

# X-ray



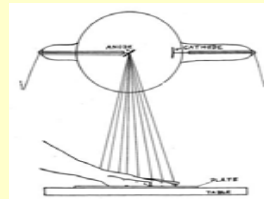
## production and properties



Glass tube with two electrodes in vacuum or in low pressure gas

## Experiments and observations of Wilhelm Conrad Roentgen

- cathode ray generates radiation in the wall of the tube
- the radiation induces fluorescence in barium platinocyanide
- it has much higher penetration than UV



This unknown radiation has high penetration distance

Roentgen's X-ray picture of the hand of his wife, taken December 22, 1895.



## Age of Wilhelm Conrad Roentgen

*1895 – the year*

Roentgen discovers X-ray

On November 27, 1895, in Paris, Alfred Bernhard Nobel signed his will.

The cinématographe (Auguste and Louis Lumière) was patented on 13 February 1895

U.S. patent for an automobile by George B. Selden

Jungle Book was written by Rudyard Kipling

## Discoveries of „Golden Years” in physics

1896: Becquerel – radioactivity

1897: Thomson – electron

1898: Pierre és Marie Curie – polonium and radium



## X-ray

Discovery – November 1895

Publication – December 1895

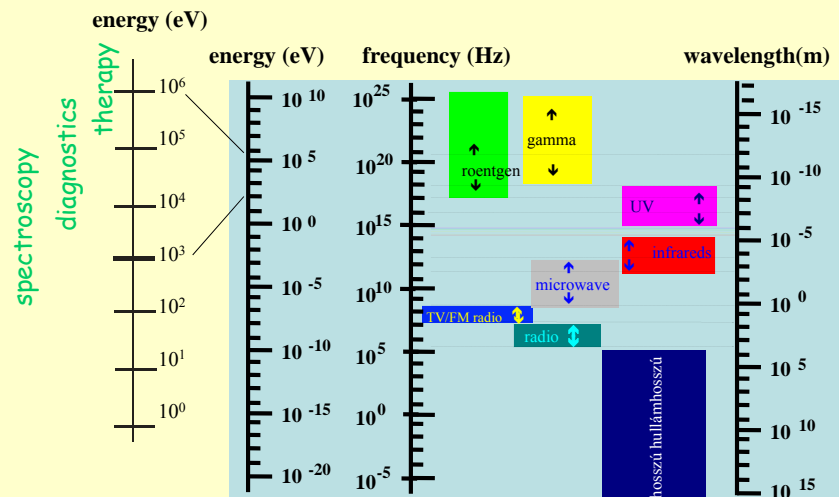
Medical application – January 1896

## Wilhelm Conrad Roentgen

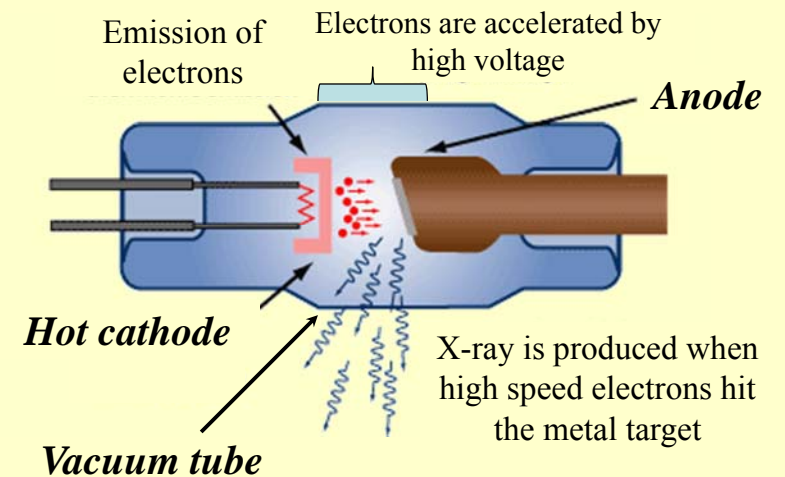
Nobel Prize in Physics 1901  
in recognition the discovery of the  
remarkable rays subsequently named  
after him

