Chapter 2

Nuclei and Nuclear Radiations

Chapter Outline

2.1 CONSTITUTION OF NUCLEUS

The atomic nuclei consist of positively charged protons and electrically neutral neutrons. If the electric charge is neglected, the properties of the proton and neutron are so similar that they both are called by one name—nucleon.

A proton is a stable particle. A free neutron is radioactive, but its binding condition is stable in a nucleus, for explanation see Section 2.6. The radioactive decay of protons with a very high half-life ($T_{1/2} > 10^{30}$ years) is supposed in some theories. Experimental investigations of the proton decay are going on till now.

The number of protons in a nucleus determines the electric charge and hence number of electrons in an atom. The number of protons is numerically equal to the ordinal number of the element in the periodic system and is called atomic number. Atomic number is denoted by the letter Z.

The number of neutrons is denoted by the letter N. The sum of the number of protons and neutrons $A = Z + N$ is called mass number and approximately defines the nuclear mass.

There is a common designation of a nucleus in the form ${}^{A}_{Z}X$, where X is the name of the element. For example, ${}^{1}_{1}\mathrm{H}$ is the nucleus of hydrogen, ${}^{235}_{92}\mathrm{U}$ is the nucleus of uranium with the mass number 235, and so on. As the name uniquely identifies the atomic number, sign Z often falls in the designation, e.g., ${}^{60}\mathrm{Co}$, ${}^{137}\mathrm{Cs}$, and so on. Sometimes the designation may be calcium-48 or Ca-48.

Nuclei with the same Z but different A are called isotopes, those with the same A but different Z are called isobars, while nuclei containing the same number of neutrons $N = A - Z$ are called isotones. A specific nucleus with given A and Z is called a nuclide. Nuclide is an official term defined by the standard [1].

In nature many elements consist of the mixture of isotopes in definite concentrations. The most part of elements with odd atomic number have only one stable isotope. The elements with even atomic number have several stable isotopes as per rule. Further, we shall use the terms "nucleus" or "nuclide" for an individual nucleus, and the terms "element" and "substance" for natural mixture of isotopes.

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In light nuclei the number of protons is approximately equal to the number of neutrons, i.e., $Z/A \sim 0.5$. For example, ${}^{4}_{2}\mathrm{He}$, ${}^{12}_{6}\mathrm{C}$, and so on up to ${}^{40}_{20}\mathrm{Ca}$. Only in hydrogen, the nucleus has only one proton, $Z/A = 1$. With the increase of Z the number of neutrons overtakes the number of protons, experiencing minor fluctuations around the average from one element to the other and reaches the value $Z/A = 0.39$ for uranium. Such a relation between the number of protons and neutrons correspond to a stable nucleus and is determined by the competition of electrostatic repulsion of protons and nuclear attraction of nucleons. If the relation between the number of protons and neutrons differs from the stable one, then the nuclei undergo radioactive decay.

In Fig. 2.1 the proton−neutron diagram of the known nuclei is presented. It is seen from the plot that for the light elements the ratio N/Z is near 1:1. The more the atomic number the more neutrons are demanded to compensate the repulsive force between protons. For the heavy elements, such as uranium, this ratio is more than 1.5, exactly $N/Z = 1.59$ for ${}^{238}\mathrm{U}$.

Nuclei become unstable if the ratio of protons and neutrons differs from the definite range. All unstable nuclei, even in a ground state, undergo spontaneous transformation that got the name "radioactive decay." There are several forms of radioactive transformations. Among well-known and most probable are alpha and beta (β^+ and β^-) decay and spontaneous fission.

Heavy elements with $Z > 82$ are decayed by alpha decay or spontaneous fission.

The nuclei properties essentially depend on the odds of the numbers Z and N. Among stable isotopes of one element, the number of even−even nuclei (even Z and even N) is the largest. Tin (Sn) has the largest number of stable isotopes—10—of which 7 are even−even. There are only four stable odd−odd nuclides: ${}^{2}_{1}\mathrm{H}$, ${}^{6}_{3}\mathrm{Li}$, ${}^{10}_{5}\mathrm{B}$, and ${}^{14}_{7}\mathrm{N}$.

In addition, it was found that nuclei containing 2, 8, 20, 28, 50, and 82 protons or neutrons and 126 neutrons possess a particularly strong structure and a greater prevalence. (We note that analogous effects take place in the physics of the atom,

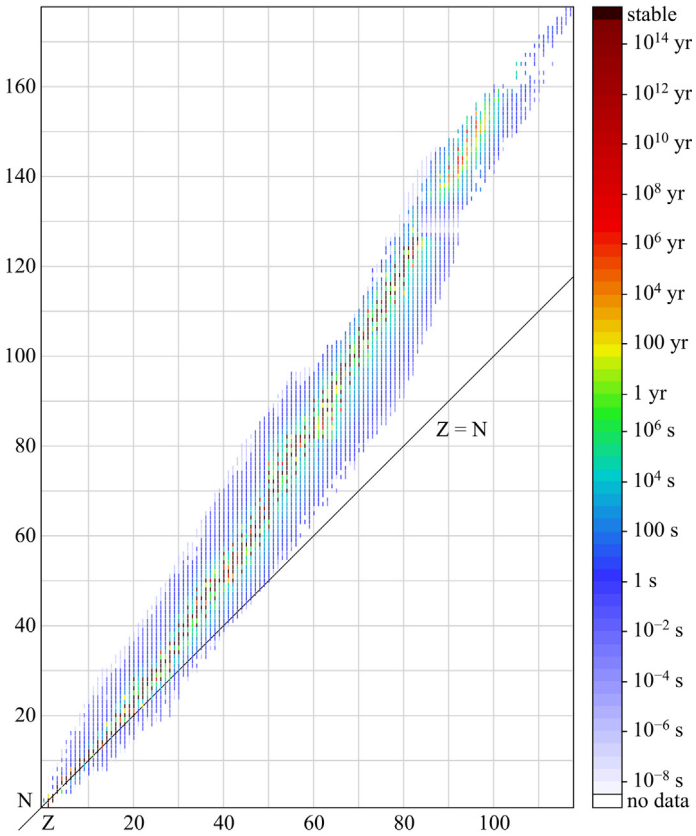

FIGURE 2.1 The proton−neutron diagram. Stable nuclides are shown by the *black points* in the middle of the gray region (colored region in the web version), which designates radioactive nuclides. Their half-lives decrease from the middle of the region to the edges (in the web version their stability is marked by color from red through green and blue to white with decreasing half-life). Above a number of stable nuclides there are radioactive nuclides experiencing mainly β^+-decay or electronic capture (EC), and below β^--decay (Section 2.7.2). *From Plot of Atomic Isotopes. http://commons.wikimedia.org/wiki/File:Isotopes_and_half-life_1.PNG.*

and the atoms having 2, 10, 18, 36, etc. of the electron have the largest values of the binding energy of the electron, i.e., the ionization potential.) The listed values of Z and N have received the name of magic numbers, and nuclei with such Z or N, the magic nuclei. The binding energy of nucleons (Section 2.2) in magical nuclei is 0.5−1 MeV higher than that of neighboring nuclei, and the binding energy in nuclei that become magic after separation of a proton or a neutron, on the contrary, by 1−2 MeV less than the neighboring ones.

If both numbers of proton and neutron are magic, such nuclei are called double magic. There are five double magic nuclei: ${}^{4}_{2}\mathrm{He}, {}^{16}_{8}\mathrm{O}, {}^{40}_{20}\mathrm{Ca}, {}^{48}_{20}\mathrm{Ca},$ and ${}^{208}_{82}\mathrm{Pb}$.

Radioactive magic nuclei have an especially long half-life, and nuclei, the decay of which leads to magical nuclei formation, on the contrary, have a short life span.

2.2 MASS OF A NUCLEUS, BINDING ENERGY

The mass of a nucleus M_{nucl} is less than the sum of the masses of its constituent nucleons (protons—m_p and neutrons—m_n). The difference ΔM between the sum of the masses of nucleons and the mass of the nucleus characterizes the binding energy of nucleons in the nucleus.

$$\Delta M = Zm_p + (A - Z)m_n - M_{nucl}. \tag{2.1}$$

The mass difference ΔM expressed in energy units is called the binding energy.

$$E_{bind} = \Delta M \times c^2. \tag{2.2}$$

The above statement is universal and applies to any bonded systems. So the mass of the atom is less than the sum of the masses of the nucleus and all electrons, and the binding energy of the electron (of one electron of the outer shell, not of all of them) in the atom is ∼10 eV. The mass of the molecule is less than the sum of the masses of the atoms making up the molecule, and the binding energy is of the order of magnitude ∼1 eV. It is seen that in the case of atoms and molecules, the mass difference is very small and its direct measurement is very difficult. It manifests itself only in the need to expend energy on the disintegration of an atom or molecule and in the release of energy during their formation. The binding energy of nucleons in the nucleus is millions of times larger, and the mass difference can be measured with high accuracy by many methods.

In nuclear physics, the mass is measured in "atomic mass units" (a.m.u.). 1 a.m.u is equal to 1/12 part of the mass of the neutral carbon atom ${}^{12}\mathrm{C}$. And a.m.u. in grams is numerically equal to the reciprocal of Avogadro's number N_A

$$1 \text{ a.m.u.} = 1/N_A = 1/6.025 \times 10^{23} = 1.66 \times 10^{-24} \text{ g} \tag{2.3}$$

In energy units

$$1 \text{ a.m.u.} = 931.481 \text{ MeV}$$

The determination of the mass of the nucleus in a.m.u. neglects the difference between the masses of the proton and the neutron, a nonmonotonous change in the ratio of the number of protons and neutrons, and the binding energy with increasing Z. Therefore, the true mass of the nucleus M_{nucl} differs from the mass calculated with the help of the a.m.u. The difference between these quantities is called the mass defect.

$$\Delta = M_{nucl} - A \times (\text{a.m.u.}). \tag{2.4}$$

The mass defect shows the accuracy with which the mass of the nucleus can be determined if mass number A is used. The mass defect has, as a rule, a positive value for light nuclei (up to $A \sim 20$) and is exactly zero for ${}^{12}\mathrm{C}$. It is essential that the mass defect is different from zero for the proton and neutron. At $A > 20$, the mass defect has a negative value, and it grows slowly in absolute value, reaches a maximum at $A \sim 110-120$ (here the mass defect reaches ∼90 MeV), and then decreases monotonically. For a large number of nuclei, the mass defect does not exceed 0.1% of the nucleus mass, and only in some cases it approaches 1% for light nuclei.

