Biophysics I

11. X-ray

production, spectral characteristics, and interactions with matter

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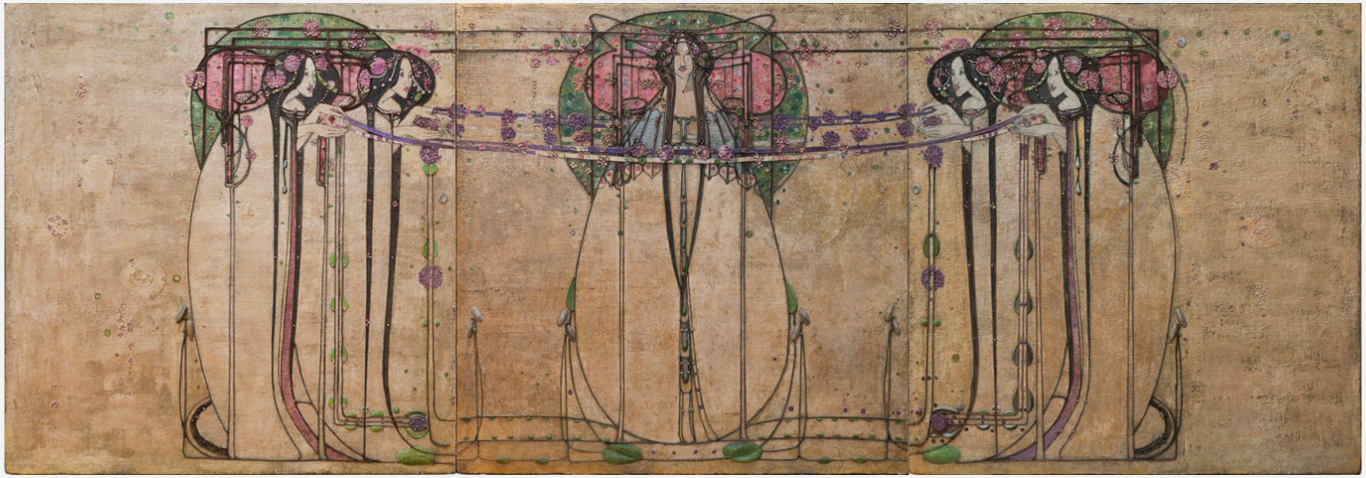
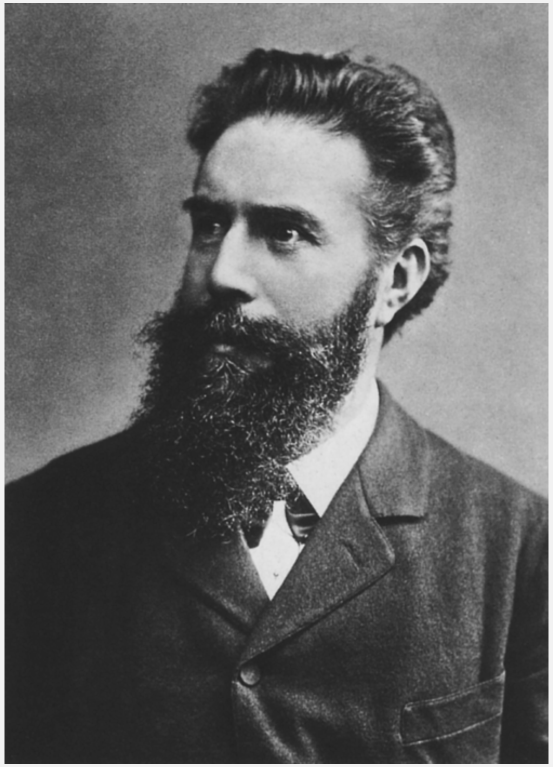
Röntgen and the "golden years" in physics

1895: Röntgen discovered the unknown "X" radiation
(Alfred Nobel's will, cinématographe, automobile)
1896: Becquerel discovered radioactivity
1897: Thomson discovered the electron
1898: Pierre and Marie Curie discovered polonium and radium
1900: Max Planck derives the law for thermal radiation



Margaret and Frances MacDonald – Art Nouveau

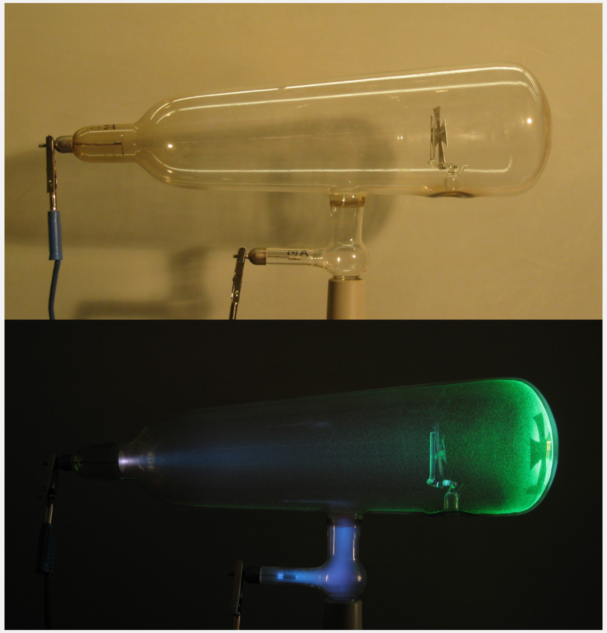


Wilhelm Conrad Röntgen

1901: Nobel prize in physics for the discovery of X ray

Discovery – early November 1895
Publishing – 28th december 1895
(> thousand publication in 1896)
First medical usage – January 1896
- Edison's fluoroscope is ready for mass production in May 1896

22th december 1895 – an image of the hand of Röntgen's wife



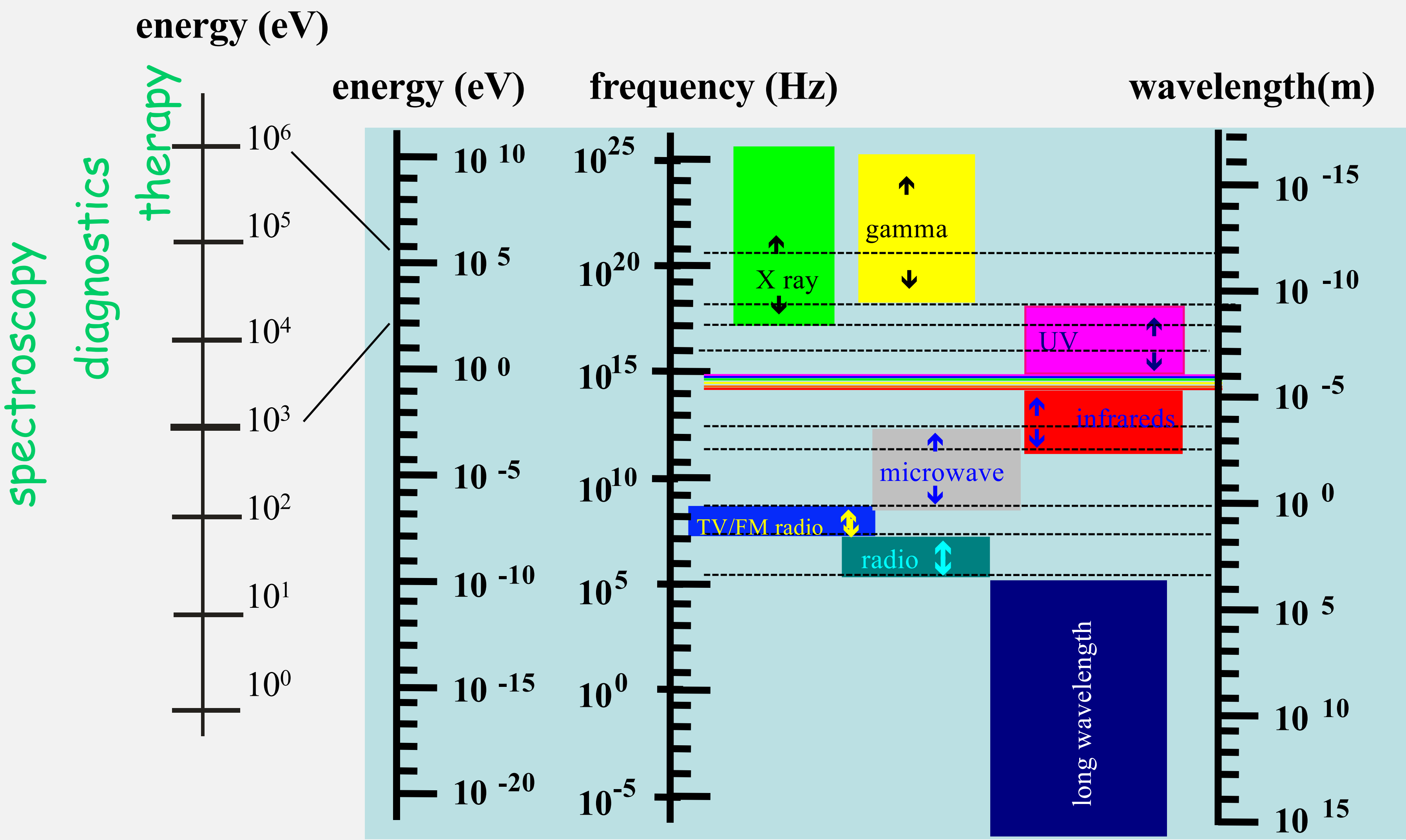
the discovery

William Crookes' tube: electrical discharge tube with partial vacuum - cathode rays - fluorescence

