Micro- and Nano- Tomography of Biological Tissues

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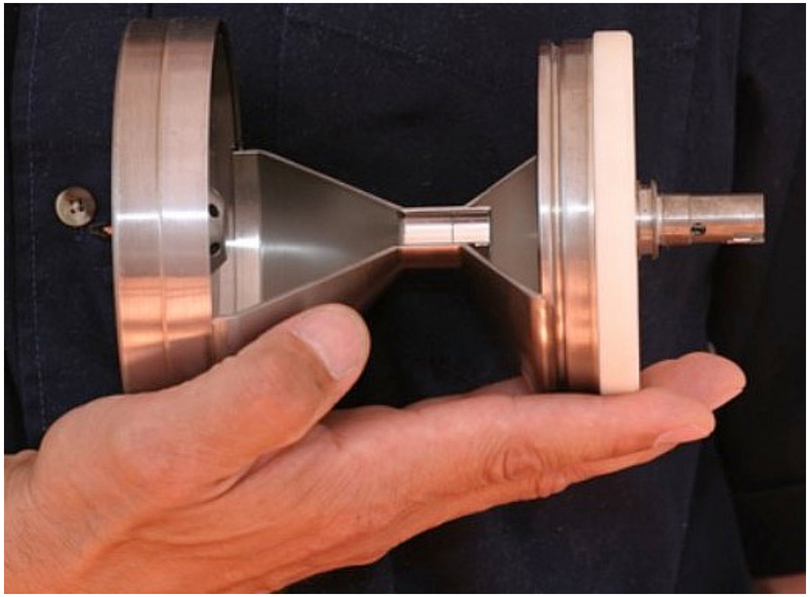
ETH-227-0965-00 L

X-ray sources



X-ray tubes

- Compact, light source
- Availability, cheap

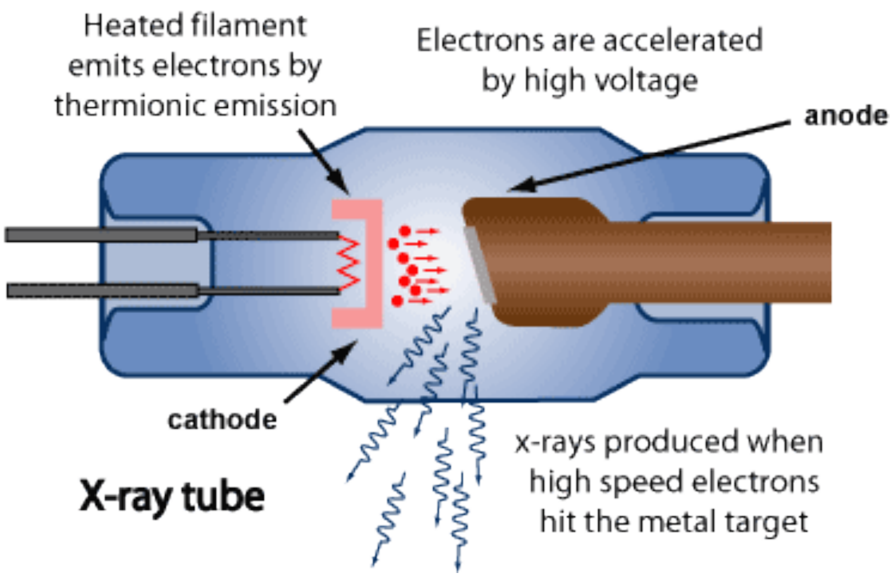
- Polychromatic
- Low flux
- Highly divergent

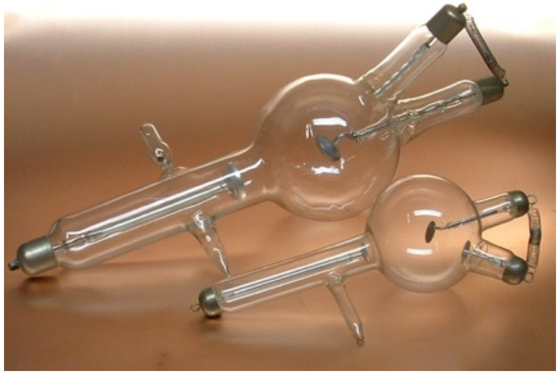
Synchrotron radiation

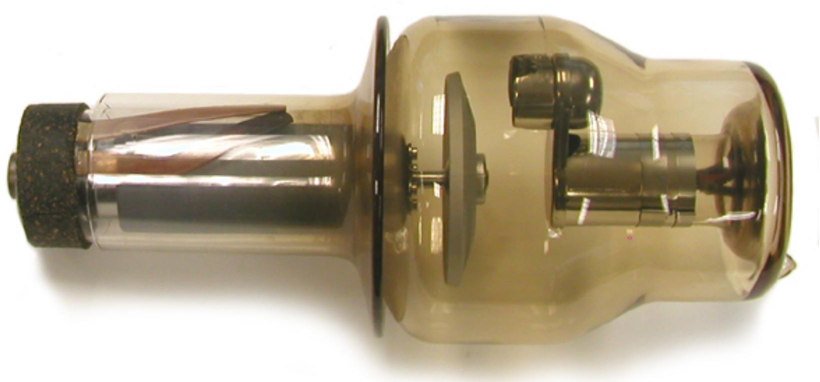
- Monochromatic
- High flux
- Highly collimated
- Polarized

