

EXPERIMENTAL METHODS TO STUDY BIOLOGICAL STRUCTURES II

LUMINESCENCE, LASER

MIKLÓS KELLERMAYER

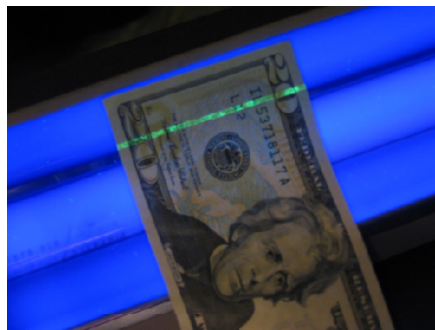
Definitions of luminescence

- Relaxation from excited state followed by light emission
- Radiation emitted by matter in excess of thermal emission
- “Cold light”
- Processes of fluorescence and phosphorescence

Emission by luminescence: everywhere



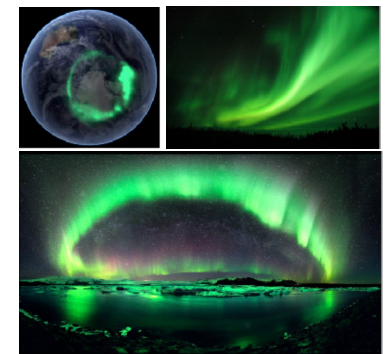
Photoluminescence



Luminescence everywhere



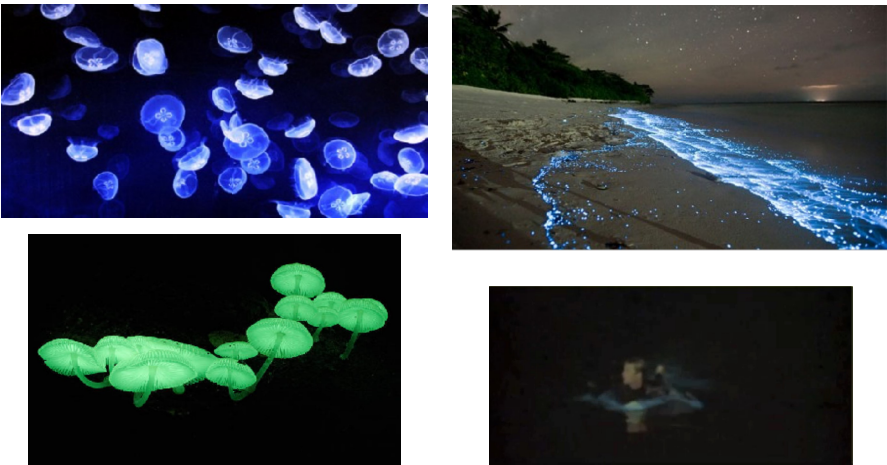
Display lights



Aurora borealis

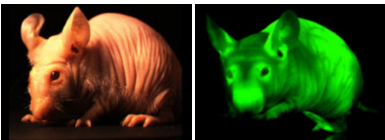
Radioluminescence

Luminescence everywhere

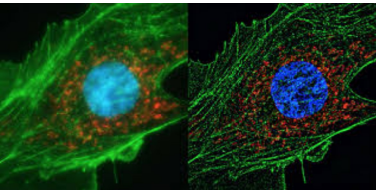


Bioluminescence

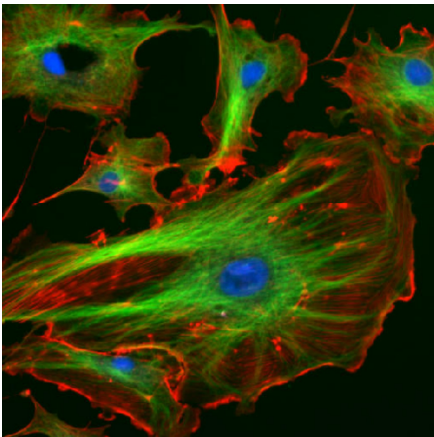
Luminescence everywhere



GFP-mouse (green nude mouse)



Superresolution microscopy (Nobel-prize 2014)



Epifluorescence microscopy (cytoskeletal system)

Fluorescence

Luminescence everywhere



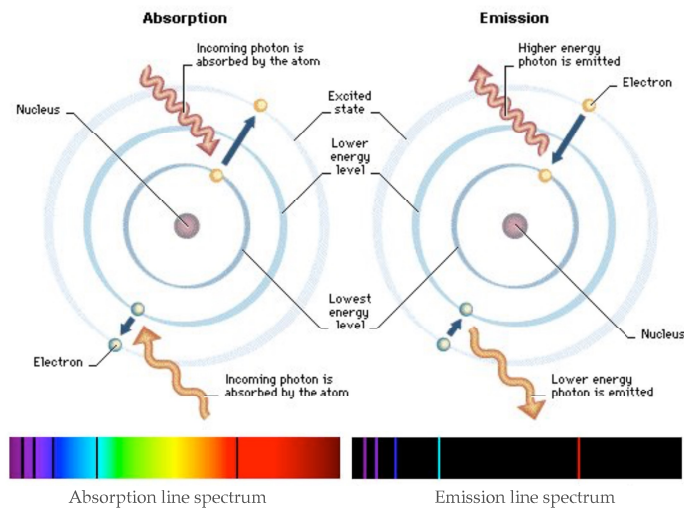
Bioluminescence
Firefly



Types of luminescence

| (a) Excitation Mode | Luminescence Type |
|--|------------------------------------|
| absorption of radiation (UV/VIS) | photoluminescence |
| chemical reaction | chemiluminescence, bioluminescence |
| thermally activated ion recombination | thermoluminescence |
| injection of charge | electroluminescence |
| high energy particles or radiation | radioluminescence |
| friction | triboluminescence |
| sound waves | sonoluminescence |
| (b) Excited State (Assuming Singlet State) | Luminescence Type |
| first excited singlet state | fluorescence, delayed fluorescence |
| lowest triplet state | phosphorescence |

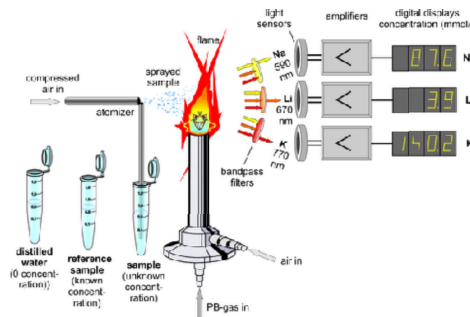
ABSORPTION AND EMISSION BY AN ATOM



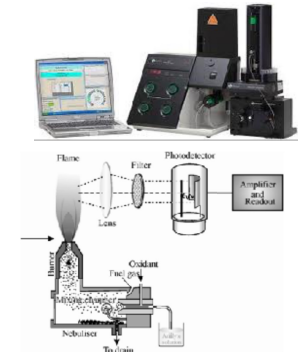
APPLICATION OF EMISSION SPECTROSCOPY

Flame photometry

Qualitative and quantitative analysis of alkali metals

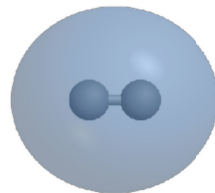


Clinical practice: determination of serum ions (Na^+ , K^+)



STATE OF A MOLECULE IS AFFECTED BY ITS MOTIONAL MODES

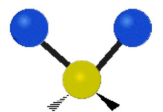
Molecule: atoms connected by chemical bonds
Simplest case: diatomic molecule (e.g., hydrogen molecule)



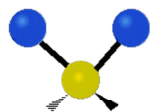
Molecules *vibrate* and *rotate*!