Note that E_{bond} is the energy necessary for the collapse of the nucleus into its constituent nucleons. It differs from the binding energy with respect to the emission of one particular particle or the collapse of a heavier nucleus into light nuclei, e.g., the disintegration of ${}^{16}\mathrm{O}$ into four alpha particles.

For a deuteron (${}^{2}\mathrm{H}$), consisting of one proton and one neutron, the detachment energy of any nucleon is naturally equal to each other and equal to the binding energy $E_{bond}({}^{2}\mathrm{H}) = 2.22$ MeV. In all other cases the nucleon detachment energy is noticeably less than the binding energy and in some cases may be even less than the excitation energy of the nucleus. Then the excited nucleus can emit a proton or a neutron, depending on what particles in the nucleus are in excess.

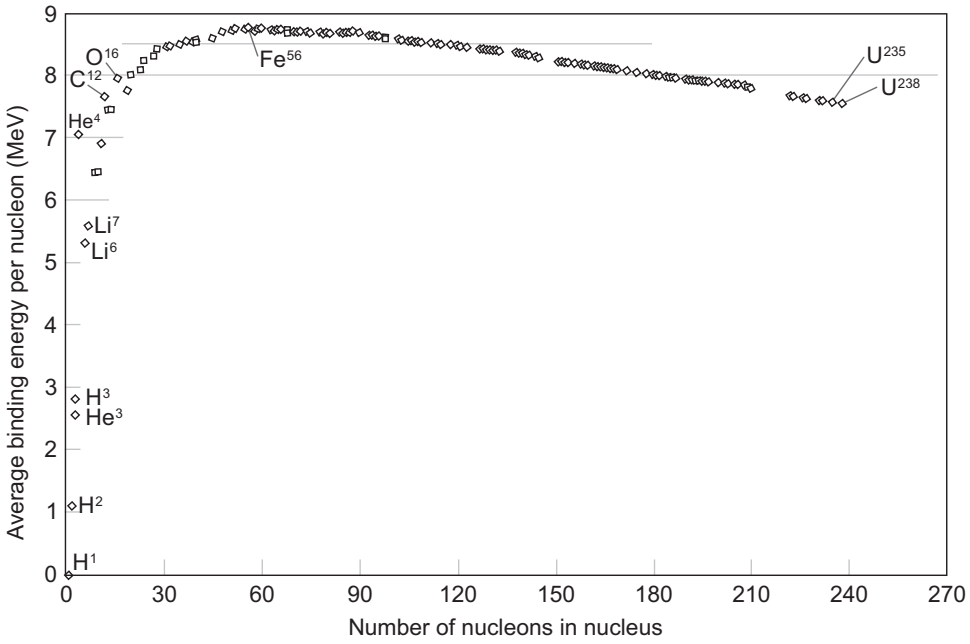

FIGURE 2.2 The dependence of specific binding energy on mass number. *From Nuclear Binding Energy. Wikipedia. https://en.wikipedia.org/wiki/Nuclear_binding_energy.*

A convenient characteristic that makes it possible to compare different nuclei is the specific binding energy of the nucleus, which is equal to the ratio of the total binding energy to the number of nucleons A

$$\varepsilon = E_{bond}/A. \tag{2.5}$$

The greater the specific binding energy, the stronger the nucleus.

The graph of the dependence of the specific binding energy on the mass number is shown in Fig. 2.2.

The typical value of the specific binding energy is several MeV. Thus, for the lightest nucleus consisting of only two nucleons, for a light isotope of hydrogen, deuterium, $\varepsilon = 1.1$ MeV, for a helium nucleus (alpha particle) $\varepsilon = 7.07$ Mev, and for its neighbors $\varepsilon(^3\text{He}) = 2.53$ MeV, $\varepsilon(^6\text{Li}) = 5.3$ MeV. Further, by increasing A the quantity ε grows nonmonotonically, reaches a flat maximum in the region $A \sim 50 \div 70$ ($\varepsilon_{max} = 8.8$ MeV at $A \sim 60$), and then slowly drops to $\varepsilon = 7.6$ MeV for the heaviest element—uranium. (For most tightly bound nuclei—$^{62}_{28}\text{Ni}$, $^{58}_{26}\text{Fe}$, $^{56}_{26}\text{Fe}$—$\varepsilon = 8.8$ MeV).

If in any way to break up the nucleus to the right of the maximum, the fragments formed will have a large binding energy, which means the energy will be released. This is the basis for modern nuclear power. If in some way to merge the nuclei located to the left of the maximum, then in this case energy will be released also. The thermonuclear energy of the future is based on this.

2.3 NUCLEAR SIZE

The boundaries of a microparticle are usually determined by the volume in which the substance creating the interaction is enclosed. The nucleons inside the nucleus participate in all known types of interaction. In this section, two of them are essential—electromagnetic due to the electric charge of protons and a special, so-called "strong" or "nuclear" due to the "nuclear charge" of nucleons. If these two kinds of charge are distributed in the nucleus differently, then the size of the nucleus depends on the way it is determined.

If we assume that the nucleus has a spherical shape, then the radius of the nucleus is

$$R_{nucl} = r_0 A^{1/3}. \tag{2.6}$$

where the value of the parameter r_0 slightly depends on the method of measuring the size of the nucleus. Thus, in measuring the scattering of fast electrons by nuclei, an "electromagnetic" radius is obtained for which $r_0 = (1.2 - 1.3) \times 10^{-13}$ cm. When measuring neutron scattering by nuclei, a "nuclear" radius is obtained for which $r_0 = (1.3 - 1.4) \times 10^{-13}$ cm. This, in particular, means that the electric charge and the substance responsible for the nuclear interaction are not distributed in the nucleus in an absolutely similar manner.

The relation (Eq. 2.7) shows that the nucleus volume is proportional to mass number A

$$V = \left(\frac{4}{3}\right)\pi R_{nucl}^3 = \left(\frac{4}{3}\right)\pi r_0^3 A. \tag{2.7}$$

Therefore, the density does not depend on A and for different nuclei is practically similar and equals to $\sim 2 \times 10^{14}$ g/cm^3.

Note that the nuclei do not necessarily have a spherical shape. Many nuclei have the shape of a prolate or an oblate triaxial ellipsoid, and some are even more complex.

Our ideas about the shape and size of microparticles to some extent are naturally based on our everyday experience of the surrounding bodies and, in particular, the observation of the planets. Note that the occurrence of solid surfaces in these bodies means that these bodies have a short-range repulsion. From this point of view, the nucleus resembles a liquid drop with a solid core; short-range repulsion exists, but it is deep inside the nucleus; and the bombarding particles, i.e., electrons or neutrons, can penetrate into the nucleus.

2.4 NUCLEAR MOMENTS

2.4.1 Nuclear Mechanical Moments (Angular Moment and Spin)

The nucleons inside the nucleus have their own mechanical moments s (spins). The spin of the nucleon is 1/2 (in units of $\hbar$). Besides, the nucleons have mechanical moments ℓ, related to their motion in the nucleus. By analogy with the motion of electrons in an atom, these moments are called orbital. The spin of each nucleon is added to its orbital angular momentum, forming the total angular momentum of the nucleon j, which can be either $j = \ell + 1/2$ or $j = \ell - 1/2$. The summing of the total mechanical moments of the nucleons, which occurs according to the quantum rules of moments summing, determines the mechanical moment of the nucleus J. As a rule, the parameter of J is called the nuclear spin, but it has to be presumed that the nuclear spin includes the orbital moments of the nucleons.

Because the total angular moment of an individual nucleon is half-integer, nuclei with an even number of nucleons have an integer mechanical moment, and nuclei with an odd number are half-integer. Usually in nuclei the moments of individual nucleons are antiparallel, so the nuclear spin is either zero or a relatively small value. For example, the spin of the alpha particle (helium nucleus) is 0, of the nucleus ^{40}K is 4, and of the nucleus ^{137}Cs is 7/2.

The quantum rule for moments summing states that the angular moment J of a nucleus, consisting of two nucleons with the moments j_1 and j_2, can take a positive integer ranging from $|j_1 - j_2|$ to $j_1 + j_2$. In other words, the nucleus moment is the third side of the triangle; the other two sides of which are equal to j_1 and j_2, as it is shown in Fig. 2.3. For example, if $j_1 = 5/2$ and $j_2 = 3/2$, then $J = 4, 3, 2, 1$.

Note that the method of summing up the moments described here is called the spin−orbit coupling. A variant of the so-called Russell-Saunders coupling that is quite common in atomic physics, when spins and orbital moments are summed up both independently, is rarely realized in nuclei.

2.4.2 The Nuclear Electrical Moments

Electric moments characterize the distribution of charge in the nucleus. As is known, the charge distribution can be expanded into multipoles and represent the distribution as a superposition of model combinations of electric charges: dipole, quadrupole, etc.

The dipole moment of the nucleus is zero. This means that there is no spatial separation of the proton (charged) and neutron (neutral) components in the nucleus, and the center of the charge distribution coincides with the center of gravity of the nucleus. This does not contradict the fact that these distributions may have different, but symmetrical, external boundaries (Section 2.3).

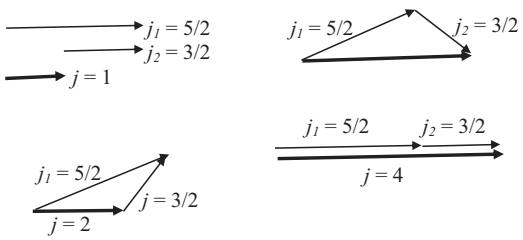

FIGURE 2.3 The possible values of the total angular moment of the nucleus, consisted of two nucleons with the moments $j_1 = 5/2$ and $j_2 = 3/2$.

For nuclei, the quadrupole moment characterizes the deviation of the charge distribution from sphericity. In spherically symmetric nuclei, it is zero. However, in nonspherical nuclei the quadrupole moment is nonzero. Thus, for a nucleus in the form of a prolate ellipsoid elongated along the spin, the quadrupole moment has a positive value, and for a nucleus in the form of an oblate ellipsoid with respect to the direction of the spin, it is negative.

Deviations from spherical symmetry in most cases do not exceed 10%.

2.4.3 Magnetic Moment of a Nucleus

The magnetic moment of a nucleus is uniquely linked with the orbital moment

$$P_m = (e/2m_e)L. \tag{2.8}$$

By definition for a negatively charged particle the magnetic moment is opposite in direction to the mechanical moment. Sometimes this is marked by the minus sign in Eq. (2.8).

In quantum mechanics the moment can take only definite values, i.e., it is quantized

$$L = \hbar[\ell(\ell+1)]^{1/2}, \tag{2.9}$$

respectively, for an electron

$$P_m = (e\hbar/2m_e)[\ell(\ell+1)]^{1/2} = \mu_B[\ell(\ell+1)]^{1/2}. \tag{2.10}$$

In this formula the value

$$\mu_B = e\hbar/2m_e \tag{2.11}$$

is called the Bohr's magneton.

