RADIOACTIVITY and NUCLEAR FISSION

ATOM STRUCTURE

An atom consists largely of empty space (where the electrons move at very high speed), and a dense core in the centre: the nucleus, comprising protons and neutrons. These so-called nucleons cling together to form the nucleus because of an attractive force (which they exert on one another when in close proximity): the nuclear force (or strong force).

An atom is very small (approximately 50,000,000 atoms, lined up in a row, would measure 1 centimetre!) but a nucleus is even more minute (the nucleus is in the same proportion to the atom as a 10 cent coin to a football pitch and occupies only about 10^{-14} of the volume of the entire atom). In spite of the size, virtually all the mass of the atom (more than 99.9 percent) is concentrated in the nucleus.

The nucleus is positively charged (each proton carries one unit of electric charge, neutrons have no charge at all). Protons, neutrons and electrons are long-lived particles present in all ordinary, naturally occurring atoms. Other subatomic particles may be found (with the addition of enormous amounts af energy), but they are short-lived.

The most significant characteristic of an atom is its atomic number (symbol Z), which is defined as the number of protons (the number of units of positive charge in the nucleus). A neutral atom has an equal number of protons and electrons, so that the positive and negative charges exactly balance. The atomic number determines the chemical properties of the atoms of an element (number and type of chemical bonds, physical forces and characteristics of bulk matter). Elements found in nature range from atomic number 1, hydrogen, to atomic number 92, uranium. Artificial elements with atomic number beyond 100 have been produced, but most of them are neither stable nor useful.
The total number of nucleons (both protons and neutrons) in an atom is the atomic mass number (symbol A). The number of neutrons can be easily calculated, being (A - Z).

ISOTOPES

Atoms with the same atomic number but different masses are called isotopes. All isotopes of a given element occupy the same place in the periodic table and have identical chemical properties; yet they can have very different nuclear properties (such as radioactivity). Gallium, for example, has two isotopes: ^{69}Ga and ^{71}Ga (or Ga-69 and Ga-71).

Most elements have stable, naturally occurring isotopes; more can be prepared artificially. For example, hydrogen has three isotopes, each with one proton. The nucleus of ordinary hydrogen is an isolated proton, but the isotope deuterium has one neutron bound to the proton; both of these isotopes are stable. The third hydrogen isotope, tritium, has two neutrons and is radioactive.

The relative isotopic abundance for each element is practically constant in all analysed samples.

NUCLEAR STABILITY

Isotopes are stable when they show no tendency to change spontaneously, in normal conditions, one into another.

A uniform scale of nuclear stability, one that applies to stable and unstable isotopes, is based on a comparison of measured isotopes masses with the masses of their constituent electrons, protons and neutrons. The actual masses of all the stable isotopes differ appreciably from the sums of their individual particle masses: they are smaller than the calculated ones. The difference in mass is called the mass defect: the larger the mass defect, the greater the stability of the isotope. The mass defect is often expressed as energy by using Einstein's equation: $E = mc^2$ (c is the speed of light). The quantity of energy calculated in this way is called the nuclear binding energy.

For example, the isotope ^{12}C, which has a particularly stable nucleus, has an atomic mass of exactly 12.00000 amu (atomic mass unit). The total separate masses of 6 electrons, 6 protons and 6 neutrons add up to 12.09894 amu and thus the mass defect is 0.09894 amu.

RADIOACTIVE ISOTOPES

Isotopes which are not stable indefinitely, disintegrate with processes broadly indicated as radioactive decay. Many elements have unstable isotopes in nature. Without replenishment, any radioactive isotope will ultimately vanish. Some isotopes, however, decay so slowly that they persist on Earth today (after about $6\cdot10^9$ years after the last significant injection of freshly synthesized atoms from some nearby stars). The presence of radioisotopes that decay more rapidly can be explained: by the slow decay of long-lived radioisotopes or by the interaction of cosmic rays with the atmosphere or by nuclear testing and reactors.