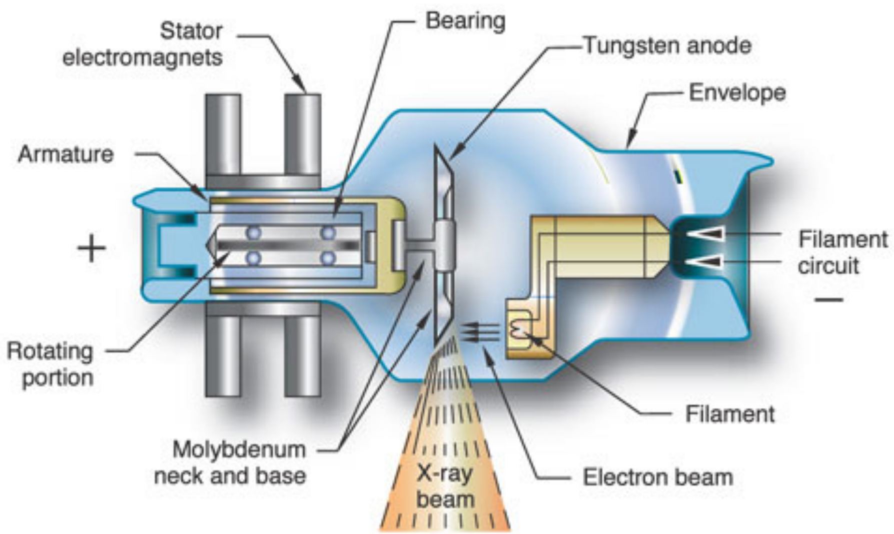
- Large scale facility
- Very expensive

X-ray tubes



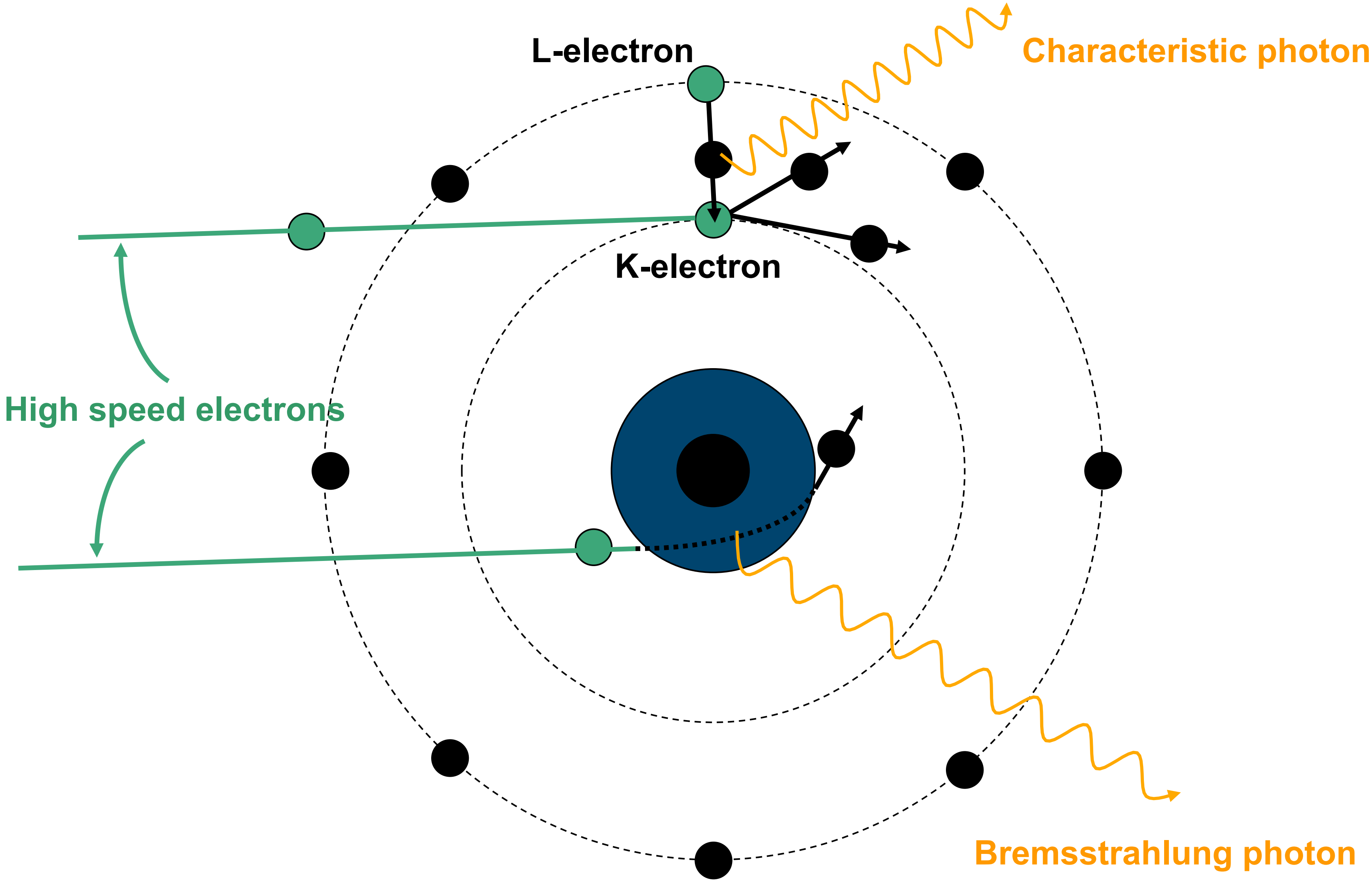




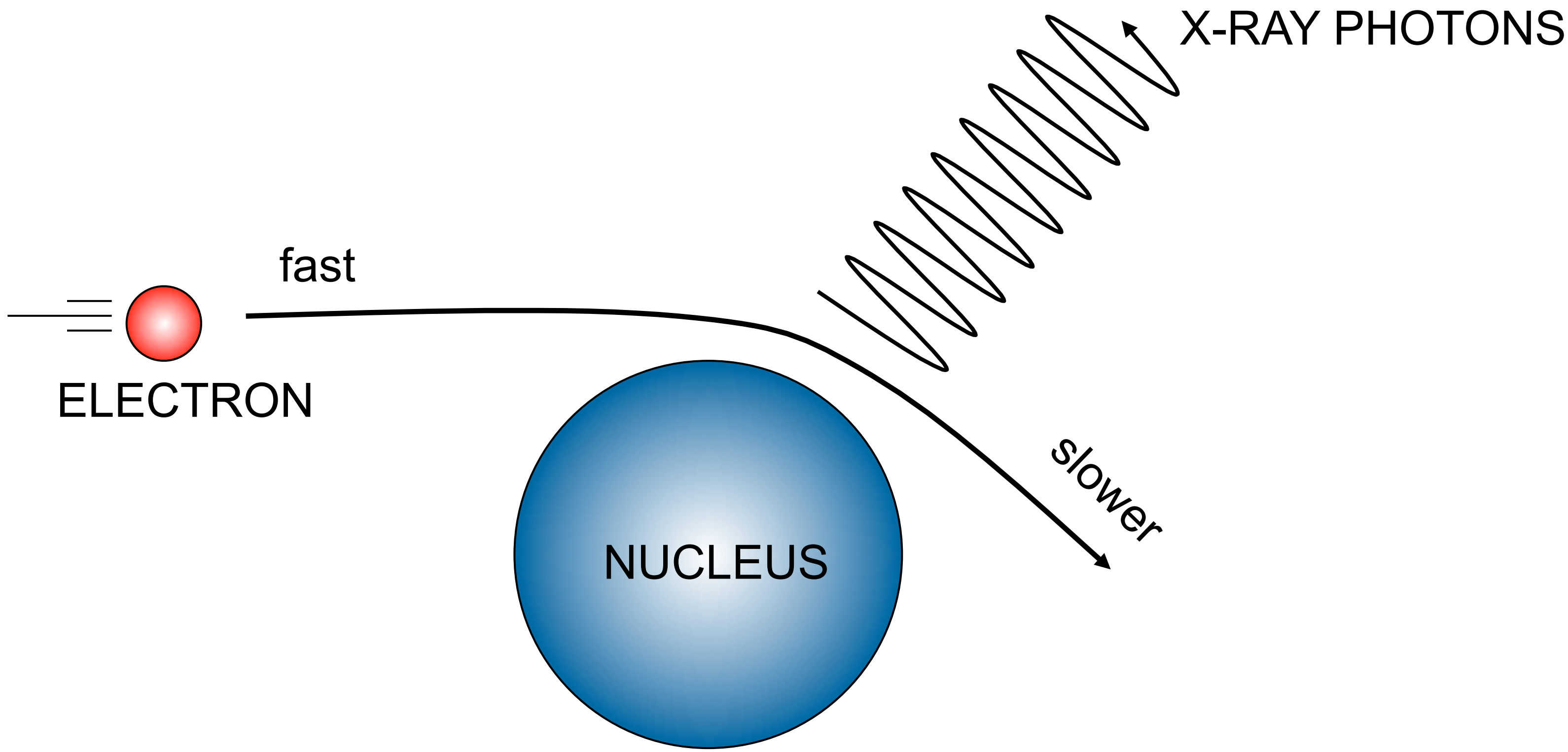


http://www.orau.org/ptp/collection/xraytubescoolidge/xraytubescoolidge.htm
http://www.arpansa.gov.au/radiationprotection/basics/xrays.cfm

Kinetic of X-rays production



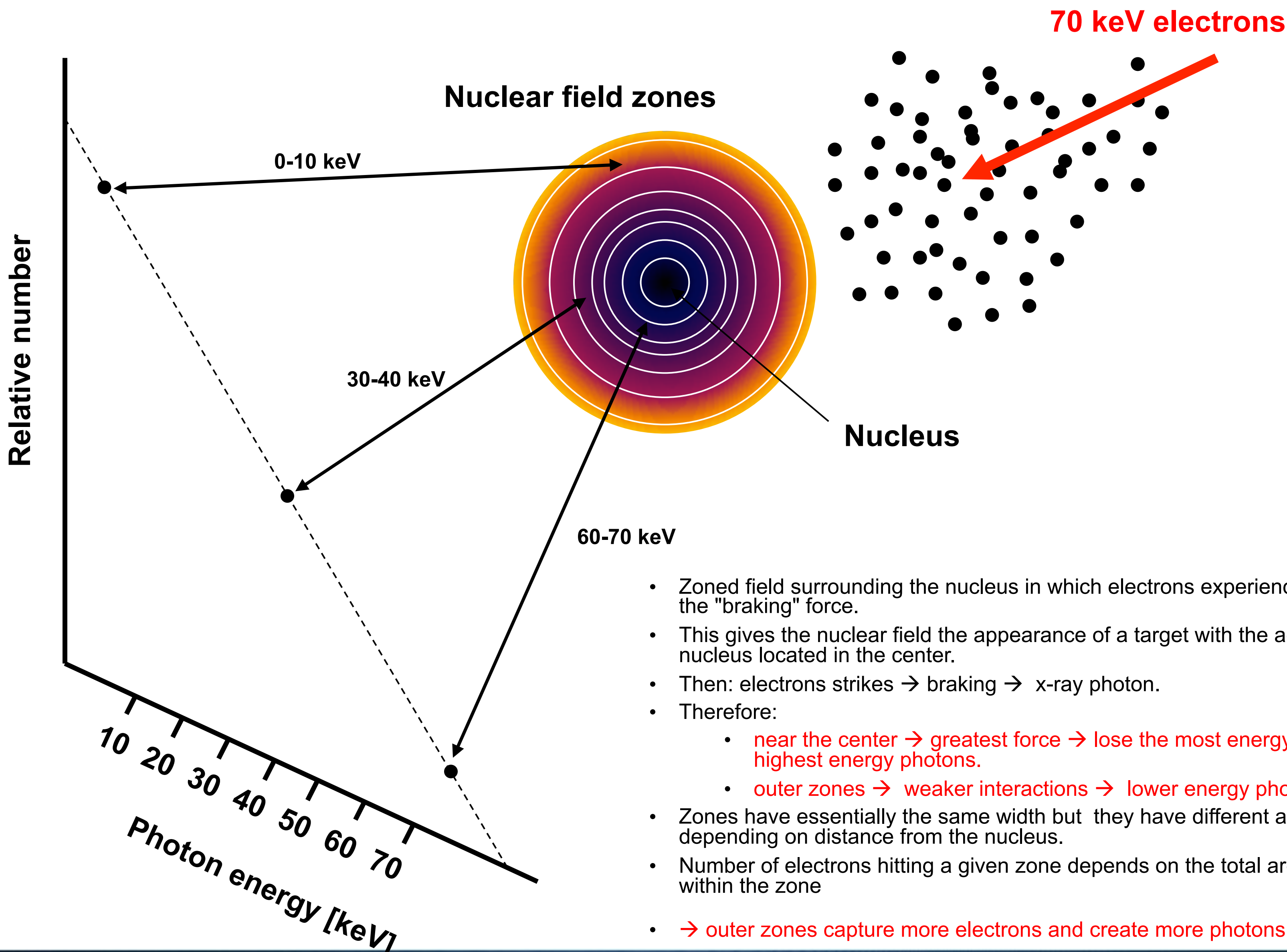
X-ray generation: Bremsstrahlung



A fast moving electron decelerates when it swings around a heavy nucelus:

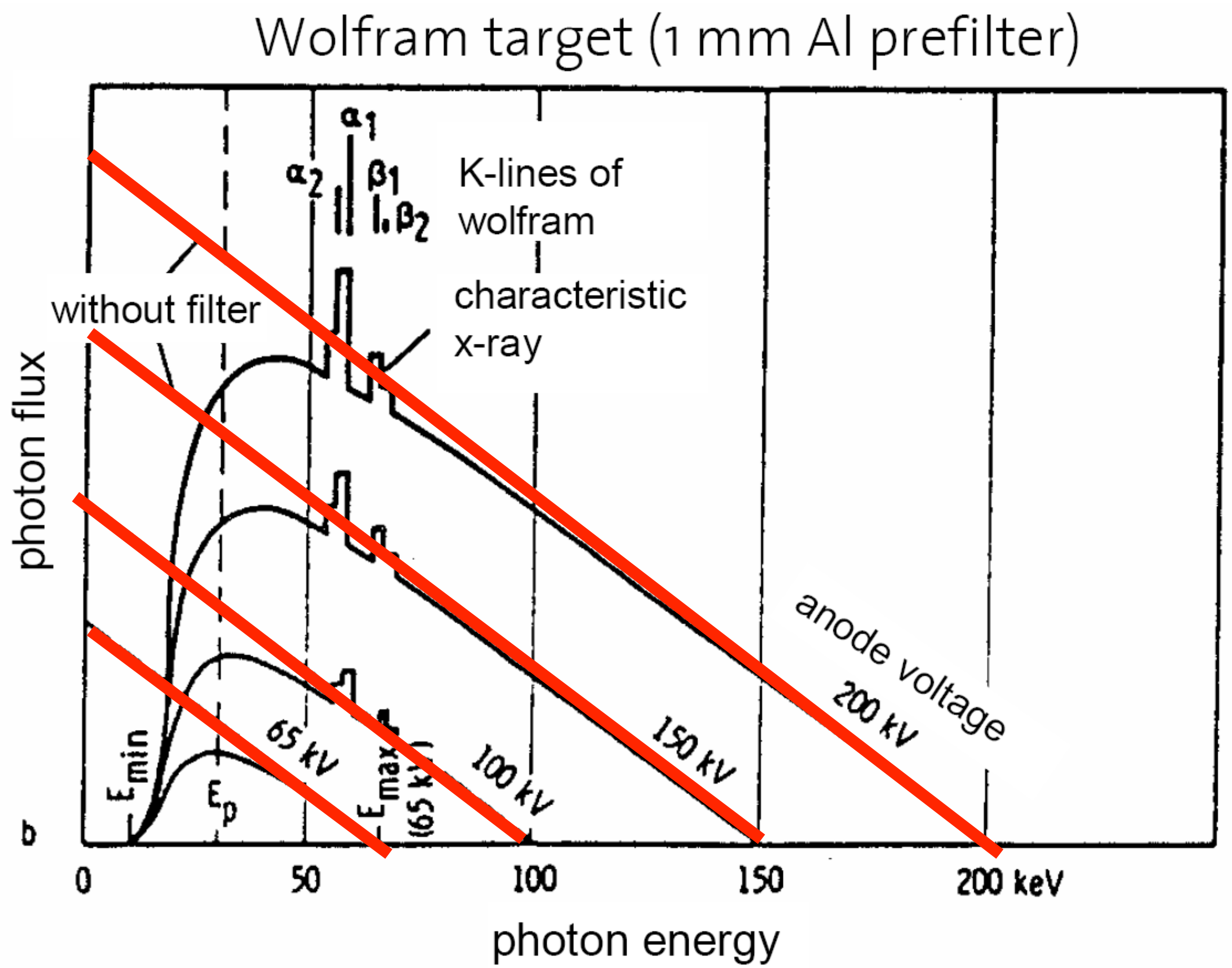
- electron interacts with electrons in outer shells
- energy depends in distance at which electrons passes the nuclei
- spectrum continuous until E_{max}
- interaction cross section depends on Z value of nuclei and E of the moving electron