The ratio of the magnetic moment to the orbital is called the gyromagnetic ratio

$$g = P_m/L = e/2m_e. \tag{2.12}$$

Let us note that for the intrinsic mechanical moment of an electron (spin), the gyromagnetic ratio is twice as large in comparison with the orbital moment

$$g_{spin} = e/m_e. \tag{2.13}$$

In the formula for the magneton, the mass of the particle is in the denominator, so we can expect that the nuclear magneton will be smaller than the Bohr magneton by as many times as the electron mass is less than the proton mass, i.e.,

$$\mu_{nucl} = e\hbar/2m_p. \tag{2.14}$$

However, it turns out that the intrinsic magnetic moment of the proton is $\mu_p = 2.79\mu_{nucl}$. Moreover, the neutron, despite its electrical neutrality, has its own magnetic moment, equal to $\mu_n = -1.91\mu_{nucl}$ (the minus sign indicates that the direction of the spin is opposite to the direction of the magnetic moment). Such difference between the magnetic moments of nucleons and those expected from elementary considerations means that the nucleons are not elementary.

The proton also moves in the nucleus, which means that it must also have an orbital magnetic moment. The magnetic moments of the nuclei are made up of the intrinsic magnetic moments of the protons and neutrons and from the magnetic moments of the protons associated with the motion of the protons in the nucleus. As a result, the magnetic moments of nuclei with the even Z and N are zero, and those with the odd ones are determined by the moment of the excess nucleon.

2.5 NUCLEAR PARITY

The probability of transitions between nuclear levels is essentially determined by two parameters: spin and parity. Nuclear spin is discussed in Section 2.4.1. Now let us get acquainted with the concept of parity.

It is well known that the laws of conservation, to which phenomena in the physical world are obeyed, reflect the symmetry properties of space−time.

The law of conservation of energy is a manifestation of the homogeneity of time. The operation, which turns out to be invariant in this case, is a time shift operation.

The law of conservation of momentum is a manifestation of the homogeneity of space and demonstrates invariance with respect to a shift in space.

The law of conservation of angular momentum reflects the isotropy of space; it shows that the laws of nature do not change when the coordinate system in space rotates.

Here we can add the law of conservation of electric charge, reflecting some deep, not yet completely understandable, symmetry of our world.

The space−time transformations listed above are continuous; an arbitrarily small change in the parameter (time, distance, or angle of rotation) can occur.

The above-listed conservation laws are exact and are fulfilled in all cases known to science.

Besides continuous transformations of space−time, a discrete one is possible: a mirror reflection (inversion of coordinates), which is denoted by P.

In more detail here we consider the symmetry problem with respect to mirror reflection. Note at once that the conservation law, which follows from symmetry with respect to mirror reflection, is not strict, i.e., in certain cases it may be violated.

The operation of spatial inversion is reduced to the replacement of the radius vector r by $-r$. In Cartesian coordinates, x, y, z are replaced by $-x$, $-y$, $-z$. Repetition of the mirror operation returns the system to its original state. Invariance, with respect to mirror reflection, means that the laws of nature do not change when replacing the left one with the right one.

To describe the system's relation to the operation of mirror reflection, the concept of parity is introduced. Let us note that a function $f(x)$ is said to be even, if

$$f(-x) = f(x) \tag{2.15}$$

and odd, if

$$f(-x) = -f(x) \tag{2.16}$$

The real mirror reflects only one axis—perpendicular to its plane. If we consider a vector directed along this axis, e.g., movement toward a mirror, then in the mirror the direction changes to the opposite. So polar vectors—speed, force, momentum, etc.—in the case of mirror reflection, change the sign. It is easy to verify that axial vectors, for example, angular velocity, angular moment, etc., when mirrored do not change the sign.

If we talk about microparticles described by the wave functions $\psi(r)$, then the state of the system is determined by the square of the modulus of the wave function, and the state is not changed in a mirror-symmetric process.

$$|\psi(r)|^2 = |\psi(-r)|^2. \tag{2.17}$$

Extracting the square root, one obtains

$$\psi(r) = \pm\psi(-r), \tag{2.18}$$

and, consequently, the particle system can be described by both even and odd wave functions. To characterize this circumstance, we introduce the concept of parity P, which can have the value $P = \pm 1$.

In the manuals on quantum mechanics [4], it is shown that the inversion transformation (replacing all Cartesian coordinates by opposite signs) leads to the multiplication of the wave function by (-1), where ℓ is the orbital quantum number (Section 2.4.1). Thus, the parity of a state with a given value of ℓ is determined by the rule

$$P = (-1)^{\ell}, \tag{2.19}$$

i.e., all states with the even ℓ are even, and with odd ℓ are odd.

The parity of a nucleus is determined by the expression

$$P_{nucl} = (-1)^{\sum \ell}. \tag{2.20}$$

In particular, the parity of an alpha particle is equal to $+1$, as for an alpha particle $\ell = 0$, and the parity of a deuteron is equal to -1, as for a deuteron $\ell = 1$.

The law of the parity conservation states that the parity of the system does not change with time.

In the electromagnetic and strong interactions, parity is strictly preserved, but in weak interaction it is violated.

2.6 ENERGY LEVELS OF NUCLEI. EXCITED STATES

As is known, an electron in an atom is in the central Coulomb field of the nucleus (i.e., in a field where potential energy depends only on the distance to the center), and the energy levels are quantized. The scheme of energy levels of electrons in

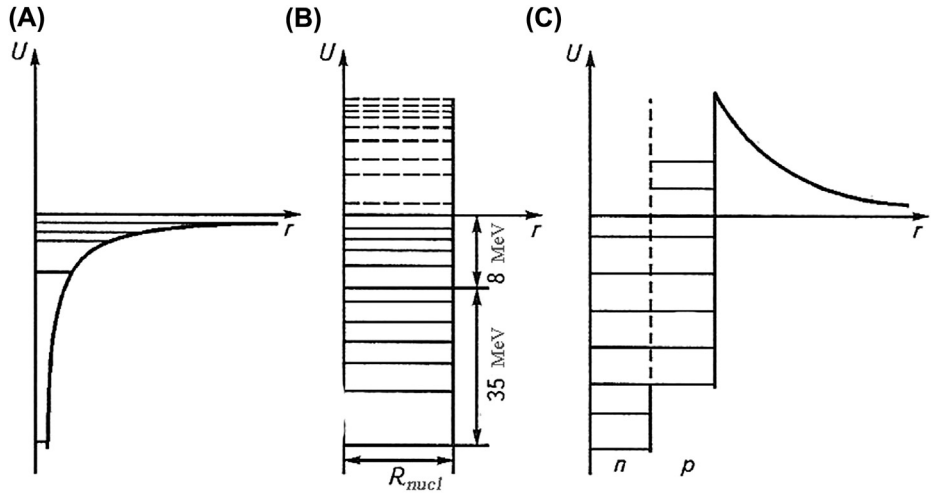

FIGURE 2.4 The scheme of energetic levels of: (A) an atom, (B) a nucleus, (C) a nucleus, with independent neutron and proton levels considered.

an atom is shown in Fig. 2.4a. The electron distribution over the levels is governed by the Pauli principle. The state of an electron in an atom is characterized by four quantum numbers.

In the case of a nucleus, the nucleon is in a field, firstly short range, and secondly, created by other nucleons. It can be simplified by assuming that the nucleon is in a rectangular potential well. Similar to electrons in atoms, nucleons in nuclei can have only certain energies, the state distribution of which also obeys the Pauli principle. The arrangement of the energy levels of the nucleons in the nucleus is shown in Fig. 2.4b.

Strictly speaking, it is necessary to distinguish between proton and neutron energy levels, and a potential well should be depicted as double, as in Fig. 2.4c.

In Fig. 2.4c the Coulomb barrier on the surface of the nucleus for protons is shown. The height of the barrier can be estimated as the energy of the Coulomb interaction at a distance equal to the radius of the nucleus (Section 2.3)

$$U_C = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{zZe^2}{R_{nucl}} = zZ/A^{1/3}\ \text{MeV}, \tag{2.21}$$

where z and Z are the atomic numbers of a particle and of a nucleus respectively. For protons in hydrogen, $Z = 1$, $A = 1$, $U_C \approx 1$ MeV, and in uranium, $Z = 92$, $A = 238$, $U_C \approx 17$ MeV. For alpha particles the Coulomb barrier is twice as high.

The lowest states in the unexcited nucleus are filled. Within the potential well of the nucleus, there are free levels (unfilled). The last of the filled levels is separated from the edge of the well by the binding energy of the nucleon. A typical value of the binding energy is $\sim$8 MeV, and a typical depth of the well is $\sim$35 MeV.

In atoms, if the energy of excitation of an electron exceeds the ionization energy, then the electron goes outside the atom and becomes free, and its energy can take any value.

In contrast to the atom, the energy levels in the nucleus, as a rule, remain discrete even for the excitation energy, which is greater than the nucleon separation energy. Accordingly, the spectrum of the nucleus remains also discrete when excitation is sufficient to separate the nucleon. This is due to the fact that the excitation energy is not fixed on a single nucleon but is distributed over a large number of particles. As a result, each of them does not get enough energy for leaving the nucleus. The distribution of excitation energy over a large number of particles means that in highly excited nuclei the nucleons effectively interact inside the nucleus.

However, for nuclei in ground state, the situation is opposite to the one described. In the first approximation, we can assume that the nucleons in the nucleus practically do not interact. This is due to the fact that in ground state, in accordance with the Pauli principle, all lower levels are filled. Collisions between particles should lead to the exchange of energy. But if a particle that received energy can, actually, rise to a higher level, which is free, then a particle that lost energy can not exactly descend to a lower level, for it is certainly busy.

