PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 21900

General Physics II

Electricity, Magnetism and Optics

Lecture 28 – Chapter 28.4-7

Radioactive Decays and Nuclear Reactions

Fall 2015 Semester

Prof. Matthew Jones

Announcement

Final Exam

Friday, December 18th 3:30-5:30 pm

Room PHYS 112

Covers material from lectures 16-28:

- Propagation of light, refraction and reflection
- Lenses and mirrors
- Diffraction and interference
- Electromagnetic waves, polarization
- Quantum optics, the Bohr model of hydrogen
- de Broglie waves
- Nuclear structure and decay

Nuclear Structure

- The chemical properties of the elements are mostly determined by the configuration of electrons in the outer orbits.
- A neutral atom contains equal numbers of electrons and protons.
- Protons are confined to the nucleus which is 10,000 times smaller than the atom and contains most of its mass.
- Neutrons counteract the electrostatic repulsion of the positive charge and stabilize the nucleus via the *strong nuclear force*.

Mass/Energy Relationship

- The kinetic energy formula $KE = \frac{1}{2}m\,v^2$ is only accurate when $v \ll c$.
- This is the case for classical mechanics
  - Balls rolling down incline planes
  - Planetary motion
- Generally not true for nuclear processes
- The special theory of relativity shows that energy and momentum are related by

$$E = \sqrt{m^2c^4 + p^2c^2}$$

- When $v \ll c$ this is approximately

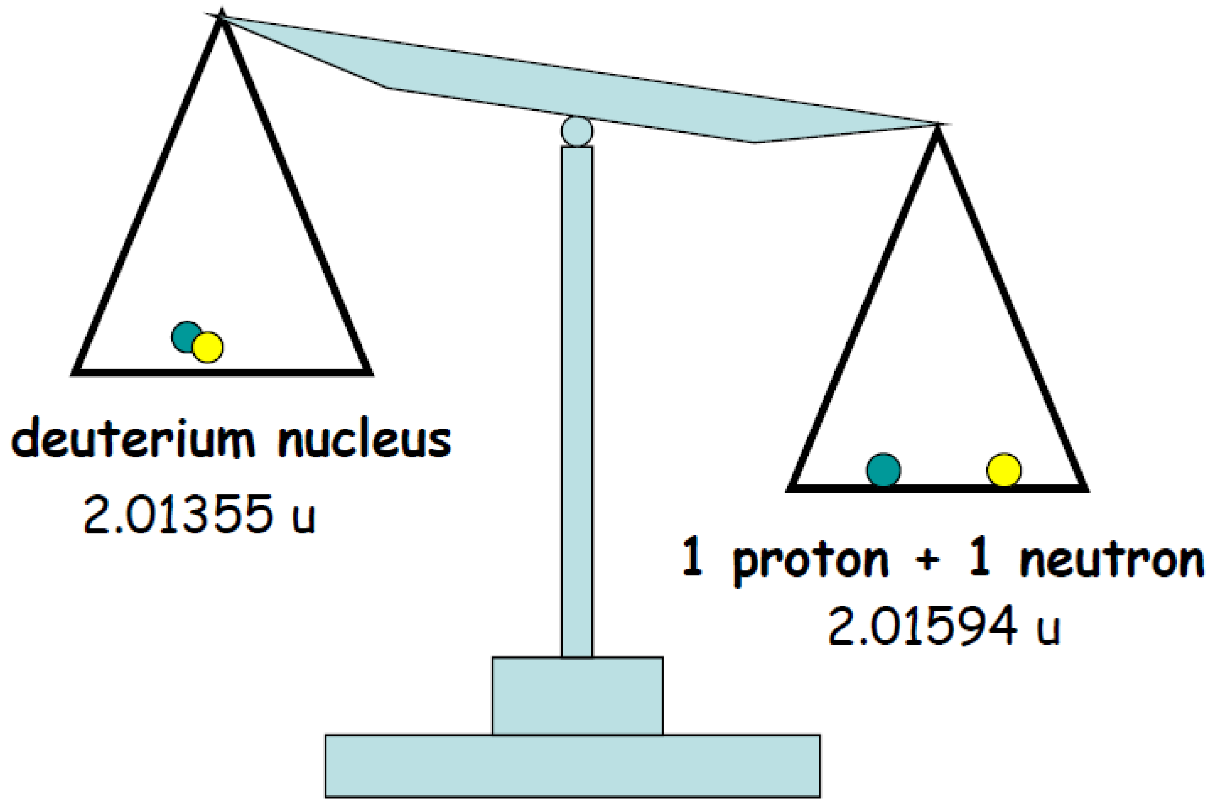
$$E \approx mc^2 + \frac{p^2}{2m} = mc^2 + \frac{1}{2}mv^2$$

