X-ray

Generation, properties

X-ray

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

Sitzungs-Berichte
der
Physikalisch-medicinischen Gesellschaft
zu
WÜRZBURG.

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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.

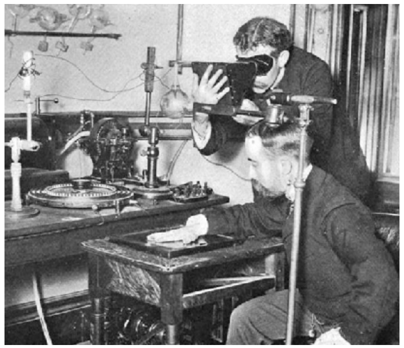
2. Das an dieser Erscheinung zunächst Auffallende ist, dass durch die schwarze Cartonhülse, welche keine sichtbaren oder ultravioletten Strahlen des Sonnen- oder des elektrischen Bogenlichtes durchlässt, ein Agens hindurchgeht, das im Stande ist, lebhafte Fluorescenz zu erzeugen, und man wird deshalb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

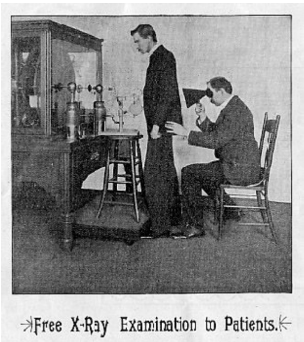
Man findet bald, dass alle Körper für dasselbe durchlässig sind, aber in sehr verschiedenem Grade. Einige Beispiele führe ich an. Papier ist sehr durchlässig:[1]) hinter einem eingebun-

[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

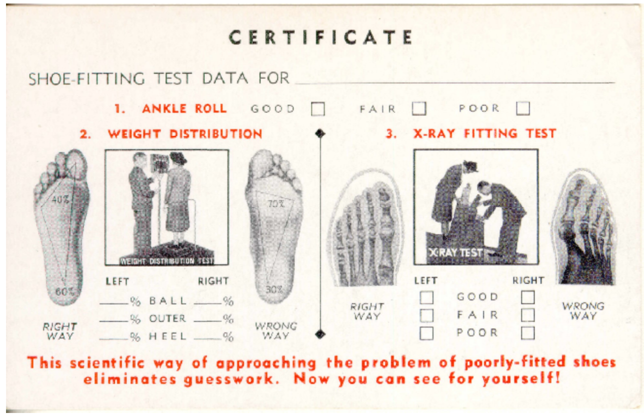




Late 1890s

I. World war

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!

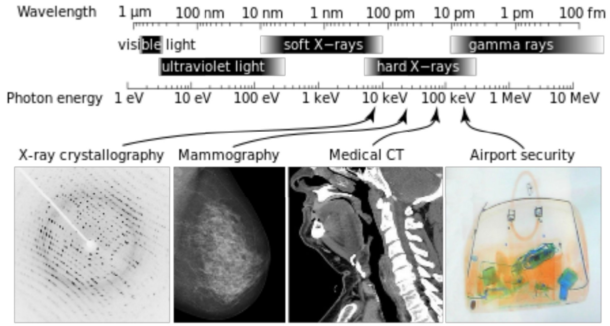
Medical diagnostics

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

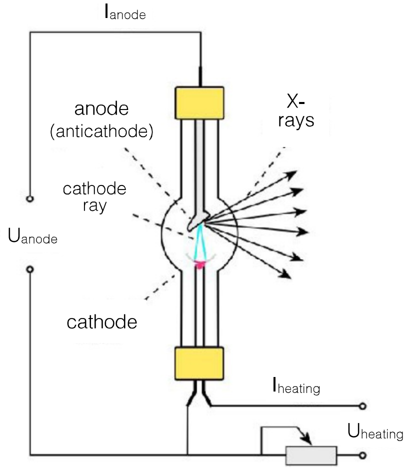
Generation of X-ray (non-conventional)

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



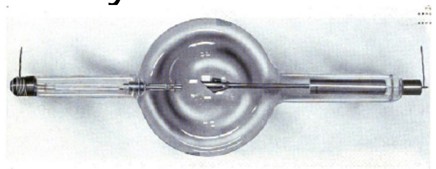
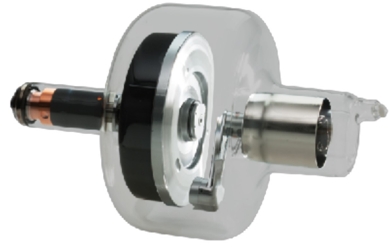
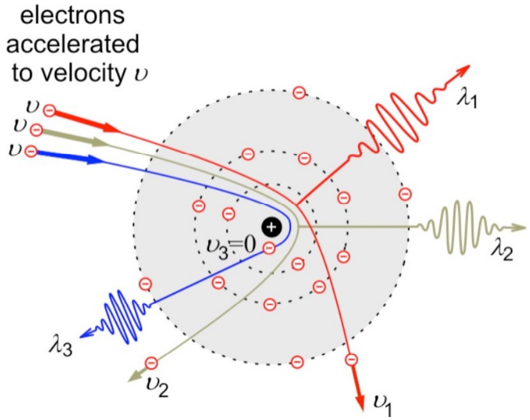