Thus, the nucleus in the ground state is similar to a highly rarefied gas, where the particles, placed in a vessel with impermeable walls, from which the particles repel, rarely collide with each other. Let us draw attention to the fact that such a phenomenon occurs in spite of the fact that the nucleons are tightly packed in the nucleus, i.e., the average distance between them is of the order of their size, and the nucleus is similar to an incompressible fluid. In a quantum language,

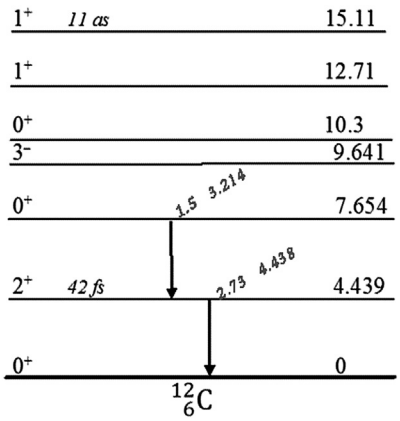

FIGURE 2.5 Levels of the nucleus ^{12}C. To the right on the level lines, the level energy in MeV is indicated, e.g., 0, 4.439, etc. The spin and level parity, e.g., 0+, 2+, etc., are also indicated to the left. If known, the lifetime of the level is indicated, e.g., for the level of 7.6540 MeV the lifetime is equal to 0.05 fs. Between the levels are shown transitions at which γ-quanta are emitted (see Chapter 5). Above the transitions the relative intensity of the lines and the energies of quanta are marked. Only known transitions are shown, the other transitions are expected but not yet observed. According to R.B. Firestone, S.Y.F. Chu, C.M. Baglin. Table of Isotopes, Eighth ed. 1999, Update with CD-ROM. https://application.wiley-vch.de/books/info/0-471-35633-6/toi99/doc_info/pref99.pdf.

such a system of particles, according to the Pauli principle, completely fill the lower levels and is called a degenerate Fermi gas. That is why the model of a rectangular potential well can be used to describe the motion of nucleons in the nucleus.

The Pauli principle does not permit a neutron to disintegrate within a stable nucleus. Thus, there is no place for the proton to be formed in the decay because all levels are already occupied, and to occupy a higher level, additional energy is required. If the energy released during the neutron decay is not enough to move a proton to the available free level, then decay is impossible.

The energy levels of the nucleons in the nucleus have a finite width. A typical level width is about 0.1 eV.

The nucleon energy levels in the nucleus are characterized by the energy of the level, spin, and parity. In Fig. 2.5, e.g., the energy levels of ^{12}C are indicated together with their characteristics.

2.7 RADIOACTIVE DECAY AND RADIOACTIVE RADIATIONS

It has been said above that nuclei become unstable if the ratio of protons and neutrons differs from the definite range. All unstable nuclei, even in a ground state, undergo spontaneous transformation that got the name "radioactive decay."

There are several forms of radioactive transformations. Among the well-known and most probable are alpha decay, beta decay, and spontaneous fission. In these transformations, the composition of the nucleus does actually change, so the application of the term "decay" is fair. Gamma radiation is emitted by nuclei at transitions between energy levels without changing their composition. So the gamma transition is not, in fact, a decay but, according to the tradition, sometimes the term "decay" is also used in this case. All processes of decay are spontaneous, but as to the fission, this process, as it is usually pointed out, is called spontaneous to distinguish this relatively rare process from the main process in nuclear energetics—fission of nuclei under the action of neutrons.

The radioactivity of the nuclides existing in nature is called natural. The radioactivity being a result of nuclear reactions is called artificial or induced activity. Many properties of alpha and beta emitters are discussed in Section 17.2.

2.7.1 Alpha Decay

In heavy nuclei, the Coulomb energy of proton repulsion becomes very significant and this makes the nuclei unstable. It turns out that it is energetically more profitable for a nucleus to throw out a stable system of four particles, i.e., an alpha particle, than individual nucleons. The alpha particle is the nucleus of helium; its charge is 2, and the mass number is 4.

The alpha decay is a property of heavy elements with $Z > 82$ and $A > 200$. Because of emission of an alpha particle, the nuclear charge decreases by 2 units and its mass number by 4 units. In this case, the nucleus of the element is formed, which is located two cells to the left of the original in the periodic table. For example, $^{226}\text{Ra} \rightarrow {}^{222}\text{Rn}$.

Alpha particles emitted during a certain transition in the nucleus have the same energy, i.e., they are monoenergetic (Fig. 2.6). The energies of alpha particles with an accuracy of 1 eV can be determined by thorough measurements

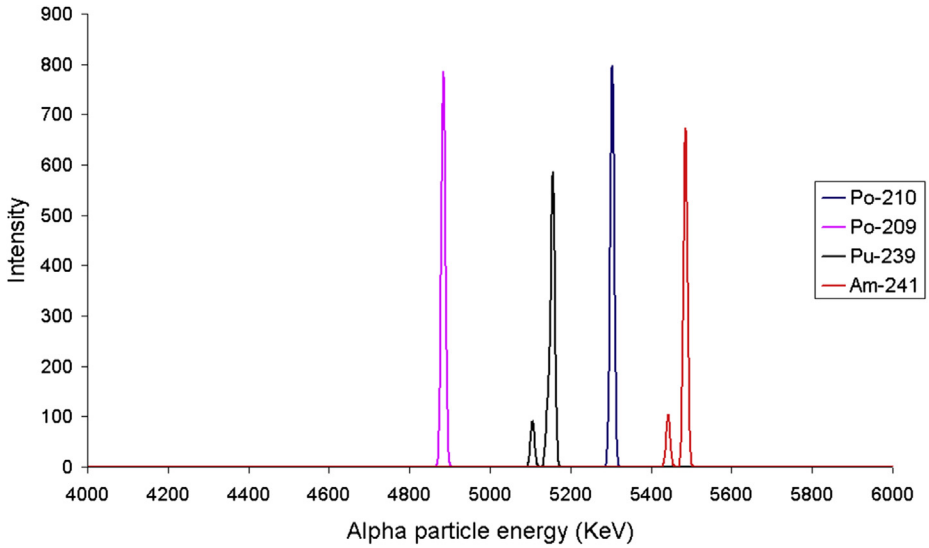

FIGURE 2.6 Spectrum of alpha radiation for four nuclides. It is seen that some nuclides emit several alpha lines of different intensity. *From Alpha-Particle Spectroscopy. Wikipedia. https://en.wikipedia.org/wiki/Alpha-particle_spectroscopy#/media/File:Alpha1spec.png.*

(magnetic spectrometers). There is reason to believe that the intrinsic line width is of the order of 0.1 eV, which characterizes the true degree of monoenergeticity of the alpha particles.

In the series of alpha active isotopes of one element, the smaller the energy of alpha particles, the heavier the isotope. In a series of elements for fixed A, the energy of the alpha particles increases with increasing Z.

The energy of α-particles for different radioactive nuclides varies within relatively narrow limits from 4 to 9 MeV. At the same time, the half-life varies enormously—from 10^{-7} s to 14 billion years, i.e., more than 10^{24} times.

The quantitative relationship between the half-life and the energy of alpha particles was established as early as in 1912 by the Geiger–Nuttall law (Fig. 2.7)

$$lgT_{1/2} = A + B/E_{\alpha}^{1/2}. \tag{2.22}$$

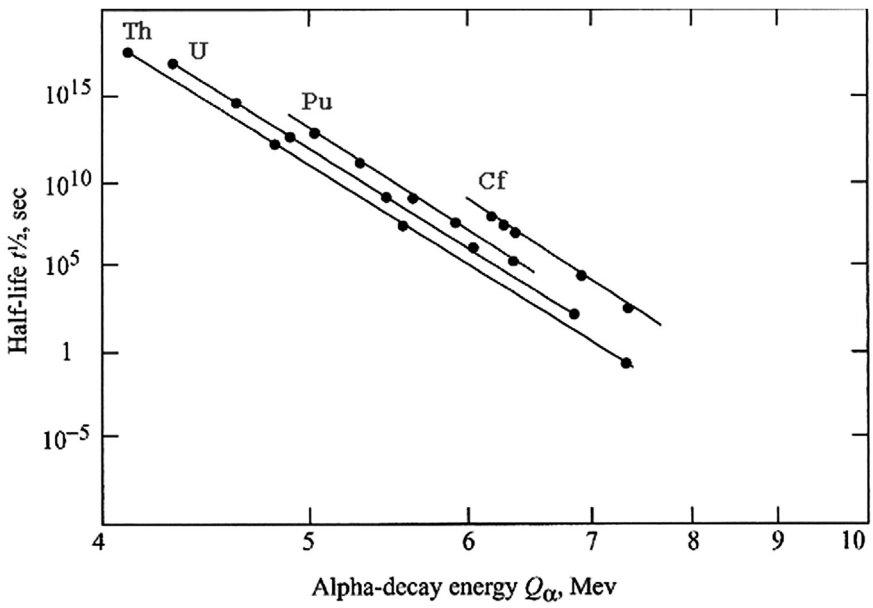

FIGURE 2.7 The Geiger–Nuttall law for several radioactive chains. $E_{\alpha}^{1/2}$ is plotted along the abscissa axis and $lgT_{1/2}$ along the ordinate axis.

In this expression constants A and B have slightly different values for different radioactive chains. Thus, the Protactinium isotope ^{219}Pa has $T_{1/2} = 53$ ns, $E_\alpha = 9.9$ MeV, and ^{232}Th has $T_{1/2} = 1.41 \times 10^{10}$ years, $E_\alpha = 4.08$ MeV.

The Geiger–Nuttall law received the theoretical justification in the tunnel theory of alpha decay, suggested by G. Gamov in 1928.

For additional information about alpha radiation and alpha sources, see Section 17.2.

2.7.2 Beta Decay

Beta decay is the transformation of an unstable nucleus into a nucleus with the same atomic weight, i.e., into an isobaric nucleus differing in charge from the initial nucleus by ±1, accompanied by the emission of an electron or a positron, or capture of an electron. At the same time, the nucleus emits neutrino or antineutrino.

There are three types of beta decay:

1. β^--Decay. The atomic number here is increased by one, and the electron and the antineutrino ν^* are emitted from the nucleus

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \nu^*, \tag{2.23} $$

where X and Y are certain nuclei. A particle that flies out in this process is called antineutrino because in nuclear physics there is a rule because of which the sums of particles and antiparticles in both parts of reaction (2.23) must be equal. Neutron, proton, and electron, by definition, are particles. Thus, there is one particle to the left in Eq. (2.23), and two particles to the right. Therefore, the third particle on the right of the reaction (2.23) must be an antiparticle. β^--Decay means that the neutron decays in the nucleus according to the scheme

$$ n \rightarrow p + e^- + \nu^* \tag{2.24} $$

β^--Decay is specific for neutron-rich nuclei.

2. β^+-Decay. In this case the atomic number decreases by one, and the positron and the neutrino ν are emitted from the nucleus.

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu. \tag{2.25} $$

β^+-Decay means that the proton decays in the nucleus according to the scheme

$$ p \rightarrow n + e^+ + \nu \tag{2.26} $$

Such type of decay is specific for neutron-deficient nuclei.