Mass/Energy Relationship

- For particles at rest, $v = 0$ and
$$E = mc^2$$
- Since $m = E/c^2$, a convenient unit for mass is eV/c^2 or MeV/c^2.
- Example: what is the mass of a hydrogen atom in its ground state?
$$m_H = m_p + m_e - \frac{13.6\ eV}{c^2}$$
- The binding energy lowers the total mass compared to the masses of its constituents.
- This is a tiny effect for Hydrogen:
$$m_p = 938.28\ MeV/c^2$$
$$m_e = 0.511\ MeV/c^2$$
$$\Delta E = 13.6\ eV$$
- Total mass is 0.000001% lower than the mass of the proton and electron...

The mass of the parts is more than the whole??

The mass of a nucleus is NOT equal to the sum of its parts!



	2.01594 u
-	2.01355 u
	0.00239 u

The "lost" mass (mass deficit) is converted to a "binding energy" given by $\Delta E = \Delta mc^2$

Nuclear Binding Energy

- The effect is much larger for nuclei.
- The strong nuclear force between an proton and a neutron is *attractive*.
  - a proton and neutron have a larger potential energy when separated by a large distance
  - just like two opposite point charges
- Deuterium (an isotope of hydrogen, ^2H) is a bound state of a proton and a neutron.
- The binding energy of deuterium is $\Delta E = 2.22\ MeV$.

$$m_d = m_p + m_n - \Delta E$$
$$m_p = 938.28\ MeV/c^2$$
$$m_n = 939.57\ MeV/c^2$$
$$\Delta E = 2.22\ MeV$$

- This is a 0.1% effect but it is very important.

