Nuclear Theory - Course 127

FISSION

After having looked at neutron reactions in general, we shall use this lesson to describe the fission reaction and its products in some detail.

The Fission Reaction

Production of nuclear power relies on the fact that some nuclei will fission, and that energy is released during this fission process because a loss of mass occurs ($E = mc^2$). There are two types of fission; *spontaneous* and *induced*.

(a) Spontaneous Fission

In this reaction, a nucleus fissions entirely spontaneously, without any apparent external cause. It is quite a rare reaction, generally only possible for nuclei with atomic masses of around 232 amu or more. (As the atomic mass number increases, spontaneous fission becomes more and more probable. One could argue that there is an infinite number of heavy elements which do not exist, because they are not stable against spontaneous fission decay.) The table below shows the spontaneous fission and alpha decay rates of the U-235 and U-238 isotopes.

TABLE 1

Spontaneous Fission and Alpha Decay Rates of Uranium

	$t_{\frac{1}{2}}(\alpha)$ (years)	$t_{\frac{1}{2}}$(s.f.) (years)	α decay rate (atoms $s^{-1}g^{-1}$)	s.f. decay rate (atoms $s^{-1}g^{-1}$)
U-235	7.1×10^8	1.2×10^{17}	79×10^3	0.3×10^{-3}
U-238	4.5×10^9	5.5×10^{15}	12×10^3	6.9×10^{-3}

From this table you will be able to appreciate that spontaneous fission has no significance in the production of power. Nevertheless, it is important in that it represents a small uncontrollable source of neutrons in a reactor.

(b) Induced Fission

Certain heavy nuclei can be *induced* to fission as a result of neutron capture. In most cases the energy of the captured neutron must be very high before fission can occur, and therefore we can restrict our discussion to those nuclei which can be fissioned by neutron energies likely to be found in a reactor. In practice, we are then dealing with neutrons ranging from 10 MeV down to *thermal energies.**

Practical Fission Fuels

The only nuclei of practical importance to us are the U-233, U-235 and U-238 isotopes of uranium, and the Pu-239 and Pu-241 isotopes of plutonium. For all of these, except U-238, fission with thermal neutrons (*thermal fissions*) is much more probable than fission with fast neutrons (*fast fissions*). This is an important (and desirable) nuclear property, and such nuclides are said to be *fissile*. U-238, which will not fission with thermal neutrons, but which will fission with fast neutrons of energy greater than about 1.2 MeV, is merely said to be *fissionable.* It does, nevertheless, make a small contribution to the power produced in a reactor.

Natural uranium only contains U-235 (0.72%) and U-238. Over a period of reactor operation, Pu-239 and also some Pu-241 will be built up in the fuel as a result of neutron capture:

$$
\begin{aligned}
{}_{92}U^{238} + n \longrightarrow\ & {}_{92}U^{239} + \gamma \\
t_{1/2} = 24\text{m} \quad & \searrow \\
& \quad {}_{93}Np^{239} + \beta^{-}, \gamma \\
t_{1/2} = 2.4\text{d} \quad & \quad \searrow {}_{94}Pu^{239}
\end{aligned}
$$

Pu-239 is fissile like U-235. If it does not undergo fission, it may capture a neutron to form Pu-240. Although this is fissionable it is much more likely to capture another neutron to form fissile Pu-241. A significant fraction of the total power produced by fuel during its life in our reactors is due to fission

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* Thermal energy is the energy of a free neutron which is in thermal equilibrium with the atoms or molecules surrounding it. Neutrons of this energy are known as *thermal neutrons*. At 20°C, thermal energy is 0.025 eV.

of the fissile plutonium isotopes. We will deal with this in more detail later on in the course.

U-233 does not exist in natural uranium. This is a pity, because it has the most desirable properties of all of the fissile nuclides. It is of importance in reactor systems which convert thorium (Th-232) to U-233 by neutron capture followed by two successive β^- decays.

Fission Fragments

The fission fragments formed when spontaneous or induced fission occurs are two new nuclei. These may be any two of about 300 nuclides which are known to be formed as a result of fission.

