X-radiation
and its interaction with matter

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Outline

- Discovery of X-rays
- What is X-ray?
- Production of X-ray
- Bremsstrahlung and characteristic X-ray
- Interaction of X-ray with the matter
- Bases of X-ray diagnostics
- Particle accelerators

Warning: *This presentation on its own is* *not enough* *to learn this topic!*

Textbook chapter: II/3.1.; II/3.2.6.; VIII/3.1.

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

Discovery of X-rays

Wilhelm Conrad Röntgen
1845-1923
Nobel prize: 1901

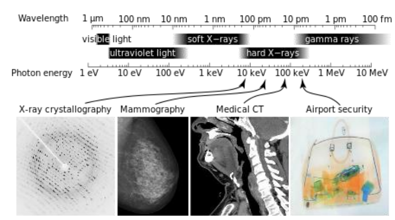
Crookes tube

„Hand mit Ringen"
22 Dec 1895

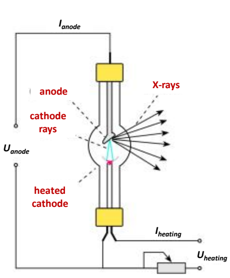
What is X-radiation?

A form of electromagnetic waves.
X-rays
f = 10^{15} - 10^{18} Hz (penta-exahertz)
λ = 10 nm - 0.01 nm
ε = 100 eV- 100 keV (-MeV)
(diagnostic: up to 200 keV; therapeutic: approx. 10 MeV)

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

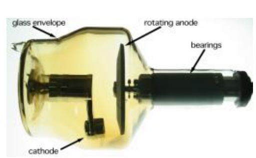


Production of X-ray



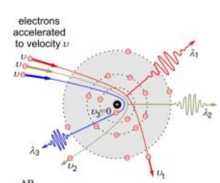
Schematic X-ray tube

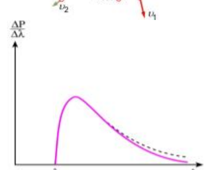
X-ray tube from the 1930-s.



X-ray tube with rotating anode

Bremsstrahlung: „braking radiation"





$$\varepsilon_{kin} = e \cdot U_{anode}$$
$$\varepsilon_{max} = h \cdot \frac{c}{\lambda_{min}}$$

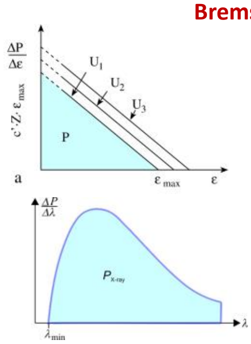
Duane-Hunt law:

$$\lambda_{min} = \frac{h \cdot c}{e} \cdot \frac{1}{U_{anode}}$$

$$\lambda_{min} = \frac{k}{U_{anode}}$$

$(k = 1230\ pm \cdot kV)$

Bremsstrahlung



P= AUC (Area Under Curve)

Total emitted power:

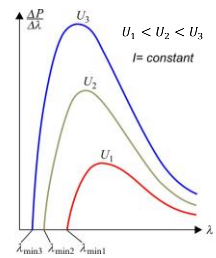
$$P = C_X \cdot U_{anode}^2 \cdot Z \cdot I_{anode}$$

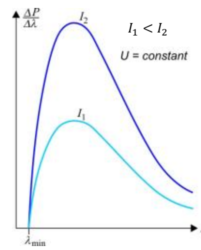
Radiation production efficiency

$$\eta = \frac{P_{emitted}}{P_{invested}} = \frac{C_X \cdot U_{anode}^2 \cdot Z \cdot I_{anode}}{U_{anode} \cdot I_{anode}}$$

$$\eta = C_X \cdot U_{anode} \cdot Z$$

Bremsstrahlung – characteristic spectral changes

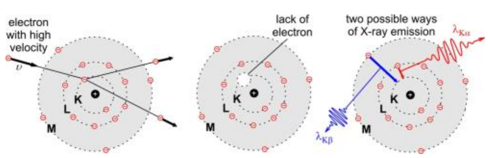


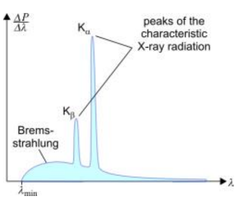


$$\lambda_{min} = \frac{k}{U_{anode}}$$

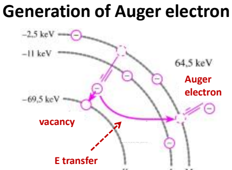
$$P = C_X \cdot U_{anode}^2 \cdot Z \cdot I_{anode}$$

Characteristic X-radiation



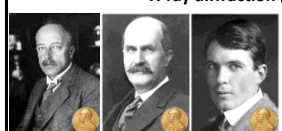


Generation of Auger electron

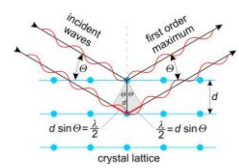


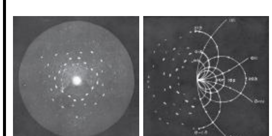
Interaction of X-ray with the matter I.

