MPM: 203 NUCLEAR AND PARTICLE PHYSICS

UNIT –I: Nuclear Stability

Lecture-18

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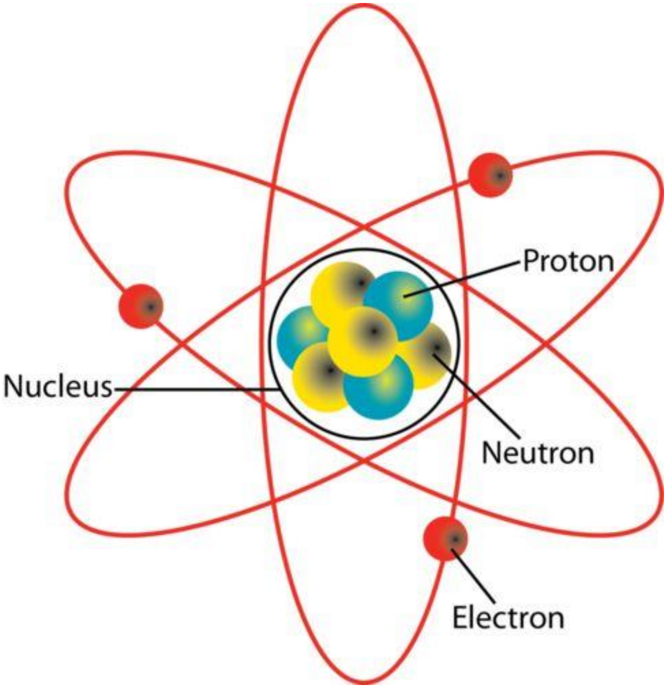
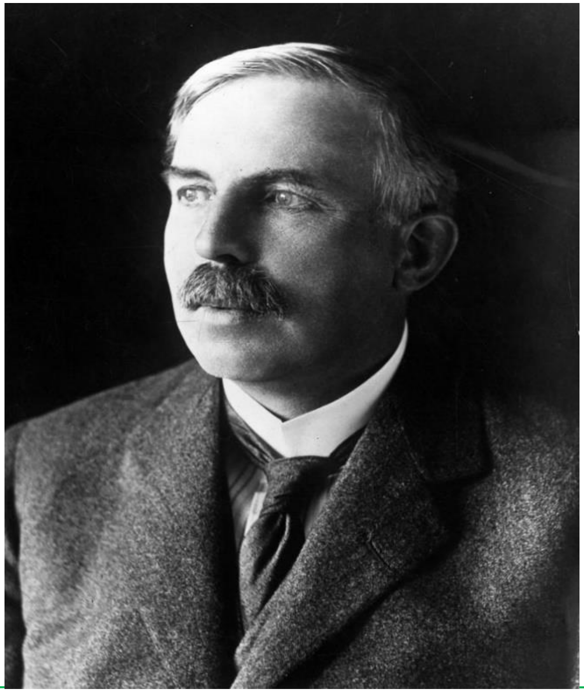




$$n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U}^* \rightarrow {}^{99}_{40}\mathrm{Zr} + {}^{134}_{52}\mathrm{Te} + 3n$$

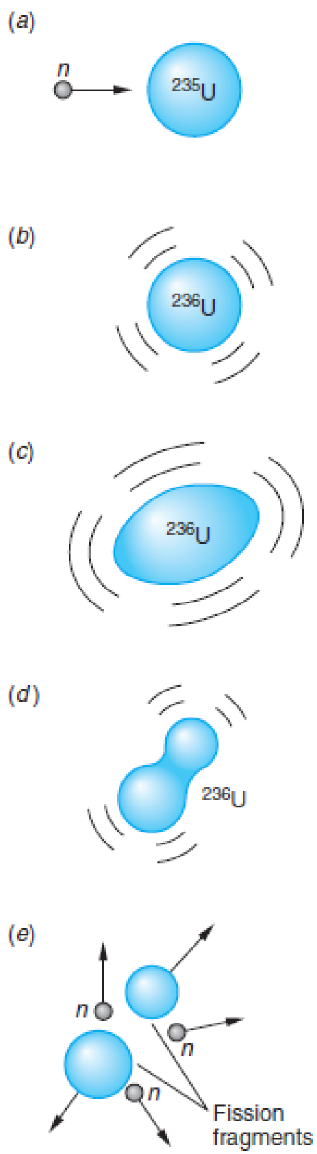


Figure 11-46 Schematic illustration of nuclear fission. (*a*) The absorption of a neutron by ^{235}U leads to (*b*) ^{236}U in an excited state. (*c*) Oscillation deforms the excited ^{236}U nucleus. (*d*) The oscillation of ^{236}U has become unstable. (*e*) The nucleus splits apart into two nuclei of medium mass and emits several neutrons that can produce fission in other nuclei.

