MUNI
PHARM

Structure of Matter

Ionizing radiation, types, interaction with matter. Methods of detection.
Interaction of ionizing radiation with living matter, its use in medicine.

Non-ionizing electromagnetic radiation. Properties of radiation. Radiation sources.
The influence of visible light, UV radiation and IR radiation to organism.

Biophysics

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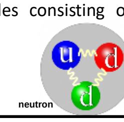
The Structure of Matter

Elementary particles (no internal structure)
- Particles of matter (Fermions)
  - Leptons (electron, muon, tau, neutrinos)
  - Quarks (u, c, t, d, s, b)
- Particles of interactions (Bosons)
  - Photon
  - Gluon
  - Boson W and Z
  - Graviton (hypothetical)

- Baryons (composite particles) – heavy particles consisting of quark, e.g. proton (u, u, d), neutron (d, d, u)
- Antiparticle – eg. positron, antiproton



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The four fundamental interactions of nature

Gravitational force

- Interaction that acts on all particles having mass, energy and/or momentum
- The weakest interaction of the four interactions (is very important for macroscopic objects and over macroscopic distances)
- Cannot be absorbed, transformed, or shielded against
- Always attracts and never repels

$$F_{grav} \propto \frac{m_1 * m_2}{d^2}$$

where F_{grav} represents the force of gravity between two objects
$\propto$ means "proportional to"
m_1 represents the mass of object 1
m_2 represents the mass of object 2
d represents the distance separating the objects' centers

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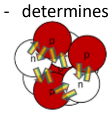
The four fundamental interactions of nature

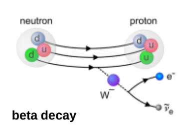
Strong interaction

- The interaction of quarks in the nucleus - determines its structure (it varies with distance)
- The particles of strong interaction are gluons



Weak interaction

- Destructive – is responsible for some nuclear phenomena such as beta decay (e.g. beta decay of a neutron transforms it into a proton)
- The particles of strong interaction are bosons called the W and Z bosons



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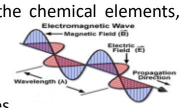
The four fundamental interactions of nature

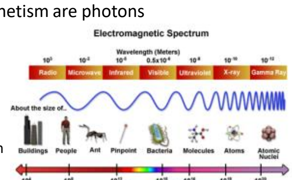
Electromagnetism

- Electromagnetism fundamentally determines all macroscopic, and many atomic levels, properties of the chemical elements, including all chemical bonding



- Acts between electrically charged particles
- The particles of electomagnetism are photons

$E = h*f = h*c/\lambda$
h - Planck constant
($6{,}63 \times 10^{-34}$ J.s),
f - frequency,
c - the speed of light in vacuum
λ - wavelength



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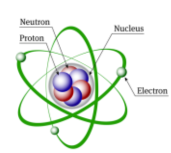
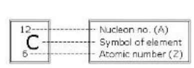
Atomic structure

- The size of the atom 10^{-10} m
- The size of the nucleus 10^{-15} m
- Weight of the nucleus = 99.9% of weight of the atom

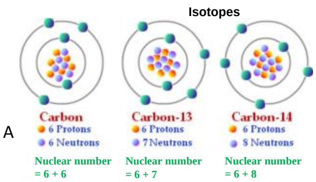


Atom nucleus

- Atomic number Z
- Neutron number N
- Nucleon (mass) number A



Isotopes



Stable   Stable $^{14}_{6}C \longrightarrow ^{14}_{7}N + e^- + \bar{\nu}_e$

Use: Isotopic labeling   Radiocarbon dating

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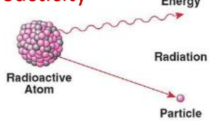
Atomic structure: Radioacticity

Radioactivity is the spontaneous decay of an unstable atom to be a stable atom by emitting radioactive rays or energetic particles.



Radioactive decay (also known as radioactivity) is the process by which the nucleus of an **unstable atom loses energy** by emitting radiation, including **alpha particles (helium nuclei $^{4}_{2}He^{2+}$)**, **beta particles (electrons)** and **gamma rays (photons)**.

A **radionuclide** (radioactive nuclide, radioisotope or radioactive isotope) is an atom that has excess nuclear energy, making it unstable.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e$$

Some decay processes lead to the formation of another element's atom. This is known as **nuclear transmutation**.

