Basics of Nuclear Physics and Fission

A basic background in nuclear physics for those who want to start at the beginning.
Some of the terms used in this factsheet can be found in IEER's on-line glossary.

A. Structure of the Atom

The atoms of which every element of matter is composed have a nucleus at the center and electrons whirling about this nucleus that can be visualized as planets circling around a sun, though it is impossible to locate them precisely within the atom. The nuclei of atoms are composed of protons, which have a positive electrical charge, and neutrons, which are electrically neutral. Electrons are electrically negative and have a charge equal in magnitude to that of a proton.

The number of electrons in an atom is normally equal to the number of protons in the nucleus. As a result, atoms of elements are normally electrically neutral. The mass of an atom lies almost entirely in its nucleus since protons and neutrons are far heavier than electrons.

Free neutrons are unstable particles which decay naturally into a proton and electron, with a half-life of about 12 minutes.

neutron ===> proton + electron + antineutrino

However, it is remarkable that neutrons, when they exist together with protons in the nucleus of atoms, are stable. Protons are about 1,836 times heavier than electrons, and neutrons are about 1,838 times heavier than electrons. The energy balance in the decay of a neutron is achieved by the anti-neutrino, a neutral particle that carries off surplus energy as the neutron decays. The nominal mass of an atom of an element is measured by the sum of the protons and neutrons in it. This integer is called the **mass number.** The nominal mass of an atom is not affected by the number of electrons, which are very light. Hence the nominal mass, based on the mass number, *approximates* the actual atomic mass. The number of protons in the nucleus, which determines the chemical properties of an element, is called the **atomic number.** Elements are arranged in ascending order of atomic number in an arrangement called the periodic table. The term derives from the tendency to periodicity of chemical properties deriving from arrangements of electrons in atoms.

B. Radioactive Decay

The nuclei of some elements are not stable. These nuclei are **radioactive,** in that they emit energy and particles, collectively called "radiation." All elements have at least some isotopes that are radioactive. All isotopes of heavy elements with mass numbers greater than 206 and atomic numbers greater than 83 are radioactive.

There are several ways in which unstable nuclei undergo radioactive decay:

- Alpha decay, which the emission of a helium-4 nucleus containing two protons and two neutrons. This is the least penetrating form of radiation. It is stopped by the dead layer of skin and so does

no harm when outside the body. But it is the most damaging form of radiation when deposited inside the body.
- Beta decay, which the emission of an electron or a positron (a particle identical to an electron except that it has a positive electrical charge).
- Electron capture, which is the capture by the nucleus of an electron from among the ones whirling around it. In effect, the electron combines with a proton to yield a neutron.
- Spontaneous fission, which is the fission of a heavy element without input of any external particle or energy.

Often, there is still excess residual energy in the nucleus after the emission of a particle or after electron capture. Some of this residual energy after radioactive decay can be emitted in the form of high-frequency electromagnetic radiation, called gamma rays. Gamma rays are essentially like X-rays and are the most penetrating form of radiation. [1] It should be noted that the emission of gamma rays does not change the mass number or atomic number of the nucleus — that is, unlike radioactive decay by emission of particles, spontaneous fission, or electron capture, it does not cause the transmutation of the nucleus into another element.

Each quantum, or unit, of a gamma ray (or other electromagnetic energy) is called a **photon.** Gamma rays are like light, except that they are much higher frequency electromagnetic rays. Photon energy is directly proportional to the frequency of the electromagnetic radiation. Photons of gamma rays can damage living cells by splitting molecules apart or ionizing elements in them.

Many heavy nuclei emit an energetic alpha particle when they decay. For instance uranium-238 decays into thorium-234 with a half-life of almost 4.5 billion years by emitting an alpha particle:

92-uranium-238 ====> 90-thorium-234 + alpha particle (nucleus of 2-helium-4)

The mass number of uranium-238 declines by four and its atomic number by two when it emits an alpha particle. The number before the element name is the atomic number and that after the element name is the mass number. The totals of the atomic numbers and the mass numbers, respectively, on both sides of the nuclear reaction must be the same. (This is like balancing a chemical equation, in which the number of atoms of each element on both sides of the reaction must be equal)

In beta decay, the atomic number increases by one if an electron is emitted or decreases by one if a positron is emitted. For instance thorium-234, which is the decay product of uranium-238, in turn beta-decays into protactinium-234 by emitting an electron:

90-thorium-234 ====> 91-protactinium-234 + beta particle (electron)

The nuclei that result from radioactive decay may themselves be radioactive. Therefore, some radioactive elements have decay chains that may contain many radioactive elements, one derived from the other. (See Uranium Factsheet for a diagram of the decay chain of uranium-238.)

