Medical biophysics II

Medical biophysics II

- Generation and properties of X-ray
- Fundamentals of X-ray diagnostics
- Sound, ultrasound
- Thermodynamics - equilibrium, change, laws
- Transport processes I: Diffusion, Brown-motion, Osmosis
- Transport processes II: Flow of fluids and gases. Blood as fluid
- Bioelectric phenomena
- 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 diffration, mass spectrometry, infrared spectroscopy
- Methods of investigating biomolecular structure and dynamics. Radiospectroscopic methds, fundamentals of MRI.
- Blood circulation and cardiac function.
- Biophysics of pulmonary function. Physical examination

X-ray

Generation, properties

X-ray

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 Zehnder 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.

Paper funnel radioscope
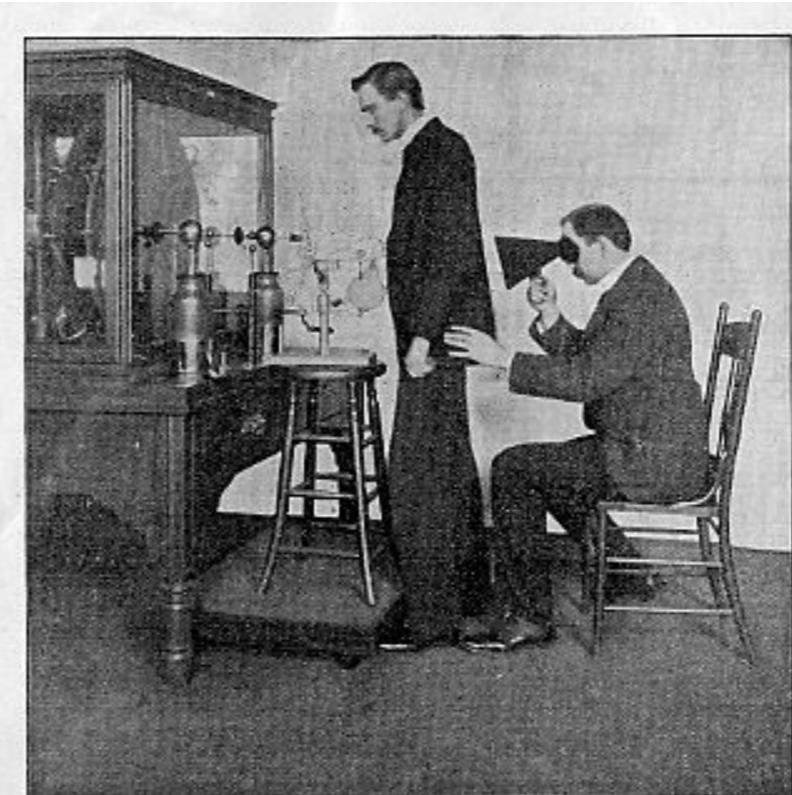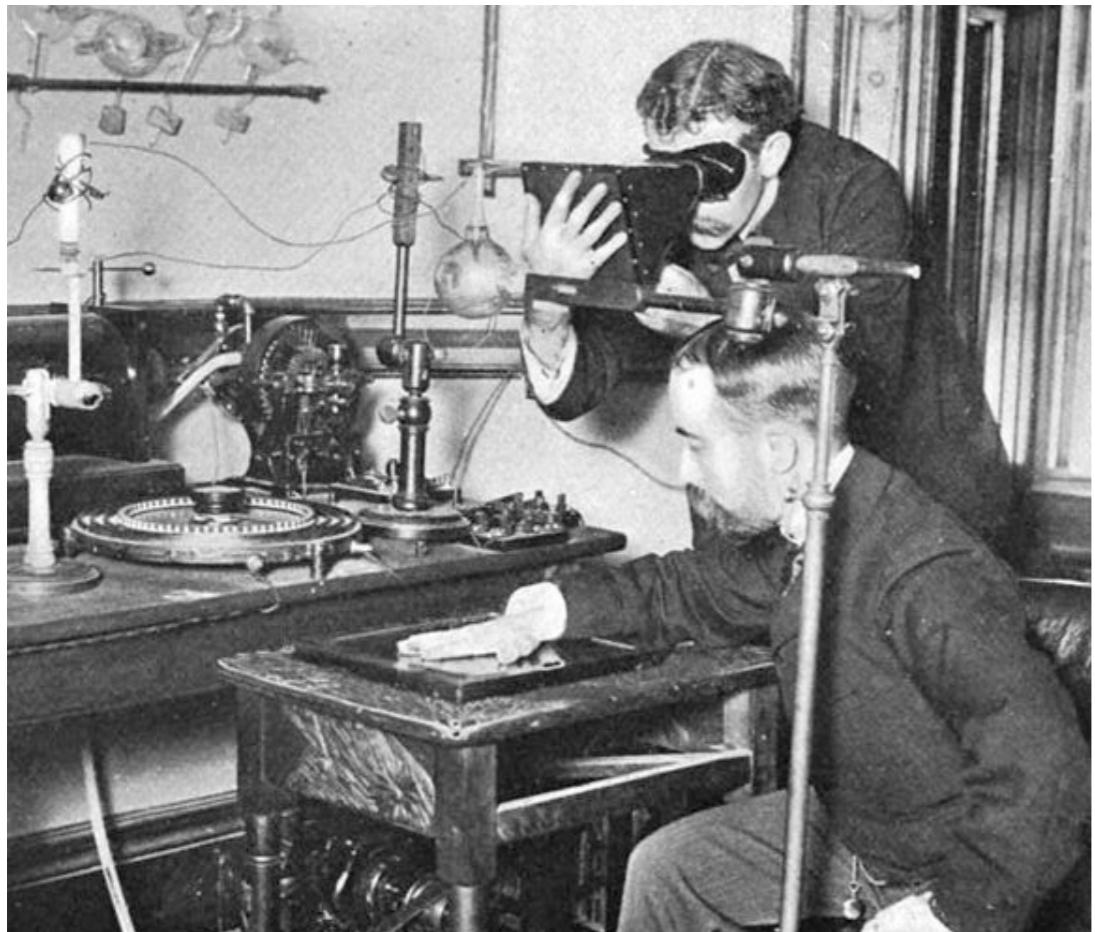
Late 1890s

Free X-Ray Examination to Patients.

I. World war

Shoe-fitting fluoroscope (1930-50)

Medical diagnostics

1940

1950

today

X-rays are electromagnetic waves
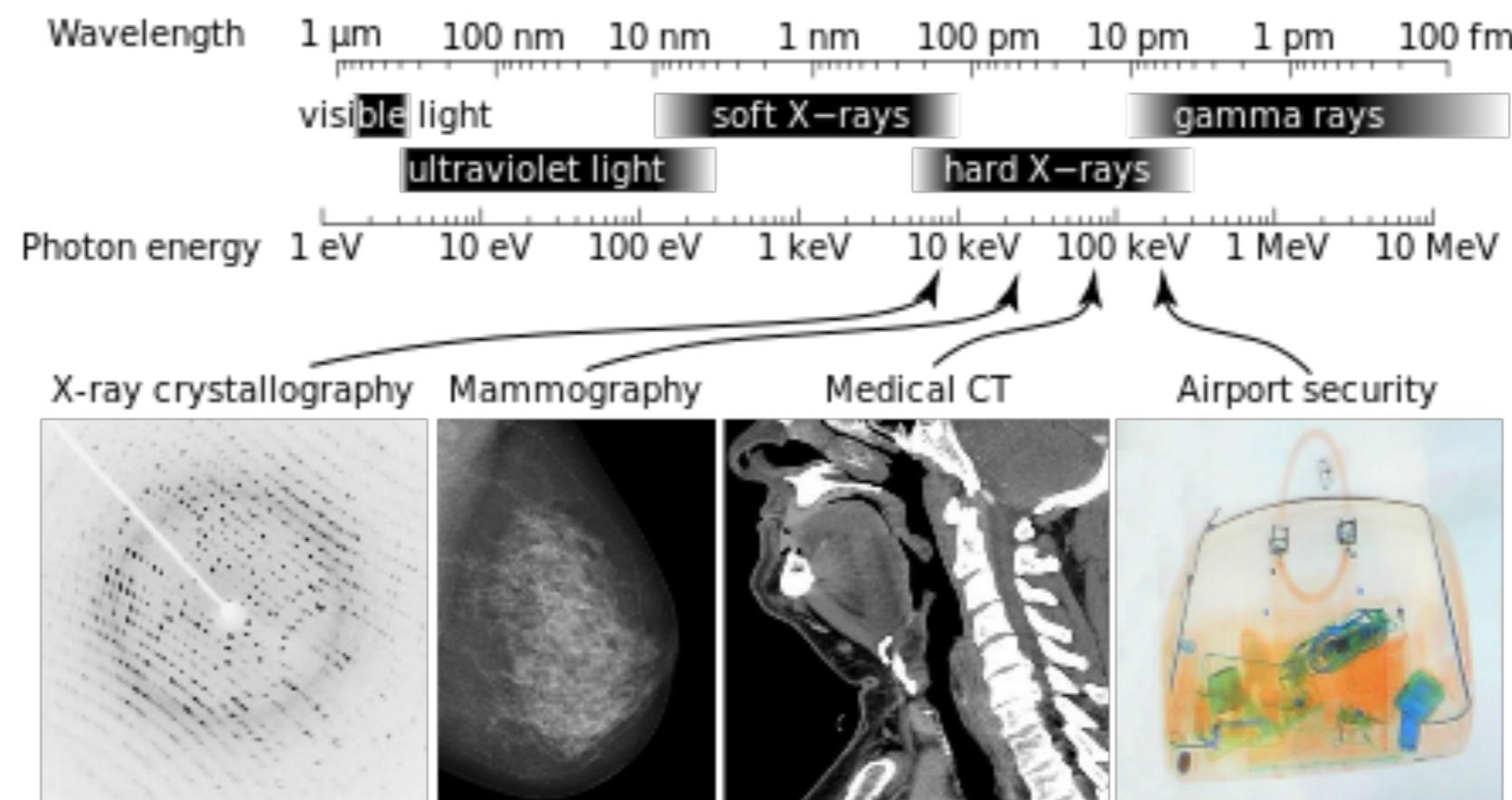
Wavelength 10 - 0.01 nm. **Frequency** 30×10^{15} - 30×10^{18} Hz. **Energy** 120 eV - 120 keV.
(petaherz - exahertz)