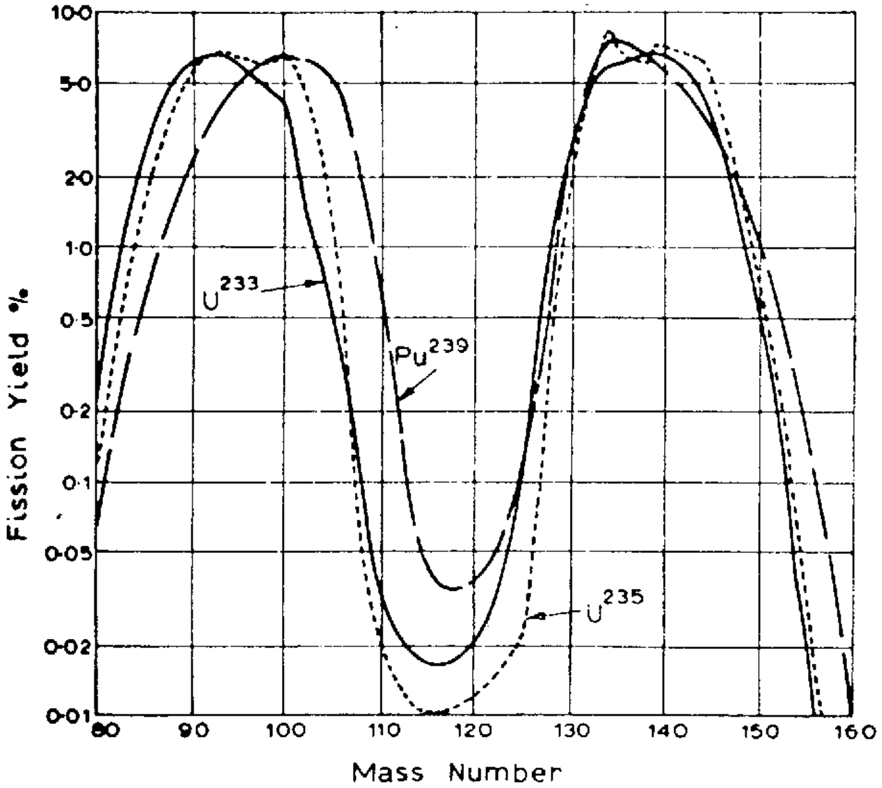


Fig. 1. Fission Yield of U-233, U-235 and Pu-239

Fig. 1 shows the relative frequency with which nuclides of specific mass numbers are produced as fission fragments. Such a curve is known as a *fission yield curve* (since two fragments are produced per fission, the area under the curve adds up to 200%).

You can see that both fission fragments are likely to consist of a substantial piece of the original nucleus. They are likely to have mass numbers between 70 and 160, with those around 95 and 140 being the most probable. Note that symmetrical fission (equal fragments) is quite rare.

Fission Products

The fission fragments are almost invariably radioactive. The reason for this is that the neutron/proton ratio of the fragments is about the same as that of the fissioned nucleus, and this is too high for stability at medium mass numbers. The fragments will therefore try to reduce their n/p ratio by successive β^-,γ decays until stability is reached. A typical decay chain is shown in Fig. 2. All the members of such chains are known as *fission products*.

$$\begin{tikzcd}
 & {}_{54}\mathrm{Xe}^{139} \arrow[r, "\beta^-", "\gamma"'] & {}_{55}\mathrm{Cs}^{139} \arrow[r, "\beta^-", "\gamma"'] & {}_{56}\mathrm{Ba}^{139} \arrow[r, "\beta^-", "\gamma"'] & {}_{57}\mathrm{La}^{139} & \\
n + {}_{92}\mathrm{U}^{235} \arrow[ur] \arrow[r] \arrow[dr] & n + n + \gamma & & & & \\
 & {}_{38}\mathrm{Sr}^{95} \arrow[r, "\beta^-"] & {}_{39}\mathrm{Y}^{95} \arrow[r, "\beta^-", "\gamma"'] & {}_{40}\mathrm{Zr}^{95} \arrow[r, "\beta^-", "\gamma"'] & {}_{41}\mathrm{Nb}^{95} \arrow[r, "\beta^-", "\gamma"'] & {}_{42}\mathrm{Mo}^{95}
\end{tikzcd}$$

Fig. 2 Fission Product Decay Chain

The half-lives of fission products range from fractions of a second to thousands of years. (It is this activity that causes so much concern in atomic bomb fall-out). There are four important consequences of fission product production in the fuel:-

(a) The fission products must be held in the fuel by encasing it in a sheath, so that they do not enter the heat transport system and hence leave the reactor core. Since many of them have long half-lives, their presence in the heat transport system would be a radiation hazard which would prevent access to equipment even when the reactor is shut down.

