ATOMIC PHYSICS

1. Quantized energy of electromagnetic radiation

revision – topic Electromagnetic radiation

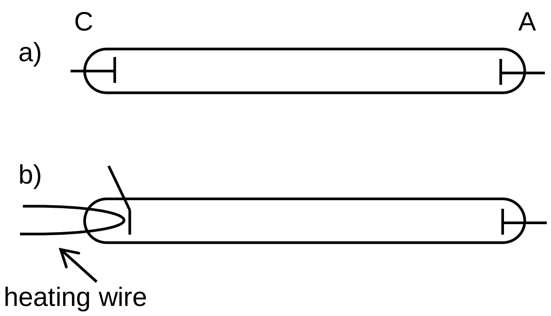
Planck (1900):
Energy of electromagnetic radiation is released or absorbed only in multiples of some smallest amounts of energy = energy of a quantum E_q

$E_q = hf$ $\qquad$ $h = 6.625 \times 10^{-34}\,\mathrm{J \cdot s}$ Planck constant

http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html
http://www.astro.ufl.edu/~oliver/ast3722/lectures/BasicDetectors/DetectorBasics.htm
http://en.wikipedia.org/wiki/Black_body

2. Cathode rays

End of 19th century – many experiments with a glass tube ("bulb") and low pressure gases or vacuum inside 2 electrodes, voltage across $\longrightarrow$ different phenomena observed $\longrightarrow$ very popular



A.......anode (+)
C.......cathode (-)
a) directly heated
b) indirectly heated

$\Rightarrow$ "cathode rays" (=stream of high speed electrons)

1. travel from cathode in straight lines
2. cause some substances to fluoresce
3. possess E_k
4. can be deflected by - electric fields
   - magnetic fields
5. produce X-rays on striking matter

http://highered.mcgraw-hill.com/sites/0072512644/student_view0/chapter2/animations_center.html#

Questions:
1. Why did they say "cathode rays" instead of electrons?
2. In which of the tubes is the current bigger (assume the same U)?
3. Describe the properties of cathode rays. Which of them prove that it cannot be electromagnetic radiation?

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3. Electron

a) discovery

Joseph John Thomson 1897 (1856 – 1940)
- head of the Cavendish's laboratory in Cambridge; buried in Westminster Abbey

he measured:
- speeds
- $\frac{e}{m_e}$ charge - to - mass ratio (specific charge) of CATHODE RAYS $\Rightarrow$ he assumed that cathode rays cannot be elmag. waves, because

1. their speed is about 1/10 *c* in vacuum (air)
2. they can be deflected in electric and magnetic fields

$\Rightarrow$ results for any source $\frac{e}{m}$ were always the same, *e* calculated from electrolyses for monovalent ion

$e = 1.66\times10^{-19}$ C

$m_e = 9.1\times10^{-31}$ kg

b) electron dynamics

ELECTRIC FIELD

1. speed

$$U = \frac{W}{Q} = \frac{W}{e} \Rightarrow$$

$$W = eU$$

$v_o = 0$ at cathode (-)

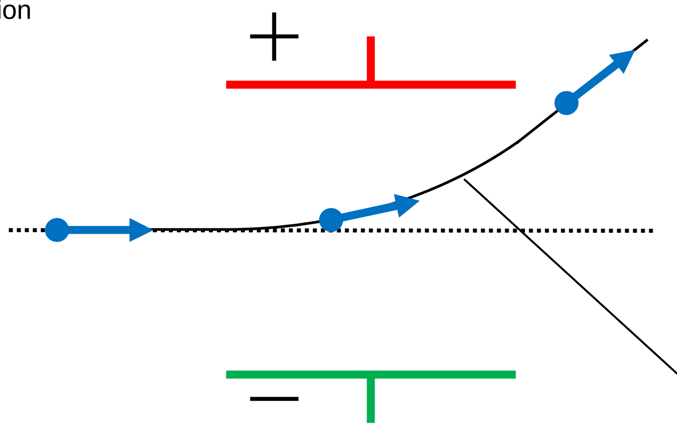
$$W = \Delta E_k = \frac{1}{2}m_e v^2 - \frac{1}{2}m_e v_o^2$$