The radioactive decay of nuclei is described probabilistically. Within any given time period, a particular unstable nucleus has a fixed probability of decay. As a result, each radioactive element is characterized by a “half-life,” which is the time it takes for half the initial atoms to decay (or transmute into another element or nuclear state). At the end of one half-life, half the original element is left, while the other half is transformed into another element. After two half-lives, one fourth of the original element is left; after three half-lives one eighth is left, and so on. This results in the build-up of decay products. If the decay products themselves decay into other elements, a whole host of radioactive materials come into being. The decay products of radioactive elements are also called **daughter products** or **progeny.**

C. Binding Energy

Nuclei are tightly bound together by the strong nuclear force and each nucleus has a characteristic **binding energy.** This is the amount of energy it would take to completely break up a nucleus and separate all the neutrons and protons in it. Typically, binding energy increases by several megaelectron-volts (MeV) for every proton or neutron added to a nucleus. (Since protons and neutrons are constituent particles of nuclei, they are known collectively as **nucleons.**) The release of nuclear energy derives from the differences in binding energy between the initial nucleus (or nuclei) and relative to the end-products of the nuclear reaction, such as fission or fusion.

The electrons that whirl around the nucleus are held together in their orbits by electrical forces. It takes on the order of a few electron-volts to dislodge an electron from the outer shell of an atom. The "binding energy" of a nucleon is on the order of a million times greater. Electrons are the particles the enable chemical reactions; nucleons take part in nuclear reactions. The huge differences in binding energy are one measure of the differences in the quantities of energy derived from nuclear compared to chemical reactions.

It must be stressed that the binding energy is the amount of *energy that would have to be added to the nucleus to break it up.* It can be thought of (approximately) as the amount of energy liberated when a nucleon is drawn into the nucleus due to the short range nuclear attractive force. Since energy and mass are equivalent, *nuclei with higher binding energy per nucleon have a lower atomic weight per nucleon.*

The key to release of nuclear energy from fission of heavy elements and fusion of light elements is that elements in the middle of the periodic table of elements, with intermediate mass numbers have a higher binding energy per nucleon (that is a lower atomic weight per nucleon). Therefore when a heavy nucleus is fissioned, the resultant products of the nuclear reaction have a slightly smaller combined nuclear mass. This mass difference is converted to energy during nuclear fission.

D. Nuclear Fission

Nuclear energy is produced by the conversion of a small amount of the mass of the nucleus of an atom into energy. In principle, all mass and energy are equivalent in a proportion defined by Albert Einstein's famous equation

$$E = mc^2$$

where E stands for energy, m for mass and c for the speed of light. Since the speed of light is a very large number–300 million meters per second–a small amount of mass is equivalent to a very large amount of energy. For instance, one kilogram (about 2.2 pounds) of matter is equivalent to

$E = 1\ kg \times (3 \times 10^8\ meters/sec)^2 = 1 \times 3 \times 10^8 \times 3 \times 10^8$ joules
$= 9 \times 10^{16}$ joules

This is a huge of amount of energy, equivalent to the energy content of over three million metric tons of coal.

Heavy atoms such as uranium or plutonium can be split by bombarding them with neutrons. [2] The resultant fragments, called fission products, are of intermediate atomic weight, and have a combined mass that is slightly smaller than the original nucleus. The difference appears as energy. As explained in the previous section, this mass difference arises from the binding energy characteristics of heavy elements compared to elements of intermediate atomic weight. Since the binding energy of the fission products per nucleon is higher, their total nucleonic mass is lower. The net result is that fission converts some of the mass of the heavy nucleus into energy.

