X - rays

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Discovery

Wilhelm Conrad Roentgen
(1845-1923)

Discovery in November -> publication in December -> -> 1896 January: **Medical applications**

Hungary: Device for Medical diagnostics Technical University (Budapest) in 1896

Figure 4.10 Two radiographs taken by Röntgen. (a) The hand of Mrs. Röntgen. *(The Bettmann Archive/Bettmann Newsphotos.)* (b) Radiograph of a fully clothed man, showing not only the man's skeleton but also the keys in his pockets, the nails of his shoes, and the metal clasps of his garters. *(Deutsches Museum, Munchen.)*

First Nobel laurate in physics 1901

"in recognition of the extraordinary services he has rendered by the ***discovery of the remarkable rays*** *subsequently named after him".*

(Medicine: Adolf von Behring - *for his work on serum therapy, especially its application against diphtheria*

Chemistry: Jacobus Henricus van 't Hoff - *chemical dynamics and osmotic pressure in solutions*)

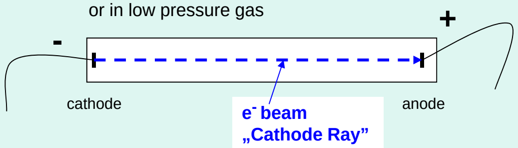
The „Golden Years" of physics

1895: X-radiation – Röntgen
1896: radioactivity – Becquerel
1897: electron – J. J. Thomson
1898: Radium – Pierre and Mme Curie

Basic experimental device: Cathode Ray Tube – CRT

- discovery of X-rays
- discovery of the electron

Glass tube with two electrodes in vacuum or in low pressure gas



Electrons emitted by the cathode due to field emission, and accelerated by the positive potential of the anode.

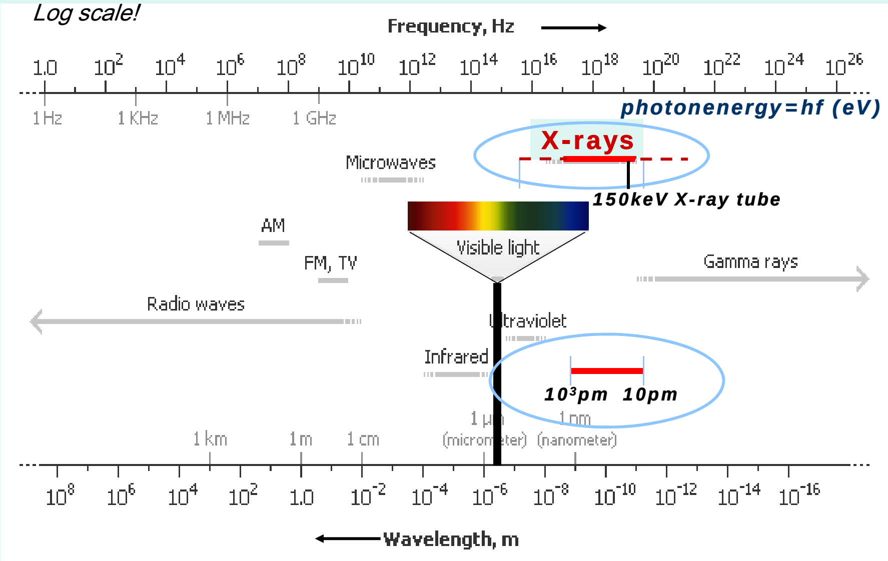
Later: cathodes were heated by an electric circuit to emit more electrons

Roentgen's observations

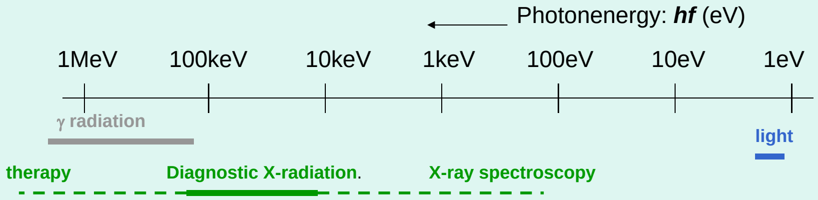
- cathode ray generates radiation in the wall of the tube
- the radiation is similar to UV light – induces fluorescence
- but is of much higher penetration
- is not reflected and refracted like light

X-rays in the spectrum of elecromagnetic radiations

$10^{-9}\, m = 1\, nanometer$



X-rays in the spectrum of elecromagnetic radiations



X-radiation: *electromagnetic radiation of high photonenergy as compared to light*

Dual nature: photon or wave –models?

