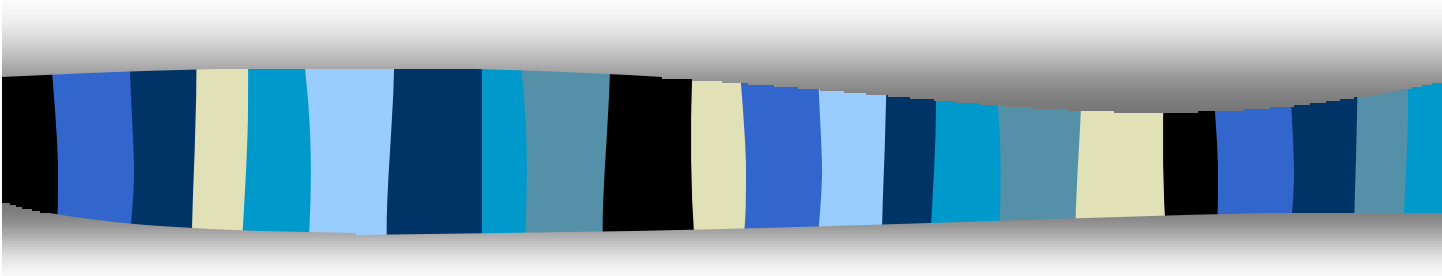


Nuclear Reactions

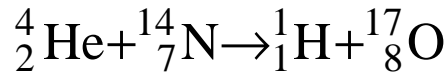


PHY 3101
D. Acosta



Nuclear Alchemy

- First nuclear reaction performed by Rutherford in 1919 using α -particles:

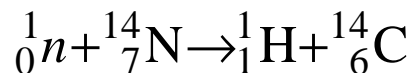


- **Reaction Energy:**

$$Q = [M(\text{initial products}) - M(\text{final products})] \times c^2$$

- **Exothermic:** energy released in reaction
- **Endothermic:** energy absorbed in reaction
 - Goes into mass

- Nuclear reactions take place in atmosphere:



- Carbon binds to form CO_2 which is absorbed by plants and animals

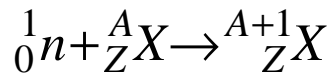
- **Carbon-14 dating:**

- ${}^{14}\text{C}$ is continually replenished until the plant or animal dies
- ${}^{14}\text{C}$ decays, and amount left gives age
- $t_{1/2} = 5730$ years

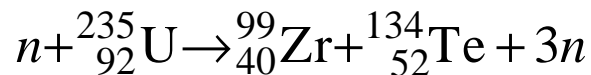


Nuclear Fission

- Enrico Fermi and Italian groups bombard nuclei with neutrons to produce new isotopes:



- In 1938, Hahn and Strassman in Germany **split** uranium
- Frisch and Lise Meitner call it **fission** (like cell division) and observe that excess energy is shed (**exothermic**)
- Excess neutrons are released which may catalyze more reactions
- Niels Bohr points out that ${}^{235}\text{U}$ (0.7% natural abundance) is more likely than ${}^{238}\text{U}$ (99.3%) to fission because of odd number of neutrons
 - Need to use enriched uranium
- Many possible fission fragments are possible
- For example:



- Energy released is:
 $1.0087\text{u} + 235.04\text{u}$
 - $98.92\text{u} - 133.91\text{u} - 3(1.0087\text{u}) = 0.2\text{u} \Rightarrow 185\text{ MeV}$
- Average number of neutrons released is 2.3



Nuclear Fission

- Uranium is on the downward slope of the binding energy per nucleon curve
- More energetically favorable for Uranium to split into smaller nuclei
- More neutrons are released than incident
- If the released neutrons are absorbed, this starts a **chain reaction**
- **Critical Mass:**
 - Larger mass sustains chain reaction
 - Smaller mass implies neutrons escape
 - Critical mass is a few kg for uranium
- Controlled fission: moderators slow and absorb neutrons
- More efficient fission from **plutonium**, which can be produced by bombarding ^{238}U with neutrons to get ^{239}Pu
 - Average of 2.7 neutrons per Pu fission
 - $t_{1/2} = 24,000$ years

