Chapter 45

Applications of Nuclear Physics

44.1 Interactions Involving Neutrons

44.2 Nuclear Fission

44.4 Nuclear Fusion

Processes of Nuclear Energy

- Fission
  - A nucleus of large mass number splits into two smaller nuclei.
- Fusion
  - Two light nuclei fuse to form a heavier nucleus.
- Large amounts of energy are released in both cases.

45.1 Interactions Involving Neutrons

Interactions Involving Neutrons

- Because of their charge neutrality, neutrons are not subject to Coulomb forces.
- As a result, they do not interact electrically with electrons or the nucleus.
- Neutrons can easily penetrate deep into an atom and collide with the nucleus.

45.1 Interactions Involving Neutrons

Fast Neutrons

- A fast neutron has energy greater than approximately 1 MeV.
- During its many collisions when traveling through matter, the neutron gives up some of its kinetic energy.
- For fast neutrons in some materials, elastic collisions dominate.
  - These materials are called **moderators** since they moderate the originally energetic neutrons very efficiently.
    - Moderator nuclei should be of low mass so that a large amount of kinetic energy is transferred to them in elastic collisions.
    - Materials such as paraffin and water are good moderators for neutrons.

45.1 Interactions Involving Neutrons

Thermal Neutrons

- Most neutrons bombarding a moderator will become **thermal neutrons.**
  - They are in thermal equilibrium with the moderator material.
  - Their average kinetic energy at room temperature is about 0.04 eV.
  - This corresponds to a neutron root-mean-square speed of about 2 800 m/s.
    - Thermal neutrons have a distribution of speeds.

45.1 Interactions Involving Neutrons

Neutron Capture

- Once the energy of a neutron is sufficiently low, there is a high probability that it will be captured by a nucleus.
- The **neutron capture** equation can be written as

$$ {}_{0}^{1}n + {}_{Z}^{A}X \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z}X + \gamma $$

  – The excited state lasts for a very short time before it undergoes gamma decay.

  – The product nucleus is generally radioactive and decays by beta emission.

  – The neutron-capture rate depends on the type of atoms in the sample and on the energy of the incident neutrons. The interaction of neutrons with matter increases with decreasing neutron energy because a slow neutron spends a larger time interval in the vicinity of target nuclei.

45.2 Nuclear Fission

Nuclear Fission

- A heavy nucleus splits into two smaller nuclei.
- Fission is initiated when a heavy nucleus captures a thermal neutron.
- The total mass of the daughter nuclei is less than the original mass of the parent nucleus.
  - This difference in mass is called the **mass defect.**
  - Multiplying the mass defect by c^2 gives the numerical value of the released energy.
    - This energy is in the form of kinetic energy associated with the motion of the neutrons and the daughter nuclei after the fission event.

45.2 Nuclear Fission

Short History of Fission

- First observed in 1938 by Otto Hahn and Fritz Strassman following basic studies by Fermi.
  - Bombarding uranium with neutrons produced barium Ba (Z=56) and lanthanum La (Z=57).
- Lise Meitner and Otto Frisch soon explained what had happened.
  - After absorbing a neutron, the uranium nucleus had split into two nearly equal fragments.
  - About 200 MeV of energy was released.

45.2 Nuclear Fission

Fission Equation: ^{235}U

• Fission of ^{235}U by a thermal neutron

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

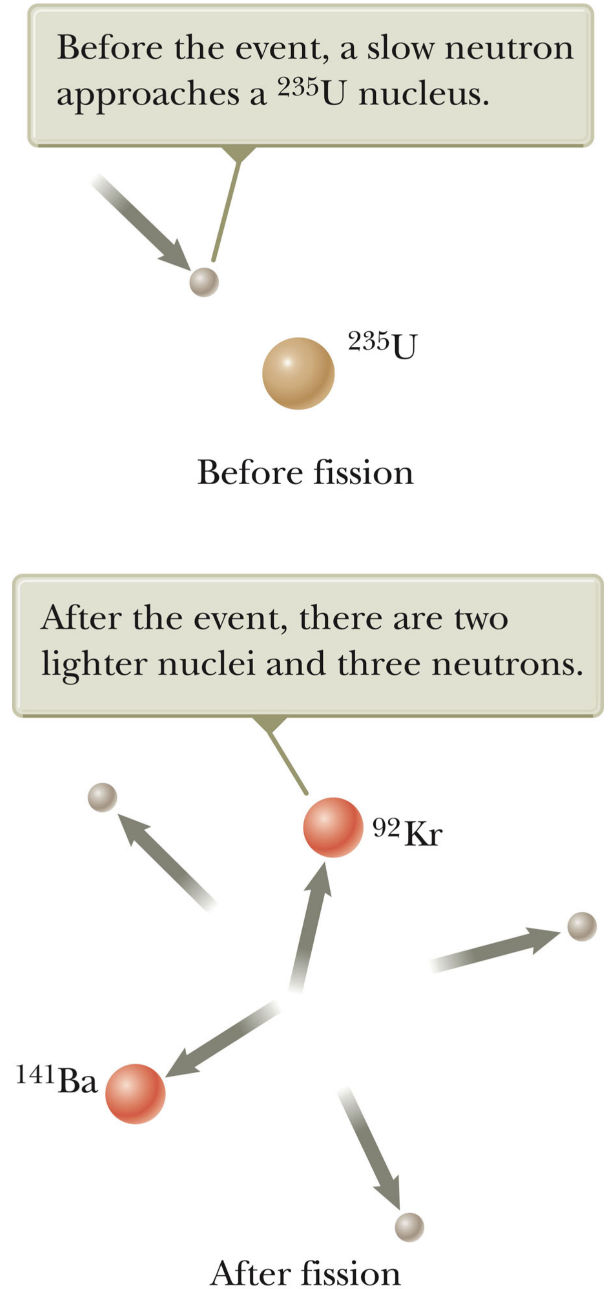
- $^{236}U^*$ is an intermediate, excited state that exists for about 10^{-12} s before splitting.
- X and Y are called **fission fragments.**
  - Many combinations of X and Y satisfy the requirements of conservation of energy and charge.

