Radioactivity, Fission, and Fusion

High School Physics

Chapter 13

NAD 2023 Standard FFRD1 (Radioactive Decay)
NAD 2023 Standard FFRD2 (Nuclear Fission)
NAD 2023 Standard FFRD3 (Nuclear Fusion)

Credits

- This Slideshow was developed to accompany the textbook
  - *OpenStax High School Physics*
    - *Available for free at https://openstax.org/details/books/physics*
    - *By Paul Peter Urone and Roger Hinrichs*
    - *2020 edition*
- Some examples and diagrams are taken from the *OpenStax College Physics, Physics,* and *Cutnell & Johnson Physics* 6th ed.

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13-01 Radioactivity

In this lesson you will…

- Describe the nucleus of an atom
- Explain radioactive decay
- Write equations for the three types of radioactive decay

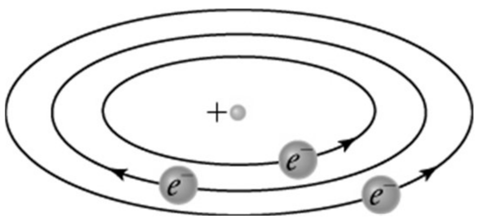
OpenStax High School Physics 22.1-2
OpenStax College Physics 2e 30.1-30.2, 31.1-31.4

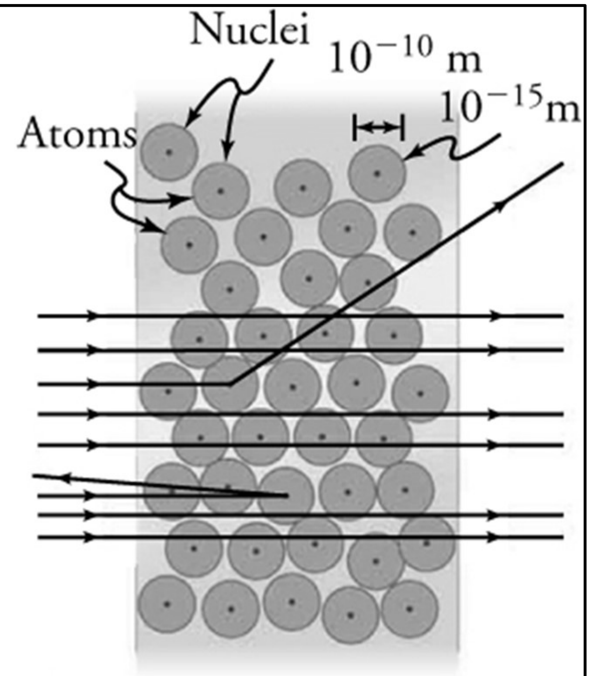
13-01 Radioactivity

- Structure of the atom
  - Early 1900's atom model was "plum pudding"
    - Everything spread evening throughout
- Rutherford's Experiment
  - Shot α-particles (2 proton, 2 neutrons) at thin gold foil
  - Expected to pass mostly straight though with little scattering
    - The α-particle has lots of energy and would blow through the "pudding"
  - Actually, most passed straight through without scattering
    - Some scattered a lot – even straight back

13-01 Radioactivity

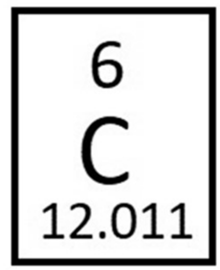
- Showed the nucleus was very small and much open space around it
- Rutherford proposed planetary model of the atom
  - Nucleus like sun
  - Electrons like planets
  - Electrical force like gravity