## X-ray

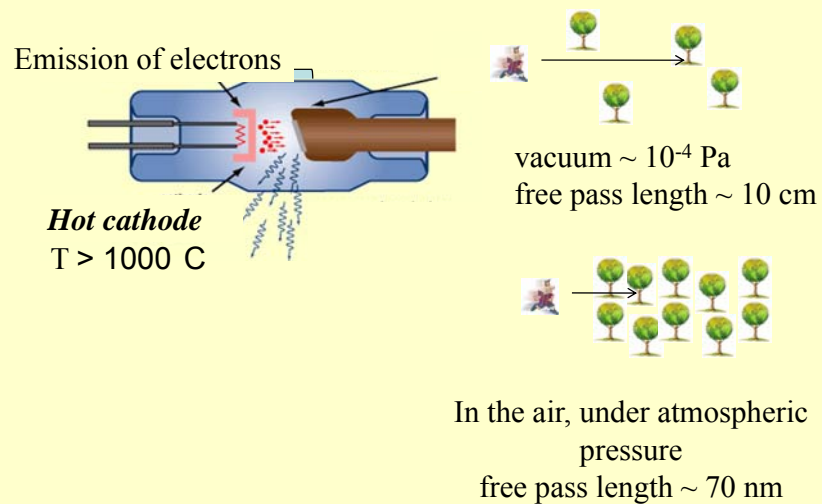
### Elektromagnetic radiation



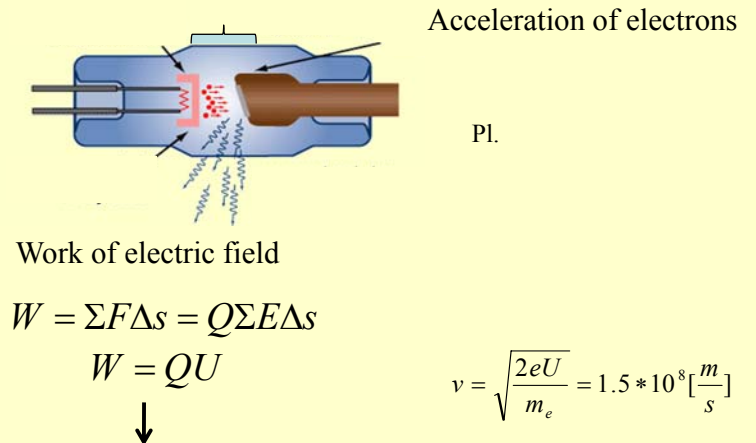
## X-ray tube



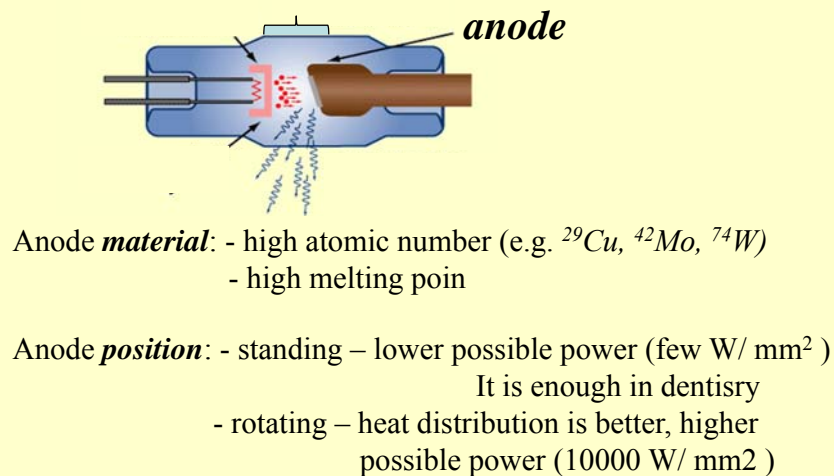
## Steps of producing X-ray



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## Steps of X-ray production