$$W = \frac{1}{2}m_e v^2$$

$$eU = \frac{1}{2}m_e v^2$$

$$v = \sqrt{2U\frac{e}{m_e}}$$

2. deflection



MAGNETIC FIELD

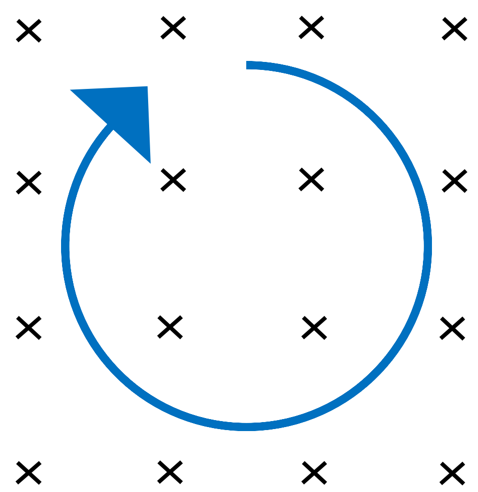
$F = B \cdot Q \cdot v \cdot \sin\alpha$

F - on a moving charge
B - magnetic flux density
Q and v - charge and speed of Q
α - between v and B

when $Q = e \wedge \alpha = 90^\circ \left(\Rightarrow \vec{v} \perp \vec{B} \right)$

size: $F = Bev$

direction: $\vec{F} \perp \vec{v} \wedge \vec{F} \perp \vec{B}$; Fleming's left-hand rule



$$F_c = F$$
$$m_e a_c = Bev$$
$$m_e \frac{v^2}{r} = Bev$$
$$\frac{v}{Br} = \frac{e}{m_e} (= \text{const.})$$

Questions:
4. An electron emitted from a hot cathode in an evacuated tube is accelerated by a p. d. of 1000 V.
a) calculate the speed acquired by the electron
b) the electron now enters a mag. field B = 1 mT. Determine its path

a)

$$v = \sqrt{2U\frac{e}{m}}$$
$$v = 1.9 \times 10^7 \, \text{m} \cdot \text{s}^{-1}$$

b)

$$Bev = m\frac{v^2}{r}$$
$$r = \frac{mv}{Be} = 0.1\,\text{m}$$

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5. Calculate the electric field strength of a uniform el. field which when applied perpendicularly to the mag. field will compensate the mag. deflection. Assume the distance between the plates 2 cm and calculate the p. d. between them.

$E = \frac{F}{q} = \frac{F}{e} \Rightarrow F = Ee$ .... electric

$F = Bev$ .... magnetic

$Ee = Bev$

$E = Bv = 1.8 \times 10^4 V \cdot m^{-1}$

$E = \frac{U}{d} \Rightarrow U = Ed = 360$ V

6. Describe and explain the behaviour of an electron in electric and magnetic field (different directions related to the movement of the electrons).

c) Millikan's experiment

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previous Thomson's experiments $\Rightarrow$ measurement of $\frac{e}{m_e}$

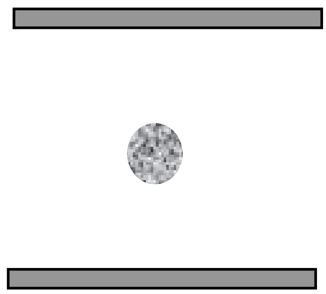
this experiment $\rightarrow$ multiple of elementary charge e

} calculate m_e

arrangement:

- 2 charged plates in the gravitational field
- oil drops sprayed between

$\Rightarrow$ search the one "at rest" $\Rightarrow$



$F_g = F_e$

$mg = EQ$

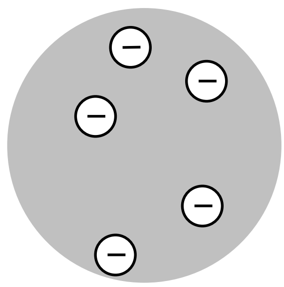
$mg = \frac{U}{d} k \cdot e$

k → some multiple of e

4. Models of atom

a) Thomson's "pudding" model

Explain the importance of cathode ray experiment for this model of the atom:



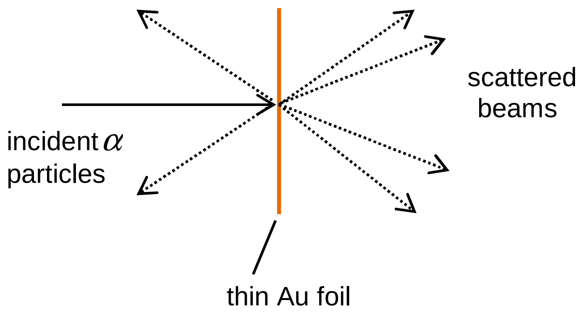
Why did Rutherford's α - scattering experiment lead to another model of the atom?

b) Rutherford's model

http://highered.mcgraw-hill.com/sites/0072512644/student_view0/chapter2/animations_center.html#
http://www.worsleyschool.net/science/files/rutherford/atom.html

$\Rightarrow$ NUCLEUS + electrons around

- NUCLEUS → small +
- electrons around → quite a lot of space



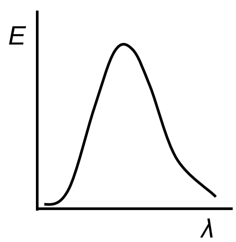
This model does not correspond with classical physics because:

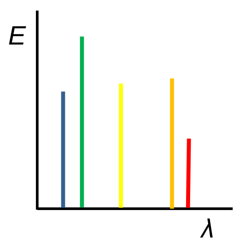
- Electrons orbiting should have "acceleration" = a_c $\Rightarrow$ emit electromagnetic wave $\Rightarrow$ lose energy $\Rightarrow$ spiral towards the nucleus, WHICH DOESN´T HAPPEN
- Line spectra of substances cannot be explained $\Rightarrow$

LINE SPECTRA

http://www.colorado.edu/physics/2000/quantumzone/index.html

hot objects (sun, filament lamps) X hot gases and metal vapours
produce many $\lambda \sim T$ — produce just some particular λ
$\Rightarrow$ CONTINUOUS SPECTRUM — $\Rightarrow$ LINE SPECTRUM





LINE SPECTRUM
- Emission - emitted by heated gas
- Absorption - missing from "white" gone through the gas

Joseph Balmer investigated H_2 spectra in the visible range of frequencies - he found that

$$f = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad n = 3,4,...$$

of the line   Rydberg´s frequency $R = 3.29 \times 10^{15}\,\mathrm{Hz}$

c) Bohr's model

Niels BOHR (Dain, 1913) $\longrightarrow$ 2 suggestions

a) Electrons can revolve round nucleus only in certain "allowed orbits"; when they are in these orbits they don´t emit radiation and they have a definite amount of energy = energy of the orbit

b) Electrons can jump from higher energy orbit (E_2) to lower energy orbit E_1; the energy difference between the orbits CAN be emitted as a quantum of electromagnetic radiation of frequency f_{21}

$$E_2 - E_1 = hf_{21} \qquad h = 6.625 \times 10^{-34}\,\mathrm{J \cdot s} \qquad \text{Planck constant}$$

If the same amount of energy is absorbed, electron can jump from E_1 to E_2 of course.

MODEL OF HYDROGEN ATOM

This model is based as well on other discoveries - line spectra in UV & IR, all of the lines obey equation

$$f = R\left(\frac{1}{m^2} - \frac{1}{n^2}\right) \qquad n \rangle m,\ n, m = 1,2,3,4,...$$

for m = 1 LYMAN series in UV
for m = 2 BALMER series in VISIBLE!
for m = 3 PASCHEN series in IR

Use additional materials to sketch the energy levels and series of lines:

- if we assume that the frequency of radiation emitted is connected with energy $\Rightarrow$

$$E_n - E_m = hf_{nm} = hR\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

$$-E_m = hR\frac{1}{m^2}$$

$$E_m = -\frac{hR}{m^2}$$

$$E_1 = -13.6\ \mathrm{e}\cdot\mathrm{V} = -21.8x10^{-19}\ \mathrm{J}$$

= IONIZATION ENERGY ~ if supplied to e^- in H at E_1 $\Rightarrow$ it will escape from the atom.

