Types of radioactive decay

Previous chapter: 5.2.2 *Quantities and Units*

The transformation of radioactive nuclei is accompanied by an *emission of a particle*. In some cases, electromagnetic radiation γ quantum (pure γ emitters are usually nuclear isomers) is emitted.

In all cases of transformation, the physical dimensions remains preserved. The dimensions referred to are the electric charge, the number of nucleons, the momentum, and the energy.

The electric charge is the algebraic sum of the charge of the nucleus, and the charge of the emitted particles remains constant. For example, if the nucleus emits one electron carrying negative elementary charge, the nucleus gains one positive elementary charge.

The number of parental nucleus‘ nucleons before transmutation will equal the sum of the daughter nucleus‘ nucleons + the emitted nucleons.

The sum of the momentum of the daughter nucleus and the momentum of the emitted particles equals zero when transforming a nucleus according to the scheme X → X´ + emitted particle.

The total energy remains the same when transforming a nucleus according to the scheme X → X´ + particle + hυ. Nuclear transformation serves the purpose of reaching a more stable energetic state.

Alpha decay

Alpha decay is the longest known and the most often observed case of a spontaneous emission of a heavy particle from an atomic nucleus. This decay occurs only in *heavy natural radionuclides*, and can be explained by the mutual repulsive forces between protons. The repulsive forces increase with the increasing proton number.

Alpha particle is composed of *two protons* and *two neutrons*. As these 4 nucleons possess quite a high binding energy, the group behaves like one single particle. Alpha particle has two positive elementary charges due to the presence of two protons. When emitting an alpha particle, the paternal nucleus undergoes radioactive transformation as described bellow:

→ +

Following this transformation, a *daughter nucleus* is formed. In the periodic table this nucleus is located 2 places to the left from the original paternal nucleus. The emitted particle has a low weight compared to the weight of the emitting nucleus. Due to the low weight, the nuclear kinetic energy during the emission of alpha particle is practically negligible. The kinetic energy of the emitted alpha particle usually does not equal the decay-energy (Q), but is somewhat lower. After the emission of an alpha particle, the daughter nucleus is in an *excited state*. Then the nuclei almost immediately transitions into the ground state, via the emission of an electromagnetic γ radiation quantum. That is why, during alpha decay, the emission of monoenergetic alpha particles is accompanied by the emission of γ radiation quantum. The energetic spectrum of alpha decay is composed of lines. The speed of alpha particles is always characteristic for the emitting radionuclide, and can reach values up to 10^7 m.s-1.

Decay β+, β -, and electron capture

Beta decay is described as an *isobaric nucleus transformation*, during which the number of nucleons remains constant. This type of decay is characteristic for artificial radionuclides, and is also found mainly in light nuclei of natural radionuclides. These nuclei are unstable due to the neutron number. An excess of neutrons causes lack of positive charge, and insufficiency of neutron in the nucleus gives an abundance of positive charge. The subject field of nuclear stability is very narrow and the nucleus reaches such stability via internal reorganisation. According to Fermi (1934), this reorganisation can be imagined as the transition of one nucleon from neutron state into proton state, and vice versa.

Electron emission (β- decay)

The nucleus of a paternal radionuclide emits electron and undergoes the following transformation:

$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^{-} + \bar{\nu}_{e}$$

The paternal nucleus emits a negatively charged electron and electron-type antineutrino. The proton number of the daughter element is one higher than the proton number of the paternal element. During this transformation one of the nuclear neutrons changes into proton, while electron and electron-type antineutrino are released. The emitted electrons show a continuous energy spectrum because part of the energy released during the nuclear decay is used to carry away the produced electron-type antineutrino.

Positron emission (β+ decay)

The nucleus of a paternal radionuclide emits positron and undergoes the following transformation:

$$^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N' + e^{+} + \nu_e$$

The paternal nucleus emits positively charged positron and electron-type neutrino. The proton number of the daughter element is one lower than the proton number of the paternal element. During this transformation, one of the nuclear protons changes into a neutron, while a positron and an electron-type neutrinos are released. The emitted positrons share a continuous energy spectrum, because part of the energy released during the nuclear decay is used to carry away the produced electron-type neutrino.

Electron capture

most often refers to an electron from the electron cloud, usually from the K-sphere. Schematically the process can be described as:

$$^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-1}N' + \nu_e$$

During this transformation one of the nuclear protons is changed into neutron. The proton number of the daughter element becomes one lower than the proton number of the paternal element, as seen above in the case of β+ decay. The nucleus emits an electron-type neutrino, and releases transmutation energy (11p → 10n + υe). When the nucleus captures the electron there is a free space created in the lower energy levels of the electron cloud. An electron from a higher energy level fills this space. The electron that migrates creates a free space in the higher energetic level, which then becomes filled with another electron from even higher energy level and so on. Each “electron jump“ is accompanied by an emission of X-radiation. The source of the X-radiations is the electron cloud itself.

All types of beta decay usually produce a daughter nucleus in an excited state. Then it practically immediately transforms into the ground state via the emission of an electromagnetic γ radiation quantum. This is why, for practical use, there are more mixed radiation sources than pure radiation sources. Mixed sources emit β and γ radiation, and pure radiation sources emit β radiation only.