3. Electronic capture (EC). In reactions of the type (Eq. 2.23–2.26), any particle, replacing it with an antiparticle, can be transferred from one part of the relation to another. If in this case an obtained process is allowed by the conservation laws, then such a process can be observed. Thus, if in the reaction (2.25) the positron from the right side is transferred to the left, replacing it by an electron:

$$ e^- + {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \nu, \tag{2.27} $$

then such a process of electron capture by a nucleus, with the escape of neutrinos exclusively from the nucleus, turns out to be energetically favorable and, indeed, experimentally observed. The capture of an electron from the K shell is most likely; therefore, this process is often called K-capture, but capture from the other shells, e.g., L-capture, etc., is possible.

As a result of the EC, a vacancy is formed on the K shell of the atom, which is filled up when the electrons move from the higher levels. In this case, the characteristic X-rays or Auger electrons are emitted (Section 4.6).

It is convenient to analyze the above relations and other regularities of beta decay in the energy diagram of the isobar family (mass chain), i.e., nuclides with the same mass number. In Fig. 2.8 the isobar family $A = 40$ is presented.

In most such families there is a single stable nucleus with the smallest mass. On the left side there are beta minus nuclei, and on the right-hand side there are beta plus (or EC) nuclei. And in the left and right branches there are chains of decays,

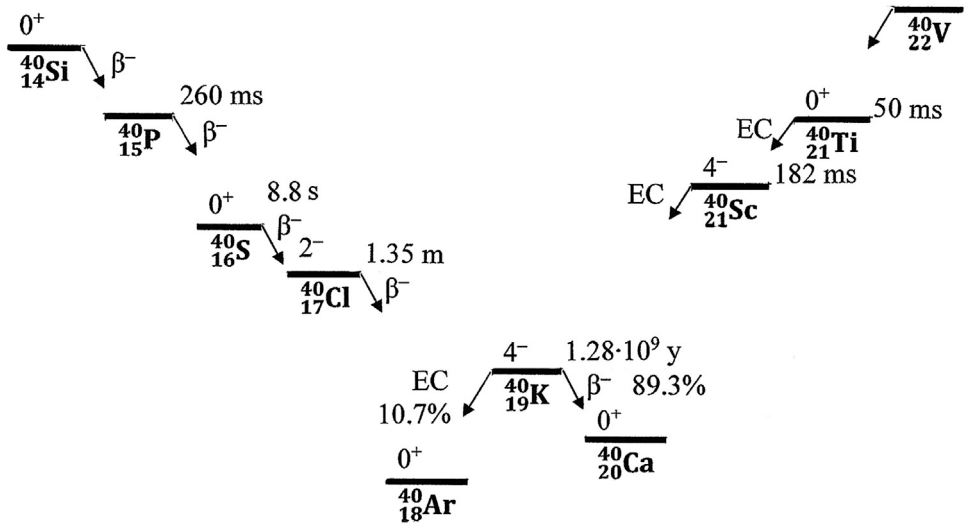

FIGURE 2.8 The isobar family $A = 40$. In the diagram the abscissa means the atomic number, and along the ordinate is the mass of the nucleus. The nuclear spins and parities are indicated on the left above the levels, for example, for ^{40}K—spin is 4, the parity is negative (−), above the level the half-life is indicated (if known), for example, for the nuclide ^{40}Cl $T_{1/2} = 1.35$ min. *The figure is built by the author on the basis of data from R.B. Firestone, S.Y.F. Chu, C.M. Baglin. Table of Isotopes, eighth ed, 1999. Update with CD-ROM.* https://application.wiley-vch.de/books/info/0-471-35633-6/toi99/doc_info/pref99.pdf.

the nuclide with a larger mass decays, turning into an adjacent nuclide with a smaller mass, and so on to the stable lightest nucleus. Nucleus located far from stable has small half-lives, and by approaching the center, the periods increase.

In some cases in families of even−even isobars there may be two or even three stable nuclides. In total 56 pairs and 3 triples ($A = 96$, 124, and 130) of stable isobars are known. For example, in Fig. 2.8 there are two stable nuclides ^{40}Ar and ^{40}Ca, besides the mass of ^{40}Ca is greater than the mass of ^{40}Ar. It means that probably the $2\beta^+$-decay is possible

$$^{40}_{20}\mathrm{Ca} \rightarrow {}^{40}_{20}\mathrm{Ar} + 2e^+ + 2\nu. \tag{2.28}$$

Energy laws of beta decay allow concurrent processes to take place simultaneously: β^+-decay and electron capture, and β^--decay and β^+-decay. Such competing processes occur during the decay, e.g., of the nuclide $^{40}_{19}$K. In 89.3% of cases the nuclide ^{40}K emits an electron, transforming into ^{40}Ca, and in 10.7% of cases it capture an electron, transforming into ^{40}Ar. With a probability of 0.001% β^+-decay competes with EC. The decay scheme for ^{40}K is shown in Fig. 17.1.

The main feature of the spectrum of electrons (positrons) emitted during β-decay is its continuity. Typical forms of the beta spectrum of certain nuclides are shown in Fig. 2.9. For each nuclide, there is a maximum electron energy E_{max}. Forms of beta spectra differ slightly for different nuclides. So in the ^{3}H spectrum the maximum of distribution occurs at $0.15E_{max}$, in the ^{32}P spectrum at $0.4E_{max}$. In the spectra of ^{35}S, ^{90}Sr, the maximum is not shown at all, the spectrum gradually increases to zero. As the spectrum is not symmetrical, the average energy is higher than the energy of maximum. For the most part of beta-active nuclides the ratio of the average energy to the maximum energy E_{av}/E_{max} is from 0.25 to 0.4. In average this ratio is equal to 1/3.

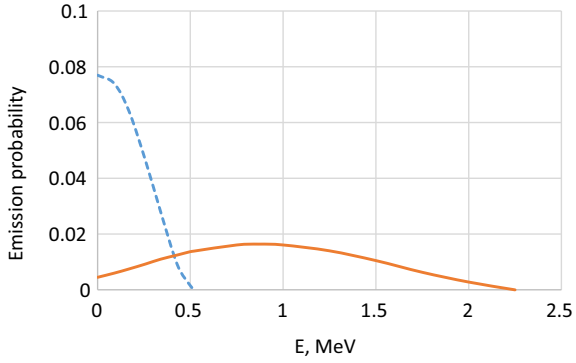

FIGURE 2.9 Typical forms of the beta spectrum of several nuclides solid line - ^{90}Sr, dashed line - ^{90}Y.

The probability of beta decay is determined by the energy of decay and the selection rules. The structure of the nucleus manifests itself in the values of spin and level parity and determines the decay probability.

The probability of transitions differs depending on the variation in the spin and parity of corresponding levels. It is accepted to distinguish the transitions:

- the super-allowed transitions, which occur without any change in the nuclear structure ($\Delta J = 0$, the parity does not change, e.g., the decays of ^{1}n, ^{3}T, ^{14}O),
- the normally allowed transitions, which occur with some rearrangement of the nucleus ($\Delta J = \pm 1$, the parity does not change);
- the forbidden transitions are characterized by a violation of the selection rules, $\Delta J > \pm 1$; depending on the value of ΔJ the transitions can be of different degree of prohibition;
- the unique transitions associated with large value of ΔJ and the change in parity. For example, the decay of $^{40}\text{K} \rightarrow {}^{40}\text{Ca}$ is a transition of the third order of prohibition, the spin of ^{40}K is 4, the spin of ^{40}Ca is 0, and the parities are opposite. Therefore, the transition probability is extremely small, and the half-life is very long ($T_{1/2} = 1.28 \times 10^{9}$ years).

For additional information about beta radiation and beta sources see Section 17.2.

2.7.3 Gamma Radiation of Nuclei

Gamma radiation is a rigid electromagnetic radiation at the short-wave edge of the electromagnetic wave spectrum. By tradition, gamma radiation refers to radiation originating in nuclei, and X-ray radiation arises in the electron shells of atoms.

The rest mass, the electric charge, and the magnetic moment of the gamma quantum equal to zero.

Gamma radiation is emitted, absorbed, and transported as separate quanta. The energy of gamma quantum is related to the frequency ν and the wavelength λ by the relation

$$E = h\nu = hc/\lambda. \tag{2.29}$$

Gamma quanta are emitted when the nucleus passes to the ground state from the excited ones, which are formed either in the processes of alpha or beta decay, or in nuclear reactions.

The energy spectrum of gamma radiation is always discrete.

The probabilities of gamma transitions are determined by the selection rules in a manner analogous to that for optical spectra.

For additional information about gamma radiation and gamma sources see Section 17.2 and about gamma interaction with matter see Chapter 6.

2.7.4 Isomers

Usually the lifetime of the nucleus in the excited state is small: $\sim 10^{-13}$ s. However, there are cases when the selection rules for transitions greatly reduce the transition probability and, accordingly, increase the lifetime. In this case, there occurs a phenomenon called nuclear isomerism.

Nuclear isomers are nuclei in an excited state that have a significant lifetime ($>10^{-9}$ s). The isomers can undergo an isomeric transition to the ground state with the emission of a gamma quantum or undergo beta decay from an isomeric state [7].

Isomers are designated by the letter *m* (from English metastable) in the index of the mass number (e.g., ^{80m}Br). Isomer ^{99m}Tc is the main diagnostic radionuclide of modern nuclear medicine. Isomer ^{178m2}Hf has a half-life of 31 years (index 2 means that there is also a lower-lying isomer ^{178m1}Hf). The possibility of creating a special hafnium atomic bomb based on the isomer ^{178m2}Hf has been discussed [8]. ^{180m}Ta is the isomer of tantalum with the extremely long half-life, $T_{1/2} > 10^{15}$ years. Experimentally, the decay of this isomer was not observed, it is present in natural tantalum at a concentration of 0.012%.

2.7.5 Internal Conversion

In addition to gamma radiation, another way of eliminating the excitation of the nucleus is possible, by direct energy transfer to one of the electrons of the electron shell. In this case, the electron is emitted from an atom with the energy

$$E_e = h\nu - U_{\mathrm{K,L\ldots}}. \tag{2.30}$$

where $U_{\mathrm{K,L}}\ldots$ is the binding energy of electrons on K, L, etc. shells.

Obviously, unlike the beta decay, monoenergetic electrons are emitted from the atom as a result of internal conversion. After the electron is emitted, a vacancy appears on the shell, which is rapidly filled by electron transitions from the upper shells. For more details of processes during ionization of inner shells, see Section 4.6.

2.7.6 Energy Diagram of Radioactive Decay

Decays can be visually displayed on the energy diagram. The abscissa is the atomic number Z, and the ordinate is the mass of the nucleus (usually in energy units, often conditionally, without observing the scale). The ground state of the daughter nucleus is usually taken as zero. Thus, the alpha decay is represented by the diagram of Fig. 2.10a. Here the arrows indicating the decay are directed from right to left; in alpha decay the nuclear charge decreases. Here not only the ground states of the nuclei but also the excited levels participate in the decay, this is also shown in the diagram.