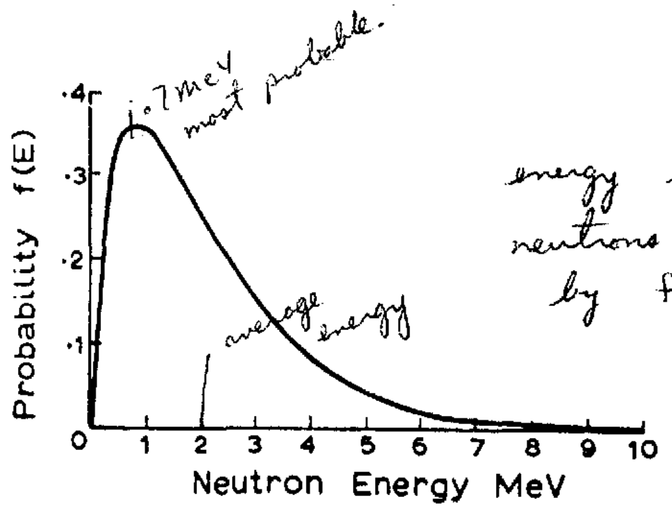
(b) Heavy shielding is required around the reactor to avoid exposure to the gamma radiation emitted by the fission products.

(c) Fuel must be changed remotely, and special precautions must be taken in handling and storing spent fuel.

(d) Some of the fission products have a high affinity for neutrons and thereby *poison* the reactor. The two most important poisons are Xe-135 and Sm-149. They are produced in a relatively high percentage of fissions, and they capture a significant number of neutrons.

Prompt and Delayed Neutron Emission

The fission fragments are produced in an excited state and will immediately emit perhaps two or three neutrons and some gamma photons. These are called *prompt neutrons* and *prompt gammas*.



energy spectrum of neutrons emitted at fission. by f.p.

Fig. 3. Prompt Neutron Energy Spectrum

Fig. 3 shows the energy distribution of prompt neutrons. The average energy is about 2 MeV, although the most probable energy is only 0.72 MeV.

A very small number of neutrons (less than 1%) appear long after fission occurs, and these are known as *delayed neutrons*. They arise from the radioactive decay of certain fission product daughters. For example, Bromine-87 decays by β^- emission to Krypton-87. The Krypton-87 formed in this way is sufficiently unstable to be able to emit a neutron to become Kr-86, and in fact it does this more often than not. The neutron emission is instantaneous (with respect to Kr-87), but obviously occurs some time after the original fission because the Br-87 must decay first. In fact, it appears to be emitted with the 55 second half-life of Br-87.

Nuclei such as Br^{87} whose production in fission may eventually lead to the emission of a delayed neutron are known as *delayed-neutron precursors*. At the present time, it is believed that there may be as many as twenty precursors, although only about half a dozen have been positively identified. These precursors and their respective half-lives are given in Table 2. They are usually divided into six groups according to their half-lives.

TABLE 2

Delayed-Neutron Precursors

(Uncertain Quantities are Indicated by Brackets)

Precursor	Half-life and Group	
Br^{87}	54.5	Group 1
I^{137}	24.4	Group 2
Br^{88}	16.3	
I^{138}	6.3	Group 3
$Br^{(89)}$	4.4	
$Rb^{(93,94)}$	6	
I^{139}	2.0	Group 4
(Cs,Sb or Te)	(1.6-2.4)	
$Br^{(90,92)}$	1.6	
$Kr^{(93)}$	∼1.5	
(I^{140}+Kr?)	0.5	Group 5
(Br,Rb,As+?)	0.2	Group 6

For thermal fission of U-235, the total contribution of all the delayed neutrons is only 0.65% of the total neutrons produced. With Pu-239, the total delayed fraction is even less at 0.21%. Despite the fact that these fractions are quite small, they have a very important effect on the time dependent behaviour of thermal reactors. We shall discuss this aspect of delayed neutrons in a later lesson on Reactor Control.

Table 3 gives the probability of a particular number of neutrons being emitted in the thermal fission of a U-235 nucleus. This includes both prompt and delayed neutrons.

TABLE 3

Neutron Emission in Thermal Fission of U-235

Number of Neutrons Emitted	Number of Cases per 1000 Fissions
0	27
1	158
2	339
3	302
4	130
5	34

ν = average yield for fission.

The average number of neutrons emitted per fission is an important quantity in reactor physics. It is universally denoted by the Greek letter ν ("new"). For thermal fission of U-235 $\nu = 2.430$. (Fast fissions usually produce marginally more neutrons).

