Atomic and Nuclear Physics.

An atom is the smallest constituent unit of the substance carrying the properties of a certain chemical element. Every atom is composed of a **nucleus** and one or more **electrons** bound to the nucleus. The nucleus consist of one or more **protons** and typically a similar number of **neutrons**. Protons and neutrons are called **nucleons**. The protons have a positive electric charge (+e), the electrons have a negative electric charge (–e), and the neutrons have no electric charge. The dimensions of atoms are of some angstrom's (Å) by the order of magnitude (1 Å = 10^{-10} m). The dimensions of nuclei are of some femtometers (1 fm = 10^{-15} m = 1 fermi). It is obvious to give the masses of the subatomic particles in the units of MeV using the rest energies according to the Einstein formula $E = mc^2$. The rest energy of the electron is 0.511 MeV according to the its mass of $m_e = 9{,}11 \cdot 10^{-31}$ kg. The rest energy of the proton is 1836.1 times bigger and so it equals 938.2 MeV. The rest energy of the neutron is 939.5 MeV.

Pauli exclusion principle states that in the same atom can not exist two electrons possessing the same set of four quantum numbers (n, l, m and s). Almost one quantum number must differ. The volume determined by the set of three first quantum numbers (n, l, m) can contain at maximum two electrons possessing countrary oriented spins and localized in the same volume. Such electrons are called paired electrons.

Shell structure of the electronic cloud is forming by the addition of electrons in the atom in such a way that the requirements of the energetic minimum principle and the Pauli exclusion principle are both fulfilled. The number of shell is the main quantum number n, used already in the Bohr model. One shell can contain at maximum $2n^2$ electrons. Electron shells can be subdivided into subshells which are the sets of similar orbitals (2p or 3d-orbitals, for instance). The maximum number of subshells is equal to the shell number. Every subshell is described by his own orbital quantum number l. The subshell possessing lower sum of quantum numbers $n + l$ is filled first. If the sum $n + l$ is equal for two subshells, then the subshell possessing lower quantum number n is filled first. For the 4 -subshell $n + l = 4$, for 3d-subshell $n + l = 5$ and for 4p-subshell $n + l = 5$. So the filling sequence of them is 4s, 3d, 4p, 5s and so on.

Selection rules describe the allowed transitions between states in quantum systems (atoms, for instance). They are determined by the conservation law of the angular momentum. The most important selection rule is $\Delta l = \pm 1$, the orbital quantum number should change by the transition. If the photon is absorbed by the atom, then the angular momentum equal to the one reduced Planck constant $\hbar = h/(2\pi) = 1.054 \cdot 10^{-34}$ J·s is added to the atom. So the orbital quantum number l of one electron in this atom should increase by one: $\Delta l = +1$. If the photon is emitted, then the orbital quantum number of one electron should decrease by one: $\Delta l = -1$.

X-rays are commonly produced by accelerating or decelerating charged particles; examples include a beam of high-energy electrons striking a metal plate in an X-ray tube and a circulating beam of electrons in a synchrotron particle accelerator or storage ring. In addition, highly excited atoms can emit so-called characteristic X-rays with discrete wavelengths or frequencies characteristic of the energy level spacings in the atoms. The X-ray region of the electromagnetic spectrum falls far outside the range of visible wavelengths. However, the passage of X-rays through materials, including biological tissue, can be recorded with photographic films and other detectors.

Moseley law is an empirical law concerning the characteristic X-rays that are emitted by atoms. the law states that the square root of the frequency of the emitted X-ray is proportional to the atomic number. The photon energy of the most intensive line of the characteristic X-rays (called K_α line) is described by the formula $hf = 3/4 \; R\,(Z-1)^2$, where R is the Rydberg constant (13.6 eV) and Z is the sequence number (in the periodic system) of the element (in most cases some metal) used as the material of the X-ray tube anode.