Bremsstrahlung: qualitative explication



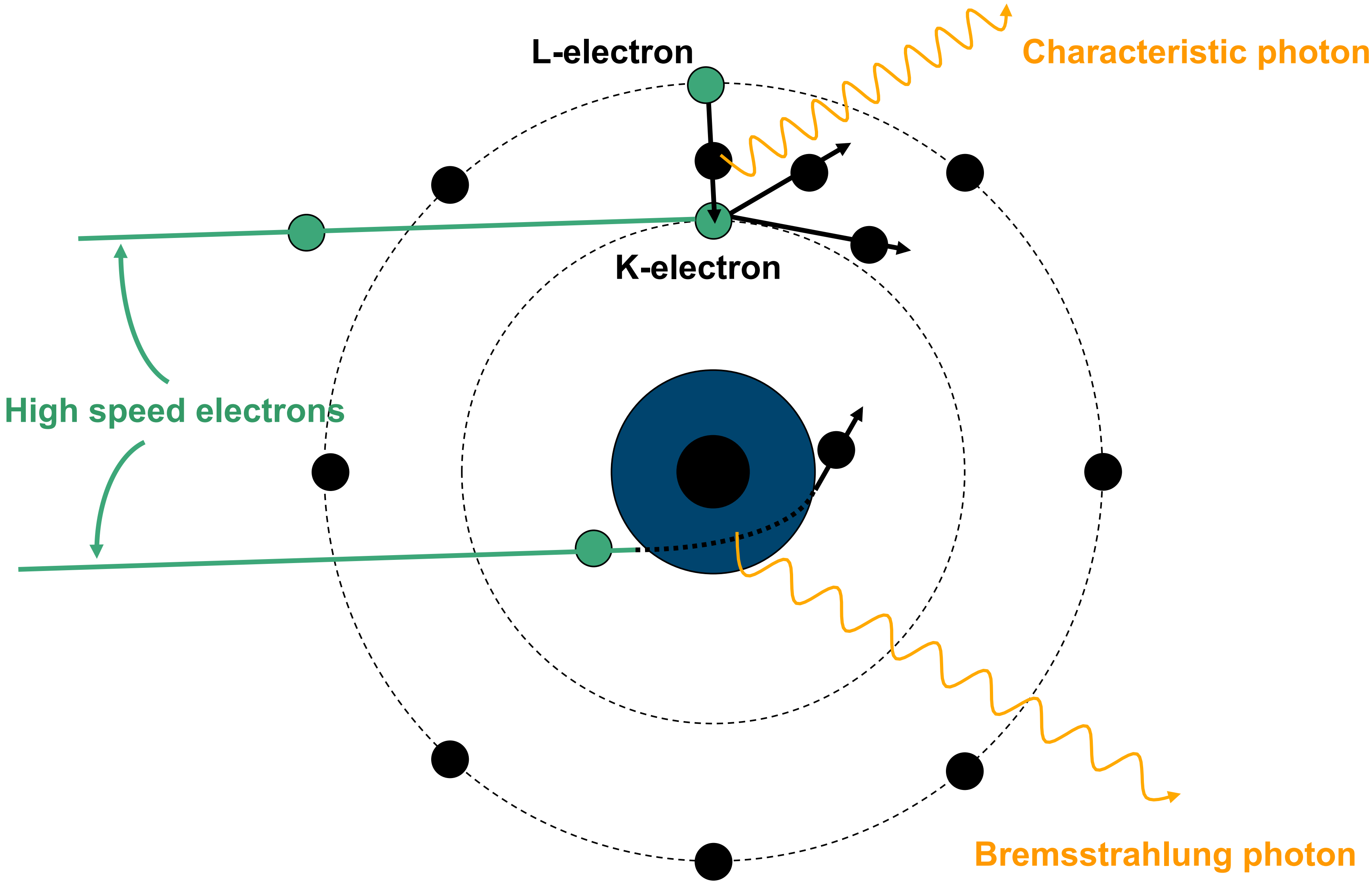
- Zoned field surrounding the nucleus in which electrons experience the "braking" force.
- This gives the nuclear field the appearance of a target with the actual nucleus located in the center.
- Then: electrons strikes → braking → x-ray photon.
- Therefore:
  - near the center → greatest force → lose the most energy → highest energy photons.
  - outer zones → weaker interactions → lower energy photons.
- Zones have essentially the same width but they have different areas, depending on distance from the nucleus.
- Number of electrons hitting a given zone depends on the total area within the zone
- → outer zones capture more electrons and create more photons.

