

Chapter 2

Nuclear Power and Radiation

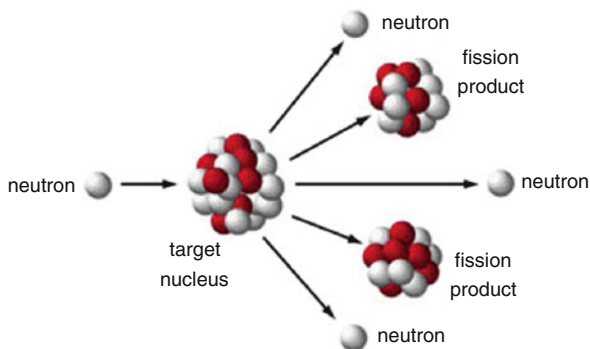
2.1 Nuclear Fission Reaction

How the nuclear fission of uranium was discovered is detailed in, e.g., Jeremy Bernstein's "Plutonium" (Bernstein 2007). The phenomenon of nuclear fission itself was first discovered by E. Walton and J. Cockcroft in 1932 with regard to the reaction of proton with ${}^7_3\text{Li}$, which produced two α -particles (helium nuclei). Enrico Fermi and his associates in Rome studied the reaction of neutrons with uranium in 1934. Lise Meitner, along with Otto Hahn and Fritz Strassmann, worked on this issue as well. They found that one of the products was barium. Hahn and Strassmann published their results in December 1938. Hahn was skeptical, but Meitner realized that uranium was split into smaller nuclei, one of which was barium. Hence, she was the first to recognize a nuclear fission reaction (of uranium), but, unfortunately, she did not share the Nobel Prize, which was awarded to Otto Hahn. Meitner was the first Austrian woman physicist and a Jew, and had a lot of trouble during the 1930s because of the rise of the Nazi movement.

A neutron can collide easily with a nucleus, because of its electrical neutrality. However, a neutron with a high speed may often fly by a nucleus without getting captured. Whether it happens that way or not is dependent on the cross section of a nucleus. A nucleus that has a relatively small cross section would be able to capture more easily a slower (termed "thermal") neutron. It turned out that this is the case with uranium (${}_{92}\text{U}^{235}$; often abbreviated to U-235). The major isotope ${}_{92}\text{U}^{238}$ can be split, but only at a very low speed.

When a neutron enters a nucleus of U-235, it will deform and destabilize the shape of the liquid drop-like nucleus (the Bohr model) and soon split into two smaller nuclei. Once these two positively charged nuclei separate beyond a short critical distance, the strong nuclear force ceases to operate, and electric repulsion pushes them farther apart. This is a fission reaction (Fig. 2.1). A typical fission reaction of U-235 is exemplified by the following equation:

Fig. 2.1 A model of a nuclear fission reaction



Usually, it would not split into halves exactly, and would produce as many as 200 daughter nuclei in a nuclear reactor reaction, as well as in an atomic explosion. The distribution curve of daughter nuclei as a function of mass number has already been determined. According to this, one daughter nucleus has a mass number peaking at about 135 and the other peaks at about 95. The majority of these fission products is unstable and radioactively decays (discussed below).

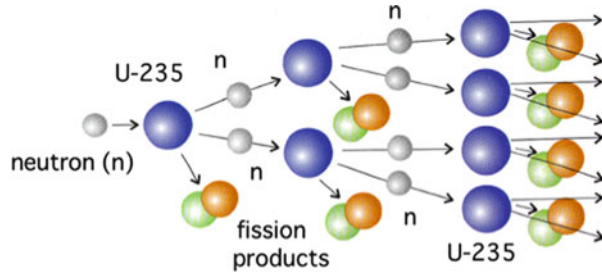
We can estimate roughly the energy change in the fission reaction based on the nuclear binding energy (BE) (Fig. 1.2). The BE of U-235 is about 7.7 MeV, and that of the two daughter nuclei are about 8.45 MeV (assuming average mass number = 117). Therefore, the energy change is estimated to be $7.7 \times 235 - 8.4 \times 234 = -168$ MeV. This is the energy change for a single nucleus of U-235 upon fission (the energy carried by an extra neutron is ignored). This energy can be converted to 6.9×10^7 kJ for 1 g of U-235. The energy released is reflected in the loss of mass in the process. In the case of the reaction cited above, the mass loss has been determined to be -0.19 u (see Note 1.5.4 for “u” at the end of Chap. 1). This mass (lost) is converted to energy through $E = mc^2$. This energy can be calculated to be 171 MeV or 7.0×10^7 kJ for 1 g of U-235. This is the basis for the atomic bomb dropped on Hiroshima and the majority of today’s nuclear power plants.

