Medical biophysics II

Medical biophysics II

- X-ray - generation and properties
- X-ray - diagnostic foundations
- Medical use of electronics
- Thermodynamics - equilibrium, change, laws
- Diffusion, Brown-motion, Osmosis
- Flow of fluids and gases. Hemodynamics
- Bioelectric phenomena
- Sound, ultrasound
- Biophysics of sensory organs. Vision and hearing
- Building blocks of life: water, macromolecules, supramolecular systems
- Molecular mechanisms of biomolecular motion. Biomechanics, biomolecular and tissue elasticity
- Methods of investigating biomolecular structure and dynamics. MRI
- Methods of investigating biomolecular structure and dynamics. X-ray diffraction, spectroscopies.
- Respiratory and cardiac biophysics. Physical examination

X-ray

Generation, properties

X-ray

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

Sitzungs-Berichte

der

Physikalisch-medicinischen Gesellschaft

zu

WÜRZBURG.

Jahrgang 1895.	Der Abonnementspreis pro Jahrgang beträgt ℳ 4.–. Die Nummern werden einzeln nicht abgegeben. Grössere Beiträge erscheinen in Sonderdrucken.	No. 9.

Verlag der Stahel'schen k. Hof- und Universitäts-Buch- und Kunsthandlung in Würzburg.

Inhalt. *Konrad Rieger*: Demonstration des sogenannten „Vogelkopfknaben" Döbos Janos aus Battonya in Ungarn (Fortsetzung), pag. 129. — *W. C. Röntgen*: Ueber eine neue Art von Strahlen, pag. 132. — *Wilhelm Wislicenus*: 46. Jahresbericht der physikalisch-medizinischen Gesellschaft zu Würzburg, pag. 142. — Mitglieder-Verzeichniss, pag. 146.

Am 28. Dezember wurde als Beitrag eingereicht:

W. C. Röntgen: Ueber eine neue Art von Strahlen.

(Vorläufige Mittheilung.)

1. Lässt man durch eine *Hittorf*'sche Vacuumröhre, oder einen genügend evacuirten *Lenard*'schen, *Crookes*'schen oder ähnlichen Apparat die Entladungen eines grösseren *Ruhmkorff*'s gehen und bedeckt die Röhre mit einem ziemlich eng anliegenden Mantel aus dünnem, schwarzem Carton, so sieht man in dem vollständig verdunkelten Zimmer einen in die Nähe des Apparates gebrachten, mit Bariumplatincyanür angestrichenen Papierschirm bei jeder Entladung hell aufleuchten, fluoresciren, gleichgültig ob die angestrichene oder die andere Seite des Schirmes dem Entladungsapparat zugewendet ist. Die Fluorescenz ist noch in 2 m Entfernung vom Apparat bemerkbar.

Man überzeugt sich leicht, dass die Ursache der Fluorescenz vom Entladungsapparat und von keiner anderen Stelle der Leitung ausgeht.

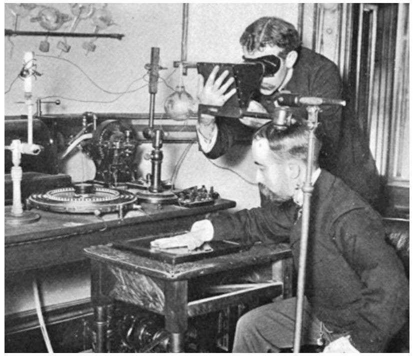
2. Das an dieser Erscheinung zunächst Auffallende ist, dass durch die schwarze Cartonhülse, welche keine sichtbaren oder ultravioletten Strahlen des Sonnen- oder des elektrischen Bogenlichtes durchlässt, ein Agens hindurchgeht, das im Stande ist, lebhafte Fluorescenz zu erzeugen, und man wird deshalb wohl zuerst untersuchen, ob auch andere Körper diese Eigenschaft besitzen.