EXAMPLE 11-20 Kilowatt-hours from ^{235}U Calculate the total energy in kilowatt-hours released in the fission of 1 g of ^{235}U, assuming that 200 MeV is released per fission.

SOLUTION

Since 1 mol of ^{235}U has a mass of 235 g and contains $N_A = 6.02 \times 10^{23}$ nuclei, the number of ^{235}U nuclei in 1 g is

$$N = \frac{6.02 \times 10^{23}\ \text{nuclei/mol}}{235\ \text{g/mol}} = 2.56 \times 10^{21}\ \text{nuclei/g}$$

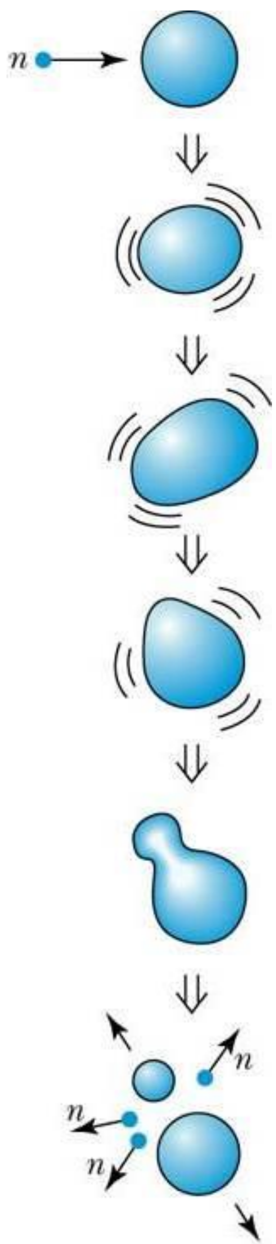
The energy released per gram is then

$$\frac{200\ \text{MeV}}{\text{nucleus}} \times \frac{2.56 \times 10^{21}\ \text{nuclei}}{1\ \text{g}} \times \frac{1.6 \times 10^{-19}\ \text{J}}{1\ \text{eV}} \times$$

$$\frac{1\ \text{h}}{3600\ \text{s}} \times \frac{1\ \text{kW}}{1000\ \text{J/s}} = 2.28 \times 10^{4}\ \text{kW}\cdot\text{h/g}$$

Remark: This is approximately equal to the amount of electrical energy used by a typical U.S. household in 15 months.

Thermal Neutron Fission



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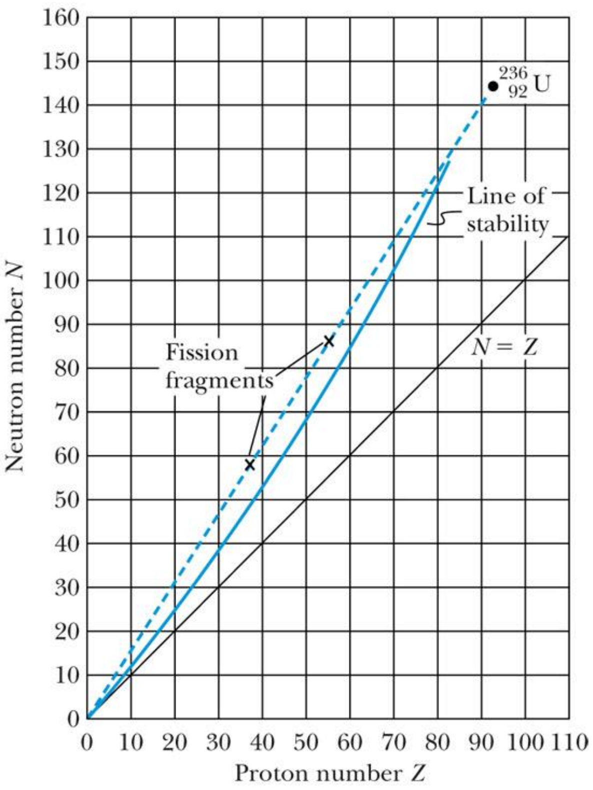
- Fission fragments are highly unstable because they are so neutron rich.

