X-radiation
and its interaction with matter

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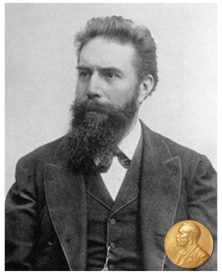
Outline of the lecture

- *Discovery of X-rays*
- *Properties of X-radiation*
- *Production of X-rays*
- *Bremsstrahlung and characteristic X-ray*
- *Interaction of X-radiation with matter*
- *X-ray diffraction*
- *X-ray diagnostics*
- *Particle accelerators*

Textbook chapters: II/3.1.; II/3.2.6.; VIII/3.1. X/6.

Related laboratory practices: X-ray, CT Scan (2nd semester)

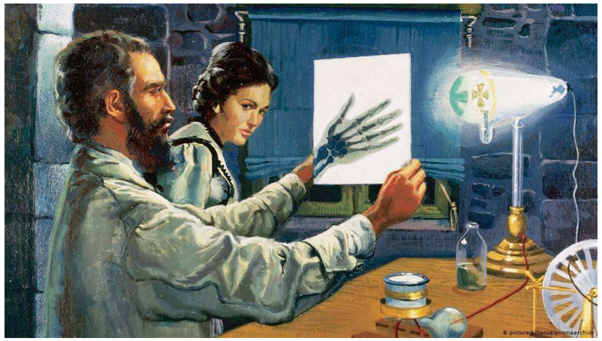
Discovery of X-rays (1895)



Wilhelm Conrad Röntgen
1845-1923

Crookes tube

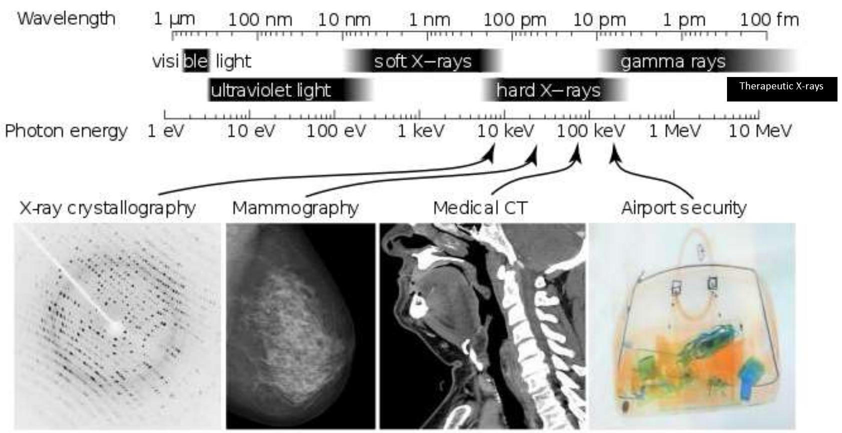
„Hand mit Ringen"
1895. dec. 22.



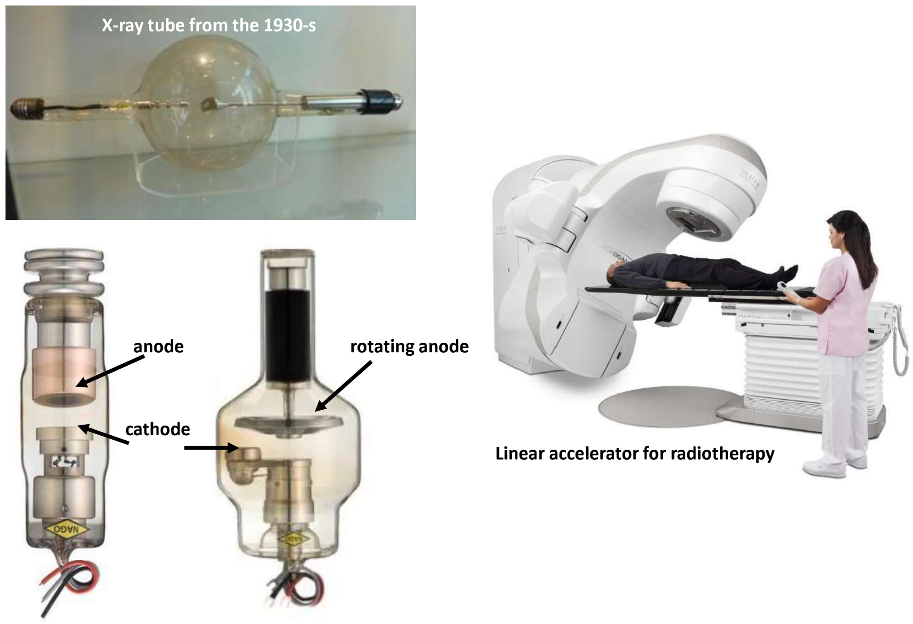
Properties of X-ray radiation

Elektromágneses hullám
f ≈ 10^{15} - 10^{18} Hz (penta-exahertz)
λ ≈ 10 nm - pm
ε ≈ 100 eV- 20 MeV
diagnostics: 30-200 keV; therapy: 5-20 MeV

