

Main properties of atoms and nucleus

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1. Atom Structure

All materials composed from atoms, atom consists of a positive charged nucleus and negatively charged electrons, enclosing it. In 1911 Ernest Rutherford has approved that mass of the atoms mainly (99.9%) concentrated in nucleus.

The atom size is approximately equal to 10^{-10} m.

The charge of one electron equal to $1.6 \cdot 10^{-19}$ C or in relative units to -1 .

2. Structure of Nuclei

Size of the nucleus is in order of $10^{-15} \div 10^{-14}$ m. Charge of the nucleus **Z** is positive and equal to serial number of current chemical element in Periodic Table of Elements

(see <http://www.webelements.com>).

For example, charge of the nucleus of oxygen atom equal to +8.

Nucleus consists of nucleons: protons and neutrons.

Proton is nucleus of hydrogen, stable particle.

Proton is stable particles and did not change own characteristics in time. Charge of one proton equal to +1. Mass of one proton equal to $1.673 \cdot 10^{-27}$ kg or 1.00782 u (atomic mass unit). 1u is the same as 1/12 of mass ^{12}C atom and equal to $1.661 \cdot 10^{-27}$ kg. Number of protons in nucleus equal to number of electrons in atom.

Neutron is neutral particle. Neutron is unstable particle when outside of nucleus, it decay to proton, electron and antineutrino. Average lifetime approximately equal 15 min.

Inside stable nucleus, neutron is stable particle. Charge equal to 0 (uncharged). Mass of one neutron approximately equal to mass of one proton: $1.675 \cdot 10^{-27}$ kg or 1.00786 u.

Proton and neutron is characterized by spin – internal moment.

Charge of nucleus equal to number of protons in nucleus. Number of protons and neutrons in nucleus called atomic mass number **A**.

3. Definition of Isotopes

Different atoms, which nuclei contain the same number of protons are named isotopes (see <http://atom.kaeri.re.kr>).

The numbers of protons in nucleus determining the numbers of electrons in atom and therefore chemical properties of isotopes. The isotopes with different numbers of neutrons have identical chemical properties. It should be mentioned that physical properties of isotopes could be essentially different. Some of them are stable, others can decay and emit particles (they are radioactive). For example, there are four well-known carbon isotopes with **A**=11,12,13,14. Carbon isotopes with atomic mass numbers 12 and 13 are stable. Carbon isotopes with atomic mass number 11 and 14 are radioactive.

Therefore, if we are interested in atoms not only from point of view of its chemical characteristics, then we are talking about it as about a nuclide. We start using the term - nuclide or radionuclide and will add to name of nuclide the atomic mass number. For example: carbon-14, cesium-137. Nuclide can be determined also by symbol with specification of its charge and number of neutrons. For example: ${}^{14}_6\text{C}_8$, ${}^{137}_{55}\text{Cs}_{82}$. Upper index is atomic mass number, left sub index is charge of element atom nucleus and right sub index is number of neutrons.

Radius of atomic nucleus depends on atomic mass number A and equal to:

$$r = r_0 \sqrt[3]{A}, \quad \text{where } r_0 = 1.35 \cdot 10^{-15} \text{ m}. \quad (1)$$

As nucleons, nucleus has a spin, which can be determined by own nucleons spins and by its movement in the nucleus. If nucleus has even number of protons and even number of neutrons, then spin of that nucleus equal to zero. Otherwise, it is determined by the spins and movement of the odd nucleons.

4. Energy Characteristics of Nuclei

The nucleons in nucleus are in constant movement. The nucleons in nucleus have different velocity of movement and different energies. The sum of nucleon energies determines full energy of nucleus (but not equal). According to quantum laws full energy of nucleus is discrete value, nucleus can have just only certain energy values.

Nucleus, which has minimally possible energy is named as nucleus in ground state, otherwise the nucleus is in excited states. Excitation energy is energy equal to difference of nucleus energy in excited state and energy of nucleus in ground state. Set of the excited states for the nucleus ${}^{56}\text{Fe}$ represented on figure 1. Zero of excitation energy on that graph represents nucleus in ground state. Electron-volt is main energy unit in nuclear physics ($1\text{eV}=1.6 \cdot 10^{-19} \text{ J}$, $1 \text{ MeV}=10^6 \text{ eV}$, $1\text{keV}=10^3 \text{ eV}$).