Photo of a Coolidge x-ray tube, from the early 1900s. The heated cathode is on the left, the anode target is on the right. The x-rays are emitted in a downward direction.



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

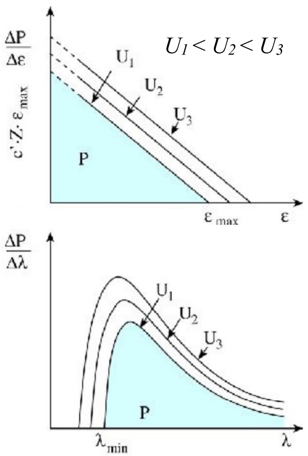
"Bremsstrahlung"



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

Spectrum of Bremsstrahlung

Continuous spectrum



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

Maximal photon energy (ε_{max})

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

e: electron's charge;
U_{anode}: accelerating voltage;
eU_{anode}: acceleration work;
h: Planck's constant;
f_{max}: limiting frequency

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

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

N.B.: Limiting wavelength is inversely proportional to avvelerating voltage.

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

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

Energy spectrum
(energy dependence of power)

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

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

Total power (P_{tot})
(based on the area of the triangle)

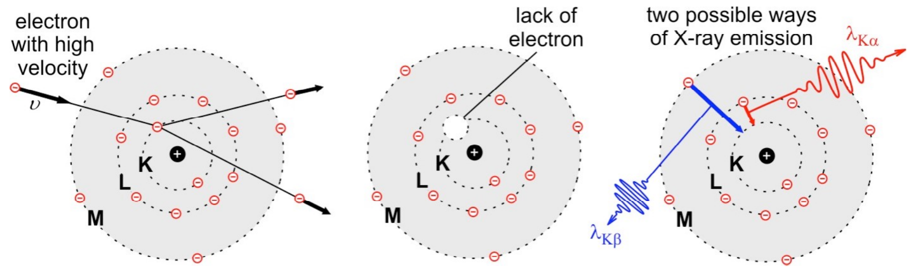
C_{Rtg}: coefficient (1.1x10^{-9} V^{-1});
I_{anode}: anode current (number of electrons hitting the anode per unit time);
Z: atomic number of the anode atoms

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

Efficiency (η)

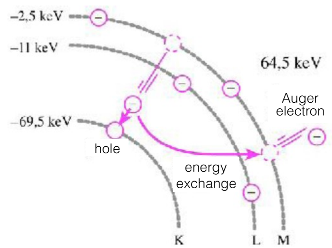
P_{in}: invested power
N.B.: Typically, $\eta < 1\%$.