An example of β^- and β^+ decays into the same daughter nucleus is shown in Fig. 2.10b. Here the arrows for β^- are directed to the right because the charge of the nucleus increases in this case, and to the left of β^+ decay the charge of the nucleus decreases.

2.8 THE RADIOACTIVE DECAY LAW

The ability of a nucleus to decay is a property that does not depend on external conditions and on other nuclei. It is particularly important that the probability of decay does not depend on time, that is, a nucleus has no history. No matter how much time has passed since the formation of a radioactive nucleus, the decay probability per unit time is a constant, which is usually denoted as λ. From this condition, the well-known law of radioactive decay is derived:

$$N(t) = N_0 \exp(-\lambda t). \tag{2.31}$$

Here N_0 is the primary number of nuclei, and $N(t)$ is the number of nucleus that do not decay till the moment t. This dependence is shown in Fig. 2.11 (solid line).

Average life span of a nucleus is equal to $\tau = 1/\lambda$. For historical reasons, in the science of radioactivity, the time during which the number of nuclei is reduced to half is used more frequent than the value of τ. This time is called the half-life $T_{1/2}$. The connection of $T_{1/2}$, τ, and λ is given by the following expression

$$T_{1/2} = \ln 2/\lambda = 0.692/\lambda = 0.692\tau. \tag{2.32}$$

The value dN/dt is the decay rate that is proportional to the number of existed nuclei N. The decay probability per unit time is equal to $-dN/dt = \lambda N$. The value λN is called activity of the definite radioactive chemical. Activity shows the number of decays in the unity of time. It is evident that the less the half-life, the greater the activity.

If the half-life is known, then the activity of the definite amount of a chemical can be easily calculated. For example, for 1 g of radium (^{226}Ra)

$$\lambda N\left(^{226}_{88}Ra\right) = \left(0.692/T_{1/2}\right) \times \left(N_A/A\right) = 3.7 \times 10^{10} \text{ per s}, \tag{2.33}$$

where N_A is the Avogadro constant.

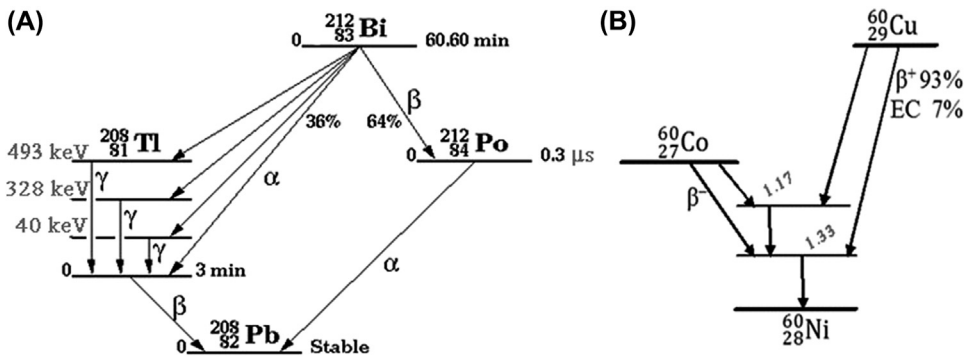

FIGURE 2.10 Energy scheme (diagram) of decays: (A) alpha-decay of ^{212}Bi, (B) β^--decay of ^{60}Co and β^+-decay of ^{60}Cu.

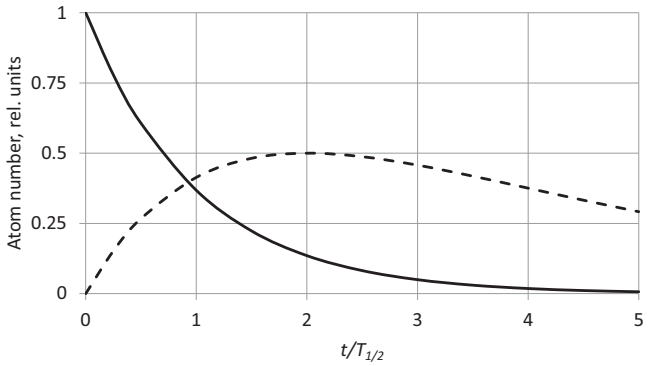

FIGURE 2.11 The law of radioactive decay. *Solid line*: the number of nuclei that did not decay till the moment t; *dashed line*: the number of radioactive daughter nuclei that are produced and then decay. It is accepted that $\lambda_2 = 0.5\lambda_1$.

The activity of 1 g radium was measured by French scientists Pierre and Marie Curie at the very dawn of nuclear physics. This value in 1910 at the International Congress of Radiology and Electricity in Brussels was adopted as a unit of activity and was named "curie." At present, the unit of activity in SI is a becquerel (Bq), named after A.H. Becquerel and equals 1 decay per second. The conversion of units is presented in Appendix.

One should note that according to the standard, activity is the number of decays per time unit rather than the number of emitted particles. The number of particles of a particular type is not necessarily equal to the number of decays. Therefore, such terms as alpha or beta activity, if they represent any number, must be understood as a tribute to history, but not taken as regular terms.

Often the decay of a nuclide (called the "parent") forms another ("daughter") nuclide that is also radioactive. Variation in the number of radioactive daughter nuclei produced, and then decayed, is shown in Fig. 2.11 (dashed curve). Provided that the half-life of the parent nuclides is much longer than all of the others', it can be shown that eventually an almost constant ratio between the numbers of parent nuclei and that of all daughter substances can be reached. This ratio is equal to the ratio of their half-lives. The rate of decay of all substances turns to be the same, and the number of nuclei decreases exponentially with the time of the parent substance, that is

$$\lambda_1 N_1 = \lambda_2 N_2 = \ldots = \lambda_n N_n. \tag{2.34}$$

In such situations, it is considered that the substances are in the radioactive balance. The relation (Eq. 2.34) is called a secular relation.

2.9 THE RADIOACTIVE CHAINS

There exist in nature three heavy radioactive nuclides with rather long half-life. They are the so-called primordial nuclides that had no time to fully decay since the formation of nuclides with which our planet, the Earth, is built. They are as follows: two isotopes of uranium, ^{235}U and ^{238}U, and one isotope of thorium, ^{232}Th. Each of these nuclides is experiencing alpha decay; a daughter nuclide is also radioactive and it undergoes alpha or beta decay, transforming again into radioactive nuclide and so on until the last daughter (great-, great-,… great-granddaughter) appears to be stable.

Such serial families of radioactive substances are called decay chains or radioactive rows. The decay of ^{238}U produces a chain that consists of 18 nuclides (uranium family, including starting material). The chain of ^{232}Th includes 12 nuclides (thorium family). All three of the above-mentioned decay chains end up by the different stable isotopes of lead.

In Section 17.1 it was pointed out that there is a lot of long-lived nuclides that keep staying on the Earth since the time of the elements' creation and have a $T_{1/2} > 10^9$ years. Here we name only the nuclides with the half-life of not much more than the age of the Earth, whose radiation could be measured. They are presented in Table 2.1. All these nuclides are beta active. In the first decay of each of these nuclides, the stable substance is produced and they do not form radioactive chains. The nuclide ^{40}K, which is presented in natural objects in the highest concentration, is discussed in more detail in Section 17.8.4.

TABLE 2.1 Some Nuclides With $T_{1/2} > 10^9$ Years

Nuclide	^{40}K	$^{87}_{37}$Rb	$^{137}_{57}$La	$^{176}_{71}$Lu	$^{187}_{75}$Re
$T_{1/2}$, years	1.28×10^9	49.2×10^9	1.02×10^{10}	3.85×10^{10}	3.85×10^{10}

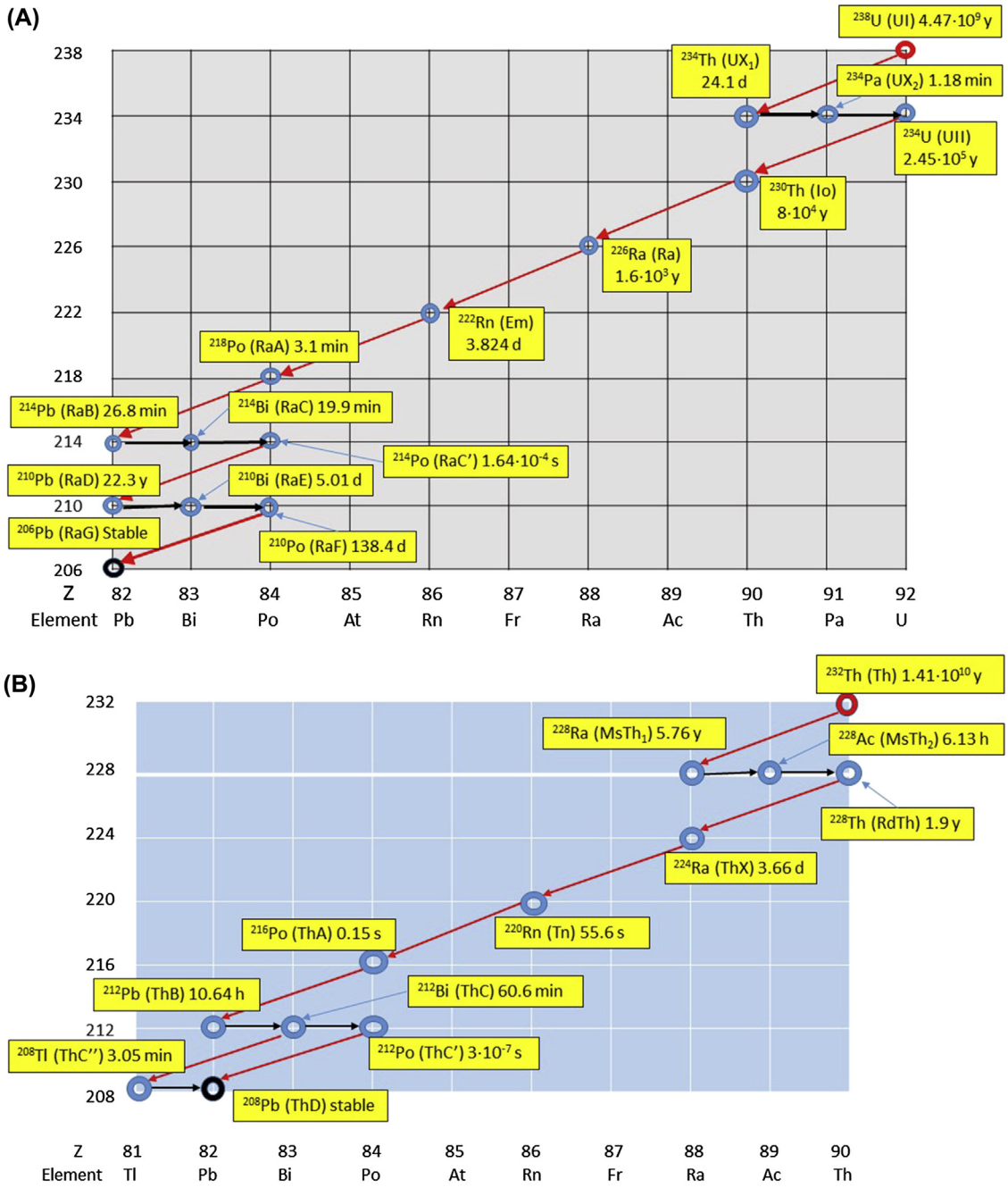

FIGURE 2.12 The decay chains of ^{238}U (A) and ^{232}Th (B). The chain is shown in a simplified version; some transitions with small probability are omitted. In the end of the thorium chain one could see the so-called "fork." ^{212}Bi can undergo alpha decay with the probability 36% and beta decay with the probability 64%. Gray arrows (*red arrows* in the web version) designate alpha decay; *black arrows*—beta decay. The first nuclide in the chain is marked by *dark gray circle* (*red circle* in the web version), the last one, stable nuclide by *black circle*.