For understanding and characterizing X radiation as emitted by a source, both the the wave- and the photon concept will be used.

For understanding the interaction of X-rays and materials, the photon concept will be used.

Phenomena that produce X-radiation:

-1. Charged particles accelerated to high kinetic energy are decelerated in a target material. Some steps of deceleration produces X-ray photons on the expense of the kinetic energy. ->

- Braking radiation - Bremsstrahlung

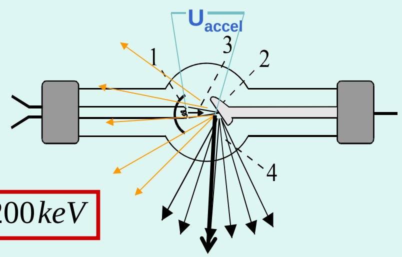
-2. Electronic deexcitation phenomena of orbital electrons leading to transitions between inner orbitals of high energy separation (elements of high atomic number). ->

Characteristic X-radiaton

X-ray luminescence

X-ray Tube: X-ray source for Medical Diagnostics

a special case of the CRT



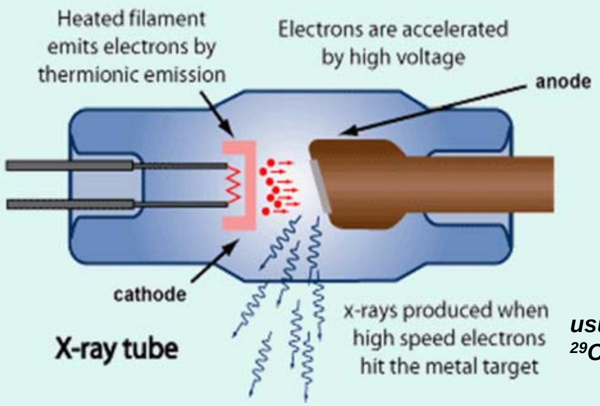
1. Heated cathode
2. Anode
3. Electron beam
4. X-radiation

$$20keV \le hf \le 200keV$$

Most of the emitted photons are generated by ***braking radiation***

(Higher photon energies required for tumor therapy are produced by particle accelerators)

More detailed schematics



usual target metals:
^{29}Cu, ^{42}Mo, ^{74}W, ^{78}Pt

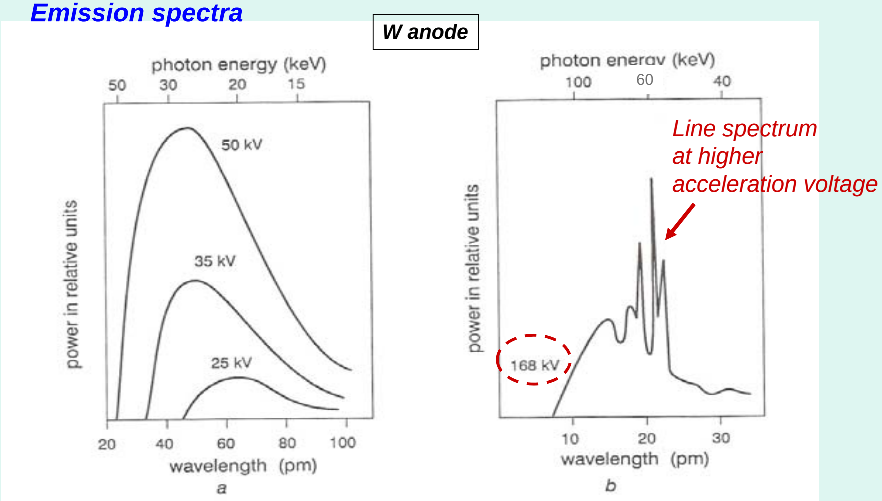
X-ray production is of very low efficiency << 1%