Nuclear Binding Energy

- An isotope X with atomic mass Z and atomic number A has binding energy

$$\Delta E = [Zm_p + Zm_e + (A - Z)m_n] - m_X$$

- Example: Binding energy of ${}^{56}_{26}Fe$

$$26\, m_p = 26\,(1.007276\, u) = 26.1892\, u$$

$$26\, m_e = 26\,(5.50 \times 10^{-4}\, u) = 0.0143\, u$$

$$30\, m_n = 30\,(1.008665\, u) = 30.2600\, u$$

TOTAL = $56.4635\, u$

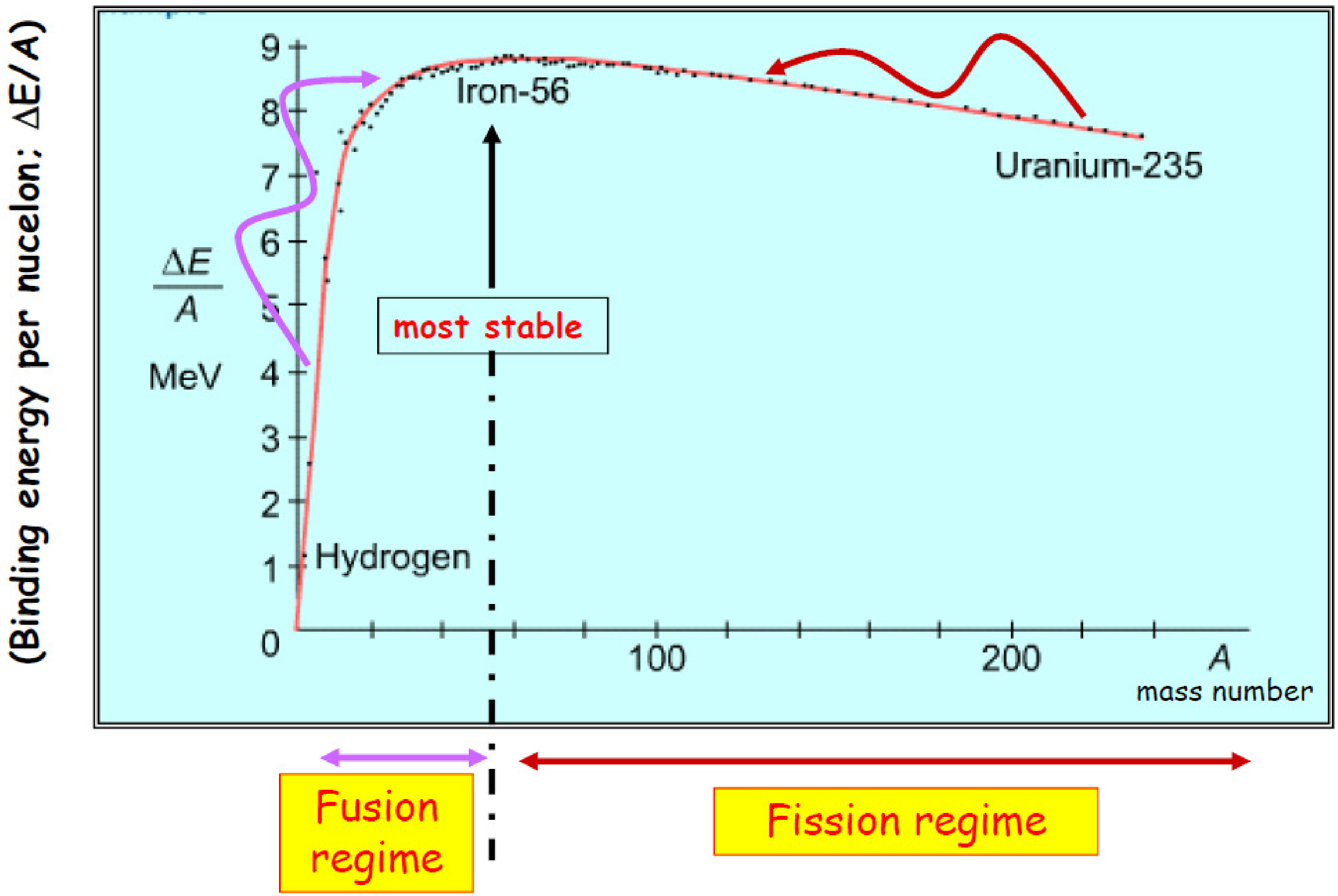
Measured mass of ${}^{56}_{26}Fe = 55.9349\, u$

$$\Delta E = 0.5286\, u = 492.3\, MeV/c^2$$

$$\frac{\Delta E}{A} = \frac{492.3\, MeV}{56} = 8.8\, MeV/nucleon$$

How much energy is required to remove one nucleon from a nucleus?

Answer depends on mass number A=N+Z



Radioactive Alpha Decay

- Neutrons stabilize the repulsive nature of protons in the nucleus
- If there are not enough neutrons, the nucleus becomes unstable and can eject an α particle.
- An α particle is the same as a helium nucleus: two protons and two neutrons.
- Example:

$$^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \alpha$$

  - Mass of the isotope decreases by 4
  - Charge decreases by 2

The rest of the energy goes into the kinetic energy of the decay products.

$$m_{U238} = 238.0508\,u$$

$$\left.\begin{array}{c} m_{Th234} = 234.0436\,u \\ m_{\alpha} = 4.0015\,u \end{array}\right\} 238.0451\,u < 238.0508\,u$$

Radioactive Beta Decay

- A free neutron is unstable because it can decay into a proton and an electron

$$m_n = 939.5654\ MeV/c^2$$

$$\left.\begin{aligned} m_p &= 938.2720\ MeV/c^2 \\ m_e &= 0.5110\ MeV/c^2 \end{aligned}\right\} 938.7830\ MeV/c^2$$

- The electron, when emitted in a nuclear decay, is called a β particle (but it is still just an electron)
- There is actually a third decay product called an electron anti-neutrino, which is almost (but not quite) massless

