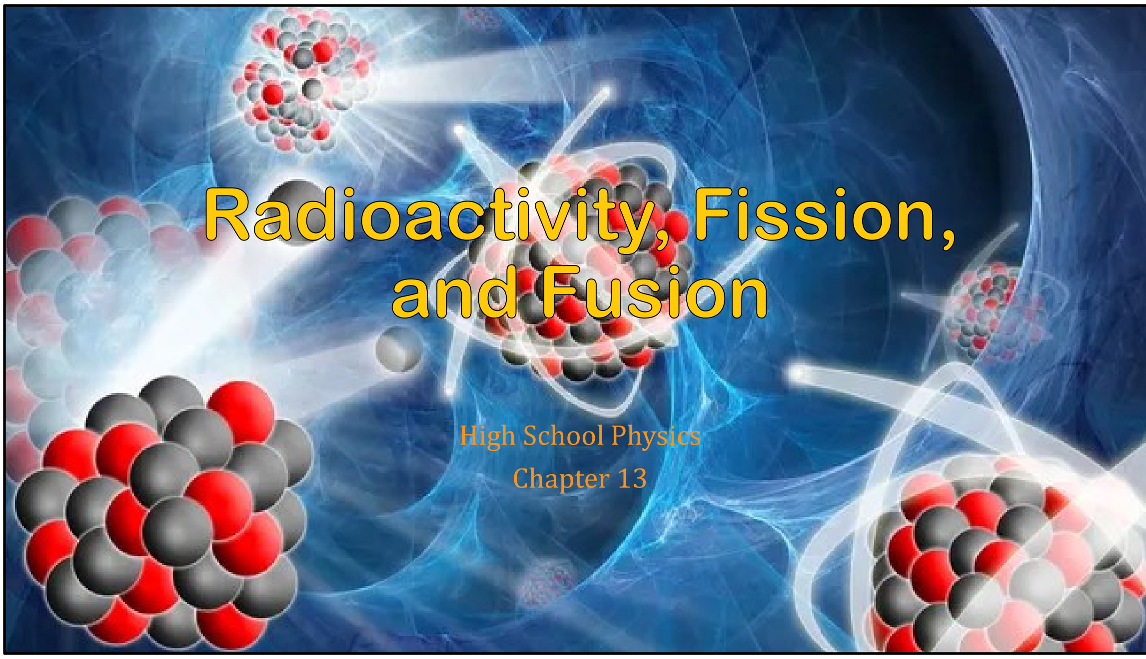

NAD 2023 Standard FFRD1 (Radioactive Decay)
NAD 2023 Standard FFRD2 (Nuclear Fission)
NAD 2023 Standard FFRD3 (Nuclear Fusion)

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.

Slides created by
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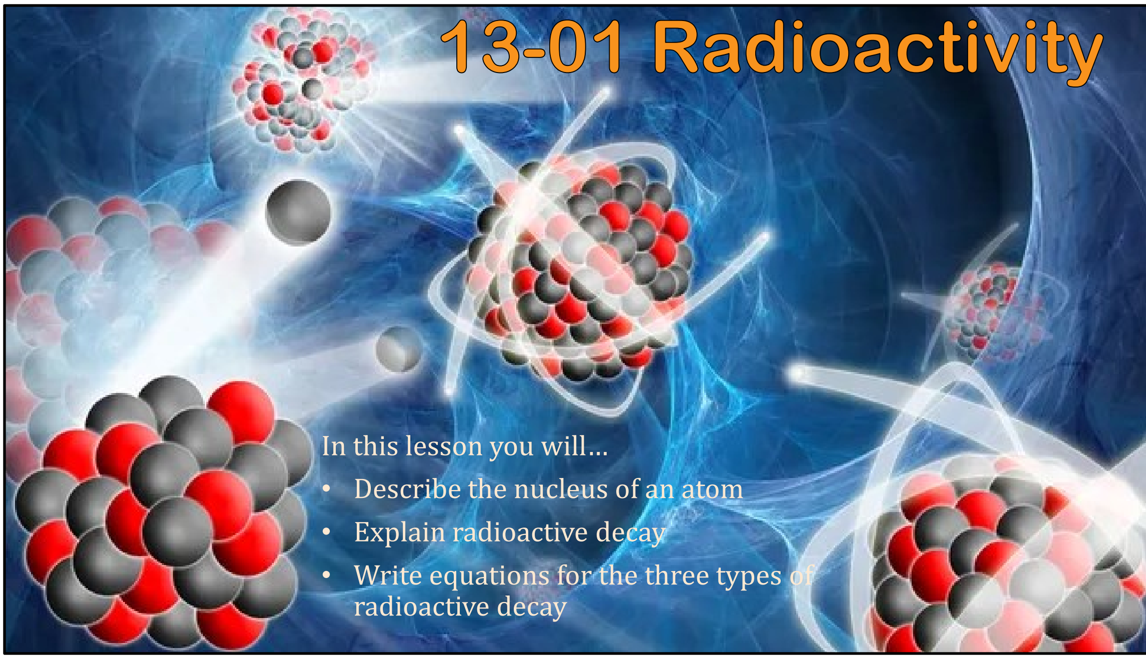