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)
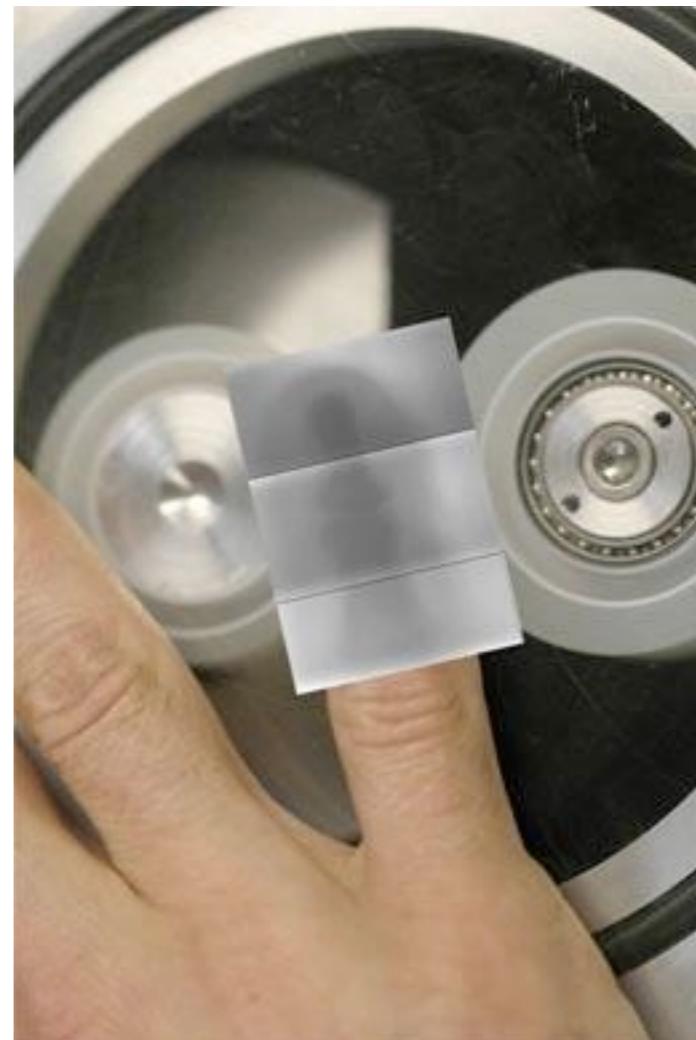
Generation of X-ray:
in Cathode Ray Tube

I_{anode}

anode
(anticathode)

X-rays

cathode ray

U_{anode}

cathode
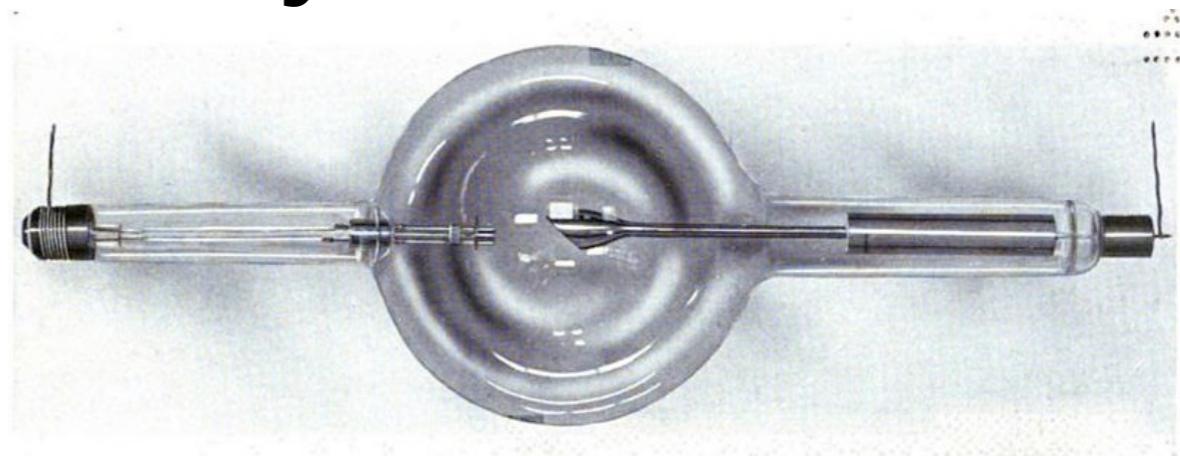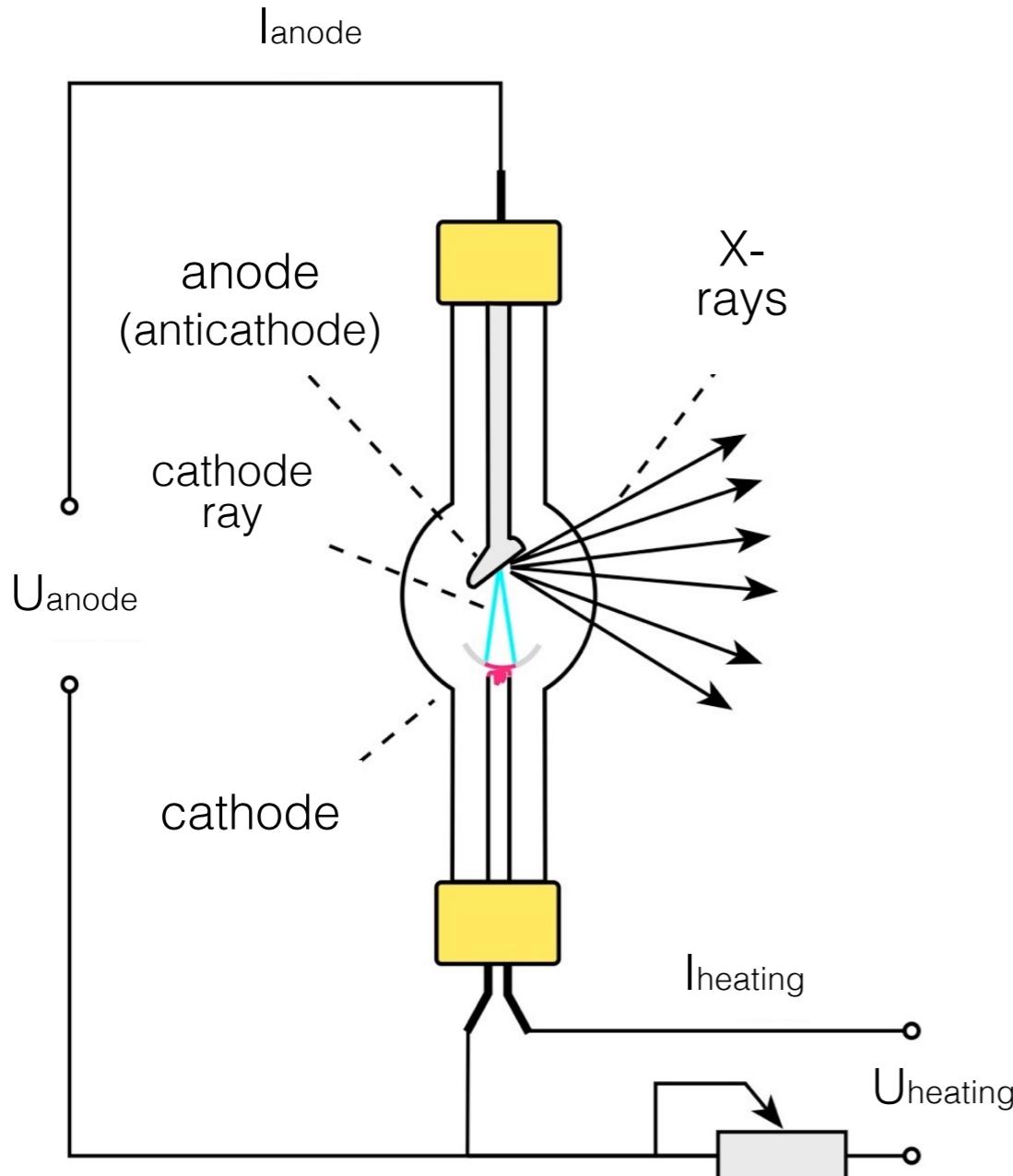
$I_{heating}$

$U_{heating}$

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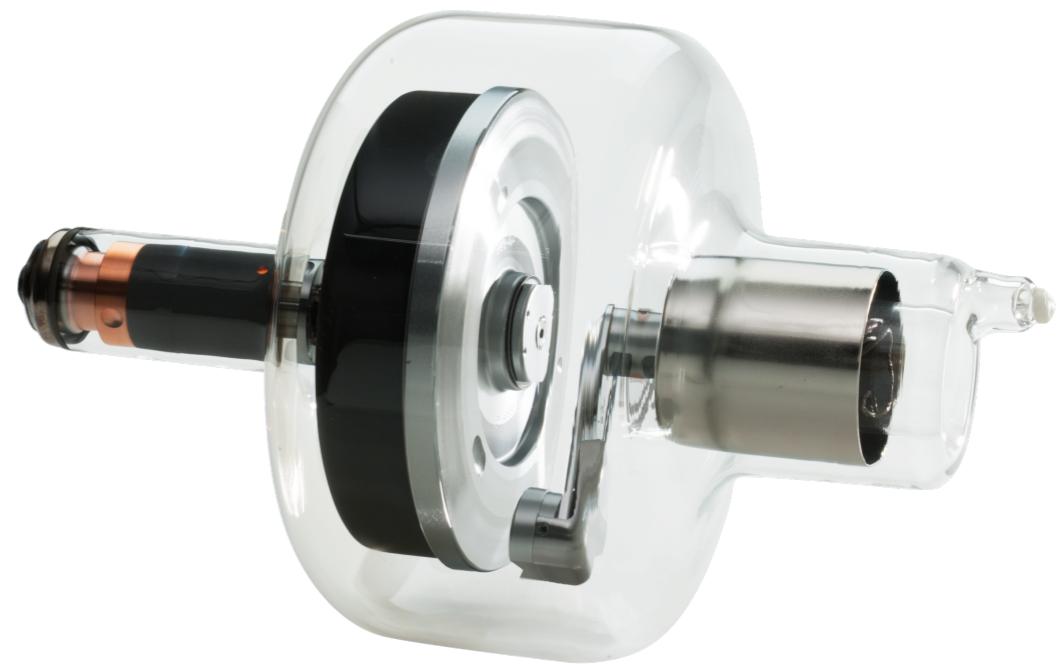
Rotating-anode X-ray tube. Anode rotation is used for *cooling*.