Vibration: periodic motion *along* the axis of the covalent bond
Rotation: periodic motion *around* the axis of the covalent bond

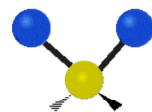
Examples of vibrational motion in the triatomic methylene group ($-\text{CH}_2-$):



Asymmetric stretching



Symmetric stretching



Scissoring

ENERGY OF A MOLECULE



Max Born
(1882-1970)



J. Robert Oppenheimer
(1904-1967)

Born-Oppenheimer approximation:

$$E_{total} = E_e + E_v + E_r$$

Important notions:

- Types of energy states are independent (not coupled)
- Energy states are non-continuous, but discrete
- Transition between states involves packets (quanta) of energy
- Scales of transition energies between different states are different:

$$E_e \sim 100 \times E_v \sim 100 \times E_r$$

$$\sim 3 \times 10^{-19} \text{ J } (\sim 2 \text{ eV}) > \sim 3 \times 10^{-21} \text{ J} > \sim 3 \times 10^{-23} \text{ J}$$

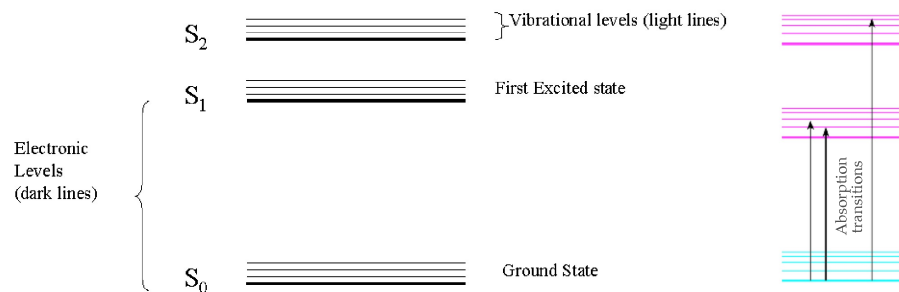
("Rule of thumb": ultraviolet > visible > infrared)

REPRESENTATION OF ENERGY STATES

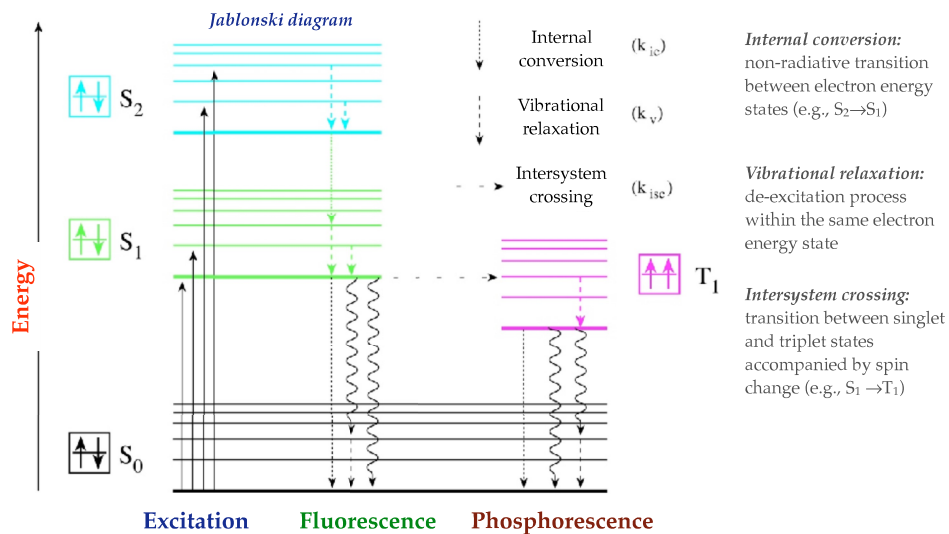
Jabłoński diagram:
illustrates the electronic states of a molecule and the transitions between them (with arrows)



Alexander Jabłoński
(1898-1980)



PROCESSES OF LUMINESCENCE



SPIN STATES

Wolfgang Pauli
(1900-1958)



Pauli's exclusion principle:

- Each quantum state can be occupied by a single electron.
- Within an atom there cannot be two electrons for which all four quantum numbers are identical.



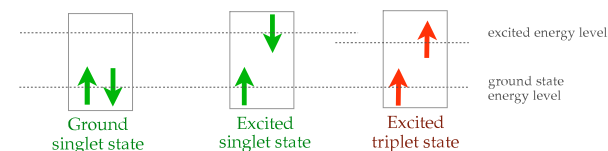
fully occupied subshell: spin pairing
(opposite-spin electrons pair)

Singlet and triplet states:

number of orientations of magnetic moment associated with net spin state (in magnetic field) = $2S+1 = 1$ (singlet) or 3 (triplet). (S = net spin, e.g., in fully occupied subshell $(+1/2)+(-1/2) = 0$)

S: singlet state: paired electrons with opposite spins, net spin (S) = 0, number of orientations ($2S+1$) = 1.

T: triplet state: there are identical spin-state electrons in the molecule, net spin = 1 (e.g., $(+1/2)+(+1/2) = 1$), number of orientations ($2S+1 = 2+1$) = 3.