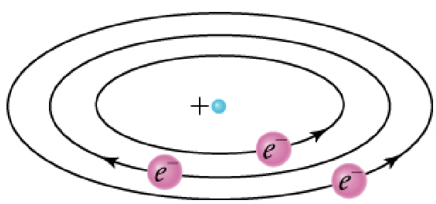
OpenStax High School Physics 22.1-2
OpenStax College Physics 2e 30.1-30.2, 31.1-31.4

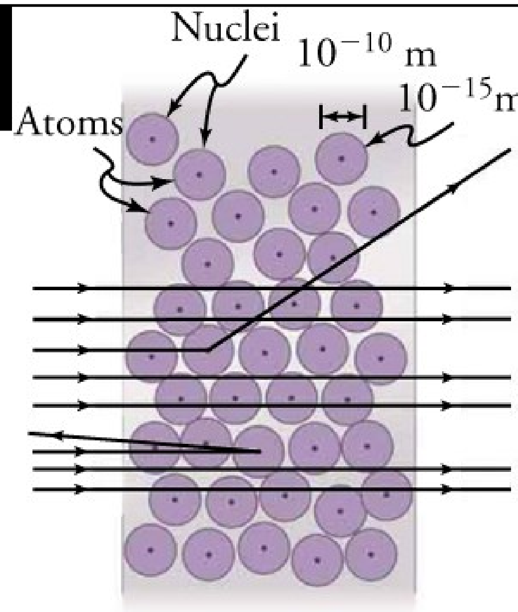
13-01 Radioactivity

- 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

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13-01 Radioactivity

Periodic Table of the Elements

1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

13-01 Radioactivity

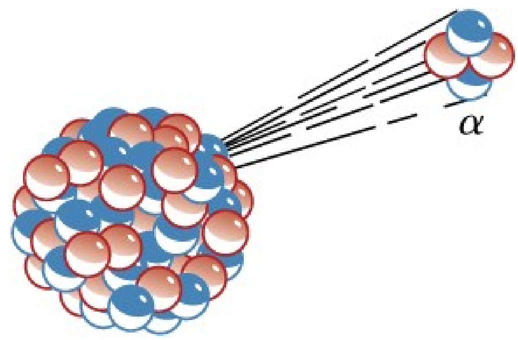
- Isotopes
  - Same element can have different number of neutrons
  - Carbon
    - Carbon-12
    - Carbon-13
    - Carbon-14
  - ${}_{Z}^{A}X$
    - A = mass number (u)
    - Z = atomic number
  - ${}^{A}X$
- Carbon-12
  - ${}_{6}^{12}C$ or ${}^{12}C$
  - Subtract A and Z to get number of neutrons
  - $12 - 6 = 6$ neutrons
- Carbon-14
  - ${}_{6}^{14}C$ 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)
    - ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$
  - ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