Other usable fissionable isotopes are ${}_{92}\text{U}^{233}$ and ${}_{94}\text{Pu}^{239}$. Indeed, the second atomic bomb dropped on Nagasaki was based on plutonium (Pu-239).

2.2 Nuclear Chain Reaction and Nuclear Power

In the fission process, as exemplified above, two or three neutrons are produced. As there are a large number of fission reactions with U-235, the average number of neutrons produced per fission has been estimated to be about 2.4 neutrons. Suppose that two neutrons are produced. Then, those two neutrons will cause the fission of two more U-235 nuclei, if the neutrons collide and are captured successfully. The

Fig. 2.2 A model of nuclear fission chain reaction (Modified from Fig. 17.24 in Atkins and Jones (2005))



result is the formation of four neutrons, which then fission four more U-235. This process of automatically repeating fission reactions once it starts is called a “chain reaction” (Fig. 2.2).

As mentioned earlier, on average, 2.4 neutrons are produced from one neutron during a fission process. If all 2.4 neutrons hit further U-235 without being lost, then the neutron multiplication factor is $K = 2.4$. If one neutron is lost on average before it hits a U-235, then $K = 1.4$. When $K = 1$, the chain reaction will barely be sustained. When this condition is met, it is said to be at a “critical state”. How many neutrons will be lost before colliding with U-235 would depend on the mass of the U-235 sample and other factors. The mass of U-235 at which the critical state is attained is called the “critical mass”.

If $K < 1$ (subcritical condition), the fission reaction will soon cease or the fission chain reaction would not commence. On the other hand, if $K > 1$, the fission reaction will be accelerated and soon explode. Clearly, the atomic bomb works under the supercritical condition $K > 1$, whereas in the nuclear reactor, it should be maintained more or less close to the $K = 1$ condition. This is the main difficulty faced in the nuclear reactor.

2.3 Atomic Bombs and Nuclear Reactors

An atomic bomb has to be maintained under subcritical conditions before use. When it is to be exploded, it has to be brought quickly to supercritical conditions. In the atomic bomb dropped on Hiroshima, two separate U-235 masses (under subcritical conditions) were brought together by the action of a gun; one mass was shot towards the other mass. The overall mass then instantly became supercritical and it exploded. The other atomic bomb dropped on Nagasaki was based on plutonium, and the mechanism to bring about a supercritical condition was different (implosion). Atomic bombs require no other consideration technically; all it has to do is bring about a supercritical condition to cause an explosion. No other control was necessary in principle; the only purpose was to explode and destroy everything in its vicinity.

On the other hand, the so-called “peaceful” use of nuclear power requires a strict control of the fission reaction under conditions close to the “critical state”. Otherwise, it easily leads to an explosive disaster, as happened in the nuclear facility at Chernobyl in the former Soviet Republic (1986). Several designs of nuclear reactor are based on how to moderate the neutron speed and its number (to control the K -value). This treatise is not intended to discuss the technical details of a nuclear reactor. Therefore, the most commonly used type, i.e., the boiling water reactor, is mentioned briefly here.

Light water (in contrast to heavy (deuterium) water) is used in the core surrounding the nuclear fuel rods (containing enriched U-235), and functions both as the coolant (and energy carrier as vapor) and the neutron moderator. Control rods would be inserted among the fuel rods. The control rod should contain substances that absorb neutrons efficiently. A typical control rod for a light boiling water-type reactor is made of an alloy of silver (Ag), indium (In), and cadmium (Cd). Another is boron (B), particularly ${}^5\text{B}^{10}$, which has a large neutron cross section so that it easily absorbs neutrons; it is commonly used as boron carbide rod. During the process, ${}^5\text{B}^{10}$ turns into another stable isotope, ${}^5\text{B}^{11}$. When the control rods are fully inserted, insufficient neutrons become available, and the fission reaction will cease. So that is how extensively the control rods are to be inserted in order to regulate the fission reaction. This is the most critical device in the nuclear power reactor.