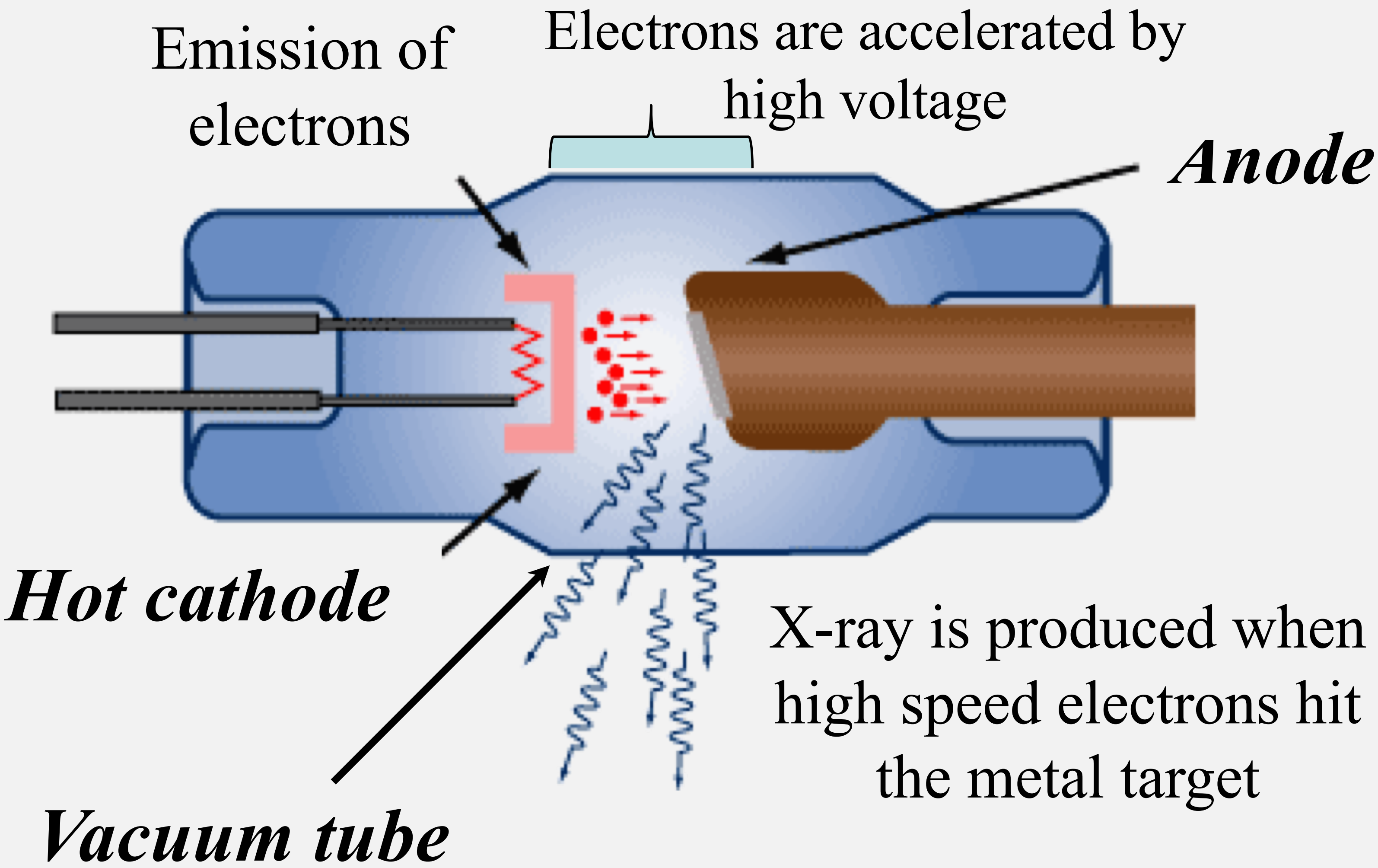
A barium platinocyanide screen fluoresces in the vicinity of Crookes tube.

- Röntgen was investigating cathode rays from a Crookes tube which he had wrapped in black cardboard so that the visible light from the tube would not interfere, using a fluorescent screen painted with barium platinocyanide. He noticed a faint green glow from the screen, about 1 meter away. Röntgen realized some invisible rays coming from the tube were passing through the cardboard to make the screen glow. He found they could also pass through books and papers on his desk. Röntgen threw himself into investigating these unknown rays systematically. Two months after his initial discovery, on 28th December 1895 submitted it's paper to Würzburg's Physical-Medical Society journal.

X ray as an electromagnetic ray

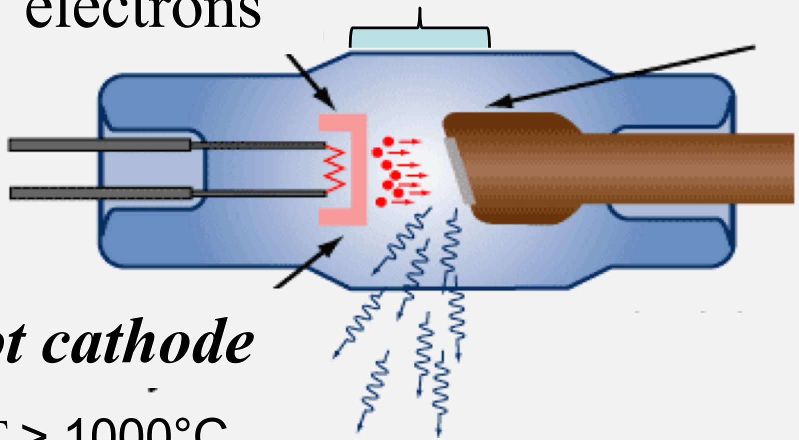


Structure of an X ray tube



Operation of an X ray tube

Emission of electrons

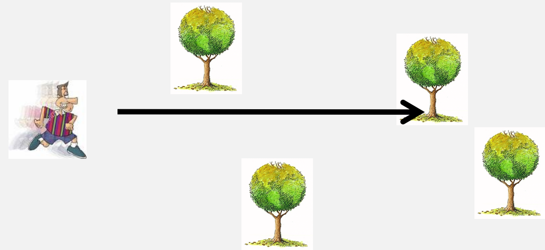


Hot cathode

T > 1000°C

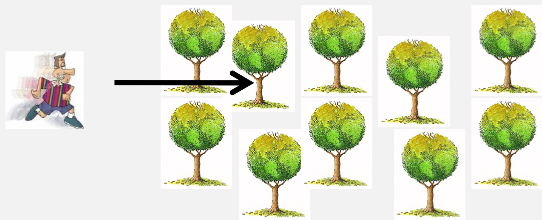
$$I_{anod} = \frac{Q}{t} = \frac{n * e}{t}$$

$$P_{electric} = UI$$



vacuum ~ 10^{-4} Pa

free pass length ~ 10 cm



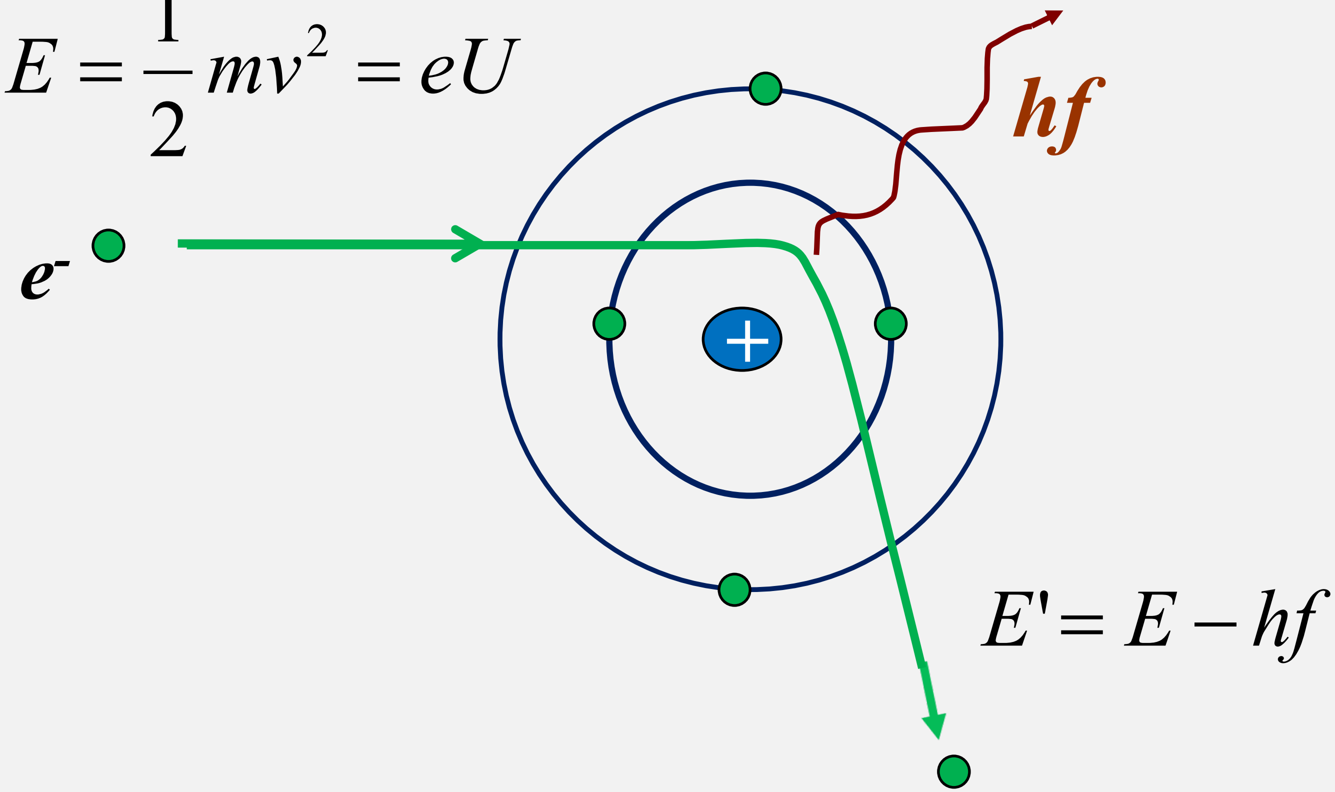
In the air, under atmospheric pressure

free pass length ~ 70 nm

Mechanisms of X-ray production

1. Bremsstrahlung or "braking radiation"

$$E = \frac{1}{2}mv^2 = eU$$



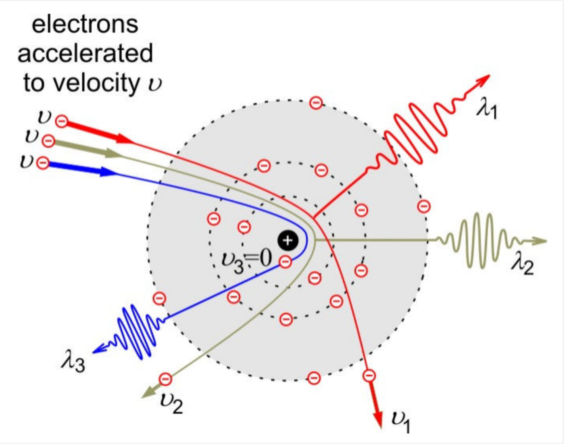
The electron is deflected from its original path and decelerated.