X-ray tube spectrum: Bremsstrahlung

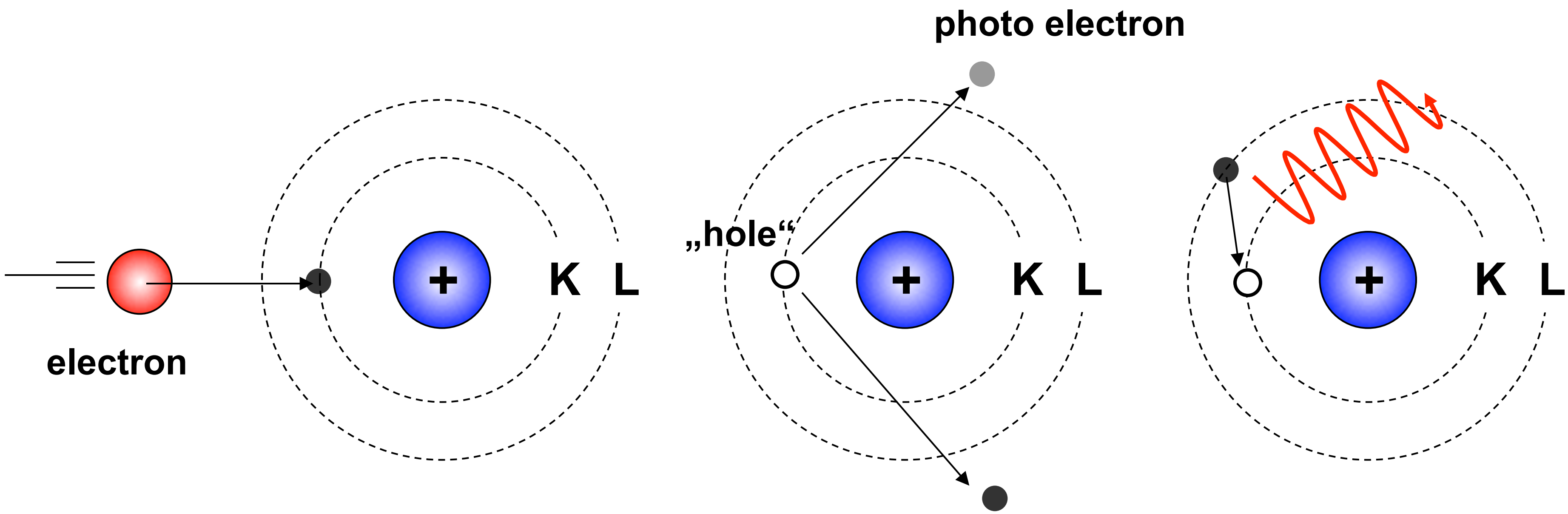


Bremsstrahlung → **Continuous spectrum**

Kinetic of X-rays production



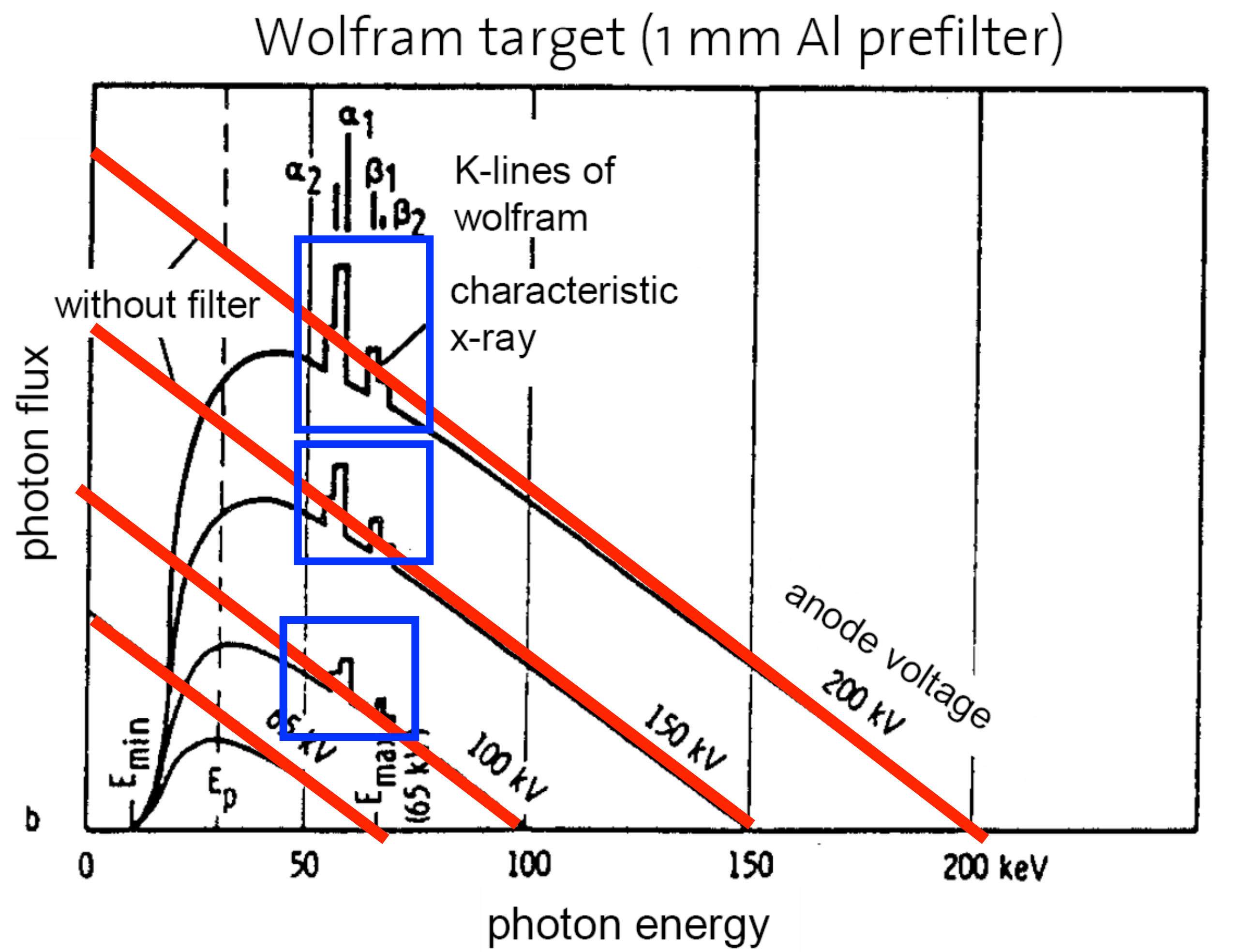
Characteristic radiation



Fast moving electron interacting tightly with bound electrons in target:

- K-shell electrons is ejected
- Electron energy: $E_{electron} > E_{binding,\ K}$
- Discrete energy of emitted radiation $E = E_{binding,K} – E_{binding,L}$
- The number of photons created at each characteristic energy is different because the probability for filling a K-shell vacancy is different from shell to shell.

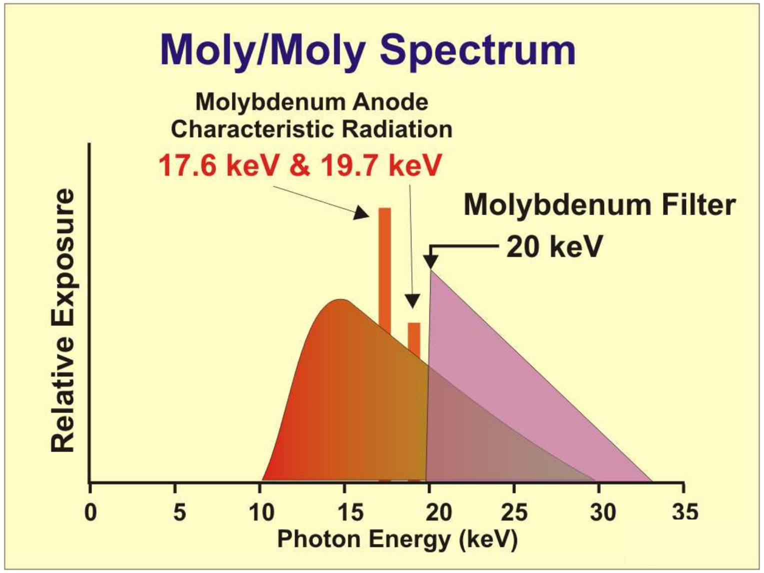
X-ray tube spectrum: characteristic radiation

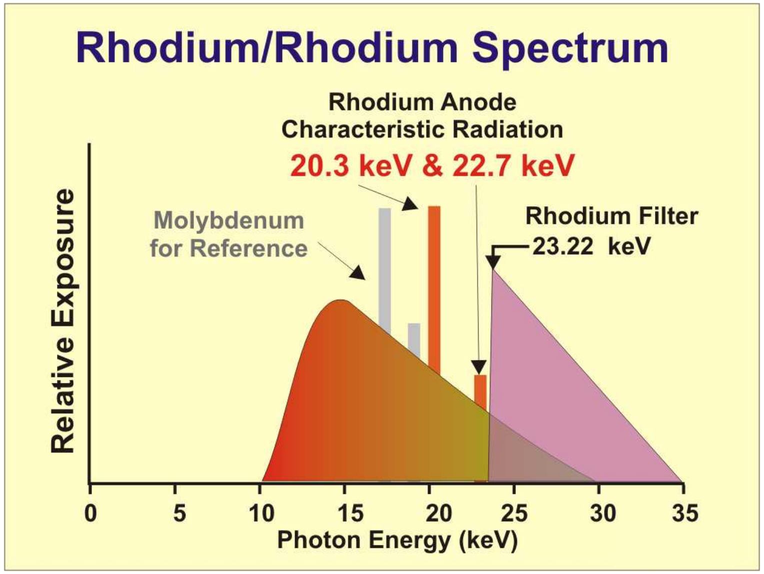


Bremsstrahlung → **Continuous spectrum**

Characteristic radiation → **Peaks / Lines**

Designing X-ray spectra





“Moly-Moly" spectrum

- The molybdenum anode produces two peaks of characteristic radiation at 17.6 keV and 19.7 keV.
- The x-ray beam contains bremsstrahlung spectrum with energies extending up to the set KV value.
- Use an additional molybdenum filter (K-edge principle)
- A significant portion of the spectrum is in the range from 17.6 to 20 keV

Dual-track x-ray tubes

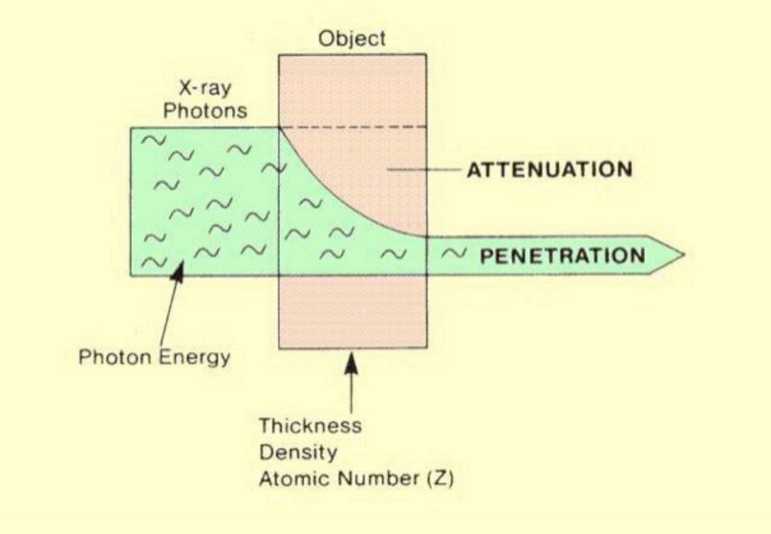
- Either molybdenum or rhodium can be selected as the active anode material
- Rhodium ‘s characteristic energy higher than molybdenum
- Beam penetration is increased.

X-ray interactions with matter

X-ray interactions with matter (relevant for microscopy)

- Terminology:
  - **Transmission:** photon passing through the body
  - **Absorption:** partial or total absorption of the photon energy
  - **Scatter:** photon deviated in a new direction
  - **Attenuation:** absorption + scatter