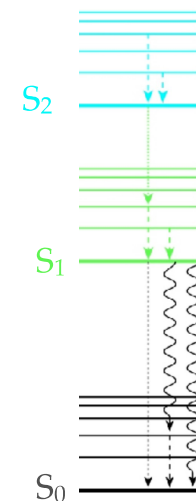


KASHA'S RULE

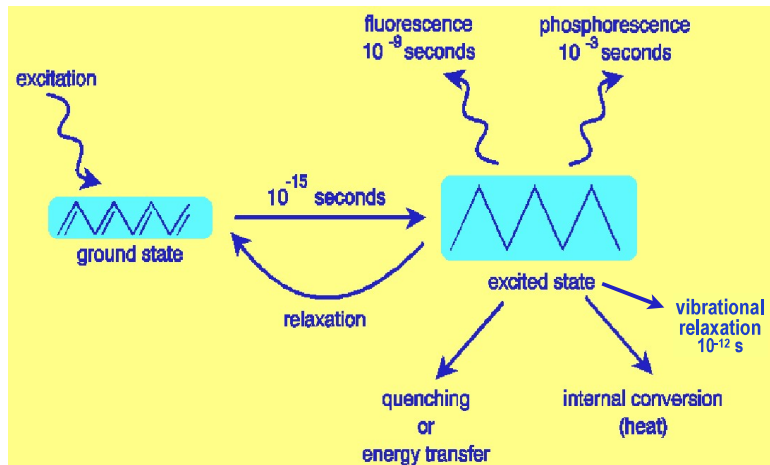
Photon emission (fluorescence or phosphorescence) occurs only from the lowest-energy excited electronic state (i.e., S_1 or T_1) of a molecule.



Michael Kasha (1920-)
American physicist

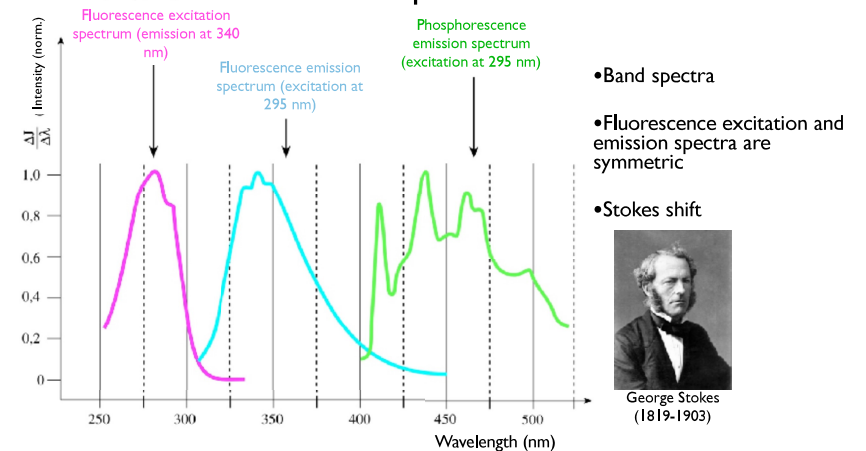


TIME SCALE OF TRANSITIONS



Characterization of luminescence

Luminescence spectra



Fluorescent dyes: "fluorophores"

By the specific attachment fluorophores, non-fluorescent molecules may also be studied (fluorescent labeling)

CHARACTERIZATION OF LUMINESCENCE II.

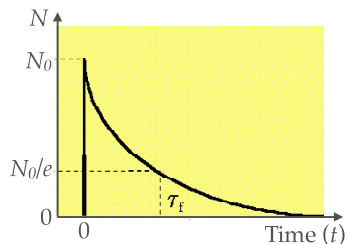
Quantum yield

$$\Phi = \frac{\text{number of emitted photons}}{\text{number of absorbed photons}} \leq 1$$

$$\Phi = \frac{k_f}{k_f + k_{ic} + k_{isc} + k_Q}$$

k_{nr} = non-radiative transition rate constants

Excited-state lifetime (τ)



$$N = N_0 e^{-(k_f + k_{nr})t}$$

N = molecules in excited state
 t = time

k_f = fluorescence rate constant

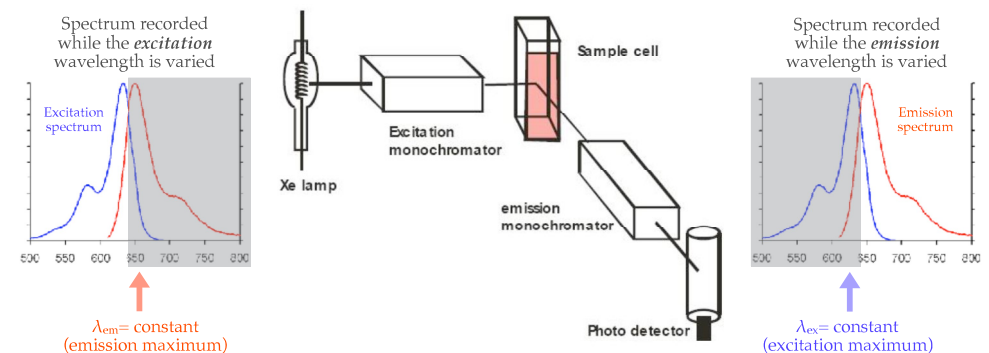
k_{nr} = non-radiative transition rate constant

τ = fluorescence lifetime

$$\tau = \frac{1}{k_f + k_{nr}}$$

MEASUREMENT OF FLUORESCENCE

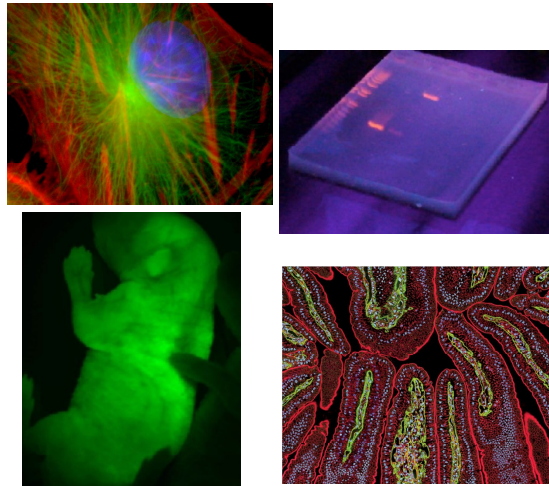
Fluorescence spectrometer ("Steady-state" spectrofluorometer)



Biomedical applications of fluorescence

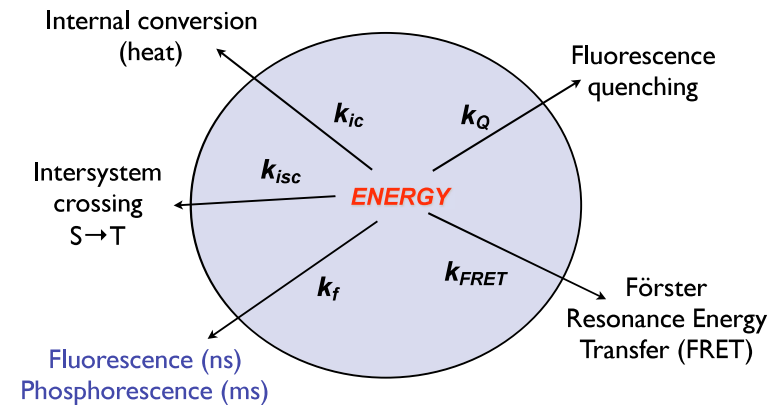
A few examples:

- Fluorescence microscopy
- DNA sequencing (chain termination method)
- DNA detection (EtBr)
- DNA microarray
- Immunofluorescence
- Fluorescence-activated cell sorting (FACS)
- Förster resonance energy transfer (FRET)
- Fluorescence recovery after photobleaching (FRAP)
- Fluorescent protein conjugation technologies
- Quantum dots
- etc...



