

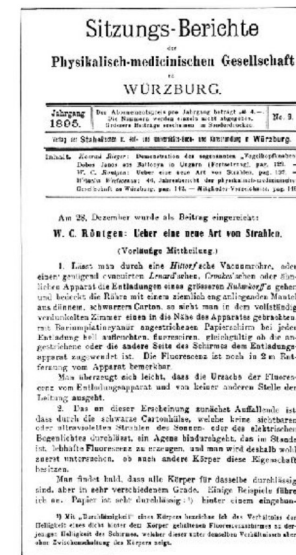
Medical biophysics II

X-ray

Generation, properties



Wilhelm Konrad
Röntgen
(1845-1923)
Nobel prize, 1901



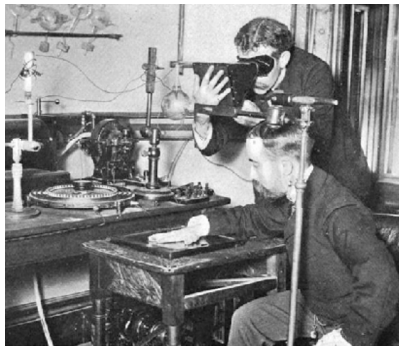
Hand mit Ringen (Hand with Ring): print of Wilhelm Röntgen's first 'medical' X-ray, of his wife's hand, taken on 22 December 1895 and presented to Professor Ludwig Zehender of the Physik Institut, University of Freiburg, on 1 January 1896. The dark oval on the third finger is a shadow produced by her ring.

Medical biophysics II

- Generation and properties of X-ray
- Fundamentals of X-ray diagnostics
- Thermodynamics - equilibrium, change, laws
- Transport processes I: Diffusion, Brown-motion, Osmosis
- Transport processes II: Flow of fluids and gases. Blood as fluid
- Bioelectric phenomena
- Sound, ultrasound
- Biophysics of sensory organs. Vision and hearing
- Building blocks of life: water, macromolecules, supramolecular systems
- Biological motion. Biomechanics, biomolecular and tissue elasticity
- Methods of investigating biomolecular structure and dynamics: X-ray diffraction, mass spectrometry, infrared spectroscopy
- Methods of investigating biomolecular structure and dynamics. Radiospectroscopic methods, fundamentals of MRI.
- Blood circulation and cardiac function.
- Biophysics of pulmonary function. Physical examination

X-ray

Paper funnel radioscope



Late 1890s

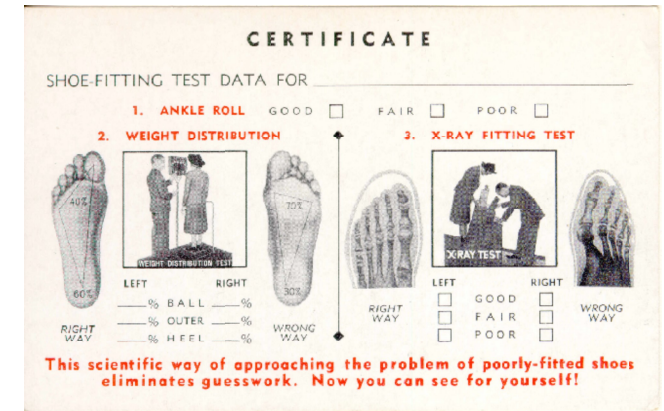


Free X-Ray Examination to Patients



I. World war

Shoe-fitting fluoroscope (1930-50)