- Physical names:
  - Photo effect
  - Compton scattering
  - Pair-production



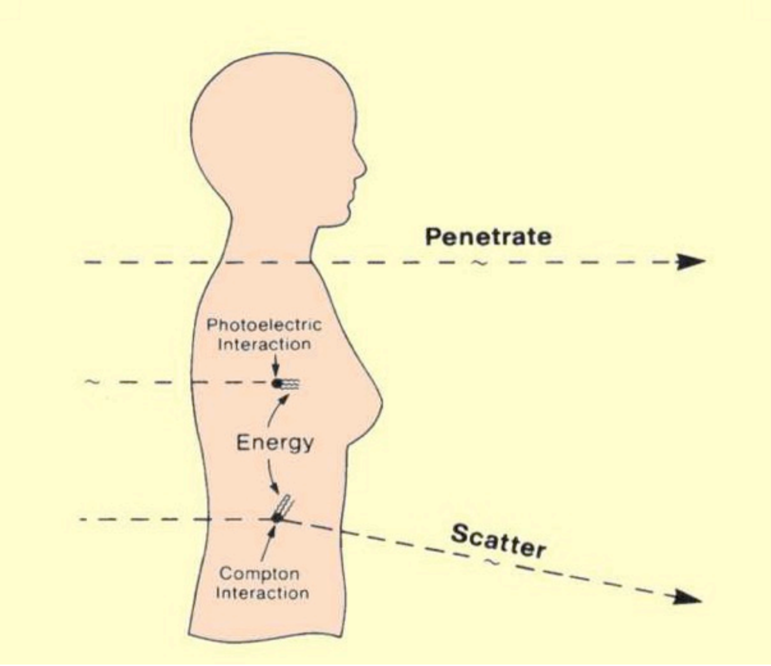


Photo effect

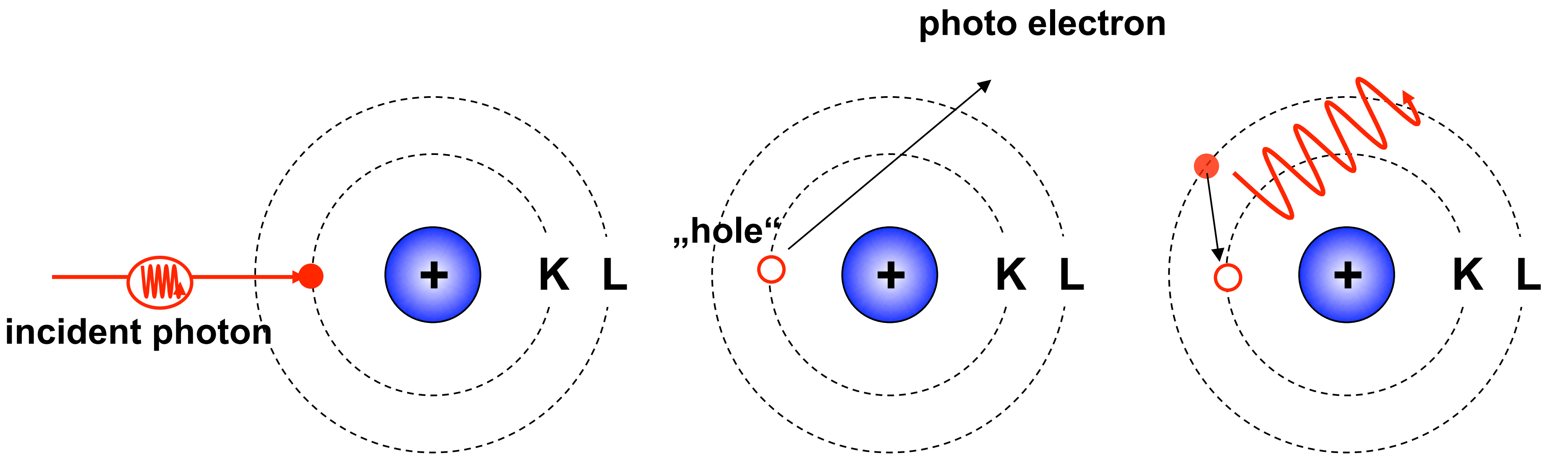


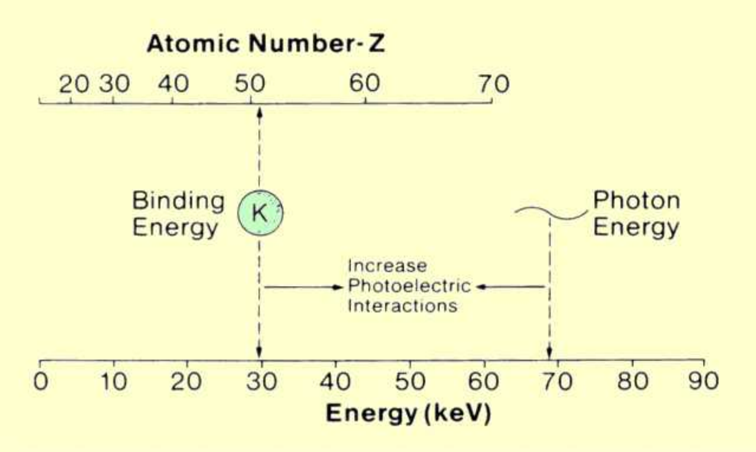
Photo effects leads to total absorption of the incident photon:

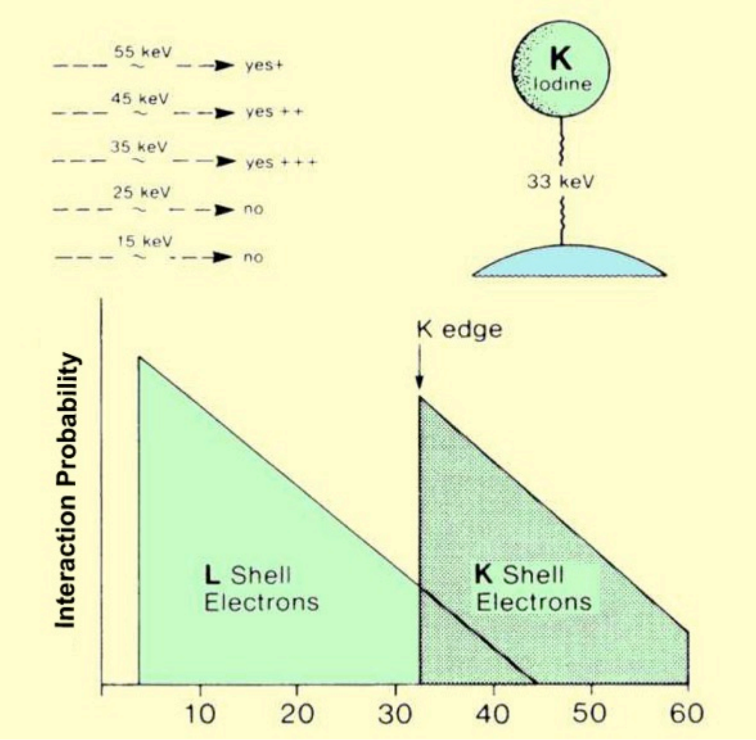
- Photo-electrons usually cause biological damage → „ionizing radiation“
- Generation of characteristic X-ray radiation with low energy
- The probability of a photoelectrical event is $\approx \rho \cdot \frac{Z^3}{E^3}$

Photo effect: rates – probabilites - dependencies

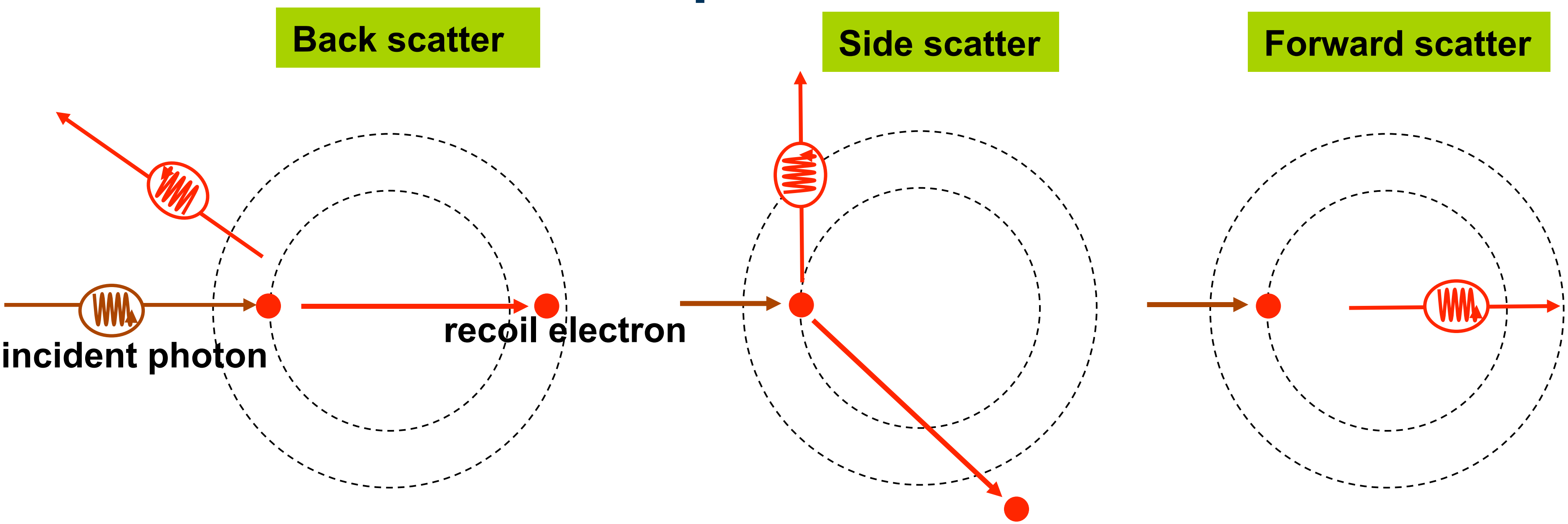
- The probability for photoelectric interactions depends on how well the photon energies and electron binding energies match:
  - a change in photon energy alters the match and the chance for photoelectric interactions.
  - with photons of a specific energy, the probability of photoelectric interactions is affected by the atomic number of the material, which changes the binding energy.

- The probability of photoelectric interaction:
  - is inversely proportional to the cube of the photon energy ($1/E^3$).
  - is proportional to Z^3.
  - it changes abruptly at one particular energy: the binding energy of the shell electrons





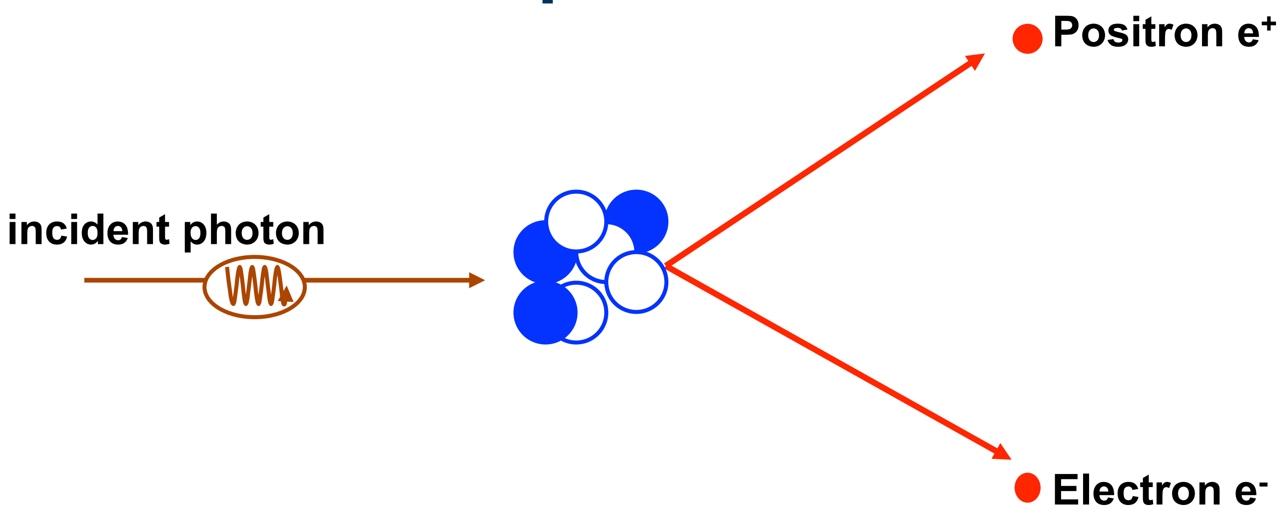
Compton effect



Compton effect leads to photon "bouncing" (scattering):

- Photon loses part of its energy in favor of kinetic energy of electron
- The photon changes its direction and wavelength: $\Delta\lambda = 0.0024 \cdot (1 - \cos\theta)$
- The recoil electron is responsible for the biological damage
- The probability of Compton event is $\approx \frac{\rho}{E}$

Pair production



Incident photons (E > 1.02 MeV) may interact with a nucleus to form an electron-positron pair:

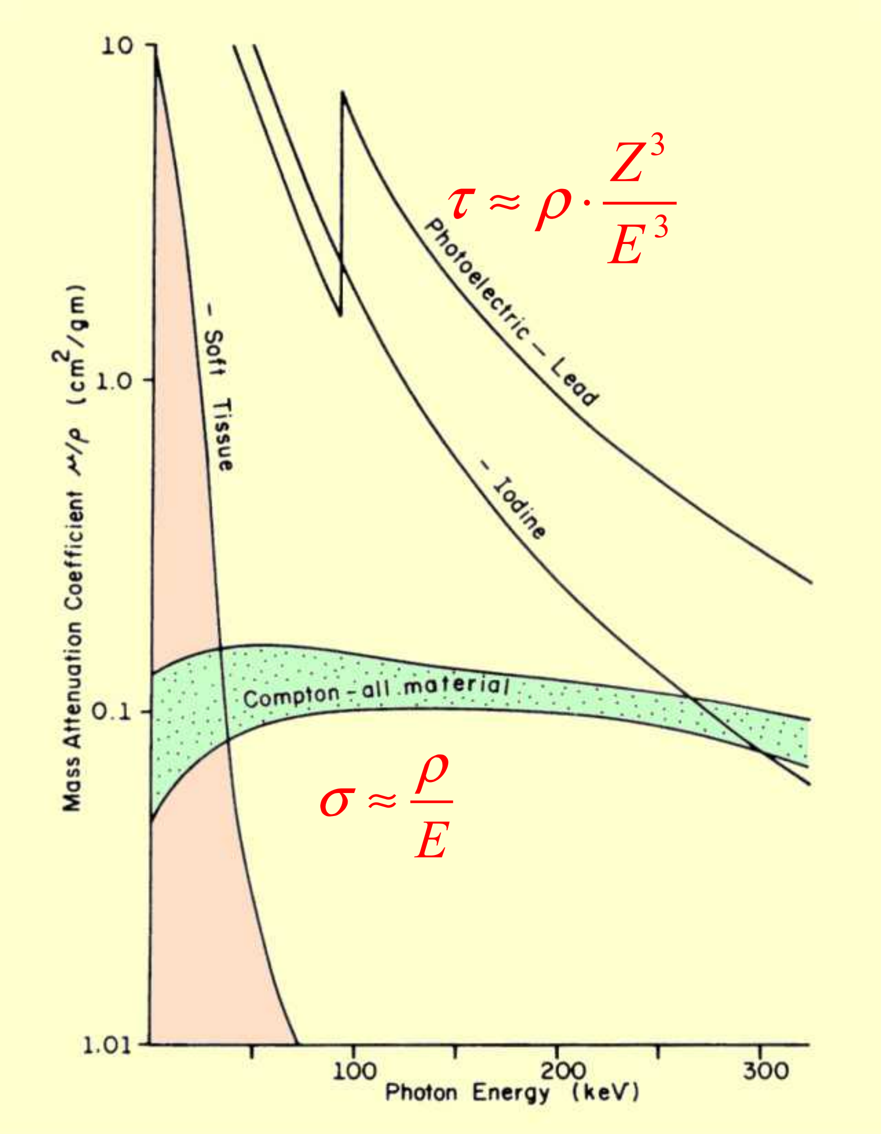
- Energy is just sufficient to provide the rest masses of the electron and positron (0.51 MeV each).
- Excess energy will be carried away equally by these two particles which produce ionisation as they travel in the material.
- The positron is eventually captured by an electron and annihilation of the two particles occurs.
- This results in the release of two photons each of 0.51 MeV known as annihilation radiation
- These two photons then lose energy by Compton scattering or photo effect.

X-ray attenuation summary

- **Photo effect τ :**
  - X-ray photon disappears
  - Photo- electron recoils
- **Compton effect σ :**
  - Interaction with free electrons
  - Scatter
- **Pair production κ :**
  - Electron-positron pair production requires E > 1 MeV
  - Not relevant in medical imaging

Linear attenuation coefficient:

$$\mu = (\tau + \sigma + \kappa)\ [\mathrm{cm}^{-1}]$$



Beer-Lambert's law

- Photons do not have the same range, even when they have the same energy.
- Some of the photons travel a relatively short distance before interacting, whereas others pass through or penetrate the object.
- The relationship between the number of photons reaching a specific point and the thickness of the material to that point is **exponential.**

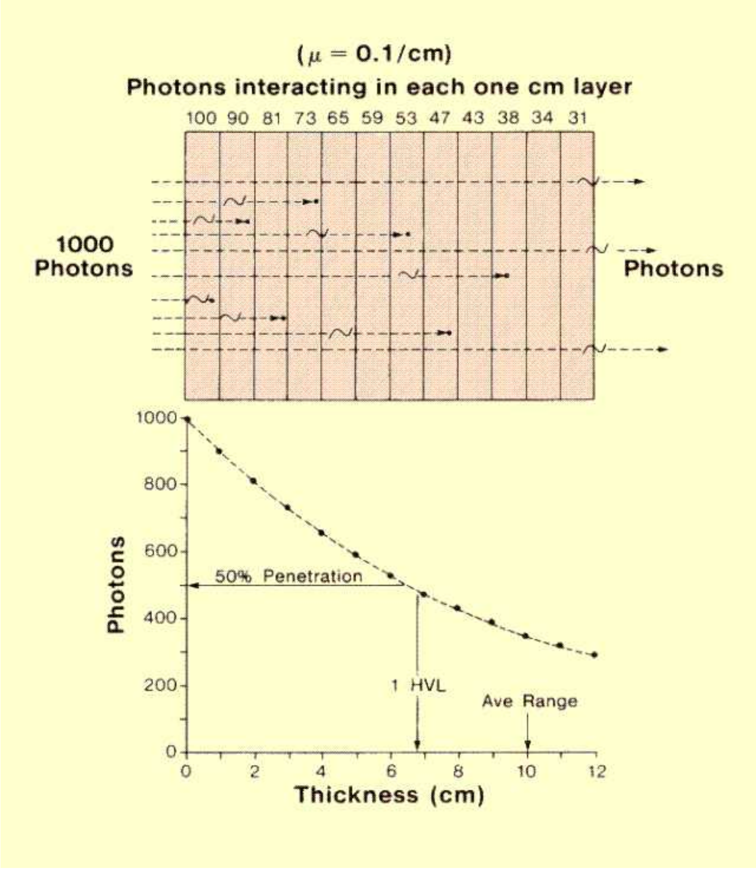
- **Beer-Lambert's law:**

object dependence

$$I = I_0 \cdot e^{-\int_{-\infty}^{\infty} \mu(x)\cdot dx}$$

$$I = \int_0^{E_{\max}} I_0(E)\cdot e^{-\int_{-\infty}^{\infty} \mu(E,x)\cdot dx}\, dE$$

energy dependence



Beer-Lambert law: behind the curtains…

- Assume that particles may be described as having an absorption cross section (i.e. area), σ, perpendicular to the path of light through a solution, such that a X-ray photon is absorbed if it strikes the particle, and is transmitted if it does not.
- Define z as an axis parallel to the direction that X-ray photons are moving, and A and dz as the area and thickness (along the z axis) of a 3-dimensional slab of material through which light is passing. We assume that dz is sufficiently small that one particle in the slab cannot obscure another particle in the slab when viewed along the z direction. The concentration of particles in the slab is represented by N.
- It follows that the fraction of photons absorbed when passing through this slab is equal to the total opaque area of the particles in the slab, $\sigma A N dz$, divided by the area of the slab A, which yields $\sigma N dz$. Expressing the number of photons absorbed by the slab as dI_z, and the total number of photons incident on the slab as I_z, the fraction of photons absorbed by the slab is given by

$$\frac{dI_z}{I_z} = -\sigma \cdot N \cdot dz$$

- The solution to this simple differential equation is obtained by integrating both sides to obtain I_z as a function of z

$$\ln(I_z) = -\sigma \cdot N \cdot z + C$$

- The difference of intensity for a slab of real thickness ℓ is I_0 at $z = 0$, and I_l at $z = \ell$. Using the previous equation, the difference in intensity can be written as,

$$\ln(I_0) - \ln(I_l) = (-\sigma \cdot N \cdot 0 + C) - (-\sigma \cdot N \cdot l + C) = \sigma \cdot l \cdot N$$

- Which finally yields:

$$I_l = I_0 \cdot e^{-\sigma \cdot N \cdot l}$$

References

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- G. D. Boreman, *Modulation Transfer Function in Optical and Electro-Optical Systems,* SPIE, Bellingham, WA, ISBN 0-8194-4143-0

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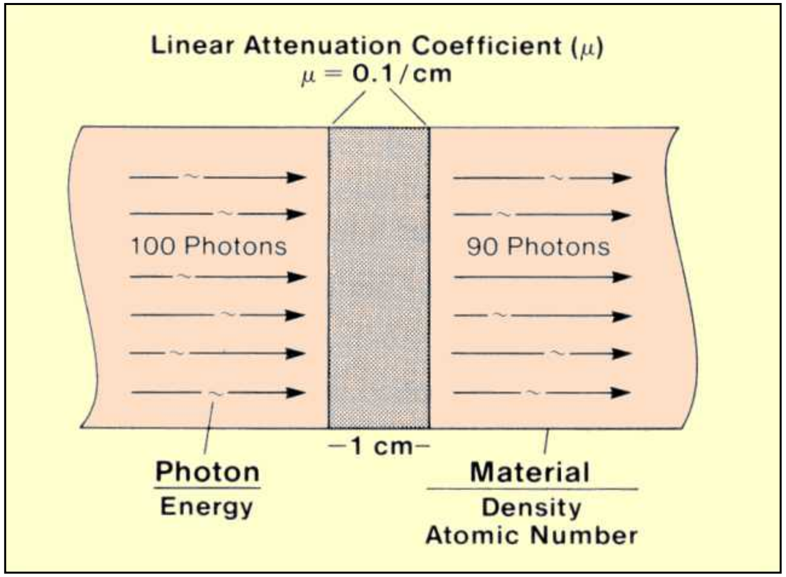
- A. C. Kak, M. Slaney, Principle of Computerized Tomographic Imaging", SIAM Classics in Applied Mathematics 33, New York, 2001, ISBN 0-89871-494-X
- F. Natterer, *"The Mathematics of Computerized Tomography",* SIAM Classics in Applied Mathematics 32, Philadelphia 2001, ISBN 0-89871-493-1
- W. A. Kalender, *"Computed Tomography – Fundamentals, System Technology, Image Quality, Applications",* 2nd revised edition, 2005, Publicis Corporate Publishing, ISBN 3-89578-216-5
- J. Hsieh, *Computed Tomography: Principles, Design, Artifacts and Recent Advances,* SPIE Press Monograph, ISBN 0-8194-4425-1