The energy and mass aspects of the fission process can be explained mathematically as follows. Let the total binding energy of the heavy nucleus and the two fission products be B_h, B_{f1}, and B_{f2}, respectively. Then:

Amount of energy released per fission $E_r = (B_{f1} + B_{f2}) - B_h$

Amount of mass converted to energy = $Er/c^2 = \{(B_{f1} + B_{f2}) - B_h\}/ c^2$

This energy appears in various forms: the kinetic energy of the neutrons, the vibrational energy of the fission fragments, and gamma radiation. All of these forms of energy are converted to heat by absorption in with the surrounding media in the reactor, mainly the coolant and the moderator (for thermal reactors). The most basic fission reaction in nuclear reactors involves the splitting of the nucleus of uranium-235 when it is struck by a neutron. The uranium-235 first absorbs the neutron to yield uranium-236, and most of these U-236 nuclei split into two fission fragments. Fission reactions typically also release two to four neutrons (depending on the speed on the neutrons inducing the fission and probabilistic factors). One of these neutrons must trigger another fission for a sustained chain reaction. The fission reactions in a nuclear reactor can be written generically as follows:

U-235 + n ==> U-236

U-236 ===> fission fragments + 2 to 4 neutrons + 200 MeV energy (approx.)

The uranium-236 nucleus does not split evenly into equal fission fragments. Rather, the tendency, especially with fission induced by thermal neutrons, is for one fragment to be considerably lighter than the other. Figure 9 (not available in on-line version of report) shows the distribution of fission products due to fission with the slow neutrons and fast neutrons. It can be seen that the fission product atomic numbers are concentrated in the ranges from about 80 to 105 and from about 130 to 150 in thermal reactors. An example of a fission reaction is:

92-U-235 + n ==> 92-U-236

92-U-236 ===> 38-strontium-90 + 54-xenon-144 + 2 neutrons + energy

While many heavy nuclei can be fissioned with fast neutrons, only a few can be fissioned with "slow" neutrons. It turns out that, with some exceptions, like plutonium-240, only nuclei that can be fissioned with slow neutrons can be used for sustaining chain reactions. Isotopes with nuclei that can be fissioned with zero energy neutrons (in practice neutrons with low energy, or "slow neutrons") are called *fissile* materials. Generally these are the odd-numbered isotopes, such as uranium-233, uranium-235, plutonium-239, and plutonium-241. Other heavy nuclei, like uranium-238, can be fissioned with fast neutrons, and so are *fissionable*, but not fissile.

There are only three fissile isotopes of practical importance: uranium-233, uranium-235, and plutonium-239. Of these, only uranium-235 occurs naturally in significant quantities. The other two occur in trace quantities only.

E. Fertile Materials

To obtain plutonium-239 and uranium-233 in amounts useful for nuclear energy production, they must be manufactured from materials that occur in relative abundance. Plutonium-239 is produced from reactions following the absorption of a neutron by uranium-238; uranium-233 is produced by neutron absorption in thorium-232. Uranium-238 and thorium-232 are called **fertile materials,** and the production of fissile materials from them is called **breeding.**
The reactions for plutonium-239 are

92-U-238 + n ===> 92-U-239

92-U-239 ====> 93-Np-239 + beta particle (electron)

93-Np-239 ====> 94-Pu-239 + beta particle (electron)

For uranium-233 the reactions are:

90-Th-232 + n ===> 90-Th-233

90-Th-233 ===> 91-Pa-233 + beta particle (electron)

91-Pa-233 ====> 92-U-233 + beta particle.

The symbol Pa stands for the element protactinium.

(See Chart of Chemical Names on IEER's On-Line classroom page for this and other chemical names and their symbols.)

Notes:

1. The terms alpha, beta, and gamma radiation, and X-rays were coined because scientists did not know the nature of these kinds of radiation when they were first detected. ? Return
2. Nuclear fission can also be induced by bombardment of the nucleus by electrically charged

particles, such as alpha particles. However, the nucleus is positively charged and alpha particles are also positively charged. Since positive charges repel each other, these types of fission reactions are more difficult to accomplish than reactions with neutrons. Fission can also be induced by bombarding the nucleus with energetic gamma rays (photons). This process is called photofission. ? Return