2.4 Radioactive Isotopes and Their Decay

As mentioned earlier, the fission reaction of U-235 leads to the production of a large number (as many as 200) of fission products (daughter nuclei). The mass numbers of these products are divided into two groups; one from about 80 to 110, and the other from 110 to 150. And when two daughter nuclides form, the total mass number of them would be 234–232 or so. In terms of elements (i.e., the number of protons = atomic number in the daughter nuclides), the atomic number of fission products ranges from about 34 (Se) to 62 (Sm). Some of these fission products are listed in Table 2.1 in the order of their yield. The majority of them turned out to be “radioactive”. Often, it is usually the case that a nuclear reaction would lead to the formation of nuclei that are not in the most stable form. An unstable, i.e., high energy, state would spontaneously turn into a more stable state. This spontaneous change in a nucleus is called “decay” or “disintegration”. The degree of blockage against decay would determine how fast the nucleus changes into a stable state, i.e., its “half-life”.

Unstable nuclei may take a number of routes to turn into more stable states. The major paths are: (1) emission of nucleons: protons, neutrons, or α -particles (helium nuclei); (2) emission of electrons (β^-) or positrons (β^+) (antielectron), and (3) emission of γ -rays (photons).

All the isotopes of the elements higher than atomic number 84 are unstable, and emit α -particles. In these nuclei, there are a sufficiently large number of protons,

Table 2.1 Major thermal nuclear fission products of U-235 and others

Isotope	Yield (%)	Decay mode	Energy (keV)	Half-life ^a	Decay product, comments
Cs-133 → Cs-134	6.79	β	211	2.065 y	Cs-133 is stable, but it captures a neutron to turn into Cs-134, which β-decays, but also captures a neutron to turn into Cs-135
Cs-134		β(γ)	2,059 (605, 796)	2.07 y	→ Ba-134; Ba-134 m1, m2 -γ→
Cs-135		β	269	2.3 My	→ Ba-135
I-135 → Xe-135	6.33	β	135	6.57 h	Neutron capture converts 10–50 % of ¹³⁵ Xe to ¹³⁶ Xe; the remainder decays (9.14 h) to Cs-135 (2.3My)
Zr-93	6.30	β, (γ)	90	1.53 My	→ Nb-93 m -γ (14 years) → Nb-93
Mo-99	6.1	β	1,357	65.94 h	→ Tc-99 m -γ (142 keV, 6 h) → Tc-99
Cs-137	6.09	β, γ	514, 662	30.17 y	→ Ba-137 m -γ → Ba-137
Tc-99	6.05	β	294	211 ky	→ Ru-99
Sr-90	5.75	β	546	28.9 y	→ Y-90
I-131	2.83	β, γ	606, 364	8.02 d	-β → Xe-131 m -γ → Xe-131
Pm-147	2.27	β	224	2.62 y	→ Sm-147
Sm-149	1.09			Stable	
I-129	0.65	β, γ	194, 236	15.7 My	-β → Xe-129 m -γ → Xe-129
Sm-151	0.42	β	77	90 y	Neutron capture to stable Sm-152
Ru-106	0.39	β	39	373.6 d	-β → Rh-106 -β → Pd-106
Kr-85	0.27	β, (γ)	250	10.78 y	→ Rb-85; 0.43 % β/γ (514 keV)
Pd-107	0.16	β	33	6.5 My	→ Ag-107
Se-79	0.051	β	151	327 ky	→ Br-79
Eu-155 → Gd-155	0.033	β	253	4.76 y	Both capture neutrons
Sb-125	0.030	B, (γ)	767 (145)	2.76 y	→ Te-125 m -γ(57.4 d) → Te-125
Sn-126	0.024	β	380	230 ky	→ Sb-126
Gd-157	0.0065			Stable	Capture neutrons
Cd-113	0.0003	β	322	14.1 y	Capture neutrons
K-40 ^b		β	1,311	1.25 Gy	90 % → Ca-40; 10 % K-40 -EC ^c / γ → Ar-40
		γ (10 %)	1,460		
U-235 ^b		α	4,679	704 My	
U-238 ^b		α	4,267	4.51 Gy	
Ra-226 ^b		α	4,817	1.6 ky	
Pu-239 ^d		α	5,245	24.4 ky	
H-3 ^e		β	18.6	12.3 y	