Generation of charged particles

$e^-$ ,  $H^+$ , light ions

Acceleration

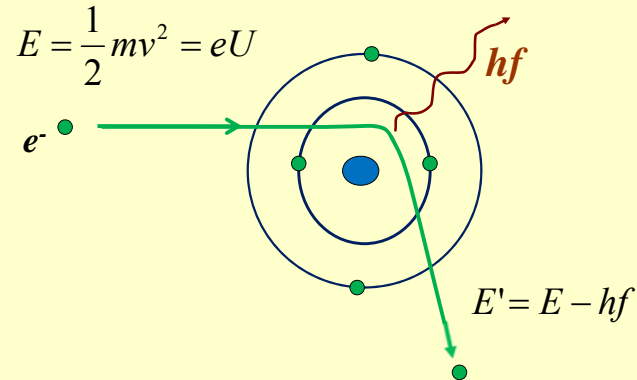
*X-ray tube, accelerators*

Deceleration

$^{29}\text{Cu}$ ,  $^{42}\text{Mo}$ ,  $^{74}\text{W}$ ,  $^{78}\text{Pt}$

# Mechanism of X-ray production

## 1. Bremsstrahlung or "braking radiation"



The electron is deflected from its original path and decelerated.

The electron's kinetic energy is reduced

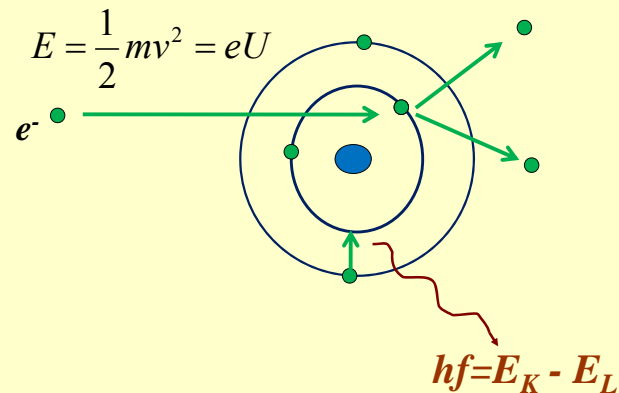
The energy lost by the electron takes the form of a Bremsstrahlung photon.

The photon energy depends on

- the kinetic energy of incoming electron
- distance of closest approach to the nucleus
- atomic number of target material

Highest photon energy is equal to the kinetic energy of incoming electron.

## 2. Characteristic radiation

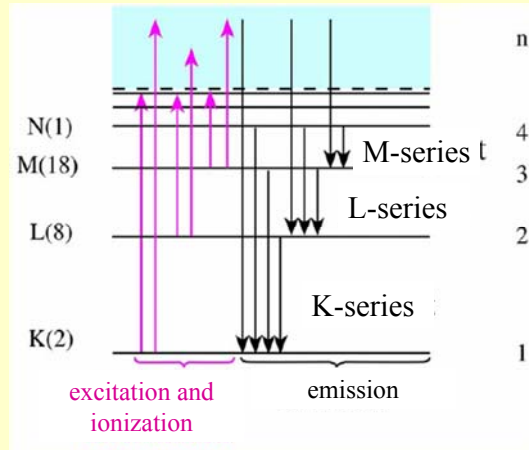


If the incident electron energy is high enough, it may interact with an (inner) orbital electron, ejecting it from its orbit (excitation/ionization).