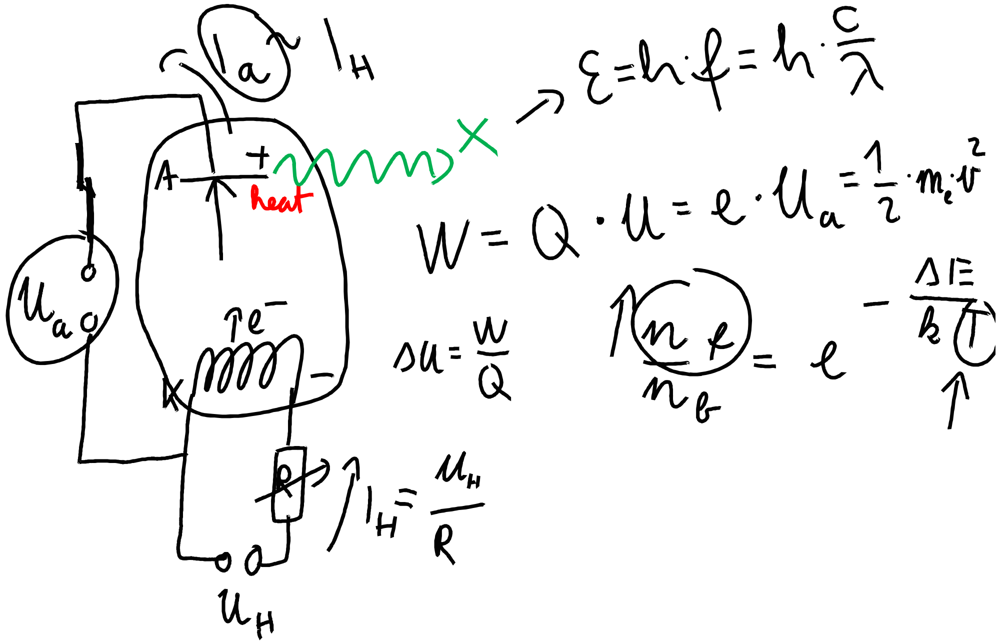
$$\varepsilon = h \cdot f = h \cdot \frac{c}{\lambda}$$



