PH102, 2012W, Lecture Notes: March 9, Fri, Class 22

Nuclear Reactions refer to any occurrences in which nucleons are changed or exchanged between nuclei. Radioactive decay is a spontaneous nuclear reaction. Nuclear reactions can be induced by striking a nucleus with another nucleus.

- Exothermic nuclear reaction:
    - Q > 0 (kinetic energy is released)
    - total mass decreases after reaction, i.e., $m_i > m_f$
    - Example:

      $${}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

      Released kinetic energy (Q) $= (10.012937 + 1.008665 - 7.016003 - 4.002603)\ uc^2 = 2.79\ MeV$

- Endothermic nuclear reaction:
    - Q < 0 (kinetic energy is absorbed)
    - total mass increases after reaction. i.e. $m_i < m_f$
    - Example:

      $${}^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + {}^{1}_{0}n$$

      Released kinetic energy (Q)
      $= (7.016003 + 1.007825 - 7.016928 - 1.008665)uc^2 = -1.64\ MeV$

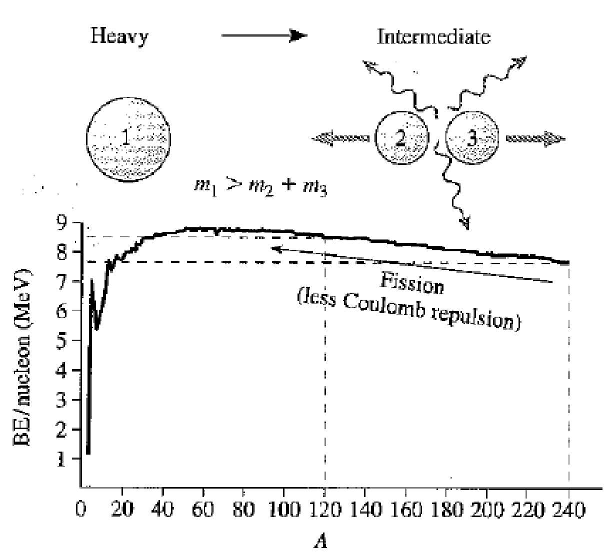
To release energy, mass must decrease after a nuclear reaction, meaning products should be more tightly bound. Considering that the binding energy per nucleon peaks at around A=60, there are two ways to achieve this:

- Nuclear fission: a heavy nucleus breaks into smaller nuclei
- Nuclear fusion: small nuclei fuse together

Nuclear Fission

- A heavy nucleus breaks into two smaller nuclei.
- When this occurs, two or more neutrons are released as soon as small nuclei are formed since large nuclei tend to include more neutrons. Then, subsequent beta decays bring their neutron/proton ratios to stable values.
- The driving force in the binding energy reduction is decrease in Coulomb repulsion.
- Figure 11.27 shows how much energy can be released per nucleon when a fission

Figure 11.27 Decreasing BE/nucleon via fission.



occurs from A=240 to A=120. The energy difference is about 0.9 MeV. So, this reaction can potentially generate over 200 MeV when all 240 nucleons are considered in the nucleus of A=240.

- Compare energy release in fission with other energies generated: typical chemical reactions ~ a few eV; spontaneous radioactive decay ~ a few MeV.
- Using the liquid-drop model, the fission process is shown below. A typical excited nucleus can be regarded as an oscillating sphere where surface tension due to strong force and Coulomb repulsions take into play. An excited nucleus can come back to its original sphere shape over time by emitting gamma rays. Sometimes, however, an excited nucleus can be distorted too much (thus Coulomb repulsions win over strong force that provides surface tension) so that the nucleus does not come back to its sphere shape and breaks apart.

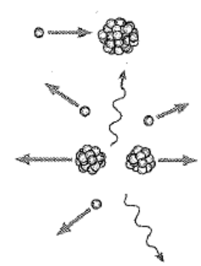
FIGURE 24.11 The oscillations of a liquid drop.