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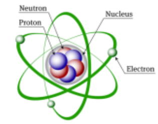
Electron shell



The electrons (and other particles) may be partly described in terms not only of particles, but also of waves: wave–particle duality.

As a result, the position of the electron in the atom and its momentum can not be determined with any precision (Heisenberg uncertainty principle). To describe the electron position we have to use probability.

Electron shell of atoms does not correspond to the idea of classical physics but is described by orbitals – space where the electron can be present. Each electron is described by the set of quantum numbers.

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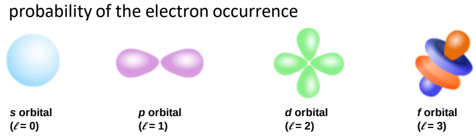
Electron shell

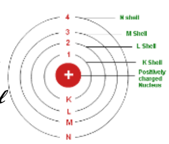
Atomic orbitals

- geometric space defining an area where there is a high probability of the electron occurrence



Quantum numbers

- **Principal** n = 1, 2, 3 .... (K, L, M, ...)
- **Azimuthal** – for each n ℓ = 0, 1, 2, ... n – 1 (orbitals *s, p, d, f* ...)
- **Magnetic** – for each ℓ m = 0, ±1, ±2, ...± ℓ (orientation of orbital in space)
- **Spin** – for each m s = ±1/2 (spin angular momentum)



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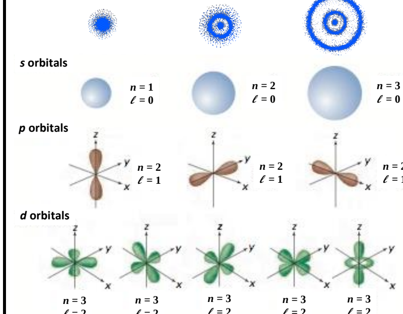
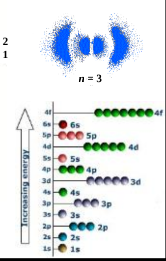
Electron shell





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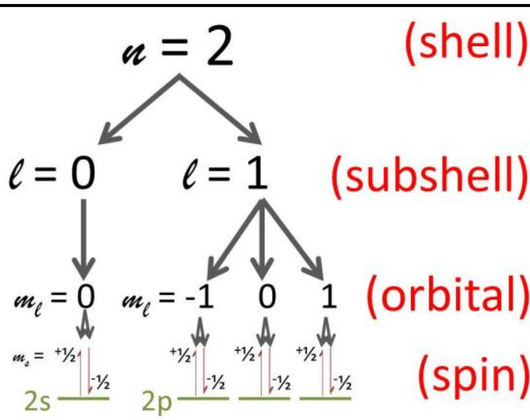

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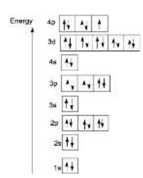
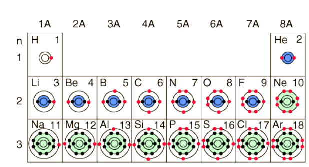
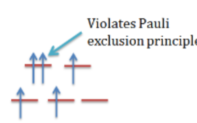
Electron shell

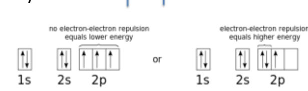




Pauli exclusion principle – states that two or more identical electrons cannot occupy the same quantum state within a quantum system simultaneously.



Hund's rule



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Electron shell

Chemical bond and reactivity

Valence electron: An electron in one of the outer shells of an atom that can participate in forming chemical bonds with other atoms.

An atom with a closed shell of valence electrons tends to be chemically inert. Atoms with one or two more valence electrons than are needed for a "closed" shell are highly reactive due to the following reasons:

1) It requires relatively low energy (compared to the lattice enthalpy) to remove the extra valence electrons to form a positive ion.

2) Because of their tendency either to gain the missing valence electrons (thereby forming a negative ion), or to share valence electrons (thereby forming a covalent bond).

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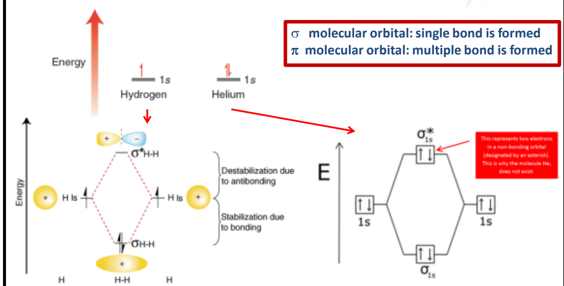
Electron shell

Chemical bond

The valence electrons participates in the formation of chemical bonds between the atoms (formation of molecular orbitals).