45.2 Nuclear Fission

Fission Example: 235U

- A typical fission reaction for uranium is

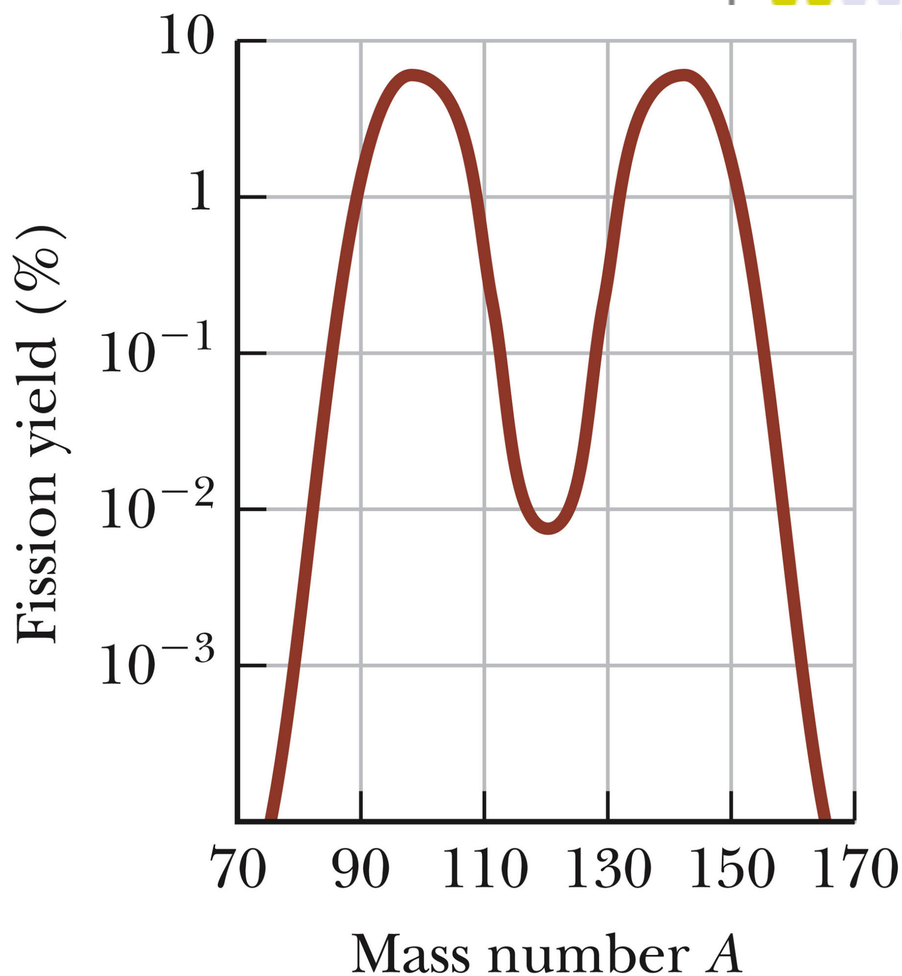
$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\left({}^{1}_{0}n\right) $$



45.2 Nuclear Fission

Distribution of Fission Products

- The most probable products have mass numbers A ≈ 95 and A ≈ 140.
- There are also 2 to 3 neutrons released per event.



45.2 Nuclear Fission

Example

Quick Quiz 45.2 Which of the following are possible fission reactions?

(a) $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2(^{1}_{0}n)$

(b) $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{132}_{50}Sn + ^{101}_{42}Mo + 3(^{1}_{0}n)$

(c) $^{1}_{0}n + ^{239}_{94}Pu \rightarrow ^{137}_{53}I + ^{97}_{41}Nb + 3(^{1}_{0}n)$

45.4 Nuclear Fusion

Nuclear Fusion

- Nuclear **fusion** occurs when two light nuclei combine to form a heavier nucleus.
- The mass of the final nucleus is less than the masses of the original nuclei.
  - This loss of mass is accompanied by a release of energy.

