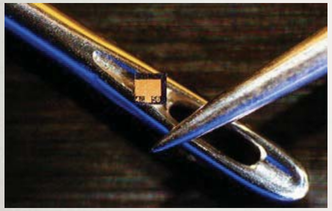
Laser

Basic principles, characteristics, applications

Lasers are everywhere



5 mW diode laser
few mms

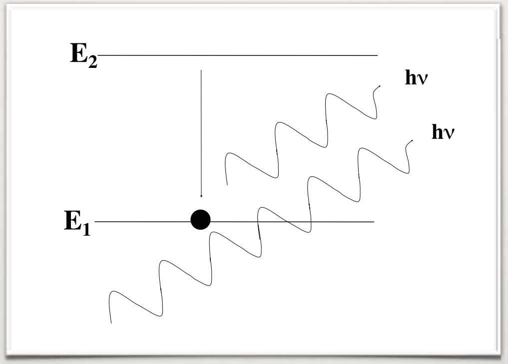
Terawatt NOVA laser - Lawrence Livermore Laboratories
Size of a football field

Laser

1. What is laser?
2. Short laser history
3. Foundations of laser function
4. Properties of laser light
5. Types of lasers
6. Biomedical applications of lasers

Laser:

"Light Amplification by Stimulated Emission of Radiation"



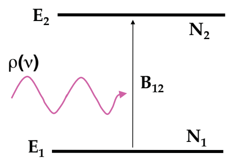
MASER: Microwave Amplification by Stimulated Emission of Radiation

Laser history in a nutshell

- **1917** - *Albert Einstein:* theoretical prediction of stimulated emission.
- **1946** - G. Meyer-Schwickerather: first eye surgery with light.
- **1950** - *Arthur Schawlow and Charles Townes:* emitted photons may be in the visible range.
- **1954** - *N.G. Basow, A.M. Prochorow, and C. Townes:* ammonia maser
- **1960** - *Theodore Maiman:* first laser (ruby laser)
- **1964** - *Basow, Prochorow, Townes (Nobel-prize):* quantum electronics
- **1970** - *Arthur Ashkin:* laser tweezers
- **1971** - *Dénes Gábor (Nobel-proze):* holography
- **1997** - *S. Chu, W.D. Phillips and C. Cohen-Tanoudji (Nobel-prize):* atom cooling with laser.
- **2013, october 8:** *NIF* (National Ignition Facility, USA): launching nuclear fusion with 192 laser beams, positive energy balance.

Principles of laser I.
Stimulated emission

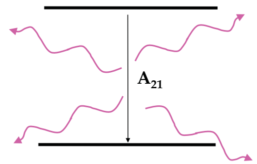
1. Absorption



Frequency of transition:
$n_{12}=N_1B_{12}\varrho(\nu)$

$\Delta E= E_2-E_1=h\nu$
energy quantum is absorbed.

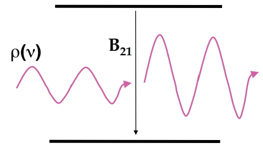
2. Spontaneous emission



Frequency of transition:
$n_{21}=N_2A_{21}$

E_2-E_1 photons travel independently in all directions.

3. Stimulated emission



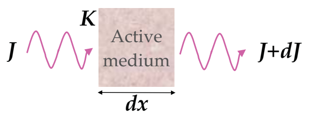
Frequency of transition:
$n_{21}=N_2B_{21}\varrho(\nu)$

In the presence of exernal field. Field energy is increased. Phase, direction and frequency of emitted and external photons are identical.

Explanation: two-state atomic or molecular system.
E_1, E_2 : energy levels, $E_2>E_1$
$\varrho(\nu)$: spectral energy density of external field.
N_1, N_2 : number of atoms or molecules on the given energy level.
B_{12}, A_{21}, B_{21}: transition probabilities (Einstein coefficients), $B_{12} = B_{21}$

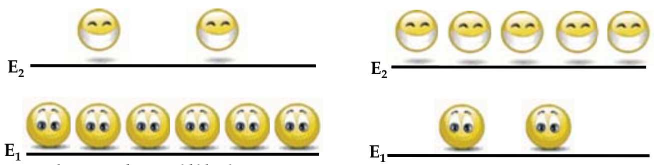
Principles of laser II.
Population inversion

Light amplification depends on the relative population of energy levels.

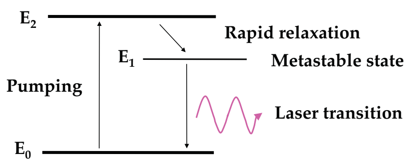


$$dJ=JK(N_2-N_1)dx$$

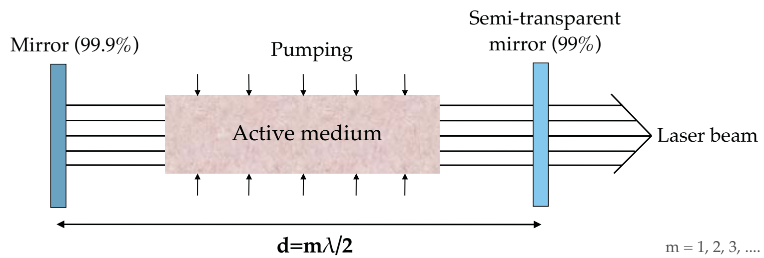
J = intensity
K = constant
x = distance travelled within medium
N_1, N_2 = number of atoms on the E level



- Population inversion only in multiple-state systems!
- Pumping: electrical, optical, chemical energy



Principles of laser III.
Optical resonance

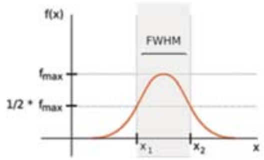


Resonator:
- two parallel (or concave) mirrors
- part of the exiting light is coupled back into the medium
- positive feedback -> self-excitation -> resonance

Optical switch in the resonator: Q-switch, pulsed mode

Properties of laser light I.