FIGURE 24.12 Nuclear fission according to the liquid-drop model.

- Examples of nuclear fission reactions:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$
$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{140}_{54}\mathrm{Xe} + ^{94}_{38}\mathrm{Sr} + 2\,^{1}_{0}\mathrm{n}$$
$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{132}_{50}\mathrm{Sn} + ^{101}_{42}\mathrm{Mo} + 3\,^{1}_{0}\mathrm{n}$$

Figure 11.28 Neutron-induced fission, freeing more neutrons.



- Since nuclear fission reactions start with a highly energetic neutron striking a large nucleus and highly energetic neutrons are produced as a result of fission reactions, a chain reaction is possible when multiple nucleons are present. See Figure 11.28.

- Consider that a fission reaction generates E_0 and n neutrons. The first generation of fission would create n neutrons each of which can generate nE_0. The jth generation of fission reactions would create

$$E_j = E_0 n^j$$

- In nature, spontaneous chain reactions of fission do not occur because nuclei that participate in the process are not purified or near one another in mass. For a chain reaction to sustain, a critical assembly of a right size, a right geometry, and purification is needed.
- $^{235}_{92}U$ can be engaged in three fission processes. One process generates two neutrons, as compared to three in the other two. Thus the actual energy generated by the nuclear fission of $^{235}_{92}U$ can be written as

$$E_j = E_0 k^j$$

Where $k > 1$ exponential energy increase
$k = 1$ controlled energy release
$k < 1$ exponential energy decrease

Nuclear Fusion

- Light nuclei are less tigtly bound than those of intermediate mass number. When light nuclei form heavier ones, the total mass decreases and therefore kinetic energy will be released.

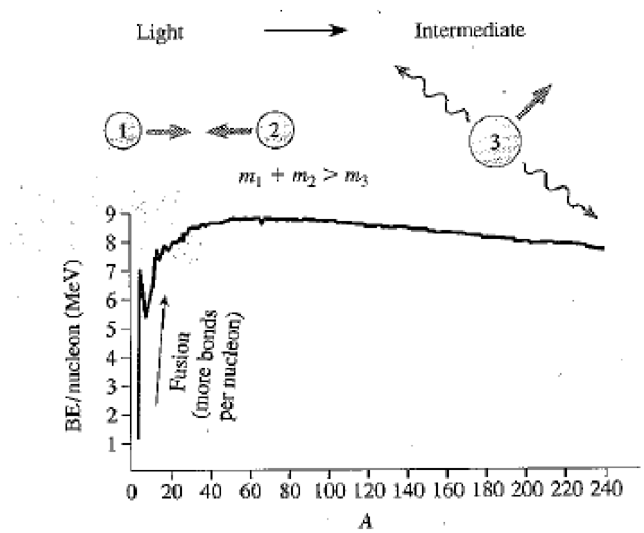
  Example:

  $$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

  $$Q = (2.0141 + 1.0078 - 3.0160)uc^2$$
  $$= 5.48\ MeV$$

- A series of fusion occurs in stars.

Figure 11.30 Decreasing BE/nucleon via fusion.



Proton-Proton Cycle:

Step 1: $^1_1H + ^1_1H \rightarrow ^2_1H + {}_{+1}^{\ 0}\beta + \nu$ (Q=0.42 MeV)
Step 2: $^2_1H + ^1_1H \rightarrow ^3_2He$ (Q=5.48 MeV)

Step 3: $^3_2He + ^3_2He \rightarrow ^4_2He + ^1_1H + ^1_1H$ (Q=12.9 MeV)

Step 1: $^1_1H + ^1_1H \rightarrow ^2_1H + {}_{+1}^{\ 0}\beta + \nu$ (Q=0.42 MeV)
Step 2: $^2_1H + ^1_1H \rightarrow ^3_2He$ (Q=5.48 MeV)

Net Results: Four protons fuse to ^4_2He with Q=24.7 MeV

$$^1_1H + ^1_1H + ^1_1H + ^1_1H + ^1_1H + ^1_1H \rightarrow ^4_2He + ^1_1H + ^1_1H + 2\,{}_{+1}^{\ 0}\beta + 2\nu$$

Since there is no bound state between two protons, in Step 1, one proton changes into a neutron and emits a positron and a neutrino, which is relatively a slow process involving weak force.