"Bremsstrahlung"
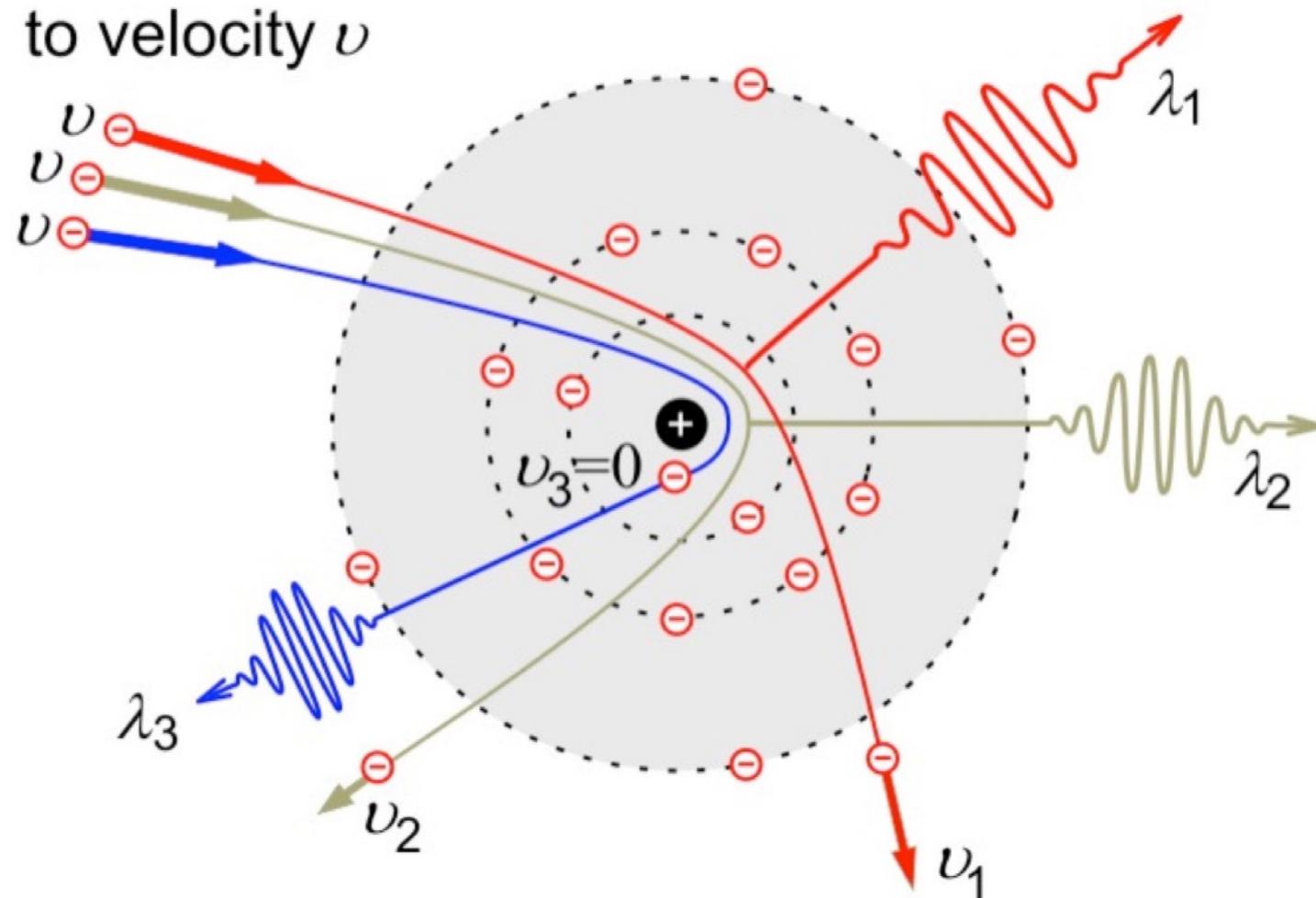
Electrons *decelerate*, thereby loose their kinetic energy, when interacting with the atoms of the anode ("braking radiation").

Spectrum of Bremsstrahlung

Continuous spectrum

$U_1 < U_2 < U_3$

(Plot: $\frac{\Delta P}{\Delta \varepsilon}$ vs ε, y-axis $c' \cdot Z \cdot \varepsilon_{max}$, curves U_1, U_2, U_3, area P, x-intercept ε_{max})

(Plot: $\frac{\Delta P}{\Delta \lambda}$ vs λ, curves U_1, U_2, U_3, area P, starting at λ_{min})
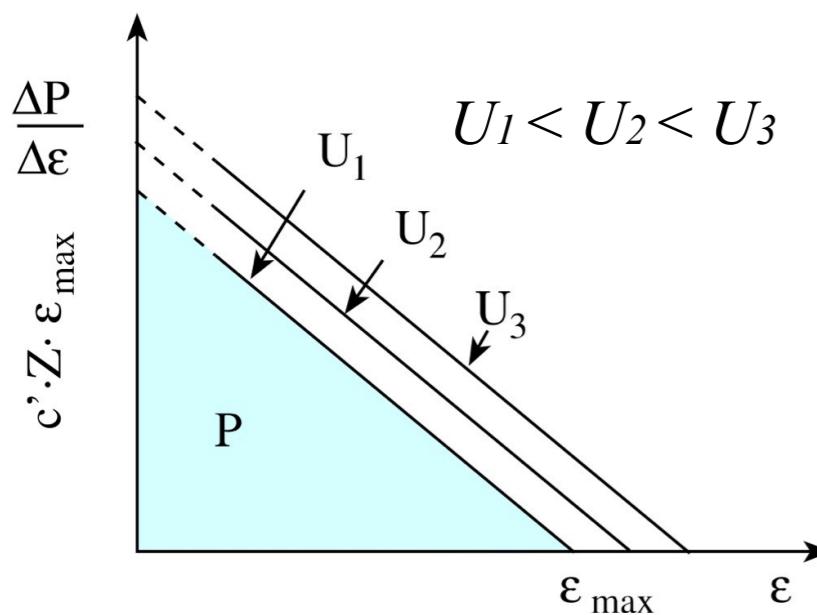
Maximal photon energy (ε_{max})

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

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

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 avvelerating voltage.

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

c: light speed;
hc/e: constant (1.2398 kV·nm)

Energy spectrum
(energy dependence of power)

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

Total power (P_{tot})
(based on the area of the triangle)
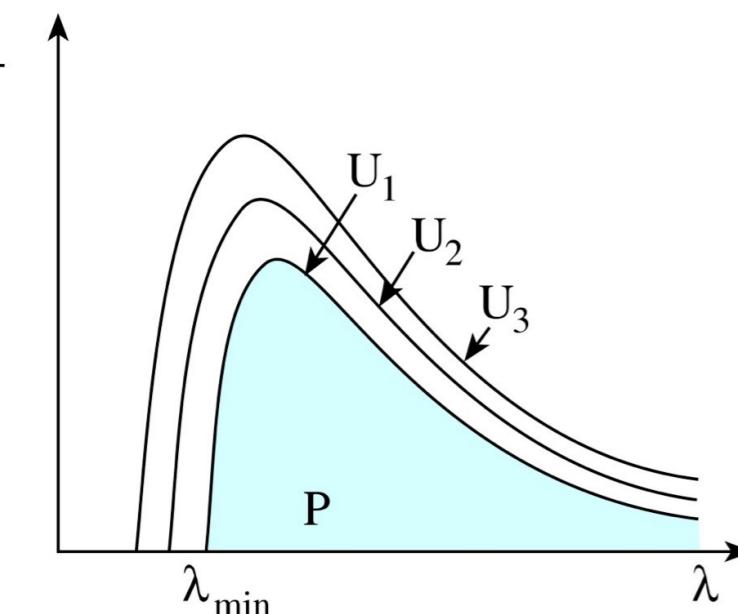
$$P_{tot} = \frac{1}{2} c' \cdot Z \cdot \varepsilon_{max}^2 = c \cdot Z \cdot U_{anode}^2 \cdot e^2$$

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

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

## Efficiency (η)

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

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

Characteristic X-ray

electron with high velocity

v

lack of electron

two possible ways of X-ray emission

$\lambda_{K\alpha}$

$\lambda_{K\beta}$

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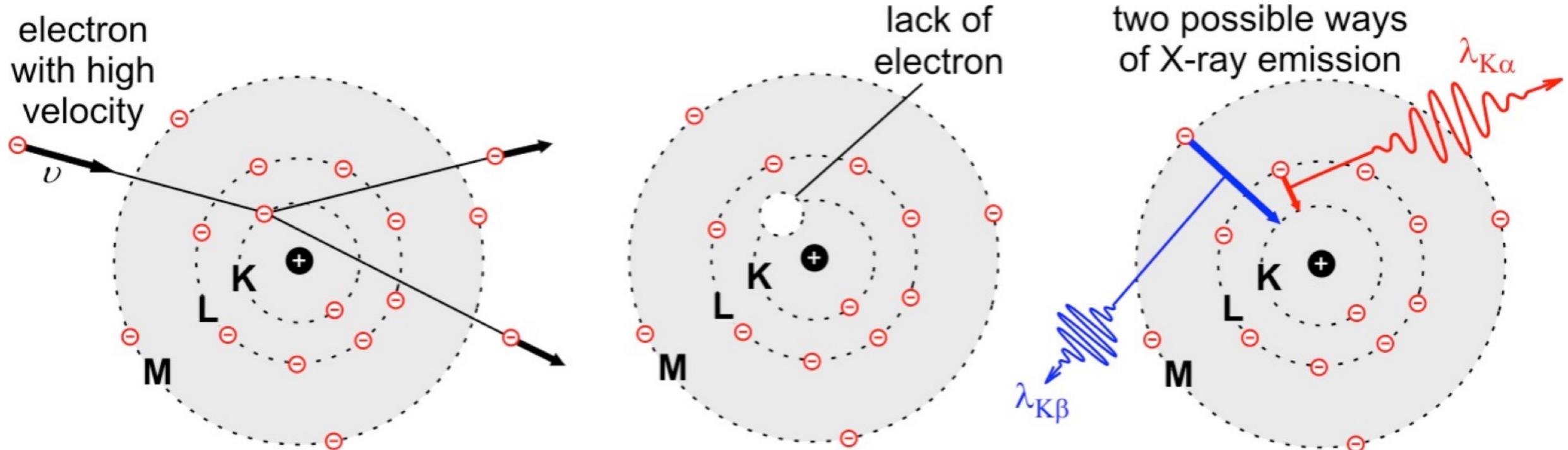
Knocked-out inner-shell electron is replaced by one on a higher-energy shell

