Nuclear reactions

Nuclear reactions

A nuclear reaction is a nuclear transformation caused by mutual collision with other nuclei or particles. Every nuclear reaction satisfies certain conditions, namely the laws of conservation of energy, momentum and mass, the law of conservation of charge, the law of conservation of the number of nucleons and other laws.

Nuclear reactions are written in the same way as chemical reactions, but it is important to write the numbers of protons and nucleons in addition to the elemental symbols.

From the energy point of view, there are two types of nuclear reactions: endoenergetic and exoenergetic. In endoenergetic reactions, energy must be supplied for the reaction to take place. In exoenergetic reactions, energy is released during the reaction. Not surprisingly, in terms of practical applications, exoenergetic reactions are of particular interest. These are mainly nuclear fission, in which heavy nuclei are decayed into lighter nuclei, or nuclear fusion, in which lighter nuclei are fused into heavier ones. Whether a given element fissions or fuses depends on its separation energy.

In practice, fission is mostly used in nuclear power plants.

In a nuclear reaction, energy is released in the form of kinetic energy of the expanding particles, but it can also be carried away by particles with zero rest mass moving at the speed of light (photons). By the difference between the energy input to the reaction and the energy output from the reaction, we can get an energy balance, i.e. how much energy we get.

Suitable nuclear reactions in nuclear reactors produce artificial radionuclides for use in medicine.

For more information, see Radionuclides in nuclear medicine.

Separation energy

We denote the separation energy by the Greek letter εj. It is the binding energy per nucleon.

We calculate it using the relation ε = E/A. We introduce this quantity to make it easier to compare the individual binding energies of the nuclei of the elements.

The binding energy is the energy (work) that must be done to split the nucleus into individual nucleons. Its magnitude is therefore dependent on the nucleon number A. It also depends on the mass loss. The binding energy can be calculated from the relation $Ej=(Zm_p+Nm_n-m_j)c^2$, for which mp is the rest mass of the proton, mn is the rest mass of the neutron, mj is the rest mass of the atom, and c is the speed of light in vacuum.

Thus, in simple terms, nuclear fusion can be used to make a heavier and more stable nucleus from two nuclei lighter than ^{56}Fe. However, it is not possible to produce a nucleus heavier than ^{56}Fe.

By fusing a heavier nucleus, two lighter and more stable nuclei can be produced. However, they may not always be stable. The so-called stability river helps us to determine whether a nucleus will be stable or not. Most of the products of nuclear fission are not stable, however, and after a short or long time they spontaneously change into other nuclei. In this case we are talking about radioactivity.

Nuclear fission

Nuclear fission is a nuclear reaction in which the nucleus of a heavy element is broken into two lighter, approximately equal nuclei by a foreign particle (usually a neutron) to release energy. The two resulting nuclei are called fission debris. The fission of a heavy nucleus (e.g. uranium) usually also produces two or three high-energy neutrons. For a fission nuclear reaction to take place, several conditions must be met. The nuclide involved must be fissile. This means that it undergoes a fission nuclear reaction when the neutron is captured (some nuclides capture the neutron without fission). Furthermore, the neutron must be slowed down (usually by water or paraffin, generally by a moderator). Such a neutron introduces almost no energy into the nucleus other than its rest energy. Fission by a high-energy neutron is unlikely, since in such a case the neutron may scatter elastically or inelastically on the nucleus. If we slow down the neutrons produced in a fission nuclear reaction, they can further induce fission of other nuclei, and so a nuclear chain reaction can occur. This occurs when a critical amount of fissile material is available (that is, an amount at which the number of neutrons produced in two successive reactions is equal). If more fissile material is available, we speak of a supercritical amount. In this case, the reaction proceeds uncontrolled (an explosion occurs). If less material is available than the critical amount, we speak of a subcritical amount. Experiments have shown that there are only four nuclides for which a nuclear chain reaction can take place and which can therefore serve as fuel for nuclear power. These are uranium $^{235}{}_{92}$U, uranium $^{233}{}_{92}$U, plutonium $^{239}{}_{94}$Pu and plutonium $^{241}{}_{94}$Pu.

Nuclear fusion

Nuclear fusion is a process in which the nuclei of two lighter elements merge to form a heavier nucleus; at the same time, energy is released. It is a process that takes place in the universe commonly in the cores of stars and by which all elements heavier than helium are formed. The simplest example of nuclear fusion is the fusion of two hydrogen nuclei into a deuterium nucleus. This reaction takes place in the sun and is part of the reaction cycle that produces helium and solar radiation.

Nuclear fusion is being talked about as a possible future energy source. However, for this reaction to take place, the electrostatic repulsive force of the nuclei, the so-called potential barrier, must be overcome (the positively charged nuclei must be brought close enough together so that the attractive nuclear force prevails and the nuclei merge into one). This can be achieved in several ways, but high temperature and pressure seem to be the most advantageous for energy applications (the thermal movement of particles ensures that the potential barrier is overcome). In this case we speak of thermonuclear fusion.

The reaction between deuterium and tritium is the most interesting for energy applications on Earth, as it is the easiest to carry out and releases a large amount of energy. However, the problem is in the extraction of tritium, which is very scarce in the wild, radioactive (with a half-life of 12 years) and toxic. One way of extracting tritium is to irradiate lithium with neutrons. Another relatively convenient reaction is the synthesis of two deuterium nuclei, which are found in seawater in the form of D2O, a heavy water.

TOKAMAK

TOKAMAK or "toroidaľnaya kamera s magnitnymi katuškami" is a Russian invention that allows to maintain very hot plasma using a strong magnetic field. In essence, it is a large transformer containing a secondary coil with a single coil in the shape of a toroidal tube. Inside this toroidal tube is a plasma formed from deuterium and tritium nuclei.

Due to the induced electromotive voltage, a discharge is generated in the gas inside the toroidal tube. With this discharge, the gas is ionised. The induced current of 10^3-10^6 A heats the ionised gas with a particle density of 10^{18}-10^{21} m^{-3} to a high temperature of the order of 11.6×10^6 K. Additional heating continues.

Such high temperatures would not be sustained by any material in contact with the walls and would cause serious problems, so the plasma is maintained by a strong magnetic field in the axis of the toroidal tube. This prevents the plasma from contacting the surrounding reactor walls and reduces the thermal load on the walls to a technologically feasible limit. The walls are then further cooled to temperatures in the range of 1000-1300 °C. Once heated to the required temperature, thermonuclear fusion occurs, releasing energy carried by neutrons. These then heat the water in the primary circuit. This then goes to the heat exchanger where the water in the secondary circuit is heated. The water in the secondary circuit produces steam, which drives the steam turbine. The general scheme is identical to that of a nuclear power plant using fission reactions. Any products produced are purified in a cryodistillation apparatus and tritium is returned to the toroidal tube and deuterium is replenished. Helium is taken away.

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