Medical diagnostics



1940

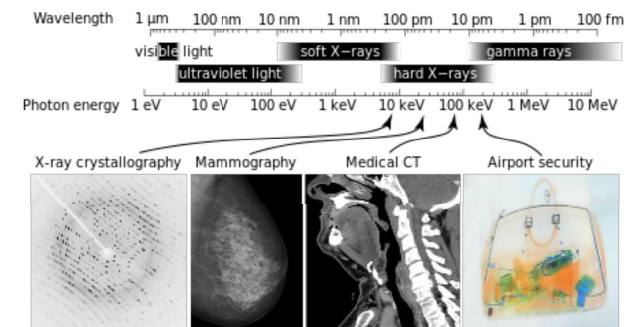


1950



today

X-rays are electromagnetic waves



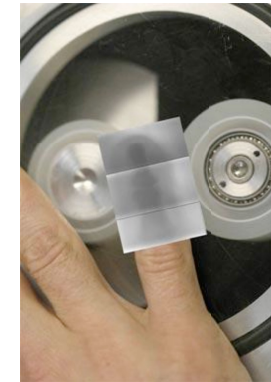
Wavelength 10 - 0.01 nm. **Frequency** 30×10^{15} - 30×10^{18} Hz. **Energy** 120 eV - 120 keV.
(petahertz - exahertz)

X-rays

- Generation of X-rays
- X-ray spectrum
- Interaction with matter 1: diffraction
- Interaction with matter 2: absorption
- X-ray absorption mechanisms:
Photoelectric effect
Compton scatter
Pair production

Generation of X-ray (non-conventional)

Triboluminescence: light emission evoked by scratching or rubbing. Francis Bacon, 1605.



Peeling away sticky tape emits light...

...and X-rays. (Nature News, October 2008)

Generation of X-ray: in Cathode Ray Tube

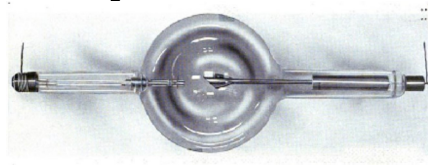
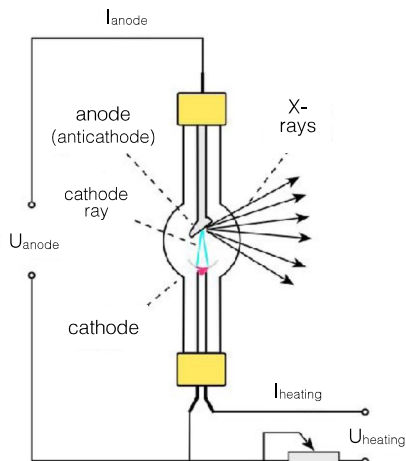
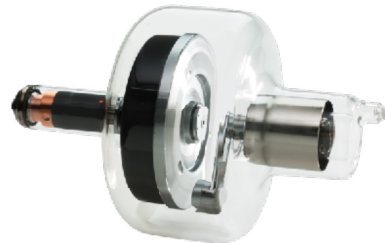
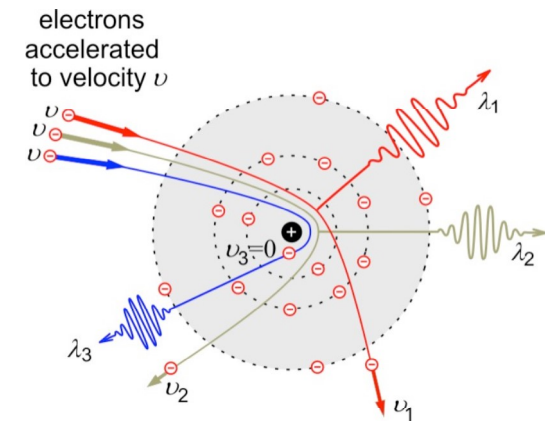


Photo of a Coolidge x-ray tube, from the early 1900s. The heated cathode is on the left, the anode target is on the right. The x-rays are emitted in a downward direction.



Rotating-anode X-ray tube. Anode rotation is used for cooling.

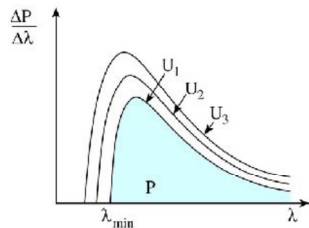
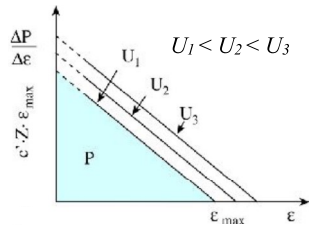
“Bremsstrahlung”



Electrons decelerate, thereby lose their kinetic energy, when interacting with the atoms of the anode (“braking radiation”).