The electron's kinetic energy is reduced.

The energy lost by the electron takes the form of a Bremsstrahlung photon.

The photon's 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.

Spectrum of Bremsstrahlung

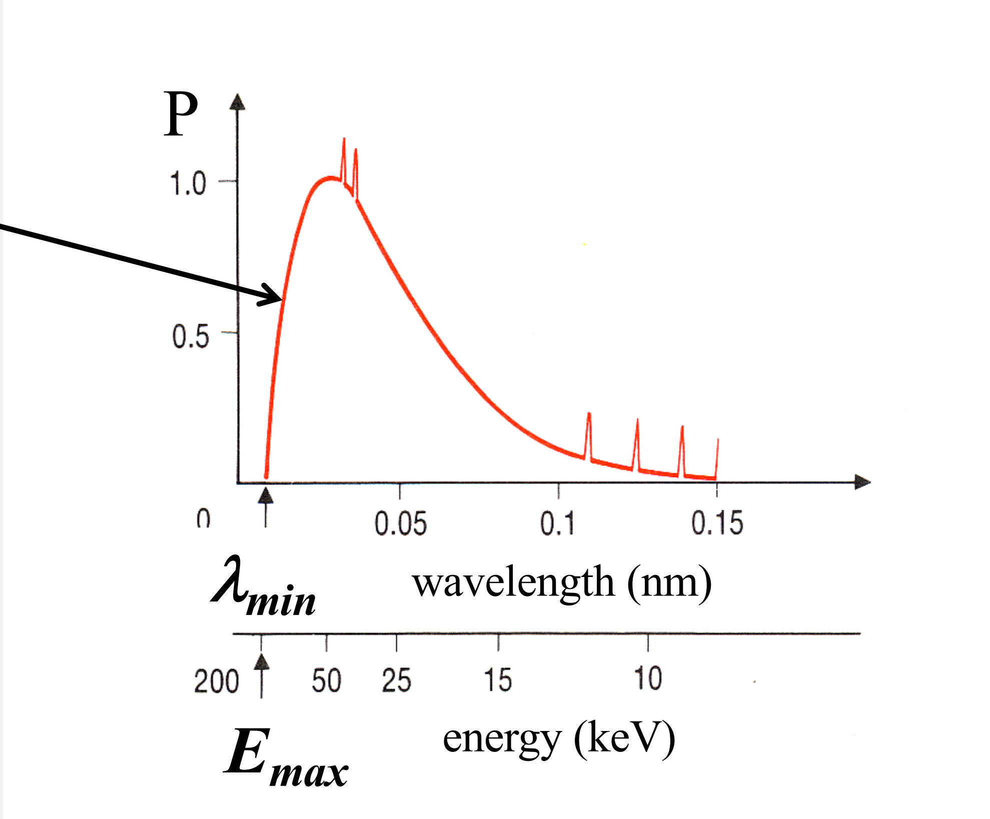
continuous spectrum

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

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

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

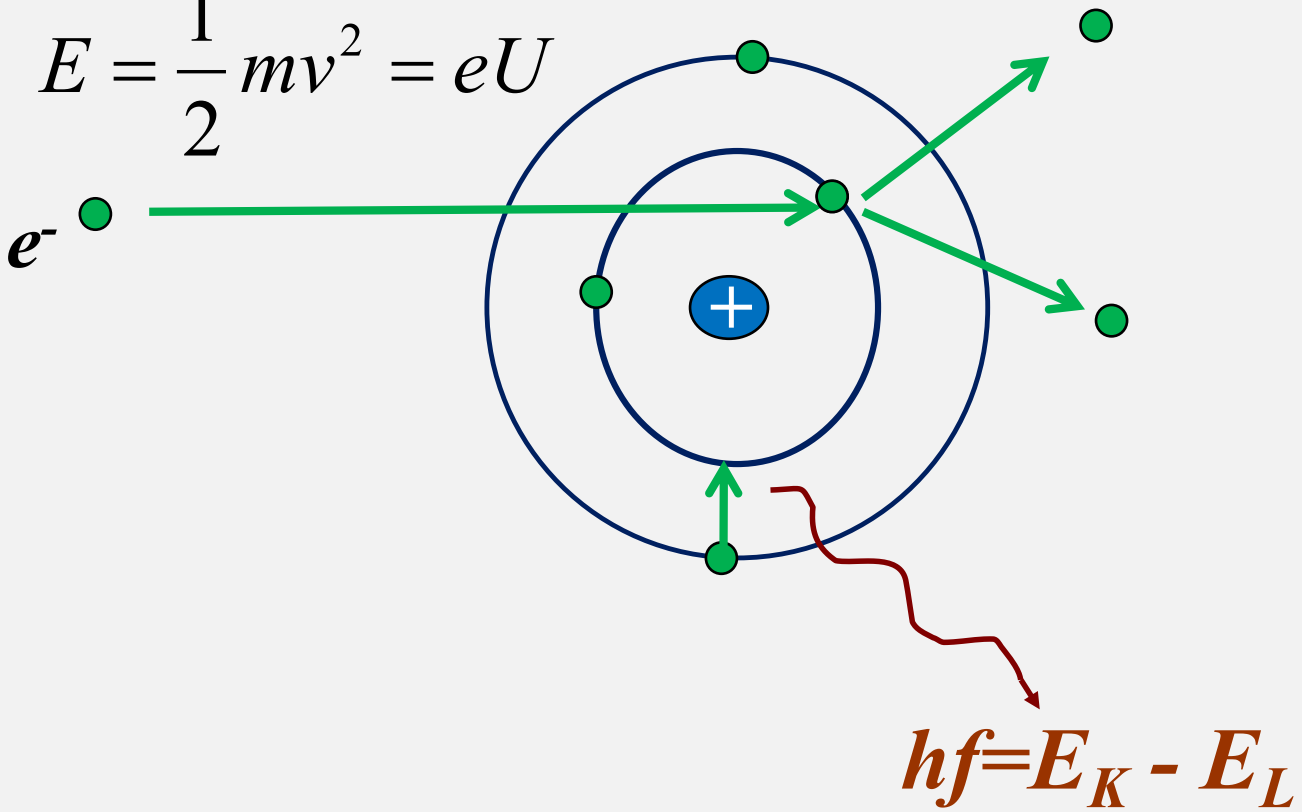
Duane-Hunt law



Mechanisms of X-ray production

2. Characteristic radiation

$$E = \frac{1}{2}mv^2 = eU$$



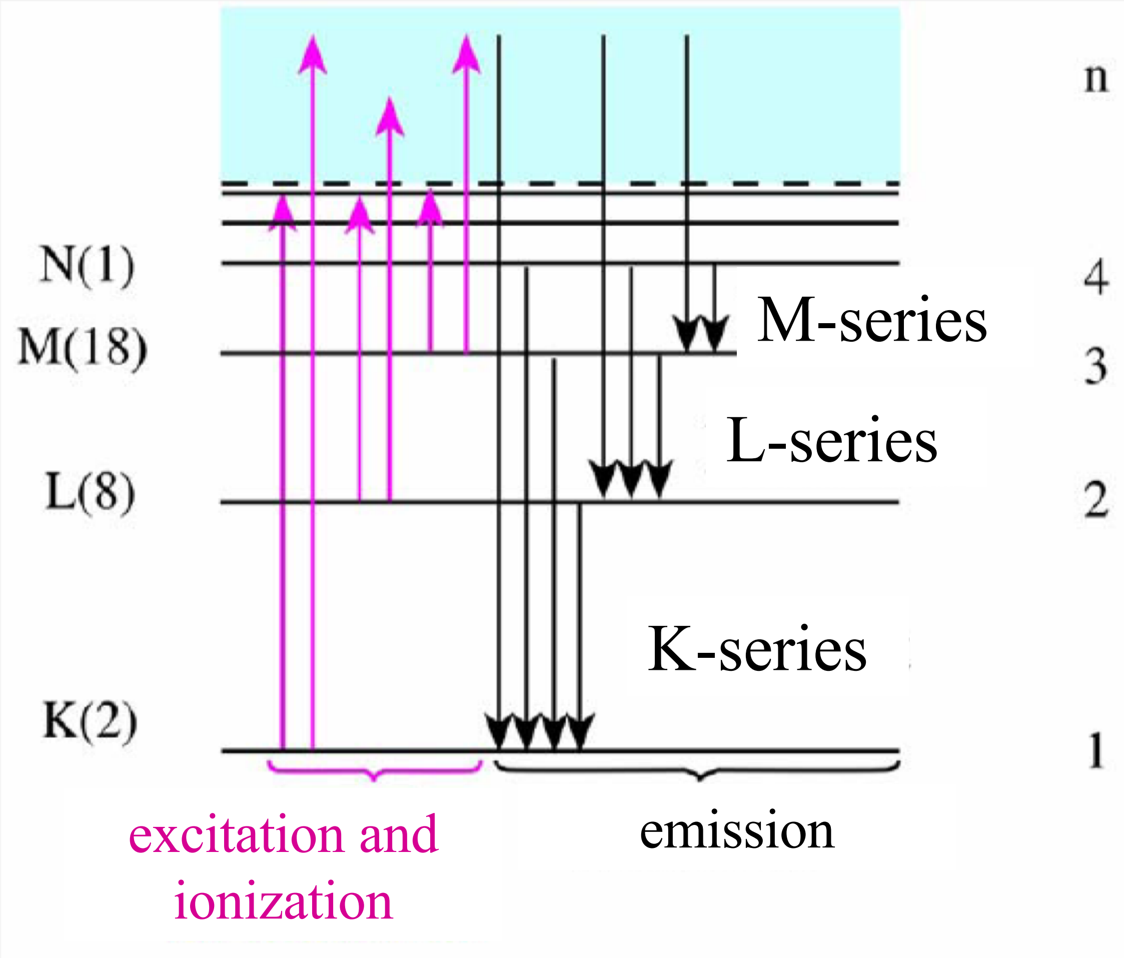
If the incident electron energy is high enough, it may interact with an inner shell electron, ejecting it from its position (excitation/ionization).