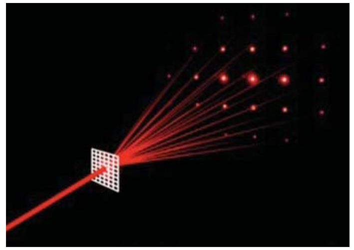
1. **Small divergence**
   Parallel (collimated) beam
2. **Large power**
   In continuous (CW) mode, tens, hundreds of W (e.g., CO_2 laser)
   In Q-switched mode, momentary power is enormous (GW)
   Because of small divergence, large spatial power density.
3. **Small spectral bandwidth**
   "Monochromaticity"
   Large spectral energy density



4. **Often polarized**
5. **Possibility of extremely short pulses**
   ps, fs

Properties of laser light II.

6. **Coherence**
   phase identity, interference tendency
   temporal coherence (phase identity of photons emitted at different times)
   spatial coherence (phase identity across beam diameter)



Application: holography

Types of lasers

Based on active medium:

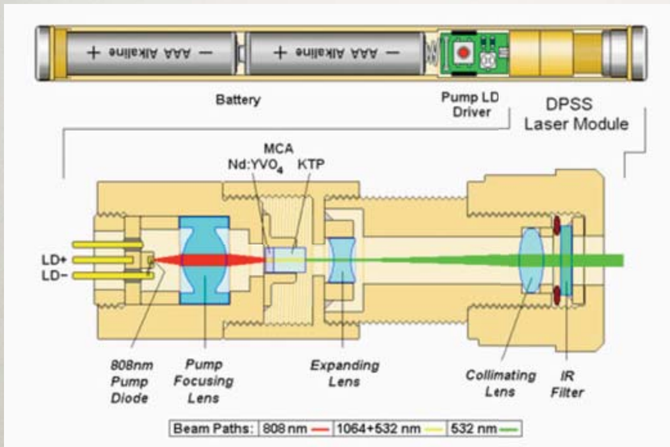
1. Solid state lasers
Metal doping in crystals or glasses; Ruby, Nd-YAG, Ti-sapphire
Red-infrared spectral range; CW, Q-switched mode, large power

2. Gas lasers
Best known: *He-Ne laser* (10 He/Ne). Small energy, wide use
CO_2 laser: CO_2-N_2-He mixture; λ~10 μm; Huge power (100 W)

3. Dye lasers
Dilute solution of organic dyes (e.g., rhodamine, coumarine); Pumped by another laser.
Large power (Q-switched mode); Tunable

4. Semiconductor lasers
On the boundary of p- and n-type doped semiconductors.
No need for resonator mirrors (total internal reflection)
Red, IR spectral range. Huge CW power (up to 100W)
Beam characteristics are not very good. Wide use because of small size.

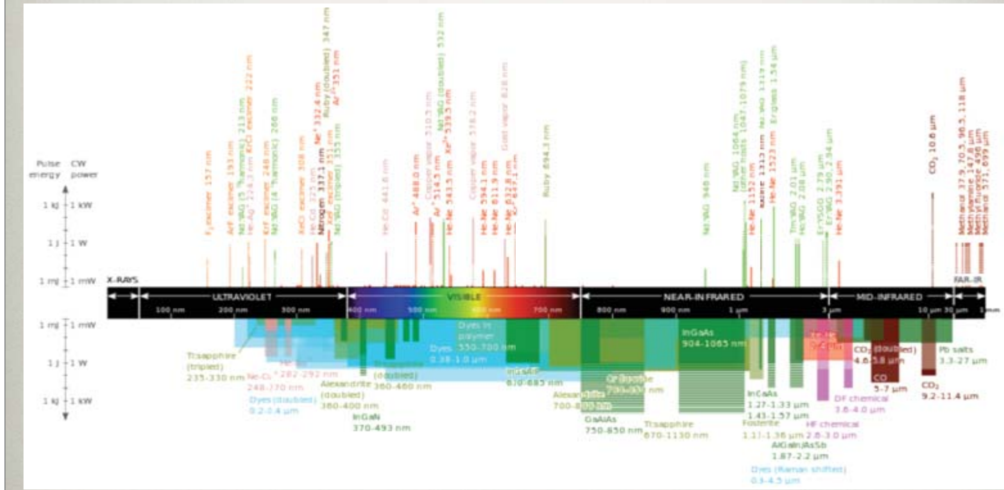
The green laser pointer



Steps:
1. Diode laser (808 nm) pumps
2. Solid state laser (neodimium-yttrium-vanadate) generates 1064 nm light
3. KTP (potassium titanyl phosphate) crystal doubles frequency (halves wavelength): 532 nm (green)

*Notes:
DPSS: diode-pumped solid state
MCA: multiple crystal assembly
LD: laser diode