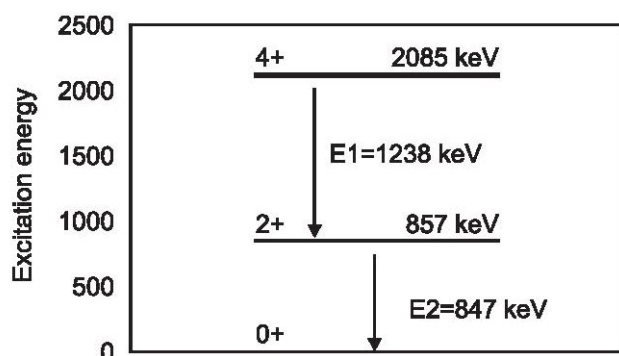


Figure 1. The excited states of Fe-56 nucleus

γ -quantum or γ -rays is electromagnetic waves having very short wavelength in comparison to other electromagnetic waves such as visible light, heat rays, and radio waves, which can be escaped from the nucleus during radioactive decay. Because of some special laws, which are not the aim of that chapter, γ -rays of certain energies will be escaped from excited nucleus until nucleus becomes in the ground state. For example, if Fe-56 atom nucleus is in excited state with excitation energy equal to 2085 keV, from that nucleus can escape γ -rays with energy equal to 1238 keV and after that γ -rays with energy equal to 847 keV or one γ -ray with energy equal to 2085 keV.

Emission of γ -rays from the nucleus is not unique process of changing of nucleus state. Excitation energy can be transferred to nearby atomic electron.

Other fundamental value for nuclear physics is binding energy per nucleon **B**. Binding energy of nucleus is energy, which should be transfer to nucleus for liberation of all nucleons from nucleus. Binding energy per nucleon **B** is equal to binding energy of nucleus divided on number of nucleons in nucleus (atomic mass number **A**). Binding energy per nucleon ranged from 1 MeV for H-2 to 8.7 MeV for Fe-56. Binding energy per nucleon **B** is a measure of nucleus stability. If two nuclei with equal number of nucleons have different value **B**, than for nucleus with less **B** is favourably to change current state and become nucleus with higher value of **B**. As more energy it should be spent to liberate of all nucleons from nucleus as less energy of nucleus. During the process of energy dissemination the γ -ray will be escaped from nucleus.

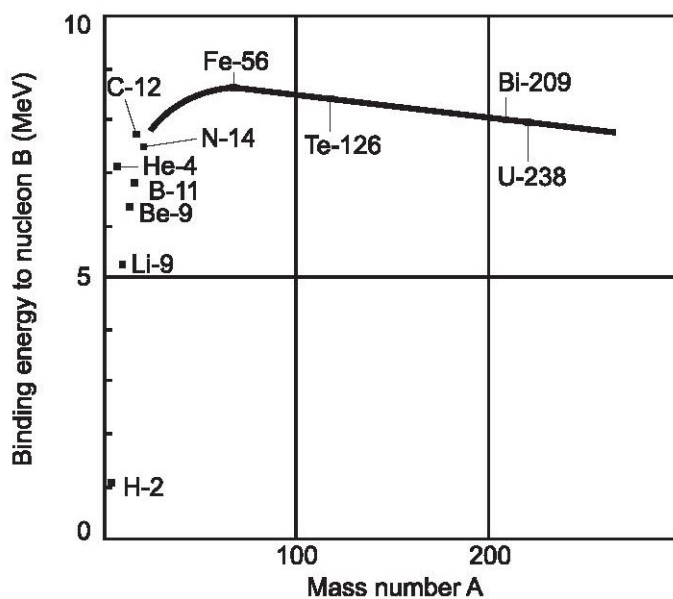


Figure 2. The binding energy per nucleon **B** (MeV) for nucleus with different atomic mass number **A**.

Figure 2 represents the binding energy per nucleon **B** (MeV) for nucleus with different atomic mass number **A**.

From that figure it is seen that, if U-238 with **B**=7.5 MeV will be divided to two parts, for each part, **B** will be about 8.5 MeV. That means that in such process will be produced about 1MeV for each nucleon. For 200 nucleons it will be about 200 MeV. This fact is basement for nuclear energy production technologies.

5. Laws of Radioactive Nuclei Transformation

In 1905 Einstein approve mass-energy equivalence equation ($E = m \cdot C^2$). In that equation **E** is energy, **m** is mass, and **C** is the velocity of light. That is main law of mass and energy equivalence.

As it was mentioned, that you should spend some energy to separate all nucleons in nucleus. Therefore nucleus mass **M(A,Z)** should be less than sum of masses of all nucleons in nucleus. This is a basis for radioactive decay.