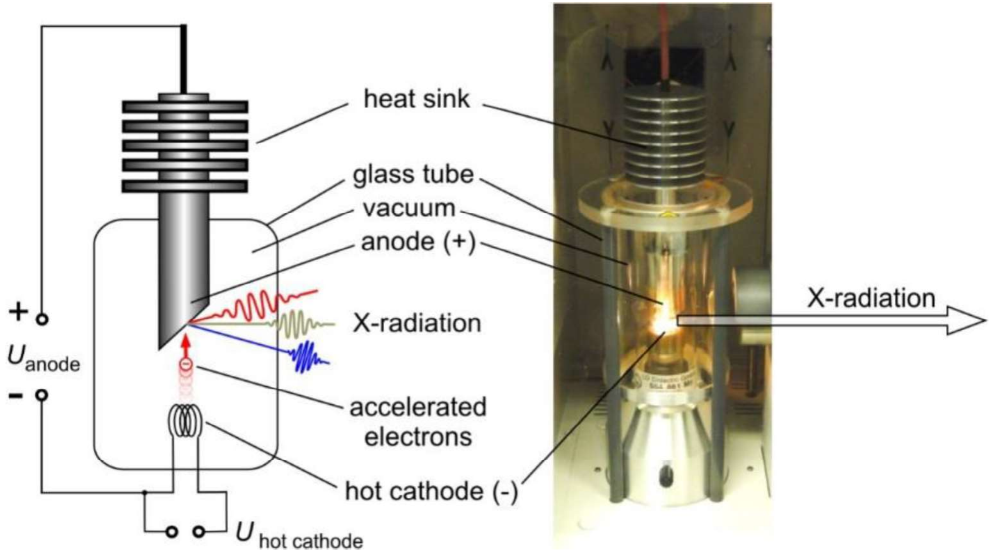
Production of X-rays

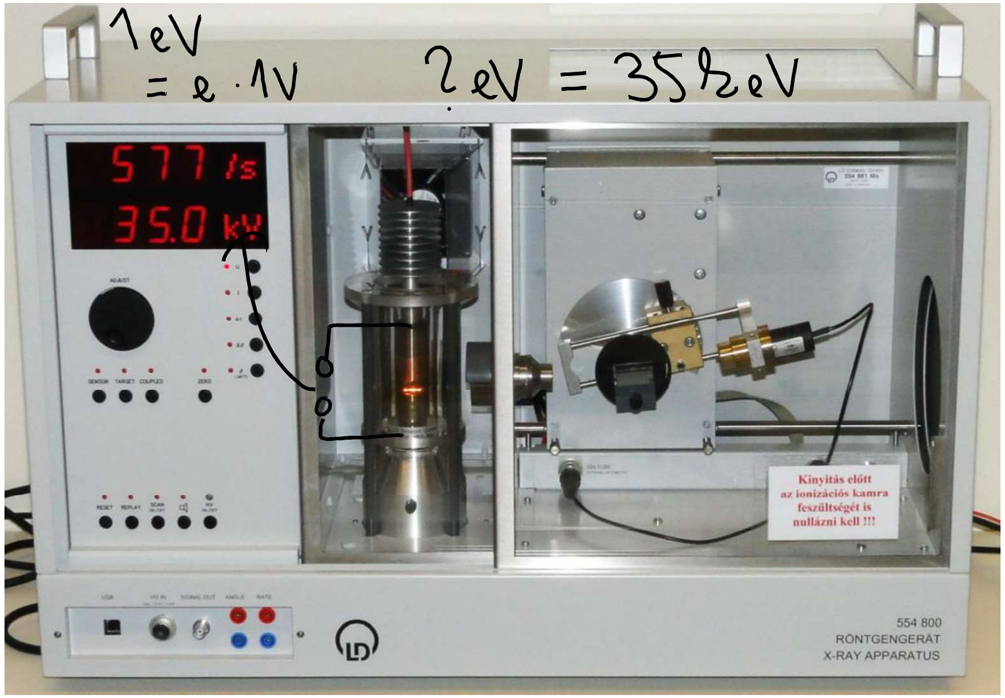


Schematic structure of the X-ray tube

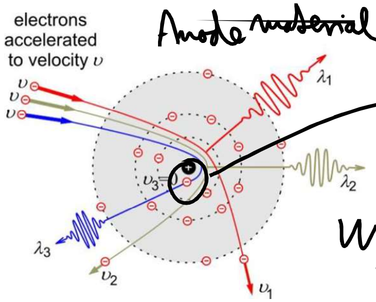


Schematic structure of the X-ray tube





Bremsstrahlung: „braking radiation”



Anode material

$$\mathcal{E}_{max} = e \cdot U_a = h \cdot f_{max} = h \cdot \frac{c}{\lambda_{min}}$$

Z=74 **Duane-Hunt law:**

W tungsten T ~ 3400 °C

$$e \cdot U_a = h \cdot \frac{c}{\lambda_{min}}$$

$$U_a = \frac{h \cdot c}{e \cdot \lambda_{min}}$$

Mo Z=42

$$U_a = \frac{k}{\lambda_{min}}$$

k = 1230 kV·pm

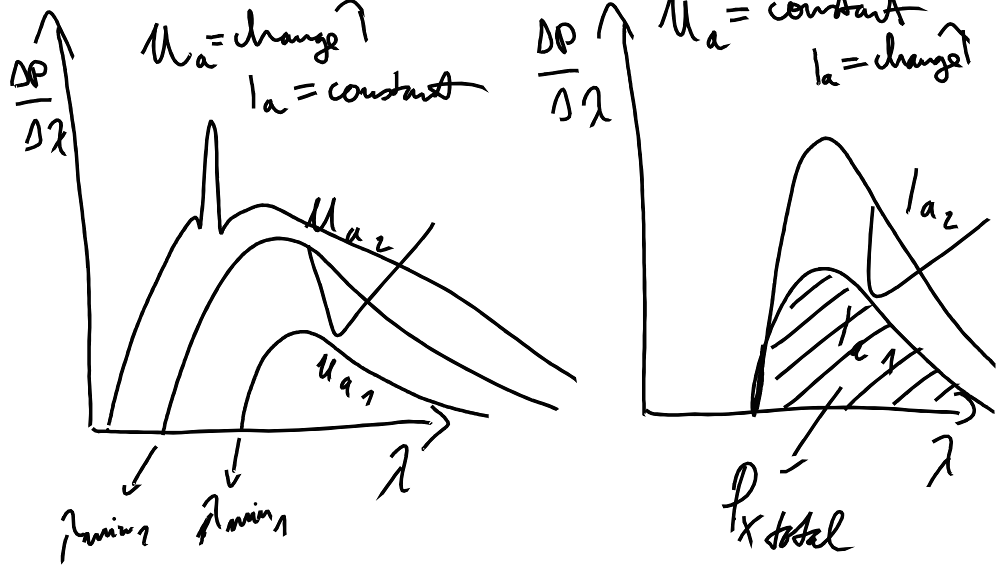
Total emitted power:

$$P_x = C_x \cdot U_a^2 \cdot Z \cdot I_a$$

Radiation production efficiency: 1%

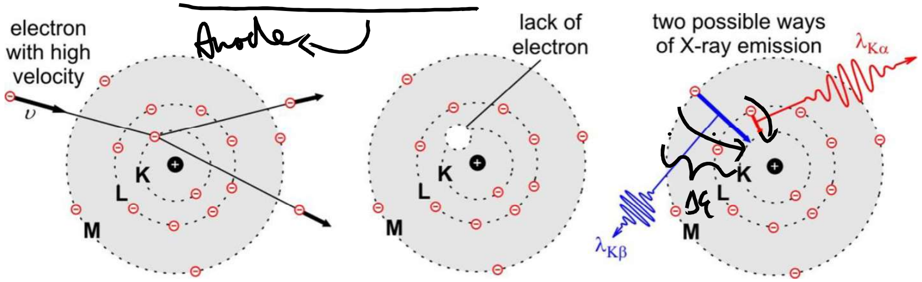
$$\eta = \frac{P_x}{P_{in}} = \frac{C_x \cdot U_a^2 \cdot Z \cdot I_a}{U \cdot I} = C_x \cdot U_a \cdot Z$$

Bremsstrahlung – spectral changes

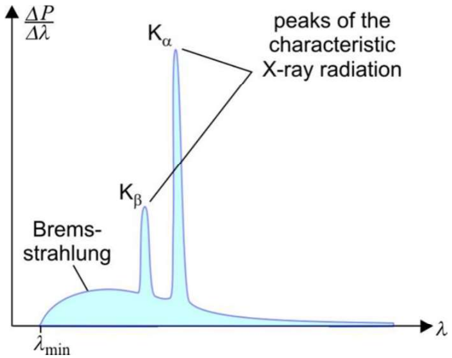


Characteristic X-radiation

Anode



field of application: mammography, diffraction



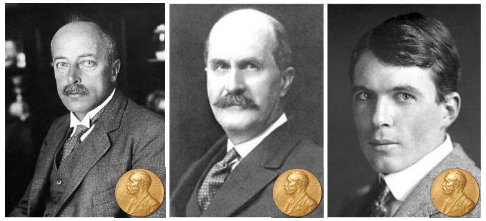
Interaction of X-radiation with matter

1. **Diffraction – elastic scattering, or reflection**
   crystallography – determining crystal structure

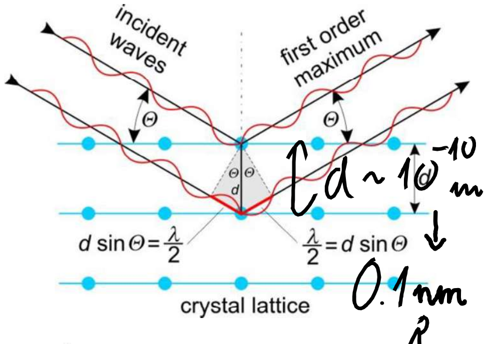
2. **Absorption**
   medical diagnostics and theraphy

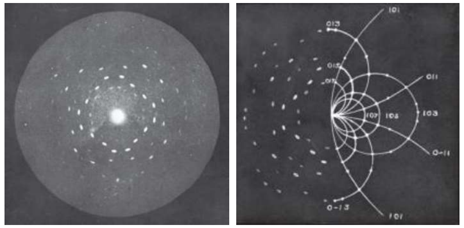
Interaction of X-radiation with matter I.