Lasers, spectral lines and bands



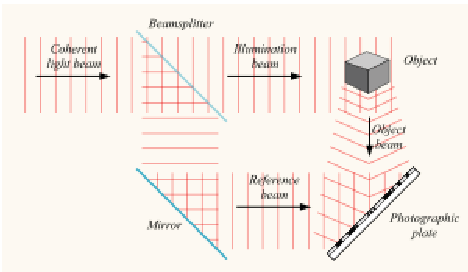
Application of lasers

based on power

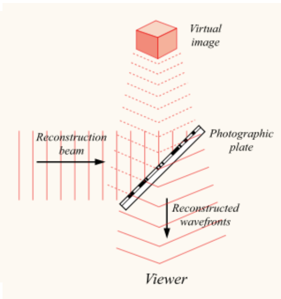
- 5 mW – CD-ROM drive
- 5–10 mW – DVD player or DVD-ROM drive
- 100 mW – high-speed CD-RW writer
- 250 mW – DVD-R writer
- 1–20 W – solid-state laser for micromachining
- 30–100 W – surgical CO_2 laser
- 100–3000 W – industrial CO_2 laser (laser cutter)
- 1 kW – 1 cm diode laser bar

Holography

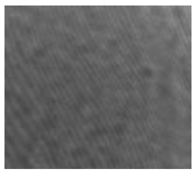
Dénes Gábor
(1900-1979)



Recording a hologram



Visualization of a hologram

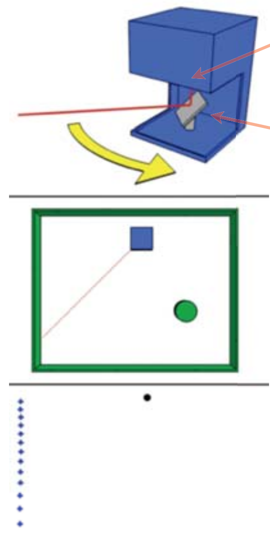


Surface of a hologram recording

Holograms

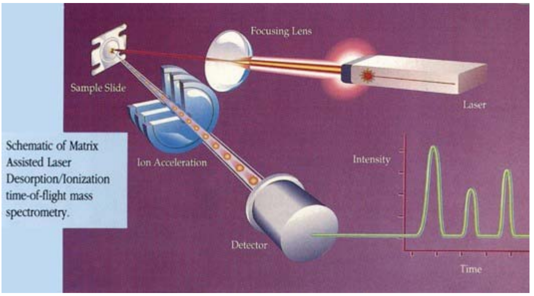
Speed measurement with laser

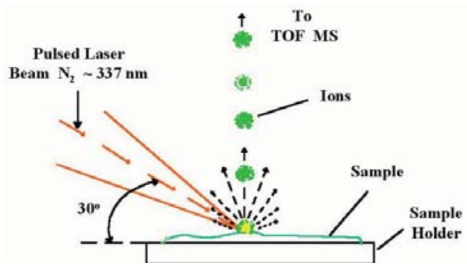
LIDAR: "Light Detection and Ranging"



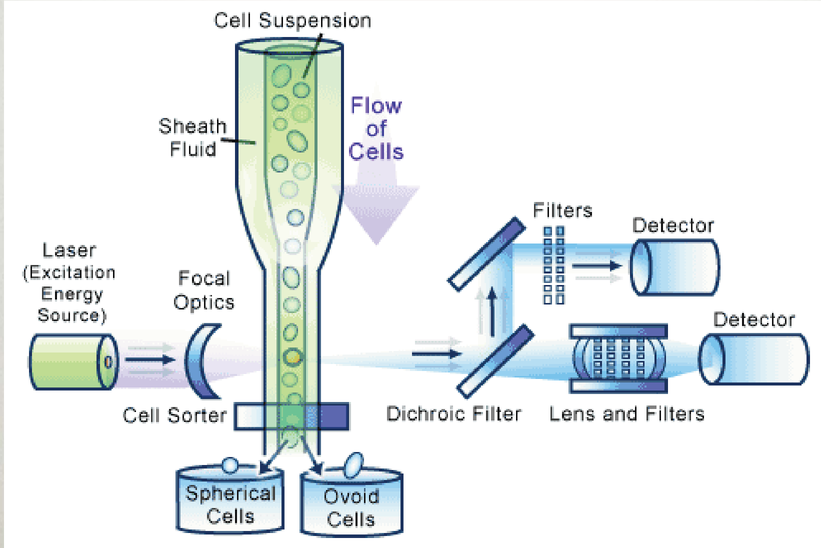
Recording:
reconstructed spatial arrangement.
In traffic speedometer:
100 pulses in 0.3 s

MALDI-TOF:
Matrix-assisted laser desorption/ionization time of flight mass spectrometry

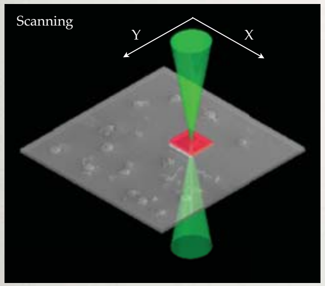


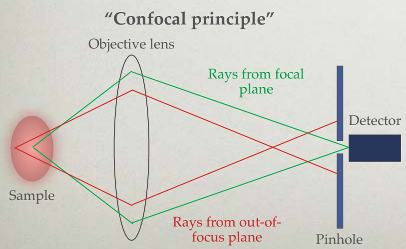


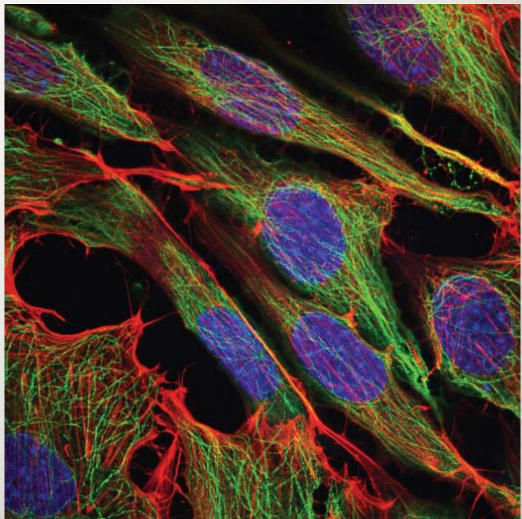
Fluorescence activated cell sorter (FACS)