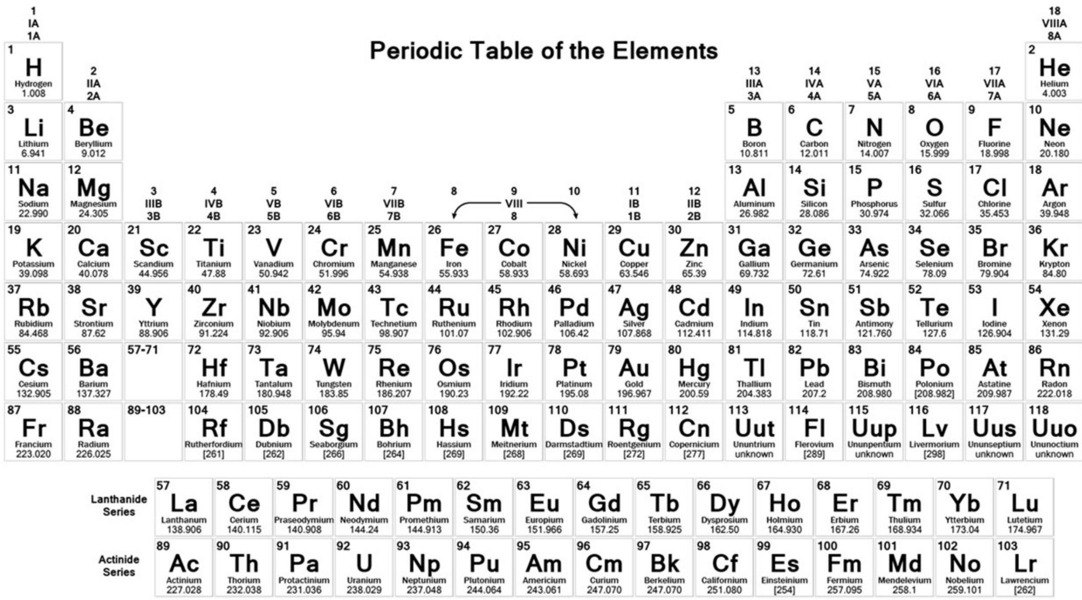


13-01 Radioactivity

- Nucleus
  - Contains protons and neutrons
    - Approximately equal mass
- Atomic mass unit (u)
  - Neutral carbon-12 = 12 u
  - About 1000 times more mass in nucleus than in electrons
  - C-12 has 6 protons, 6 neutrons
  - Proton and neutrons = 1 u
  - 1 u = 931.5 MeV/c^2
- Atomic Number (Z)
  - Number of protons in nucleus
  - Determines the element
- Mass Number (A)
  - Number of protons and neutrons



13-01 Radioactivity



13-01 Radioactivity

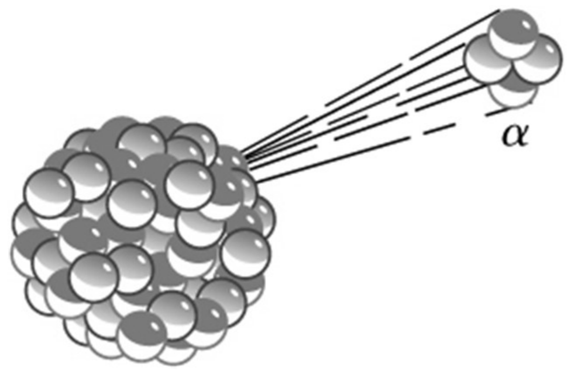
- Isotopes
  - Same element can have different number of neutrons
  - Carbon
    - Carbon-12
    - Carbon-13
    - Carbon-14
  - ${}^{A}_{Z}X$
    - A = mass number (u)
    - Z = atomic number
  - ${}^{A}X$
- Carbon-12
  - ${}^{12}_{6}C$ or ${}^{12}C$
  - Subtract A and Z to get number of neutrons
  - 12 − 6 = 6 neutrons
- Carbon-14
  - ${}^{14}_{6}C$ or ${}^{14}C$
  - Subtract A and Z to get number of neutrons
  - 14 − 6 = 8 neutrons
- Then number of neutrons changes behavior of nucleus

13-01 Radioactivity

- Large force required to break apart nucleus (it wants to stick together)
- Resist putting pushed close to each other
- Strong nuclear force
  - Holds nucleus together
  - Very strong
  - Acts at distance less than 10^{-15} m
- Electric forces try to break nucleus apart
- When electric forces are more than strong nuclear force, nuclear particles are ejected from nucleus
  - Radioactivity
- Nucleus wants
  - About same number of protons and neutrons
  - Smaller radius than strong nuclear force