−2,5 keV

−11 keV

64,5 keV

−69,5 keV

hole

Auger electron

energy exchange

K   L   M

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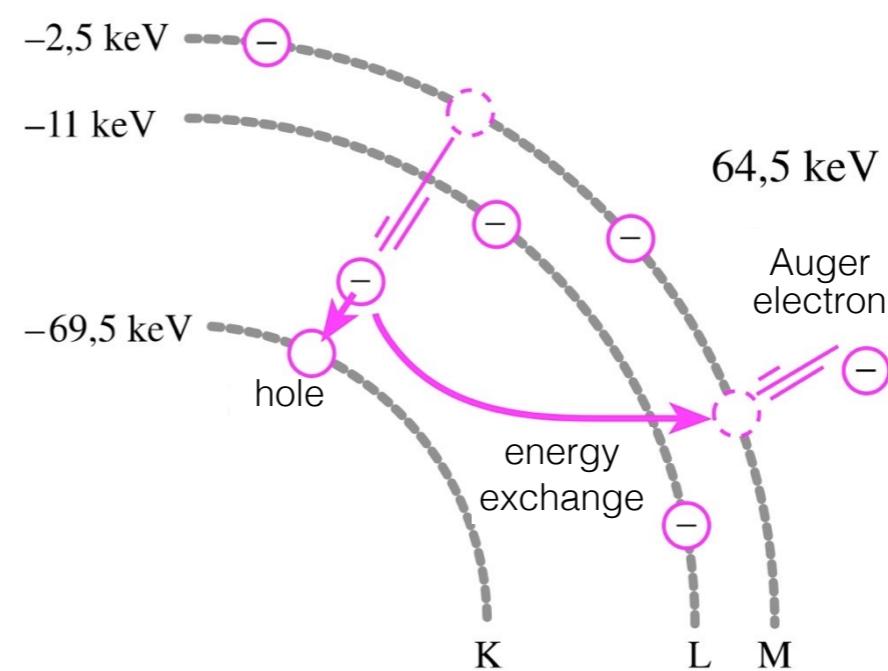
Spectrum of characteristic X-ray

Line spectrum
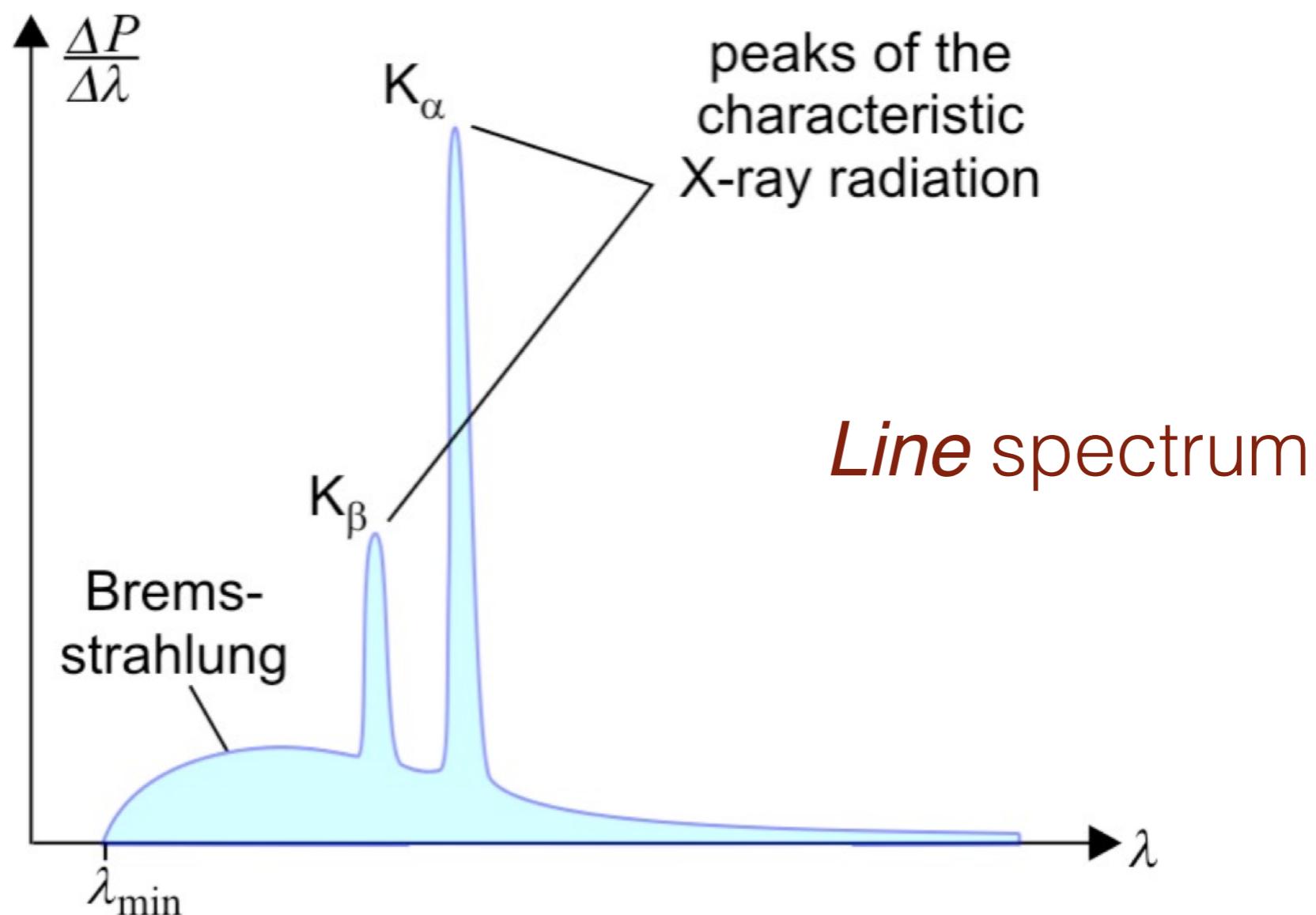
X-ray spectrum characterizes *atomic* composition

Because inner-shell electrons participate in characteristic X-radiation, only the *atomic* (and not the molecular) properties are revealed
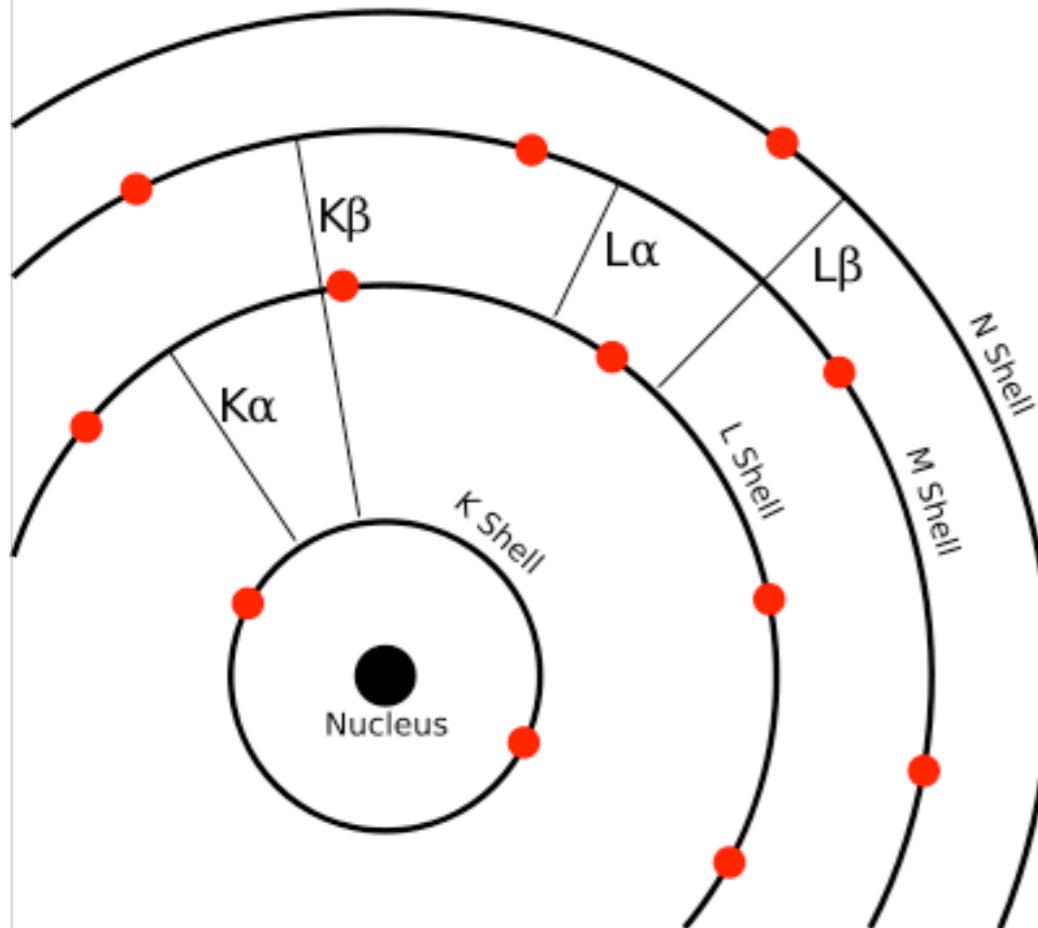
Electronic transitions in a calcium atom.
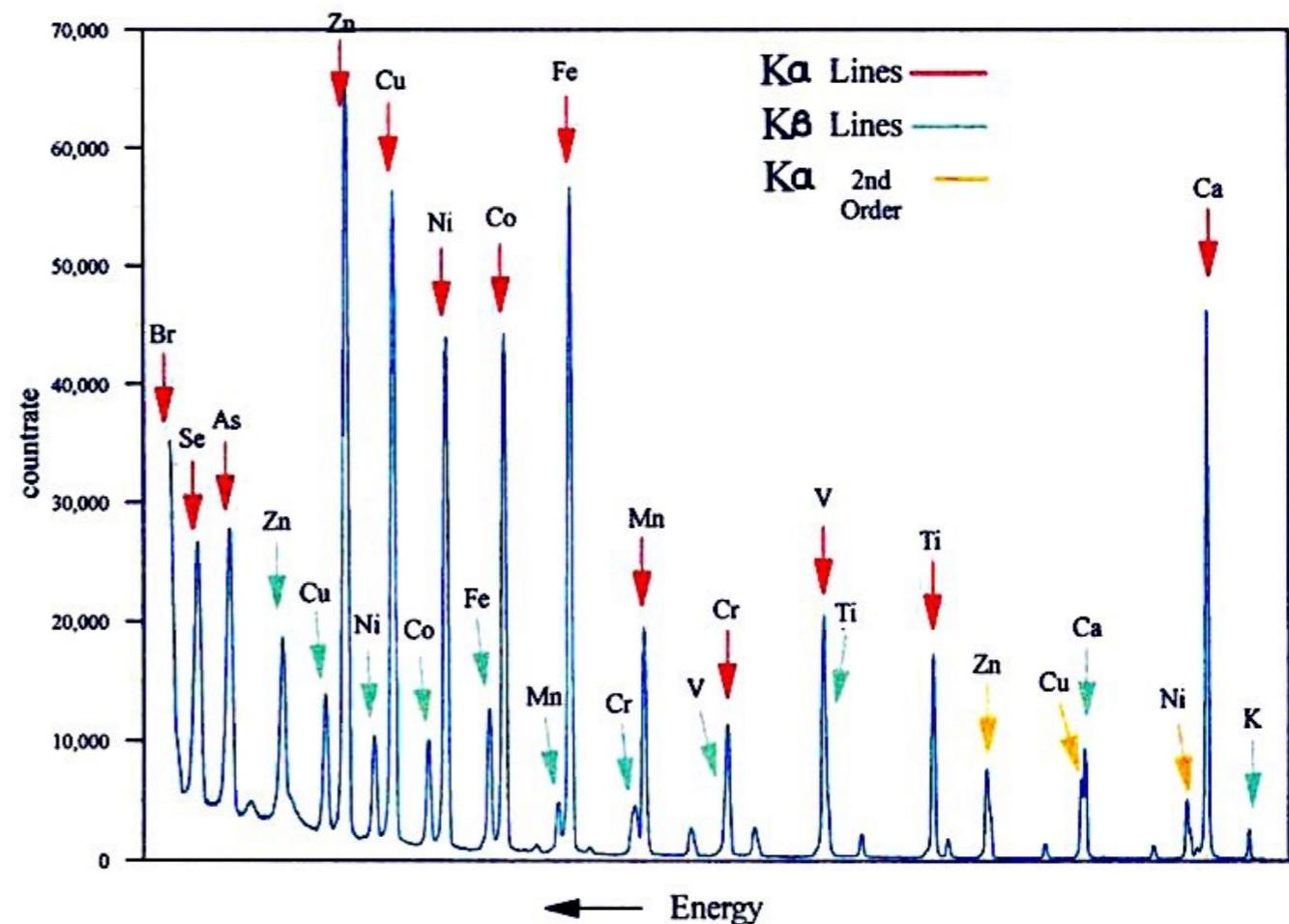
Energy dispersive X-ray fluorescence spectrum.