The vacancy is occupied by an electron from a higher shell.

↓

The discrete excess energy is emitted as a characteristic photon.

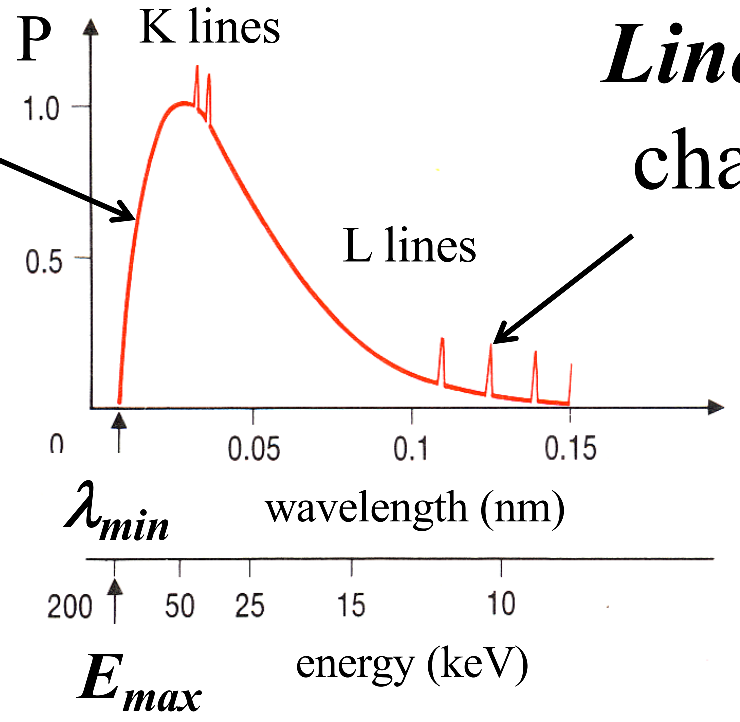
Possible energy transitions of the Cu-atom with 29 electrons



Possible photon energies depend on the electron shell structure of the atom.

Spectral properties of X-ray

Continuous spectrum of bremsstrahlung



Line-spectrum characteristic X-ray

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

Duane-Hunt law

Power and efficiency of X-ray tube

$$P = cIU^2 Z$$

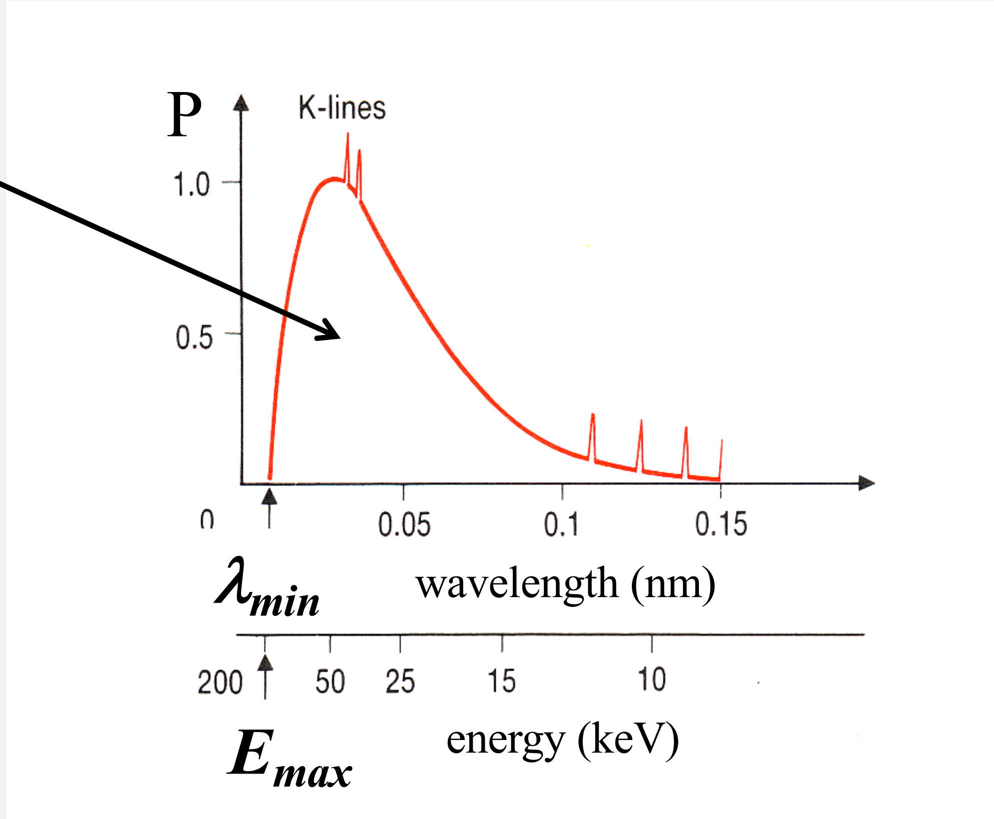
$c=1,1\times10^{-9}$ [1/V]

input electric power:

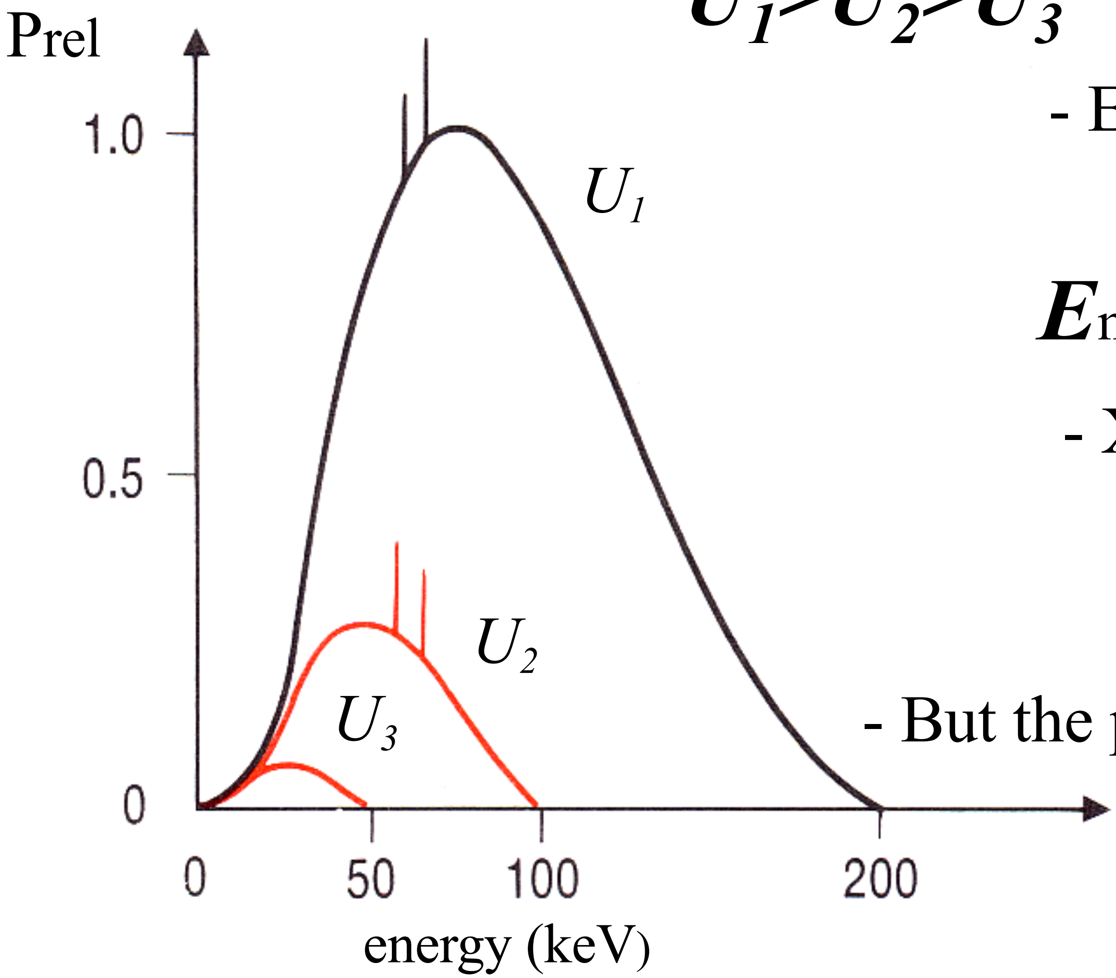
$$P' = IU$$

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

$$\eta < 1\%$$



Change of accelerating voltage:



$\boldsymbol{U_1 > U_2 > U_3 \rightarrow P_1 > P_2 > P_3}$

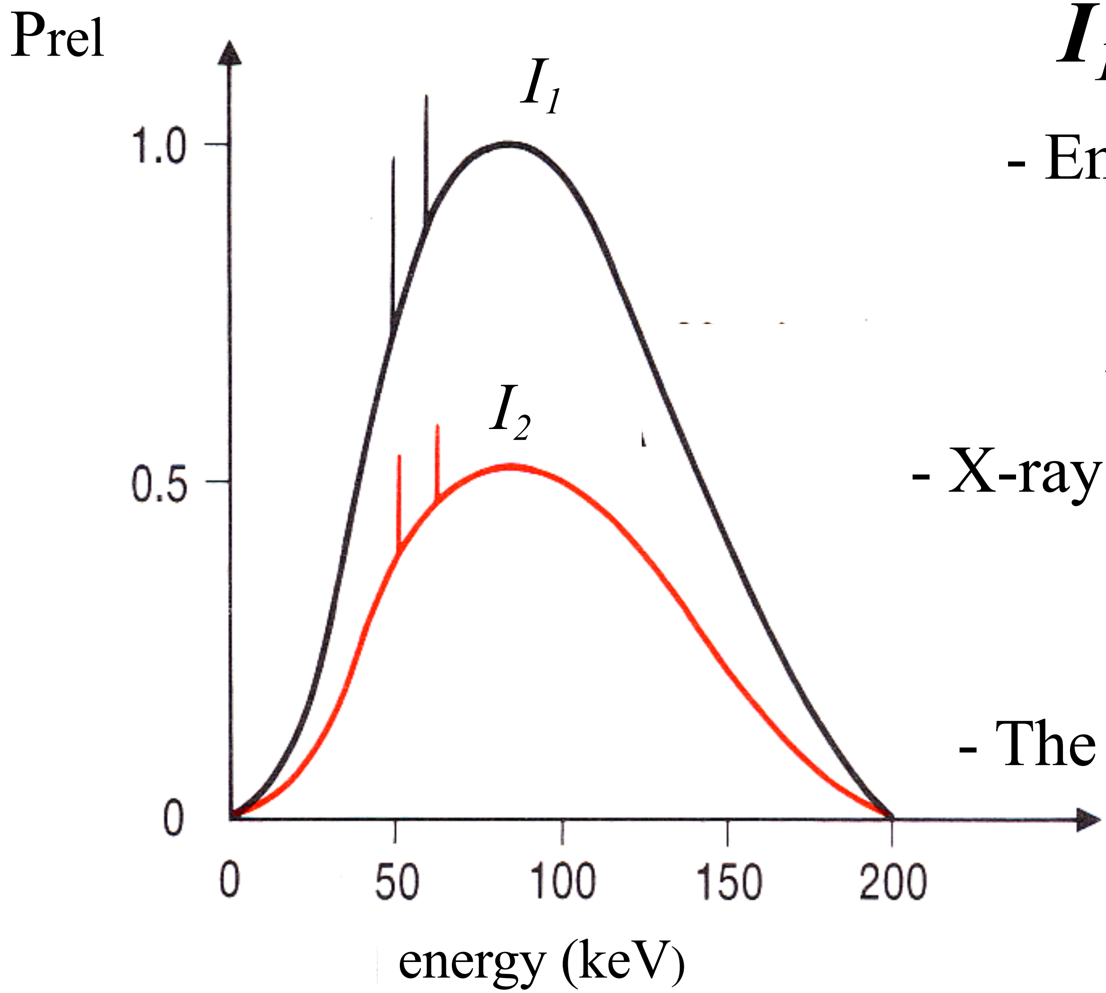
- Emitted power dicreases

$\boldsymbol{E_{\max 1} > E_{\max 2} > E_{\max 3}}$

- X-ray becomes softer

- But the positions of characteristic lines remains the same!

Change of anode current



$$I_1 > I_2 \rightarrow P_1 > P_2$$

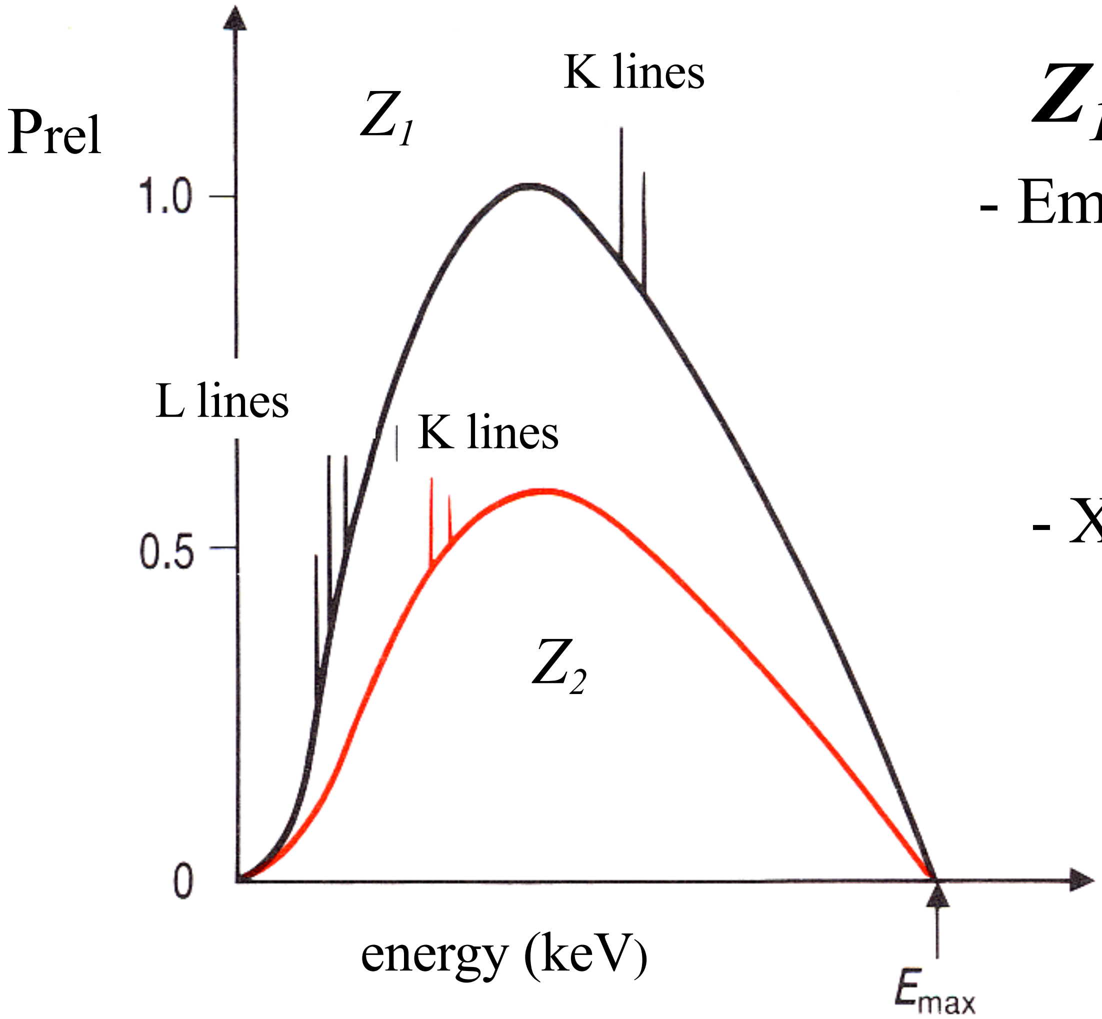
- Emitted power dicreases

$$E_{max_1} = E_{max_2}$$

- X-ray energy remains the same.

- The positions of characteristic lines remains the same.

Effect of target (anode) material



$Z_1 > Z_2 \rightarrow P_1 > P_2$

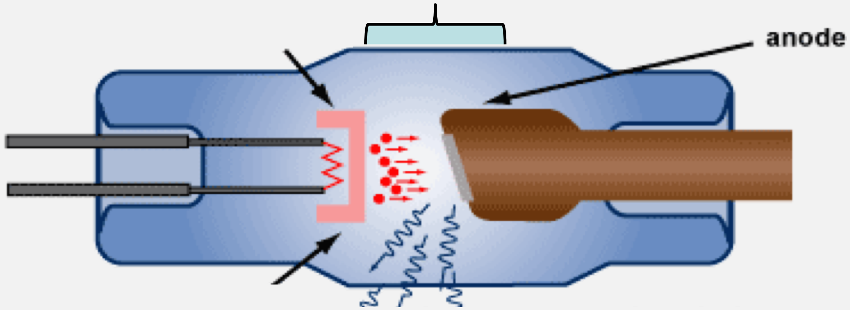
- Emitted power dicreases

$E_{max_1} = E_{max_2}$

- X-ray energy remains the same.

- Positions of characteristic lines change!

X-ray tube in medical settings



Anode: higher atomic numbers and higher melting points needed.

Focal spot on anode: small=sharper image, big=improved heat distribution but blurred image

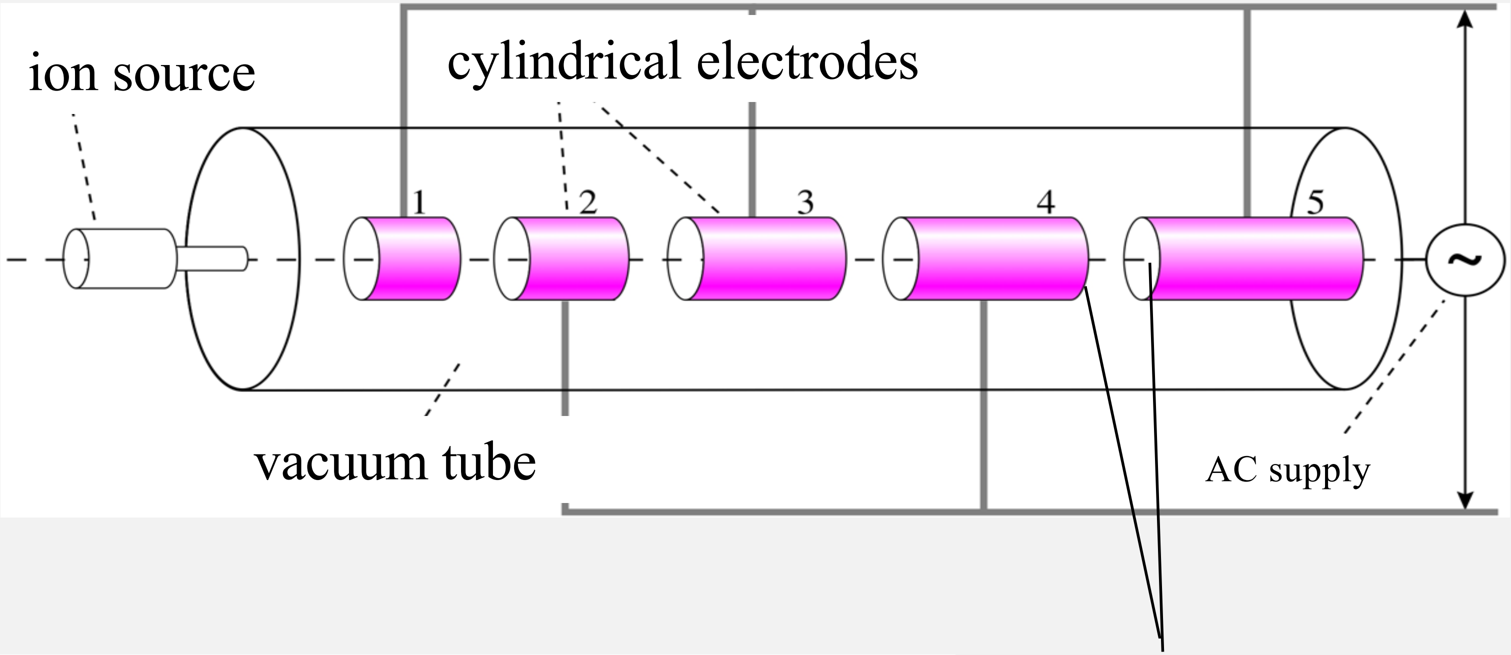
Anode position: fixed = reduced thermal load, ~W/mm^2 (dentistry)
rotating = improved thermal load up to 10000 W/mm^2