Most common types of radiation are attributed to radioactive decay are alpha, beta and gamma rays.

Gamma (γ) rays (γ -quantum or γ -photons) are electromagnetic waves having very short wavelengths in comparison to other electromagnetic waves such as visible light, heat rays, and radio waves. Gamma rays originate from atomic nuclei. Electromagnetic waves have no mass; essentially, an individual wave or photon consists of oscillating electric and magnetic fields, which are propagated together through space. All photons travel at the velocity of light. Their energies, however, vary over a wide range.

The gamma decay appear because of nucleus can change their excite state to excite state with less energy or to ground state. Energy of gamma rays is equal to subtraction of energy of resulting state from energy of initial state of nucleus.

Intensity of the gamma rays determined by quantum characteristics of initial and resulting state of nucleus and by their spins.

The energies of γ -photons are normally expressed in terms of electron-volts, usually millions of electron-volts (MeV).

The energy of gamma photons is very important characteristic of gamma rays. The energy of a photon has tremendous influence on its ability to penetrate through the matter.

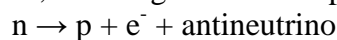
Many types of nuclear transformations are accompanied by the emission of gamma rays. For example, alpha and beta decay of many radionuclides is frequently accompanied by gamma rays. When the parent radionuclide decays to a daughter radionuclide, the daughter nucleus is frequently containing the excess of the energy and is unstable. Stability is usually achieved very quickly through the release of energy in the form of one or more γ -photons. In such cases, the daughter nucleus decays from one energy state to another without changing of atomic weight or number.

Beta particles (β) are electrons or positrons, which are spontaneously ejected from the nuclei of radioactive atoms during the decay process. These particles are electrons for beta-minus decay or positrons for beta-plus decay.

The beta-minus decay can appear when mass of initial nucleus $M(A,Z)$ higher than mass of resulting nucleus more than mass of one electron. The resulting nucleus has the same number of nucleons as initial nucleus.

There is an optimum neutron/proton ratio for stability of the atom. If nucleus has much more neutrons, than protons it is unstable. Nuclides with the optimum ratio are stable. The further the neutron/proton ratio from the optimum, the less stable the nuclide and the more probable that a given atom will disintegrate within a specified time interval.

If the neutron/proton ratio in the nuclei is exceed the optimum, then beta-minus decay is extremely probable. During beta-minus decay, one of the neutrons in nucleus is converted to a proton, reducing the neutron/proton ratio.



and nucleus spontaneously decays with emission of electron and antineutrino.

The charge is changed by +1 since in terms of electric charge. The other feature is the antineutrino, a small particle that always accompanies beta emission.

The antineutrino has very little mass and is electrically neutral; therefore, it could transmit very little energy to the medium through which it travels. It does, however, carry off a variable part of the energy of the radioactive decay. This is explanation, why beta particles are emitted from a given radionuclide with a spectrum of kinetic energies varying from zero up to a specific maximum. The energy of antineutrino is the difference between the maximum possible beta-particle energy and the actual energy of a particle.

On the figure 3 is shown the energy spectrum of the electrons of beta-minus decay. T_e is kinetic energy of beta-particles.

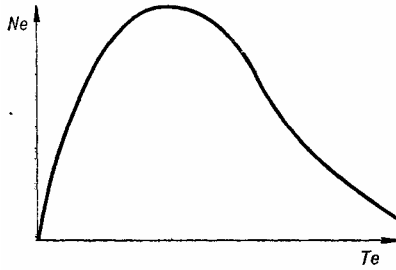
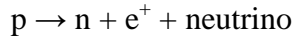


Figure 3. Energy spectrum of the electrons of beta-minus decay

The beta-plus decay can appear when mass of initial nucleus $M(A,Z)$ higher than mass of resulting nucleus $M(A,Z-1)$ more than mass of one positron. The resulting nucleus has the same number of nucleons as initial nucleus.

If the neutron/proton ratio less than optimum, then beta-plus decay is probable. One of the protons in nucleus is converted to neutron, changing the neutron/proton ratio.



and nucleus spontaneously decays with emission of positron and neutrino.

The charge is changed by -1 since in terms of electric charge.

Except for electrical charge, the properties of positrons are identical to beta particles and they may be detected with the same methods.

Radionuclides with a neutron/proton ratio less than optimum may also decay by a process called "electron capture". In this process, the parent nucleus may capture an orbital electron (usually neighbour to nucleus) and subsequently emit an antineutrino and one or more photons, ridding itself of excess energy.