Spectroscopic applications

Fate of absorbed energy



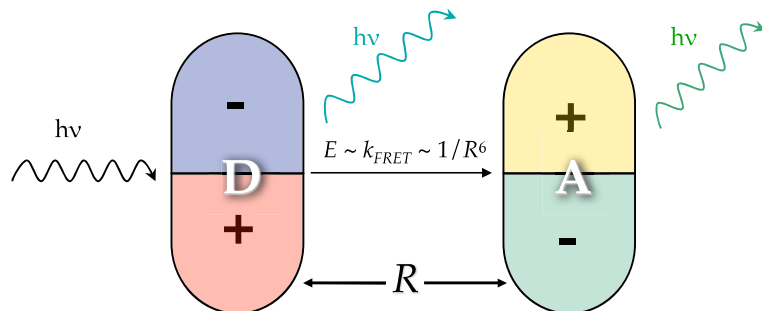
Radiative and non-radiative transitions!

Förster Resonance Energy Transfer (FRET)

- Occurs by non-radiative dipole-dipole interaction between an excited **donor (D)** and an proper **acceptor (A)** molecule under certain conditions (spectral overlap and close distance).
- Fluorescence Resonance Energy Transfer (FRET)**: if the participants of the transfer are fluorophores.

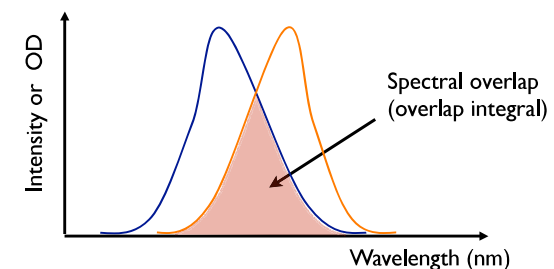


Theodor Förster
(1910-1974)



Conditions of FRET

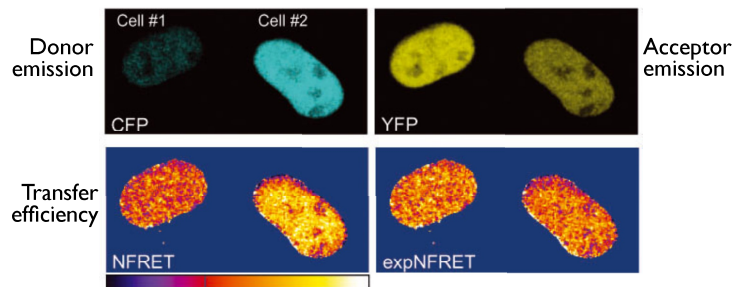
- Fluorescent** donor and acceptor molecules.
- The distance (**R**) between donor and acceptor molecules is 2-10 nm!
- Overlap** between the emission spectrum of the **donor** and the absorption spectrum of the **acceptor**.



Applications of FRET

- **Molecular ruler:** distance measurement on the nm (10^{-9} m) scale.
- High sensitivity (see sixth-power dependency)!
- **Applications:**
 - Measurement of **interactions** between molecules.
 - Measurement of **structural** changes on molecules.

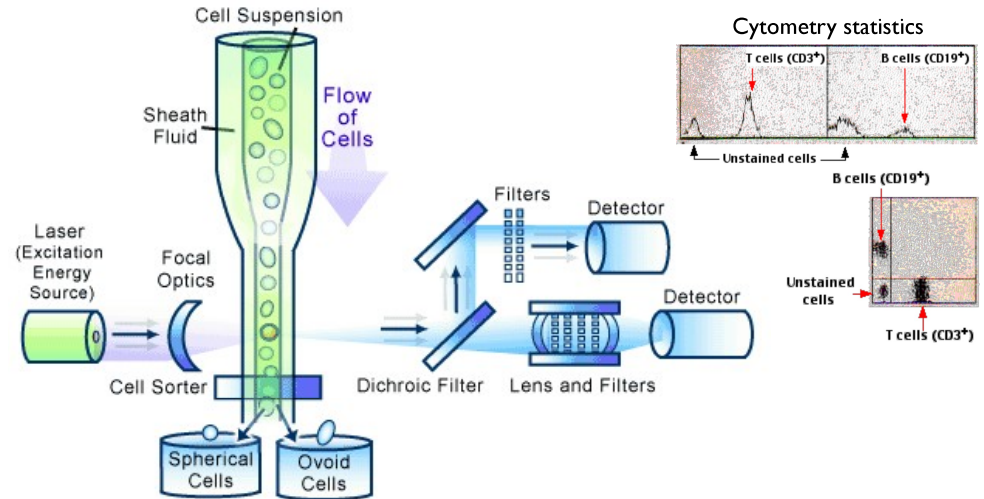
FRET microscopy



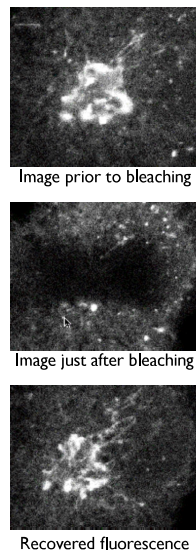
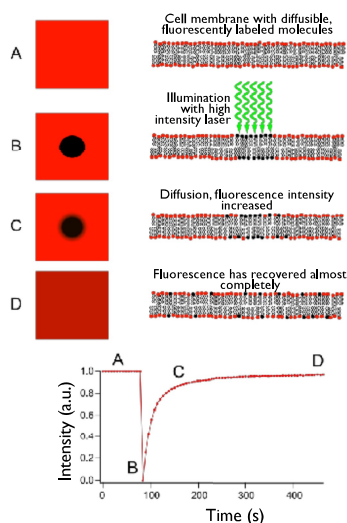
Fluorescence activated cell sorter (FACS)

Flow cytometry

- A cell suspension, fluorescently labeled by using specific antibodies, is analyzed cell by cell
- Numerous parameters are measured simultaneously (fluorescence intensity at several wavelengths, small- and large-angle scatter)
- Statistical analysis
- If needed, cells can be separated according to their fluorescence



Fluorescence Recovery After Photobleaching (FRAP)

