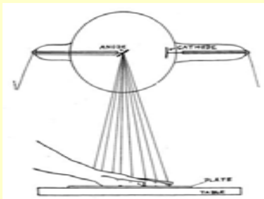
X-ray

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 – electront

1898: Pierre és Marie Curie – polonium and radium

X-ray

Discovery – November 1895

Publication – December 1895

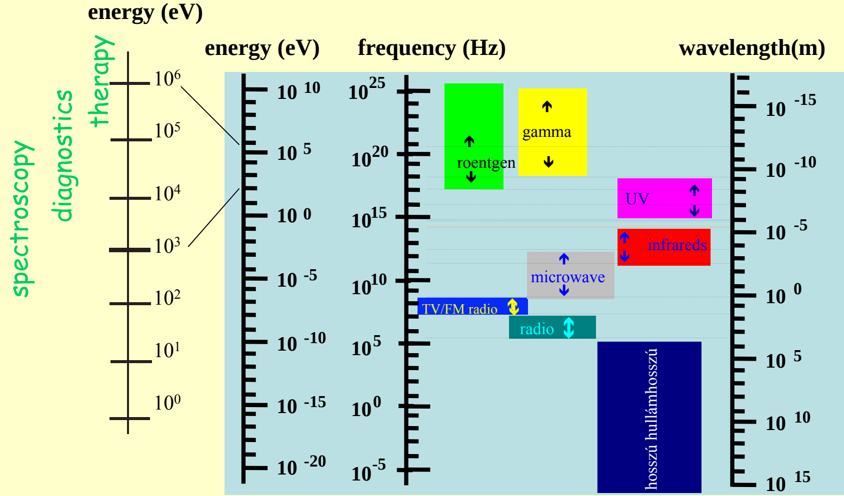
Medical application – January1896

Wilhelm Conrad Roentgen

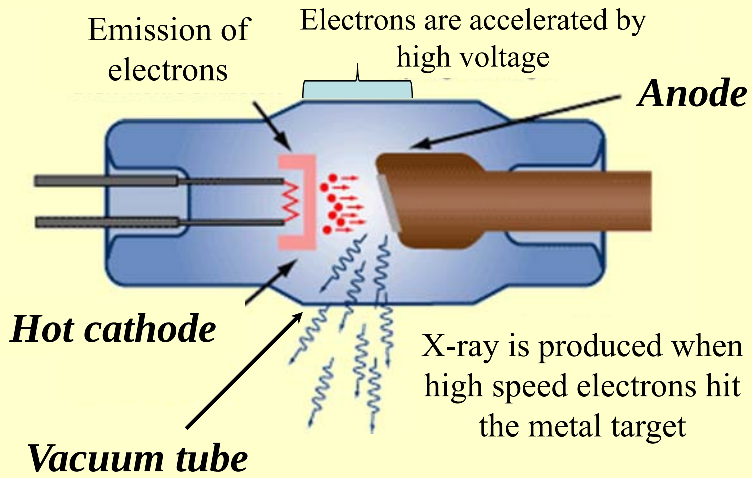
Nobel Prize in Physics 1901
in recognition the discovery of the remarkable rays subsequently named after him