An alpha particle (α), essentially a helium nucleus without orbital electrons, is composed of two protons and two neutrons with a charge of plus two. Alpha particles originate primarily from nuclear decay of a number of the radioactive elements with atomic mass numbers more than 82. Nearly all the energy liberated by this transformation is carried by the alpha particle as kinetic energy.

Alpha decay can appear when mass of initial nucleus $M(A,Z)$ higher than mass of resulting nucleus $M(A-4,Z-2)$ more than mass of one alpha particle. The charge is changed by -2 since in terms of electric charge and atomic mass number is changed by -4. Figure 4 represents alpha decay process of Pu-238.

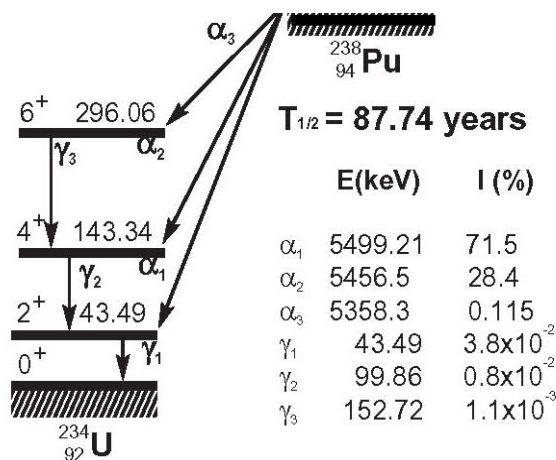


Figure 4. Alpha decay of Pu-238

Radioactivity is the result of the process in which parent radionuclide undergoes spontaneous disintegration and forming daughter nuclide. The number of nuclear disintegration per unit time is proportional to the number of radioactive atoms in the sample. Symbolic representation of radioactive decay law is as follows:

$$\frac{dN}{dt} = -\lambda \cdot N \quad (2)$$

where N is number of radioactive atoms, t is time, and λ is the decay constant. The expression dN/dt is the derivative of number of radioactive atoms with respect to time (velocity of number of atoms changing though time). This equation is equivalent to

$$N = N_0 \cdot \exp(-\lambda \cdot t) \quad (3)$$

where N_0 is number of radioactive atoms in initial moment of time.

Radionuclide half-life ($T_{1/2}$) is a value of time t in which the number of radioactive atoms decreased by factor of two (when $N = \frac{1}{2} \cdot N_0$).

It easy to see from equation 3 that

$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \quad (4)$$

The half-life of radionuclides is defining the prolongation of the radiation hazard.

The quantity of radioactive substance may be expressed either as activity (number of disintegration per unit time) or as mass of substance.

Specific activity is the ratio between the activity and the mass of material giving rise to the activity.

From equation 3 it is seen that instantaneous rate change in the number of nuclear disintegration is the product of the decay constant λ and the number of atoms. Using the notation for activity A^* (disintegration/time or becquerel/sec (Bq)), one can write

$$A^* = \lambda \cdot N. \quad (5)$$

It is clear that activity is proportional to the number of radioactive atoms. The number of radioactive atoms N in sample of specific radionuclide is given by

$$N = (m \cdot N_A) / A \quad (6)$$

where m is the mass of substance in grams, N_A is Avogadro's number ($6.025 \cdot 10^{23}$ atom/mol), and A is atomic mass of radionuclide grams/mol. Therefore,

$$\frac{A^*}{m} = \frac{\ln 2 \cdot N_A}{T_{1/2} \cdot A} \quad (7)$$

where A^*/m is the specific activity of the radionuclide.

Let us now consider the conventional unit of radioactivity, the curie (Ci). The curie was originally designated as the amount of radioactivity emitted by 1g. of radium. This is approximately equal $3.7 \cdot 10^{10}$ Bq. It is important to note that the Curie unit only specifies the number of nuclear disintegration per second and does not specify number or types of radiation emitted per unit time.

Exponential law of radioactive decay, given by equation 3, is correct only when number of radioactive nuclei decreased due to decay and there are no other sources of new radioactive nuclei creation.

In that case, the law will be much more complicated. For example, if N_2 radioactive nuclei with decay constant λ_2 will be created as the result of radioactive decay of N_1 nuclei with decay constant λ_1 , then law should be expressed as follows:

$$\frac{dN_1}{dt} = -\lambda_1 \cdot N_1$$

$$\frac{dN_2}{dt} = -\lambda_1 \cdot N_1 - \lambda_2 \cdot N_2$$

More

<http://www.epa.gov/rpdweb00/understand/index.html>