σ molecular orbital: single bond is formed
π molecular orbital: multiple bond is formed



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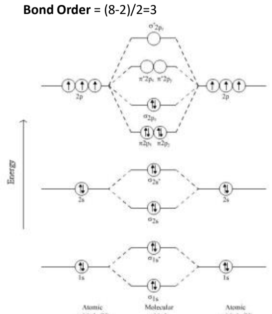
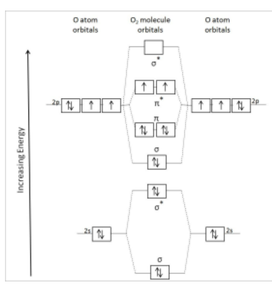
Electron shell: Chemical bond

Bond Order = (number of valence e⁻ in MO) – (number of valence e⁻ in MO*) / 2

N: Outer shell has 5 valence electron
Bond Order = (8-2)/2=3

O: Outer shell has 6 valence electron
Bond Order = (8-4)/2=2





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Interaction of Electromagnetic Radiation with Matter

Biophysics

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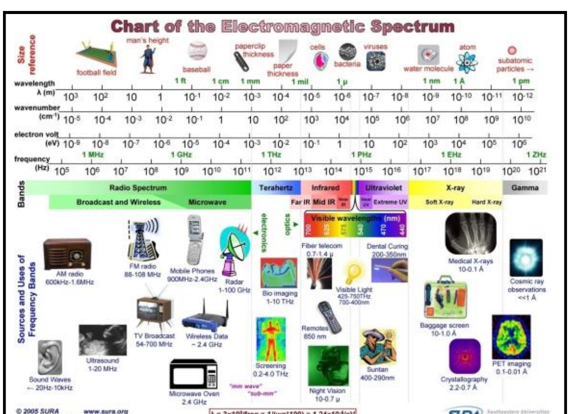

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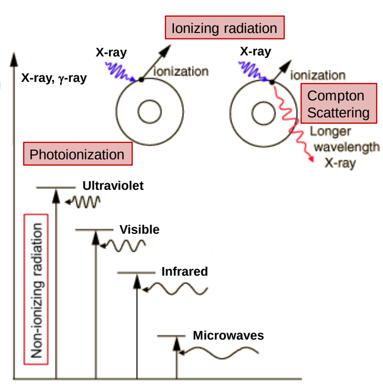
The interaction of radiation with matter



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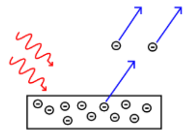
Interaction of γ radiation and X-ray with electron shell

- Photoionization

  (low-energy phenomena < 0.1 MeV)

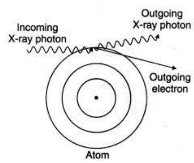
  The incident photon interacts with an atom of the absorbing material, and the photon completely disappears; its energy is transferred to one of the electrons of the atom (electron is ejected at high velocity).



- Compton scattering

  (mid-energy phenomena > 1 MeV)

  The incident photon transfers only a portion of its original energy to the electron from which it scattered, producing an secondary electron. After the interaction, the scattered photon has an energy that has decreased by an amount equal to the energy transferred to the secondary electron.



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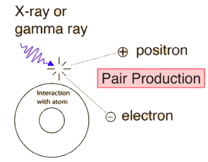
Interaction of γ radiation and X-ray with electron shell

- Electron-positron pair formation

  (high-energy phenomena > 1 MeV)

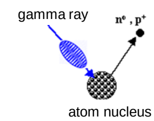
  Incident photon creating an electron-positron pair near a atom nucleus (the higher the charge of nuclei, the greater the probability of the phenomenon).



- Interactions with the atomic nucleus

  (high-energy phenomena > 8-10 MeV)

  If the photon energy is sufficiently high, may cause radioactive decay of the atomic nucleus (neutron or proton is ejected from the nuclei).