The vacancy is occupied by an electron from a higher orbits

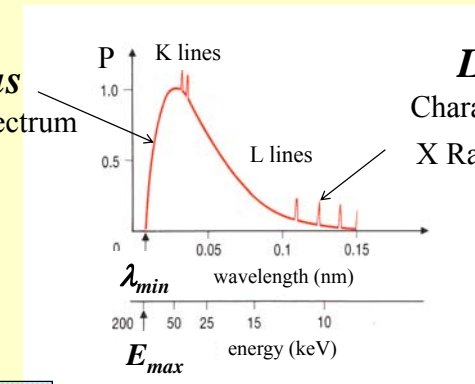
The discrete excess energy is emitted as a characteristic photon

## Possible energy transitions of the Cu-atom with 29 electrons



## Spectral properties of X-ray

**Continuous**  
Bremsstrahlung spectrum

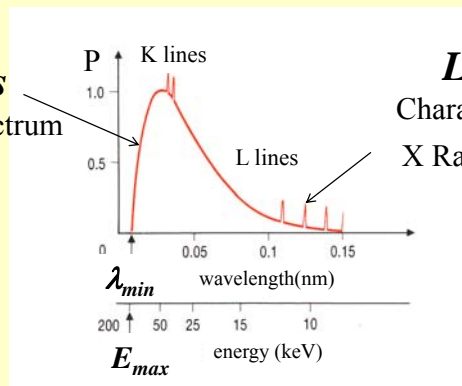


**Line**  
Characteristic  
X Radiation

$$\lambda_{min} = \frac{hc}{eU}$$

## Spectral properties of X-ray

**Continuous**  
Bremsstrahlung spectrum



**Line**  
Characteristic  
X Radiation

$$\lambda_{min} = \frac{hc}{eU}$$

**Duane-Hunt law**

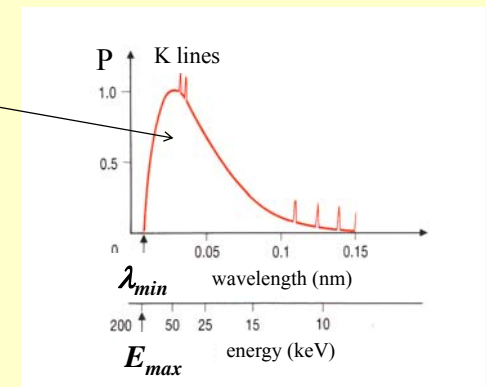
## Power and efficiency of X-ray tube

$$P = cIU^2Z$$