Appendix I

Appendix Ia: Linear/mass attenuation coefficient

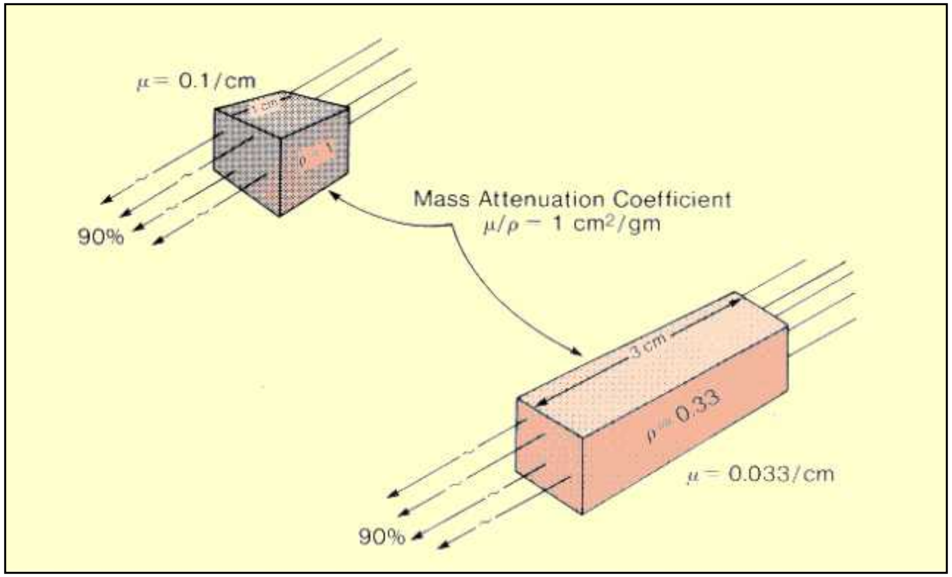
Linear attenuation coefficient:

$$\mu = \mu' \cdot \rho \ [\mathrm{cm}^{-1}]$$



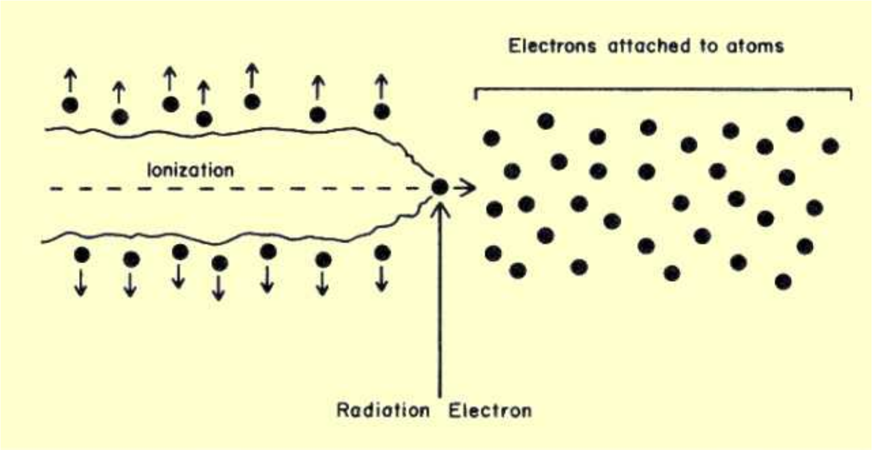
Mass absorption coefficient:

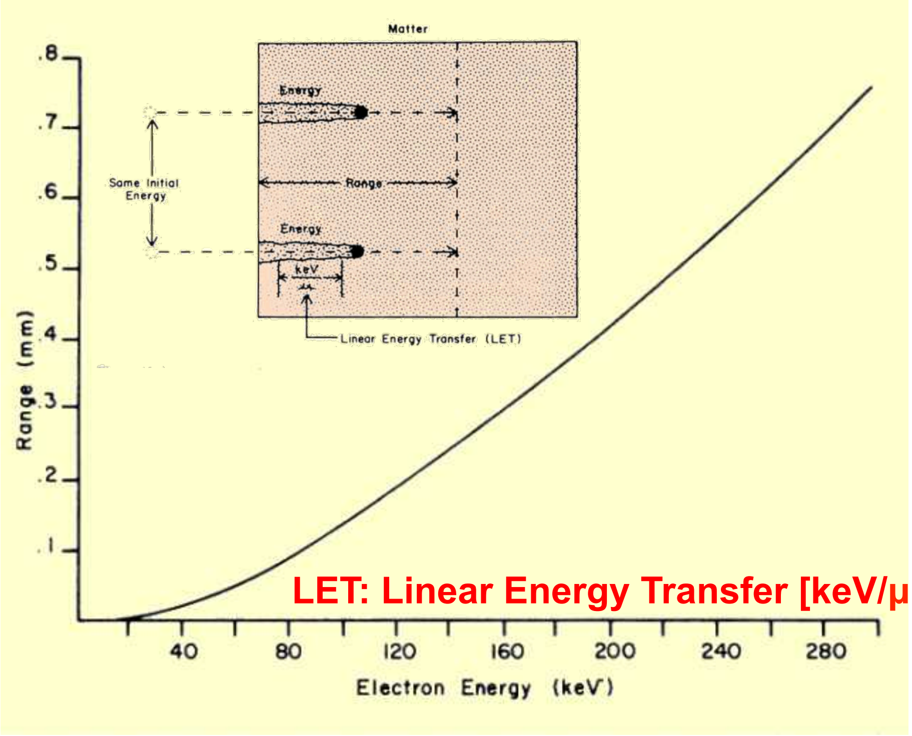
$$\mu' \ [\mathrm{cm}^2/\mathrm{g}]$$



Appendix Ib: Biological damage, energy deposition

- Most of the **ionization produced by x-radiation is the result of interactions of the energetic electrons** with the material.
- As the electrons leave the interaction site, they immediately begin to **transfer their energy** to the surrounding material.
- Because the electron carries an electrical charge, it can interact with other electrons without touching them.
- As it passes through the material, the electron, in effect, “pushes” the other electrons away from its path.
- If the force on an electron is sufficient to remove it from its atom, ionization results.
- Electron travel range depends on:
  - the initial energy of the electrons
  - the density of the material.
- Electrons of the same energy have the same range in a specific material





Appendix II: What can X-rays tell you ?

- Where we come from
- How to cure rabies
- How we evolved
- How Beethoven died
- How lichens survive
- How to store energy

X-ray astronomy

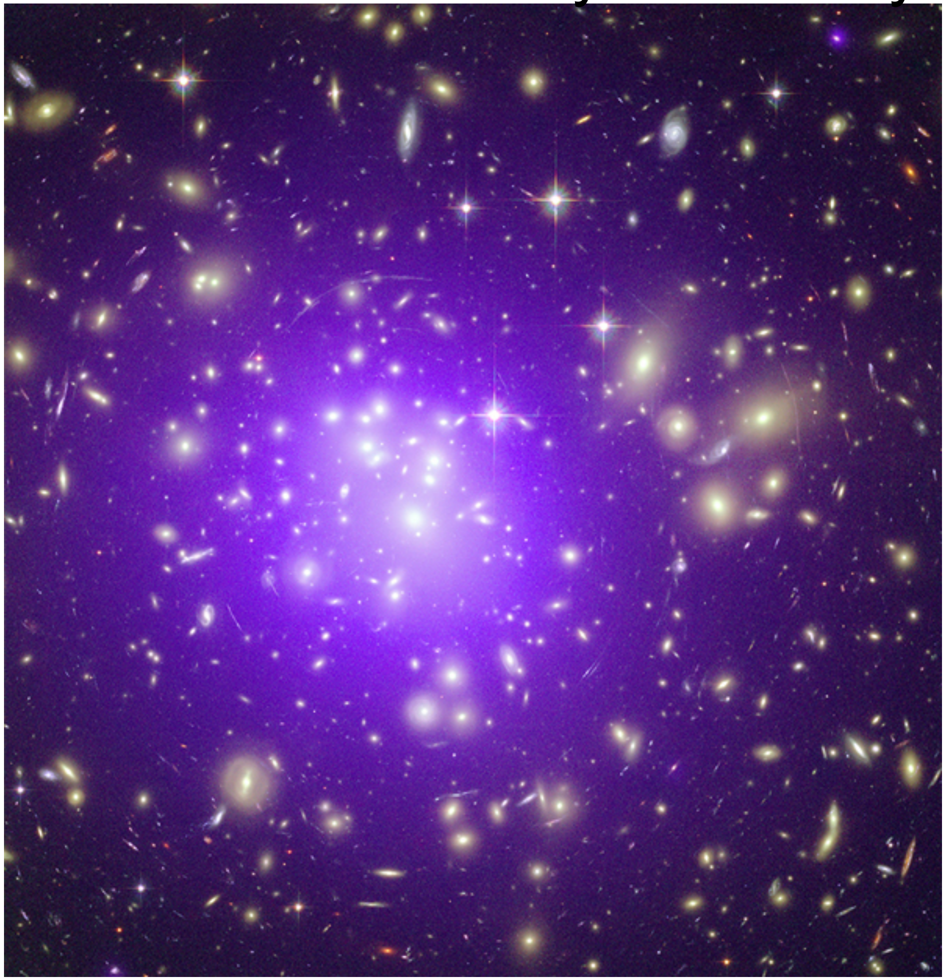


Image Credit: X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI)

Composite Chandra X-ray Observatory (purple) and the Hubble Space Telescope (yellow).
Merging and arching caused by gravitational lensing… Mass?