Characteristic X-ray

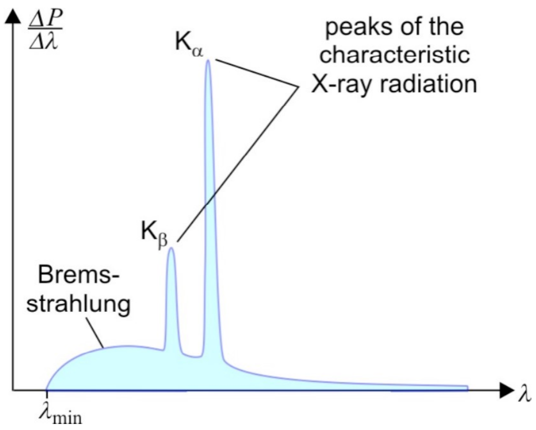


Knocked-out inner-shell electron is replaced by one on a higher-energy shell

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



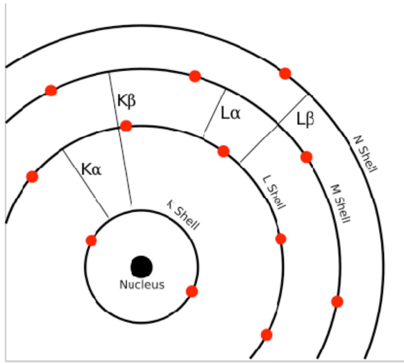
Spectrum of characteristic X-ray



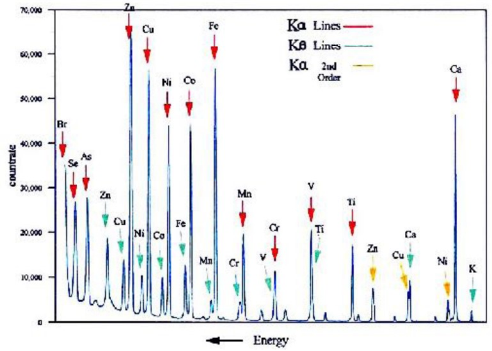
Line spectrum

X-ray spectrum characterizes the atomic composition

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



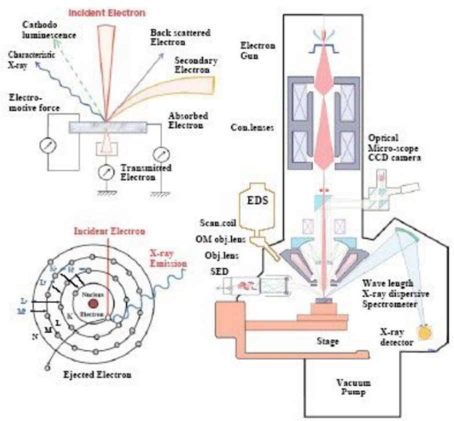
Electronic transitions in a calcium atom.



Energy dispersive X-ray fluorescence spectrum.

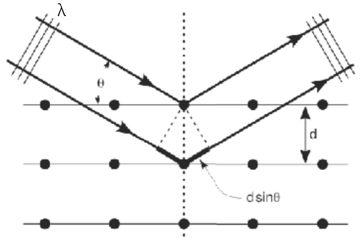
Detection of characteristic X-ray

Electron probe microanalyzer

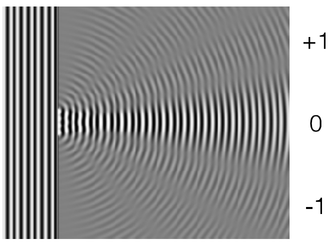


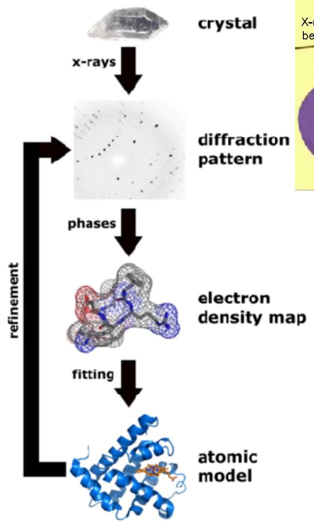
N.B.: electron microscope!

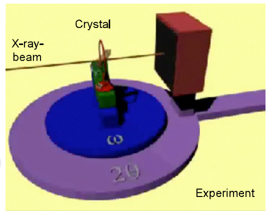
X-ray diffraction

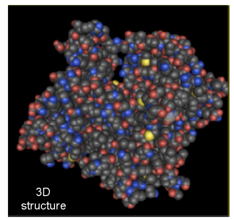


Condition of constructive interference: $2d\sin\theta = n\lambda$

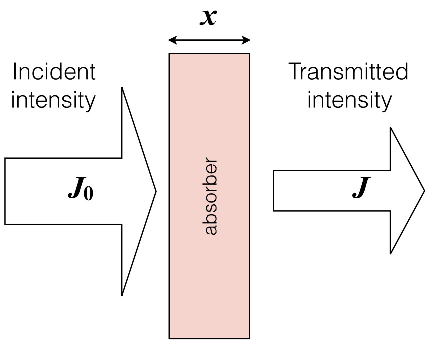




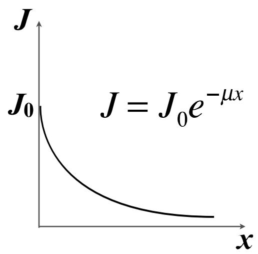




X-ray absorption



Exponential attenuation principle



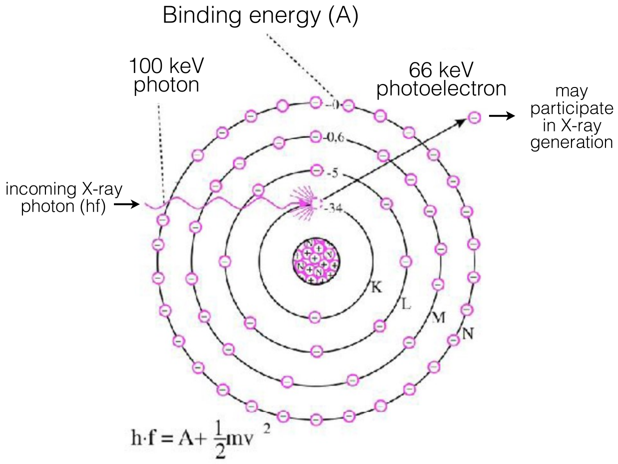
$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

