

MUNI

Matter and Energy

- Everything is made up of basic particles of matter and fields of energy / force, which also means that the fundamental structural elements of the organic and inorganic world are **identical**.
- Living matter differs from non-living matter mainly by its **much higher level of organisation**.

Elementary Particles of Matter

(i.e. having - probably - no internal structure)

➤ „force“ particles – integer spin – **bosons**

➤ Vector bosons – spin 1

- Foton
- Gluons
- W, Z (weak bosons)
- Graviton

➤ Scalar boson – spin 0

- Higgs boson

➤ „matter“ particles – noninteger (odd) spin - **fermions**

➤ The elementary particles of matter are **leptons** and **quarks**

➤ **Leptons** – electrons, muons, neutrinos and their anti-particles – light particles without internal structure

➤ **Quarks** (u, c, t, d, s, b) – heavier particles without internal structure

➤ **Composite particles**

➤ **Hadrons** – heavy particles formed of quarks - **baryons** (fermions - **proton** (u, u, d), **neutron** (d, d, u)) **mesons** (bosons (quark-antiquark))

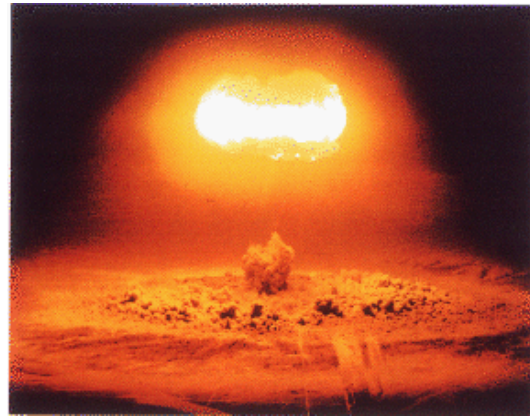
The Four Fundamental Energy / Force Fields



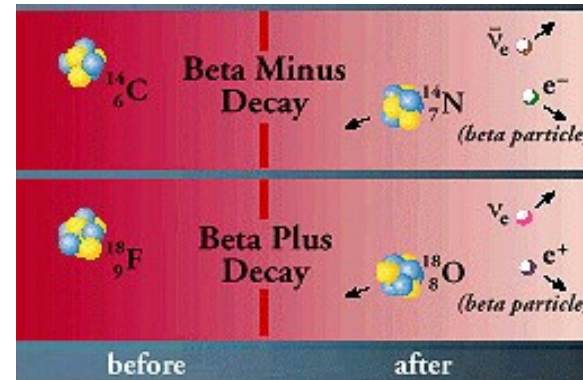
gravitational



electromagnetic



strong



weak

Strong : weak : electromagnetic : gravitational force - $1 : 10^{-5} : 10^{-2} : 10^{-39}$ at interaction distance of about 10^{-24} m; $10^{-7} : \sim 0 : 10^{-9} : 10^{-46}$ at a distance of about 10^{-18} m (1/1000 of atom nucleus dimension). In the distance equal to nucleus dimension goes to zero also strong interaction.

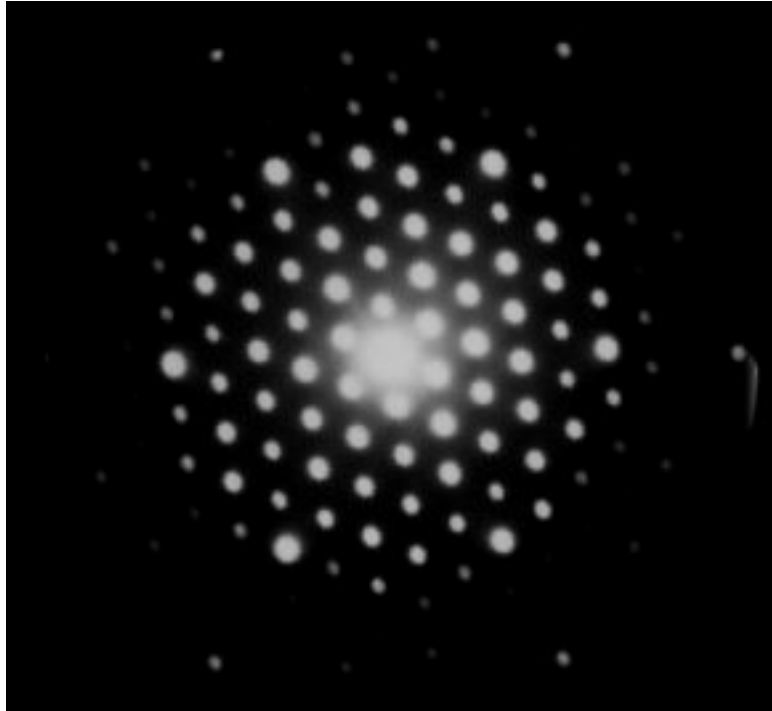
Photons

- Photons - energy quanta of electromagnetic field, zero mass
- Energy of (one) photon: $E = hf = hc/\lambda$
 h is the Planck constant ($6.62 \cdot 10^{-34}$ J·s),
 f is the frequency,
 c is speed of light in vacuum,
 λ is the wavelength.