Detection of characteristic X-ray

Electron probe microanalyzer
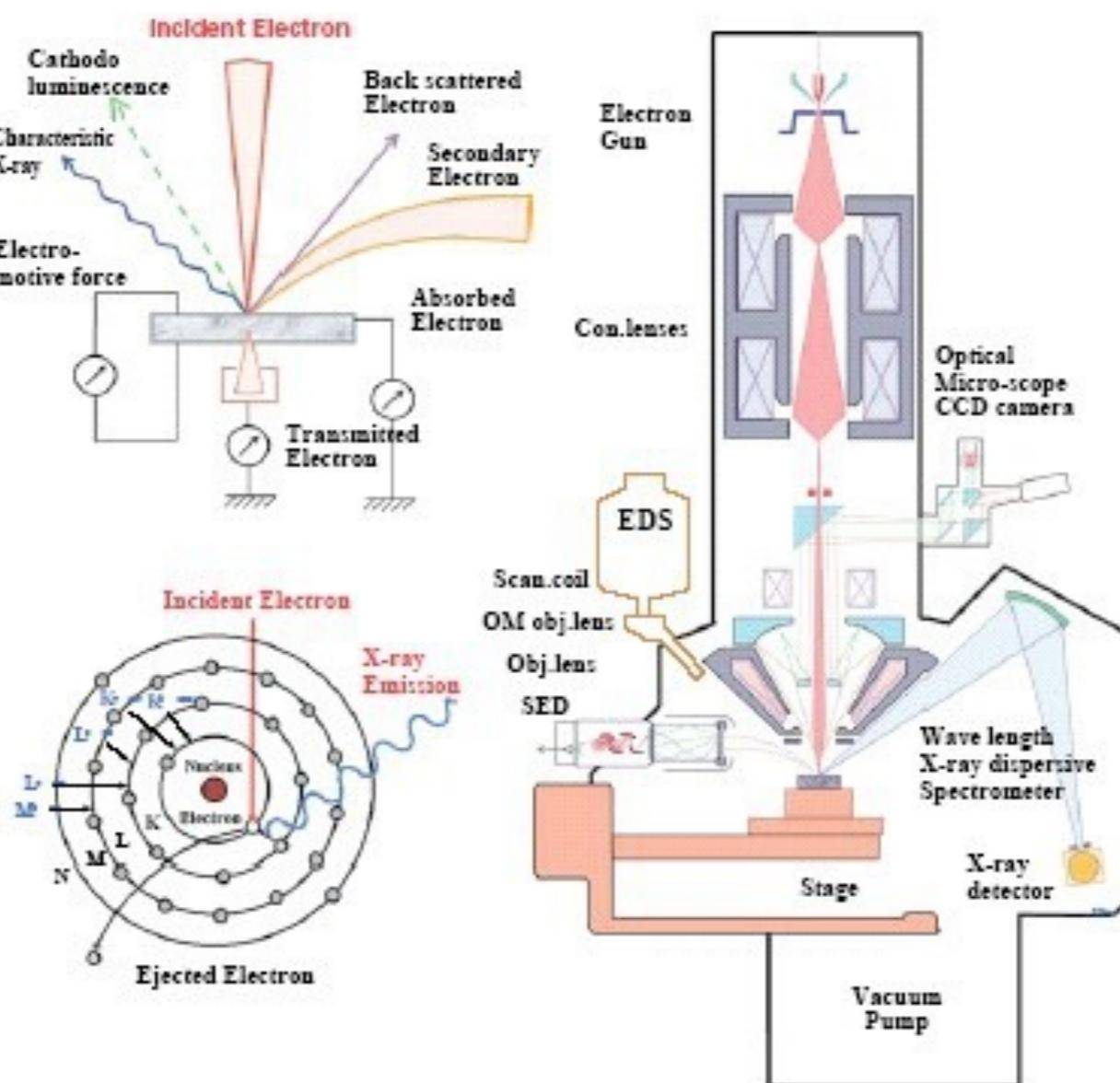
N.B.: electron microscope!

X-ray diffraction

λ

θ

d

d sinθ
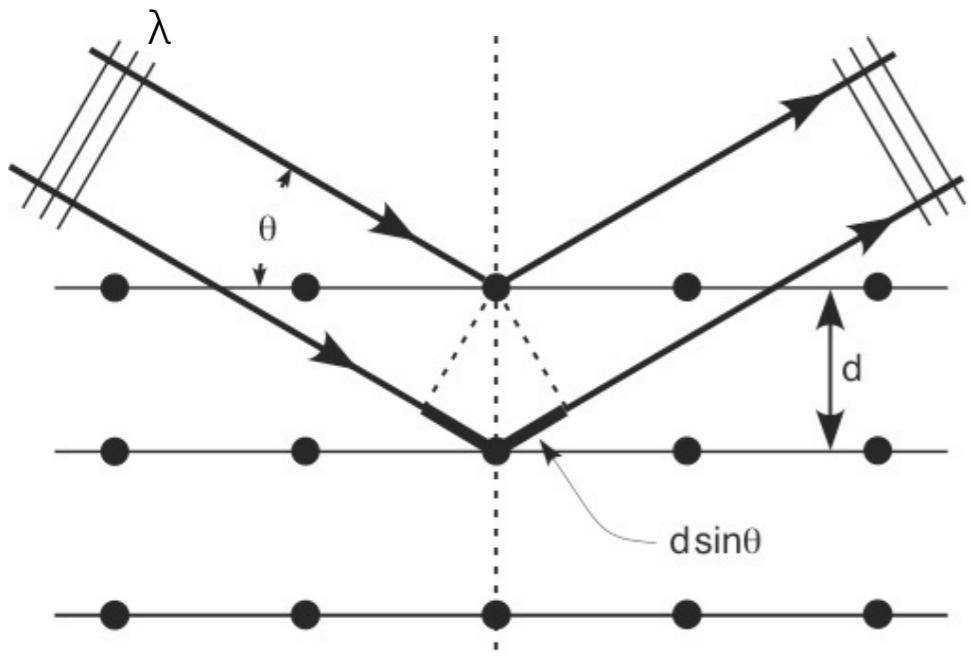
Condition of constructive interference:

$$2d\sin\theta = n\lambda$$

+1

0

-1

crystal

x-rays

diffraction pattern

phases

refinement

electron density map

fitting

atomic model

Crystal

X-ray-beam

ω

2θ

Experiment

3D structure
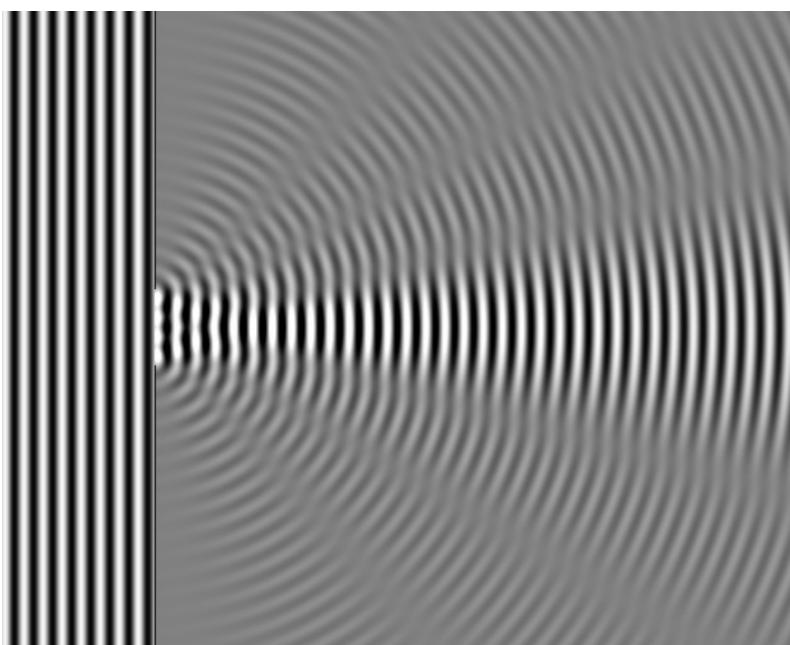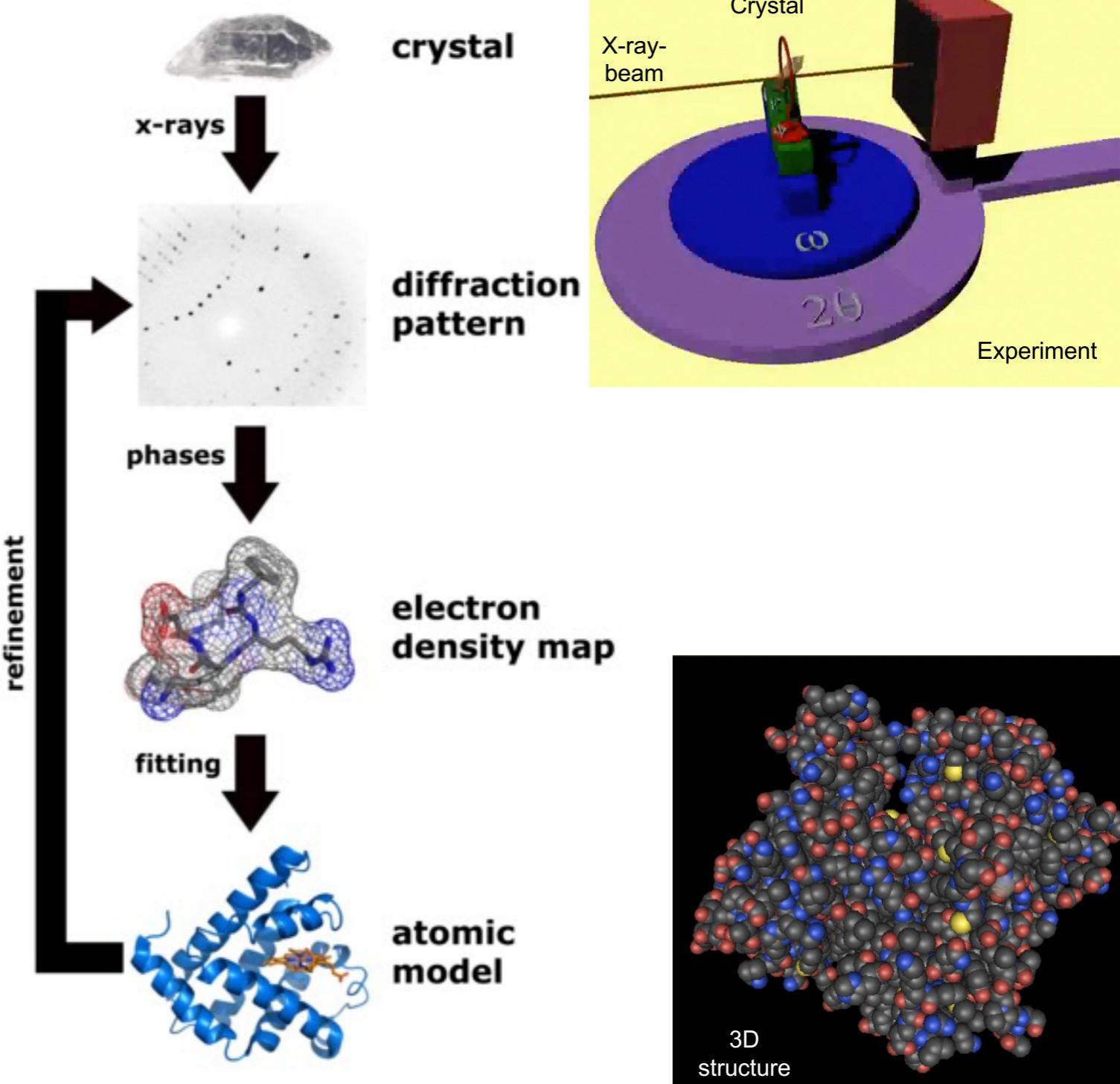
X-ray absorption

Exponential attenuation principle

x

Incident intensity

J_0

absorber

Transmitted intensity

J

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

J_0

J

x

$$\mu = \mu_m \rho$$
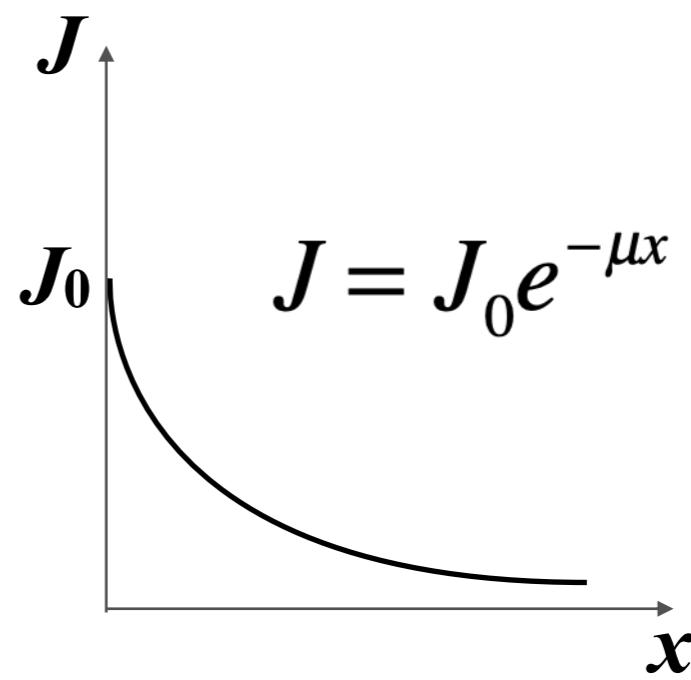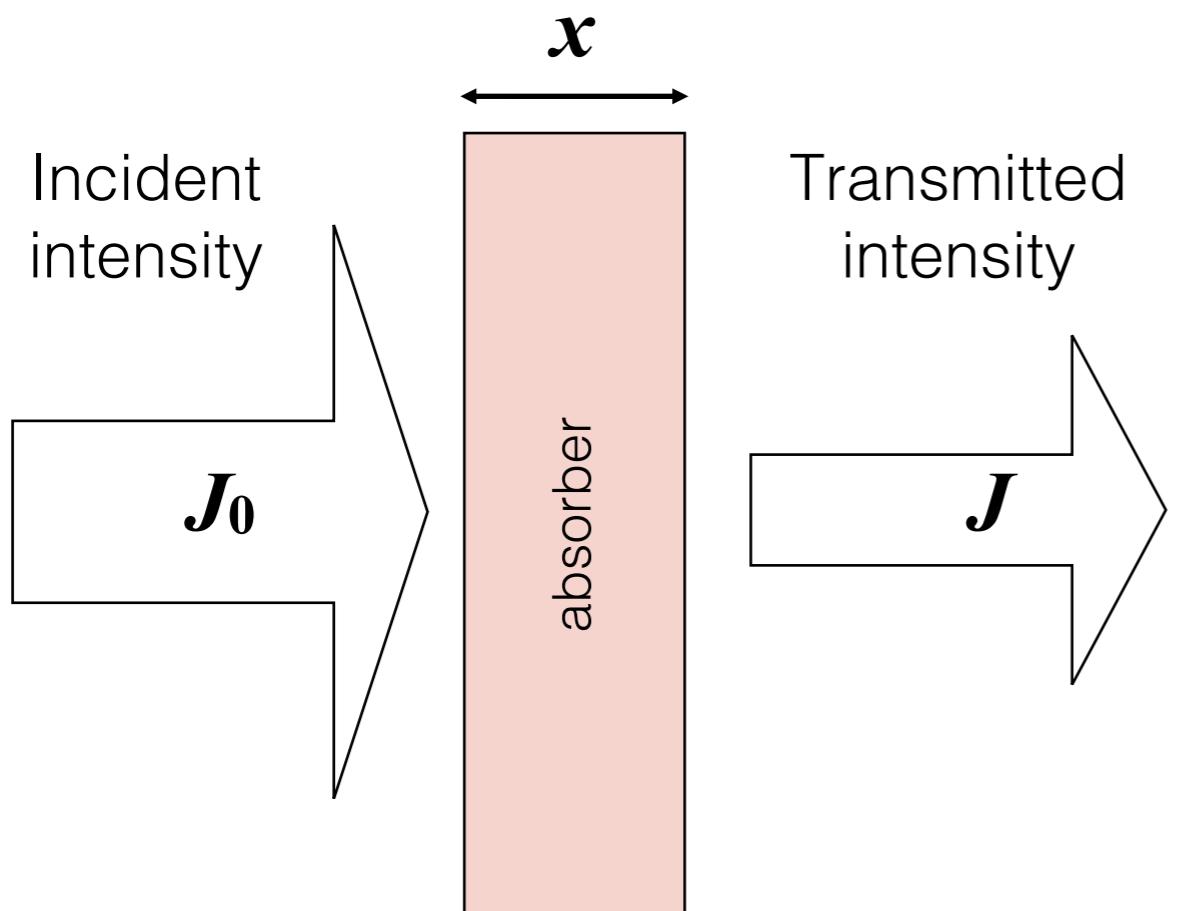
μ : attenuation coefficient
μ_m : mass attenuation coefficient (cm^2/g)
ρ : density (g/cm^3)