The nucleus is a small and very dense region consisting of protons and neutrons at the center of an atom. Almost all of the mass of an atom is located in the nucleus. Protons and neutrons are bound together to form a nucleus by the nuclear force originated by the strong interaction. Only the strong interaction is able to hold the positively charged and so electrically repelling protons together at such small distances. The branch of physics concerned with the study and understanding of the atomic nucleus, including its composition and the forces which bind it together, is called **nuclear physics**.

Binding energy of the nucleus is the energy required to break down a nucleus into its component nucleons. Nuclear binding energies are usually expressed in terms of MeV's per nucleon. Calculation of the nuclear binding energy involves the following three steps: 1) determining the mass defect ΔM, 2) conversion of mass defect into binding energy E_b, according to the formula $E_b = \Delta M c^2$ and 3) expressing nuclear binding energy as energy per nucleon $E_{bn} = E_b / A$, where A is the number of the nucleons: $A = Z + N$. Here Z is the number of protons and N is the number of neutrons for the certain nucleus.

The mass defect ΔM is the difference between the mass of a nucleus and the sum of the masses of the nucleons of which it is composed. Three things need to be known in order to calculate the mass defect are: 1) the actual mass of the nucleus, 2) the composition of the nucleus (number of protons and of neutrons), 3) the masses of a proton and of a neutron. If we want to calculate the mass defect, we should add up the masses of each proton and of each neutron that make up the nucleus, and then subtract the actual mass of the nucleus from the combined mass of the components to obtain the mass defect.

The binding energy per nucleon E_{bn} is the most important parameter in the nuclear physics. The nuclei possessing medium number of nucleons (A in the interval from 50 to 60) have the biggest binding energy per nucleon and so they are the most stable ones. So two types of energetically useful nuclear reactions exist: a) nuclear fission of very big nuclei into smaller parts and b) integration of very small nuclei called thermonuclear fusion.

Nuclear fission of an atomic nucleus into two parts of the same size is typically caused by the collision of a particle. Nuclear fission may also occur spontaneously in the case of very heavy nuclei. The capture of a neutron induces fission of the nucleus of uranium-235 (denoted as ^{235}U, possessing $Z = 92$, $N = 143$ and $A = 235$). The ^{235}U is the main fuel used in the nuclear power plants. During the fission, in general two fission products and two to three neutrons are generated. In addition some energy is released. For nuclei heavier than nickel-62 (^{62}Ni) the binding energy per nucleon decreases with the mass number. It is therefore possible for energy to be released if a heavy nucleus breaks apart into two lighter ones.

The process of alpha decay is in essence a special type of spontaneous nuclear fission. It is a highly asymmetrical fission because the two protons and two neutrons which make up the alpha particle (nucleus of a helium atom) are especially tightly bound to each other, making production of this nucleus in fission particularly likely.

The chain reaction. From certain of the heaviest nuclei whose fission produces free neutrons, and which also easily absorb neutrons to initiate fission, a self-igniting type of neutron-initiated fission can be obtained. It is called a chain reaction. In the case of chain reactions the products of the initial reaction are able to start a new reaction immediately.

Thermonuclear fusion is a way to achieve nuclear fusion by using extremely high temperatures. There are two forms of thermonuclear fusion: uncontrolled, in which the resulting energy is released in an uncontrolled manner, as it is in thermonuclear weapons such as the hydrogen bomb, and controlled, where the fusion reactions take place in an environment allowing some of the resulting energy to be harnessed for constructive purposes. The thermonuclear fusion of hydrogen into helium takes place in the Sun and this reaction is the main energy source of the Sun and the other main sequence (Sun-like) stars. The studies oriented to performance of the controlled thermonuclear fusion in some power plant are implemented already during decades and the final breakthrough is prognosed in the next 20-30 years.