13-01 Radioactivity

- Types of radioactivity
  - Alpha Decay (α)
    - Most common decay type
    - Happens when too many protons in nucleus
    - Nucleus ejects 2 protons and 2 neutrons (Helium nucleus)
    - ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$
  - ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

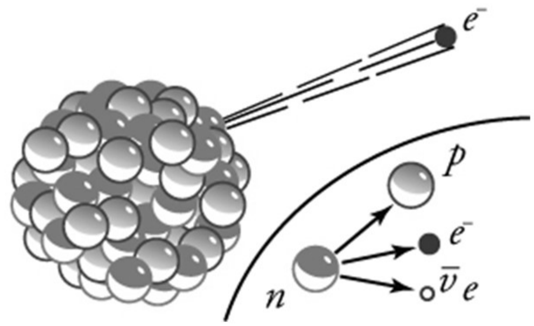


13-01 Radioactivity

- Notes about α-decay
  - During α-decay, the atomic number changes and one element changes into another
  - The α-particle quickly gains two electrons and becomes a stable helium atom
    - source of all helium on earth
  - The total number of particles stays the same
    - Law of Conservation of Mass and Energy
      - Any change in mass is converted to energy by $E = mc^2$
    - Law of Conservation of Charge

13-01 Radioactivity

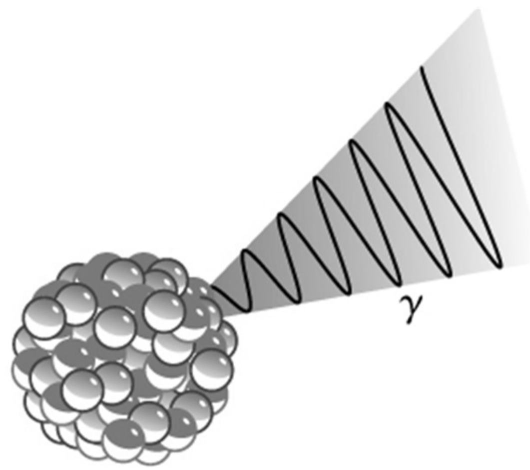
- Beta decay (β)
  - Imbalance of protons and neutrons
  - A neutron changes into a proton and electron or vice versa
  - ${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e + \nu$
    - e is electron
    - ν is neutrino
  - ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + \nu + e^{-}$



β^- decay a neutron turns into proton and electron and antineutrino
β^+ decay a proton turns into a neutron and positron and neutrino
Neutrino is tiny neutral particle

13-01 Radioactivity

- Gamma decay (γ)
  - Occurs when nucleus drops from excited state to ground state releasing energy as a photon
  - ${}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$
  - ${}^{137}_{56}Ba \rightarrow {}^{137}_{56}Ba + \gamma$



13-01 Radioactivity

- α-particles are massive (4 u) and have +2 charge, so they quickly interact with matter and can be stopped quickly
  - Sheet of paper,
  - few cm of air,
  - fraction of mm of tissue
- β-particles are smaller (mass of e) and −1 charge, so they penetrate farther
  - Thin aluminum plate,
  - tens of cm of tissue
- γ-particles have no mass or charge and barely interact with matter, so they penetrate very far
  - Several cm of lead,
  - meters of concrete

13-01 Radioactivity

- Write the complete decay equation in ${}^{A}_{Z}X$ notation for beta decay producing ${}^{60}_{28}\text{Ni}$. Refer to the periodic table for values of Z.

$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e + \nu$$

Since the atomic number increases by 1, the parent element is one less than Ni which is Co

$${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + e + \nu$$

13-01 Radioactivity

- Find the energy emitted in the α decay of ^{226}Ra.

Start by writing chemical equation

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

Now find the change in mass (look the masses up online)

$$^{226}Ra = 226.025402\ u$$

$$^{222}Rn = 222.0175763\ u$$

$$^{4}He = 4.002602\ u$$

$$\Delta m = m(Ra) - \big(m(Rn) + m(He)\big)$$

$$\Delta m = 226.025402\ u - (222.0175763\ u + 4.002602\ u) = 0.0052237\ u$$

Convert to energy

$$0.0052237\ u \left(\frac{931.5 \frac{MeV}{c^2}}{1\ u}\right) = 4.86587655 \frac{MeV}{c^2}$$

$$E = mc^2$$

$$E = \left(4.86587655 \frac{MeV}{c^2}\right) c^2 = 4.87\ MeV$$

13-01 Practice Work

- Radioactivity can be harmful to your health, but solving problem is beneficial.

