LIGHT: WAVE AND PARTICLE

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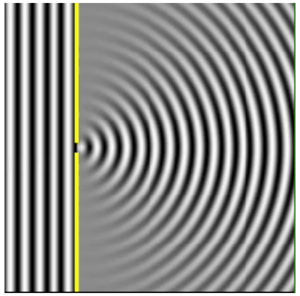
Biophysics of light

- Light as wave. Wave phenomena.
- Electromagnetic waves, spectrum.
- Light as particle. Photoelectric effect.
- Dual nature of light.
- Matter waves. Electron as wave.
- Applications

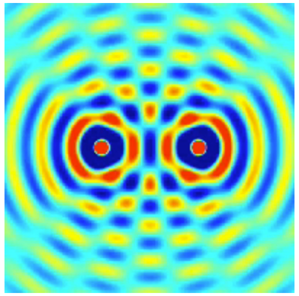
Light as wave: "wave phenomena" are displayed

Diffraction



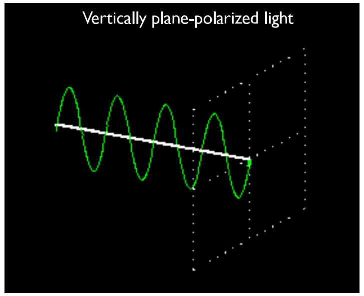
Light "bends" into unexpected areas

Interference



Spatial and temporal pattern of high- and low-amplitude regions

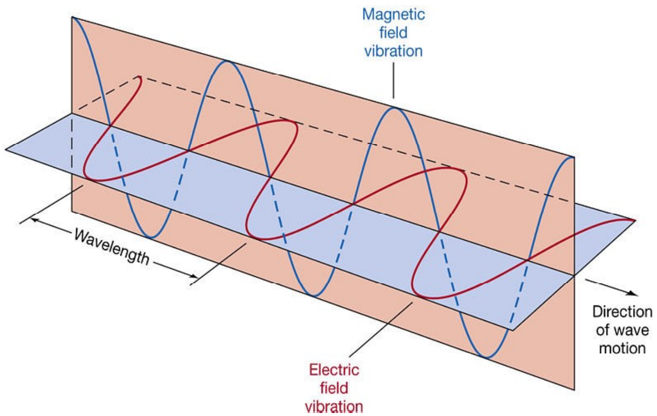
Polarization



Oscillation occurs in a preferred direction

What kind of wave is light?
Electromagnetic wave

Electromagnetic disturbance propagating in space.
No elastic medium is required for its propagation.



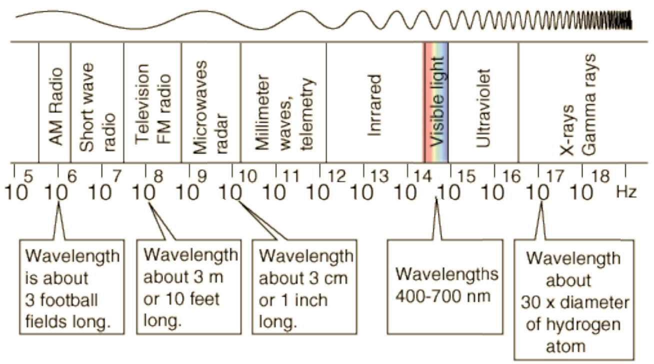
James Clerk Maxwell (1831-1879)

Propagation velocity:

$$c = \lambda f$$

c_{vacuum}=2.99792458 × 10^8 ms^{-1}

The electromagnetic spectrum



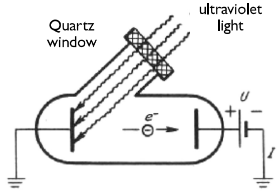
N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a function of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

What happens if an object is illuminated with light?

Photoelectric effect: The experiment

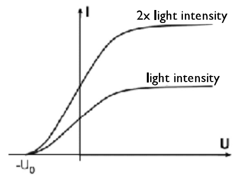
Hallwachs-effect:
Upon UV illumination, negative charges leave the metal surface


Wilhelm Hallwachs (1859-1922)



Measurements, observations


Philipp Lenard/ Lénárd Fülöp (1862-1947)



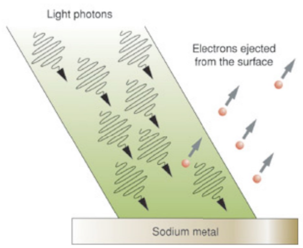
- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

Photoelectric effect

The explanation

1905: *"Annus mirabilis"*
- photoelectric effect
- diffusion
- special relativity


Albert Einstein (1879-1955)



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

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

Light is *at once* wave and particle!


Christiaan **Huygens** (1629-1695)


Sir Isaac **Newton** (1643-1727)

Wave ⟷ **Particle**

During propagation

Manifestations:
- Diffraction
- Interference
- Polarization

During interactions

Manifestations:
- Photoelectric effect
- Refraction
- Excitation, Ionization
- Compton scatter
- Pair production

If light can be a particle, then can a particle be a wave?