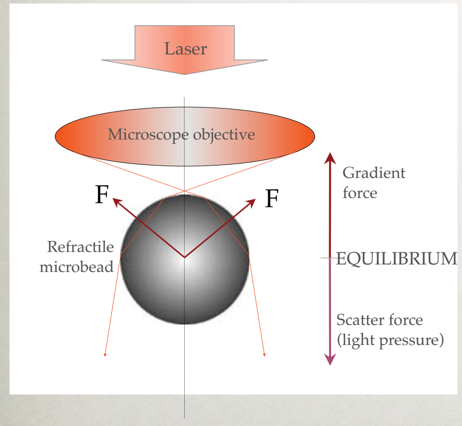
Laser scanning confocal microscope







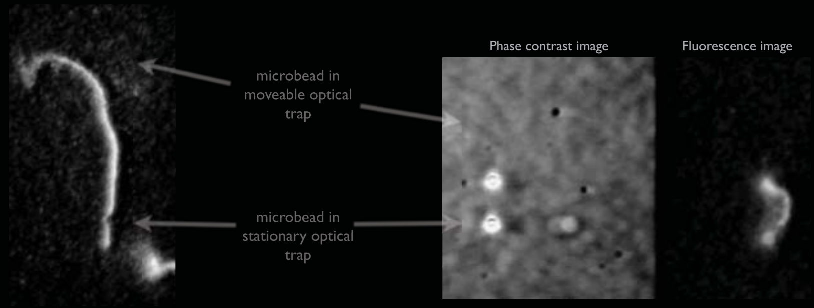
Optical tweezers



Tying a knot on a molecular filament with laser tweezers

Actin filament

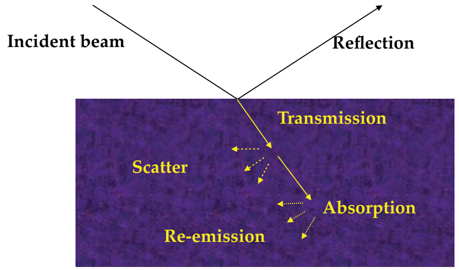
dsDNA



Biomedical applications of lasers I.

Principles:

1. Interaction of light with matter



2. Properties of laser beam:
Focusing, wavelength, power

3. Properties of biological tissue:
Transmittivity, absorbance, light-induced reactions

Biomedical applications of lasers II.

Surgical disciplines: "laser knife", coagulation, blood-less surgery. Tumor removal, tattoo removal. CO_2 and Nd:YAG lasers.

Dermatology: wide-spread uses (tattoo removal, naevus removal, etc.)

Dentistry: caries absorbs preferentially.

Photodynamic tumor therapy: laser acivation of photosensitive chemicals preferentially taken up by the tumor.

Opthalmology: Retina lesions, photocoagulation, glaucoma, photorefractive keratektomy (PRK).

Dermatological applications:
1. Considerations

1. Employed wavelengths:
- •Argon: 488 or 514.5 nm
- •Ruby: 694 nm
- •Alexandrite: 755 nm
- •Pulsed diode array: 810 nm
- •Nd:YAG: 1064 nm

2. Pulse width
3. Size of illuminated area (8-10 mm diameter)
4. Energy flux (J/cm^2)
5. Repetition rate (accumulation effects)
6. Epidermal cooling (gels, liquids, sprays, air)

Dermatological applications:
2. Hair removal

Phototricholysis, photoepilation

Basis: selective photothermolysis
selective absorption by chromophores

Employed chromophores:

1. Carbon (exogenous, carbon or graphite-containing creams)
2. Hemoglobin (endogenous)
3. Melanin (endogenous)

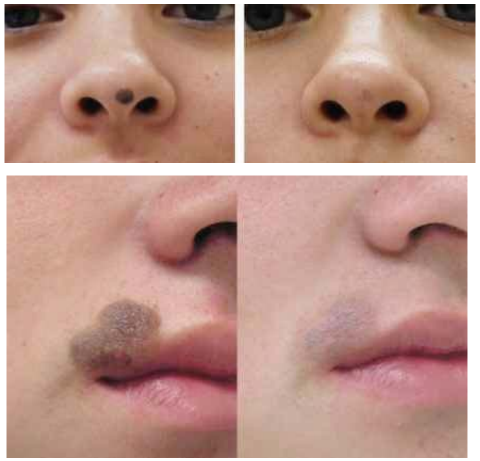
Before treatment | After treatment

Dermatological applications:
3. Tattoo removal

Q-switched Nd:YAG laser (1064 nm)

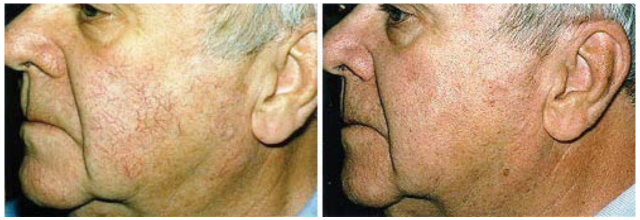
Before treatment | After treatment

Dermatological applications:
4. Naevus removal



Before treatment | After treatment

Dermatological applications:
5. Removal of superficial blood vessels, veins



Before treatment | After treatment

Before treatment | 2 years after treatment

Dermatological applications:
6. Bőr felületi módosítása ("resurfacing")

