelastic scattering* with nuclei can take place in which the recoil nucleus is elevated to one of its excited states during the collision. The nucleus quickly de-excites, emitting a gamma ray, and the neutron loses a greater fraction of its energy than it would in an equivalent elastic collision. Inelastic scattering and the subsequent secondary gamma rays play an important role in the shielding of high-energy neutrons but are an unwanted complication in the response of most fast neutron detectors based on elastic scattering.

Summary:

Charged particles:

- collide with electrons of the detector material
- ionization and excitation of electrons of atoms
- Bethe-Bloch theory

Electromagnetic radiation: Gamma rays

- cannot collide directly with the electrons of the detector material
- Photoelectric Effect, Compton Scattering, Pair Production
- Annihilation radiation: 511 keV
- Bremsstrahlung
- Scattered electrons in CS follow Klein-Nishina theory

Electrons:

- collide directly with electrons
- ionization and excitation of electrons of the atoms
- Bremsstrahlung radiation
- Cherenkov
- Bethe-bloch theory

Neutrons

- Collide with the nucleus of the detector material
- Different reactions as a result of nuclear interactions
- Scattering, capture, fission

**Questions
to me?**

Questions to you

1. How do gamma rays interact with matter and cause ionization? Explain the most important processes.
2. A gamma ray sees electrons of the atoms in two different ways. Can you explain them and why?
3. How do the cross sections of the different processes depend on energy and detector material characteristics for a gamma-ray interaction through matter?
4. If we want to measure the energy of the incoming gamma ray, what process is the most ideal one?
5. How does a neutron interact with matter in general? What type of processes might occur depending on neutron's being fast or slow?
6. When a photon has incident energy in the GeV regime, what process can you expect?
7. How do electromagnetic showers develop? How much energy is needed for an electromagnetic shower to develop?