Matter waves: The electron as a wave

Einstein: mass-energy equivalence $E = mc^2$

Planck: law of radiation $E = hf$

Maxwell: speed of light $c = \lambda f$

Louis-Victor-Pierre-Raymond, 7th duc de Broglie (1892-1987)

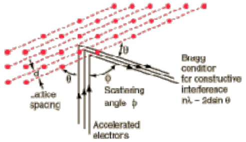
$$mc^2 = h \cdot \frac{c}{\lambda}$$

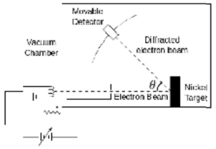
Momentum of particle (or phtoton!): $P = \frac{h}{\lambda}$

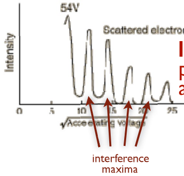
Wavelength of particle ("de Broglie wavelength"): $\lambda = \frac{h}{mv}$

Davisson-Germer experiment

Clinton Joseph Davisson (1881 –1958) Lester Halbert Germer (1896–1971)



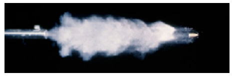




Interference pattern appears!

The electron is thus a *wave*!

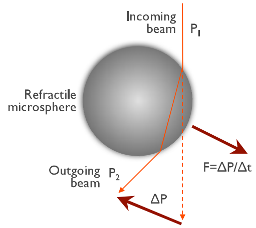
Why don't we experience the wave nature of macroscopic particles (e.g., bullet)?



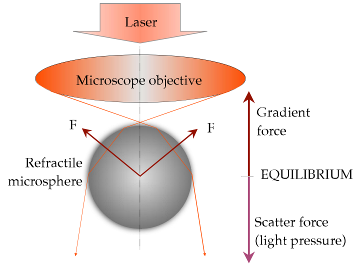
Bullet: for m=1 g and v=1 kms^{-1}, λ= 6 x 10^{-34} m!!

We can now better understand optical tweezers

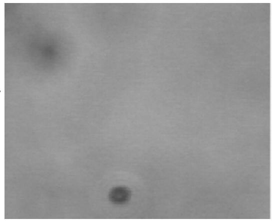
Refraction is accompanied by photonic momentum change (ΔP) (Theory later):



Refractile particles may be ***captured*** *with photonic forces:*



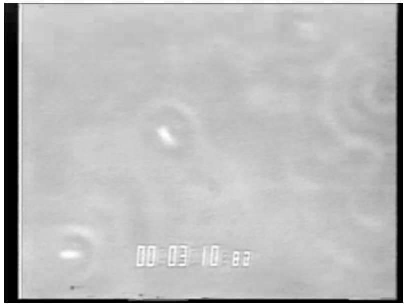
In the ***optical trap*** *a momentum change occurs between the photons and the trapped particle:*



3 µm latex (polystyrene) microspheres in the optical trap

N.B.: the terms optical tweezers, optical trap, laser tweezers, laser trap are synonymous

Capturing cells with optical tweezers



Trapping of bacterial cells

The optical trap is 3D handle without a shaft:

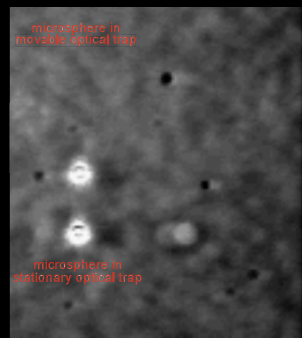
A knot can be tied on a molecular filament without releasing its ends

Actin filament

Fluorescence image

DNA

Phase contrast image

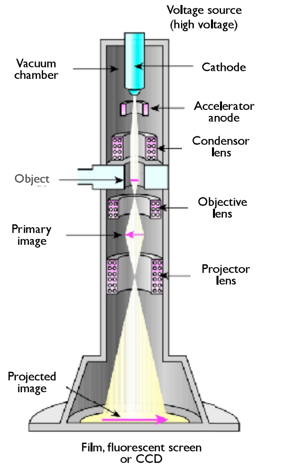


Fluorescence image

Arai et al. Nature 399, 446, 1999.

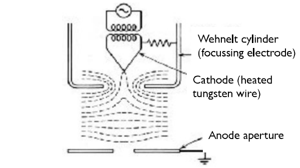
Applications I.

Matter waves: Electron microscope

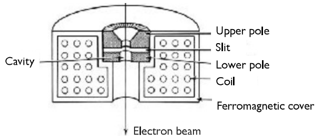


Transmission electron microscope (TEM)

Ray source: electron gun



Focusing: diverting the electron with magnetic lens



$$F = eBV_e \sin\alpha$$

F=force on the electron; e=electron's charge; B=magnetic field; V_e=electron's speed; α=angle between the optical axis and the direction of the magnetic field

Resolution: $$d = \frac{\lambda}{\alpha}$$

d=smallest resolved distance
λ="de Broglie" wavelength
α=angle between the optical axis and the direction of the magnetic field

Based on the de Broglie wavelength the theoretical resolution is: d~ 0,005 nm (=5 pm).

Applications II.

Photoelectric effect: photodetection, photocell, CCD, etc, etc.....

Light detection, image recording, CCD camera

CCD chip in mobile-phone camera

Harvesting and transformation of light energy

Solar panels

Light amplification, intensification

Silence of the lambs night vision scene: Buffalo Bill wearing a night-vision goggle - a microchannel-plate intensifier