1993. Adrian
CO_2, Erbium:YAG laser

Wrinkle removal

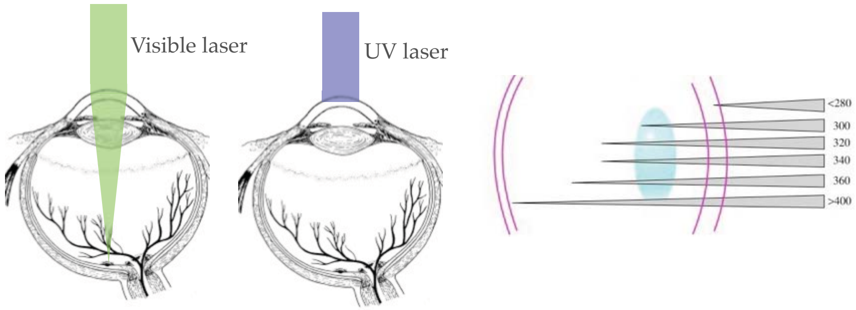
Sun damage

Rhinophyma

Systemic epidermal naevus

Ophthalmologic applications:
1. Principles

Transmittivity of optical media is wavelength-dependent



Ophthalmologic applications:
2. LASIK

"Laser-assisted In Situ Keratomileusis"
One type of refractive laser eye surgery

History:
Jose Barraquer, 1970: construction of a microkeratome, with which he was able to cut lines and lobes in the cornea with laser (keratomileusis).
Lucio Buratto (Italian) and Ioannis Pallikaris (Greek), 1990: combination of keratomileusis photorefractive keratectomy.
Thomas and Tobias Neuhann (Germany), 1991: automated microkeratome.

Steps:
1. Removal of contact lens (7-10 days prior to treatment)
2. Scanning the topography of the cornea with low-power laser.
3. Cutting and lifting a layer of the cornea with femtosecond laser.
4. Removal of material from the corneal stroma (few tens of microns). Excimer laser (193 nm).

Photorefractive keratektomy (PRK)
Another type of refractive laser eye surgery.
But, there is no layer removal. The surface restructuring is smaller. However, it is more painful, and regeneration is slower.

Photodynamic therapy

Photodynamic therapy (PDT):
Roswell Park Cancer Institute 1970's.

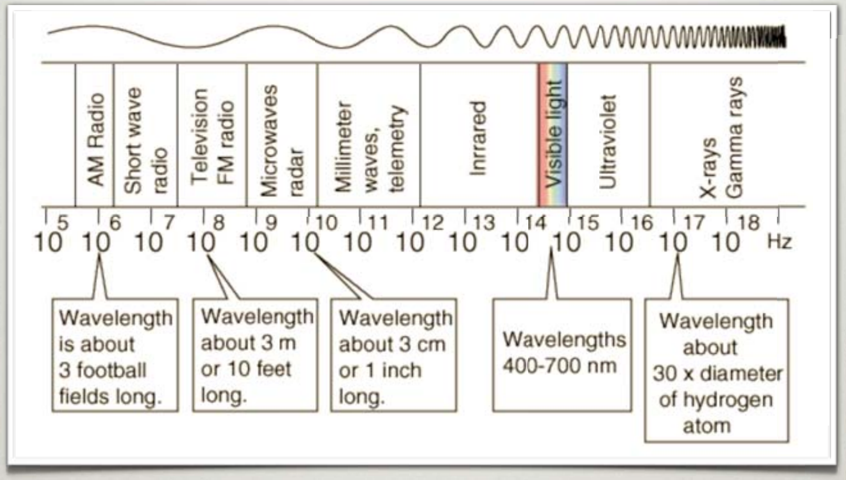
Three-component tumor therapeutic method:
1. Photosensitizing agent, 2. Light, 3. Oxygen.

Steps:
1. Administration of photosensitizing agent (aminolevulic acid, ALA).
2. Incubation for few hours. ALA is transformed into protoporhyrin IX.
3. Illumination of target area with diode laser (few minutes).
4. Protoporphyrin absorbs -> excited singlet state -> triplet state -> energy transfer with triplet oxygen -> excited, reactive oxygen -> tissue reaction
5. The illuminated area necrotizes in a few days.

X-RAY

Spectral features
Interaction with matter

X-rays are electromagnetic waves



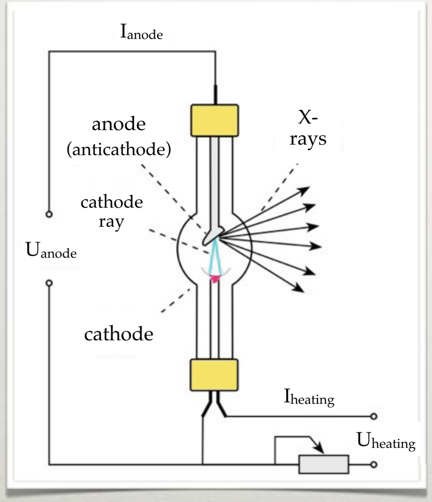
Wavelength 10 - 0.01 nm. ***Frequency*** 30×10^{15} - 30×10^{18} Hz. ***Energy*** 120 eV - 120 keV.