X-ray diffraction

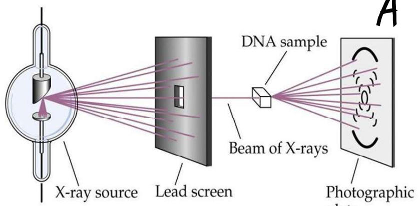


Max von Laue *William Henry and Lawrence Bragg*



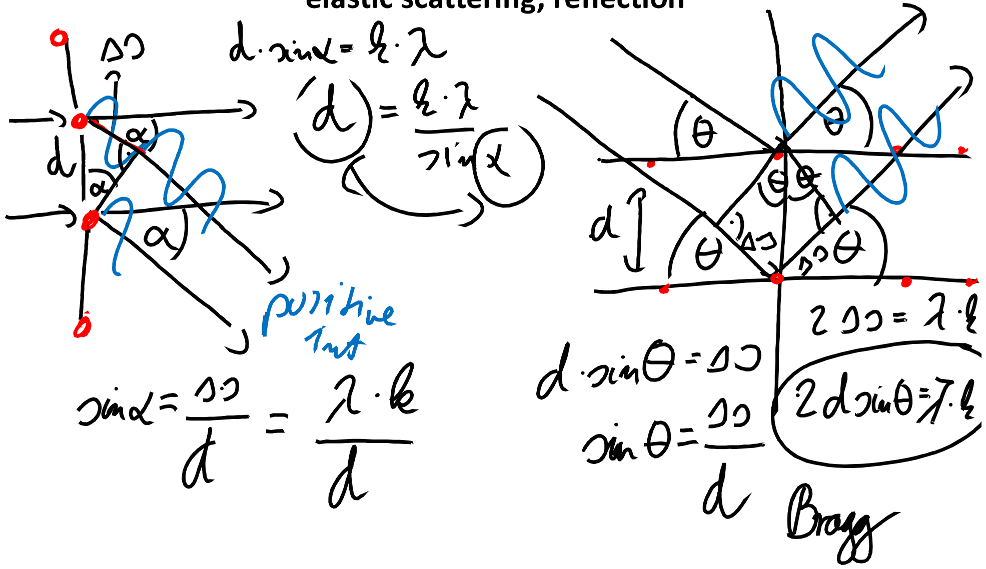


X-ray diffractogram of a crystal and L. Bragg's calculations



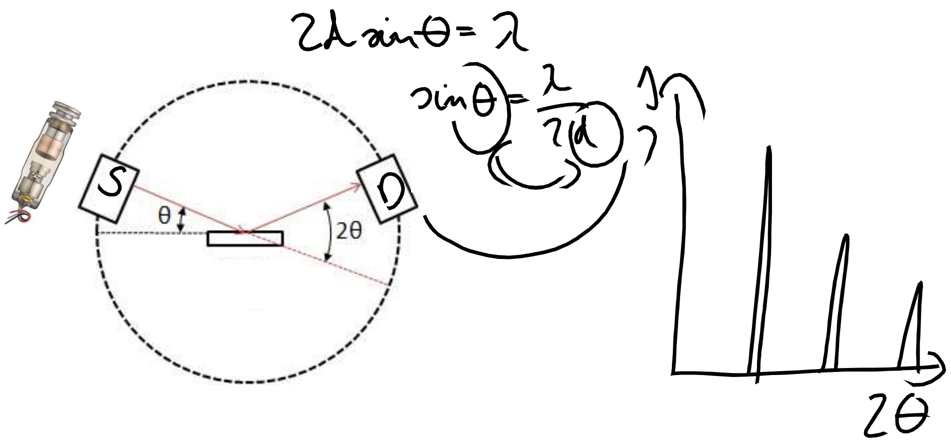
X-ray diffraction

Interaction of X-radiaton photons with the matter – elastic scattering, reflection