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Radioactive Beta Decay

- Isotopes with too many neutrons typically undergo beta decay.
- Example: Tritium is ${}^{3}_{1}H$ (1 proton + 2 neutrons)

$$ {}^{3}_{1}H \rightarrow {}^{3}_{2}He + e^{-} + \bar{\nu}_e $$

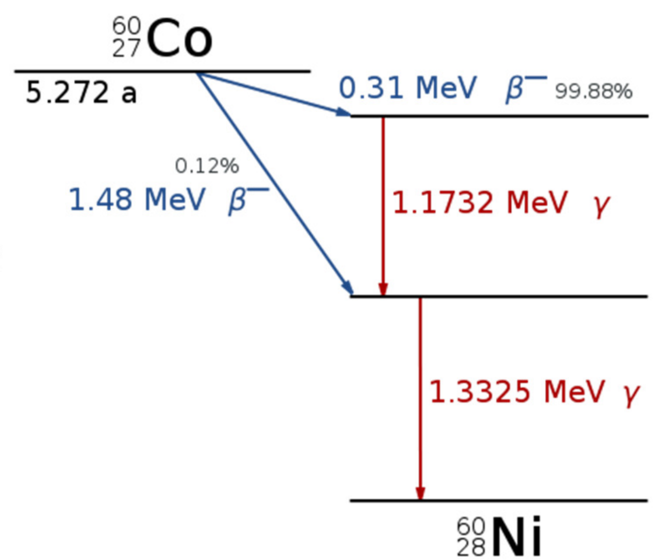
  - One of the neutrons decayed into a proton
  - The atomic mass doesn't change because the number of nucleons remains unchanged
  - The atomic number increases by 1 to conserve charge

Radioactive Gamma Decay

- The protons and neutrons in a nucleus are arranged in orbits, just like electrons in an atom.
- Nucleons in an excited state decay to a less excited state by emitting a high energy photon
- Neither the atomic mass nor the atomic number change
- Isotopes usually end up in an excited state due to a previous radioactive decay
- Example:

$$^{60}_{27}Co \rightarrow \, ^{60}_{28}Ni^{*} + e^{-} + \bar{\nu}_e$$

$$^{60}_{28}Ni^{*} \rightarrow \, ^{60}_{28}Ni + \gamma$$



Nuclear Fission

- Some heavy nuclei are so unstable that they just fall to pieces (spontaneous fission)
- Some heavy nuclei absorb a neutron and then fall apart (neutron induced fission)
- Example:

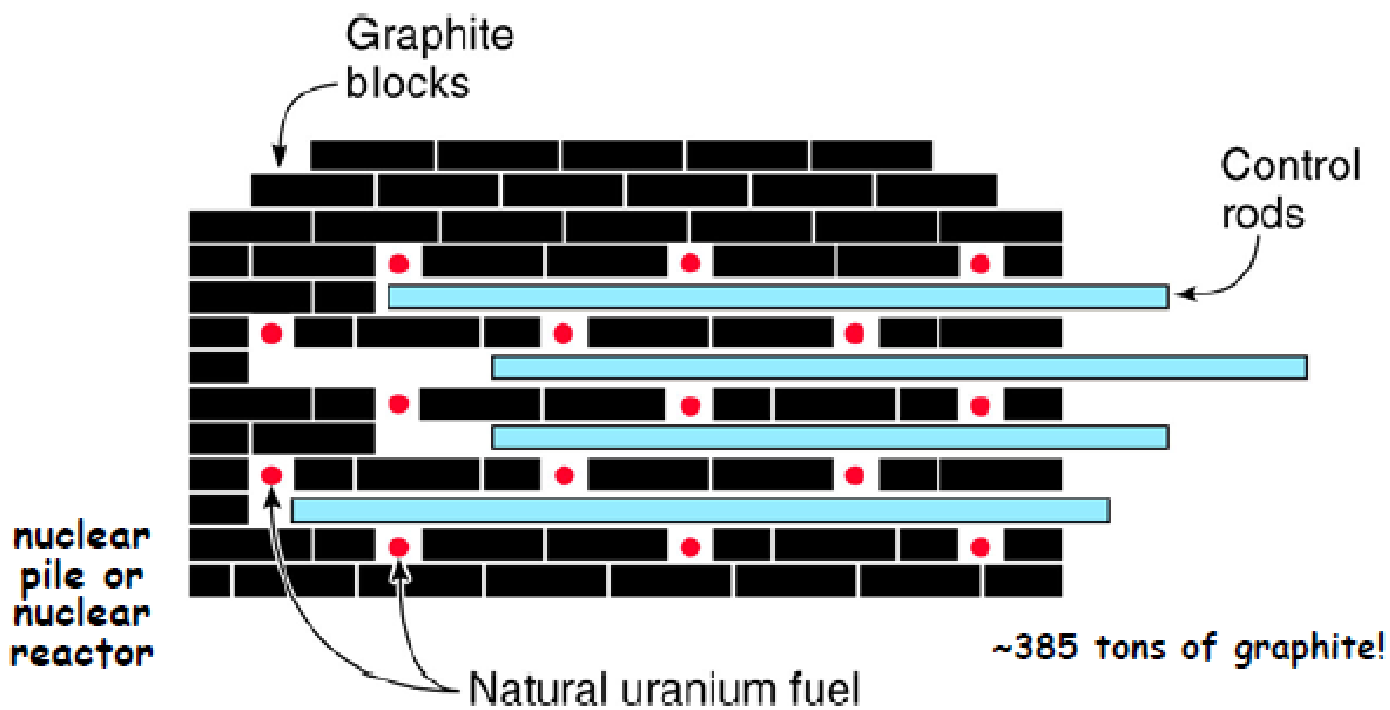
$$^{235}_{92}U + n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n$$