Atomic Bomb

- Suppose 1 kg of enriched ^{235}U fissions:

$$Q = \frac{185 \text{ MeV}}{\text{fission}} \times \frac{1 \text{ kg}}{235 \text{ u}} \times \frac{1 \text{ u}}{1.66 \times 10^{-27} \text{ kg}} = 4.7 \times 10^{32} \text{ eV}$$

$$Q = 7.6 \times 10^{13} \text{ J} = 18 \text{ kT}$$

(1 kT of TNT = $4.2 \times 10^{12} \text{ J} = 10^{12} \text{ calories}$)

- Large as this is, it is still small compared to the total rest mass energy:

$$E = mc^2 = (1 \text{ kg})(3 \times 10^8 \text{ m/s})^2$$

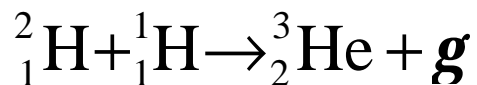
$$E = 9 \times 10^{16} \text{ J} = 21400 \text{ kT} = 21.4 \text{ MT}$$

- Only 1/1000 of energy released in fission



Nuclear Fusion

- Dividing high Z elements liberates energy, but so does **fusing low Z elements** (upward part of binding energy per nucleon curve)
- Consider the fusion of deuterium and hydrogen (powers the Sun and H-bomb)



$$Q = [2.0141\text{u} + 1.00783\text{u} - 3.01603\text{u}] \times c^2$$

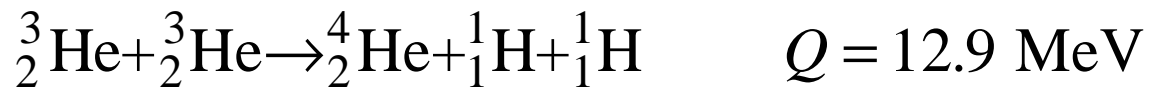
$$Q = 0.0059\text{u}c^2 = 5.5 \text{ MeV}$$

Solar Reactions

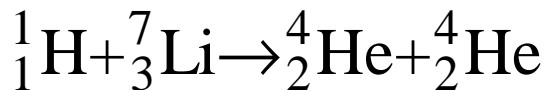
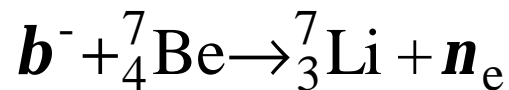
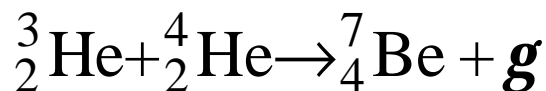
- The “burning” of hydrogen into helium and higher Z materials in stars:

H.A. Bethe

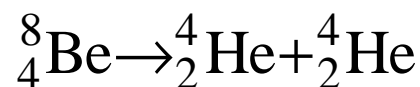
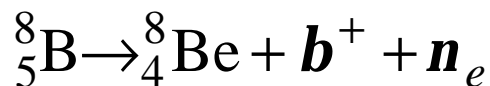
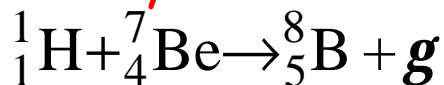
- **PPI cycle:**



- **PPII cycle:**



- **PPIII cycle:**





Stars

- Fusion of higher Z elements occurs when lower Z fuel is exhausted
- Continues until ^{56}Fe is produced, which is at the peak of the binding energy vs. Z curve
 - Not energetically favorable to fuse higher Z nuclei
- Without energy source, star collapses and may explode as a supernova
- All elements in the periodic table besides H and He are produced (and released) by stars in the universe
- Direct evidence for solar fusion is available because we have detected the neutrinos released in the solar reactions