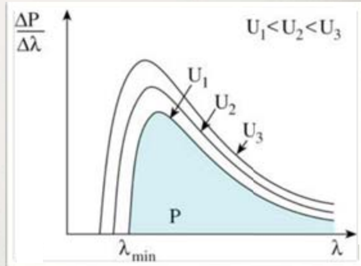
X-rays

- Generation of X-rays
- The X-ray spectrum
- X-ray microprobe analysis
- Interaction with matter 1: diffraction
- Interaction with matter 2: absorption
- X-ray absorption mechanisms:
  Photoelectric effect
  Compton scatter
  Pair production

Generation of X-ray

Wilhelm Konrad Röntgen (1845-1923)





Duane-Hunt formula:

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

h=Planck's constant
c=speed of light
e=elementary charge

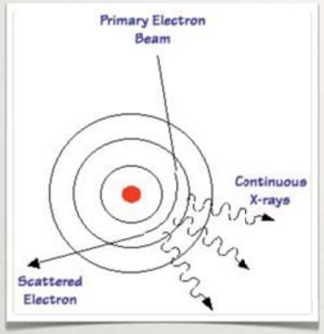
Generation of X-ray

Triboluminescence: light emission evoked by scratching or rubbing. Francis Bacon, 1605.

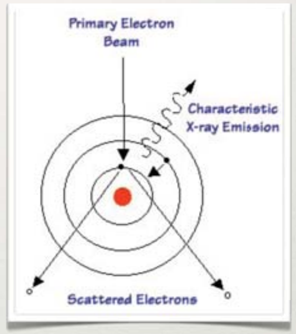
Peeling away sticky tape emits light...

...and X-rays. (Nature News, October 2008)

Mechanisms of X-ray generation



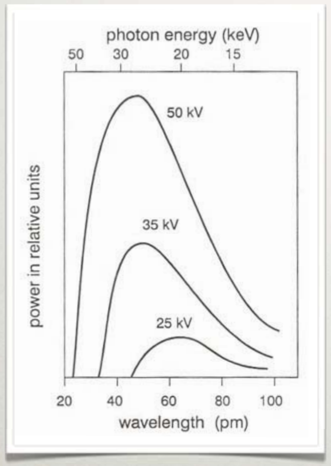
"Bremsstrahlung"
Breaking radiation
Deceleration radiation



Characteristic radiation
X-ray fluorescence

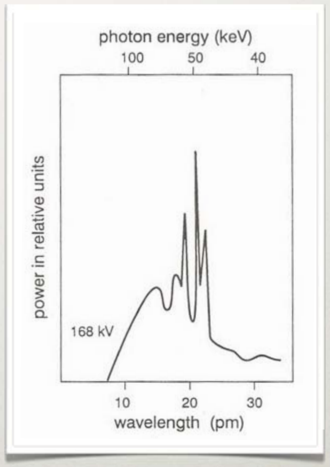
Spectral features of X-ray

"Bremsstrahlung"



Continuous spectrum

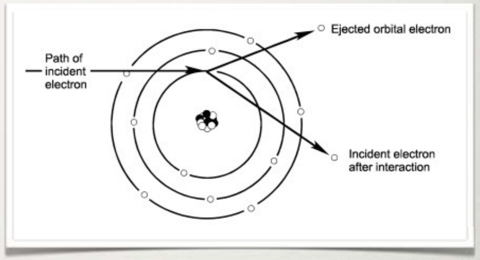
Characteristic radiation



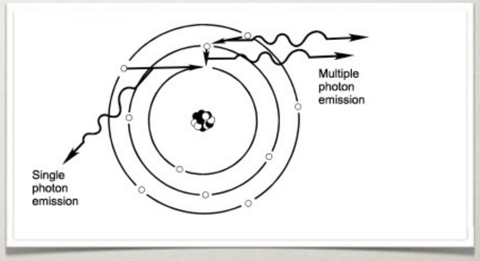
Linear spectrum

Generation of characteristic X-ray

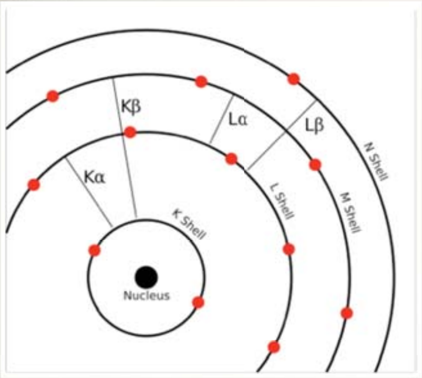
Step 1 - excitation:
ejection of orbital electron



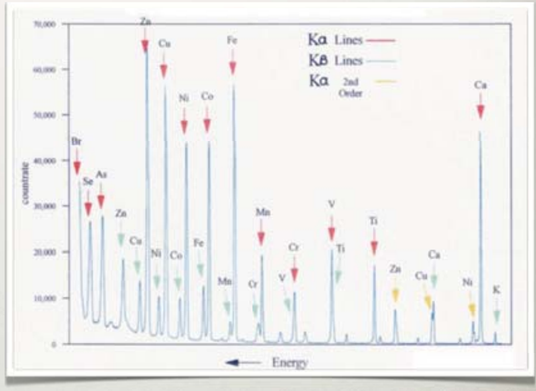
Step 2 - emission:
generation of characteristic photons



X-ray spectrum characterizes the element

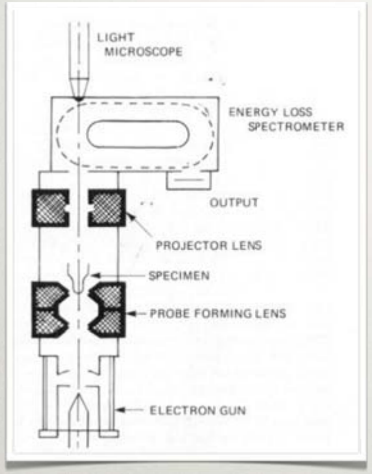


Electronic transitions in a calcium atom.