- Because one neutron is absorbed and 3 neutrons are produced, it is possible to sustain a chain reaction.
- However, only 0.72% of natural uranium is $^{235}_{92}U$
- The more abundant isotope $^{238}_{92}U$ captures fast neutrons but does not undergo fission.
- To make a chain reaction, you need to slow down the neutrons before they can be absorbed.

First controlled nuclear chain reaction
University of Chicago
3:30 PM, December 2, 1942

(dawn of nuclear power)

Graphite (carbon) was selected as a "moderator" to slow the neutrons emitted from the Uranium fuel.



Nuclear Fission

- How much energy is released?
- Consider the reaction:

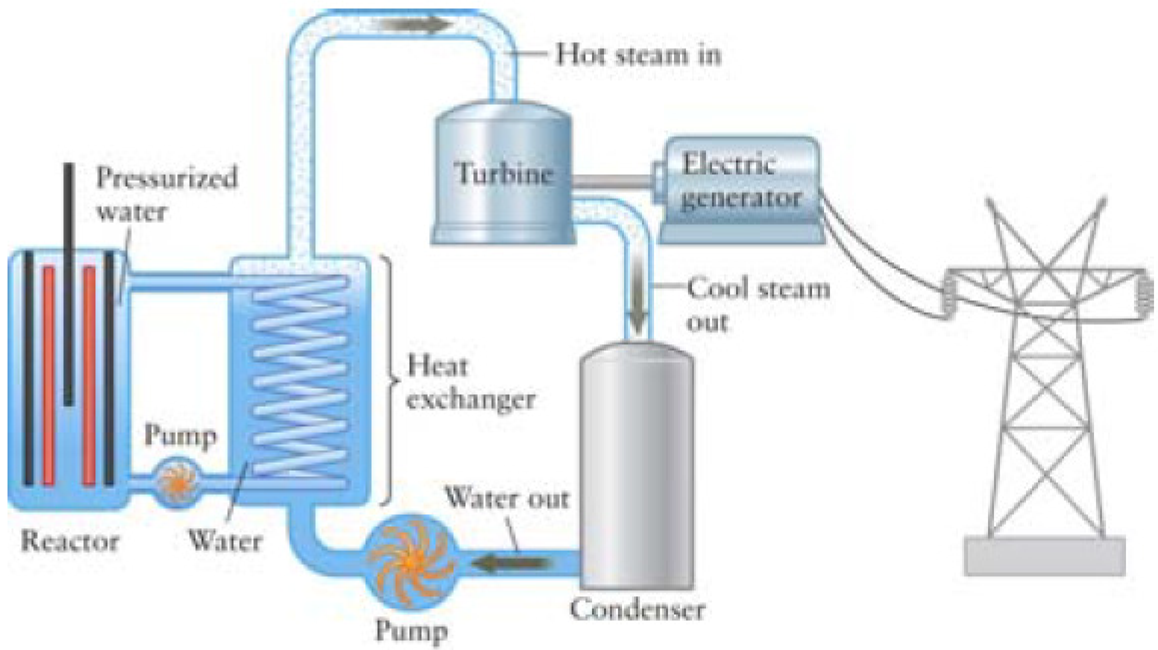
$$^{235}_{92}U + n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n$$

