Lec #32: 7 November 2011 Chapter 6.1, .2, .5

Energy Generation Within Stars:

- Nuclear Physics Basics
- Fusion
- PP, CNO, and Triple-Alpha Processes

NEXT: Main-Sequence Evolution (6.5)

THEN: Post Main-Sequence Evolution (6.6-6.8)

Energy Generation via Grav. Contraction

- Luminosity = energy generation (~$M^{3.5}$)
- contraction (V decreases; P, T increase) -> gas couples to radiation; energy radiates out
- $\Delta E \sim 0.3\, GM^2/R\ (1/R_2 - 1/R_1)$
- let $R_1=\infty$, $R_2=R_{sun}$ -> $\Delta E \sim 10^{48}$ erg
- L $t_{KH} = \Delta E$ -> $t_{KH} \sim 10^7$ years
  - this would only keep the Sun shining for 10 million years, but we know it's older than that!

Chemical or Nuclear Energy Generation?

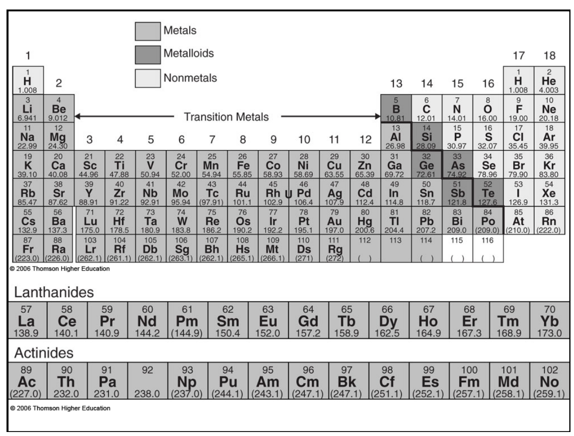
- energy available in a chemical reaction is roughly the binding energy of the atoms or molecules, which is typically 1-50 eV
- multiply that by the number of available molecules, and you get a timescale longer than t_{KH} but still much shorter than the age of the Sun
- binding energy of nuclei is in the MeV-TeV range; multiply that by the number of nuclei, and there's plenty of available energy to keep the Sun shining for 10 billion years

Main-sequence lifetimes

Mass ($M_\odot$)	*Time (years)*
0.1	6×10^{12}
0.5	7×10^{10}
1.0	1×10^{10}
1.25	4×10^{9}
1.5	2×10^{9}
3.0	2×10^{8}
5.0	7×10^{7}
9.0	2×10^{7}
15	1×10^{7}
25	6×10^{6}

Fundamentals of Nuclear Physics

1. Mass of free particles (E=mc^2)
   - proton = 1.6726E-27 kg = 938.3 MeV/c^2
   - neutron = 1.6749E-27 kg = 939.6 MeV/c^2
   - electron = 9.1094E-31 kg = 0.511 MeV/c^2
2. Binding Energy and Mass of atom < $m_p n_p + m_n n_n + m_e n_e$
   - Δmc^2 = binding energy
   - most of this (MeV's) is in nucleus
3. Nuclear Structure (proton+neutron)
   - EM repulsion of protons; neutron immune to EM force
   - force stronger than EM operating over tiny distances
   - more protons -> more EM; more neutrons -> some "shielding"
   - Atomic Number: Z = # of protons
   - Nucleon Number: A = # of nucleons (protons + neutrons)
   - ${}_Z^A X$; X is chemical symbol e.g. ${}_{92}^{238}U$ (or just ${}^{238}U$)



Fundamentals of Nuclear Physics (cont.)

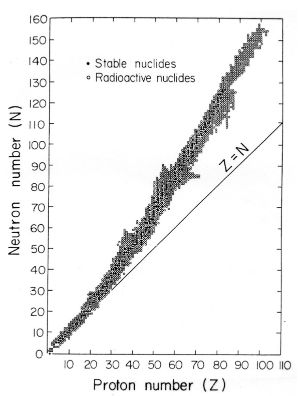
B. ISOTOPES

- same Z, therefore same chemical properties
- different A, therefore
  - different mass
  - different binding energy
  - different stability
  - different behavior in nuclear reactions
- elements form with a mix of isotopes
- over time, this mix changes, as “unstable” isotopes “decay”
  - e.g. ^{1}H = hydrogen 99.985%
  - . ^{2}H = deuterium 0.015%
  - . ^{3}H = tritium ~0.000%
  - e.g. ^{238}U 99.3%
  - . ^{235}U 0.7%

Fundamentals of Nuclear Physics (cont.)

C. STABILITY OF ISOTOPES

- certain combinations of neutron # and proton # hold together for a long time
- others transmute themselves to a different element by...
  - radioactive decay
  - nuclear fission
  - electron capture
- adding neutrons to stable nucleus generally makes it unstable
- ~400 stable nuclei known; all have $Z \leq 83$ (Bismuth)
- generally stable if Z or N = 2, 8, 20, 28, 50, 82, 126
  - nuclear “shell” structure analogous to atomic shells



Nuclear Reactions & Nucleosynthesis

- Initial and final states have different binding energies, different masses ($\Delta E = \Delta mc^2$)
- Where does energy “go”?
- We are interested in “exothermic” reactions...

A. Radioactive Decay

B. Nuclear Fission

C. Nuclear Fusion

Nuclear Reactions

A. Radioactivity

1. Alpha Decay: Emission of a helium nucleus (2P, 2N) $\Delta Z = -2$

$${}_Z^{A}X \dashrightarrow {}_{Z-2}^{A-4}Y + {}_2^{4}He$$

$$Heat = (M_x - M_Y - M_\alpha)c^2 \rightarrow K.E. \text{ of } X, Y, \alpha$$

2. Beta Decay: Emission of an electron or positron $\Delta Z = +/-1$

$${}_Z^{A}X \dashrightarrow {}_{Z+1}^{A}Y + \beta^- + \underline{\nu}$$

$${}_Z^{A}X \dashrightarrow {}_{Z-1}^{A}Y + \beta^+ + \nu$$

3. Gamma Decay: Emission of a photon (de-excitation) $\Delta Z = 0$

$${}_Z^{A}X^* \dashrightarrow {}_Z^{A}X + \gamma$$

4. Electron Capture: ${}_Z^{A}X + {}_1^{0}e \dashrightarrow {}_{Z-1}^{A}X + \nu$