Tipical accelerating voltage: 25-200 kV, anode current: 1-1000 mA,
anode material: W (Mo in mammography)

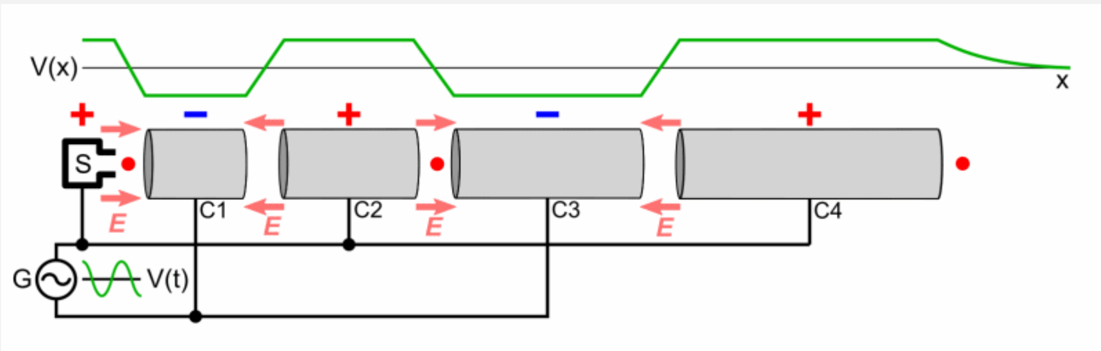
Special ways of X-ray production:

particle accelerators

Linear accelerators

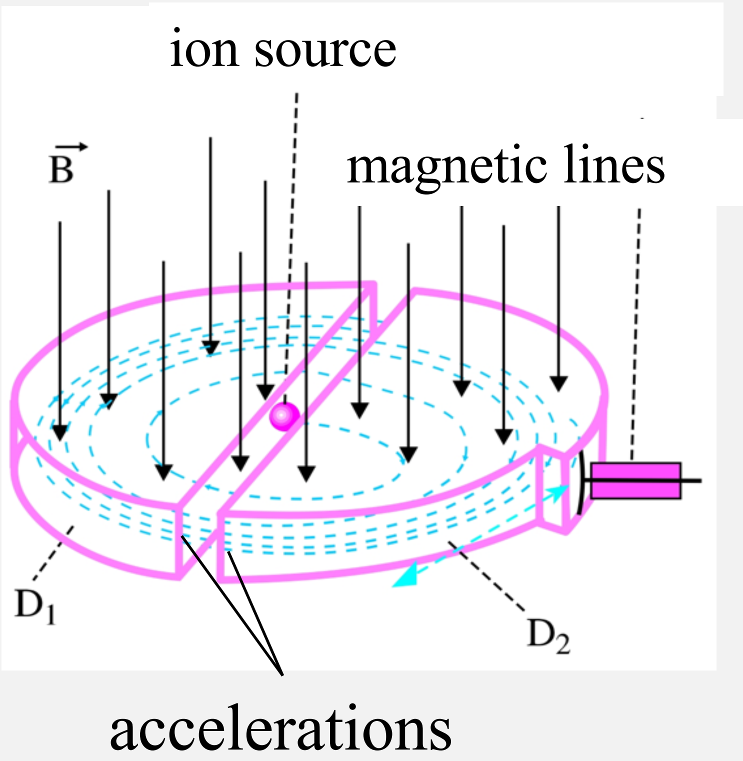


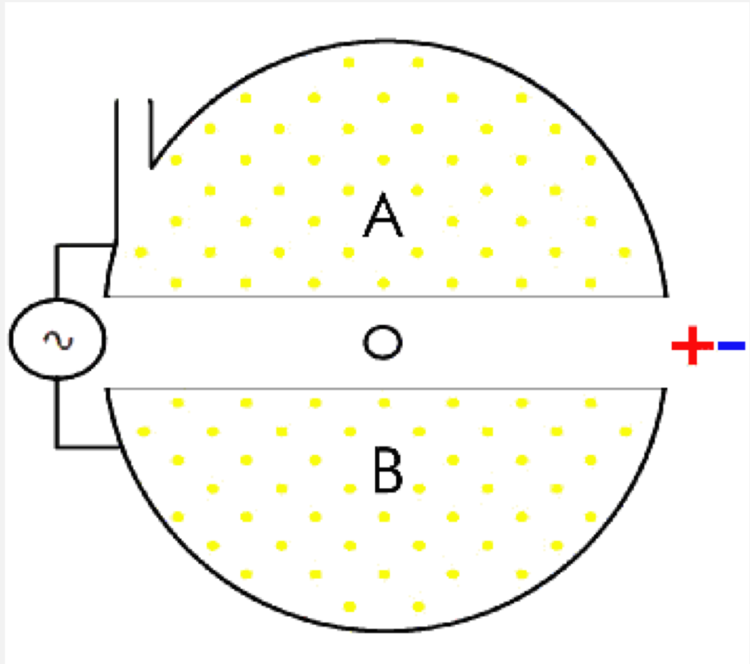
accelerations



Applications in radiation therapy (4-25 MeV)

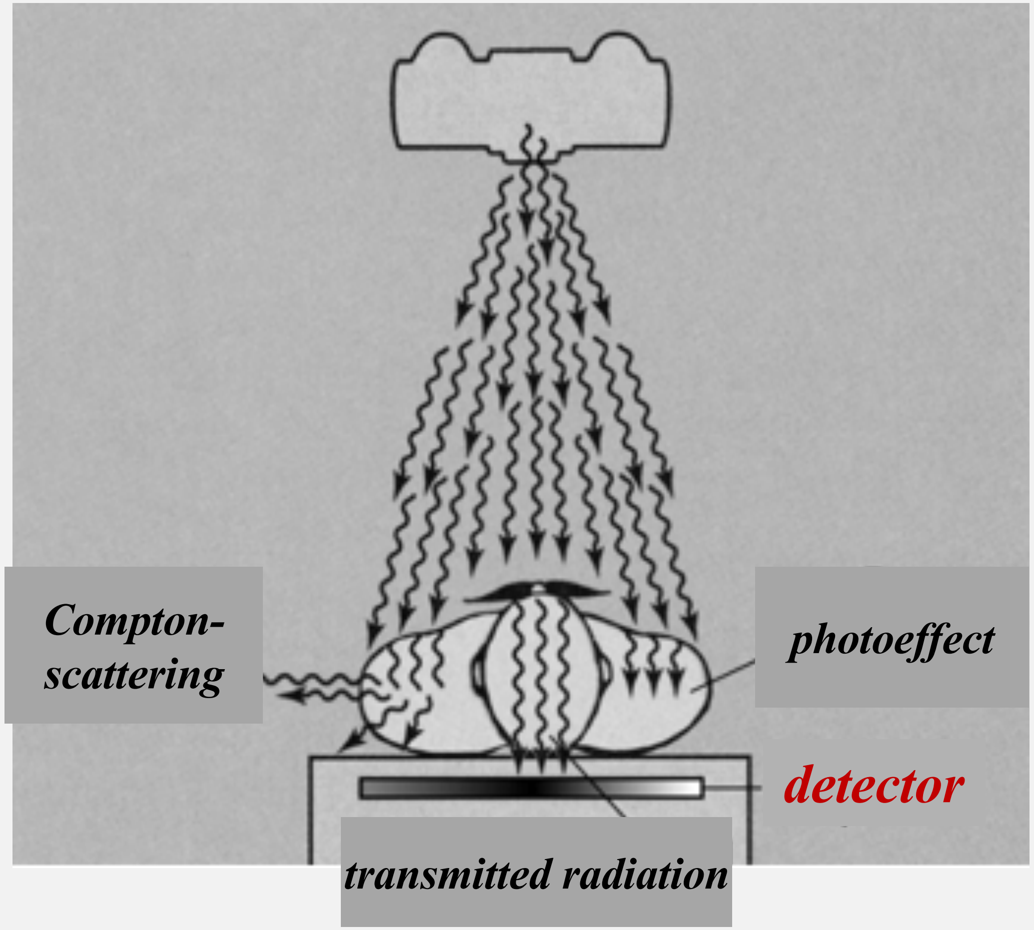
Cyclotron





magnetic field → Lorenz force → circular path
electric field → acceleration, increasing radius
medical application: production of PET radionuclids