- Prompt neutrons are emitted simultaneously with the fissioning process. Even after prompt neutrons are released, the fission fragments undergo beta decay, releasing more energy.

- Most of the ~200 MeV released in fission goes to the kinetic energy of the fission products, but the neutrons, beta particles, neutrinos, and gamma rays typically carry away 30–40 MeV of the kinetic energy.

Chain Reactions

- Because several neutrons are produced in fission, these neutrons may subsequently produce other fissions. This is the basis of the *self-sustaining chain reaction*.
- If slightly more than one neutron, on the average, results in another fission, the chain reaction becomes *critical*.
- A sufficient amount of mass is required for a neutron to be absorbed (a statistical process), called the *critical mass*.
- If less than one neutron, on the average, produces another fission, the reaction is *subcritical*.



If more than one neutron, on the average, produces another fission, the reaction is *supercritical*.

An atomic bomb is an extreme example of a supercritical fission chain reaction.

Chain Reactions

- A critical fission reaction can be controlled by absorbing neutrons. A self-sustaining controlled fission process requires that not all the neutrons are *prompt*. Some of the neutrons are *delayed* by several seconds and are emitted by daughter nuclides. These delayed neutrons allow the control of the nuclear reactor.

- *Control rods* regulate the absorption of neutrons to sustain a controlled reaction.

Fission Reactors

Table 13.1 Energy Content of Fuels

Material	Amount	Energy (J)
Coal	1 kg	3×10^7
Oil	1 barrel (0.16 m^3)	6×10^9
Natural gas	1 ft^3 (0.028 m^3)	10^6
Wood	1 kg	10^7
Gasoline	1 gallon (0.0038 m^3)	10^{10}
Uranium (fission)	1 kg	10^{14}

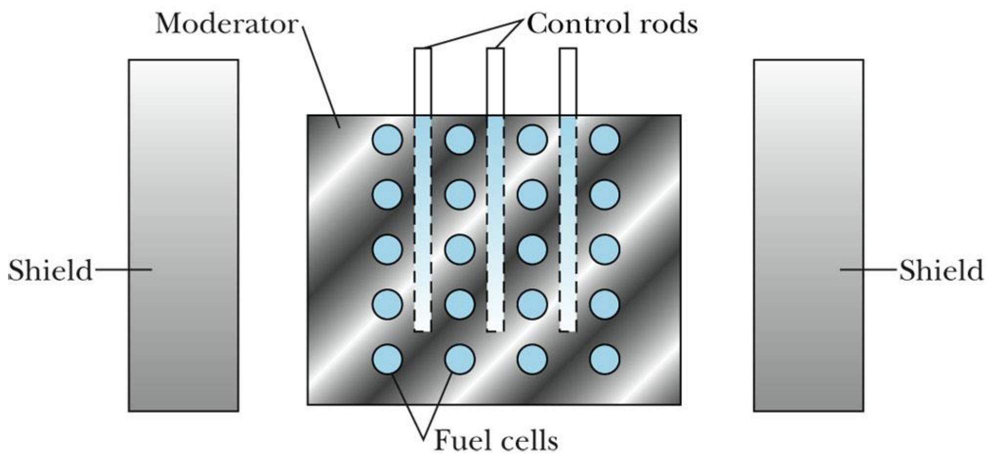
Table 13.2 Daily Fuel Requirements for 1000-MWe Power Plant

Material	Amount	
Coal	8×10^6 kg	(1 trainload/day)
Oil	40,000 barrels (6400 m^3)	(1 tanker/week)
Natural gas	2.5×10^6 ft^3 (7.1×10^4 m^3)	
Uranium	3 kg	

- Several components are important for a controlled nuclear reactor:
  1) Fissionable fuel
  2) Moderator to slow down neutrons
  3) Control rods for safety and to control criticality of reactor
  4) Reflector to surround moderator and fuel in order to contain neutrons and thereby improve efficiency
  5) Reactor vessel and radiation shield
  6) Energy transfer systems if commercial power is desired
- Two main effects can "poison" reactors: (1) neutrons may be absorbed without producing fission [for example, by neutron radiative capture], and (2) neutrons may escape from the fuel zone.