The part of the nuclear transformation energy that is not used up by the emitted electromagnetic gamma radiation or by the emitted particle, can sometimes be passed on the electrons in the electron cloud. Most commonly they are passed to electron clouds belonging into the electron shell K or L – inner radiation conversion. A part of the passed energy is used for the work invested in liberating the electron from the electron cloud. The electron itself takes the rest of the energy away in the form of a kinetic energy. The emission of electron during the inner radiation conversion is also accompanied by an emission of characteristic X-radiation quantum. The energy level that is freed up by the electron emission is filled with some of the higher energy level electrons. The difference between their energies is emitted in a form of radiation as well. The energy spectrum of this radiation is not continuous.

The speed of β particles is characteristic for the type of radionuclide that emits them and can reach values up to 10^8 m.s-1.

Gamma decay

Nuclear reaction of any type usually doesn’t produce a new nucleus in a ground state. The **ground state** is the lowest possible energy state. After either forced or natural spontaneous transformation, such nucleus usually remains in an energetically **excited state**. During the process of gradual or direct transformation, the *excessive energy* is then liberated. The nucleus turns back to a ground state when the energy is liberated, either in the form of emitted particles or as emitted photons of gamma radiation.The time during which the particle remains in the excited state is extremely short and practically immeasurable. The photon is therefore practically emitted at the same time as the physical particle.

The ionizing γ radiation is related, not only to X-radiation, but also to light rays with lower wavelength – about 10-13 m. Due to the very short wavelength, gamma radiation possesses very high energy levels and is therefore very penetrative. Gamma radiation is very often produced by naturally radioactive elements, during the transition of an excited nucleus to an energetically lower state (α and β decay). Emission of gamma radiation does not change proton or nucleon number.

The life length of the excited state can only become long enough to be measurable under certain specific conditions. Such nucleus would then display its own radioactivity γ, characterised by a certain physical half-life. This phenomenon is connected to nuclear isometrics.The process of the transition from metastable form into lower or ground state is called isomeric transition. This phenomenon is successfully used for a number of medical applications that require stable and pure sources of gamma radiation, mainly in the field of nuclear medicine. These can be prepared with the use of nuclear reactions, in nuclear reactors, or are produced by generators etc.

Because the photons of gamma radiation have the same physical basis as any other type of electromagnetic radiation, the speed of these photons equals the **speed of light**.

Neutrons

The hypothesis about atomic nucleus being made up of protons and neutrons was first introduced following the discovery of one of these elementary particles. These particles were called neutron due to its **electric neutrality** (Chadwick, 1932). In this scenario the neutrons supply the nucleus with mass without adding any electric charge. When neutron is found outside the atomic nucleus it acts as a very **unstable particle**. The mean half-life is about 10^3 s and the mass only slightly higher than the mass of a proton. Atomic nuclei with excessive neutrons can remove some of them through the process of β-decay (see 8.8.2). According to current understanding, it is impossible to distinguish which nucleon inside the nucleus is without a charge, and which nucleon possesses a positive charge at a given moment.When the nucleon is liberated from the nucleus, it either does or does not have a specific electric charge. Therefore a neutron can be characterised as a **nucleon**, which up until the moment of leaving the nucleus did not have any electric charge. Neutrons can only be obtained via nuclear reactions. These can occur from a number of various sources, such as *neutron generators, radionuclide sources, nuclear reactors* and *nuclear explosions*.

Cosmic radiation

Cosmic ray is a *current of particles* with very high (1010 to 1018 eV) energies originating in *outer space*.

Primary cosmic rays are composed of *mesons, protons* (up to 80%), *helions* (helium nuclei) and the *nuclei of heavy particles*. They enter the Earth’s atmosphere from astrophysical sources in the outer space. Except for the galactic rays, they contain rays originating from large solar eruptions, consisting of high-energy protons, helions, electrons and X-rays. The dose rate changes only slightly with latitudes, but very significantly with elevation above sea level. Up to the altitude of about 20 km the intensity of cosmic rays increases with the height above sea level. That is why the citizens of Teheran and Mexico City are exposed to a radiation 2-3x higher than people living at the sea level. For the next 20 km upwards the intensity of cosmic rays slowly decreases and is stabilised on constant levels. One exception is the Van Allen radiation belt. This is a belt of increased number of protons 450 – 8 000 km from the Earth’s surface, and with increased number of electrons and protons 15 000 – 70 000 km from the Earth’s surface.

Secondary cosmic rays are created as a result of the primary cosmic rays undergoing a number of various interactions *during their passage through the Earth’s atmosphere.* Cosmic rays have two components, the *soft* and *hard*. The **soft component** of cosmic rays is made up of *electrons, positrons* and *high-energy photons*. The **hard component** contains *mesons, protons, neutrons* and *nuclei of light particles.*

Cosmic rays are a constant part of human living environment. An estimated yearly dose equivalent of cosmic radiation is about 280 µSv at the sea level. The Earth’s atmosphere provides a sufficient enough protection from its possible harmful effects. Flights of commercial airplanes reaching the altitude of about 10 km are also considered to be safe, with the dose equivalent rate is estimated to be about 1,35 µSv . h-1. Supersonic airplanes, which reaches altitudes of about 20 km are subjected to levels of dose equivalent of about 9 µSv .h-1. However the total dose equivalent will be lower than the one of a commercial airplane, seeing as supersonic airplanes reaches their destinations faster. Currently no supersonic airplanes operate commercially, with the exception of commercial space programs. Biological effects of the cosmic rays can have harmful effects during long-term cosmic flights. Securing a sufficient physical protection of cosmic airplanes is difficult due to the very high energy of cosmic rays, and due to the fact that the thickness of a protective layer of the airplane is somewhat limited.

Links

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