Spectrum of Bremsstrahlung

Continuous spectrum



$$eU_{anode} = \varepsilon_{\max} = hf_{\max}$$

$$\lambda_{\min} = \frac{hc}{e} \cdot \frac{1}{U_{\text{anode}}}$$

$$\frac{\Delta P}{\Delta \varepsilon} = c' \cdot Z \cdot (\varepsilon_{\max} - \varepsilon)$$

$$P_{tot} = \frac{1}{2} c' \cdot Z \cdot \epsilon_{\max}^2 = c \cdot Z \cdot U_{anode}^2 \cdot e^2$$

$$P_{tot} = C_{Rtg} \cdot I_{anode} \cdot U_{anode}^2 \cdot Z$$

$$\eta = \frac{P_{tot}}{P_{in}} = \frac{C_{Rtg} \cdot I_{anode} \cdot U_{anode}^2 \cdot Z}{I_{anode} \cdot U_{anode}} = C_{Rtg} \cdot U_{anode} \cdot Z$$

Maximal photon energy (ε_{max})

N.B.: Total kinetic energy of electron is transformed in one step (rare event).

e : electron's charge;
 U_{anode} : accelerating voltage;
 eU_{anode} : acceleration work;
 h : Planck's constant;
 f_{max} : limiting frequency

Limiting wavelength (λ_{min})

(Duane-Hunt Law)
N.B.: Limiting wavelength is inversely proportional to accelerating voltage.
 c : light speed;
 hc/e : constant (1.2398 kV·nm)

Total power (P_{tot})

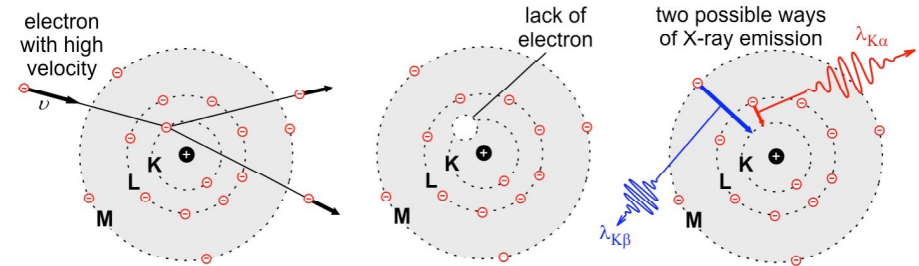
(based on the area of the triangle)

C_{Rtg} : coefficient ($1.1 \times 10^{-9} \text{ V}^{-1}$);
 I_{anode} : anode current (number of electrons hitting the anode per unit time);
 Z : atomic number of the anode atoms

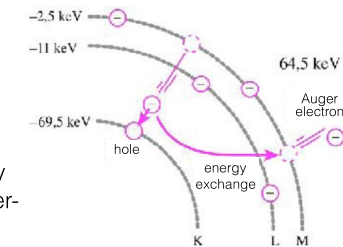
Efficiency (η)

P_{in} : invested power
N.B.: Typically, $\eta < 1\%$.

Characteristic X-ray

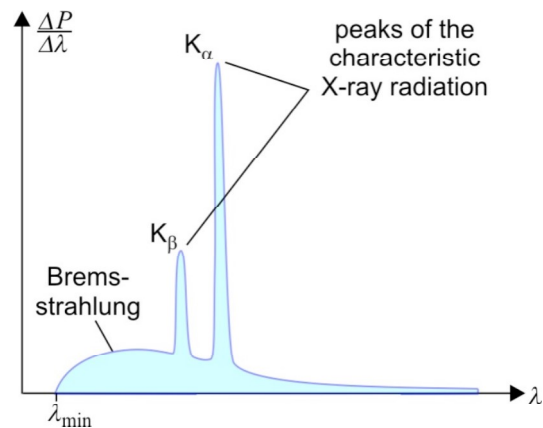


Knocked-out inner-shell electron is replaced by one on a higher-energy shell



Energy of electron transition may be used for the escape of an outer-shell electron: Auger electron