- Read
  - OpenStax College Physics 2e 31.5
  - OR
  - OpenStax High School Physics 22.3

13-02 Radiometric Dating

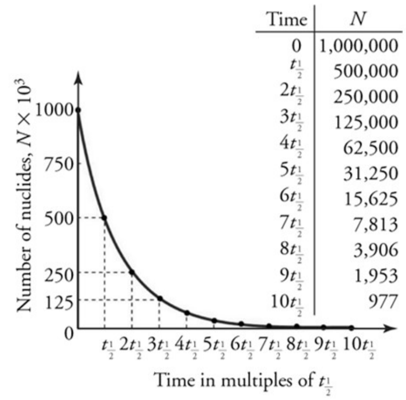
In this lesson you will…

- Understand half-life
- Use radiometric dating

OpenStax High School Physics 22.3
OpenStax College Physics 2e 31.5

13-02 Radiometric Dating

- Half-Life
  - Measures rate of radioactive decay
  - One half-life is time it takes for ½ of the nuclei to decay
  - Assumed to be constant for each isotope
  - $N = N_0 e^{-\lambda}$
  - Where N is number of nuclei at time t, N_0 is # of nuclei at time 0, λ is the decay constant
    - $\lambda = \frac{\ln(2)}{t_{1/2}}$



13-02 Radiometric Dating

- Radioactive Dating
  - Method used to date minerals
  - Assumptions
    - Amount of starting material known
    - No radioactive material enters or leaves the mineral
    - No new radioactive material created by other sources such as cosmic rays or other radioactive reactions
    - Decay rate is constant

13-02 Radiometric Dating

- Carbon-14 has a half-life of 5730 years. If there was originally 20 grams, but only 15 grams remains. How much time elapsed?

$$\lambda = \frac{\ln(2)}{t_{1/2}}$$

$$\lambda = \frac{\ln(2)}{5730} = 1.21 \times 10^{-4}\ /yr$$

$$N = N_0 e^{-\lambda t}$$

$$15\ g = (20\ g)e^{-\left(1.21\times 10^{-4}\frac{}{yr}\right)t}$$

$$0.75 = e^{-(1.21\times 10^{-4}\ \backslash\mathrm{yr})t}$$

$$\ln(0.75) = -\left(1.21 \times 10^{-4}\frac{}{yr}\right)t$$

$$t = 2378\ yrs$$

13-02 Radiometric Dating

- What is the half-life of technetium-99 if 20% decays in about 488000 years?

Amount remaining $= 100\% - 20\% = 80\%$

$$N = N_0 e^{-\lambda}$$

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$0.80 = e^{-\lambda(488000\ yr)}$$

$$\ln(0.80) = -\lambda(488000\ yr)$$

$$\lambda = 4.57 \times 10^{-7} \frac{}{yr}$$

$$\lambda = \frac{\ln(2)}{t_{1/2}}$$

$$4.57 \times 10^{-7} \frac{}{yr} = \frac{\ln(2)}{t_{1/2}}$$

$$t_{1/2} = \frac{\ln(2)}{4.57 \times 10^{-7} \frac{}{yr}} = 1.52 \times 10^{6}\ yr$$

13-02 Practice Work

- Talking about radioactivity is a sure way to get a date.