X-ray diffraction (Bragg-diffraction)



Max T.F. Laue *William H. és William L. Bragg*





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

Bragg formula:

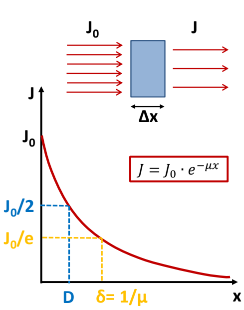
$$2d \cdot sin\Theta = n \cdot \lambda$$

Application:

- spectrum measurement
- crystallography

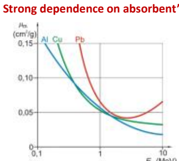
Interaction of X-ray with the matter II.

Absorption – general rules



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

Strong dependence on absorbent's Z and E_{photon}:



Mass attenuation coefficient:

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

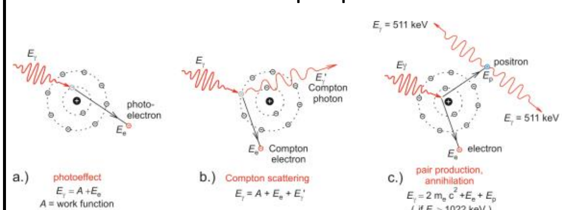
Mechanisms at atomic scale:

- Photoeffect
- Compton scattering
- (Pair production)

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

Interaction of X-ray with the matter III.

Atomic scale absorption processes



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

Bases of X-ray diagnostics

- Shadow image.
- Based on absorption.
- Summation image: 2D representation. (except for 3D reconstructions in tomography

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

mass attenuation coeff. — *density*

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

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

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

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Bases of X-ray diagnostics

Absorption in tissues

ABSORPTION PROCESS	μ_m as a function of the atomic number Z	μ_m as a function of the photon energy E
elastic scattering	$\mu_m \sim Z^2$	$\mu_m \sim 1/E^2 \sim \lambda^2$
photoeffect	$\mu_m \sim Z^3$	$\mu_m \sim 1/E^3 \sim \lambda^3$
Compton scattering	does not depend	decreasing slightly

- Contrast between soft tissues and bone : mainly photoeffect.
- Contract insode soft tissues: mainly Compton scattering.
- Importance of „soft" and „hard" radiation.

Effective atomic number of a tissue:

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

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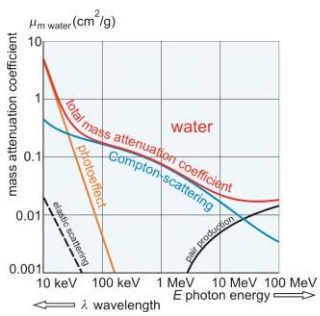
Bases of X-ray diagnostics

Absorption in tissues



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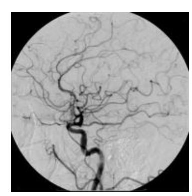
Bases of X-ray diagnostics

Contrast agents

double contrast: $BaSO_4$ + air



cerebral angiography with KI contrast

gold nanoparticles in the kidney

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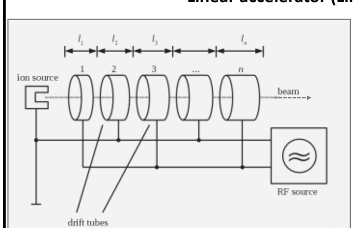
Particle accelerators

Linear accelerator (Linac)



Charged particles (p⁺, e⁻) accelerate gradually between electrodes of alternating polarity (but not inside the electrodes).

Length of electrodes gradually increases.

Beam can be used directly or indirectly. In the latter case beam hits a target to produce high energy X-ray.

Few 10-s of MeV-s energies can be reached.

speed of electron in accelerating electric field:

$$E_{pot} = e \cdot U$$
$$E_{kin} = \frac{1}{2} \cdot m_e \cdot v^2$$
$$E_{kin} = E_{pot}$$
$$v_{max} = \sqrt{\frac{2 \cdot e \cdot U}{m_e}}$$

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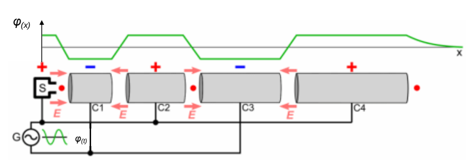
Particle accelerators

Linear accelerator (Linac)



Chetvorno, Wikimedia commons

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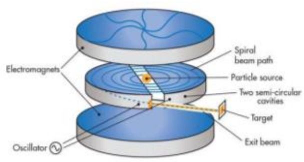
Particle accelerators

Cyclotron



Symmetry Magazine

angular velocity of the particle: $\omega = \frac{q \cdot B}{m}$

linear velocity: $v_l = r \cdot \omega = \frac{r \cdot q \cdot B}{m}$

Charged particles (p^+, e^-) accelerate gradually between electrodes (dees or chamber halves) of alternating polarity (but not inside the electrodes).

Magnetic field (Lorentz-forces) forces particles to circular path.

Beam can be used directly or indirectly. In the latter case beam hits a target to produce high energy X-ray.

Few 10-s of MeV-s energies can be reached.

Usual mwthod to produce positron emitting isotopes for PET.

Thank you for your attention!