Radioactive decay (also known as *nuclear decay* or *radioactivity*) is the process by which the nucleus of an unstable atom loses energy by emitting some radiation. This radiation can include: alpha particles (helium nuclei), beta particles (high-energy electrons created by conversion of a neutron into a proton, electron and antineutrino), gamma rays (electromagnetic photons generated by the transitions between the nuclear energy levels), and conversion electrons. A material that spontaneously emits such radiation is considered radioactive. Radioactivity refers to the particles which are emitted from nuclei as a result of nuclear instability. Because the nucleus experiences the intense conflict between the two strongest forces in nature (strong and electromagnetic), it should not be surprising that there are many nuclear isotopes which are unstable and emit some kind of radiation.

The law of radioactive decay: Radioactive decay is a statistical process which depends upon the instability of the particular radioisotope, but which for any given nucleus in a sample is completely unpredictable. The decay process and the observed half-life dependence of radioactivity can be predicted by assuming that individual nuclear decays are purely random events. If there are N radioactive nuclei at some time t, then the number ΔN which would decay in any given time interval Δt would be proportional to the initial amount of nuclei N. So we have $N(t) = N_0 \exp(-p\,t) = N_0 \exp(-t/\tau) = N = N_0\, 2^{-t/T}$, where N_0 is the initial number of radioactive nuclei (at the time instant $t = 0$) and $N(t)$ is the number of nuclei at the time t. The quantity p is the probability of the decay in the unit interval of time, $\tau = 1/p$ is the lifetime or time constant. It is the time during which the number of nuclei decreases of Euler number (e = 2,7183) times. T is the half-life time, $\tau = T/\ln 2$. During the half-life time the number of nuclei decreases twice (until half of the initial value). So the law of radioactive decay is the typical exponential decay in time.

Radiocarbon dating is a technique used by scientists to learn the ages of biological specimens (for example, wooden archaeological artifacts or ancient human remains) from the distant past. The method is using the properties of radiocarbon (^{14}C, possessing half-life $T = 5730$ years), a radioactive isotope of carbon. In the living organism the radiocarbon is present in a certain concentration determined by the metabolic exchange of organic substances between the organism and the environment. If the organism dies, the concentration of radiocarbon can only decay. The dating technique is based on the determining of the remained concentration of radiocarbon and estimating from the radioactive decay law the time interval during which the radioactive decay of radiocarbon has taken place. An analogous technique for the dating of the geological sedimentary layers and the whole Earth is based on the use of the isotopes possessing ultra long half-life times (for instance ^{40}K, possessing $T = 1{,}25$ billions of years).

The activity of the radioactive preparate shows us the number of radioactive nuclei decaying in preparate during a time unit. A **becquerel** (symbol 1 Bq) is the SI derived unit of activity. One becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. The becquerel is therefore equivalent to an inverse second, s^{-1}.

Radiation dose has many forms and includes: absorbed dose, equivalent dose and effective dose. Absorbed dose is used to assess the potential for biochemical changes in specific tissues. Absorbed dose D is determined by the energy of radiation absorbed by the amount of the substance possessing unit mass: $D = E_{rad}/m$. Equivalent dose or biodose is used to assess how much biological damage is expected from the certain absorbed dose. It is so because different types of radiation have different damaging properties. Effective dose is used to assess the potential for long-term effects that might occur in the future.

The grey (1 Gy) is the SI unit of the absorbed dose. The dose is one grey when in the one kilogram of substance the radiation energy of one joule is absorbed: 1 Gy = 1 J /1 kg.

The sievert (1 Sv) is a derived SI unit of the equivalent dose. It is a measure of the health effect of low levels of ionizing radiation on the human body. In the case of X-rays, gamma rays and beta rays the equivalent dose 1 Sv corresponds to the absorbed dose 1 Gy. In the case of alpha or neutron irradiation the equivalent dose corresponding to the absorbed dose 1 Gy is 3-10 Sv. According to the widely accepted agreement the lethal equivalent dose is 5 Sv.

The power of dose P_D shows us the dose acquired during the unit time interval: $P_D = D/t$. The power of natural background biodose is approximately 0.1 μSv/h.