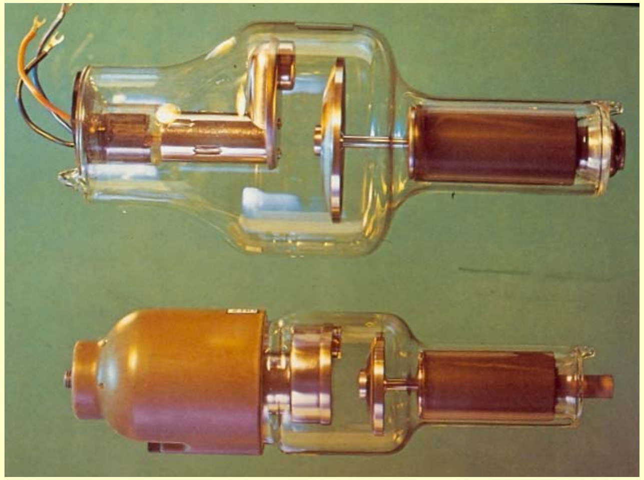
X-ray

Elektromagnetic radiation



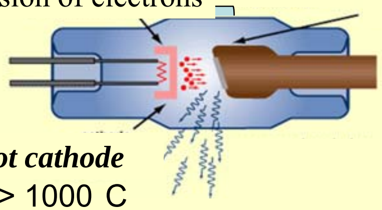
X-ray tube





Steps of producing X-ray

Emission of electrons



Hot cathode

T > 1000 C

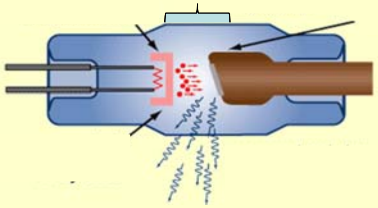
Current density ~ T^2

$$I_{anod} = \frac{Q}{t} = \frac{n*e}{t}$$

$$P_{electric} = UI$$

Steps of producing X-ray

Acceleration of electrons



Pl. U = 60 kV

$m_e = 9{,}1.10^{-31}$ kg

$e = 1{,}6.10^{-19}$ C

$$eU = \frac{1}{2} m_e v^2$$

$$v = \sqrt{\frac{2eU}{m_e}} = 1.5*10^8 [\frac{m}{s}]$$

Work of electric field

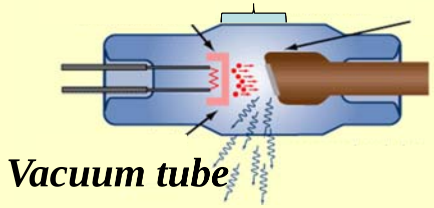
$$W = \Sigma F \Delta s = Q \Sigma E \Delta s$$

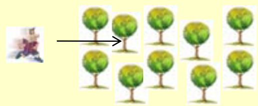
$$W = QU$$

$$\downarrow$$

$$W = \frac{1}{2} m_e v^2$$

Steps of producing X-ray

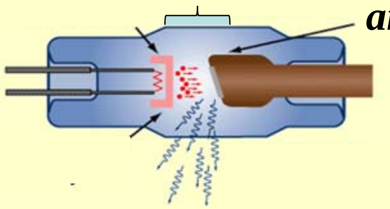




In the air, under atmospheric pressure
free pass length ~ 70 nm

vacuum ~ 10^{-4} Pa
free pass length ~ 10 cm

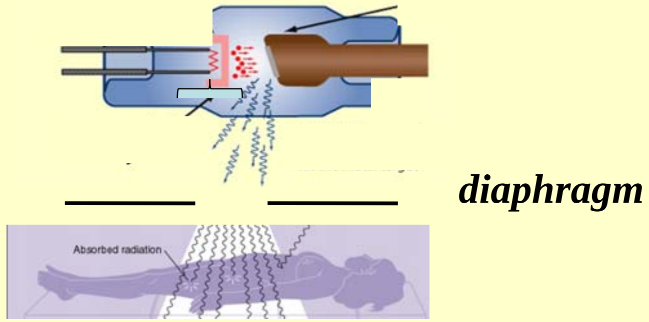
Steps of producing X-ray



Anode ***material***: - high atomic number (e.g. ^{29}Cu, ^{42}Mo, ^{74}W
- high melting poin

Anode ***position***: - standing – lower possible power (few W/ mm^2)
It is enough in dentisry
- rotating – heat distribution is better, higher possible power (10000 W/ mm2)

Adjustable beam definer



Steps of X-ray production

Generation of charged particles

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

Acceleration

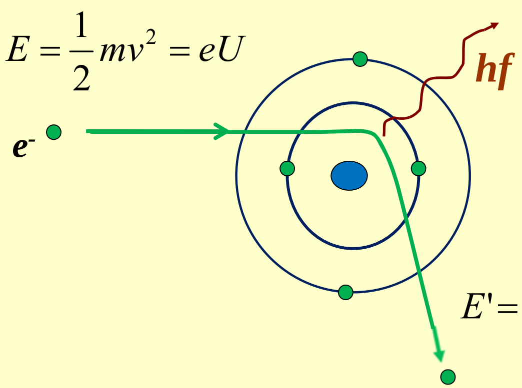
X-ray tube, accelerators

Deceleration

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

Mechanism of X-ray production

1. Bremsstrahlung or "braking radiation "



The electron is deflected from its original path and decelerated.