How X-ray tubes really look like

X-ray production is of very low efficiency << 1%
high heat generation → cooling (circulating oil)
→ rotating anode

The radiation emitted by the X-ray Tube

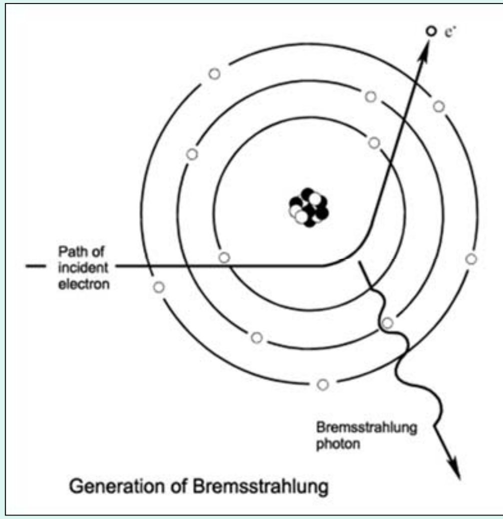
Emission spectra

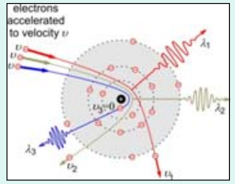


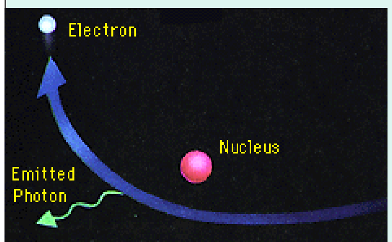
Spectra of Braking Radiation ***Lines of Characteristic X Radiation***

Braking radiation - Bremsstrahlung

Mechanism







Braking Radiation - Bremsstrahlung

Spectral properties

1. Spectrum is ***continuous: all*** λ ***and hf***

- ***above a certain wavelength***
- ***below a certain photonenergy***

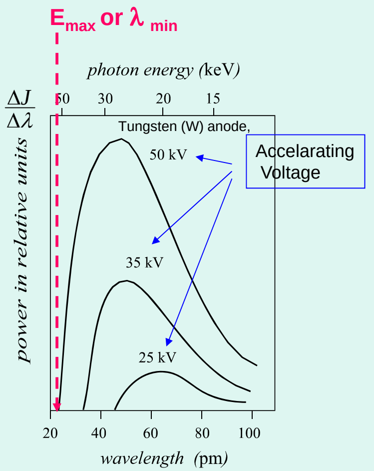
$$hf_{max} = h\frac{c}{\lambda_{min}} = q_{electron} U_{accel}$$

Planck's constant

Duane-Hunt law

$$\lambda_{min} = \frac{hc}{q_e}\frac{1}{U_a}$$

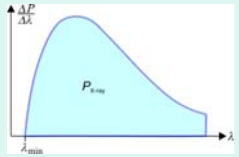
Increased accelerating voltage broadens the spectrum towards shorter wavelengths (higher photonenergies)



Braking Radiation - Bremsstrahlung

Spectral properties

2. The total emitted power increases with the voltage



$$P_{total} = const_{Xray} \cdot U_{anode}^{2} \cdot Z_{anode} \cdot I_e$$

$$const \approx 1.1 \cdot 10^{-9} V^{-1}$$

empirical constant

$$P_{total} \approx U^2$$

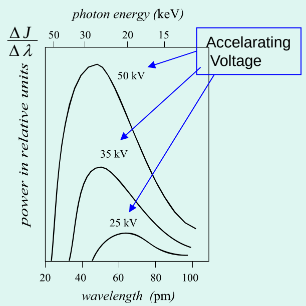
$$P_{total} \approx I$$

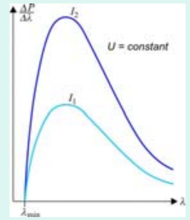
Adjustable parameters of X-ray tube

Different effects!