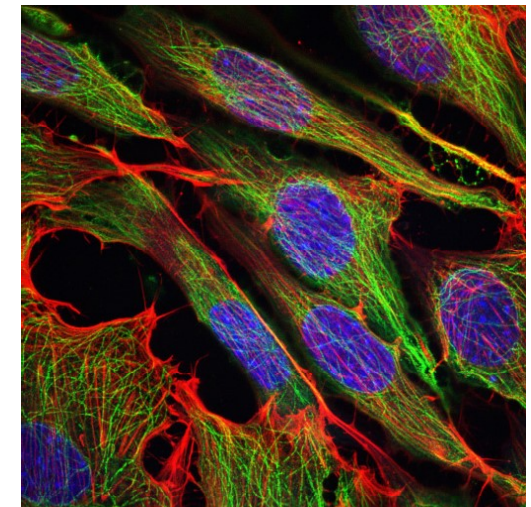
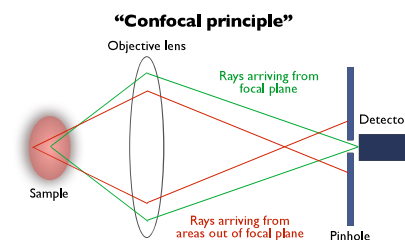
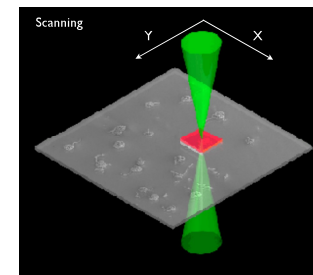


The diffusion coefficient can be determined from the time-dependent recovery of fluorescence as:

$$D = \frac{w^2}{4t_D}$$

D = diffusion coefficient
w = width of bleached area
t_D = time constant

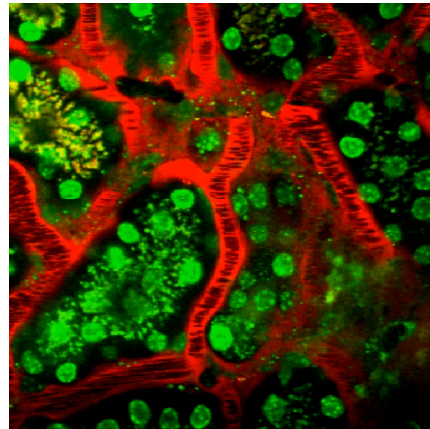
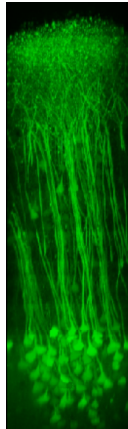
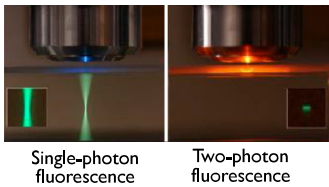
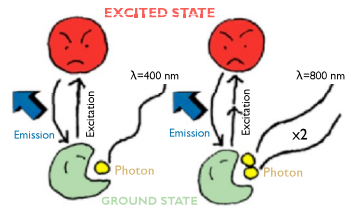
Laser scanning confocal microscopy



Green: microtubules; Red: actin; Blue: nuclei

Multiphoton microscopy

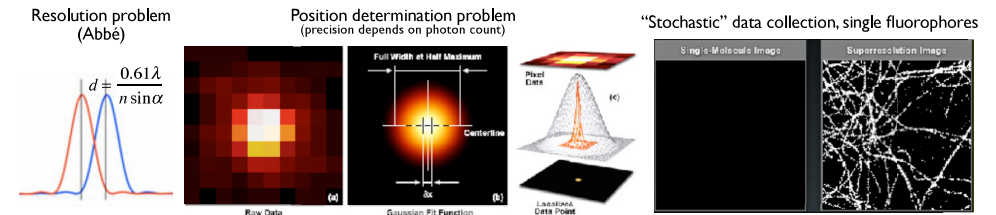
- Energy of two (or more) photons are added during excitation
- Excitation (hence emission) only in the focal point (limited photodamage)
- Excitation with long wavelength (near-IR), short (fs) light pulses
- Large (up to 2 mm) penetration due to long wavelength



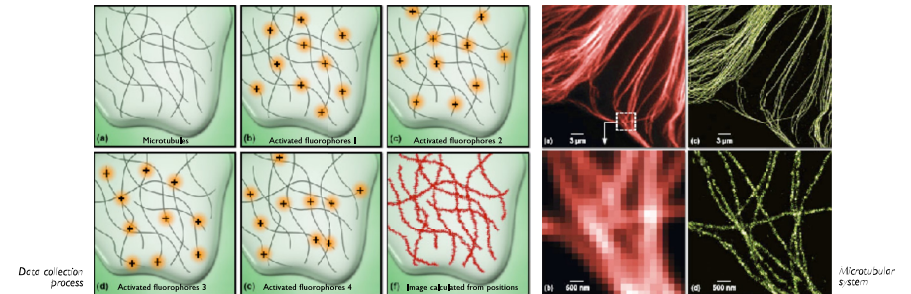
Super-resolution microscopy

Chemistry Nobel-prize, 2014

Resolution problem is converted into position-determination problem



STORM ("stochastic optical reconstruction microscopy"); PALM ("photoactivated localization microscopy")

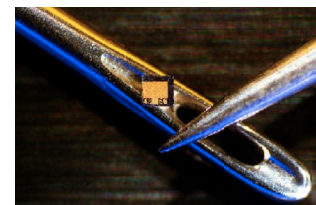


Lasers are everywhere

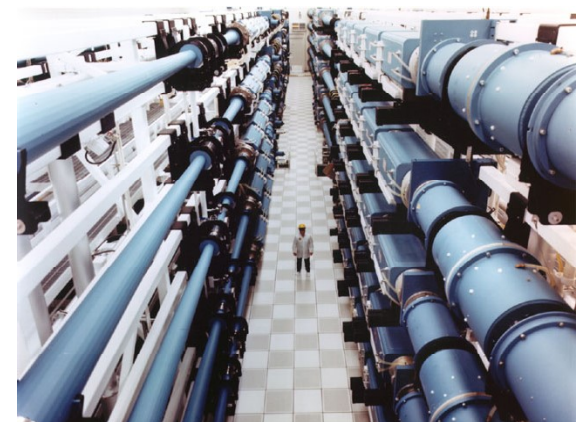
Laser: "Light Amplification by Stimulated Emission of Radiation"

Luminescent light source based on light amplification.