X-ray diagnostics based on absorption



Photon interactions with matter:

photoeffect

Compton scattering

pair production

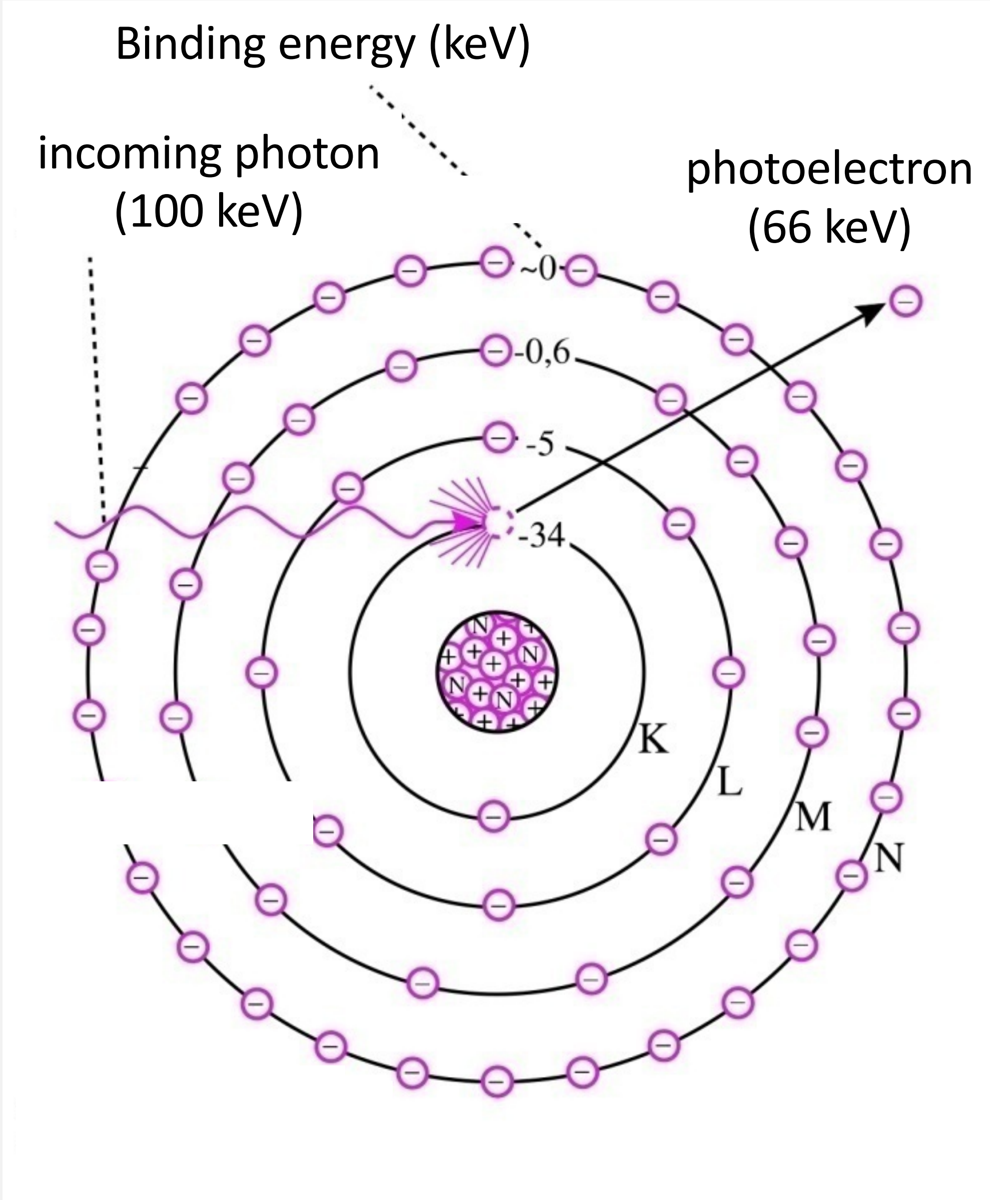
elastic scattering
(no interaction)

Mechanism of interaction (1)

Photoeffect

energy balance:

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

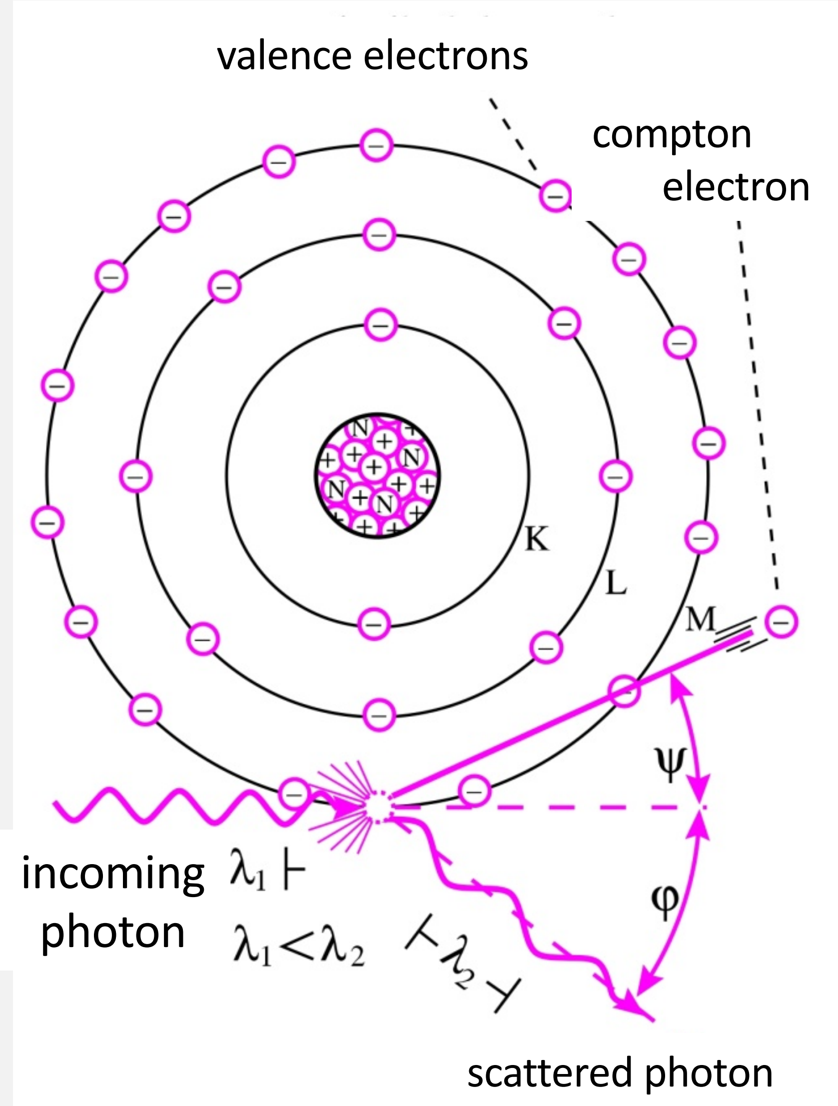


Mechanism of interaction (2)

Compton scattering

energy balance:

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



Mechanism of interaction (3)

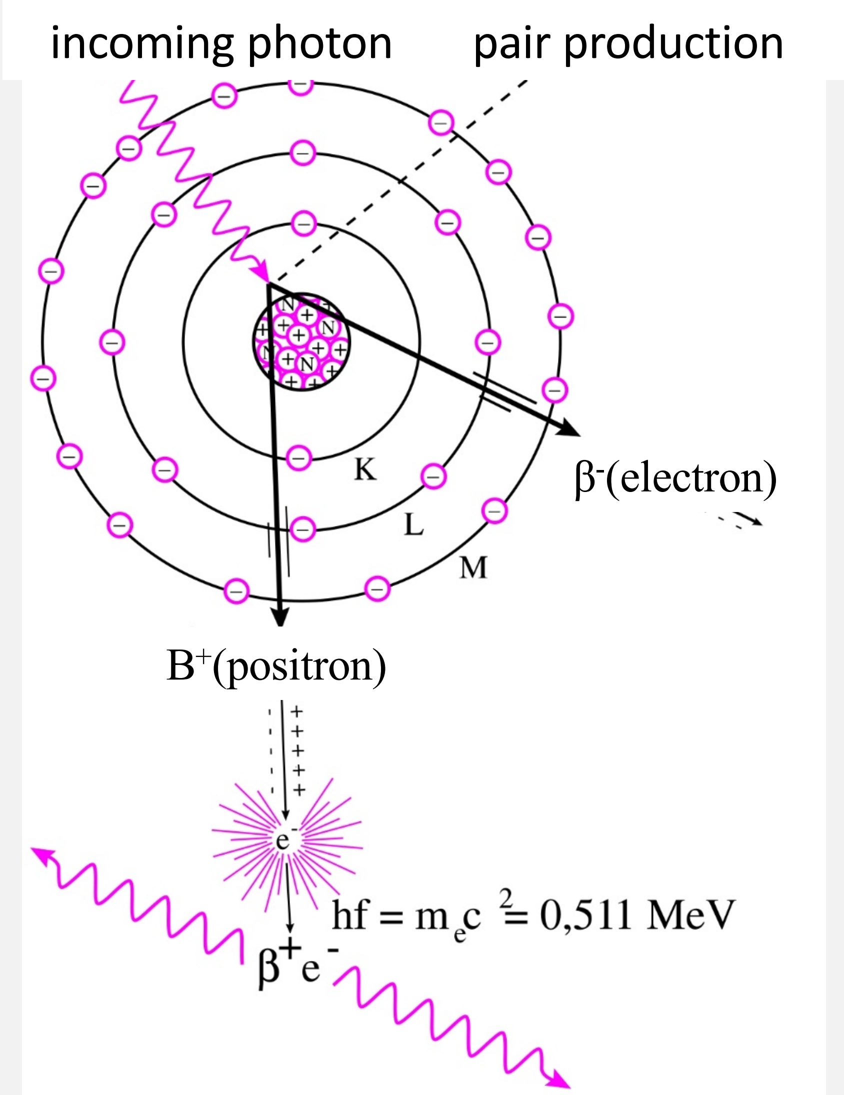
Pair production

energy balance:

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

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

$$\boxed{hf \geq 1.02 MeV}$$



Interaction of X-ray with matter

Law of radiation attenuation: $$J = J_0 e^{-\mu x}$$

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 photon energy and the atomic number of absorber

With mass attenuation coefficient, the law of radiation attenuation:

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

$$x_m = \rho x \qquad \mu_m = \frac{\mu}{\rho}$$

x_m [g/cm^2]: surface density

$$\left.\begin{aligned} \mu &= \frac{0.693}{D} \\ D_m &= \rho D \end{aligned}\right\} \quad \boxed{\mu_m = \frac{0.693}{D_m}}$$

Probability of interaction (absolute and relative) depends on

- the photon energy
- atomic number of absorber

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

photoeffect (τ) Compton scattering (σ) pair production (κ)

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

	Atomic number	energy
photoeffect	$\tau_m \sim Z^3$	$\tau_m \sim 1/E^3$
Compton scattering	~ independent	slightly decreases

Application of radiation filters

Modification oft he properties (spectrum, special distribution) of radiation

Inherent filter elements.