- Read
  - OpenStax College Physics 2e 32.6
  - OR
  - OpenStax High School Physics 22.4

13-03 Nuclear Fission

In this lesson you will…

- Explain nuclear fission
- Find the energy from a fission reaction

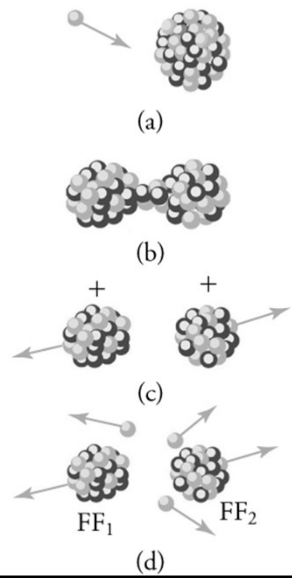
OpenStax High School Physics 22.4
OpenStax College Physics 2e 32.6

13-03 Nuclear Fission

- Fission
  - Splitting of a nucleus
  - Releases a lot of energy

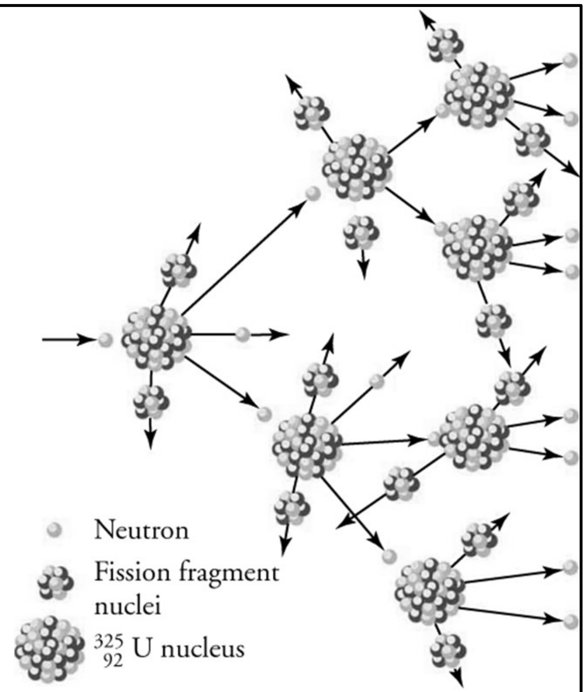
  - An unstable nucleus can naturally decay with α or β radiation, but can take a long time

  - Purposely done by hitting a large nucleus with a neutron (β radiation)



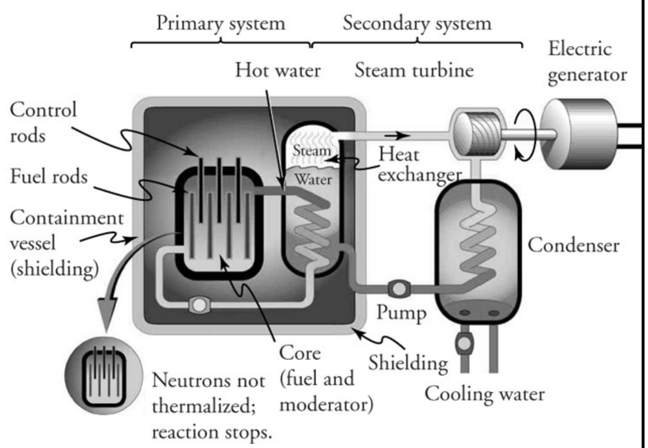
13-03 Nuclear Fission

- Chain reaction
  - When the nucleus splits it releases free neutrons
  - Those can hit other nuclei and split them
  - Critical mass – Minimum amount of fissable material necessary to sustain fission chain reaction
  - Number of fission reactions increases exponentially
    - bomb



13-03 Nuclear Fission

- Nuclear Reactor
  - To keep a nuclear fission reaction from becoming a bomb, slow down the neutrons with water
  - Fuel rods contain Uranium
  - Control rods absorb neutrons
    - Insert control rods to slow reaction
  - Fission reaction heats water
  - Steam turns turbines to make electricity
  - Cool water goes back to be heated



13-03 Nuclear Fission

- Energy from Fission
  - The mass of the products of fission is less than parent nucleus
  - That mass is converted to energy by $E = mc^2$
  - Average fission reaction produces about 200 MeV of energy

13-03 Nuclear Fission

- Find the energy released in the fission of uranium-235 given in the equation $^{1}_{0}\mathrm{n} + ^{235}_{92}\mathrm{U} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\ ^{1}_{0}\mathrm{n}$

- Masses
  - Neutron: 1.008665 u
  - ^{235}U: 235.0439299 u
  - ^{141}Ba: 140.9144035 u
  - ^{92}Kr: 91.926173094 u