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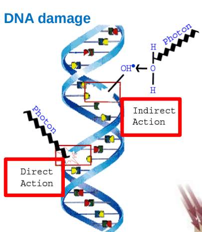
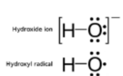
Biological effects of ionizing radiation



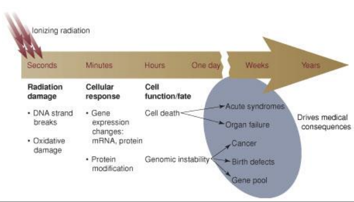
Free radical formation by radiolysis of water

$H_2O + \gamma \text{ ray} = H_2O^+ + e^-$

$H_2O^+ = H^+ + {}^\bullet OH$



Hydroxyl radical
- it is very reactive; reacts with biomolecules and damages their structure.



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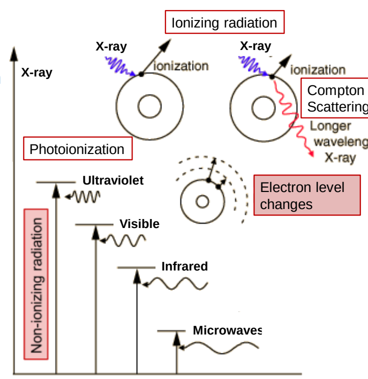
The interaction of radiation with matter



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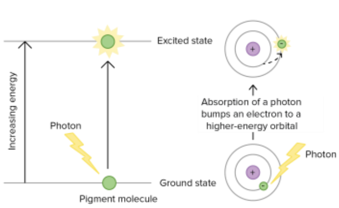
Interaction of UV/VIS radiation with electron shell



The UV/VIS photon is absorbed by the molecule if its energy (wavelength) corresponds to the energy difference between the electron levels.

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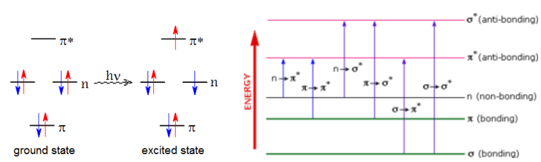
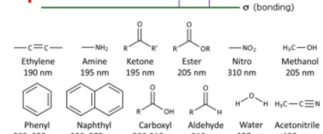
Interaction of UV/VIS radiation with electron shell



π→π*: unsaturated compounds

n→π*: -C=O -C=S -N=O

Other transitions require UV radiation of higher energy (λ<200 nm), which is also absorbed by air.



Chromophore: the part of a molecule responsible for UV/VIS absorption. UV/VIS radiation that hits the chromophore can thus be absorbed by exciting an electron from its ground state into an excited state.

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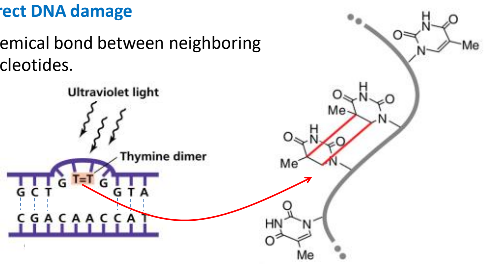
Biological effects of UV radiation

Direct DNA damage

Chemical bond between neighboring nucleotides.



UV radiation produced a thymine dimer and the surrounding DNA is opened to form a bubble. This damage create impediments to replication or transcription.

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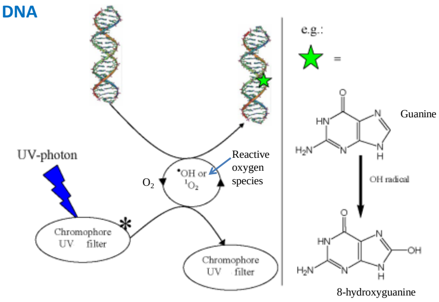
Biological effects of UV radiation

Indirect DNA damage



Reactive oxygen species (ROS) are able to oxidize other molecules. Formation of 8-hydroxyguanine can lead to transversion mutations (cancer).

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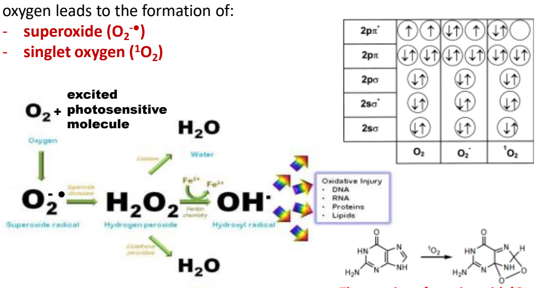
Biological effects of UV radiation

Indirect DNA damage

Absorption of UV radiation by endogenous (e.g. flavins, porphyrins, melanin) or exogenous (e.g. NSAIDs) molecules. Subsequent reaction with oxygen leads to the formation of:

- superoxide ($O_2^{-\bullet}$)
- singlet oxygen ($^1O_2$)



The reaction of guanine with $^1O_2$

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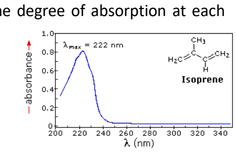
UV/VIS spectrophotometry

- When sample molecules are exposed to light having an energy that matches a possible electronic transition within the molecule, some of the light energy will be absorbed as the electron is excited to a higher energy orbital.
- An optical spectrometer records the wavelengths at which absorption occurs, together with the degree of absorption at each wavelength.
- The resulting spectrum is presented as a graph of absorbance (A) versus wavelength.



Absorbance (quantitative determination):

$A = \log I_0/I$

$A = \varepsilon * c * l$ Lambert-Beer law

c = Concentration (mol/l); l = Length of light path through the sample (cm); ε = Molar absorptivity (constant for the substance at a certain wavelength; $dm^3.mol^{-1}.cm^{-1}$).

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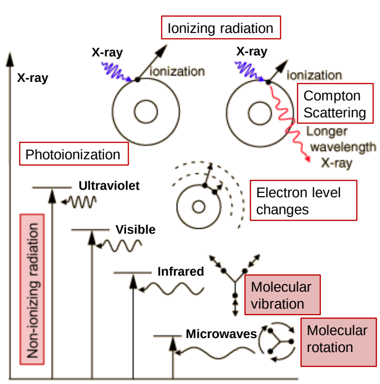
The interaction of radiation with matter



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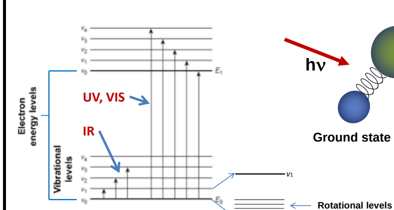
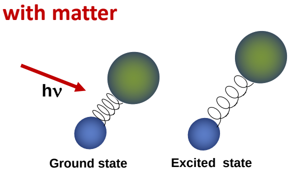
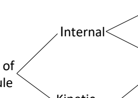
IR radiation interaction with matter







Energy of molecule:

- Internal
  - Energy levels of atoms
  - Energy levels of electrons E_E (influenced by UV/VIS radiation)
- Kinetic
  - Translational energy E_T (is not quantized)
  - Rotational energy E_R (influenced by microwaves)
  - **Vibrational energy** E_V (influenced by IR radiation)

$E_E > E_V > E_R > E_T$

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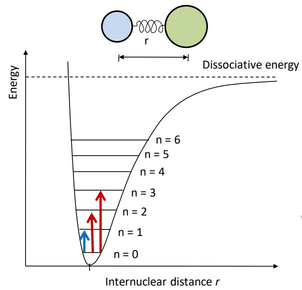
IR radiation interaction with matter



— middle IR — near IR

- The energy of infrared radiation is converted into the energy of the bond vibration - thermal radiation
- Different types of bonds absorb IR radiation of different energies (frequencies) - structure analysis
- The energy of the bond vibration can take on different energy levels (depends on the wavelength of the IR radiation; middle or near IR)

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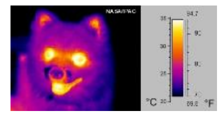
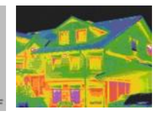
IR radiation interaction with matter

Therapeutic use is based on **the absorption of IR radiation** by the object. Analgesic and antispasmodic effects due to the direct action of higher temperature.

Diagnostic use is based on **the emission of IR radiation** by the object.

Thermal camera





Medical thermometer

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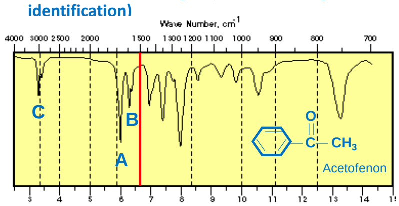
IR radiation interaction with matter

Pharmaceutical analysis (structure analysis, raw materials identification)



A) C=O (1730) B) C=C aromatic (1590) C) C-H aromatic (3050)

- identification of functional groups in organic compounds - characteristic bands (4000–1500 cm^{-1})

$$\tilde{\nu} = \frac{1}{\lambda}$$

- identification of compound - fingerprint region (1500–400 cm^{-1}) - spectra libraries

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