Yield data are from Wikipedia, and others from many different sources

^ad = days, y = years, ky = 10³ y, My = 10⁶ y, Gy = 10⁹ y

^bThese are naturally occurring

^cElectron capture

^dThis forms from U-238 through neutron capture and two consecutive β-emissions

^eIs tritium and is not a fission product but forms in a nuclear reactor

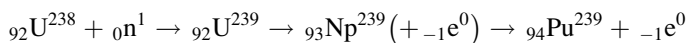
which exert destabilizing repulsive effects. This is reflected in the decrease in the nuclear binding energy, as seen in Fig. 1.2. The release of a highly stable α -particle would reduce this tension, and the energy released is then transferred to the kinetic energy of the particle emitted, and this is α -radiation. The kinetic energy of an α -radiation is determined by the energy state of the nucleus and its change, and is independent of the circumstances under which it occurs. Hence, it is possible to identify the nucleus by measuring the radiation energy.

A nucleus that has too many neutrons may reduce its high energy level by either releasing a neutron or converting a neutron to a proton. The former process does not change the atomic number (hence, the identity of the element), and only diminishes the mass number by one. More often, the latter process takes place. When a neutron turns to a proton, an electron is released to compensate for the electric charge (which needs to be conserved), and another particle, an antineutrino, is released alongside. The electron emitted with high kinetic energy is the β -particle. Because of the extra particle, the antineutrino, the kinetic energy carried by the β -particle will vary depending on how the antineutrino behaves. However, the average value (or the distribution) of the energy can be used to determine the identity of the β -emitting isotope.

The β -decay product may not be the most stable state of a nucleus (called the “metastable state” and denoted “m” after the mass number), and, if so, the extra energy would be emitted as a photon, γ -radiation. Hence, β -decay (radiation) is accompanied by γ -radiation in many cases. γ -radiation also occurs along with α -radiation, although not always. As the photon emission depends only on the two energy states of a nucleus, it is characteristic of it. The energy of γ -emission can, thus, be used to identify the isotope.

Some of the representative decay energy values are given in Table 2.1. They range from 20 to 5,200 keV (5.2 MeV). This value should be compared to the chemical energy, the typical value of which is on the order of 1–10 eV. Hence, the nuclear decay energy is several thousand to millions of times as large as the chemical energy.

Table 2.1 includes four naturally occurring radioisotopes, U-235, U-238, Ra-226, and K-40. There are a few other naturally occurring radioisotopes, including Th-230, and the decay products of U-238 and Th-230, such as Ra-226, Rn-222, and Po-220. Pu-239 is an example of transuranium elements that are artificially produced from U or other elements through neutron bombardment, α -particle bombardment, or by other means. Pu-239 occurs via the neutron bombardment of U-238:



The intensity of radioactivity is measured as how many decay processes take place over a unit time (second). The unit of radioactivity is called the “Becquerel” (Bq). H. Becquerel was the French scientist who first discovered the phenomenon of radiation. Radioactivity used to be expressed in terms of “Curie” (Ci). Marie

Table 2.2 Quantity to represent radioactivity (Bq)