Core Components

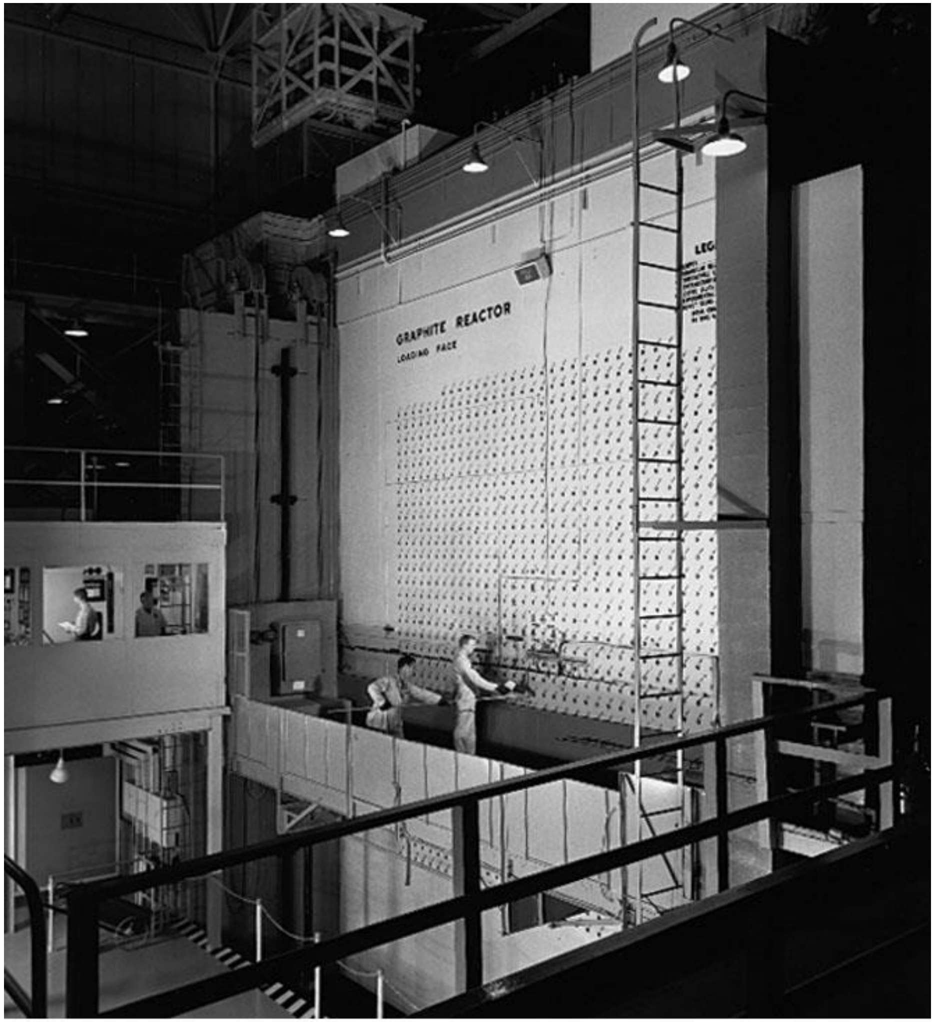
- Fission neutrons typically have 1–2 MeV of kinetic energy, and because the fission cross section increases as $1/v$ at low energies, slowing down the neutrons helps to increase the chance of producing another fission. A *moderator* is used to elastically scatter the high-energy neutrons and thus reduce their energies. A neutron loses the most energy in a single collision with a light slow moving particle. Heavy hydrogen (in heavy water), carbon (graphite), and beryllium are all good moderators.
- The simplest method to reduce the loss of neutrons escaping from the fissionable fuel is to make the fuel zone larger. The fuel elements are normally placed in regular arrays within the moderator.