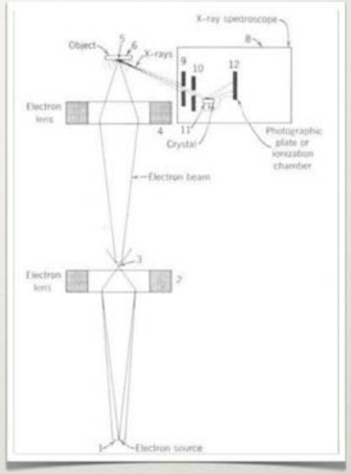


Energy dispersive X-ray fluorescence spectrum.

Detection of characteristic X-ray

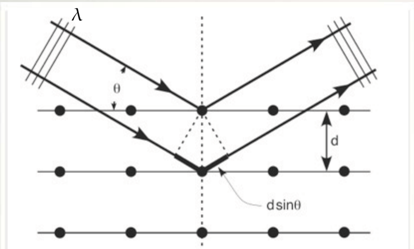


Electron probe microanalyzer

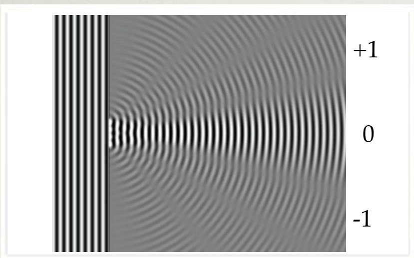


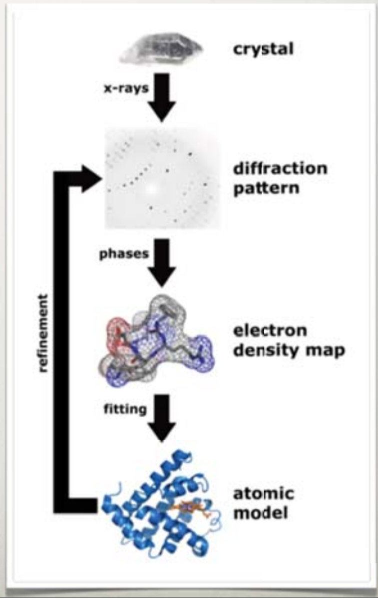
X-ray spectroscope

X-ray diffraction

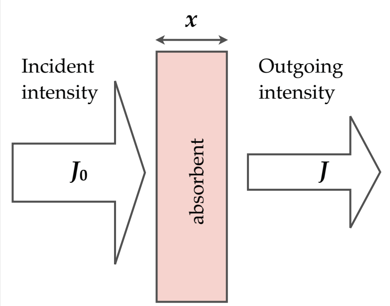


Condition of constructive interference: $2d\sin\theta = n\lambda$

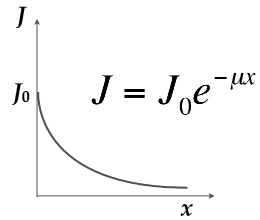




X-ray absorption



Exponential attenuation principle



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

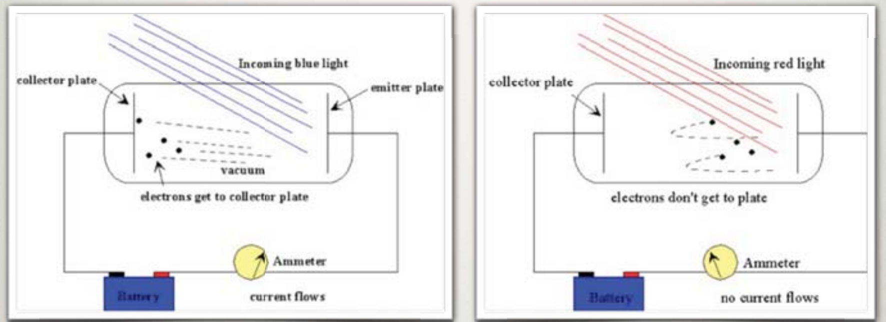
$$\mu = \mu_m \rho$$

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

X-ray absorption mechanisms

- Photoelectric effect (τ)
- Compton scatter (σ)
- Pair production (κ)

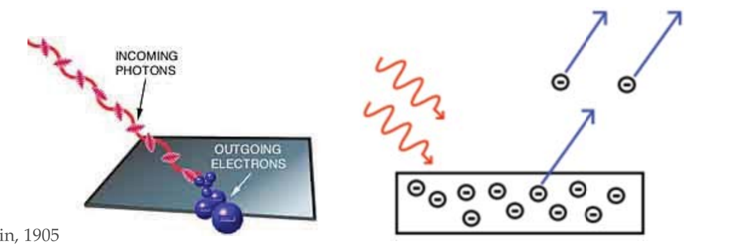
Photoelectric effect
The experiment



Wilhelm Hallwachs, 1888
Philipp Lenard, 1902

- Electron emission: instantaneous upon illumination
- Electron emission in BLUE light
- NO electron emission in RED light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