Some characteristics of the radioactive chains of ^{238}U and ^{232}Th are shown in Fig. 2.12a (^{238}U chain) and Fig. 2.12b (^{232}Th chain). In early studies of radioactivity, when real types of nuclides in chains were not yet determined, the chain members received special names. Because these names still appear in the scientific and educational literature, not only the names of nuclides in their modern notation but also their old symbols are also presented in Fig. 2.12.

It is seen from the schemes on Fig. 2.12a,b that serial alpha and beta transformations go on in chains. In each alpha decay, the mass number decreases by four units; and in each beta decay, it does not vary. Therefore, the remainder of dividing the mass number A by 4 is the same for all nuclei of the same series. For a specific radioactive family, the value of A can be expressed by the formula $A = 4n + C$, where C is a permanent part of the family and n is an integer.

It is evident that only four radioactive rows can exist with $C = 0$, 1, 2, and 3. The thorium chain appears to correspond to the formula $A = 4n$, the ^{238}U chain to $A = 4n + 2$, and the ^{235}U family to $A = 4n + 3$. The fourth row with $C = 1$ contains nuclides, including the first nuclide of the row ^{237}Np, with its short half-life, decayed long ago, and now can be produced only artificially.

The secular Eq. (2.34) extends to radioactive series because the parents are the nuclides whose half-life is much longer than the half-lives of the remaining units of the series.

2.10 X-RAYS AND SYNCHROTRON RADIATION

2.10.1 Characteristic X-Ray

Gamma radiation and X-rays are the quanta of electromagnetic radiation that differ from each other only by their origin. Gamma quanta are generated inside the nuclei, whereas X-rays are produced by electrons both at the transitions between the deep inner atomic levels and as a result of electron deceleration in matter.

It is generally accepted that X-ray radiation occupies an energy range from ca. 100 eV to 250 keV. On the scale of electromagnetic waves, two bands of electromagnetic waves overlap. There is soft gamma radiation and hard X-rays. X-rays with a photon energy greater than 5−10 keV is considered to be hard and soft with an energy of less than this value.

X-radiation was discovered by Wilhelm Roentgen, and both in Russia and Germany it is called "roentgen radiation." In English scientific literature, it is called "X-ray" as Roentgen himself called it to signify an unknown type of radiation.

X-rays are produced in special X-ray generators. The simplest example of such generator is an X-ray tube. In the X-ray tube, electrons acquire energy in the electric field due to the potential difference between the cathode and the anode, and they bombard the anode (sometimes in the case of X-ray tubes the anode is called "anticathode.") If bombarding electrons have enough energy, they knock out electrons from the deep electron shell.

The structure of the electron shells of atoms is described in Section 1.3, and transitions between levels leading to the emission of monoenergetic, characteristic X-ray quanta are shown in Fig. 2.13.

Transitions from different shells to the innermost one, called the K shell, produce the K-series, the main lines of which for most elements are the lines $K_{\alpha 1}$, $K_{\alpha 2}$, $K_{\beta 1}$, and $K_{\beta 2}$. They correspond to transitions to the K level: $K_{\alpha 1}$—from L_{III}; $K_{\alpha 2}$—from L_{II}; $K_{\beta 1}$—from M_{III}; $K_{\beta 2}$—from N_{IV}.

The ratio of the intensities of the various lines is determined by the selection rules and slightly depends on the atomic number of the substance. Approximate relationships have the form:

$K_{\alpha 1}:K_{\alpha 2}:K_{\beta 1}:K_{\beta 2} \approx 100:50:20:5.$
$L_{\alpha 1}:L_{\alpha 2}:L_{\beta 1}:L_{\beta 2}:L_{\gamma 1} \approx 100:11:60:15:10.$
$K_{\alpha 1}:L_{\alpha 1} \approx 10:1.$

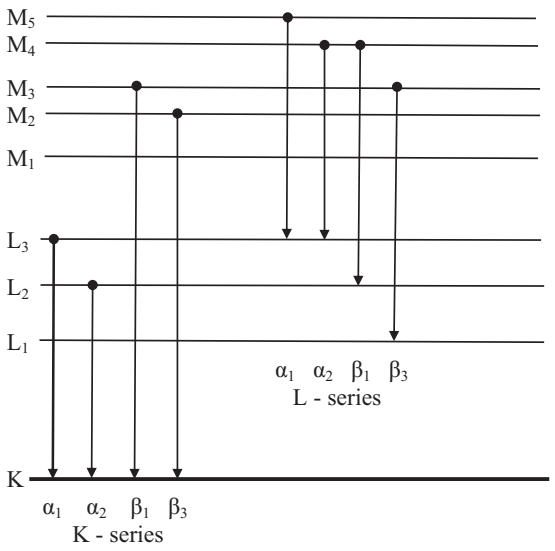

FIGURE 2.13 Structure of the deep electron levels of an atom and transitions, responsible for the emission of X-ray quanta.

TABLE 2.2 The Energies of the Characteristic Quanta for Some Anode Materials

Anode Material	Atomic Number	Photon Energy, keV		Photon Wavelength, nm	
		$K_{\alpha 1}$	$K_{\beta 1}$	$K_{\alpha 1}$	$K_{\beta 1}$
Pb	82	75.0	85.0	0.0165	0.0146
W	74	59.3	67.2	0.0209	0.0184
1In	49	24.2	27.3	0.0512	0.4541
Ag	47	22.2	24.9	0.0559	0.0497
Mo	42	17.5	19.6	0.0709	0.0632
Zr	40	15.76	17.67	0.0786	0.0702
Ga	31	9.25	10.26	0.1340	0.1208
Cu	29	8.05	8.91	0.1541	0.1392
Ni	28	7.48	8.27	0.1658	0.1500
Co	27	6.93	7.65	0.1789	0.1621
Fe	26	6.40	7.06	0.1936	0.1757
Cr	24	5.41	5.95	0.2290	0.2085

On the basis of X-ray Properties of the Elements. Berkely Lab. - http://xdb.lbl.gov/Section1/Periodic_Table/X-ray_Elements.html.

As a rule, K_α is the brightest line. The intensity of the K_β line is no more than 25% of the intensity of the K_α line. The lines of the K_β series in many cases of their registration merge into one line. The energies of the characteristic quanta determined by the anode material of X-ray tubes are given in Table 2.2.

The energy of monoenergetic quanta, arising during transitions between electron shells, is characteristic for the type of an atom emitting them. The heavier the atom, the deeper the electronic shells, the higher is the energy of the characteristic quanta.

2.10.2 Bremsstrahlung

In addition to the characteristic radiation, the deceleration of electrons in matter causes the appearance of so-called "bremsstrahlung," (in German "bremsen" means "to brake" and "Die Strahlung" means "radiation"), which is a decelerated radiation. The bremsstrahlung spectrum is continuous, and the maximum energy in the spectrum is determined by the energy of the decelerated electrons. A typical X-ray spectrum obtained from an X-ray tube is shown in Fig. 2.14. When the energy of electrons becomes enough to ionize K shell, the characteristic lines appeared, as seen in Fig. 2.14.

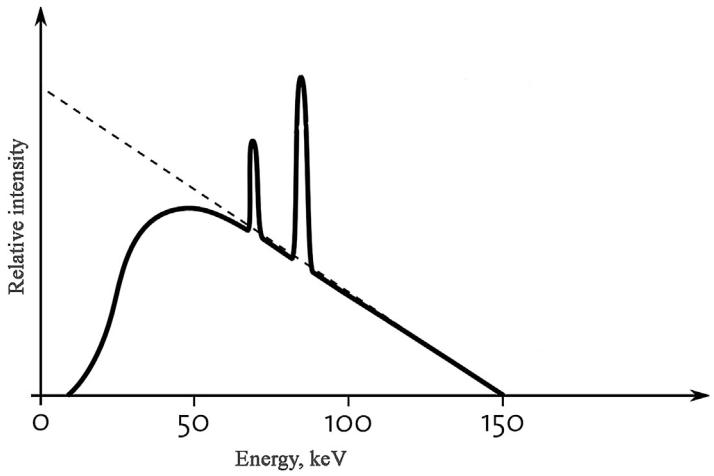

FIGURE 2.14 Typical X-ray spectrum received from X-ray tube with tungsten anode. Bremsstrahlung and two lines of characteristic radiation ($K_{\alpha 1}$, 59.3 keV; $K_{\beta 1}$, 67.2 keV) are shown. Dashed line is unfiltered bremsstrahlung, which can be observed in vacuum.

2.10.3 Synchrotron Radiation

A charged particle, when moving in a magnetic field along a curvilinear trajectory in accelerators, undergoes radial acceleration perpendicular to their trajectory, and, in accordance with the laws of electrodynamics, it emits electromagnetic quanta. The energy lost to radiation is inversely proportional to the square of the mass of the particle. Thus, the heavy particles emit significantly less energy than the light ones. For example, a proton emits 3.4×10^6 times less energy than an electron. Therefore, the radiation energy losses are most important for the lightest charged particles—electrons. This, essentially, magneto-bremsstrahlung started to be called synchrotron radiation because experimentally the radiation was first discovered by F. Haber, a graduate student, on The General Electric 80-MeV synchrotron in 1947. For the sake of justice, it should be noted that synchrotron radiation was predicted by some theorists even before the fact of discovery.