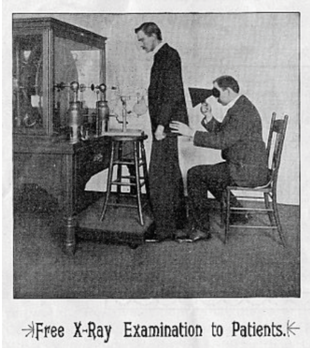
Man findet bald, dass alle Körper für dasselbe durchlässig sind, aber in sehr verschiedenem Grade. Einige Beispiele führe ich an. Papier ist sehr durchlässig:[1]) hinter einem eingebun-

[1]) Mit „Durchlässigkeit" eines Körpers bezeichne ich das Verhältniss der Helligkeit eines dicht hinter dem Körper gehaltenen Fluorescenzschirmes zu derjenigen Helligkeit des Schirmes, welcher dieser unter denselben Verhältnissen aber ohne Zwischenschaltung des Körpers zeigt.

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

I. World war

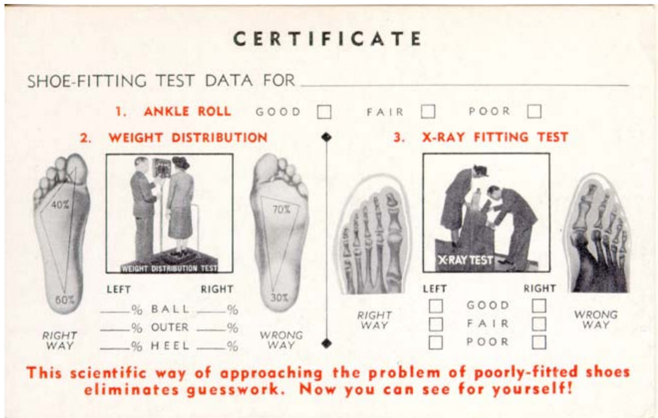
Medical diagnostics

1940

1950

today

Shoe-fitting fluoroscope (1930-50)



CERTIFICATE

SHOE-FITTING TEST DATA FOR ______________________

1. ANKLE ROLL GOOD ☐ FAIR ☐ POOR ☐

2. WEIGHT DISTRIBUTION

40%

60%

RIGHT WAY

WEIGHT DISTRIBUTION TEST

LEFT RIGHT

____% BALL ____%

____% OUTER ____%

____% HEEL ____%

70%

30%

WRONG WAY

3. X-RAY FITTING TEST

RIGHT WAY

X-RAY TEST

LEFT RIGHT

☐ GOOD ☐

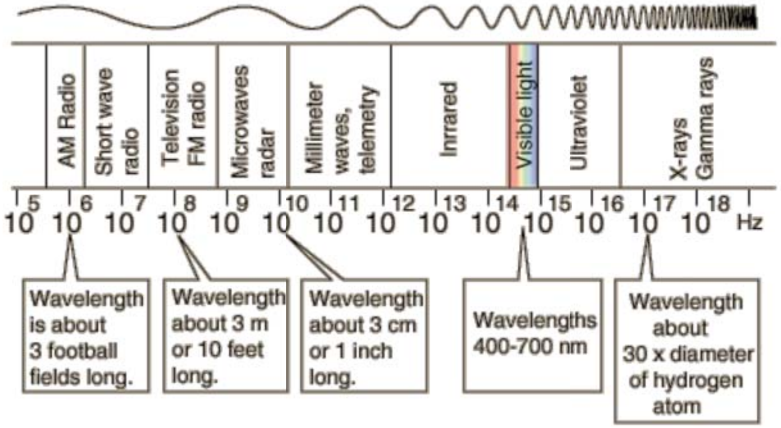
☐ FAIR ☐

☐ POOR ☐

WRONG WAY

This scientific way of approaching the problem of poorly-fitted shoes eliminates guesswork. Now you can see for yourself!