Photoelectric effect
The explanation



Einstein, 1905

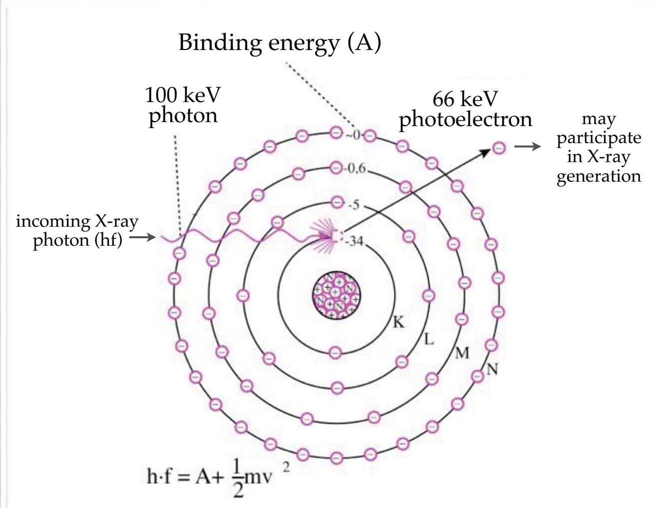
$$E_{kin} = hf - W_{ex}$$

E_{kin} = kinetic energy of escaped electron
h = Planck's constant ($6.62 \cdot 10^{-34}$ Js)
f = frequency of light
hf = light energy = light quantum, ***"photon"***
W_{ex} = work necessary for the escape of the electron from the atom

Photon:

- travels with the speed of light (c) in vacuum
- does not exist at rest, has momentum
- has no rest mass

X-ray photoeffect

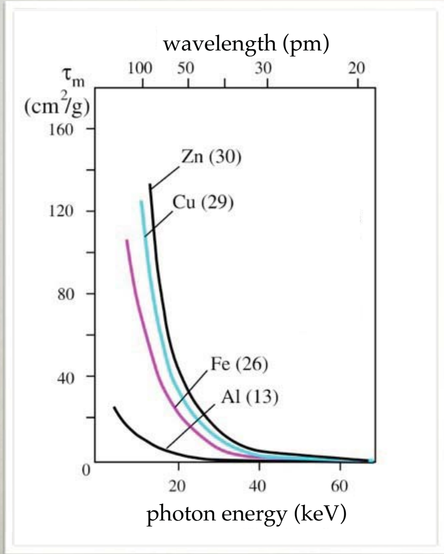


Main effect in diagostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

Photoeffect attenuation depends strongly on atomic number



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

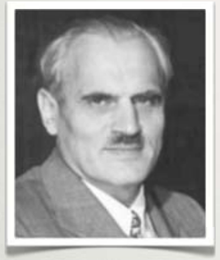
For multi-component system:
"effective atomic number" (Z_{eff})

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

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

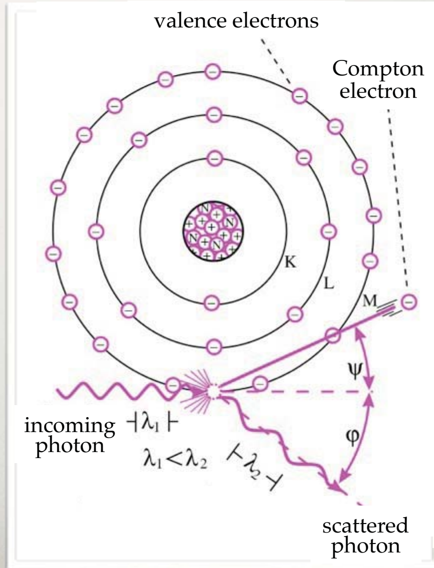
Material	Z_{eff}
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

Compton scatter

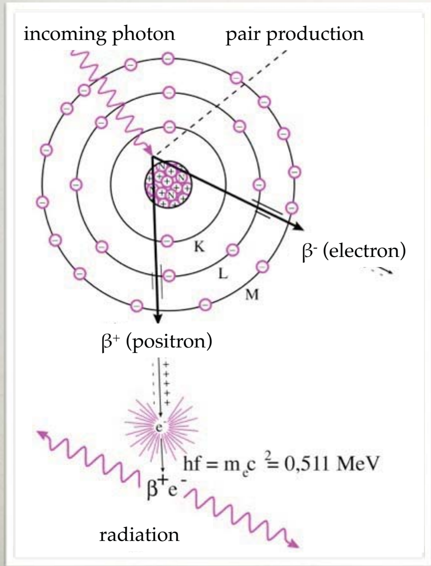


Arthur Holly Compton (1892-1962)

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



Pair production



Energy balance:

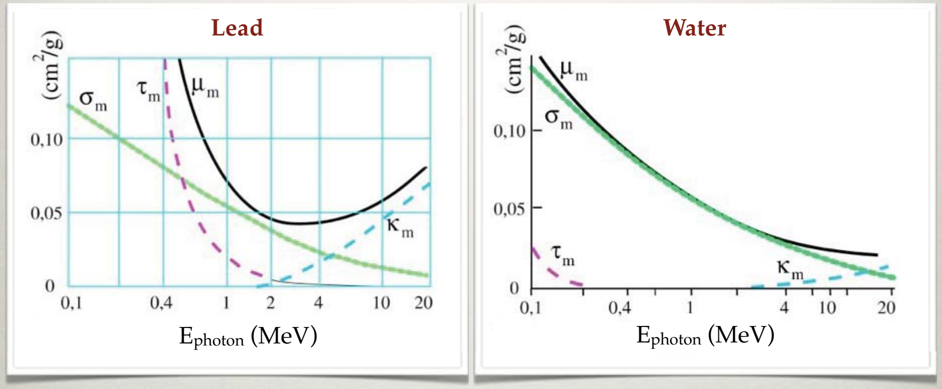
$$hf = 2m_e c^2 + 2E_{kin}$$

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 ~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 ($\sim Z^3$)