The generated synchrotron radiation has superior properties as follows:

Continuous spectrum of high intensity in a broad spectral range.
Very small natural divergence of the radiation.
Distinct linear or circular polarization, which can be selected depending on the application.

More detailed the synchrotron radiation is described in Chapter 18.

2.11 SOME ELEMENTS OF DOSIMETRY

2.11.1 Doses and Dose Rates

The impact of radiation on material objects is determined by the energy of the radiation transmitted to a substance and is measured by the dose value.

In the initial period after the discovery of X-rays and radioactivity, the main attention was focused on the effects of radiation on living organisms, primarily on the human being. Pretty quickly, in the initial years, it was found that exposure to ionizing radiation leads to radiation damage. The kind of radiation damage first discovered was a radiation skin burn—erythema. To arrange a safe operation with radiations, it was required to establish a quantitative measure of the radiation field.

Historically, the so-called "exposure dose," or simply exposure, was the first quantitative measure that was approved in 1928. It was based on the measurement of air ionization near the source of radiation, X-ray machine, or radioactive nuclide, because direct body measurements were not possible then. Exposure characterized possible effects of radiation on the soft tissues of the body pretty well because the probability of absorption of photons depends on the atomic number (Chapter 6), and the effective atomic numbers of air ($Z_{eff} = 7.64$) and soft tissue ($Z_{eff} = 7.42$) are pretty close.

The first unit of the exposure was a roentgen (symbol: R). It is important to note that the quantity exposure is only defined for X and gamma radiation and for the production of ions in air.

Subsequently, with increasing voltage on X-ray tubes, a corresponding rise of the radiation energy and greater use of radium, radiation can penetrate deeper into the body and affect the bone. It turned out that at the same magnitude of exposure, radiation effects are different in soft and in dense (bone) tissue due to the larger values of the effective atomic number of bone ($Z_{eff} = 13.8$). Also, the difference of density of soft tissue ($\rho \sim 1$ g/cm^3) and bone ($\rho = 1.85$ g/cm^3) plays a certain role.

The better way to assess the impact of radiation is the energy absorbed per mass unit of the substance. On the VII International Congress of Radiology, held in 1953 in Copenhagen, it was recommended to use the "absorbed dose."

As the unit of absorbed dose, a rad was chosen (rad is the abbreviation of the words "radiation absorbed dose").

Closely related to absorbed dose is the quantity "kerma," which is actually an acronym of "Kinetic Energy Released in MAtter." Kerma shows the sum of the initial kinetic energies of all the charged ionizing particles produced in the unit of mass. Kerma is a measure of energy liberated, rather than energy absorbed. The relation of absorbed dose and kerma is similar to the relation of the specific energy loss dE/dx and linear energy transfer LET (Section 5.2). The two will be equal under conditions of charged particle equilibrium and assuming negligible losses by bremsstrahlung radiation. Kerma has the same units as absorbed dose.

For the soft tissue in the field of X-ray or gamma radiation, 1 rad approximately correspond to the exposure equal to 1 R.

In 1960, the 11th General Conference of Weights and Measures approved the International System of Units (Système International d'Unités), usually known as "SI." Then the gradual introduction of international units in different countries and in different branches of science and economy begins.

The SI unit of exposure is coulomb per kilogram (C/kg). The unit of absorbed dose and kerma in SI is joules per kilogram (J/kg). This unit has a special name: gray (symbol: Gy), after Louis Harold Gray, a British physicist and one of the founders of radiobiology. This unit was adopted as part of SI in 1975 by the 15th GCPM (The General Conference on Weights and Measures, abbreviation is according to the French title: Conférence Générale des Poids et Mesures). The relation of the dose units is given in Appendix A.3.1.

The rate of dose accumulation is called dose rate. It shows a dose of ionizing radiation delivered per time unit, e.g., grays per second, per hour, or per year.

Note that gray and rad evaluate the physical effects of the absorbed radiation, but they do not take into account the characteristics of the biological effects occurring during irradiation. Therefore, it is necessary to introduce special units.

Biological effects of radiation on the body depend on the LET of radiation. The destructive effect of radiation is higher the more the LET. To account for this fact, the concept of "equivalent dose" was developed in the 1950s. The equivalent dose is calculated by multiplying the absorbed dose by a special factor w_R. This coefficient is called as the coefficient of relative biological effectiveness, the radiation weighting factor, or the quality factor. For more information on the difference between the definitions of these coefficients, see Section 35.13.

For the calculation of equivalent doses detailed tables of the "radiation weighting factors" are developed. For example, to adequately calculate the equivalent dose in a mixed neutron field with the known neutron energy spectrum, one can use the table with 22 points with neutron energy from 0.025 eV up to 400 MeV, with a maximum value occurring in the range of 100 keV−2 MeV. One can find them in the regulation documents [10] or, for example, in Ref. [11].

The recommended values of the radiation weighting factor have varied somewhat over the years, as evidence from biological experiments has been given and interpreted. The current values are recommended by the International Commission on Radiological Protection [12]. The table of the radiation weighting factors is presented in Appendix A.3.5.

However, even such specification of the concept of dose is not enough. Various human organs have different sensitivity to radiation (quality factors are usually defined on the basis of one biological effect, for example, such as reddening of the skin). Therefore, it is necessary to introduce a special value, the "effective dose," which considers the different radiosensitivity of different organs. Every organ of the body has its own "tissue weighting factor."

To obtain an effective dose, the amount absorbed by the organ is corrected for the radiation type using the radiation weighting factors w_R, and then it is further corrected for the tissues or organs using the tissue weighting factor w_T. The sum of effective doses to all organs and tissues of the body represents the effective dose for the whole body.

The sum of the tissue weighting factors is equal to 1.0, so that if an entire body is radiated with uniformly penetrating external radiation, the effective dose for the entire body is equal to the equivalent dose for the entire body. If only part of the body is irradiated, then only those regions are used to calculate the effective dose.

The values of the weighting coefficients are defined empirically. After the appearance of new experimental results, these values were revised in 1990 and 2007. The latest accepted values of the weight coefficients of individual organs and tissues are presented in Appendix A.3.6.

Thus, equivalent dose is a radiation-weighted dose quantity, which takes into account the type of ionizing radiation producing the dose. Effective dose is a tissue-weighted dose quantity, which takes into account the different radiosensitivity of various organs and tissues.

The units of the measurement of both equivalent and effective doses are the same.

Two types of doses, absorbed, on the one hand, and equivalent and effective, on the other hand, show different effects, so they need different units. It is needed to reflect the biological effects of radiation as opposed to the physical aspects.

The old unit of measurement of the equivalent and effective doses was "rem" (rem is the abbreviation of the words Roentgen Equivalent in Man, or Mammal). In the former USSR (now Russian Federation), this unit before the year 1963 had the name "biological equivalent of roentgen—ber" and after 1963, "biological equivalent of rad—the same ber."

After introduction of SI, the rem was replaced by sievert (Sv), which was named after Rolf Maximilian Sievert, a Swedish medical physicist, one of the founders of radiobiology.

After the introduction of SI, exposure and also exposure rate were not recommended for use, and therefore did not receive a special name. However, until the present time (October 2018) the units of exposure and exposure rate, based on the roentgen unit, are widely used. For example, on the official site of the Russian Federation national nuclear corporation Rosatom [13] dosimeter readings give the dose rate in μR/h and in μSv/h. But the radiation background in Europe is presented in nSv/h [14].

The radiation situation in the United States and some other countries on several sites [15], and [16] is given in counts per minute. Conversion of these units depends on the type of dosimeter and the type of radiation [17]. Besides on the site of the Environmental Protection Agency [16] for some US states one could find the exposure rate in mR/h.

Of particular interest is the radiation situation in the state of Nevada, which housed a test site for nuclear weapons. The information about radiation situation in Nevada is presented on the site of the Community Environmental Monitoring Program [18], and it also expresses in μR/hour.

In the use of units, the United States went its own way. It is well known that the United States uses so-called customary units that are virtually identical to the British imperial units, in its commercial activities and ordinary life, whereas science, medicine, government, and many sectors of industry use metric units. Nevertheless, roentgen, rad, and rem are still in common use, although regulatory and advisory bodies are encouraging transition to Sieverts [19].

Analysis of the risk of exposure to a large group of people—the whole population of a city, state, or all mankind—plays an important role for society. One can assess the risk for a whole group with the help of the "collective dose." It is obtained by multiplying the mean effective dose with the total number of people who have been exposed to radiation. The SI unit of measurement of the collective dose is man-sieverts. The person-rem is sometimes used as the non-SI unit in some regulatory systems. The collective dose is the basis for the risk assessment of the effects of nuclear weapons testing, operation of nuclear facilities, and other sources of radioactive pollution in the environment.

2.11.2 Microdosimetry and Nanodosimetry

When analyzing the effects of ionizing radiation on biological structure, the subject of analysis has microscopic sizes, it is cell or cell nucleus, or even a single molecule. In this case, the quantum nature of the energy loss of the charged particles and the associated statistical nature of the distribution of energy plays an important role. Analysis of fluctuations of energy is the subject of a special branch of science—microdosimetry.

Microdosimetry is a branch of radiological physics that provides quantitative characterization of the nonuniformity of energy deposition in uniformly irradiated matter [20].

Microdosimetry typically operates with the specific energy parameter Z—the ratio of the energy transmitted to the small volume of the substance to the weight of this volume. The probabilistic nature of absorption leads to fluctuations in the value of Z, which is the larger, the smaller the volume, the lesser the radiation dose, and the more the LET of ionizing particles. This fact can be illustrated with the following example. At a dose of gamma radiation 10^{-2} Gy, the deviation of Z from the average Z_{av} in the volume of a living cell is approximately 10%. In the case of neutron radiation with the same dose (ionization is produced by recoil protons, and LET is considerably larger), the fluctuations are such that in 9 cells from 10, $Z = 0$, and in every 10th cell, Z can exceed Z_{av} 10 times. In the volume occupied by the chromosome (at the same dose of neutron radiation) $Z = 0$ in 999 chromosomes from 1000, and in one of them Z may exceed Z_{av} in 1000 times. Specific energy fluctuations are significant for volumes with linear dimensions of about 1 μm.

In recent years, one can observe a further advance into the depths of matter, as nanodosimetry is coming to move microdosimetry. Nanodosimetry is the next logical extension from microdosimetry, providing information on radiation track structure at a DNA or nanometer level [21].

The opportunity to provide measurements of radiation events in nanometer-sized volumes appeared sometime after 1995, but it was the dream of microdosimetry for several decades [22,23].

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