Find change in mass:

$$\Delta\mathrm{m} = (1.008665\ \mathrm{u} + 235.0439299\ \mathrm{u}) - \left(140.9144035\ \mathrm{u} + 91.926173094\ \mathrm{u} + 3(1.008665\ \mathrm{u})\right) = 0.186023306\ \mathrm{u}$$

Covert the mass into energy

$$0.186023306\,u\left(\frac{931.5\,\frac{\mathrm{MeV}}{\mathrm{c}^2}}{1\ \mathrm{u}}\right) = 173.28\,\frac{\mathrm{MeV}}{\mathrm{c}^2}$$

$$E = mc^2$$

$$E = \left(173.2807095\,\frac{MeV}{c^2}\right)c^2 = 173.2807095\ MeV$$

The actual measurements give 202.5 MeV due to gamma radiation and decay of the neutrons

13-03 Nuclear Fission

- Calculate the amount of energy produced by the fission of 1.00 kg of ^{239}Pu, given the average fission reaction of ^{239}Pu produces 211.5 MeV. The atomic mass of ^{239}Pu is 239.05 u.

- This is a lot of energy. Over 650,000 gallons of gasoline or enough to run an average US home for 2255 years

Start by finding the number of atoms of ^{239}Pu in 1.00 kg.

$$\left(\frac{1000\ g}{239.05\,\frac{\text{g}}{\text{mol}}}\right)\left(\frac{6.022\times 10^{23}\ \text{atoms}}{1\ \text{mol}}\right) = 2.519\times 10^{24}\ \text{atoms of }^{239}\text{Pu}$$

Find the energy

$$(2.519\times 10^{24}\ atoms)\left(211.5\,\frac{MeV}{atom}\right)\left(\frac{1\times 10^{6}\ eV}{1\ MeV}\right)\left(\frac{1.60\times 10^{-19}\ J}{1\ eV}\right)$$

$$= 8.525\times 10^{13}\ J$$

This is a lot of energy. Over 650,000 gallons of gasoline or enough to run an average US home for 2255 years

13-03 Practice Work

- How many practice work assignments could be written with the energy of 1 gram of fusible material?

- Read
  - OpenStax College Physics 2e 32.5
  - OR
  - OpenStax High School Physics 22.4

13-04 Nuclear Fusion

In this lesson you will…

- Explain nuclear fusion
- Find the energy from a fusion reaction

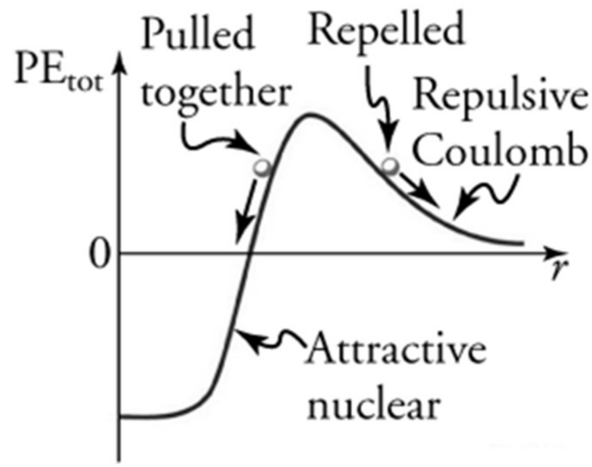
OpenStax High School Physics 22.4
OpenStax College Physics 2e 32.5

13-04 Nuclear Fusion

- Nuclear Fusion
  - Combining two nuclei into one
  - Releases a lot of energy
  - Fission breaks apart large nucleus
  - Fusion combines small nuclei
- For nuclei less than iron,
  - Nuclear forces holding the nucleus together are stronger than the electrical force pushing it apart
  - Strong nuclear force does work when adding more nucleons to small nuclei releasing energy
  - For elements higher than iron, energy must be added for fusion
    - Stars can only create elements up to iron
    - There is debate amongst atheists about where heavier elements come from