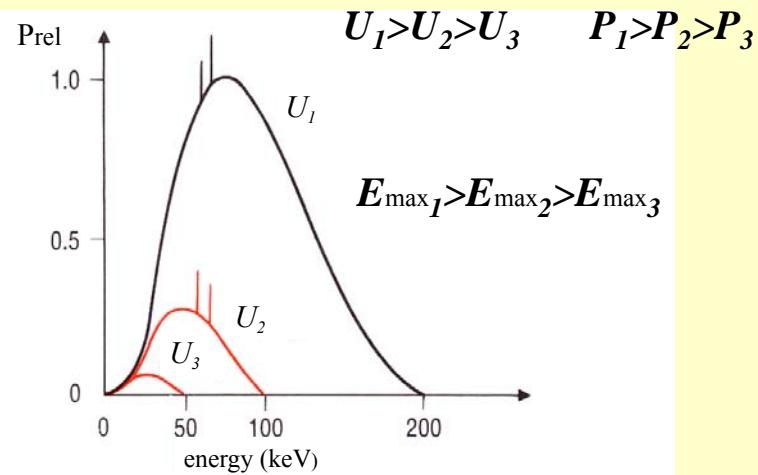
$$c = 1.1 \times 10^{-9} [1/V]$$

$$\eta = \frac{P}{P'} = cUZ$$

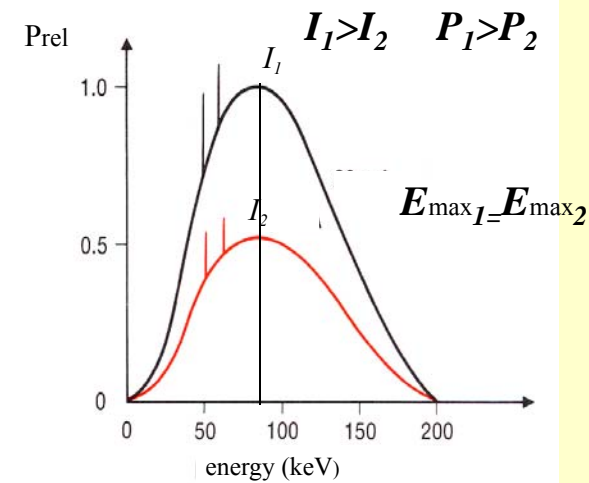
$$\eta < 1\%$$



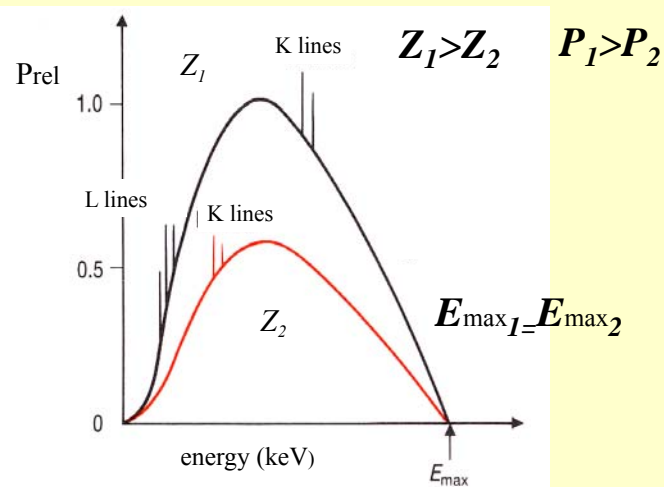
## Decrease of accelerating voltage :



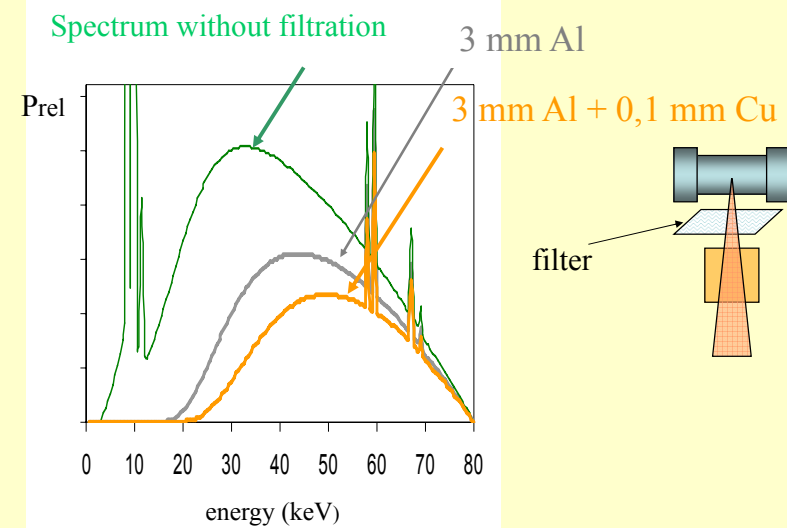
## Decrease of current:



## Effect of target (anode) material



## Application of radiation filters



## Application of radiation filters

Modification of the properties (spectrum, special distribution) of radiation

**Inherent filter** elements.

e.g., anode material, wall of the tube, diaphragm etc.

**External filters,**

typically Al or Cu plates.