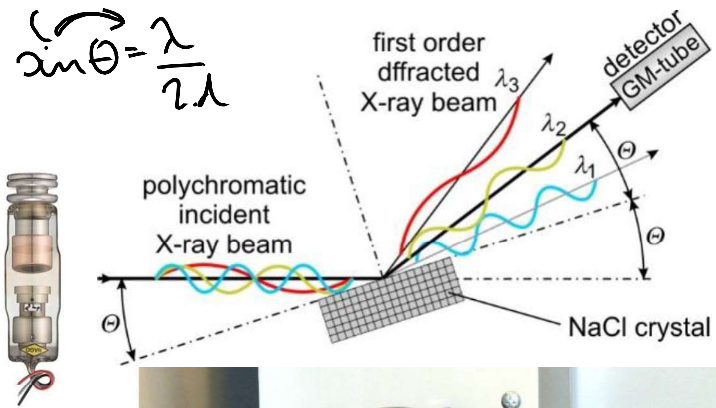


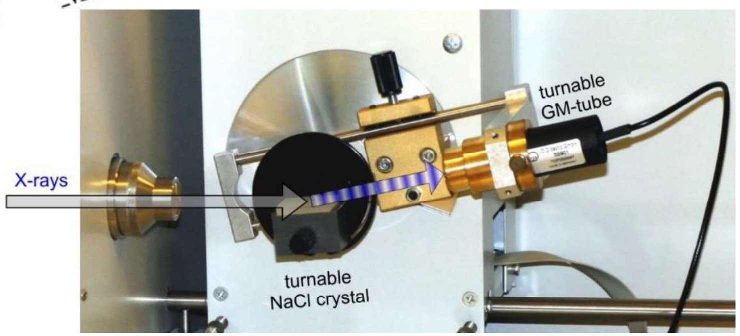
X-ray diffractometry - XRD

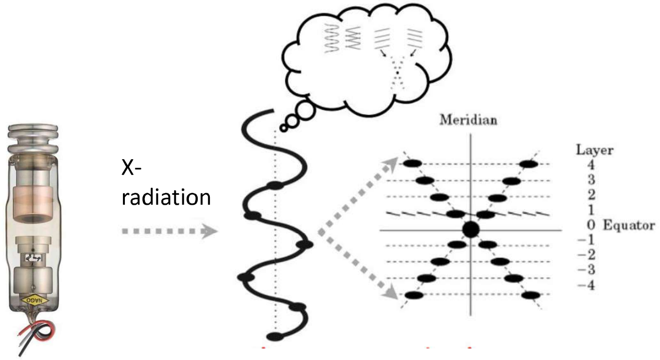
monochromatic X-radiation – use of characteristic X-ray peaks

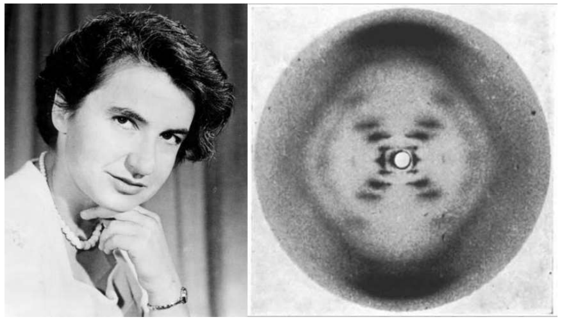


Registering the spectrum of X-radiation



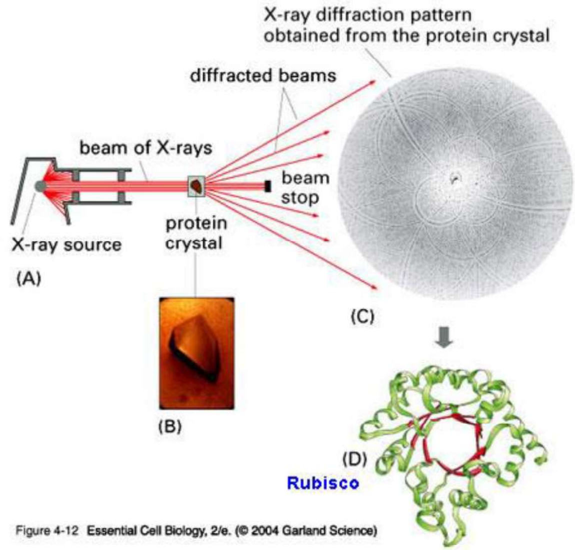






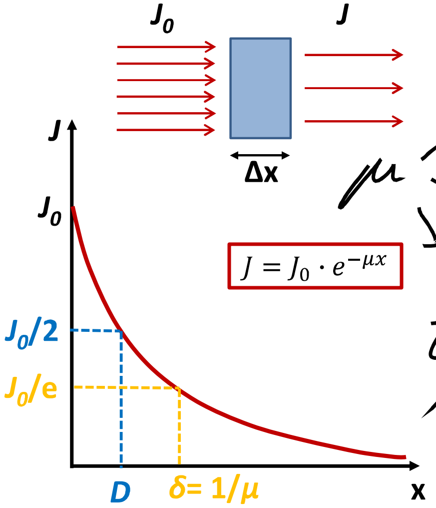
Rosalind Franklin

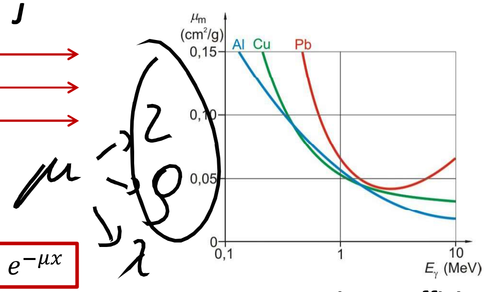
picture 51



Interaction of X-radiation with matter II.

Absorption – general principles





Mass attenuation coefficient:

$$\mu_m = \frac{\mu}{\rho} \qquad [cm^2 \cdot g^{-1}]$$

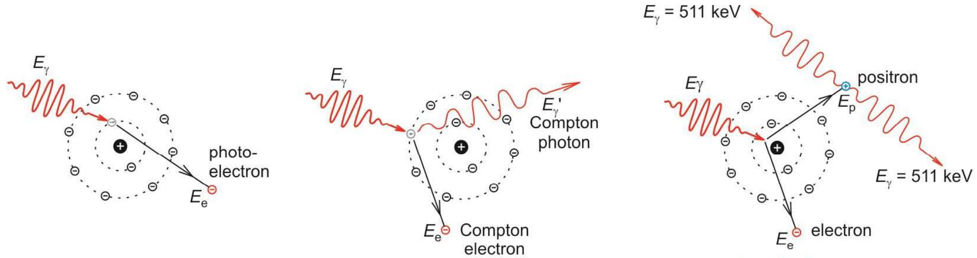
Mechanisms at atomic scale:

- Photoeffect
- Compton scattering
- Pair production (in radiotherapy)

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

Interaction of X-radiation with matter II.