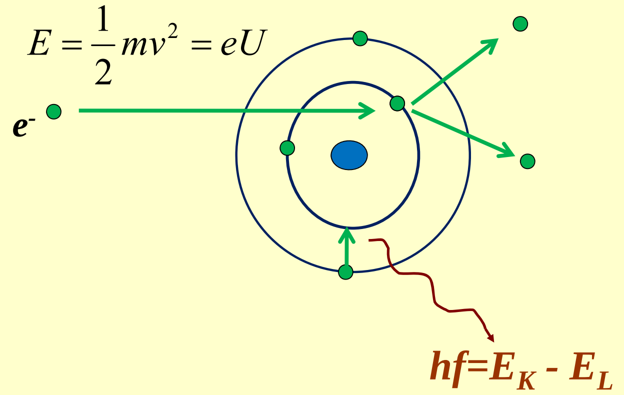
The electron's kinetic energy is reduced

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

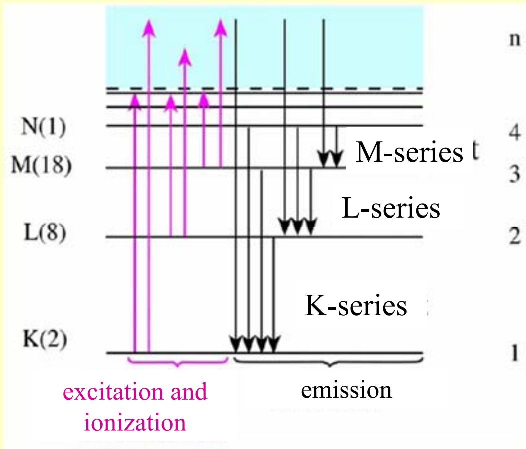


If the incident electron energy is high enough, it may interact with an (inner) orbital electron, ejecting it from its orbit (excitation/ionization).

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



Photon energies veries with the energy differences between neighbouring elecronic states.

Spectral properties of X-ray

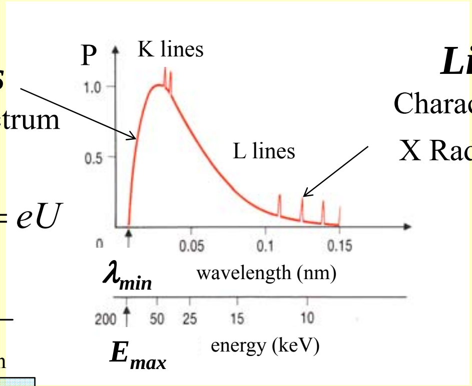
Continuous

Bremsstrahlung spectrum

Line

Characteristic

X Radiation



$$E_{\max} = \frac{1}{2} m v^2 = eU$$

$$eU = h\frac{c}{\lambda_{\min}}$$

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

Spectral properties of X-ray

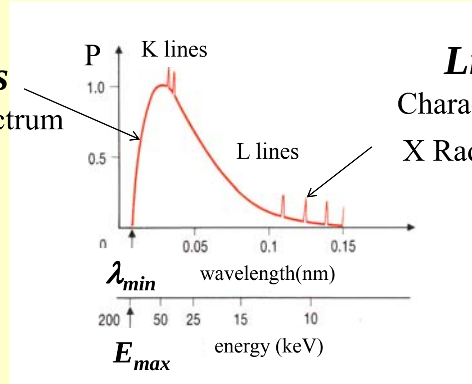
Continuous

Bremsstrahlung spectrum

Line

Characteristic

X Radiation

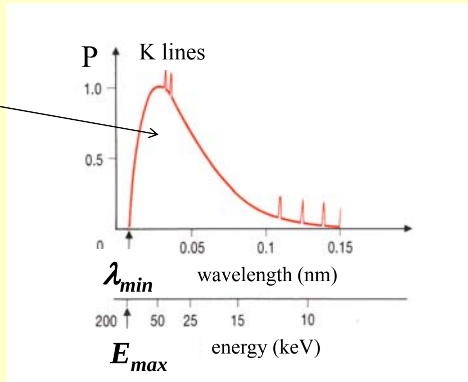


$$\lambda_{\min} = \frac{hc}{eU}$$

Duanne-Hunt law

Power and efficiency of X-ray tube

The total power of the radiation – „area below the curve"



$$P = cIU^2Z$$

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

empirical constant

Total input power:

$$P' = IU$$

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

Efficiency of X-ray tube

$\eta < 1\%$

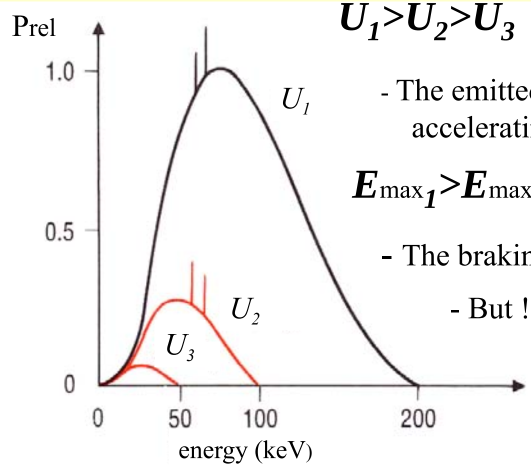
The radiation yield is very low (< 1%)

Great heat loss! (>99%)

How does *accelerating voltage influence the spectrum and radiation power?*

Decrease of accelerating voltage :

$U_1 > U_2 > U_3$ $P_1 > P_2 > P_3$



- The emitted power decreases with the accelerating voltage.

$E_{max_1} > E_{max_2} > E_{max_3}$

- The braking radiation becomes softer.

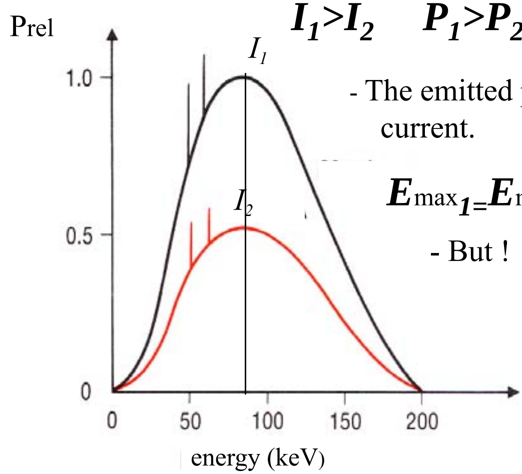
- But !

The position of characteristic lines remains the same.

How does current intensityinfluence the spectrum and radiation power?

Decrease of current:

$I_1 > I_2$ $P_1 > P_2$



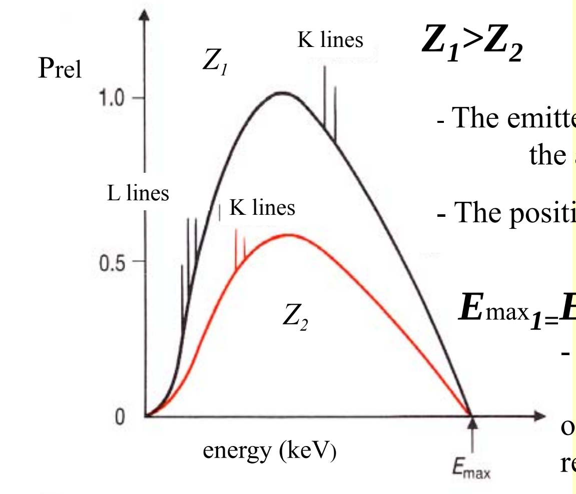
- The emitted power decreases with the current.

$E_{max_1} = E_{max_2}$

- But !

Spectral distribution and the position of characteristic lines remains the same.