Particles and Field Energy Quanta

Particles of matter and field energy quanta are capable of **mutual transformation** (e.g., an electron and positron transform to two gamma photons in the so-called annihilation – this is used in PET imaging).

Quantum Mechanics

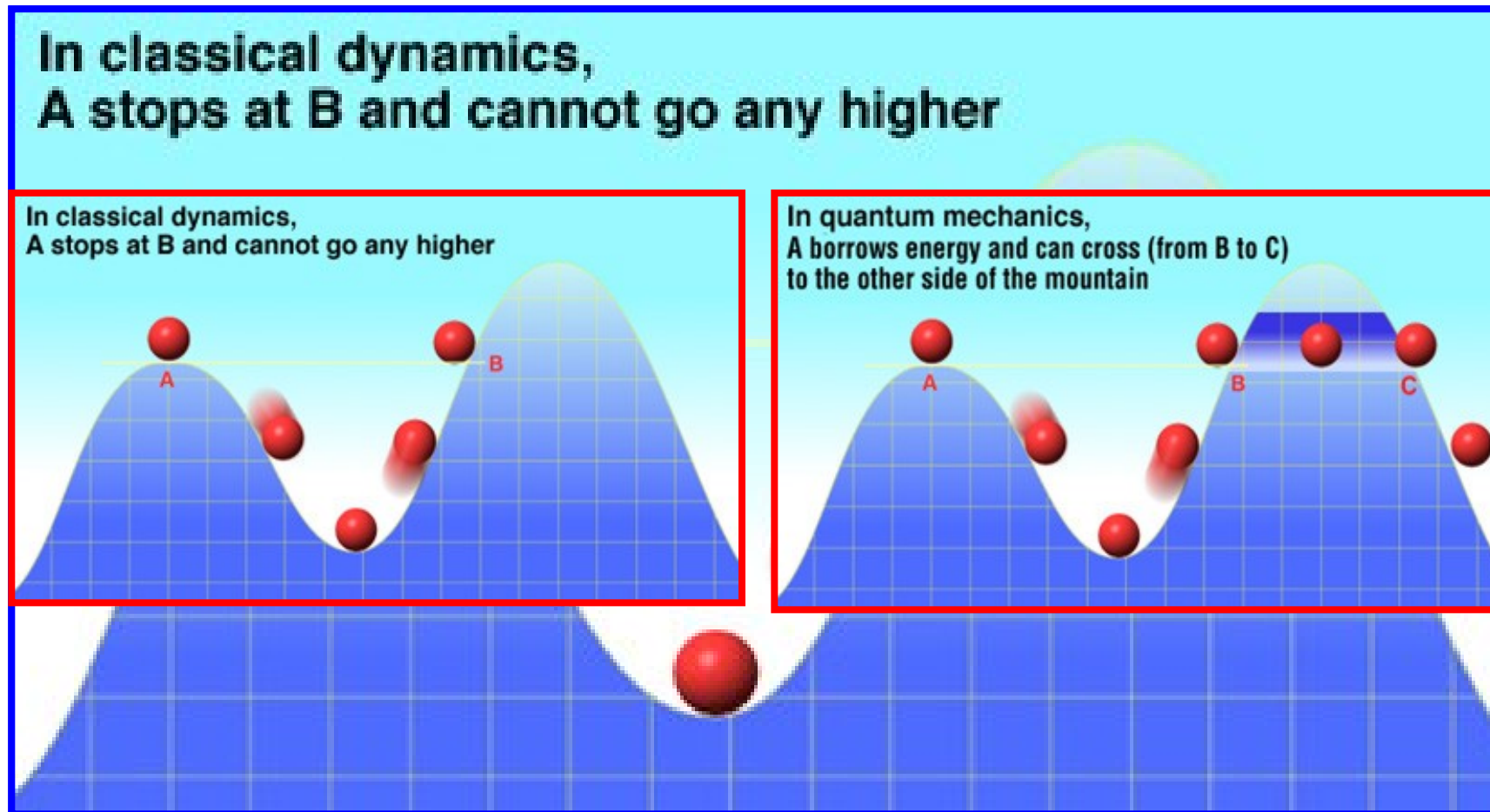


The behaviors of ensembles of a given type of particle obey equations which are similar to wave equations.

On the left pattern formed on a photographic plate by an ensemble of electrons hitting a crystal lattice. Notice that it is very similar to the diffraction pattern produced by a light wave passed through optical grating.

Quantum Mechanics

tunnel effect:



Quantum Mechanics: Heisenberg uncertainty relations

$$\delta r \cdot \delta p \geq h/2\pi$$
$$\delta E \cdot \delta t \geq h/2\pi$$

The position r and momentum p of a particle **cannot be** *simultaneously* measured with independent precision (if the uncertainty of particle position – δr – is made smaller, the uncertainty of particle momentum – δp – automatically increases). The same holds for the simultaneous measurement of energy change δE and the time δt necessary for this change. h is the Planck constant.