LASER



5 mW diode laser
few mms



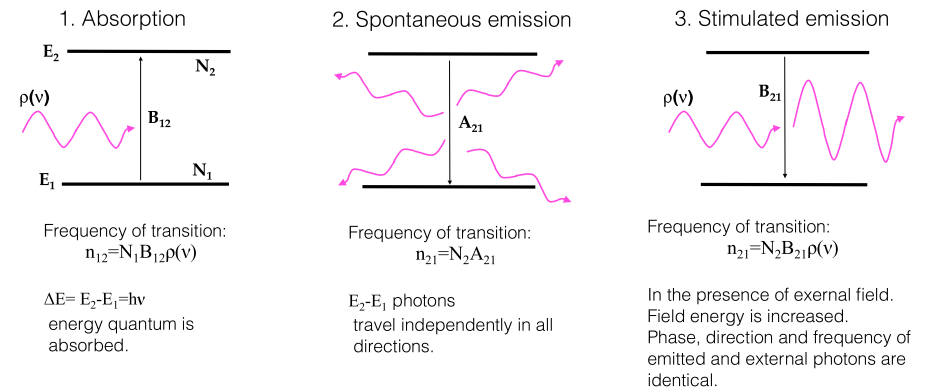
Terawatt NOVA laser - Lawrence Livermore Laboratories
Size of a football field

Laser history in a nutshell



- 1917 - Albert Einstein: theoretical prediction of stimulated emission.
- 1946 - G. Meyer-Schwickerath: first eye surgery with light.
- 1950 - Arthur Schawlow and Charles Townes: emitted photons may be in the visible range.
- 1954 - N.G. Basov, A.M. Prochorow, and C. Townes: ammonia maser
- 1960 - Theodore Maiman: first laser (ruby laser)
- 1964 - Basov, Prochorow, Townes (Nobel-prize): quantum electronics
- 1970 - Arthur Ashkin: laser tweezers
- 1971 - Dénes Gábor (Nobel-prize): holography
- 1997 - S. Chu, W.D. Phillips and C. Cohen-Tannoudji (Nobel-prize): atom cooling with laser.
- 2013, october 8: NIF (National Ignition Facility, USA): launching nuclear fusion with 192 laser beams, positive energy balance.
- 2017 - ELI (Extreme Light Infrastructure), Szeged, Hungary. generation of attosecond (10^{-18} s) light pulses.
- 2018 - Nobel-prize in physics: Arthur Ashkin (laser tweezers), Gérard Mourou and Donna Strickland (ultrashort laser pulses)

Principles of laser I. stimulated emission



Explanation: two-state atomic or molecular system.

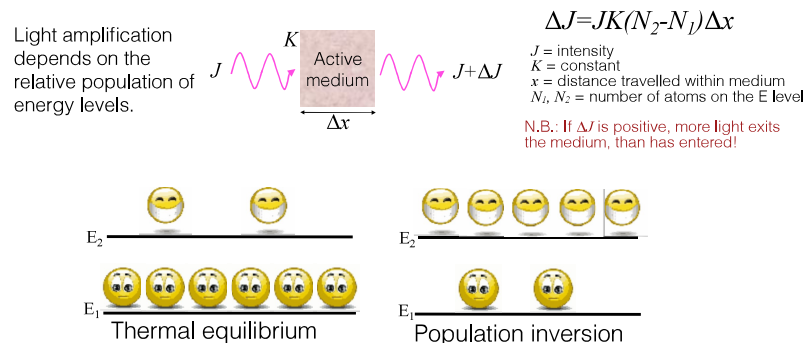
E_1, E_2 : energy levels, $E_2 > E_1$

$\rho(\nu)$: spectral energy density of external field.

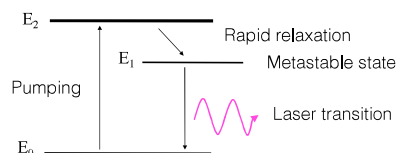
N_1, N_2 : number of atoms or molecules on the given energy level.

B_{12}, A_{21}, B_{21} : transition probabilities (Einstein coefficients), $B_{12} = B_{21}$

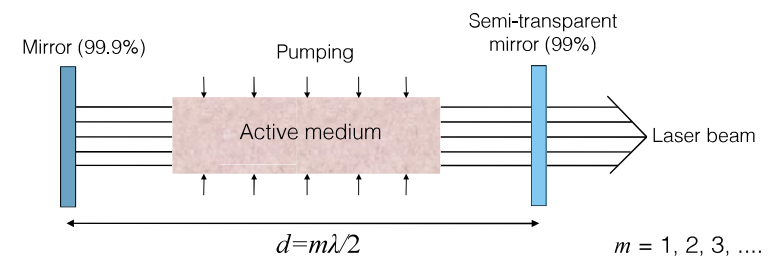
Principles of laser II. Population inversion



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



Principles of laser III. Optical resonance



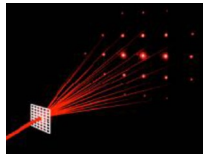
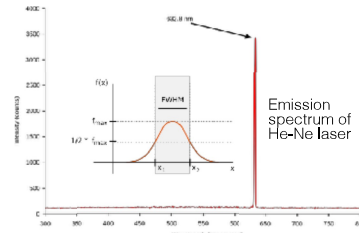
Resonator:

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

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

Properties of laser light

1. Small divergence
Parallel (collimated) beam
2. Large power
In continuous (CW) mode, tens, hundreds of W (e.g., CO₂ 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
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, optical coherence tomography



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

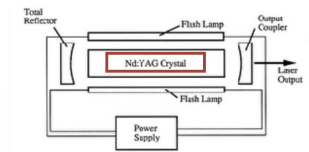
Best known: He-Ne laser (10 He/Ne). Small energy, wide use
CO₂ laser: CO₂-N₂-He mixture; $\lambda \sim 10 \mu\text{m}$; Huge power (100 W)

3. Dye lasers

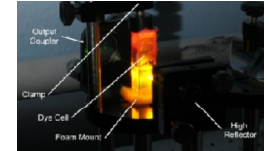
Dilute solution of organic dyes (e.g., rhodamine, coumarine);
Pumped by another laser.
Large power (Q-switched mode); Tunable

4. Semiconductor (diode) lasers

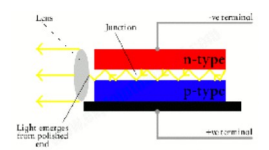
On the boundary of p- and n-type doped semiconductors.
No need for resonator mirrors (total internal reflection)
Red, IR spectral range. Huge CW power (up to 100W)
Beam characteristics are not very good. Wide use because of small size.



CO₂ laser (cutting a metal sheet)



Dye laser



Diode laser

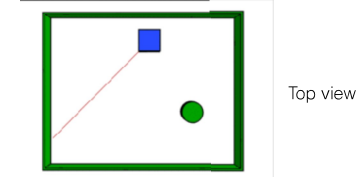
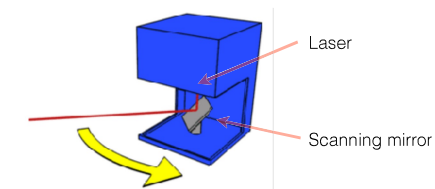
Today: laser lines (wavelengths) are available from X-rays to infrared light!