Excited state $\approx$ e^- on higher energy orbits, which can:

- Jump to lower energy level
- Absorb certain quantum $\longrightarrow$ jump to higher energy level
- More energy supplied $\longrightarrow$ leave the atom = ionization (0 energy; positive energy electrons are FREE)

Questions:
7. Explain the relation between the energy of a quantum of electromagnetic radiation absorbed/released and the energy levels, relate it to the hydrogen model

d) Schrödinger's model

- based on
  - quantized energy of electrons
  - PROBABILITY of presence of an e^- in some space round the nucleus
- quantum numbers

n - principal $\approx$ energy $\approx$ size of an orbital $\longrightarrow$ 1,2,3,...
l - subsidiary $\approx$ shape of an orbital $\longrightarrow$ s, p, d, f,...
m - magnetic $\approx$ position of an orbital in 3 dim. $\longrightarrow$ x, y, z
m_s - spin magnetic $\longrightarrow$ $+-\frac{1}{2}$

Pauli's exclusion principle:
- no electron can have the same quantum number as any other
- $n \Rightarrow 2n^2$ of different states

Questions:
8. How many quantum numbers did Schrödinger use and what do they represent?

PROBABILITY OF PRESENCE OF ELECTRONS IN DIFFERENT ORBITALS

Use different resources to find the shape of orbitals – probability of presence of electrons around the nucleus.

5. Thermionic emission

- takes place in METALS and some COMPOUNDS (sea of electrons), where the surface electrons with enough energy can be liberated
- energy is supplied as HEAT

- **WORK FUNCTION** Φ = energy which must be supplied to a metal/compound to enable ONE electron to escape from its surface

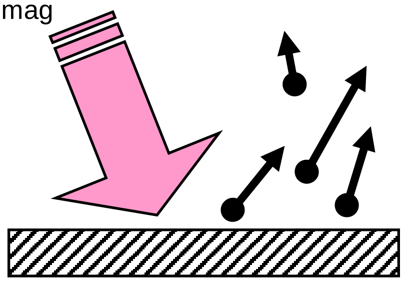
$[\Phi] = \mathrm{e} \cdot \mathrm{V}$ ... electronvolt – unit of energy/work on microscopic level

$$W = QU$$
$$1\mathrm{J} = 1\mathrm{C} \times 1\mathrm{V} = 6.25 \times 10^{18}\,\mathrm{e} \cdot \mathrm{V}$$
$$1\mathrm{e} \cdot \mathrm{V} = 1.6 \times 10^{-19}\,\mathrm{J}$$

6. Photoelectric effect

- experiments made since about 1897, explained (+eqn) by Einstein 1905 – Nobel prize

incident elmag radiation



electrons rejected from the surface

metal/compound

Zn – X-rays, UV
Na - X-rays, UV, visible except orange and red
Cs - X-rays, UV, visible, IR

a) laws of photoemission (based on experiments)

1. The number of photoelectrons emitted per second depends on the intensity of incident radiation (number of quanta incident – discovered later)
2. Speed of photoelectrons varies from zero to v_{max}, which depends on the frequency of the incident radiation but not on its intensity
3. For a given metal there is a **threshold frequency** – when the frequency is lower, there is no photoemission even for high intensity of the incident radiation.

   (*někdy se udává mezní vlnová délka dopadajícího záření* $\lambda_m = \frac{c}{f_m}$)

b) Einstein's equation for outer photoeffect

$$hf = \Phi + \frac{1}{2} m v_{max}^2$$

energy of a quantum of incident radiation (hf) — work function of CERTAIN metal (Φ) — maximum kinetic energy of a „photoelectron" ($\frac{1}{2} m v_{max}^2$)

energy of a quantum = E needed for the electron to escape + maximum possible E of the electron

OR $hf = \Phi + \frac{1}{2}mv^2 + E_{conv}$ when some energy is converted into other types and so the electron does not have the maximum speed

also $hf_m = \Phi$ for the threshold frequency

Questions:
9. Explain the laws of photoemission using Einstein's equation.
10. Explain the difference between the two first equations.
11. Explain the third equation.