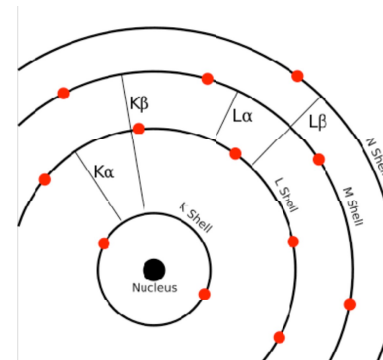
Spectrum of characteristic X-ray



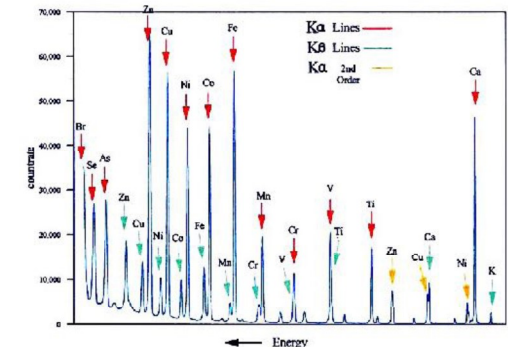
Line spectrum

X-ray spectrum characterizes the atomic composition

Because inner-shell electrons participate in characteristic X-radiation, only the atomic (and not the molecular) properties are revealed

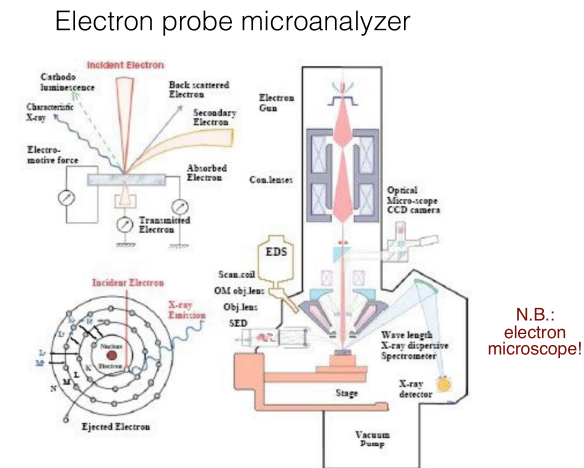


Electronic transitions in
a calcium atom.

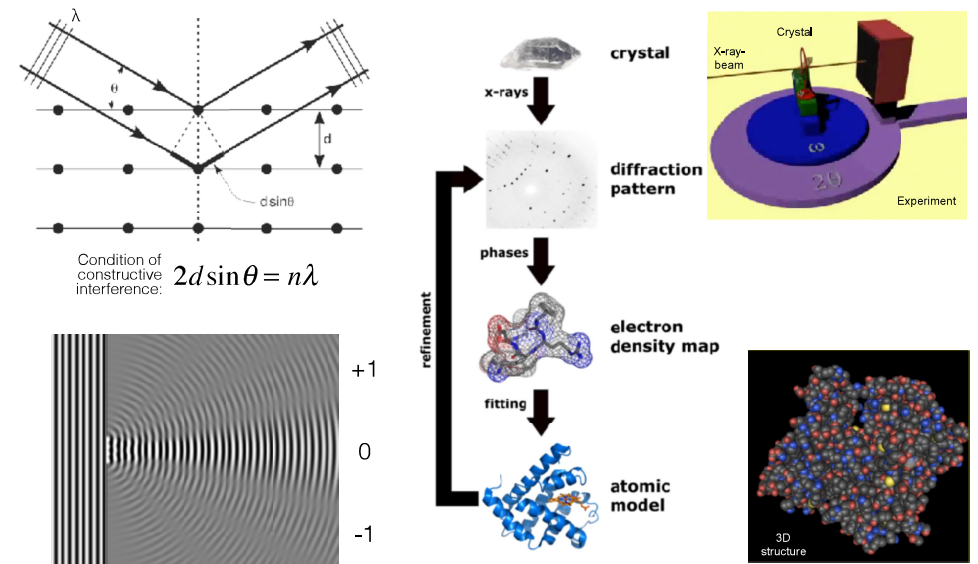


Energy dispersive X-ray
fluorescence spectrum.