Factors to be considered in laser applications

- Steerability (small divergence)
- Monochromaticity
- Coherence
- Possibility of short pulses
- 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 CO₂ laser
 - 100–3000 W – industrial CO₂ laser (laser cutter)
 - 1 kW – 1 cm diode laser bar

Speed measurement with laser

LIDAR: "Light Detection and Ranging"



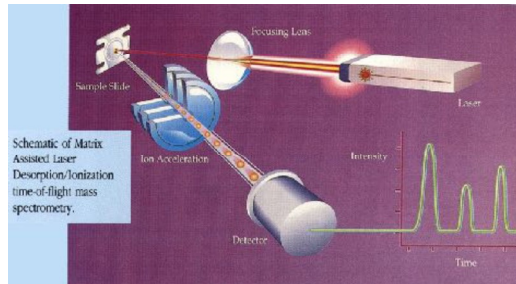
Top view



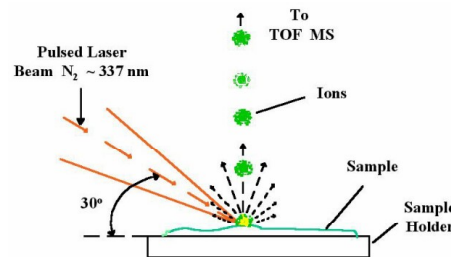
Recording:
reconstructed spatial
arrangement.
In traffic speedometer:
100 pulses in 0.3 s

Laser property
utilized:
Steerability

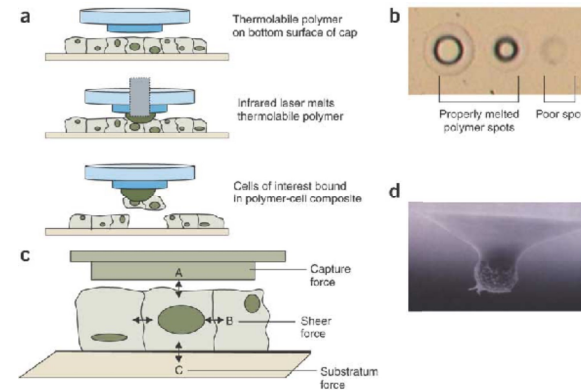
MALDI-TOF: matrix-assisted laser desorption/ionization time of flight mass spectrometry



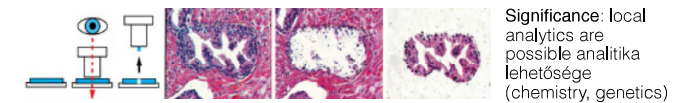
Laser property utilized: Power density



“Laser capture microdissection”

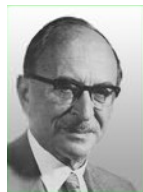


Laser property utilized: Power density, steerability

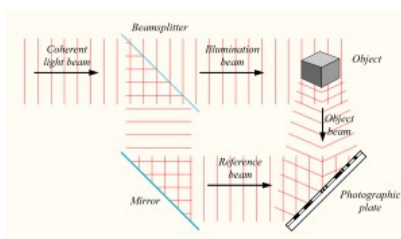


Holography

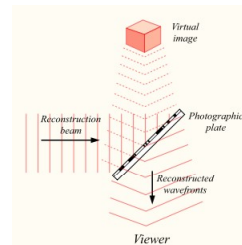
Laser property utilized: Coherence



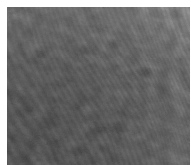
Dénes Gábor (1900-1979)