Effect of target (anode) material



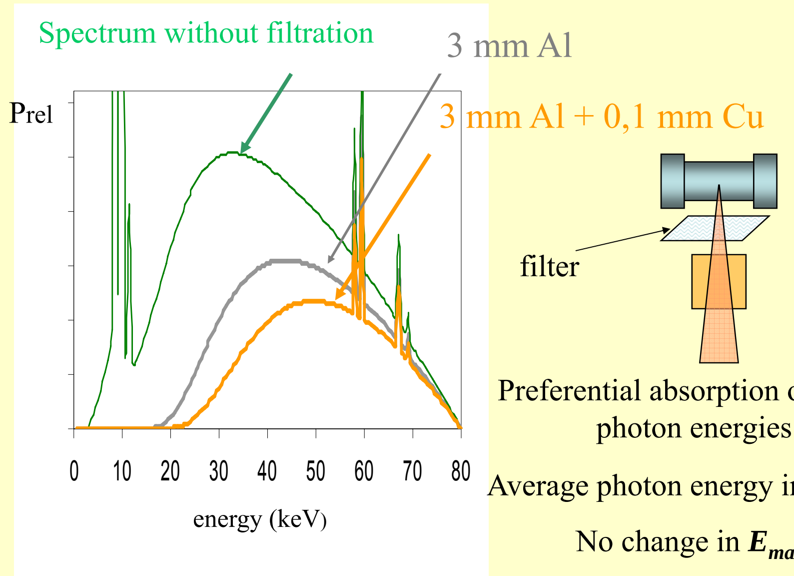
$Z_1 > Z_2$ $P_1 > P_2$

- The emitted power decreases with the atomic number of target.
- The position of characteristic lines is altered.

$E_{max_1} = E_{max_2}$

- But ! Spectral distribution of breaking radiation remains the same.

Application of radiation filters



Preferential absorption of lower photon energies

Average photon energy increases

No change in E_{max}

Application of radiation filters

Modification oft he 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

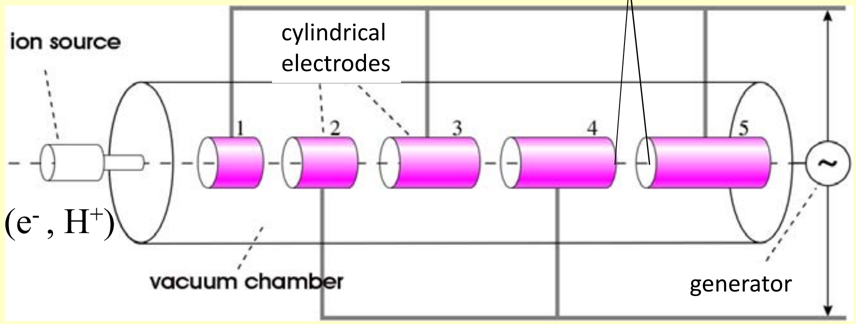
Anode material: W, in mammography Mo

Special conditions

Particle accelerators

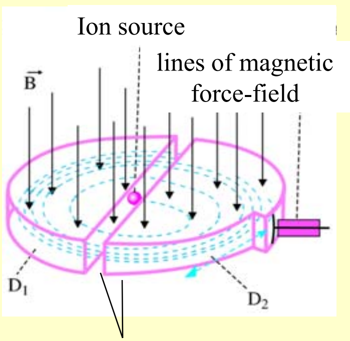
Linear Accelerator

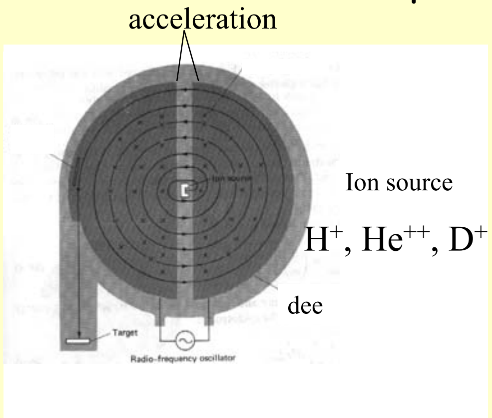
The particles are accelerated when passing through the gaps.



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

Cyklotron – acceleration on a circular path

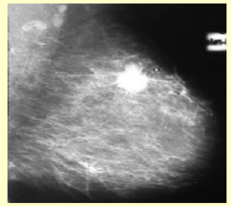




Magnetic field (Lorenz-force) → circular path
Electric field → acceleration; increased radius of circle

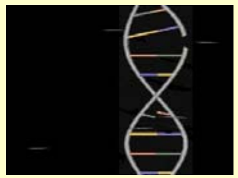
Medical applications of X-rays

X-ray diagnostics



Radiotherapy

Fertilization



Interaction of X-ray with matter

Law of radiation attenuation

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

μ (linear attenuation (absorption) coefficient) depends on
- photon energy
- quality (atomic number) of absorber
- density of absorber

μ depends on the density of absorber (!)