RADIOACTIVITY

An unstable nucleus will decompose spontaneously, or decay, into a more stable configuration only in a few specific ways by emitting certain particles or certain forms of electromagnetic energy. The parent radioactive isotope decays into one daughter (or at the most a few). The daughter may itself be unstable, in which case it will, too, decay. The process continues until a stable nuclide will be formed.

Under ordinary conditions, the disintegration of each radioactive isotope proceeds at a well defined and characteristic rate, which is expressed as half-life (the time required for one half of any given quantity of the isotope to decay - symbol $t_{1/2}$). Half-lives range from more than 1 billion years for some nuclei to less than 10^{-9}second.

What follows is all true, but it is not the whole truth!

The most common forms of spontaneous radioactive decay are emissions of alpha particles (□), beta particles (□) and gamma rays (□) from the nucleus.

In alpha decay, a helium ion (alpha particle) is ejected, a daughter nucleus is formed with 2 protons and 2 neutrons less than the parent nucleus (therefore the atomic number of the daughter is 2 less than the parent and the atomic mass number 4 less than the parent). An example is the decay of the abundant isotope of uranium, U-238, to a thorium-234 daughter plus an alpha particle (and thermal energy). The half-life of this decay is $4.51\cdot10^9$ years.

In beta-minus decay, an electron is emitted, producing a daughter nucleus of one higher atomic number and the same mass number (one can think of a neutron as composed of a proton and an electron). The radioactive parent tritium (hydrogen-3), for example, turns into the daughter helium-3 by emitting an electron (the half-life of this decay is 12.3 years). Another example is the decay of Th-234 into Pa-234. (The half-life of this process is 24.1 days.)

A third type of radiation, gamma radiation, usually accompanies alpha and beta decay. Gamma rays are stronger and more energetic than X rays and, like X rays, they are electromagnetic radiation (without mass or charge).

Important radioisotopes with very long half-lives occurring on Earth are uranium-238, uranium-235 and thorium-232. They all decay eventually into stable isotopes of lead.

NUCLEAR FISSION

This process may take place spontaneously in some cases or can be induced by excitation of the nucleus with a variety of particles (neutrons, protons, etc...) or with gamma rays.

In nuclear fission the nucleus breaks up into two lighter nuclei, a large quantity of energy is released, and several neutrons are emitted. These neutrons can induce fission in a nearby nucleus, causing a chain reaction in which a large number of nuclei rapidly undergo fission, releasing an enormous amount of energy. If controlled in a reactor, nuclear fission can provide power for society's benefit. If uncontrolled, as in the case of the so-called atomic bomb, it can lead to an explosion of awesome destructive force.

The discovery of nuclear fission has opened a new era: the Atomic Age. The potential of nuclear fission for good or evil and the risk/benefit ratio of its applications have not only provided the basis of many sociological, political, economic and scientific advances but gave concerns as well. Even from a purely scientific perspective, the process of nuclear fission has given rise to many puzzles and complexities, and a complete theoretical explanation is still not at hand.

HISTORY OF FISSION RESEARCH AND TECHNOLOGY

The term fission was first used in 1939 by Lise Meitner and Otto Frisch to describe the disintegration of a heavy nucleus into two lighter nuclei of approximately equal size.

The story of the discovery of nuclear fission began in 1932 with the discovery of the neutron. Shortly thereafter, Enrico Fermi and his associates in Italy studied extensively the nuclear reactions produced by the bombardment of various elements with neutrons. In 1934 they observed that four different radioactive species were obtained from uranium. In 1939 two German physicists recognized these products as elements in the middle of the periodic table.