Recording a hologram



Visualization of a hologram



Surface of a hologram recording

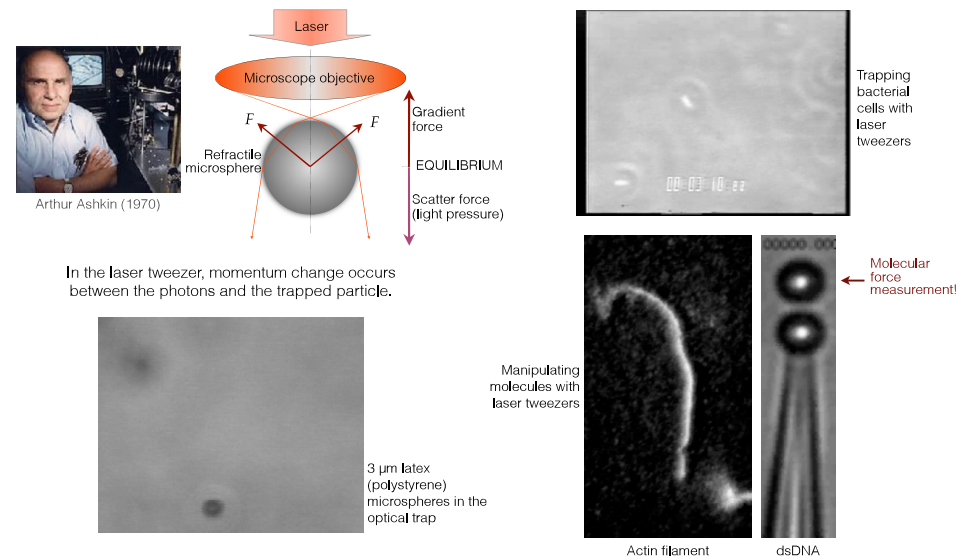


Holograms

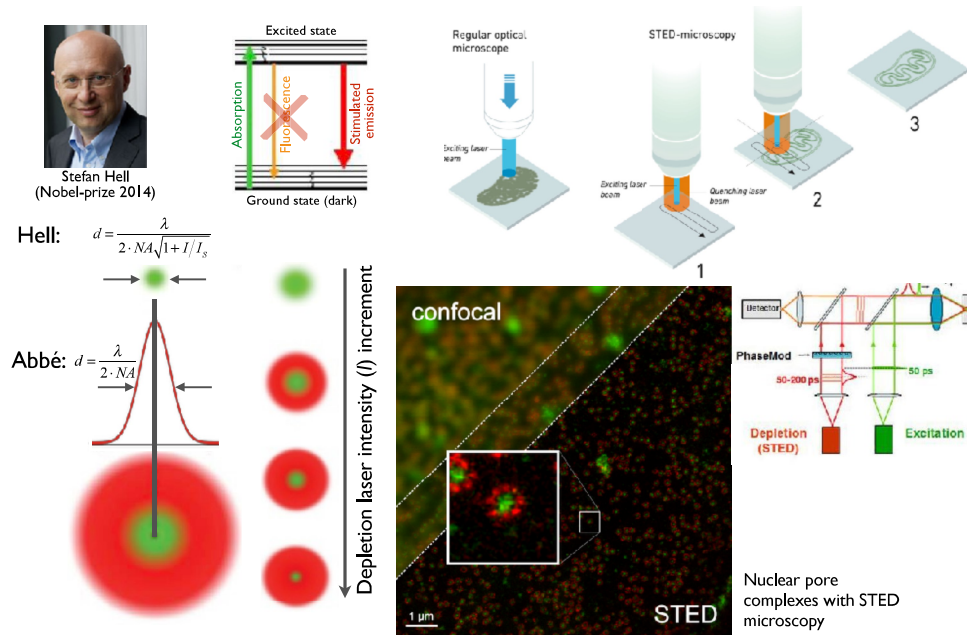


Laser tweezers

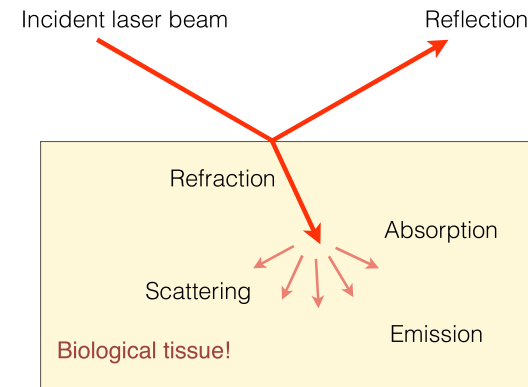
Laser property utilized: power density, steerability



STED microscopy (STimulated Emission Depletion)



Medical applications of lasers



Laser properties to consider:

- Steerability (small divergence, surgeries)
- Power (surgical applications)
- Monochromaticity (tissue absorbance)
- Coherence (interference, image formation)

The effects depend not only on the properties of the laser, but also on those of the biological tissue: absorbance, transmittivity, light-induced reactions.

Medical applications of lasers

- **Surgical disciplines:** “laser knife”, coagulation, blood-less surgery.
- **Tumor removal, tattoo removal:** CO₂ and Nd:YAG lasers, holmium laser lithotripsy (urology).
- **Dermatology:** wide-spread uses (tattoo removal, naevus removal, etc.)
- **Dentistry:** caries treatment (caries absorbs preferentially).
- **Photodynamic tumor therapy:** laser activation of photosensitive chemicals preferentially taken up by the tumor.
- **Ophthalmology:** Retina lesions, photocoagulation, glaucoma, photorefractive keratectomy (PRK).

Dermatological applications

Hair removal

Phototricholysis, photoepilation

Mechanism: 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

Tattoo removal



Before treatment

After treatment

Naevus removal



Before treatment

After treatment

Dermatological applications

Removal of superficial blood vessels



Before treatment



After treatment

Resurfacing



Wrinkle removal



Rhinophyma (sebaceous gland hypertrophy, fibrosis)

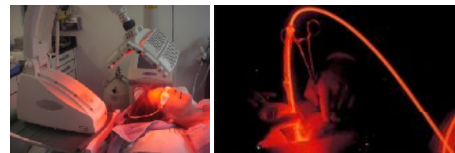
Oncological applications: Photodynamic therapy

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

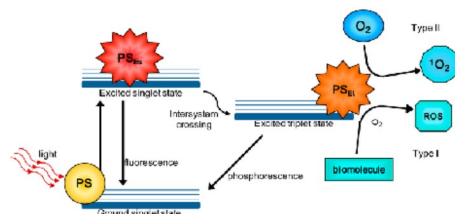
Three-component tumor therapeutic method:
1. Photosensitizing agent, 2. Light, 3. Oxygen.



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

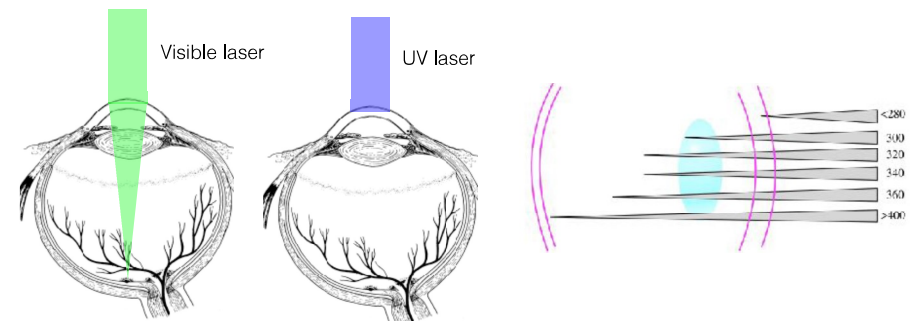


Delivery of light into the patient: surface exposure, optical fiber



Ophthalmologic applications: Considerations

Transmittivity of optical media is wavelength-dependent



Ophthalmologic applications

LASIK

“Laser-assisted In Situ Keratomileusis”
A type of refractive laser eye surgery

History:

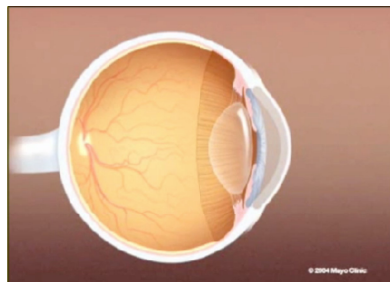
Jose Barraquer, 1970: construction of a microkeratome, with which he was able to cut lines and lobes in the cornea with laser (keratomileusis).

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).



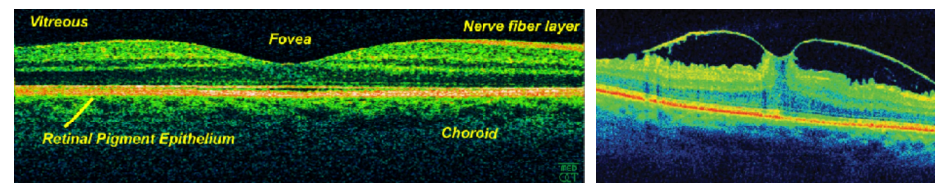
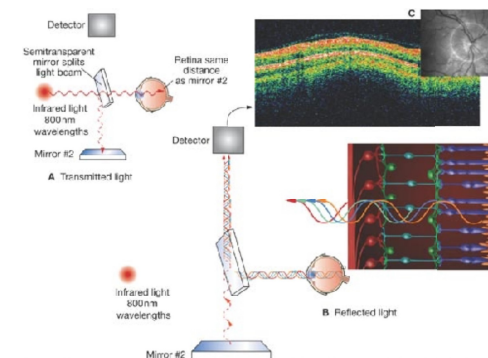
Ophthalmologic applications

Optical Coherence Tomography (OCT)

- Non-invasive
- Contrast-agent free
- Near microscopic resolution

Principles:

light rays reflected in deeper tissue layers can be separated from scatter by using **interferometry**. The spatial position of the reflecting layers can be determined. The structure of the illuminated sample can be resolved within 1-2 mm depth.



Normal retina

Macula degeneration