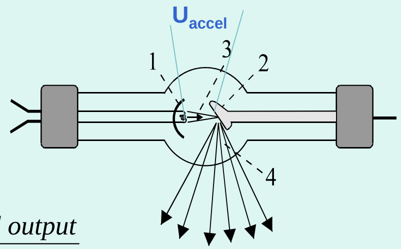
3. The electron-current intensity does not change the spectrum

Tungsten (W) anode,





Estimating the radiation yield of the X-ray Tube - Bremsstrahlung



$$efficiency\,(\eta) = \frac{useful\ output}{total\ input}$$

$$\eta = \frac{P_{radiation}}{P_{electric}} = \frac{c_{Xray} U^2 I\ Z}{U\ I} = c_{Xray} U\ Z$$

$\sim 10^{-9} V^{-1}$ 100 kV $Z_W = 74$

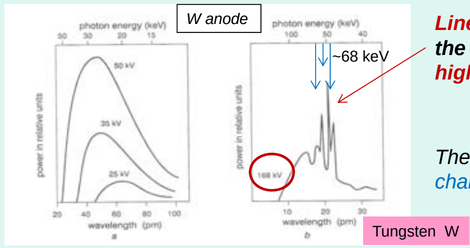
$$\eta \approx 0.008$$

The radiation yield is very low < 1%
Great heat loss!

Increasing U increases the radiation efficiency ⟷ ***BUT changes the spectrum!***

Characteristic radiation – X-ray luminescence

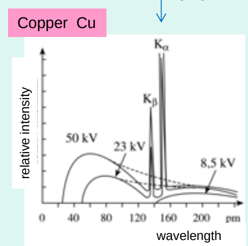
Spectra



Line spectrum appears superimposed on the continuous Bremsstrahlung at higher acceleration voltages

The photonenergies of the emission lines are characteristic for the material of the anode

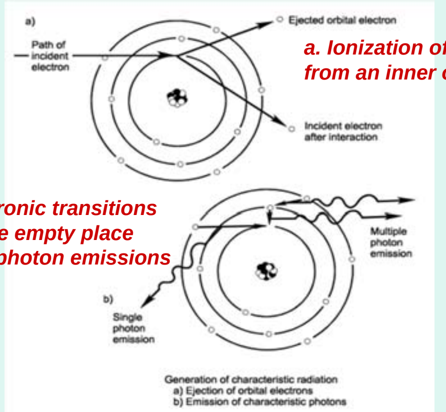
~8 keV



The photonenergies of the lines must be related to the electronic orbital energies of the target (anode) material

and do not depend on the accelerating voltage

Characteristic radiation – X-ray luminescence
Mechanism of generation

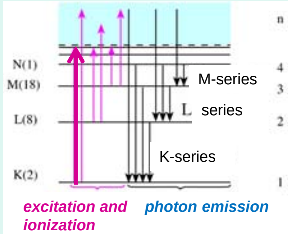


a. Ionization of electron from an inner orbital

$$\Delta E = hf$$

b. Electronic transitions to fill the empty place lead to photon emissions

Example: electronic orbitals of the ***Cu*** atom with 29 electrons



K-edge : ionization energy from the K-shell

transitions terminating in the K shell give rise to the K-lines, those terminating in the L shell produce the L -lines, and so on.

The energy differences between inner shells grow with Z (the number of electrons in the atom)

Ionization energies from the K level: „K-edge”

Al(13)	1.6 keV
Fe(26)	7.1 keV
Cu(29)	9.0 keV
Zn(30)	9.7 keV
Mo(42)	19.9 keV
W(74)	69.5 keV

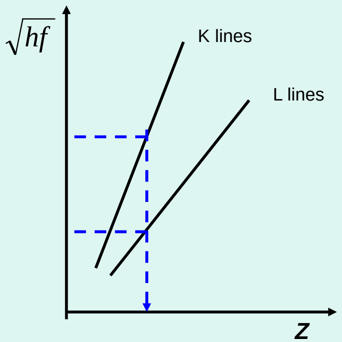
↑ atomic number: Z

The orbital energy differences are large between inner orbitals of atoms of high atomic number