$$\left.\begin{aligned} m_{U235} &= 235.0439\,u \\ m_n &= 1.0087\,u \end{aligned}\right\} \text{236.0526 u}$$

$$\left.\begin{aligned} m_{Ba141} &= 140.9144\,u \\ m_{Kr92} &= 91.9263\,u \\ 3\,m_n &= 3.0261\,u \end{aligned}\right\} \text{235.8668 u}$$

- Mass difference: $0.1858\,u = 173\,MeV/c^2$
- Energy released: $173\,MeV = 1.5 \times 10^{-10}\,J$
- But there are 2.5×10^{21} atoms in 1 gram of U-235.
- There are also other fission processes but they are similar.

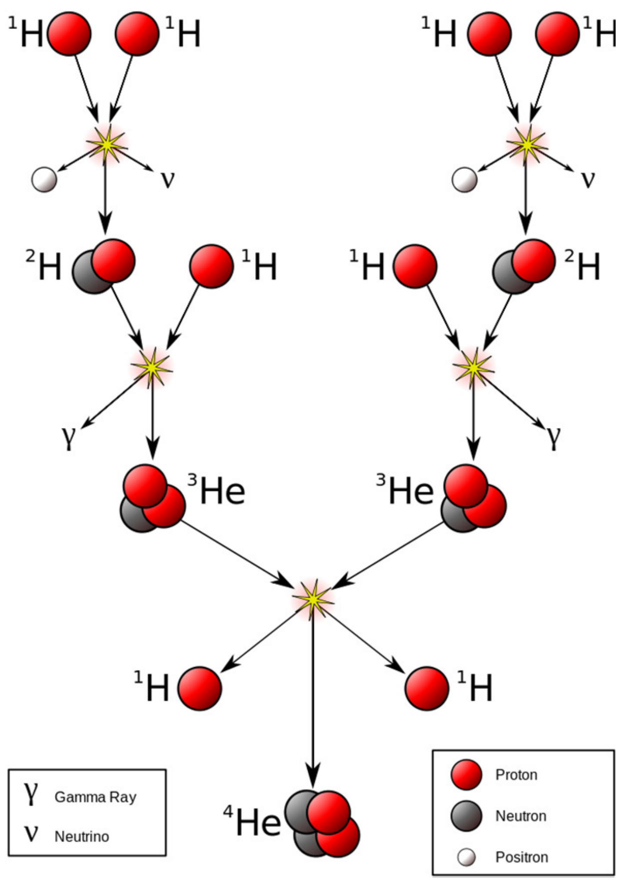
Modern Nuclear Reactors



- Nuclear fusion generates heat, just like burning coal.
  - 1 kg of coal produces 8 kWh of energy
  - 1 kg of U-235 produces 24,000,000 kWh of energy
- There are some engineering, safety, and waste disposal challenges though…

Solar Energy

- The sun converts hydrogen to heavier elements through the process of nuclear fusion.



- The total energy released is 26.22 MeV.
- The first step is very slow which is why stars burn for billions of years
- Protons usually just bounce off each other and don't fuse to form deuterium.

Semester Summary

Six BIG ideas

- Electrostatic Force – Coulomb's Law (1785)
- Induced emf – Faraday's Law (1830)
- Electromagnetic Waves – Maxwell (1865)
- Quantized Energy States – Planck, Einstein, Bohr (1900-1910)
- Particles behave like Waves – de Broglie (1923), Schrödinger (1926)
- *Relativity – Einstein (1905)*

We have covered five of these six BIG ideas. You should now have a general appreciation for why they are important.

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