X-rays are electromagnetic waves



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

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

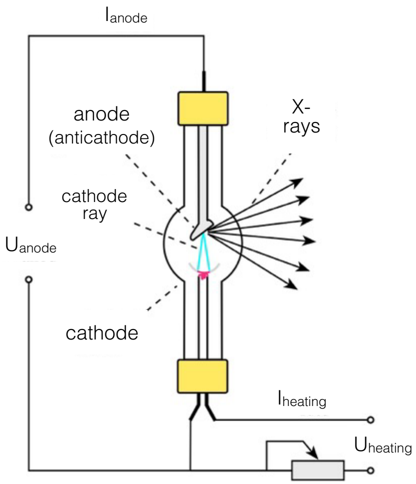
Generation of X-ray (non-conventional)

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



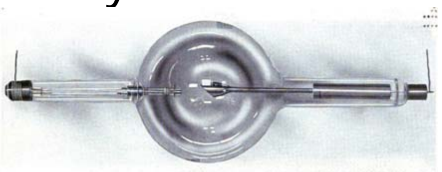
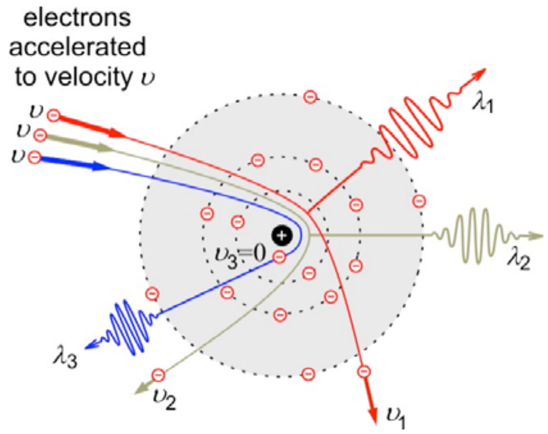


Photo of a Coolidge x-ray tube, from the early 1900s. The heated cathode is on the left, the anode target is on the right. The x-rays are emitted in a downward direction.

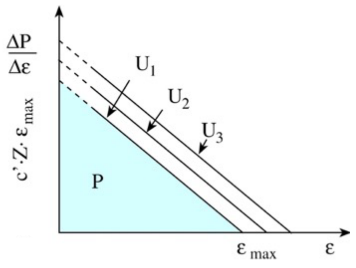
Rotating anode X-ray tube

"Bremsstrahlung"

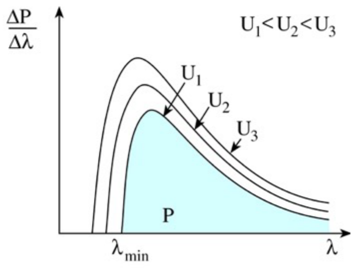


Electrons decelerate, thereby loose their kinetic energy, when interacting with the atoms of the anode ("braking radiation").

Spectrum of Bremsstrahlung



Continuous spectrum



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

Maximal photon energy (ε_{max})

h =Planck's constant; c = speed of light; e = charge of electron; eU_{anode} = work of acceleration

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

Limiting wavelength (λ_{min})
(Duane-Hunt Law)

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

Energy spectrum
(energy dependence of power)

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

Total power
(based on area of triangle)

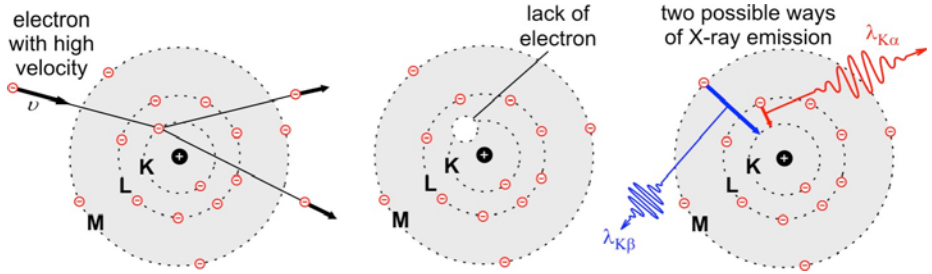
$$P_{tot} = C_{Rtg} \cdot I_{anode} \cdot U_{anode}^2 \cdot Z$$

Total power

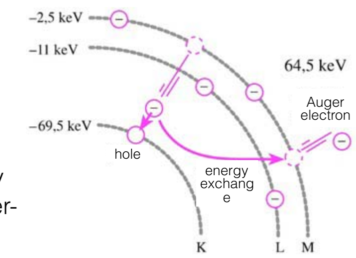
$$\eta = \frac{P_{tot}}{P_{in}} = \frac{C_{Rtg} \cdot I_{anode} \cdot U_{anode}^2 \cdot Z}{I_{anode} \cdot U_{anode}} = C_{Rtg} \cdot U_{anode} \cdot Z$$