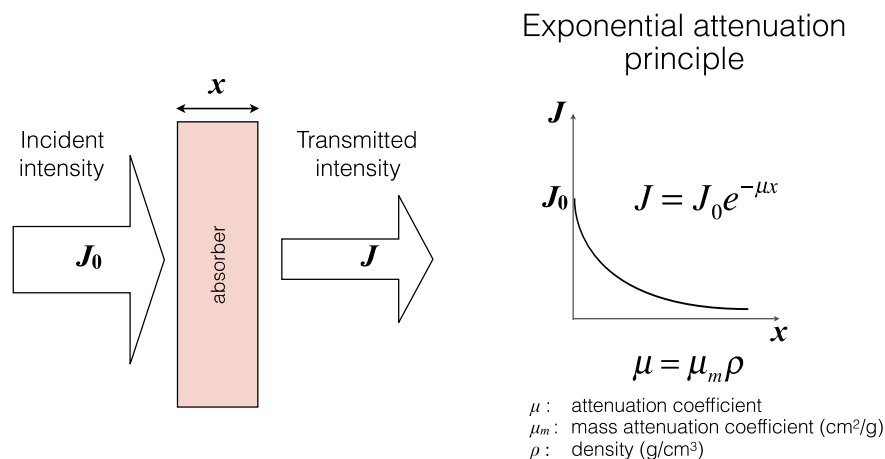
Detection of characteristic X-ray



X-ray diffraction

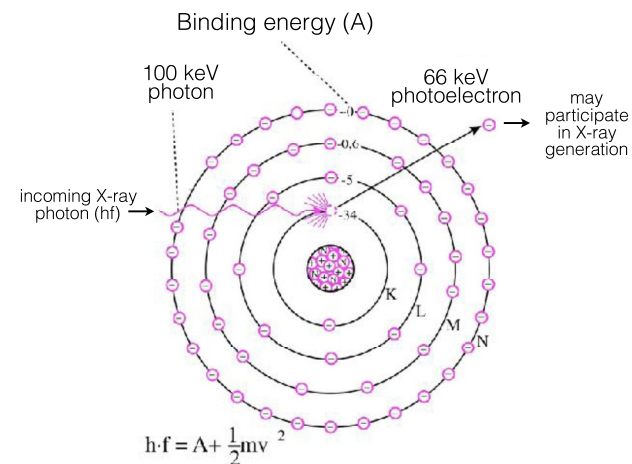


X-ray absorption



μ_m is the sum of the mass attenuation coefficients of the different absorption mechanisms.

X-ray photoeffect

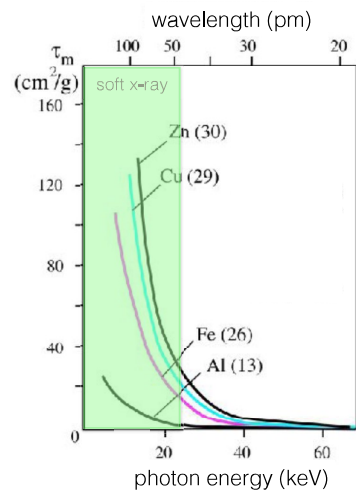


Main effect in diagnostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

Photoeffect attenuation depends strongly on the atomic number



$$\tau_m = \text{const} \cdot \frac{Z^3}{\epsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

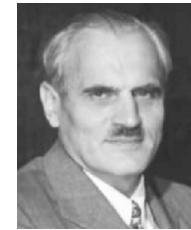
For multi-component system:
"effective atomic number" (Z_{eff})

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

ϵ = photon energy
 Z = atomic number
 w = mole fraction
 n = number of components

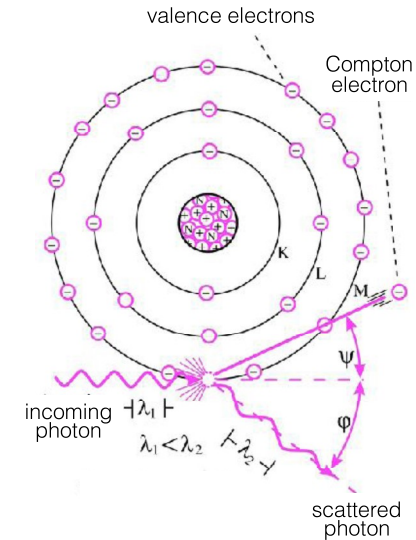
Material	Z_{eff}
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