Atomic scale absorption processes



a.) photoeffect
$E_\gamma = A + E_e$
A = work function
(escape energy)

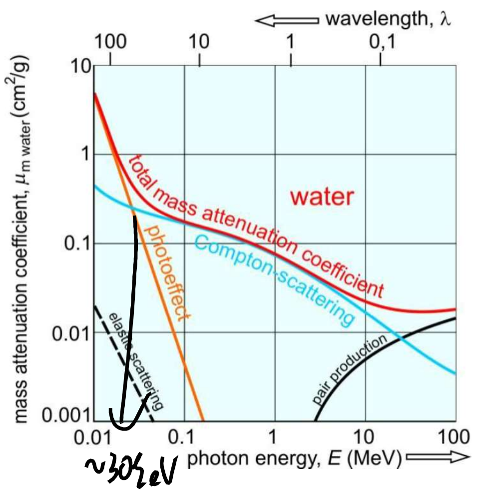
b.) Compton scattering
$E_\gamma = A + E_e + E_\gamma'$

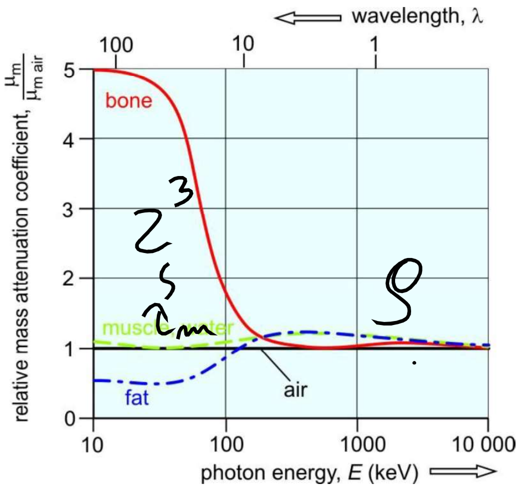
c.) pair production, annihilation
$E_\gamma = 2\,m_e c^2 + E_e + E_p$
(if $E_\gamma >$ 1022 keV)

$$\tau_m = \frac{\tau}{\rho} \qquad \sigma_m = \frac{\sigma}{\rho} \qquad \kappa_m = \frac{\kappa}{\rho}$$

X-ray diagnostics

Absorption processes and diagnostics





X-ray diagnostics

- Shadow image
- Based on absorption
- static: X-ray films, dynamic: fluoroscopy
- Summation image: 2D representation
- Tomography (sectioning): CT (CAT scan), 3D

$$J = J_0 \cdot e^{-\mu_m \cdot \rho \cdot x}$$

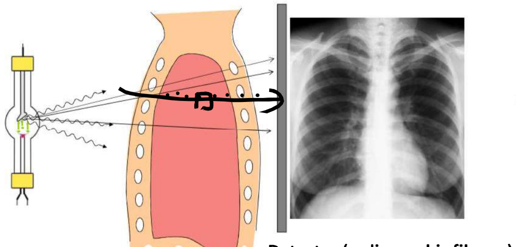
mass attenuation coefficient — *density*

$$\mu_m = \tau_m + \sigma_m \leftarrow \sigma_m = C \cdot Z/A$$

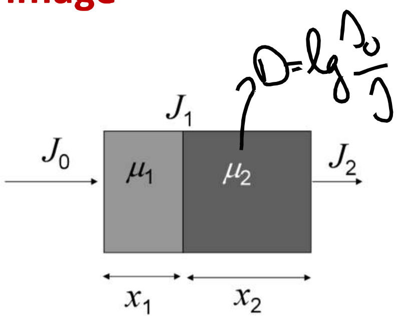
$$\tau_m = C \cdot \lambda^3 \cdot Z^3$$

medium	Z_{eff}	ρ [g/cm³]
air	7.3	$1.3 \cdot 10^{-3}$
water	7.7	1
soft tissue	7.4	1
bone	13.8	1.7-2

Summation image



Detector (radiographic film, …)



$J_1 = J_0 \cdot e^{-\mu_1 \cdot x_1}$

$J_2 = J_1 \cdot e^{-\mu_2 \cdot x_2} = J_0 \cdot e^{-\mu_1 \cdot x_1} \cdot e^{-\mu_2 \cdot x_2}$