Core Components

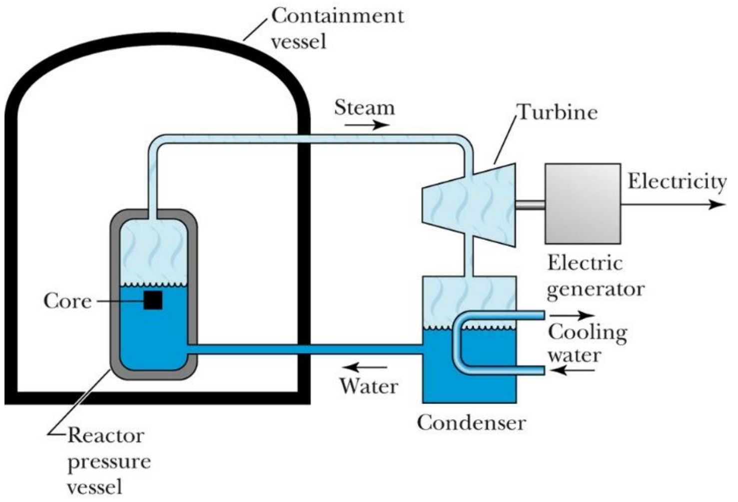
- The delayed neutrons produced in fission allow the mechanical movement of the rods to control the fission reaction. A "fail-safe" system automatically drops the control rods into the reactor in an emergency shutdown.

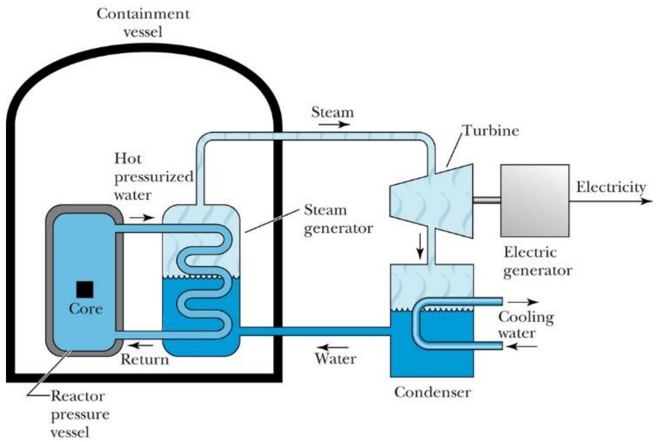
- If the fuel and moderator are surrounded by a material with a very low neutron capture cross section, there is a reasonable chance that after one or even many scatterings, the neutron will be backscattered or "reflected" back into the fuel area. Water is often used both as moderator and reflector.



Energy Transfer

- The most common method is to pass hot water heated by the reactor through some form of heat exchanger.
- In *boiling water reactors* (BWRs) the moderating water turns into steam, which drives a turbine producing electricity.
- In *pressurized water reactors* (PWRs) the moderating water is under high pressure and circulates from the reactor to an external heat exchanger where it produces steam, which drives a turbine.
- Boiling water reactors are inherently simpler than pressurized water reactors. However, the possibility that the steam driving the turbine may become radioactive is greater with the BWR. The two-step process of the PWR helps to isolate the power generation system from possible radioactive contamination.





Types of Reactors

- ***Power*** **reactors produce commercial electricity.**
- ***Research*** **reactors are operated to produce high neutron fluxes for neutron-scattering experiments.**
- ***Heat production*** **reactors supply heat in some cold countries.**
- **Some reactors are designed to produce *radioisotopes*.**
- **Several *training* reactors are located on college campuses.**

Nuclear Reactor Problems

- The danger of a serious accident in which radioactive elements are released into the atmosphere or groundwater is of great concern to the general public.
- Thermal pollution both in the atmosphere and in lakes and rivers used for cooling may be a significant ecological problem.
- A more serious problem is the safe disposal of the radioactive wastes produced in the fissioning process, because some fission fragments have a half-life of thousands of years.
- Two widely publicized accidents at nuclear reactor facilities—one at Three Mile Island in Pennsylvania in 1979, the other at Chernobyl in Ukraine in 1986—have significantly dampened the general public's support for nuclear reactors.
- Large expansion of nuclear power can succeed only if four critical problems are overcome: lower costs, improved safety, better nuclear waste management, and lower proliferation risk.

