2.3.1 Basic nuclear fission

To proceed it is necessary to outline the basic physics of nuclear fission. The speed of individual neutrons is quoted in terms of their kinetic energy in eV or *electron-volts* where 1 eV is equivalent to 4.44×10^{-26} kWh (kilowatt hours) of power. These energies range from those of so-called *fast neutrons* with energies of the order of $0.1 \rightarrow 10$ MeV down to those of so-called *thermal neutrons* with energies of the order of 0.1 eV or less. As described later, both fast and thermal neutrons play important roles in nuclear reactors.

In 1938/9 Hahn, Meitner, Strassman and Frisch (Hahn and Strassman 1939, Meitner and Frisch 1939, Frisch 1939) first showed that any heavy atomic nucleus would undergo fission if struck by a *fast* neutron of sufficiently high kinetic energy, of the order of $1 \rightarrow 2$ MeV. Shortly thereafter Bohr and Wheeler (1939) predicted that only very heavy nuclei containing an odd number of neutrons could be fissioned by all neutrons with kinetic energies down to the level of *thermal* neutrons (order 0.1 MeV). The only naturally occurring nucleus that meets this condition is the isotope U^{235} that has 92 protons and 143 neutrons. However, the isotope ^{235}U is rare; in nature it only occurs as one atom for every 138 atoms of the common isotope ^{238}U or, in other words, as 0.71% of natural uranium. The consequences of this will be discussed shortly.

When a neutron strikes a heavy nucleus there are several possible consequences:

- *radiative capture* or absorption , in which the neutron is captured by the nucleus and essentially lost.
- *elastic scattering*, during which the neutron rebounds from the collision without any loss of kinetic energy.
- *inelastic scattering*, during which the neutron is momentarily captured and then released without fission but with considerable loss of kinetic energy.
- *fission*, in which the heavy nucleus is split into several *fission fragments*, energy is generated and several *secondary* neutrons are released.

When a heavy nucleus such as ^{235}U is fissioned by a colliding neutron, several important effects occur. First and most fundamentally for our purposes is the release of energy, mostly in the form of heat (as a result of the special theory of relativity, there is an associated loss of mass). On average the fission of one ^{235}U nucleus produces approximately 200 MeV (2×10^8 eV) of energy. Thus a single fission produces roughly 8.9×10^{-18} kWh. Since a single ^{235}U atom weighs about 3.9×10^{-22} g it follows that the fission of one gram of ^{235}U produces about 23 MWh of power. In contrast one gram of coal when burnt produces only about 10^{-5} MWh and there is a similar disparity in the waste product mass.

The second effect of a single ^{235}U fission is that it releases two or three neutrons. In a finite volume consisting of ^{235}U, ^{238}U and other materials, these so-called *prompt* neutrons can have several possible fates. They can:

- collide with other ^{235}U atoms causing further fission.
- collide with other ^{235}U atoms and not cause fission but rather undergo radiative capture.
- collide with other atoms such as ^{238}U and be absorbed by radiative capture.
- escape to the surroundings of the finite volume of the reactor.

As a consequence it is useful to conceive of counting the number of neutrons in a large mass in one generation and to compare this with the number of neutrons in the following generation. The ratio of these two populations is known as the *reproduction factor* or *multiplication factor*, k, where

$$k = \frac{\text{Number of neutrons in a generation}}{\text{Number of neutrons in the preceding generation}} \tag{1}$$

In addition to k, it is useful to define a multiplication factor that ignores the loss of neutrons to the surroundings, in other words the multiplication factor for a reactor of the same constituents but infinite size, k_∞. In the section that follows the process by which k and k_∞ are used in evaluating the state of a reactor will be detailed.

An alternative to k is the frequently used *reactivity*, ρ, defined as

$$\rho = \frac{(k-1)}{k} \tag{2}$$

and this quantity is also widely used to describe the state of a reactor. Further discussion on k (or ρ) and k_∞ and the role these parameters play in the evaluation of the criticality of a reactor is postponed until further details of the neutronics of a reactor core have been established.