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

X-ray photoeffect
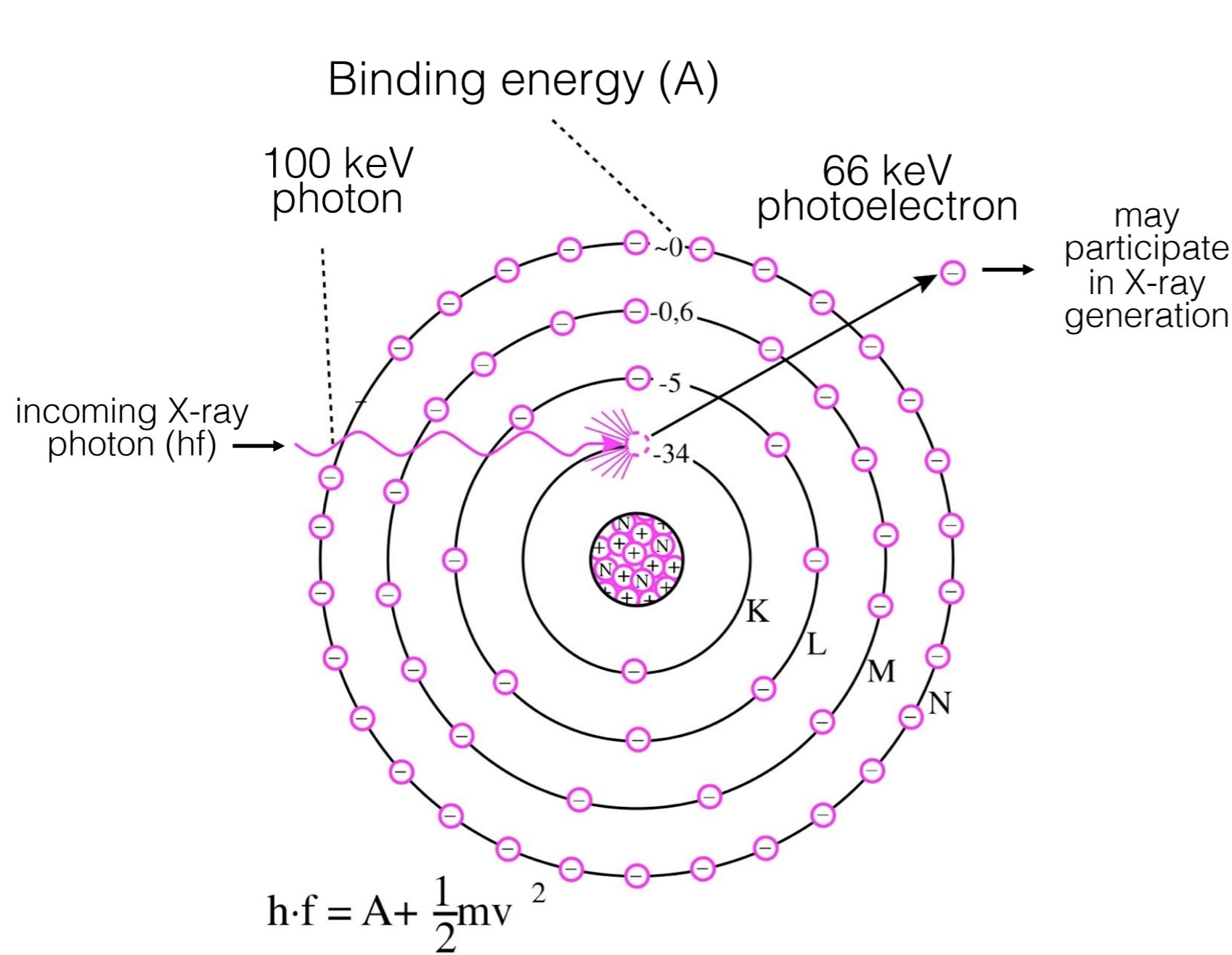
Main effect in diagostic X-ray!

Binding energy (A)

100 keV
photon

66 keV
photoelectron

may
participate
in X-ray
generation

incoming X-ray
photon (hf)

~0

-0,6

-5

-34

K
L
M
N

$$h \cdot f = A + \frac{1}{2}mv^2$$

Photoeffect attenuation
coefficient:

$$\tau = \tau_m \rho$$

τ_m=photoeffect mass
attenuation coefficient
ρ=density

Photoeffect attenuation depends strongly on the atomic number
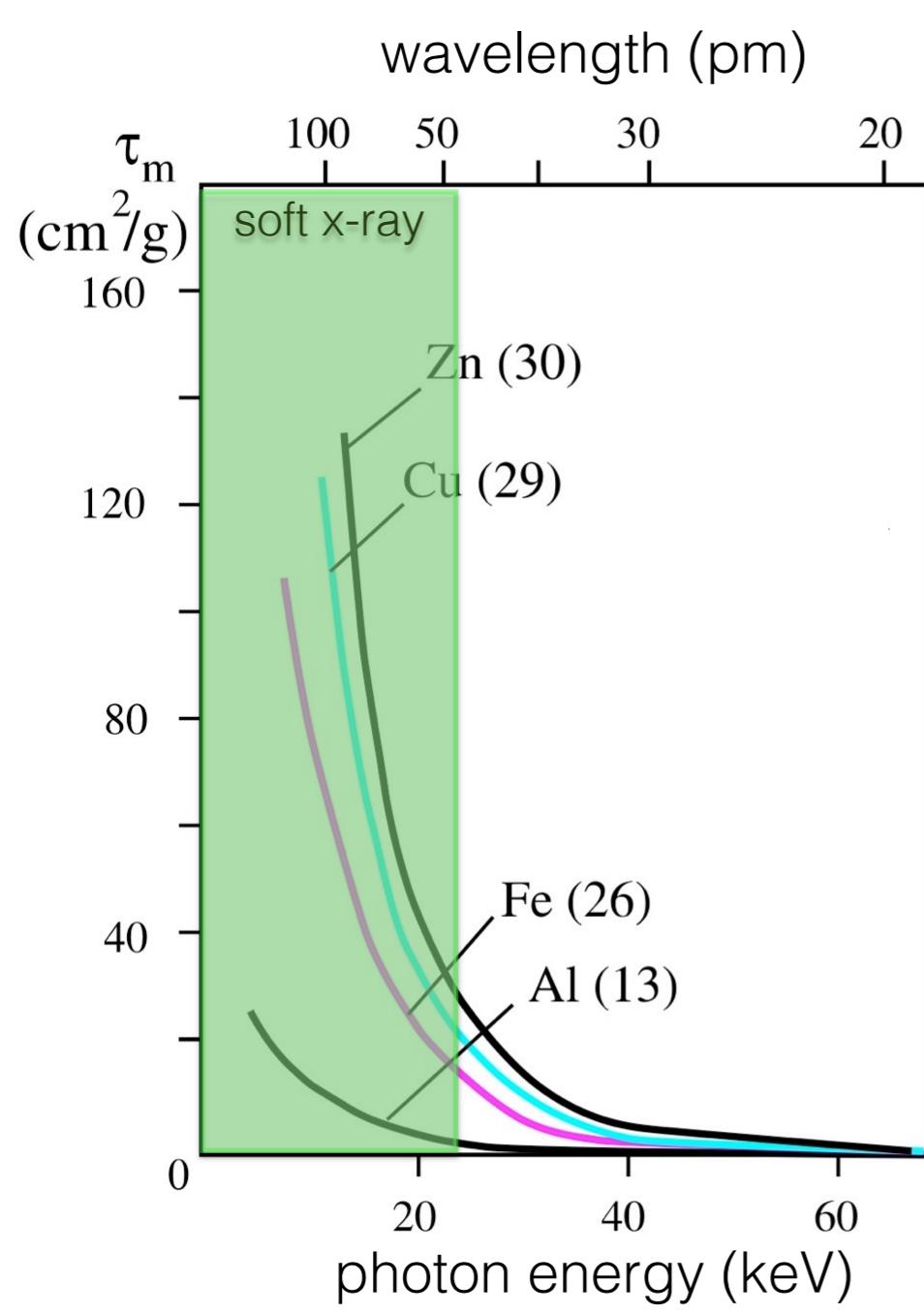
$$\tau_m = const \cdot \frac{Z^3}{\varepsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

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

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

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

wavelength (pm)

τ_m (cm^2/g)

soft x-ray

Zn (30)
Cu (29)
Fe (26)
Al (13)

photon energy (keV)

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

Compton scatter
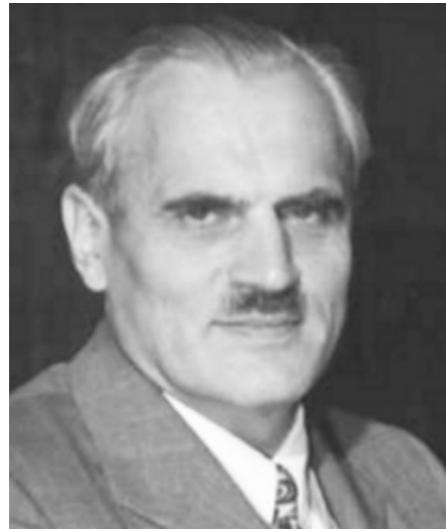
Arthur Holly
Compton
(1892-1962)

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

A=work function
hf_{scatt}=energy of scattered photon
E_{kin}=kinetic energy of Compton-electron

Compton-effect attenuation
coefficient:

$$\sigma = \sigma_m \rho$$

valence electrons

Compton
electron

K

L

M

ψ

φ

incoming
photon

$\dashv \lambda_1 \vdash$

$\lambda_1 < \lambda_2$ $\vdash \lambda_2 \dashv$

scattered photon

Pair production

incoming photon   pair production

β⁻ (electron)

β⁺ (positron)

$$hf = m_e c^2 = 0{,}511 \text{ MeV}$$

β⁺ e⁻

radiation

(relevant only in therapeutic x-ray)

Energy balance:

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

m_e=mass of electron
c=speed of light

Pair production attenuation coefficient:

$$\kappa = \kappa_m \rho$$

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

Attenuation mechanisms

Dependence on photon energy and material

Lead

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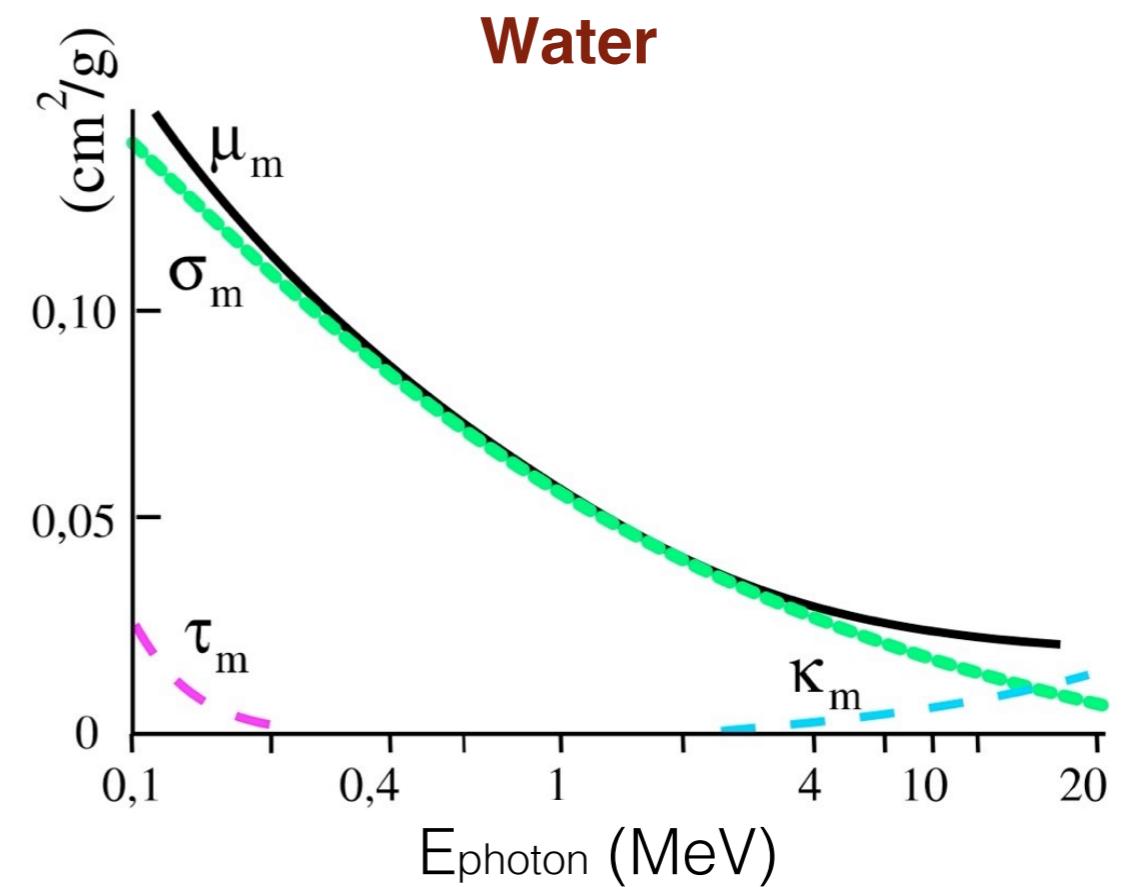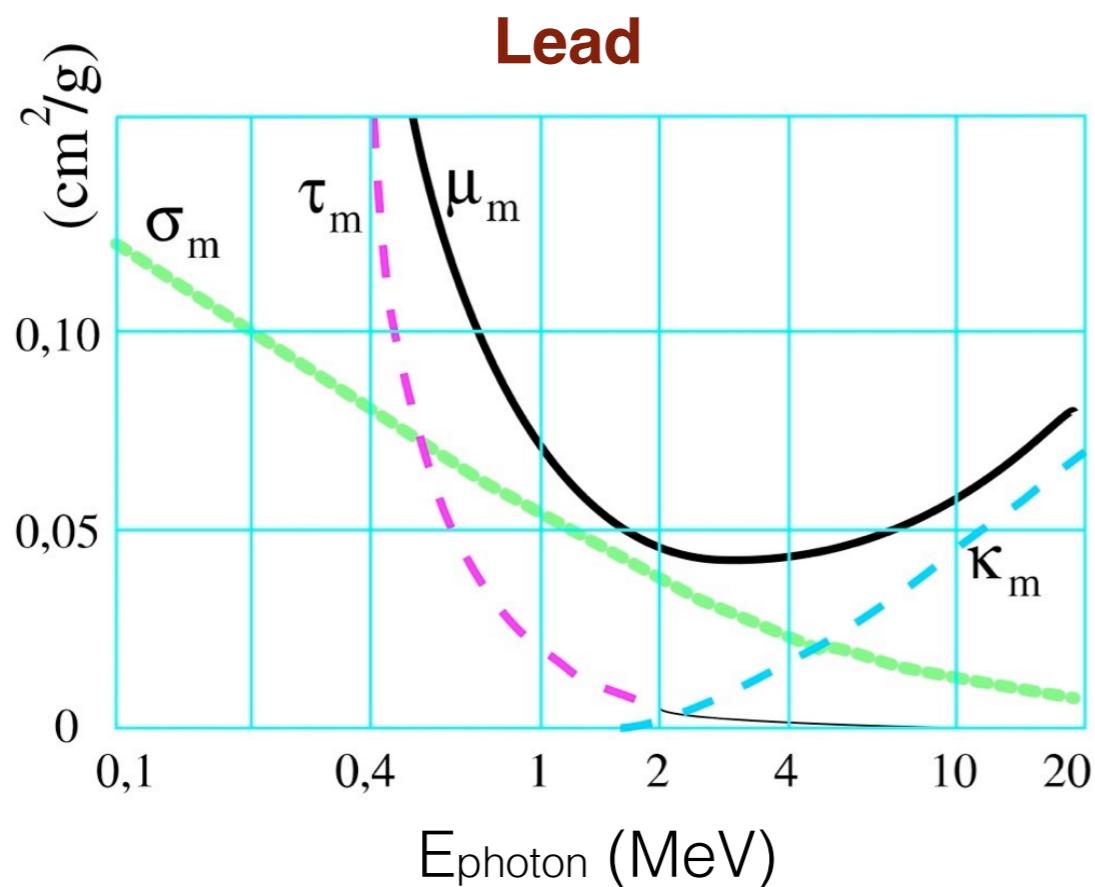
$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

μm=mass attenuation coefficient
σm=Compton effect mass attenuation coefficient

τm=photoeffect mass attenuation coefficient
κm=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	$\sim 1 / \varepsilon$	$\sim Z^2$	1 - 30 keV
Photoeffect	$\sim 1 / \varepsilon^3$	$\sim Z^3$	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
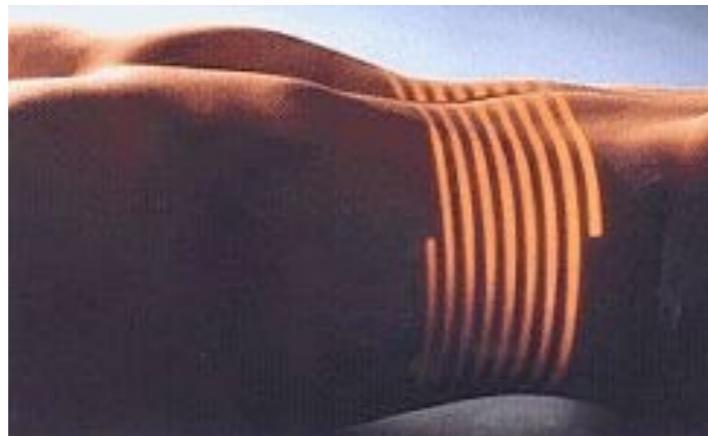
3D reconstruction

Virtual endoscopy

colonoscopy

bronchoscopy

Left   Right
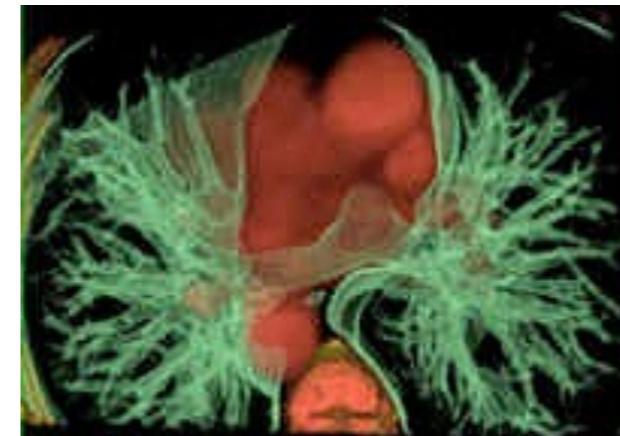
arterioscopy
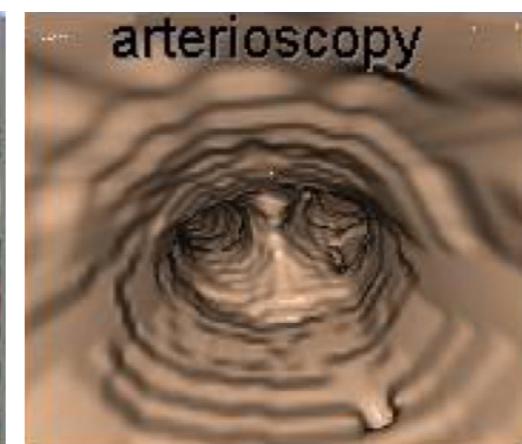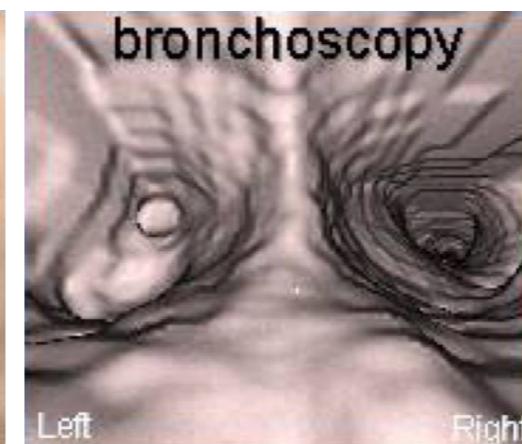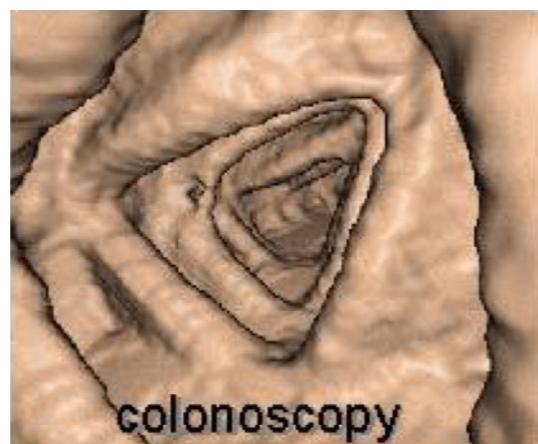
Angiography
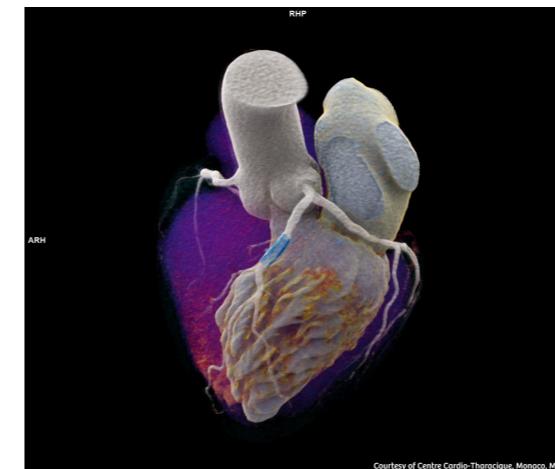
Photon Counting CT

Feedback

https://feedback.semmelweis.hu/feedback/pre-show-qr.php?type=feedback&qr=1PEHQBRA72RPDD8H