actinium (*actinoid series*), analogous to rare-earth series.

7.13 Nuclear fission

Fermi's experiments on neutron-bombardment of uranium to produce transuranic elements were repeated by other workers and the results, as already mentioned, were somewhat puzzling. There appeared too many kind of β-emissions with different half lives and too many kinds of product atoms. Working with meticulous care, Otto Hahn and Strassmann finally succeeded in 1938 to give a correct interpretation.

Hahn and his collaborators performed a series of painstaking chemical separations of the uranium sample to pinpoint the element to which the new radioactivity belonged. They found, much to their amazement, that all new radioactive atoms were members belonging nearly to the centre of the periodic table. In 1939, Otto Frisch and Lisa Meitner suggested that the uranium atom was being fragmented into two parts of more or less comparable size, $^{141}_{56}\mathrm{Ba}$ and $^{92}_{36}\mathrm{Kr}$. This phenomenon of the *division or disintegration* of a *heavy nucleus* into *two nuclei of comparable masses* is termed ***nuclear fission*** or simply ***fission***, in analogy with 'cell division' in biology. Hahn and Strassmann are credited with the observation of the first neutron-induced fission.

The schematic equation for the fission process may be written as

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow ({}^{236}_{92}\mathrm{U})^{*} \rightarrow \mathrm{X} + \mathrm{Y} + \text{neutrons}$$

where $^{1}_{0}\mathrm{n}$ is a *slow neutron* (having therefore a high value for capture cross-section), $^{236}_{92}\mathrm{U}^{*}$ a highly unstable isotope of uranium and X, Y are the fission fragments.

It is to be noted that the fragments are *not uniquely* determined and there could be various possible combinations and that a number of *neutrons* are also *given off*. It is found that more than 30 modes of fission of ^{235}U exist in each of which a different pair of fission fragments is formed.

The fission results in *two massive fragments*, having almost equal and opposite momenta as are seen beautifully in cloud chamber photographs (Fig. 7.4) where two tracks travel almost in opposite directions. The fragments are neutron-rich having too many neutrons to be stable (Fig. 7.5). Each fragment emits one or two neutrons—about 3 on an average — per fission of ^{235}U.

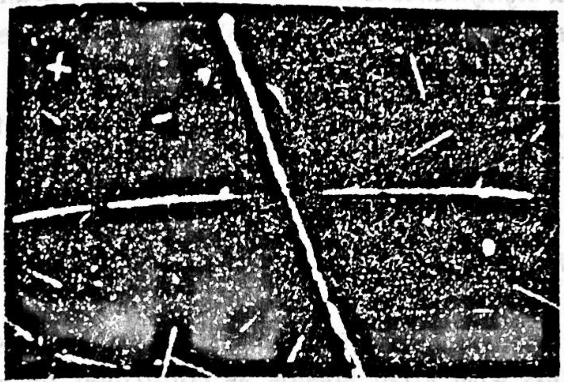

Fig. 7.4 Cloud chamber tracks of fission fragments

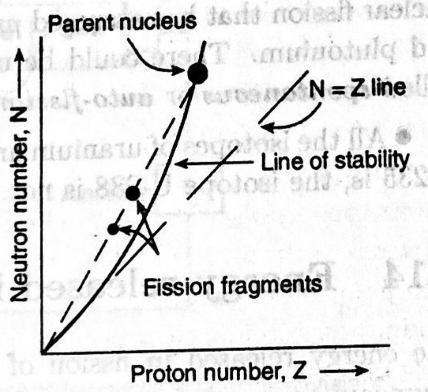

Fig. 7.5 Diagram showing that fission fragments are neutron-rich

Typical fission reactions are

$$\text{(i)}\quad {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow ({}^{236}_{92}\text{U})^* \rightarrow {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + 2\,{}^{1}_{0}\text{n} + Q$$

$$\text{(ii)}\quad {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow ({}^{236}_{92}\text{U})^* \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n} + Q$$

where Q represents the energy released in the reaction.