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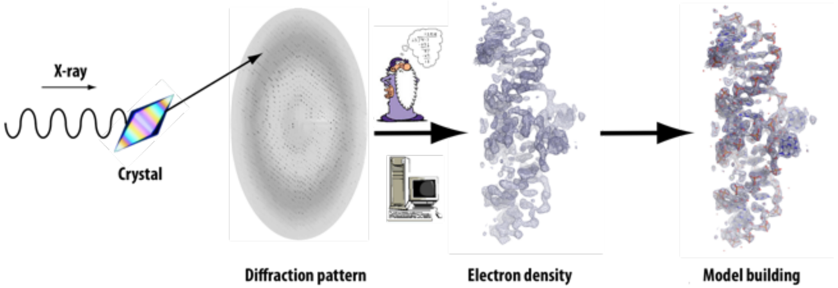
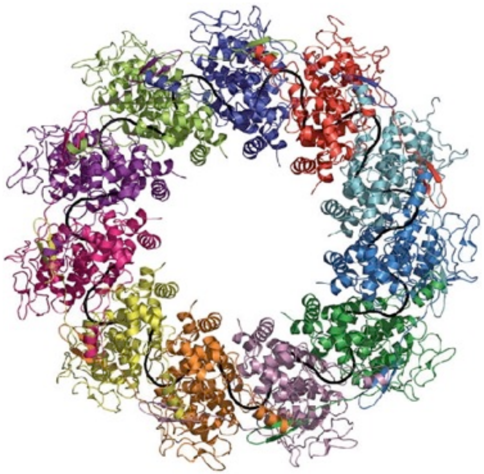


- **RNA with 99 nucleotides**
- **Shell forms two “jaws" that totally close round the RNA molecule**
- **Enzyme of immune system of host cells blocked**



Protein crystallography

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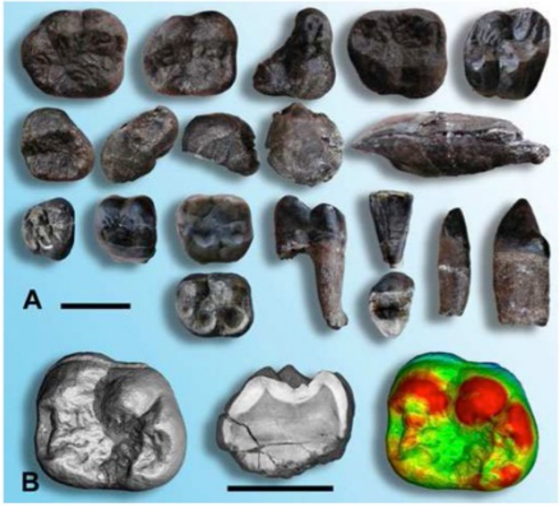

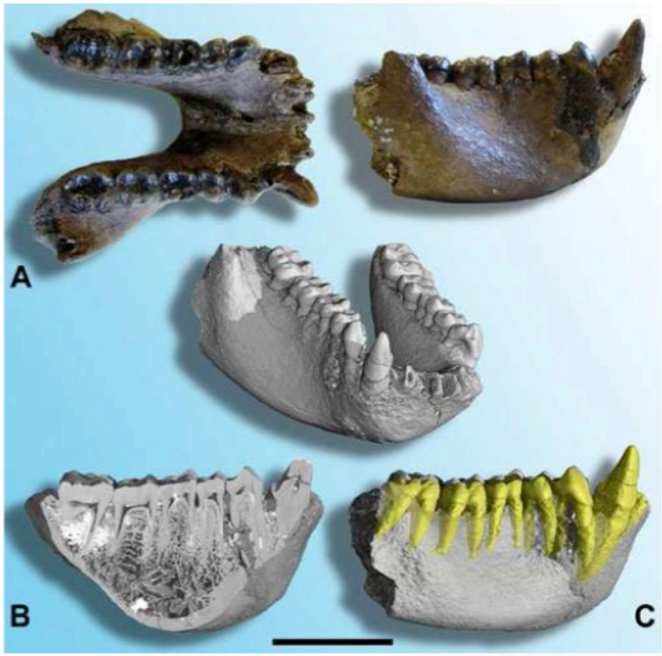

Precise thickness and distribution of the dental enamel in fossil samples

Images: courtesy of P. Tafforeau, ESRF

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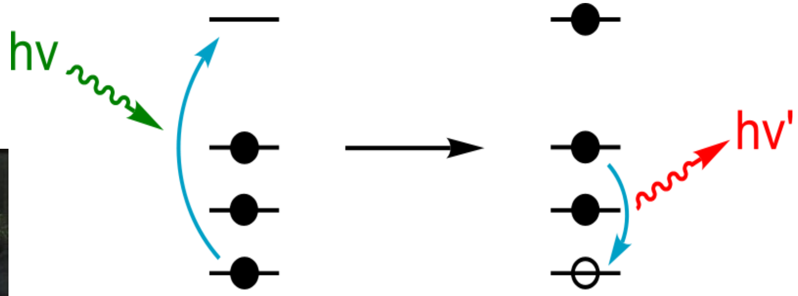

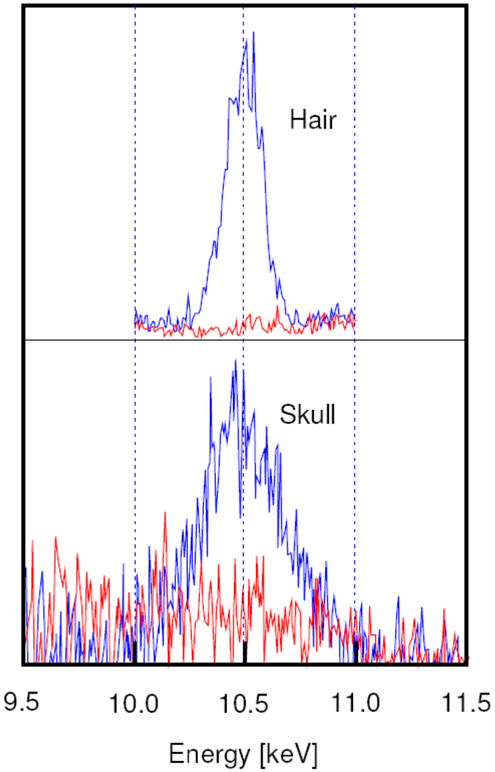

Very high lead concentration!
Plumbism? To much wine??

X-ray fluorescence

Images: courtesy of P. Willmott, PSI

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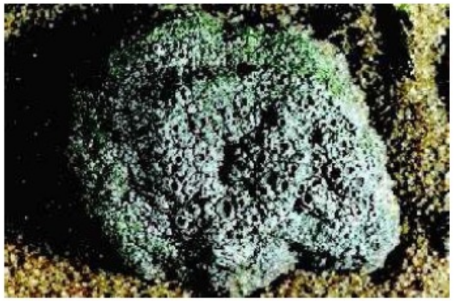
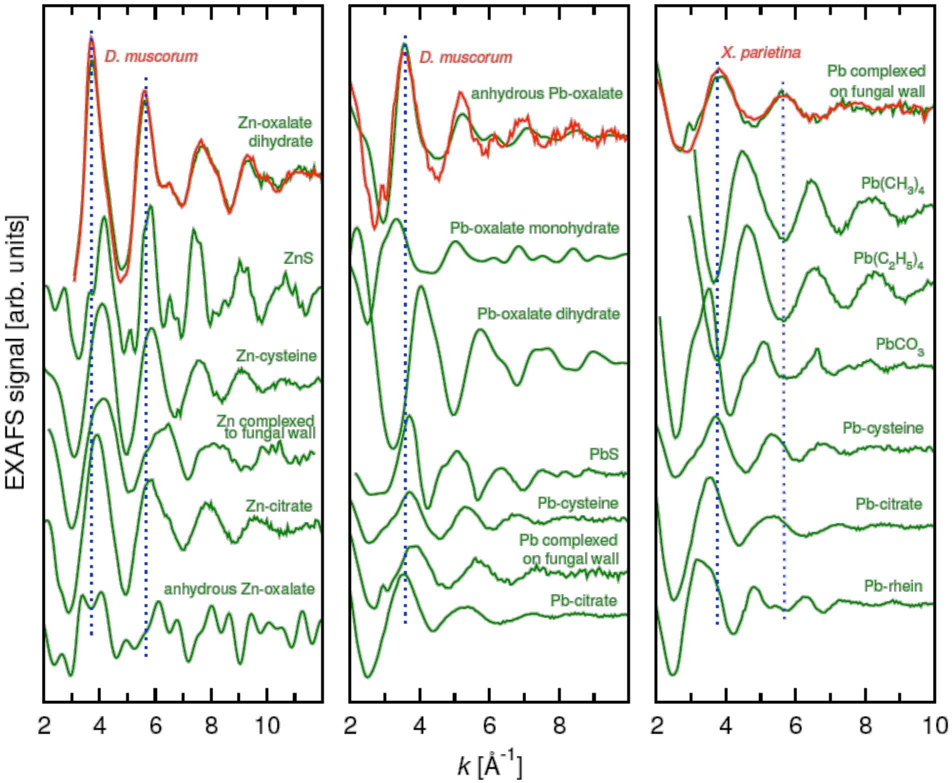
Lichens have developed the ability to tolerate high concentrations of metals



Diploschistes muscorum

Xanthoria parietina



EXAFS - Extended X-ray Absorption Fine Structure

Images: courtesy of P. Willmott, PSI

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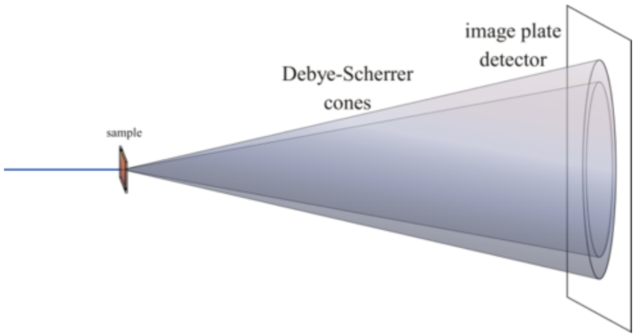
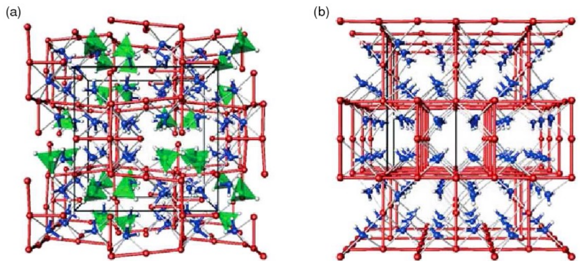
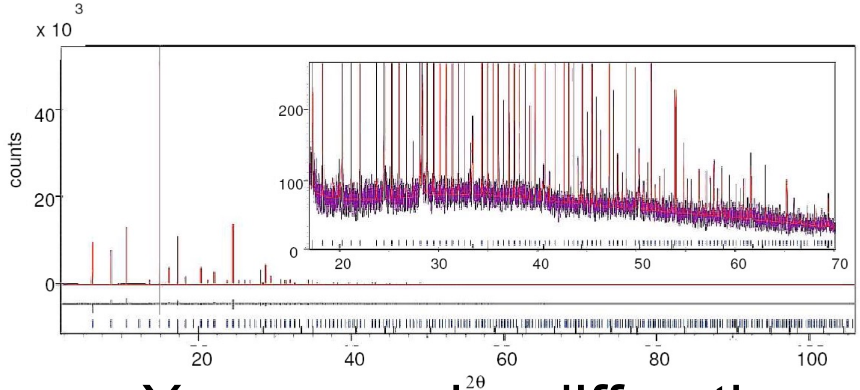
  - **Lithium amide (LiNH2) decomposes via the evolution of ammonia**
  - **In the presence of lithium hydride (LiH), it reversibly desorbs hydrogen gas.**
  - **The material has excellent hydrogen desorption properties.**







X-ray powder diffraction

Images: courtesy of P. Willmott, PSI