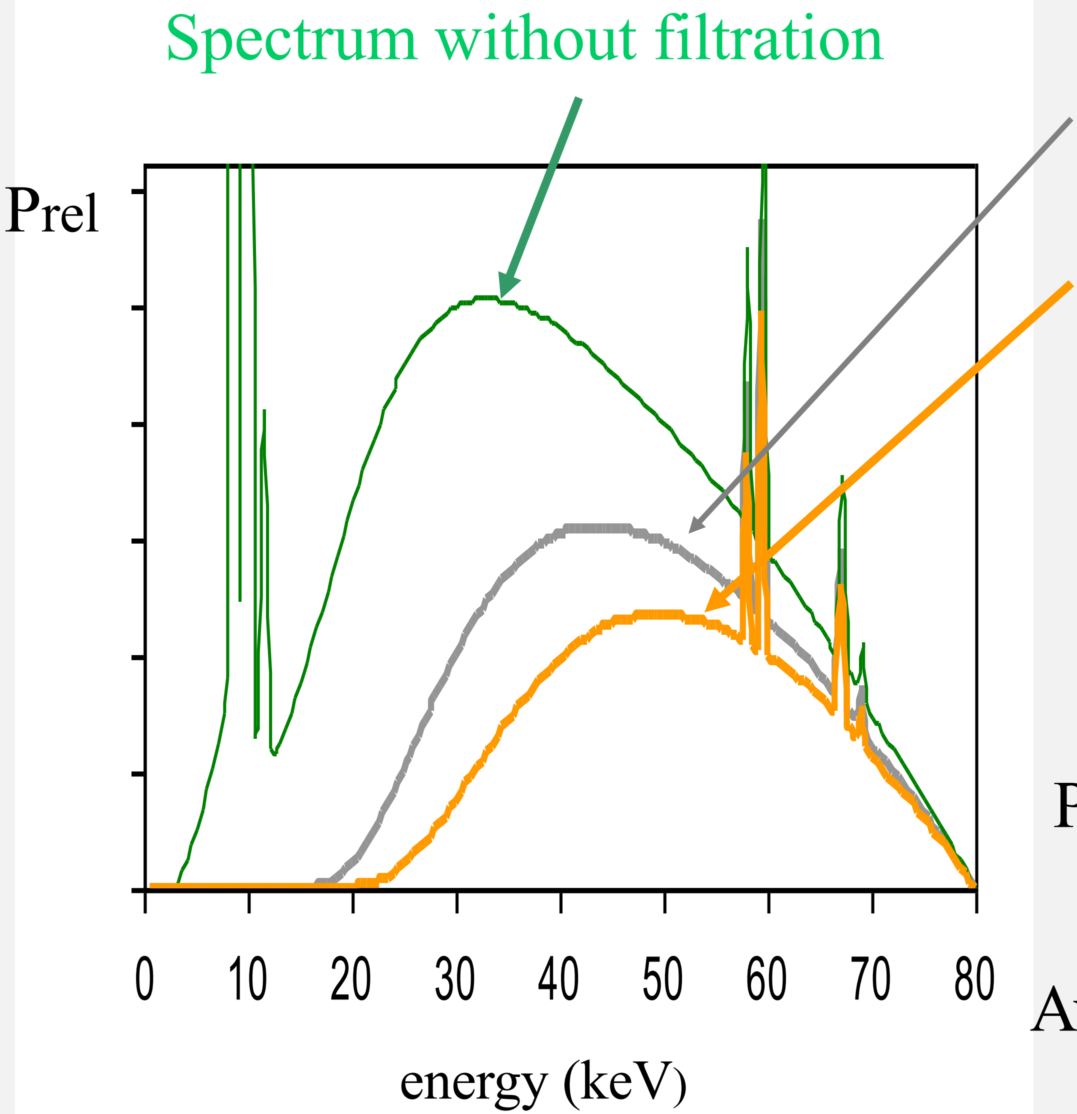
e.g., anode material, wall of the tube, diaphragm etc.

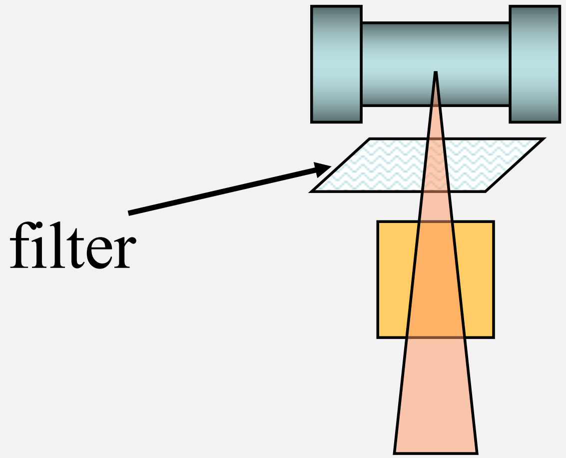
External filters, typically Al or Cu plates.

Disadvantage: reduces the intensity
increases the exposition time

Advantage: reduces – approximately 80% — the exposure of the patient

Application of radiation filters





Preferential absorption of lower photon energies

Average photon energy increases

No change in $\boldsymbol{E_{max}}$

Checklist

Structure of X-ray tube

Parameters of X-ray tube

Mechanism of generation of Bremsstrahlung and characterization of it's spectrum

Interpretation of λ_{min}

Mechanism of generation of characteristic radiation and characterization of it's spectrum

Parameters influencing the spectra of X-ray

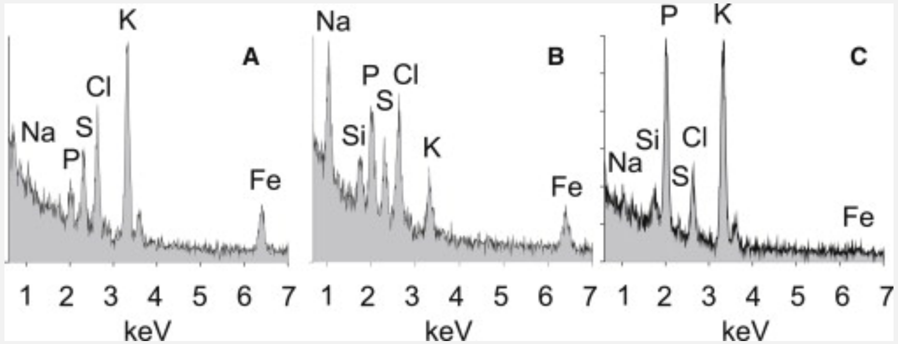
Benefits of the application of outer filters

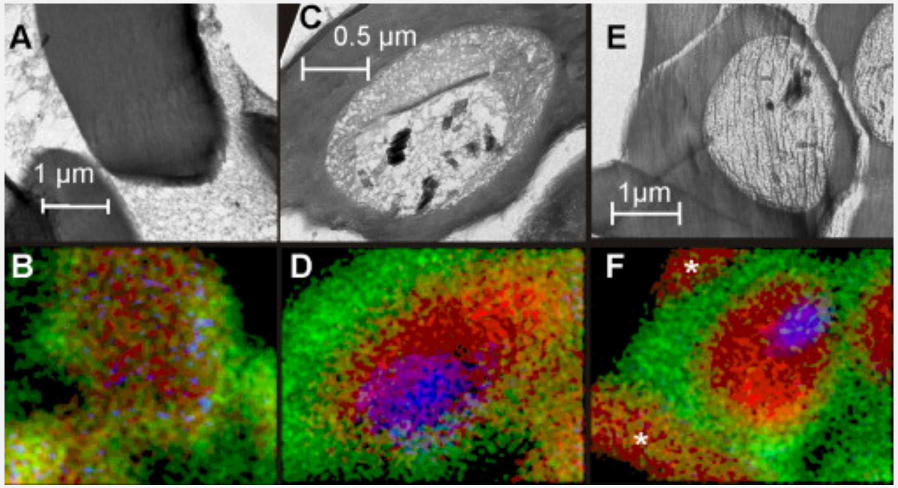
Damjanovich, Fidy, Szöllősi: Medical biophysics

II. 3.1

- 3.1.1
- 3.1.2
- 3.1.3
- 3.1.4
- 3.1.5
- 3.1.6

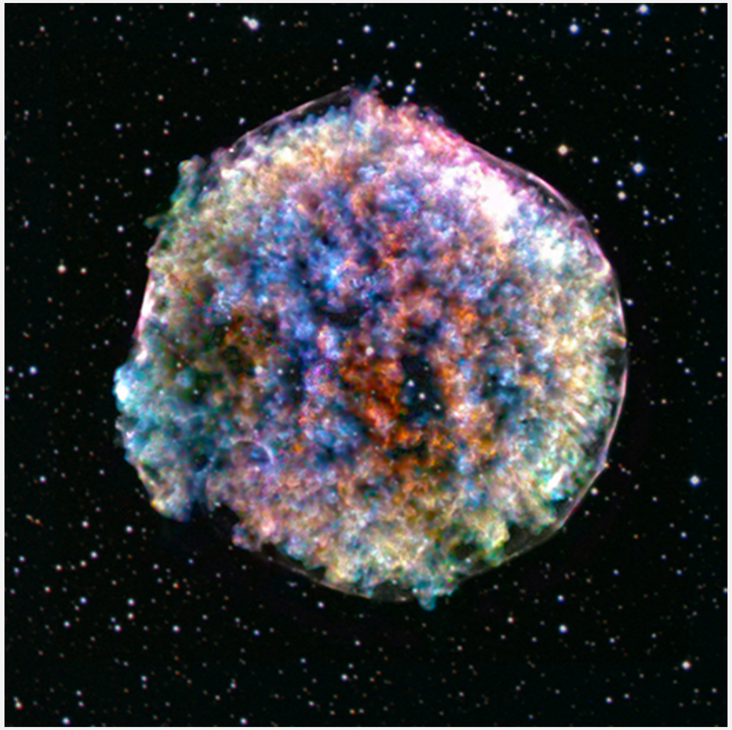
Electron microscopy: Characteristic radiation can be utilized to determine the elemental composition of samples





Mauritz JM, et al. (2011) X-ray microanalysis investigation of the changes in Na, K, and hemoglobin concentration in plasmodium falciparum-infected red blood cells. Biophys J. 100(6):1438-45

X-ray production in space



Tycho Brahe supernova in 1572, CHANDRA X-ray space telescope: 2019

Red: 0.3-1.2 keV, Yellow: 1.2-1.6 keV, Cyan: 1.6-2.26 keV, Navy: 2.2-4.1 keV, Purple: 4.4-6.1 keV