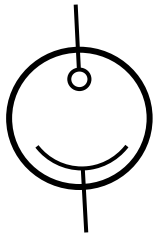
USES OF PHOTOEMISSION

- PHOTOEMISSIVE CELL

  based on the outer photoemission

  electrons released travel in the evacuated bulb – R of the cell decreases

  e.g. sound track at the side of a moving film (in the past...)



symbol

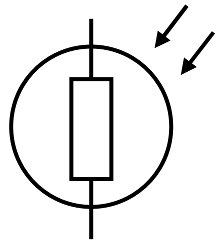
Label which part of the photoemissive cell should be plus and which minus pole of the source. Find and sketch the electric circuits using this component.

- PHOTOCONDUCTIVE CELL (or LDR – light dependent resistor)

  based on the INNER photoeffect = in SEMICONDUCTORS mainly

  electrons do not leave the material, but they are liberated within

  couple hole-electron – R decreases



symbol

Find uses of LDR in everyday life.

Questions:
12. Explain the difference between the outer and inner photoeffect and some of their uses.

7. Wave-particle duality of matter

a) particle properties of waves

Electromagnetic radiation exhibits wave phenomena (reflection, refraction, deflection, polarisation, interference, ...) but a quantum of elmag. radiation = PHOTON behaves as well like a particle!!!
This is more evident for high energy = high f = small λ photons

$E = hf$ .... „photon“ $h =$ Planck constant

PROOF:

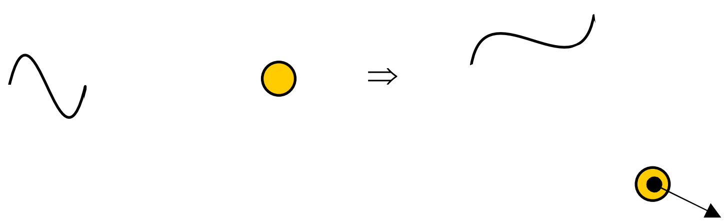
1. Quantized energy of electromagnetic radiation : $E = hf$ ... the smallest amount of energy at frequency f which can be „found“ separately

2. Photoelectric effect : energy conservation - energy of a photon is converted into the energy of a photoelectron

3. Compton effect

incident photon + „stationary“ electron $\Rightarrow$ scattered photon + moving electron

hf hf’ 〈 hf



like a collision between two particles - momentum is conserved

problem – momentum of a photon

$$p = mv = mc = \frac{E}{c^2}c = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

b) wave properties of particles

momentum of a photon: $p = \frac{h}{\lambda}$

photon wavelength – **deBroglie's wavelength**: $\lambda_B = \frac{h}{p}$

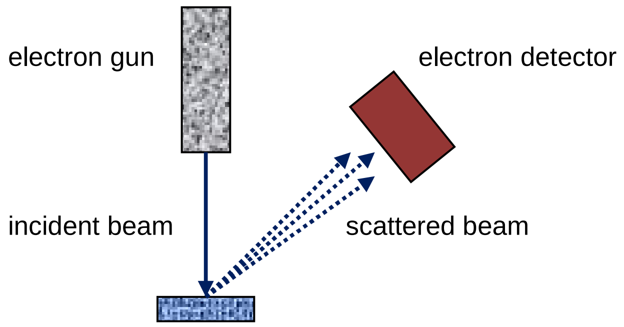
deBroglie suggested giving the wavelength to objects (mainly particles – electrons), they can exhibit some wave properties

Questions:
13. Calculate deBroglie's wavelength of Mr. Pohaněl and his car going to Prostějov at 96 $km \cdot h^{-1}$. Which type of electromagnetic radiation has similar wavelength? What can you deduce from it?