Isotope	Half-life ($t_{1/2}$)	K-value (s^{-1})	No. of atoms to give 1 Bq	Quantity (g) to give 100 Bq
U-235	7×10^8 years	3.14×10^{-17}	3.2×10^{16}	1.2×10^{-3}
U-238	4.5×10^9 years	4.88×10^{-18}	2.1×10^{17}	8.1×10^{-3}
Th-232	1.4×10^{10} years	1.57×10^{-18}	6.4×10^{17}	2.5×10^{-2}
Pu-239	2.4×10^4 years	9.16×10^{-13}	1.1×10^{12}	4.3×10^{-8}
I-131	8 days	1.00×10^{-6}	1.0×10^6	2.2×10^{-14}
Cs-137	30 years	7.33×10^{-10}	1.4×10^9	3.1×10^{-11}
Sr-90	28.8 years	7.36×10^{-10}	1.4×10^9	2.0×10^{-11}
H-3	12.3 years	1.78×10^{-9}	5.6×10^8	9.3×10^{-14}
K-40	1.25×10^9 years	1.76×10^{-17}	5.7×10^{16}	3.8×10^{-4}

Curie further studied the phenomenon and identified the radioactivity caused by radium, and the unit “Ci” was based on a gram of radium. It turned out to be too large a unit, so it was substituted by the Bq, and $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$. There is no ambiguity with the activity value Bq, as it is measured as the number of disintegrations per second, as long as it is properly measured.

The decay process obeys the first-order reaction rate equation, so it can be expressed as $-dN/dt = kN$, where k is the rate constant (representing what proportion of the nuclides would decay per second) and N is the number of radioactive nuclei. The $-dN/dt$ value represents “Bq”. The integrated form of the rate equation is given by $N = N_0 \exp(-kt)$, where N_0 is the initial quantity. When $t = T$ (half-life), N becomes half of N_0 , so that $N = N_0/2$ at $t = T$. Therefore, $\ln 2 = kT$. T (half-life) is used to express how fast the disintegration proceeds. The half-life data for the major radioisotopes found in the fission reaction products are given in Table 2.1.

Radioactivity is usually expressed in terms of Bq/kg of a sample. As the equation above indicates, it represents the quantity N (number of nuclei). For example, in today’s Japan (after the Fukushima incident), the allowable radioactivity of food is set at 100 Bq/kg. Such a sample in today’s Japan contains Cs-137 as the major component. Let us calculate the quantity of Cs in such a sample of 100 Bq/kg, assuming that it is 100 % Cs-137. The half-life of Cs-137 is 30 years, which is $9.46 \times 10^8 \text{ s}$; therefore, k (rate constant) = $7.33 \times 10^{-10} \text{ s}^{-1}$. Since $100 \text{ Bq} = kN$, N is 1.36×10^{11} ; this many Cs-137 nuclei is $2.26 \times 10^{-13} \text{ mol}$, which is $3.1 \times 10^{-11} \text{ g}$. This is a very small quantity, and cannot be determined by usual chemical analysis. Similar calculations can be done with other radioisotopes of interest, and the results are shown in Table 2.2. The table shows that significant radioactivity is brought about by a very small quantity of radioactive material. It also suggests that the biological effects of radiation should be dealt with in terms of the number of radiation particles and their energies, rather than the ordinary expression of the quantity of material in moles or weight, and of energy in joules, as will be discussed below.

The dose of exposure of a material to radiation is expressed in terms of the energy value J absorbed by the material of a unit quantity (usually 1 kg). One joule deposited in a material is defined as 1 Gray (Gy) ($= 1 \text{ J/kg}$). It is a very small quantity in terms of energy in a macroscopic world.

The impact on living organisms is expressed in dose equivalent: Sievert (Sv). It takes into consideration how effective each different radiation would be on a living organism's body, and is expressed as $\text{Sv} = Q \times \text{Gy}$. It has been officially (ICRP) defined as follows. The Q value for β - and γ -radiation is defined as "1", but $Q = 20$ for α -radiation, as it is more effective in affecting the human body. The dose exposed to neutrons depends on its speed, and Q is thought to be in the range 10–15. These Q values cannot be scientifically accurately determined in terms of expressing the real impact on living organisms, particularly in the so-called "internal exposure". The distinction between "external" and "internal" exposure will be discussed later. The most significant exposure to low-level radiation is "internal", but this was not considered in deciding the Q factors assigned to different radiation modes. The inadequacy of the Sv value in expressing the effects of radiation will be discussed later.

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