Breeder Reactors

- A more advanced kind of reactor is the *breeder* reactor, which produces more fissionable fuel than it consumes.
- The chain reaction is:

$$n + {}^{238}_{92}\text{U} \rightarrow {}^{239}_{92}\text{U}^* \rightarrow \gamma + {}^{239}_{92}\text{U}$$

$$\hookrightarrow \beta^- + {}^{239}_{93}\text{Np} + \overline{\nu}$$

$$\hookrightarrow \beta^- + {}^{239}_{94}\text{Pu} + \overline{\nu}$$

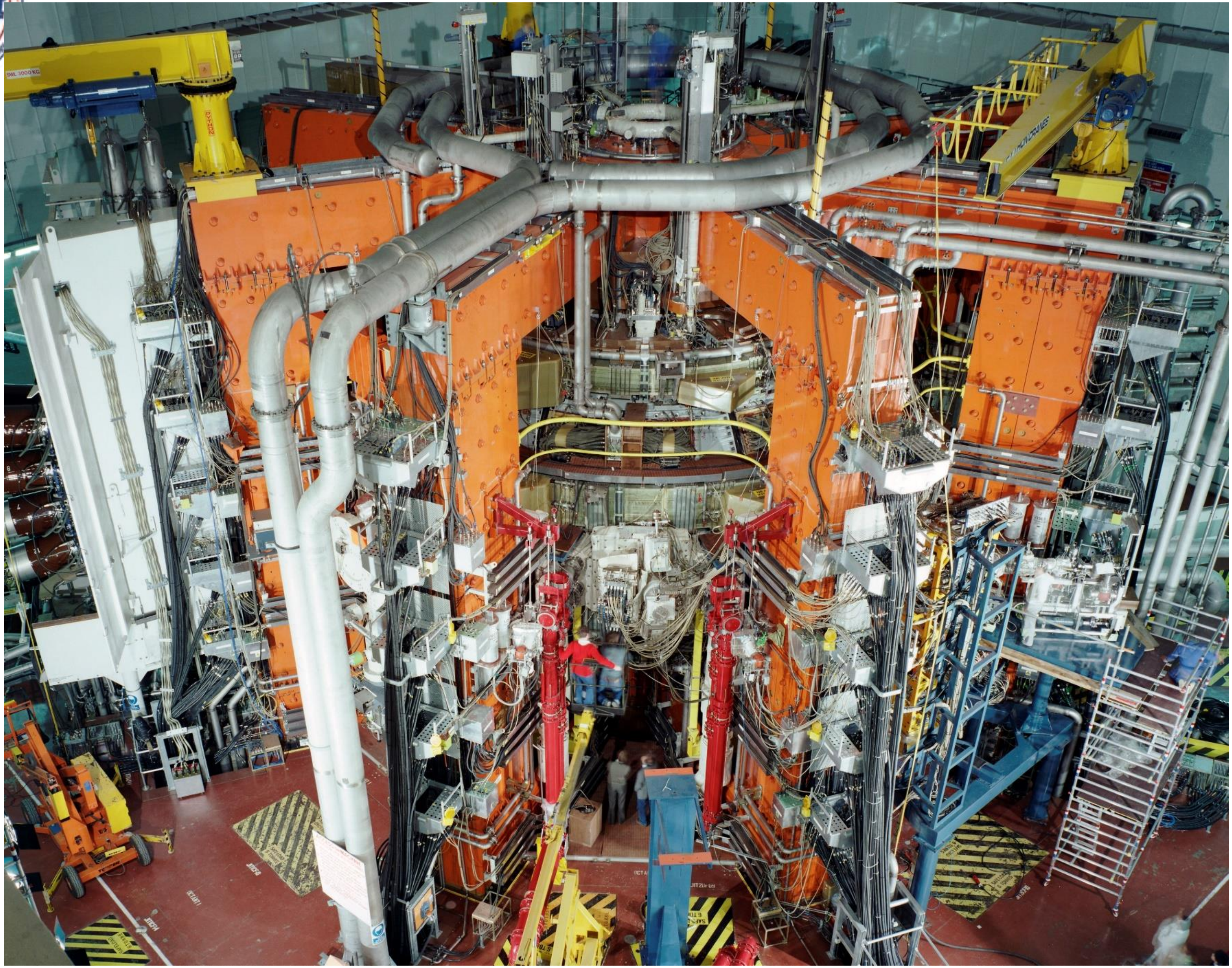
- The plutonium is easily separated from uranium by chemical means.
- *Fast breeder reactors* have been built that convert ^{238}U to ^{239}Pu. The reactors are designed to use fast neutrons.
- Breeder reactors hold the promise of providing an almost unlimited supply of fissionable material.
- One of the downsides of such reactors is that plutonium is highly toxic, and there is concern about its use in unauthorized weapons production.

Fusion

- If two light nuclei fuse together, they also form a nucleus with a larger binding energy per nucleon and energy is released. This reaction is called **nuclear fusion**.