BUT! Ratio of μ and the density is constant

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

μ_m [cm^2/g] : mass attenuation coefficient

Varies with – the photon energy
– atomic number of absorber

Law of radiation attenuation

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

$$x_m = \rho x$$

x_m [g/cm^2] : surface density

We have seen that

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

and

$$D_m = \rho D$$

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

Interaction of X-ray with matter

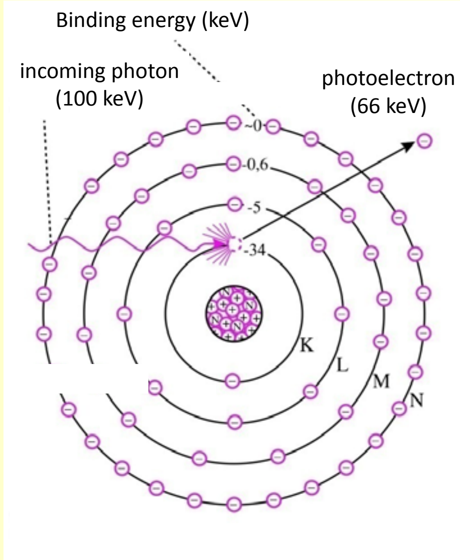
Radiation attenuation according to:

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

Varies with – the photon energy
– atomic number of absorber

Mechanism of interaction (1)

Photoeffect

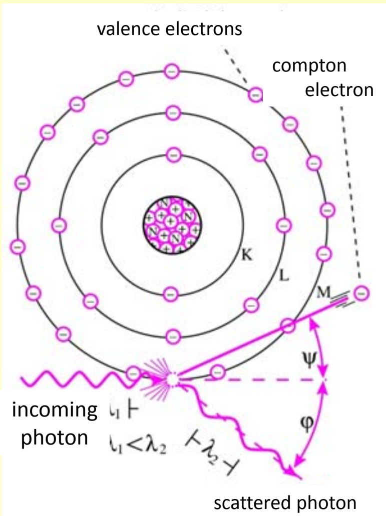


energy ballance:

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

Mechanism of interaction (2)

Compton scatter

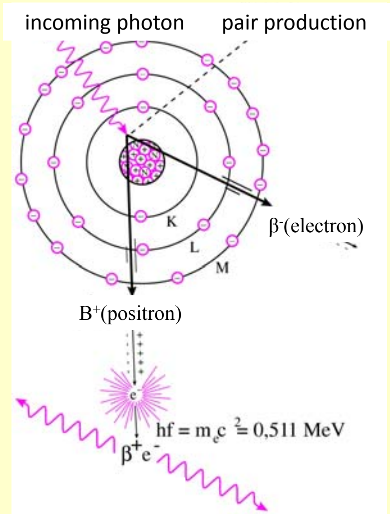


energy ballance:

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

Mechanism of interaction (3)

Pair production



energy ballance:

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

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

$$hf \geq 1.02 MeV$$

Probability of interaction (absolute and relative) depends on

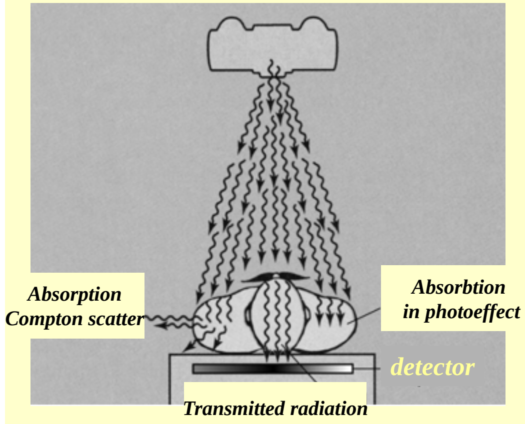
- the photon energy
- atomic number of absorber

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

photoeffect (τ), Compton scatter (σ), Pair production (κ)