Practical applications of Characteristic X-radiation

1. ***Chemical analysis***

- *from minute amounts*
- *sample plays the role of an anode*



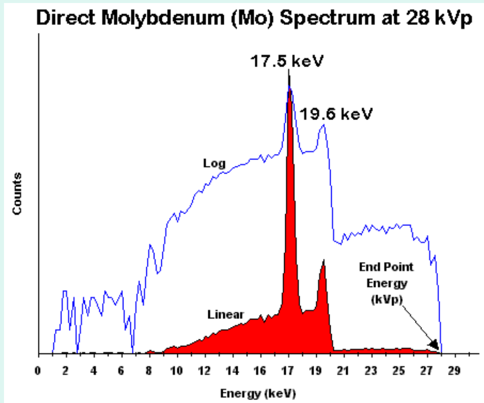
qualitative analysis:

photon energies of spectral lines define the atomic number of the sample

Analysis in criminology

2. Mammography

Characteristic X-ray emission of Mo anode is of ***low photonenergy***, ***monochromatic (~17.5 keV)***, it is ***absorbed in soft tissues*** with high probability

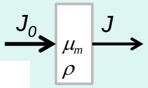


Basics of X-ray diagnostics

Diagnostic applications are based on the contrast in the image based on the ***variety of absorption in various tissues***

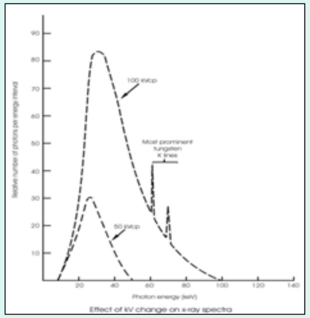
$$J = J_0 e^{-\mu x} = J_0 e^{-\mu_m \rho x}$$

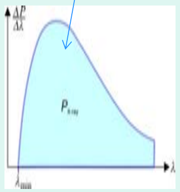
depends also on the photonenergy of X-rays



μ attenuation coefficient
μ_m mass attenuation coefficient
ρ density of absorber

$$J\left[\frac{W}{m^2}\right] = \frac{P_{total}[W]}{A[m^2]}$$



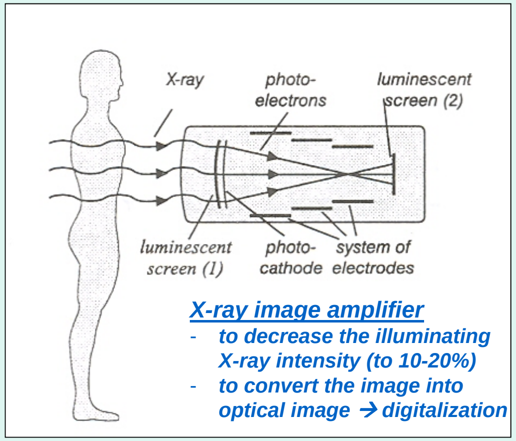


Sharp lines of characteristic radiation can be neglected in the contrast based on the variety of μ

Diagnostics is based on the absorption of Bremsstrahlung

Diagnostics is based on the absorption of X-rays of ionizing radiation

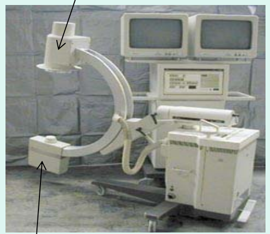
Radiation hazard !



X-ray image amplifier

- *to decrease the illuminating X-ray intensity (to 10-20%)*
- *to convert the image into optical image → digitalization*

X-ray image amplifier



X-ray tube

Mechanism of X-ray absorption in the range of the X-ray tube (20 keV<hf< 200 keV) – repetition and summary

$$J = J_o e^{-\mu x} = J_o e^{-\mu_m \rho x}$$

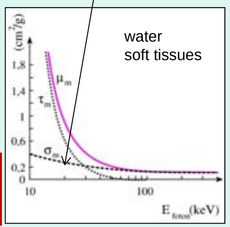
$$\mu = \mu_m \rho$$

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

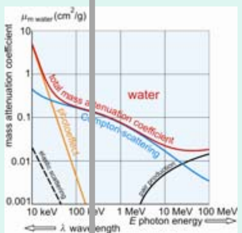
photoelectric effect is of highest probability, strongly depends on Z of absorber and on the photonenergy of X-rays