45.4 Nuclear Fusion

Fusion: Proton-Proton Cycle

- The **proton-proton cycle** is a series of three nuclear reactions believed to operate in the Sun.
- Energy liberated is primarily in the form of gamma rays, positrons and neutrinos.
- All of the reactions in the proton-proton cycle are exothermic.
- An overview of the cycle is that four protons combine to form an alpha particle, positrons, gamma rays and neutrinos.

$$ {}_1^1H + {}_1^1H \rightarrow {}_1^2H + e^+ + \nu $$

$$ {}_1^1H + {}_1^2H \rightarrow {}_2^3He + \gamma $$

Then

$$ {}_1^1H + {}_2^3He \rightarrow {}_2^4He + e^+ + \nu $$

or

$$ {}_2^3He + {}_2^3He \rightarrow {}_2^4He + {}_1^1H + {}_1^1H $$

45.4 Nuclear Fusion

Fusion in the Sun

- These reactions occur in the core of a star and are responsible for the energy released by the stars.
- High temperatures are required to drive these reactions.
  - Therefore, they are known as **thermonuclear fusion reactions.**

45.4 Nuclear Fusion

Advantages of a Fusion Reactor

- Inexpensive fuel source
  - Water is the ultimate fuel source.
  - If deuterium ${}_{1}^{2}H$ is used as fuel, 0.12 g of it can be extracted from 1 gal of water for about 4 cents.
- Comparatively few radioactive by-products are formed.

45.4 Nuclear Fusion

Considerations for a Fusion Reactor

- The proton-proton cycle is not feasible for a fusion reactor.
  - The high temperature and density required are not suitable for a fusion reactor.
- The most promising reactions involve deuterium D=$^{2}_{1}H$ and tritium T= $^{3}_{1}H$

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}H + ^{1}_{0}n \quad Q = 3.27\,\text{MeV}$$

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H \quad Q = 4.03\,\text{MeV}$$

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n \quad Q = 17.59\,\text{MeV}$$

- Tritium is radioactive and must be produced artificially.
- The Coulomb repulsion between two charged nuclei must be overcome before they can fuse.
  - A major problem in obtaining energy from fusion reactions.

45.4 Nuclear Fusion

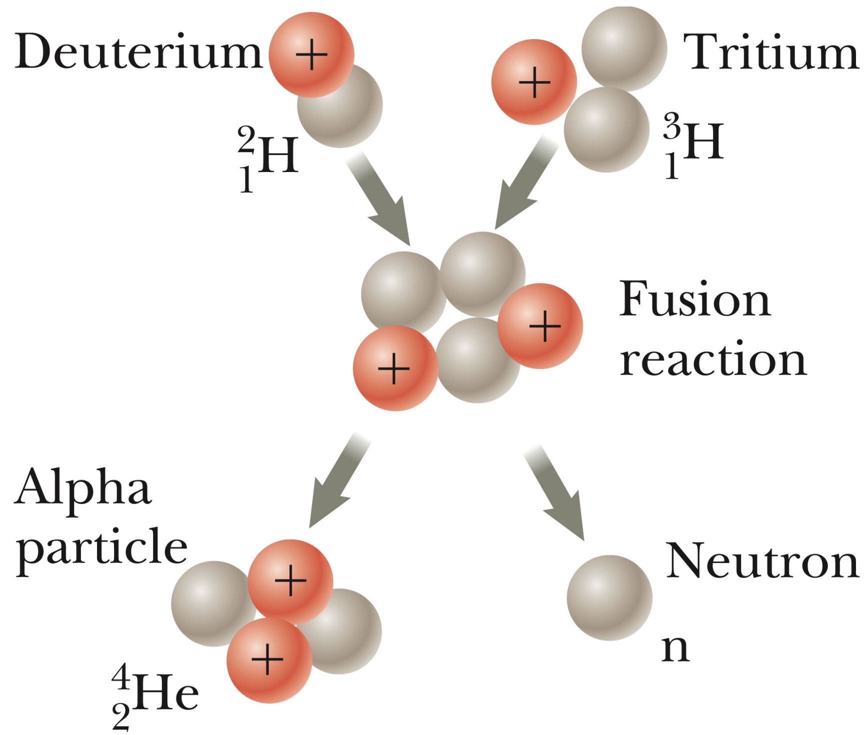
Requirements for Successful Thermonuclear Reactor

- High temperature ~ 10^8 K
  - Needed to give nuclei enough energy to overcome Coulomb forces
- Plasma **ion density**, *n*
  - The number of ions present

45.4 Nuclear Fusion

Fusion Reactor Design – Energy

- In the D-T reaction, the alpha particle carries 20% of the energy and the neutron carries 80%.
  - The neutrons are about 14 MeV.
- The alpha particles are primarily absorbed by the plasma, increasing the plasma's temperature.
- The neutrons are absorbed the surrounding of material where their energy is extracted and used to generate electric power.



45.4 Nuclear Fusion

Some Advantages of Fusion

- Low cost and abundance of fuel
  - Deuterium
- Impossibility of runaway accidents
- Decreased radiation hazards