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

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

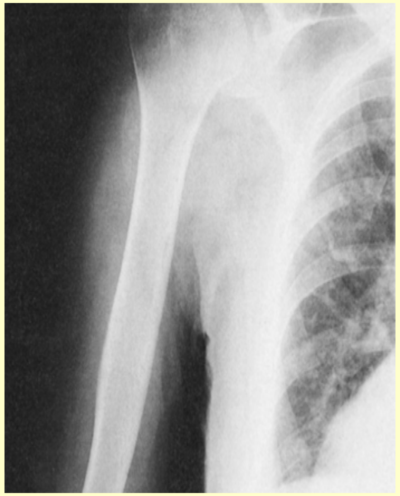


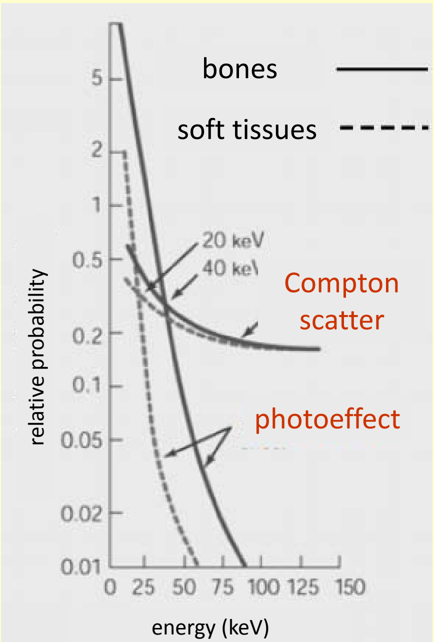
Possible interactions:

Compton scatter

photoeffect

no interaction





Attenuation decreases with increasing photon energy.

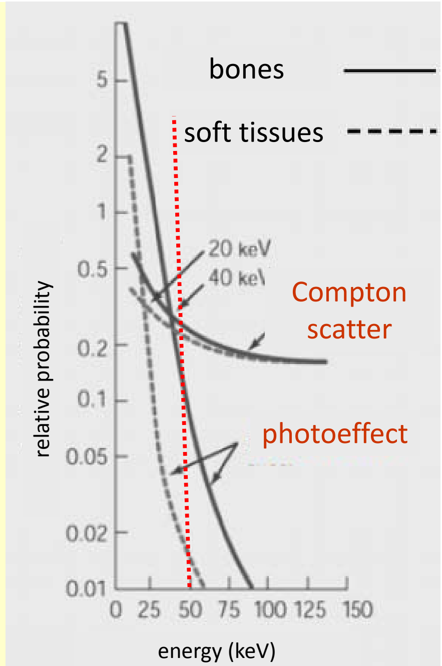
The decrease is more pronounced in the case of photoeffect.

At lower photon energies τ_m is dominant.

τ_m strongly depends on the atomic number.

$$\tau_m \approx \lambda^3 Z^3$$

Spectral changes of radiation drastically modify the attenuation processes.



Effective atomic number

$$Z_{eff} = \sqrt[3]{\sum_{i=1}^{n} w_i Z_i^3}$$

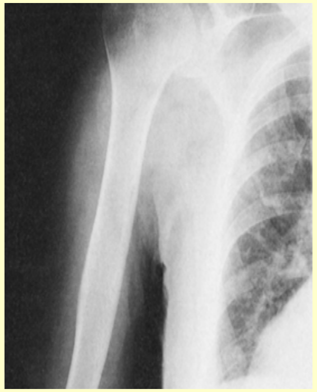
$$\tau_m = C\lambda^3 Z_{eff}^3$$

$$w_i = \frac{m_i}{m_{tot}}$$

e.g., H_2O w_{H2}=2/18

w_{O2}=16/18

Z_{eff}= 7,69

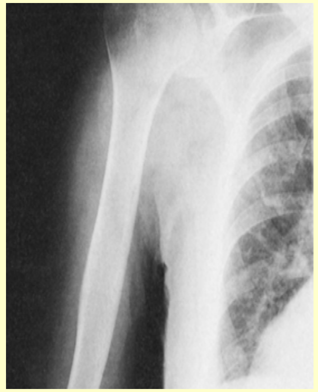


Effective atomic number

$$Z_{eff} = \sqrt[3]{\sum_{i=1}^{n} w_i Z_i^3}$$

$$\tau_m = C\lambda^3 Z_{eff}^3$$

matter	Z_{eff}
air	7,3
water	7,7
soft tissue	7,4
bone	13,8



Summary of attenuation mechanisms

	Variation with E	Variation with Z	Energy range in tissues
τ_m	$\sim 1/E^3$	$\sim Z^3$	10 – 100 keV
σ_m	Slightly falls with E	linear	0.5 – 5 MeV
κ_m	Rises slowly with E	$\sim Z^2$	>5 MeV

Main contrast mechanism in diagnostic X-ray: photoeffect ($\sim Z^3$)

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