The β-activity observed by Fermi was due to the radioactive decay of fission fragments. These are known as *fission chains*.

$${}^{140}_{54}\text{Xe} \xrightarrow{\beta^-} {}^{140}_{55}\text{Cs} \xrightarrow{\beta^-} {}^{140}_{56}\text{Ba} \xrightarrow{\beta^-} {}^{140}_{57}\text{La} \xrightarrow{\beta^-} {}^{140}_{58}\text{Ce}\ \text{(stable)}$$

$$\text{and}\quad {}^{94}_{38}\text{Sr} \xrightarrow{\beta^-} {}^{94}_{39}\text{Y} \xrightarrow{\beta^-} {}^{94}_{40}\text{Zr}\ \text{(stable)}$$

from the fission reaction (i) above. In each β^--emission, there was an emission of an anti-neutrino, $\bar{\nu}$.

So, the end product in the fission reaction (i) are ${}^{140}_{58}$Ce, ${}^{94}_{40}$Zr, 6β-particles, 6 anti-neutrinos and 2 neutrons.

Similarly, for the fission reaction (ii), the following β^--decays of fission fragments (*fission chains*) have been observed.

$${}^{144}_{56}\text{Ba} \xrightarrow{\beta^-} {}^{140}_{57}\text{La} \xrightarrow{\beta^-} {}^{144}_{58}\text{Ce} \xrightarrow{\beta^-} {}^{144}_{59}\text{Pr} \xrightarrow{\beta^-} {}^{144}_{60}\text{Nd}\ \text{(stable)}$$

$$\text{and}\quad {}^{89}_{36}\text{Kr} \xrightarrow{\beta^-} {}^{89}_{37}\text{Rb} \xrightarrow{\beta^-} {}^{89}_{38}\text{Sr} \xrightarrow{\beta^-} {}^{89}_{39}\text{Y} \xrightarrow{\beta^-} {}^{89}_{40}\text{Zr}\ \text{(stable)}$$

- Nuclear fission is a *special type of nuclear reaction* where a nucleus splits into two (or more) lighter nuclides of intermediate mass numbers.
- ***Why do the fragments exhibit β-activity?*** Taking the reaction (ii), the stable isotope of barium with maximum *A*-value is ^{138}Ba and the stable isotope of Krypton with maximum *A*-value is ^{86}Kr. So, these fission fragments must show much β-activity to get rid of the excess neutrons.
- For fission, the projectile *need not* necessarily be neutron. Protons, deuterons, α-particles and even electrons or γ-rays may also induce fission. But the only type of nuclear fission that has assumed *practical significance* is the neutron-fission of uranium and plutonium. There could be nuclear fission even without the projectile – the so-called ***spontaneous*** or ***auto-fission.***
- All the isotopes of uranium are *not fissionable* by slow neutrons. While the isotope U-235 is, the isotope U-238 is not.

7.14 Energy released in fission of U-235

The energy released in fission of ^{235}U-nucleus is so high that the two main fission fragments fly apart in opposite directions with great speeds as confirmed by cloud chamber photographs. Measured by *delicate calorimetric method*, the actual kinetic energy of the separate particles is about 180 MeV and the energy of the γ-radiation emitted in the process is about 20 MeV. So the total energy per fission of ^{235}U-nucleus is *about* **200 MeV**, and this is also seen from the following calculation.

Consider the fission reaction (i) of Art. 7.13, where the end products are $^{140}_{58}$Ce, $^{94}_{40}$Zr, 6β-particles and 2 neutrons. Now, the isotopic mass *before fission* is

$$\begin{aligned} {}^{235}_{92}\mathrm{U} &= 235.0439\ \mathrm{u} \\ {}^{1}_{0}\mathrm{n} &= 1.0087\ \mathrm{u} \\ \hline \text{Total} &= 236.0526\ \mathrm{u} \end{aligned}$$

The isotopic mass *after fission*, however, is given as under,

$$\begin{aligned} {}^{140}_{58}\mathrm{Ce} &= 139.9054\ \mathrm{u} \\ {}^{94}_{40}\mathrm{Zr} &= 93.9036\ \mathrm{u} \\ 2\,{}^{1}_{0}\mathrm{n} &= 2.0173\ \mathrm{u} \\ 6\beta^- &= 0.0033\ \mathrm{u} \\ \hline \text{Total} &= 235.8296\ \mathrm{u} \end{aligned}$$

$$\therefore \text{ Mass difference} = (236.0526 - 235.8296)\ \mathrm{u} = 0.223\ \mathrm{u}$$

This represents a *Q*-value given by $Q = 0.223 \times 931 =$ **208 MeV**

- **Leachman's time-of-flight method**—An *accurate* measurement of kinetic energies of fission fragments from thermal neutron fission of ^{235}U was made by