The interest for processes with a very large energy release was enormous and many physicists studied them all over the world. Soon it was proved that nuclear fission can produce nuclei with atomic numbers ranging from 30 (zinc) to 64 (gadolinium). Although the experiments were carried out using slow neutrons and ordinary uranium, it became rapidly clear that the rare isotope U-235 (0.7 % natural abundance) was responsible for the phenomenon (the fission of other heavy nuclei requires fast neutrons or other high energy particles.) In 1939, scientists also discovered that several neutrons were emitted in the fission of U-235 leading to the possibility of a self-sustaining chain reaction.

ATOMIC BOMB

The secret Manhattan Project (see Einstein's letter to President Roosevelt - 2.8.1939 and Fermi's pile) lead to the first atomic bomb, tested on July 16, 1945 near Alamogordo, New Mexico. The first atomic bomb to be used in warfare was dropped on Hiroshima on August 6 (equivalent to more than 15 kilotons), the second one on Nagasaki three days later (21 kilotons).

FISSION CHAIN REACTION

The emission of several neutrons in the fission process leads to the possibility of a chain reaction if at least one of the fission neutrons induces fission in another fissile nucleus, which in turn fissions and emits neutrons to continue the chain. If more than one neutron is effective in inducing fission in other nuclei, the chain multiplies more rapidly. The condition for a chain reaction is usually expressed in terms of a multiplication factor k, which is defined as the ratio of the number of fissions produced in one step in the chain to the number of fissions in the preceding generation. If k is less than unity, a chain reaction cannot be sustained . If $k = 1$, a steady-state chain reaction can be maintained; and if k is greater than 1, the number of fissions increases in each step, resulting in a divergent chain reaction.

In a fission bomb it is desirable to have k as large as possible and the time between steps in the chain as short as possible so that many fissions occur and a large amount of energy is generated in a brief period (10^{-7} s) to produce a devastating explosion. If 1 kg of uranium-235 were to fission, the energy released would be 20 ktons, equivalent to the explosion of 20,000 tons of trinitrotoluene (TNT) which was the most widely used chemical explosive in World War I and II. In a controlled nuclear reactor, k is kept equal to unity for steady state operation (k must actually be slightly greater than unity for technical reasons: this permits power levels to be increased if needed, to compensate the gradual loss of fuel by the fission process and the build-up of "poisons" among the fission products that absorb neutrons).

EFFECTS OF AN ATOMIC EXPLOSION

In conventional explosions all the energy is released as shock wave. The detonation of an atomic bomb releases enormous amounts of energy: 50% as shock wave, 35% as thermal energy and 15% as radiation (neutrons and γ rays). The shock wave propagates outward from the blast and can destroy buildings for several miles. Temperatures as high as million degrees are reached in the large fireball generated by the explosion, the heat of which can ignite ground fires and incinerate a whole city. The very strong winds created by the explosion suck dust and other ground materials into the fireball generating the characteristic mushroom shaped cloud. While radiation decreases rapidly in a range of two miles from the explosion, materials vaporized in the cloud condense to fine particles (radioactive debris) which fall to the ground after the explosion (radioactive fallout). Depending upon the height reached by the cloud, the fallout can be local, reaching the ground in a few hours, tropospheric (several months), and stratospheric which might take years to reach the ground at a great distance from the explosion, even in the other hemisphere.

FISSION REACTORS

A nuclear reactor is essentially a furnace used to produce steam or hot gases that can provide heat directly or drive turbines to generate electricity. All reactors require a coolant to remove the heat generated: water, a gas or a liquid metal may be used for this purpose.

Fission reactors can be classified by the energy of the neutrons that propagate the chain reaction. The most common type is a thermal reactor: the fission neutrons produced must be slowed down by scattering from a moderator, usually consisting of ordinary water, heavy water (D_2O) or graphite. In a fast reactor fission neutrons maintain the chain reaction and no moderator is needed.

There are many electric-power generators throughout the world as well as submarines and surface vessels. Reactors may also be used for studying the structure and properties of materials and for producing a broad range of radionuclides which have found many different applications (from cardiac pacemakers to instruments employed in outer space).