μ : attenuation coefficient
μ_m : mass attenuation coefficient (cm²/g)
ρ : density (g/cm³)

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

X-ray photoeffect



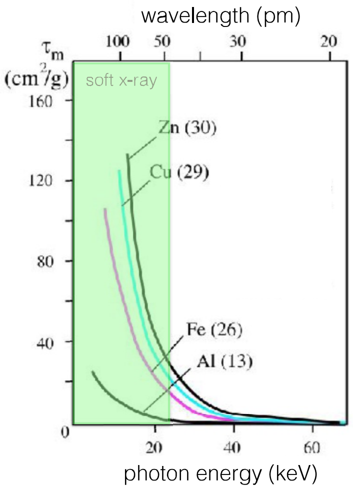
Main effect in diagostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

τ_m=photoeffect mass attenuation coefficient
ρ=density

Photoeffect attenuation depends strongly on the atomic number



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

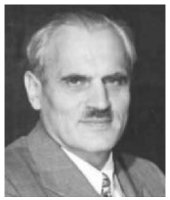
For multi-component system: "effective atomic number" (Z_{eff})

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

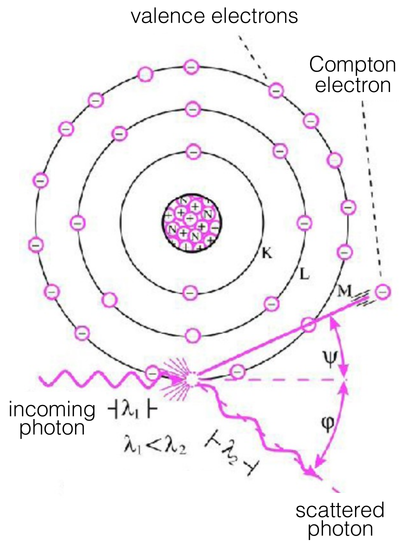
ε=photon energy
Z=atomic number
w=mole fraction
n=number of components

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

Compton scatter



Arthur Holly Compton (1892-1962)



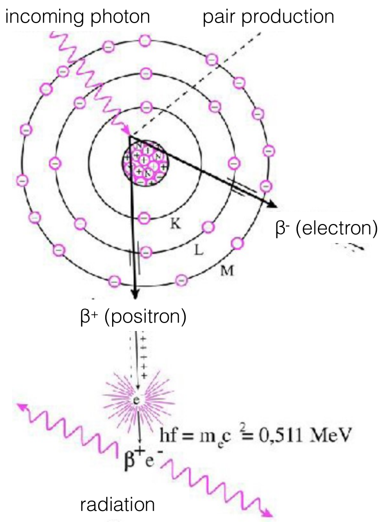
$$hf = A + hf_{scatt} + E_{kin}$$

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

Compton-effect attenuation coefficient:

$$\sigma = \sigma_m \rho$$

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

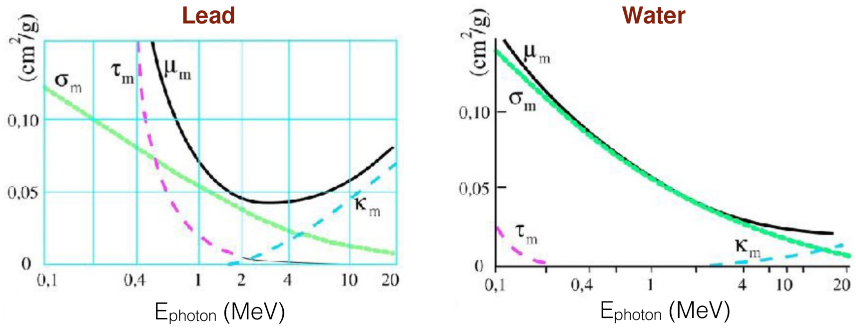
Pair production attenuation coefficient:

$$\kappa = \kappa_m \rho$$

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

Attenuation mechanisms

Dependence on photon energy and material



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

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	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	~ 1 / ε	$\sim Z^2$	1 - 30 keV
Photoeffect	$\sim 1 / \varepsilon^3$	$\sim Z^3$	10 - 100 keV
Compton scatter	falls gradually with ε	~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 ($\sim \rho$)