**Disadvantage:** reduces the intensity  
increases the exposition time

**Advantage:** reduces – approximately 80% – the exposure of the patient

## Typical conditions for diagnostic X-ray production

Accelerating voltage: 25 – 200 kV

Current: 1 – 1000 mA

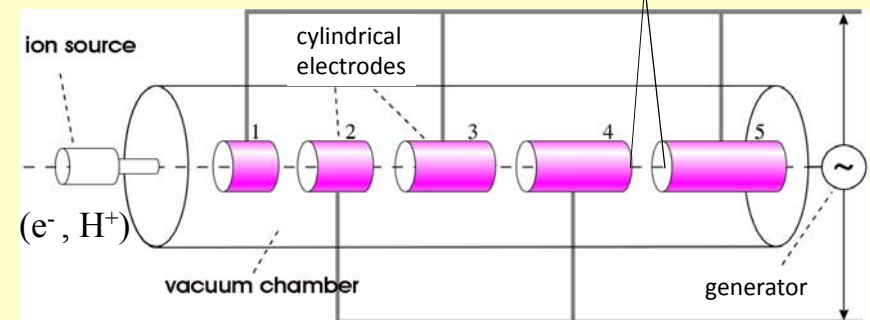
Anode material: W, in mammography Mo

## Special conditions

## Particle accelerators

## Linear Accelerator

The particles are accelerated when passing through the gaps.

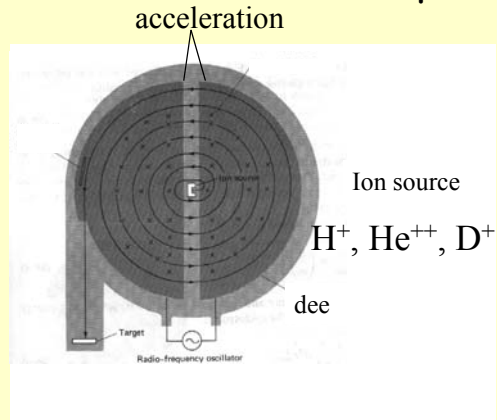
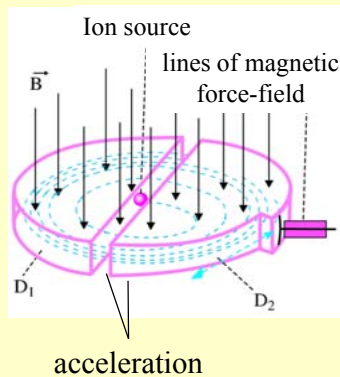


Linear accelerator (LINAC)  
is used in **Radiotherapy**





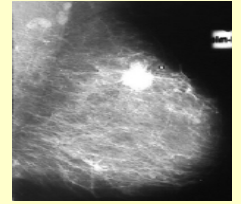
## Cyklotron — acceleration on a circular path



Magnetic field (Lorenz-force) → circular path  
Electric field → acceleration; increased radius of circle

## Medical applications of X-rays

X-ray diagnostics



Radiotherapy



Fertilization



## Interaction of X-ray with matter

Law of radiation attenuation

$$J = J_0 e^{-\mu x}$$

$\mu$  (linear attenuation (absorption) coefficient) depends on  
photon energy  
quality (atomic number) of absorber  
density of absorber