Efficiency <1%

Characteristic X-ray

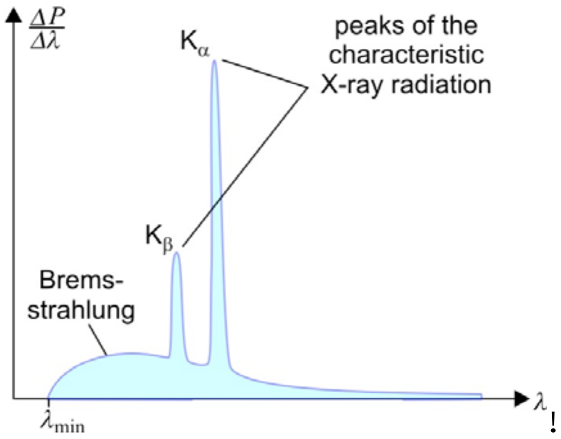


Knocked-out inner-shell electron is replaced by one on a higher-energy shell



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

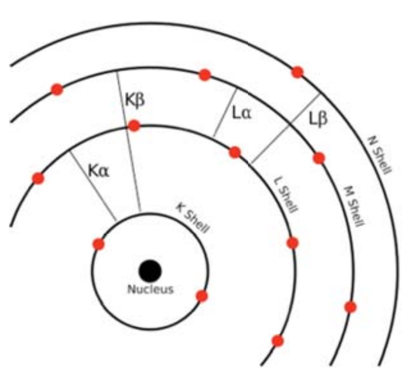
Spectrum of characteristic X-ray



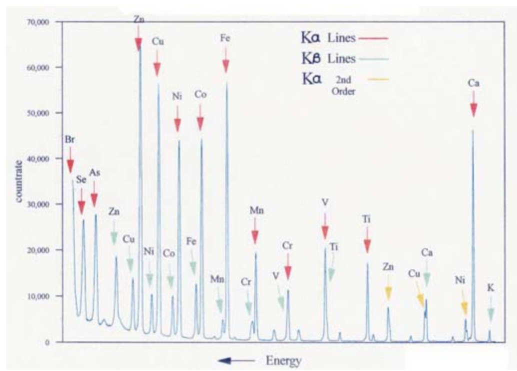
Line spectrum

X-ray spectrum characterizes the element

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

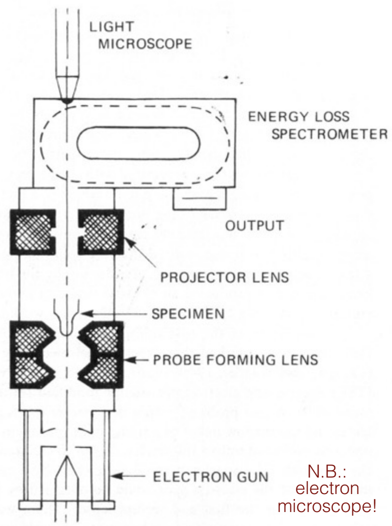


Electronic transitions in a calcium atom.



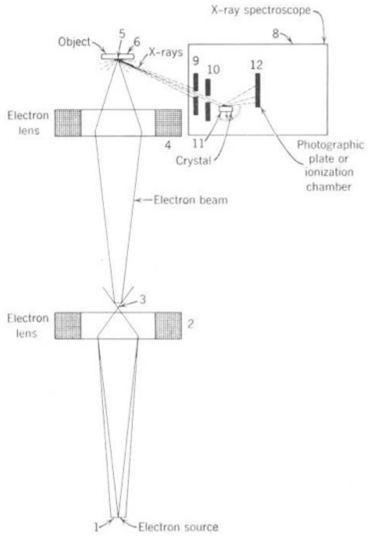
Energy dispersive X-ray fluorescence spectrum.

Detection of characteristic X-ray



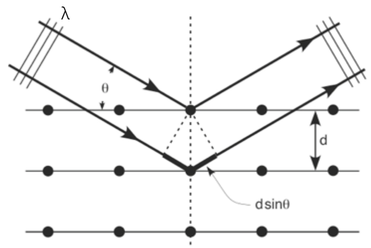
N.B.: electron microscope!