Carbon Cycle: When the temperature and ^4_2He concentration is high enough
Two ^4_2He will fuse into ^8_4Be which is unstable and would naturally decay back to two ^4_2He. However, if there is an enough number of fast moving ^4_2He is available, then a ^8_4Be and a ^4_2He will fuse to form a $^{12}_6C$. Once $^{12}_6C$ appears, more protons will fuse to ^4_2He at the faster pace than the Proton-Proton Cycle. The Carbon Cycle is shown below. At even higher temperatures, elements higher than carbon may form. Z higher than 60 may not form by fusion, but neutron

capture and subsequent beta- decay may allow Z higher than 60 to form. Heavy elements in the universe are thought to be formed in supernovae.

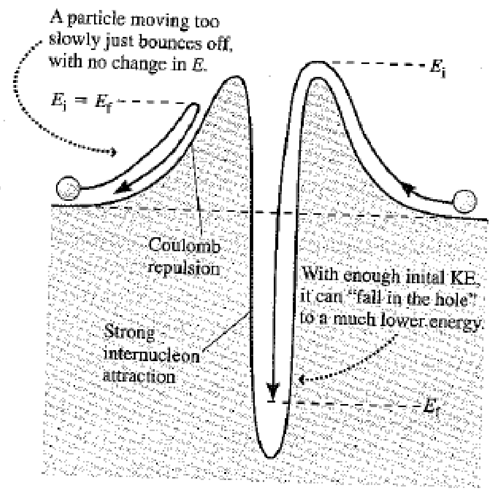
Step 1: $^{1}_{1}H + ^{12}_{6}C \rightarrow ^{13}_{7}N$
Step 2: $^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{+1}\beta + \nu$
Step 3: $^{1}_{1}H + ^{13}_{6}C \rightarrow ^{14}_{7}N$
Step 4: $^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O$
Step 5: $^{15}_{8}O \rightarrow ^{15}_{7}N + ^{0}_{+1}\beta + \nu$
Step 6: $^{1}_{1}H + ^{15}_{7}N \rightarrow ^{12}_{6}C + ^{4}_{2}He$

Net effects: 4 protons fuse into a $^{4}_{2}He$.

Fission can occur spontaneously, fusion does not occur spontaneously because protons have charges and thus have Coulomb repulsion. Coulomb repulsion should be overcome. To do this, protons should have high initial kinetic energy to get to the lower, bound energy state.

High density and high temperature are necessary to allow more frequent collisions among particles and a greater number of particles have enough energy to surmount the potential barrier.

Figure 11.32 Nuclear fusion: over the Coulomb hurdle, then into the strong force well.



These conditions can be easily met in stars but not on Earth. Hydrogen bomb uses fusion, but the conditions are set by initially exploding an atomic bomb. Since the energy difference before and after reactions is much greater in fusion than in fission, much higher energy can be released in nuclear fusion reactions.

(Power use) Fission and fusion use much smaller amounts of fuel as compared to fossil fuel and provide energy sources that do not involve carbon emission, but produce radioactive byproducts.

	Fission	Fusion
Fuel	Uranium and Thorium: Not rare and should be mined	Deuterium: Abundant and non-toxic
Waste	Highly toxic Radioactive with long half-life Disposal is a problem	He isotopes (harmless) and Tritium (radioactive with short half life and not chemically hazardous)
Chain reaction	Chain reactions are possible, thus the fission process should be controlled.	Chain reactions are not possible.