$$\mu_m = \frac{\mu}{\rho}$$

BUT! Ratio of  $\mu$  and the density is constant

$\mu_m$  [cm<sup>2</sup>/g] : mass attenuation coefficient

**Varies with – the photon energy  
– atomic number of absorber**

Law of radiation attenuation

$$J = J_0 e^{-\mu_m x_m}$$

$x_m$  [g/cm<sup>2</sup>] : surface density

$$x_m = \rho x$$

$$\mu = \frac{0.693}{D}$$

and

$$D_m = \rho D$$

$$\mu_m = \frac{0.693}{D_m}$$

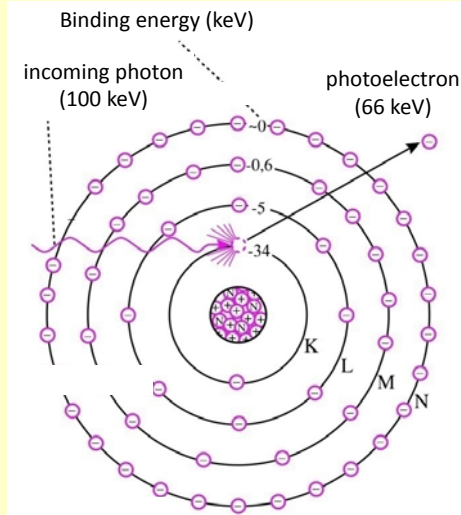


## Mechanism of interaction (1)

### Photoeffect

energy ballance:

$$hf = E_{\text{binding}} + \frac{1}{2} m_e v^2$$

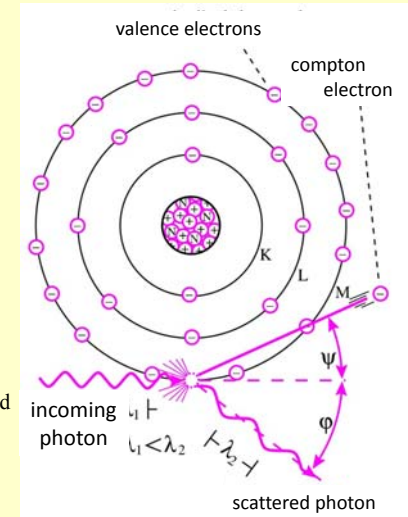


## Mechanism of interaction (2)

### Compton scatter

energy ballance:

$$hf = E_{\text{binding}} + \frac{1}{2} m_e v^2 + hf'_{\text{scattered}}$$



## Mechanism of interaction (3)

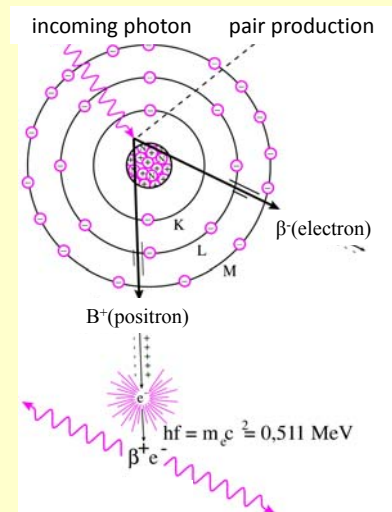
### Pair production

energy ballance:

$$hf = 2m_e c^2 + \frac{1}{2} m_e v^2$$

$$hf \geq 2m_e c^2$$

$$hf \geq 1.02 \text{ MeV}$$



Probability of interaction (absolute and relative) depends on

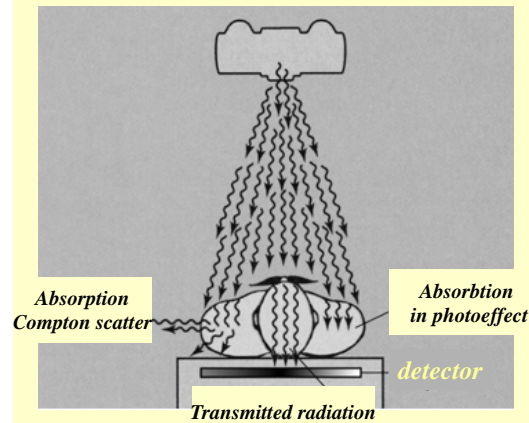
- the photon energy
- atomic number of absorber

$$\mu = \tau + \sigma + \kappa$$

photoeffect
Compton scatter
Pair production

$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

# Basic principle of X-ray diagnostic is the absorption of radiation



*Possible interactions:*

Compton scatter

photoeffect

no interaction

*Damjanovich, Fidy, Szöllősi: Medical Biophysics*

II. 3.1

- 3.1.1
- 3.1.2
- 3.1.3
- 3.1.4
- 3.1.5
- 3.1.6