$J_2 = J_0 \cdot e^{-(\mu_1 \cdot x_1 + \mu_2 \cdot x_2)}$

X-ray diagnostics

Contrast agents

double contrast: $BaSO_4$ (+) and air (-)

cerebral angiography with KI contrast (+)

$BaSO_4$ (+) swallow – fluoroscopic image

Positive contrast agents
more absorption

$\mu\uparrow$ $\mu_m\uparrow$ $Z_{eff}\uparrow$

iodine (veins),
barium
(gastrointestinal)

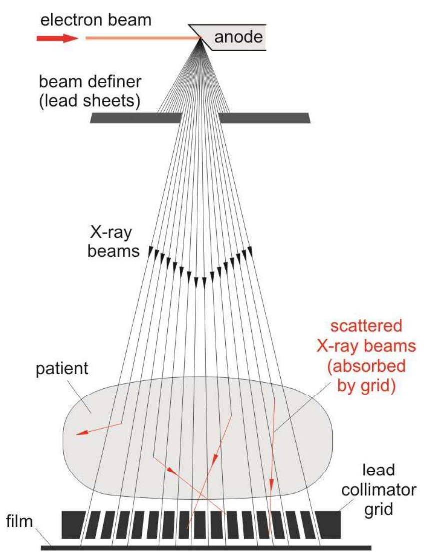
Negative contrast agents
less absorption

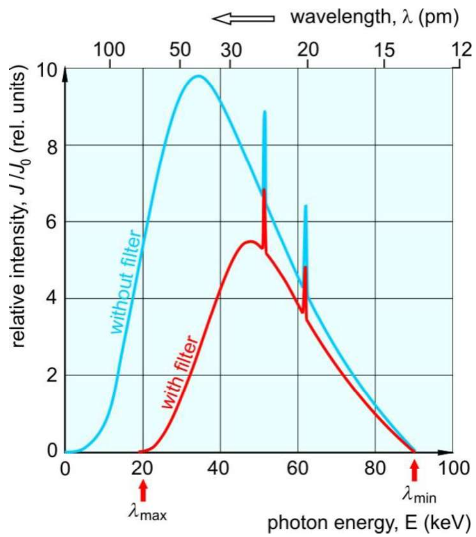
$\mu\downarrow$ $\rho\downarrow$ μ_m - Z_{eff} -

air, CO_2 (gastrointestinal)

X-ray diagnostics

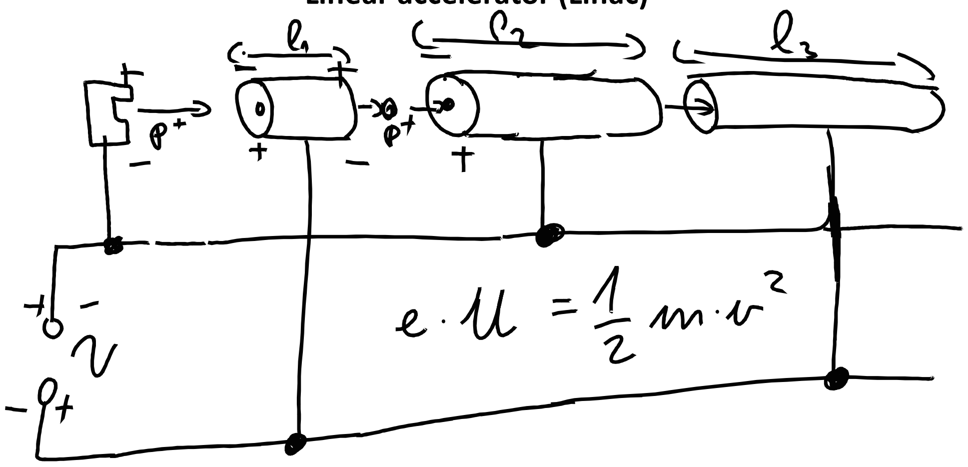
collimator, filtering





Particle accelerators

Linear accelerator (Linac)



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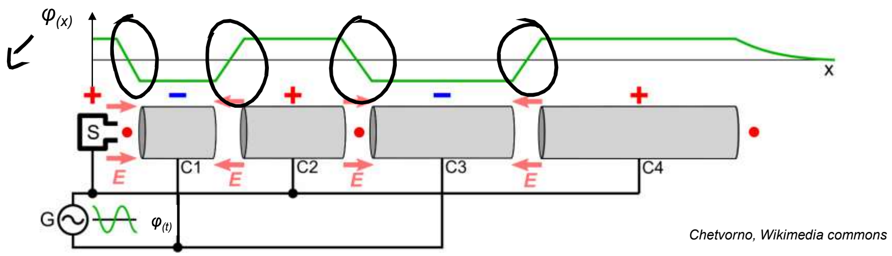

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