Energy Release From Fission

About 200 MeV of energy is liberated when a nucleus fissions. The exact value slightly depends on the fissile nucleus and on the fission fragments produced. The energy can be calculated as follows:-

Consider the example given in Fig. 2 on page 4:

$${}_{92}U^{235} + n \longrightarrow {}_{38}Sr^{95} + {}_{54}Xe^{139} + 2n$$

Total mass before fission = 235.044 + 1.009 236.053 amu
Total mass after fission = 94.903 + 138.918 + 2.018 = 235.839 amu
Loss in mass = 0.214 amu

The energy equivalent of 1 amu is given by:

$$\begin{aligned} E(\text{joule}) &= m(\text{kg}) \times c^2 (\text{m.s}^{-1})^2 \\ &= 1.66 \times 10^{-27} \times (3\times10^8)^2 \\ &= 1.492 \times 10^{-10} \text{ joule} \end{aligned}$$

1 eV = 1.602×10^{-19} joule, so

$$\underline{E = 931.5 \text{ MeV/amu}}$$

For the example considered here, the 0.214 amu mass loss then corresponds to almost exactly 200 MeV. A summary of how this energy might be distributed is given in Table 4.

TABLE 4

Approximate Distribution of Fission Energy Release in U-235

Kinetic energy of lighter fission fragment	100 MeV
Kinetic energy of heavier fission fragment	67 MeV
Energy of prompt neutrons	5 MeV
Energy of prompt γ rays	6 Mev
✓ β particle energy gradually released from fission products	7 MeV
✓ γ ray energy gradually released from fission products	6 MeV
Neutrinos (energy escapes from reactor)	11 MeV
Total	202 MeV

This is not a complete account of all the energy released in the reactor. Some of the neutrons even after losing all their kinetic energy may produce (n,γ) reactions with materials in the reactor, and up to about 8 MeV may be released in such reactions. The total amount of energy produced in a reactor per fission may therefore depend to a slight extent on the form of the reactor, but it is always within a few MeV of 200 MeV.

Reactor Power and Fuel Consumption

The 200 MeV released in one fission is not of much practical value, because it is minute. In fact, 1 watt of power requires 3.1×10^{10} fissions every second.

One Megawatt steady power requires 3.1×10^{16} fissions every second continuously. 3.1×10^{16} atoms of U-235 weigh

$$\frac{3.1 \times 10^{16} \times 235}{6.023 \times 10^{26}} = 1.21 \times 10^{-8} \text{ kg}$$

Therefore, to produce 1 Megawatt-day of energy from fission requires the fissioning of

$$1.21 \times 10^{-8} \times 24 \times 3600 = 1.0 \times 10^{-3}\ \text{kg} = \underline{1.0\ \text{g U-235}}$$

The first requirement for producing useful power from the fission process is that enough U-235 nuclei must be available for fissioning. This requirement is met by installing sufficient U-235 in the reactor in the form of fuel rods. If natural uranium is used, of which 0.72% is U-235, then about 140 g of uranium would be used to produce 1 Megawatt-day of energy. This assumes that <u>all</u> the U-235 could be fissioned. In practice this is not so, because some U-235 (~17%) is consumed in (n,γ) reactions. As a result, 165 g of natural uranium would be used.

For example, a Pickering reactor at full power generates 1744 MW from fission (540 MW of electrical power is generated then). It would therefore use about 280 kg of natural uranium a day on this basis. Because Pu-239 (and Pu-241) is produced in the fuel after a while, this contributes substantially to energy production, and the amount of fuel used is consequently smaller, being more like 180 or 200 kg of uranium.

9 fuel bundles.

The second requirement for producing this amount of power continuously is that the rate of fissioning must be maintained. The neutrons released during fission must be used to cause further fissions, so that a *chain reaction* is maintained. How this is achieved is discussed in later lessons.

ASSIGNMENT

1. A fission of U-235 has lead to nuclei of mass numbers 89 and 144. Assuming that the n/p ratio is the same in both fragments, identify the particular nuclides formed and all the fission products that will be produced as a result.

$_{35}\text{Br}^{89}$

$_{57}\text{La}^{144}$

2. The energy release per fission can also be derived from the binding energy curve in lesson 127.10-1. How?

3. For the same rate of fissioning, why should there be a difference in the energy obtained from fresh fuel and fuel that has been in the reactor for 6 months?

4. The unit used within Ontario Hydro for fuel consumption (called *burn-up*) is MWh/kg. What percentage of the available U-235 is used to produce one MWh from one kg of natural uranium?

5. What is the overall average time delay in the production of delayed neutrons if the yields (neutrons per fission) of groups 1 to 6 are 0.00052, 0.00346, 0.00310, 0.00624, 0.00182 and 0.00066 respectively?

J.U. Burnham