Electron probe microanalyzer

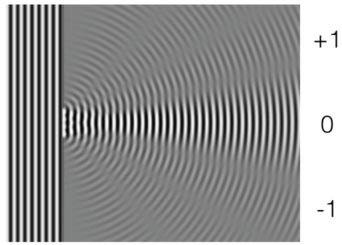


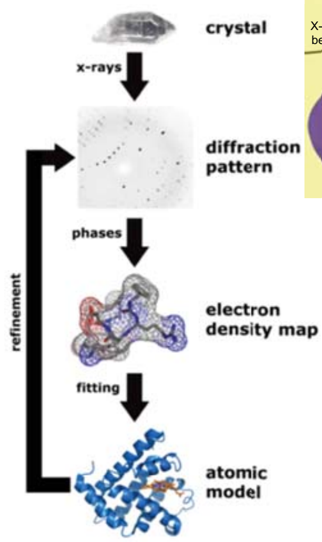
X-ray spectroscope

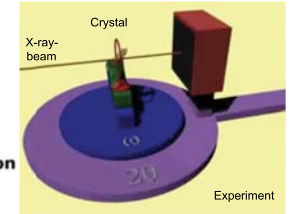
X-ray diffraction

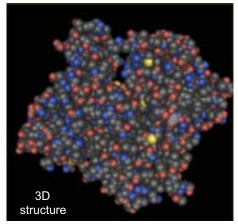


Condition of constructive interference: $2d\sin\theta = n\lambda$

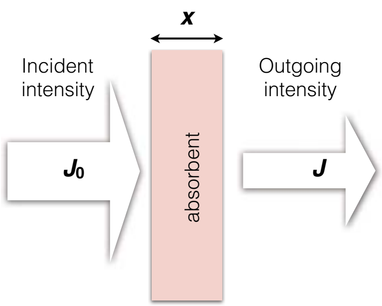




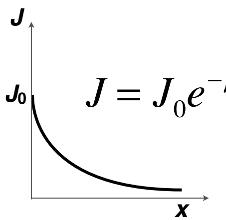




X-ray absorption



Exponential attenuation principle

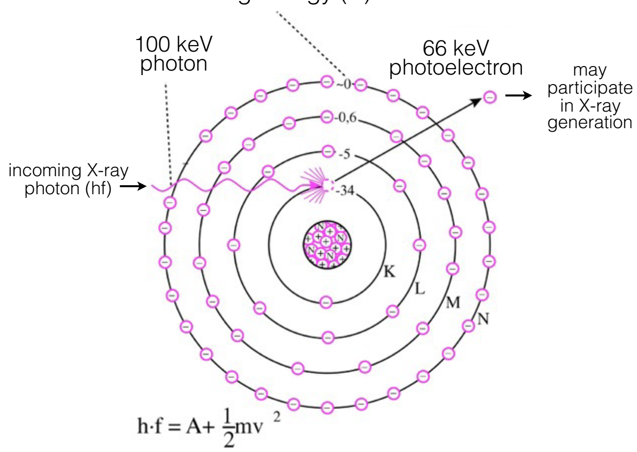


$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

μ=attenuation coefficient
μ_m=mass attenuation coefficient (cm^2/g)
ρ=density (g/cm^3)

X-ray photoeffect

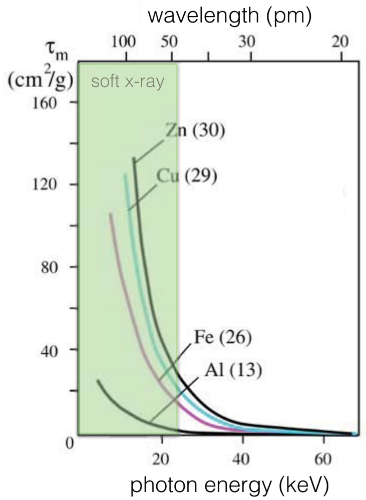


Main effect in diagostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

Photoeffect attenuation depends strongly on atomic number



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

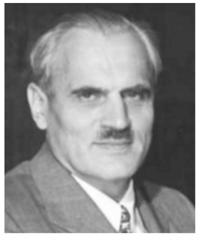
For multi-component system:
"effective atomic number" (Z_{eff})