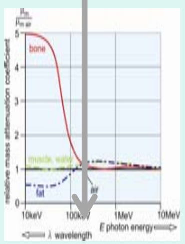
Compton effect
σ_m of water ~ constant~ 0.2cm²/g

$$\tau_m = const_1 * \lambda^3 Z^3 = const_2 * \frac{Z^3}{(hf)^3}$$



diagnostic range





X-rays of low photonenergy are very well absorbed in the tissues

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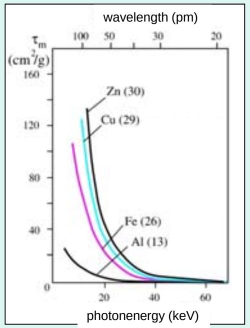
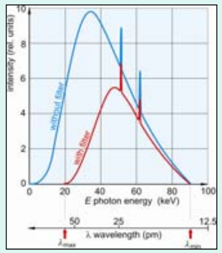
Practical acpects of X-ray diagnostics

1. ***Filtering the radiation -***
   cutting off the photons of low energy → decreasing the radiation hazard



Using Al filter eliminates the photons <20 keV and partially absorbs at higher energies.



$$\tau_m = const_1 * \lambda^3 Z^3 = const_2 * \frac{Z^3}{(hf)^3}$$

materials of ***medium Z*** are good for filtering

Photons of low energy are not absorbed in the skin, but in the filter.

2. Using contrast materials – *positive and negative contrast of organs*

Zeff takes into account the atomic composition of the absorber

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

molar ratio

$$\tau_m = const * \lambda^3 Z^3$$

$$J = J_o e^{-\mu x} = J_o e^{-(\tau_m + \sigma_m) * \rho * x}$$

material	Z_{eff}	ρ (g/cm3)
air	7,3	$1,3 \cdot 10^{-3}$
water	7,7	1
soft tissue	7,4	1
bone tissue	13,8	1,7-2

Contrast material filling the organ leads to

inreased absorption positive contrast or decreased absorption negative contrast

Positive contrast materials *(Iodine, Barium, etc.)*

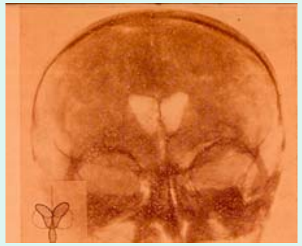
Z high → τ_m high → μ high

Negative contrast materials *(gases: air, CO_2, etc)*

ρ low → μ low

$$\mu = \mu_m * \rho$$

Bowels (positive contrast)



Air (negative contrast)

Large intestine (double contrast)

Small intestine (double contrast)

DSA method - based on positive contrast

Digital Subtraction Angiography

Image 1

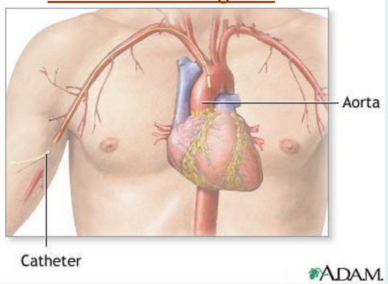
(without *I* contrast)

Image 2

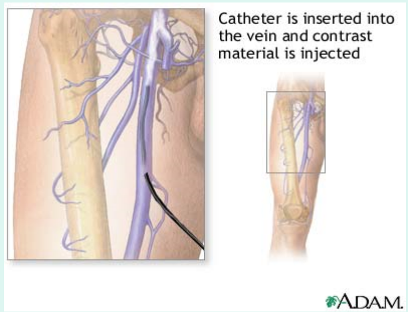
(with contrast)

DSA image:
subraction of Image1 from Image2
(contrast-native)

Cardiac arteriogram

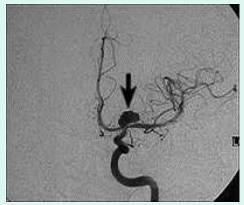


Considered as surgical intervention



Cerebral arteriograms

Normal frontal cerebral arteriogram



a large aneurysm arising from the left internal carotid artery in the brain.

X-ray computed tomography yields 3D images
„driver in a car” -- discussed later

End of the lecture