13-04 Nuclear Fusion

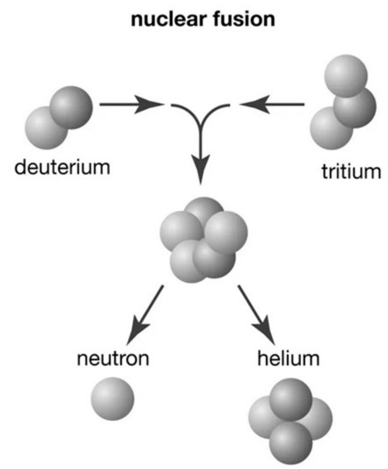
- Why fusion is difficult
  - The parent products must have enough kinetic energy to overcome the electrical force forcing the positive protons apart
    - Use high temp to make the KE
  - Once the parent elements are close enough the strong nuclear force does work pulling the pieces together into one nucleus releasing energy



13-04 Nuclear Fusion

- Process to combine H to make He
- $^1H + ^1H \rightarrow ^2H + e^+ + \nu_e$ (×2)
  - 0.42 MeV
- $^1H + ^2H \rightarrow ^3He + \gamma$ (×2)
  - 5.49 MeV
- $^3He + ^3He \rightarrow ^4He + ^1H + ^1H$
  - 12.86 MeV

- Overall cycle
- $2e^- + 4\ ^1H \rightarrow 4\ ^4He + 2\nu_e + 6\gamma$
- Releasing 26.7 MeV



e^+ is positron
ν_e is a electron neutrino

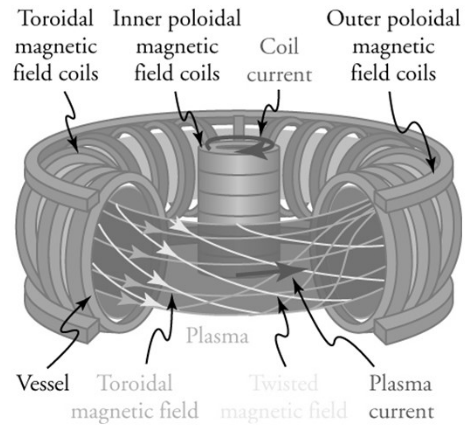
The two electrons combine with two positrons to annihilate and produce 6 gamma rays

13-04 Nuclear Fusion

- Nuclear Weapons
- Fission Bomb
  - Essentially subcritical masses are forces together by a conventional explosion
  - Forms a critical mass that builds energy exponentially until it explodes
  - 10-20 kilotons
  - Like bombs dropped on Hiroshima and Nagasaki
- Fusion Bomb
  - Fission bomb explodes next to lithium deuteride
  - γ rays heat and compress the lithium
  - The lithium undergoes fission to make ^{3}H and ^{4}He
  - The hydrogen then fuses to make more He
  - This is all surrounded by a uranium shell that reflect neutrons back into the bomb to keep the reaction going

13-04 Nuclear Fusion

- Fusion Reactor
  - Better than fission
    - Plentiful fuel
    - Products are safe
    - More energy released
  - Deuterium and tritium injected into vessel with high temp and pressure
  - EM field turn the hydrogen into plasma
  - H fuses into He
  - High-velocity neutrons released are unaffected by EM field
  - Neutrons strike sides of vessel creating heat, makes steam, turns turbine



13-04 Nuclear Fusion

- How much energy is released from the fusion of 1.00 kg of hydrogen?

- This is enough energy to run an US home for 16,900 years

4 hydrogen produce 26.7 MeV

$$\frac{26.7\ MeV}{4} = 6.675\frac{MeV}{atom}$$

Find number of H atoms in 1.00 kg

$$\left(\frac{1000g}{1.008\frac{g}{mol}}\right)\left(\frac{6.022 \times 10^{23}\ atoms}{1\ mol}\right) = 5.97 \times 10^{26}\ atoms$$

Multiply to get total energy

$$(5.97 \times 10^{26}\ atoms)\left(\frac{6.675\ MeV}{1\ atom}\right)\left(\frac{1 \times 10^{6}\ eV}{1\ MeV}\right)\left(\frac{1.60 \times 10^{-19}\ J}{1\ eV}\right)$$

$$= 6.38 \times 10^{14}\ J$$

13-04 Practice Work

- Fuse graphite with paper to write the results of this practice work.