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

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

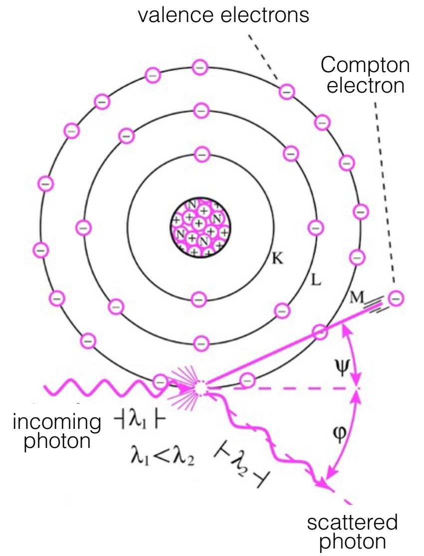
Material	Z_{eff}
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

Compton scatter

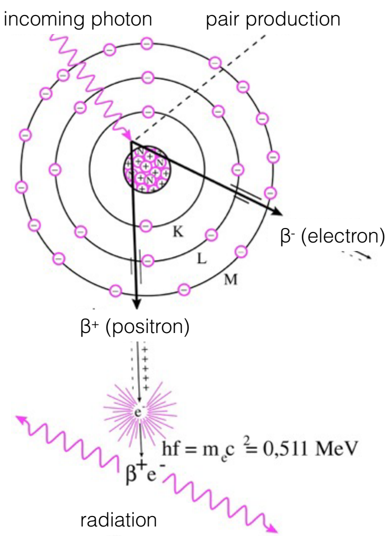


Arthur Holly
Compton
(1892-1962)

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



Pair production



(relevant only in therapeutic x-ray)

Energy balance:

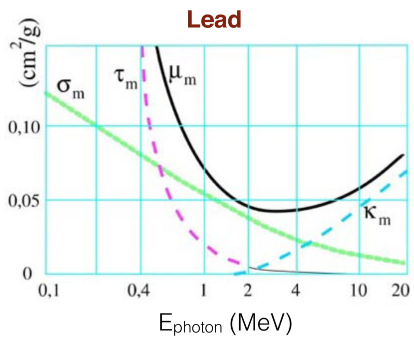
$$hf = 2m_e c^2 + 2E_{kin}$$

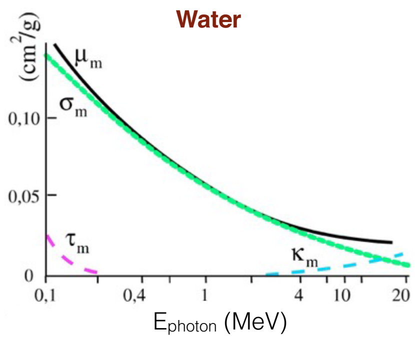
m_e=mass of electron
c=speed of light

Pair production 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

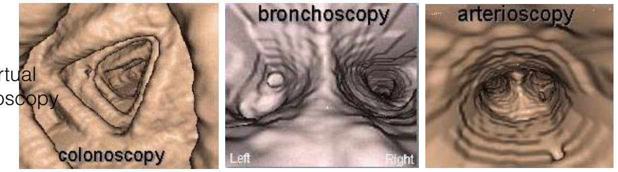
Mechanism	Variation of μ_m with E	Variation of μ_m with Z	Energy range in tissue
Rayleigh	~ 1 / E	$\sim Z^2$	1 - 30 keV
photoelectric	$\sim 1 / E^3$	$\sim Z^3$	10 - 100 keV
Compton	falls gradually with E	independent $\sim Z$	0.5 - 5 MeV
pair production	rises slowly with E	$\sim Z^2$	> 5 MeV

Main contrast mechanism in diagnostic X-ray: photoelectric effect ($\sim Z^3$)

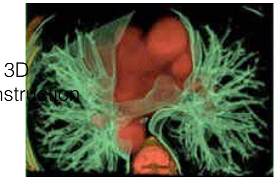
Trends of X-ray applications

Spiral CT

Virtual endoscopy



3D reconstruction



Angiography