Compton scatter

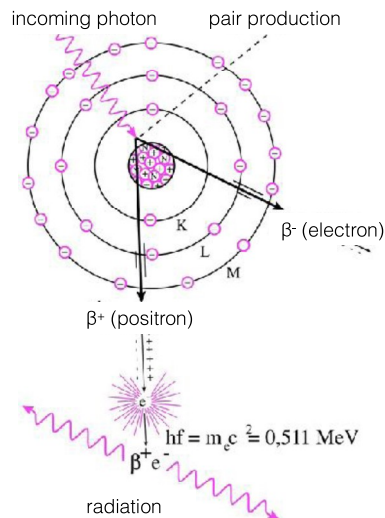


Arthur Holly Compton
(1892-1962)

$$hf = A + hf_{\text{scatt}} + E_{\text{kin}}$$



Pair production



(relevant only in therapeutic x-ray)

Energy balance:

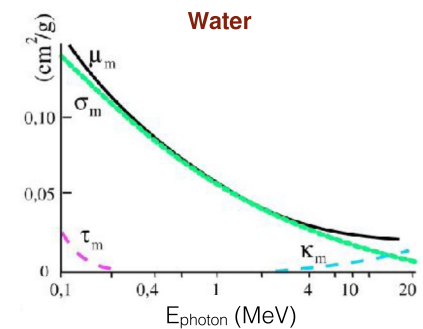
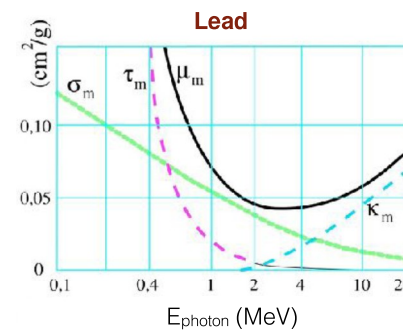
$$hf = 2m_e c^2 + 2E_{\text{kin}}$$

m_e = mass of electron
 c = speed of light

Pair production relevant in high-energy X-ray photons, γ -radiation.

Attenuation mechanisms

Dependence on photon energy and material



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

μ_m = mass attenuation coefficient
 σ_m = Compton effect mass attenuation coefficient

τ_m = photoeffect mass attenuation coefficient
 κ_m = pair production mass attenuation coefficient

Summary of attenuation mechanisms

Mechanism	Photon energy (ϵ) dependence of the mass attenuation coefficient	Atomic number (Z) dependence of the mass attenuation coefficient	Relevant energy range in soft tissue
Rayleigh scatter	$\sim 1 / \epsilon$	$\sim Z^2$	1 - 30 keV
Photoeffect	$\sim 1 / \epsilon^3$	$\sim Z^3$	10 - 100 keV
Compton scatter	falls gradually with ϵ	$\sim Z/A$ (A: mass number)	0.5 - 5 MeV
Pair production	rises slowly with ϵ	$\sim Z^2$	> 5 MeV

Diagnostic X-ray:

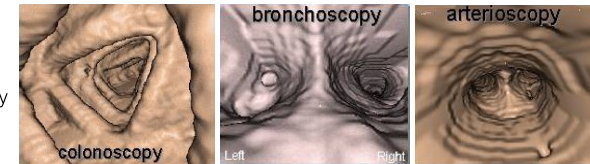
1. Contrast mechanism between soft tissue and bone: photoeffect ($\sim Z^3$)
2. Contrast mechanism within soft tissue: Compton-scatter ($\sim \rho$)

Trends of X-ray applications

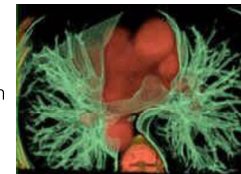
Spiral CT



Virtual endoscopy



3D reconstruction



Angiography