- The most energy is released if two isotopes of hydrogen fuse together in the reaction.

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow n + {}^{4}\mathrm{He} \qquad Q = 17.6\ \mathrm{MeV}$$



The European Fusion project, 1991

Formation of Elements

- The **proton-proton chain** includes a series of reactions that starts with two protons and ends with an ordinary alpha particle.

- As stars form due to gravitational attraction of interstellar matter, the heat produced by the attraction is enough to cause protons to overcome their Coulomb repulsion and fuse by the following reaction:

$$ {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \beta^{+} + \nu \qquad Q = 0.42\ \mathrm{MeV} $$

- The deuterons are then able to combine with ^{1}H to produce ^{3}He:

$$ {}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \qquad Q = 5.49\ \mathrm{MeV} $$

- The ^{3}He atoms can then combine to produce ^{4}He:

$$ {}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \qquad Q = 12.86\ \mathrm{MeV} $$

Formation of Elements

- As the reaction proceeds, however, the temperature increases, and eventually ^{12}C nuclei are formed by a process that converts three ^{4}He into ^{12}C.
- Another cycle due to carbon is also able to produce ^{4}He. The series of reactions responsible for the carbon or CNO cycle are

$$^{1}\mathrm{H} + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{N} + \gamma$$

$$\hookrightarrow {}^{13}\mathrm{C} + \beta^{+} + \nu \qquad t_{1/2} = 9.96\ \mathrm{min}$$

$$^{1}\mathrm{H} + {}^{13}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \gamma$$

$$^{1}\mathrm{H} + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{O} + \gamma$$

$$\hookrightarrow {}^{15}\mathrm{N} + \beta^{+} + \nu \qquad t_{1/2} = 2.04\ \mathrm{min}$$

$$^{1}\mathrm{H} + {}^{15}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

- Proton-proton and CNO cycles are the only nuclear reactions that can supply the energy in stars.

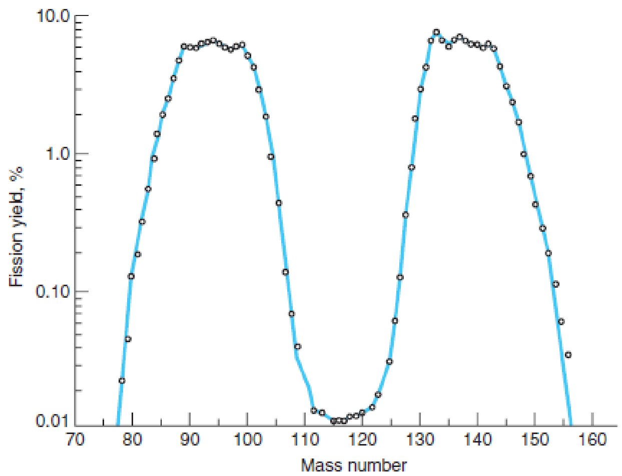


Figure 11-48 Distribution of fission fragments from the thermal-neutron-induced fission of ^{235}U. Symmetric fission, in which the uranium nucleus splits into two nuclei of nearly equal mass, is much less probable than asymmetric fission, in which the fragments have unequal masses. Note the symmetry of the light and heavy lobes of the distribution, including the small variations in the tops of the peaks and the convex outer edges. [*Data from G. J. Dilorio, Direct Physical Measurement of Mass Yields in Thermal Fission of Uranium-235, Garland, New York, 1979.*]

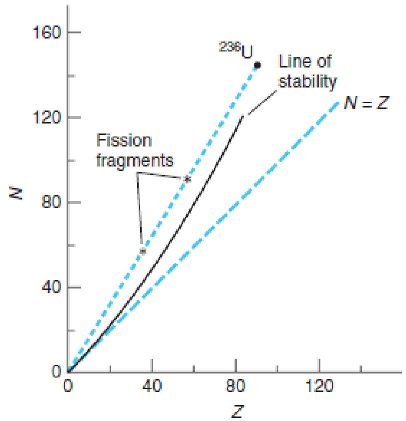


Figure 11-49 Fission of ^{236}U ($^{235}U + n$) produces fragments that are neutron-rich and well to the left of the line of stability. As a result, the fission is accompanied by the prompt emission of one or more of the excess neutrons followed by β^- decay of the fission fragments to further reduce their neutron numbers.