Schrödinger equation

(to admire 😊)

second derivative

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{8\pi^2 m}{h^2} (E - V) \psi = 0$$

position *energy* *potential energy*

„one-dimensional“ S. equation

Radial coordinates of an electron in a hydrogen atom

S. equation for the **electron** in the **hydrogen** atom

Ψ - wave function

Solution of the Schrödinger Equation

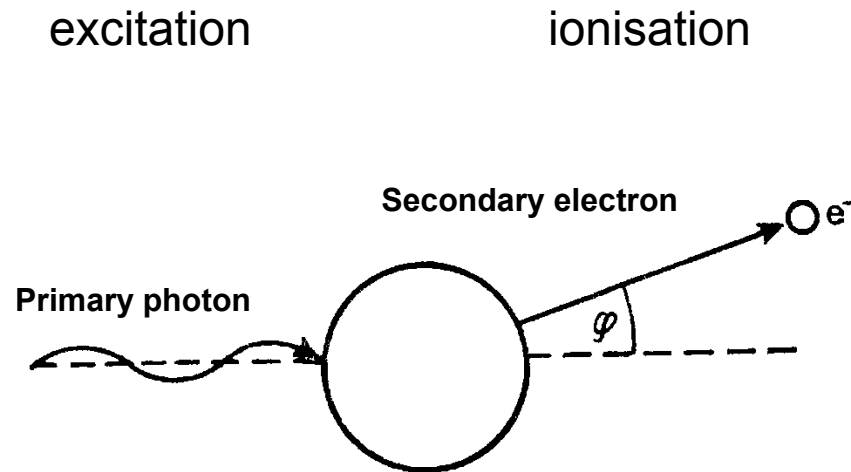
- The solution of the Schrödinger equation for the electron in the hydrogen atom leads to the **values of the energies** of the orbital electron.
- The solution of the Schrödinger equation often leads to **numerical coefficients** which determine the possible values of energy. These numerical coefficients are called **quantum numbers**

Quantum numbers for Hydrogen

- **Principal** $n = 1, 2, 3, \dots$ (K, L, M, ...)
 - **Orbital** for each n $l = 0, 1, 2, \dots, n - 1$ (s, p, d, f ...)
 - **Magnetic** for each l $m = 0, 1, 2, \dots, l$
 - **Spin magnetic** for each m $s = 1/2$
-
- **Pauli exclusion principle** – in one atomic electron shell there cannot be present two or more electrons with the same set of quantum numbers.

Ionisation of Atoms

The binding energy of an electron E_b is the energy that would be required to liberate the electron from its atom – depends mainly on the principal quantum number.



Example of ionisation:
photoelectric effect

$$h \cdot f = E_b + \frac{1}{2} m \cdot v^2$$

Emission Spectra

slits

prism

Visible emission spectrum of **hydrogen**.

modro- =
bluish
Learn the Czech
names of
colours 😊

Hydrogen
discharge tube

Excitations between *discrete* energy levels result in emitted photons with only certain *discrete* energies, i.e. radiation of certain frequencies/wavelengths.

Excitation
of
electrons

Emission
of light

Hydrogen spectrum again

magenta, cyan
and red line

according
http://cwx.prenhall.com/bookbind/pubbooks/hillchem3/media_portfolio/text_images/CH07/FG07_19.JPG

Excitation (absorption) Spectra for Atoms

Absorption lines in visible spectrum of sun light.

Wavelengths are given in Angströms (\AA) = 0.1 nm

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Transitions between discrete energy states of atoms!!

Excitation (Absorption) Spectrum for Molecules

Absorption spectrum of a dye

Absorbance

Wavelength

Atom nucleus

Proton (atomic) number – Z

Nucleon (mass) number – A

Neutron number – N $N = A - Z$

Atomic mass unit $u = 1.66 \cdot 10^{-27}$ kg, i.e. the 1/12 of the carbon C-12 atom mass

Electric charge of the nucleus $Q = Z1.602 \cdot 10^{-19}$ C

If relative mass of electron = 1

⇒ Relative mass of proton = 1836

⇒ Relative mass of neutron = 1839

Mass defect of nucleus

= measure of nucleus stability:

$$\delta m = (Zm_p + Nm_n) - m_{nuc}$$

Binding energy per one nucleon [MeV]

nuclear
synthesis

scale
change

fission

Sources:

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$$E = \delta m \cdot c^2$$

This formula allows to calculate amount of energy liberated during the synthesis of the nucleus.

nucleon number

Nuclides

- **nuclide** - a nucleus with a given A , Z and energy
- **Isotopes** - nuclides with same Z but different A
- **Isobars** – nuclides with same A but different Z
- **Isomers** – nuclides with same Z and A , but different energy (e.g., $\text{Tc}^{99\text{m}}$ used in gamma camera imaging)

Isotope composition of mercury

% of Hg atoms vs. isotope nucleon number (A)

Percentage of atoms

Nucleon number

A

What else is necessary to know?

- **Radionuclides** – nuclides capable of radioactive decay
- **Nuclear spin:**
Nuclei have a property called spin. If the value of the spin is not zero the nuclei have a magnetic moment i.e, they behave like small magnets - NMR – nuclear magnetic resonance spectroscopy and magnetic resonance imaging (MRI) in radiology are based on this property.

M U N I

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