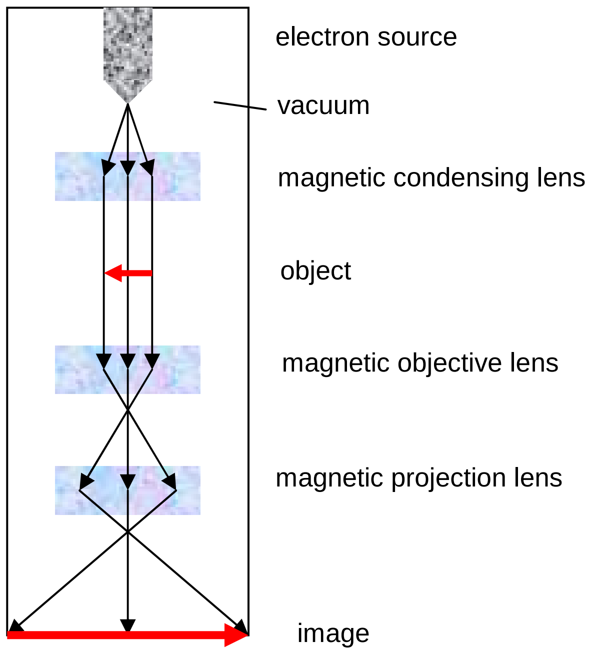
PROOF:

1. X-rays – moving electrons (particles) can reject photons, intensity – number of incident electrons (current), wavelength – speed of incident electrons, kinetic energy, voltage

2. Particle diffraction - discovered by Davisson+ Germer (USA), G.P.Thomson (GB)
incident electron beam is diffracted – info about the structure (compare X-ray crystallography)



3. Electron microscope – based on particle diffraction



Questions:
14. Why is a vacuum inside the microscope?

15. Is the DeBroglie's wavelength of electrons here bigger or smaller than light? Why?

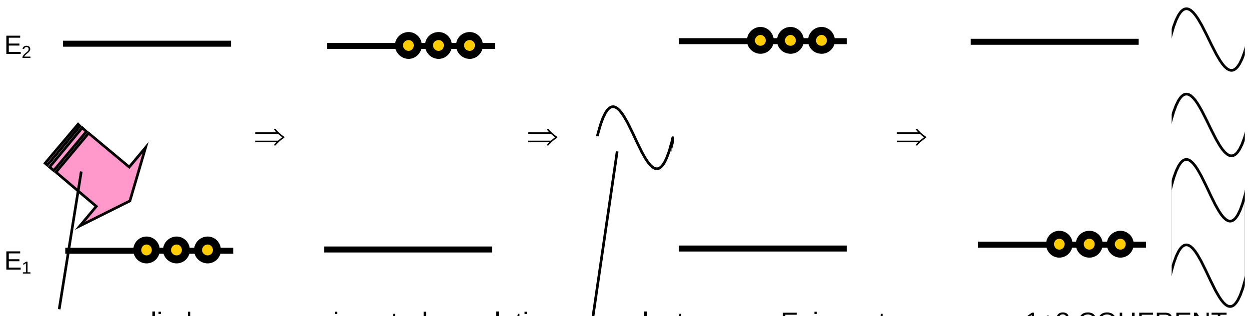
16. Explain the principle, use different resources.

8. Stimulated emission and lasers

a) spontaneous × stimulated emission

spontaneous emission – random process, even monochromatic light has photons of different PHASE

stimulated emission



energy supplied from outside („pumping“) -light, current, ...

inverted population (more e on excited level waiting for a STIMULATING photon)

electrons on E_2 jump to E_1 and they are IN PHASE with st.ph. which leaves UNCHANGED

1+3 COHERENT photons

Question:
17. What is the frequency of the stimulating photon?

18. How can we get it into the material?

b) lasers (since 1960)

light amplification by stimulated emission of radiation

- light is : coherent, monochromatic, not diverging, intense – all of that depends on the TYPE!
- types :

RUBY
- the first, optical pumping
- range finding, welding, cutting

CO_2
- about 100 W output
- surgery

He-Ne
- coherent, interferometry

SEMICONDUCTORS
- tiny, low power, less coherent, data transmission

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