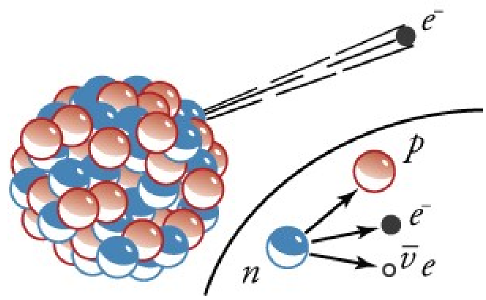


13-01 Radioactivity

- 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

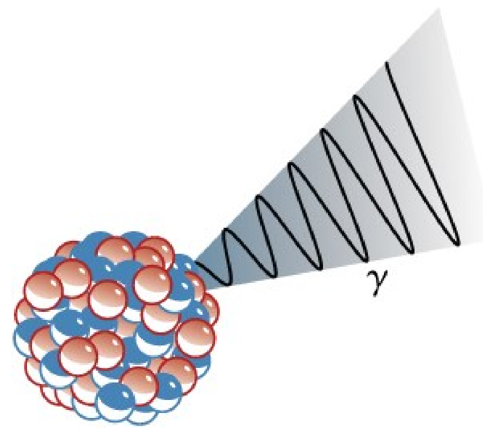
- Beta decay (β)
  - Imbalance of protons and neutrons
  - A neutron changes into a proton and electron or vice versa
  - ${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e + \nu$
    - e is electron
    - ν is neutrino
  - ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + \nu + e^{-}$



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 $^{60}_{28}\mathrm{Ni}$. Refer to the periodic table for values of Z.

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

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

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

13-01 Radioactivity

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

Start by writing chemical equation

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

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

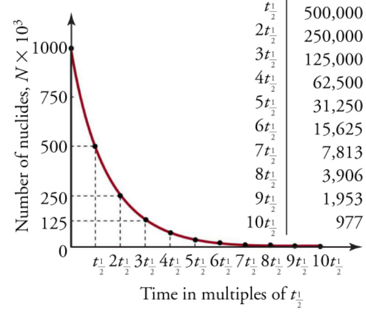
- Radioactivity can be harmful to your health, but solving problem is beneficial.

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

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
  - $N = N_0 e^{-\lambda t}$
  - Where N is number of nuclei at time t, N_0 is # of nuclei at time 0, λ is the decay constant
    - $\lambda = \frac{\ln(2)}{t_{1/2}}$



Time	N
0	1,000,000
$t_{\frac{1}{2}}$	500,000
$2t_{\frac{1}{2}}$	250,000
$3t_{\frac{1}{2}}$	125,000
$4t_{\frac{1}{2}}$	62,500
$5t_{\frac{1}{2}}$	31,250
$6t_{\frac{1}{2}}$	15,625
$7t_{\frac{1}{2}}$	7,813
$8t_{\frac{1}{2}}$	3,906
$9t_{\frac{1}{2}}$	1,953
$10t_{\frac{1}{2}}$	977

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?

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

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

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

$$15\ g = (20\ g)e^{-\left(1.21\times10^{-4}\frac{}{yr}\right)t}$$

$$0.75 = e^{-(1.21\times10^{-4}\ \backslash\mathrm{yr})t}$$

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

$$t = 2378\ yrs$$

13-02 Radiometric Dating

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

Amount remaining = 100% − 20% = 80%

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

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

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

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

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

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

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

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

13-02 Practice Work

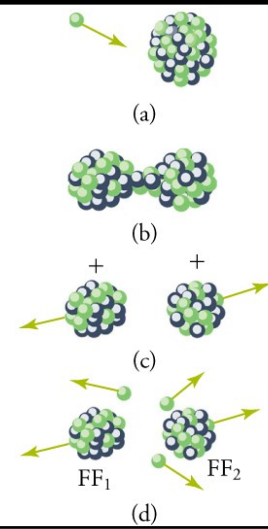
- Talking about radioactivity is a sure way to get a date.

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

OpenStax High School Physics 22.4
OpenStax College Physics 2e 32.6

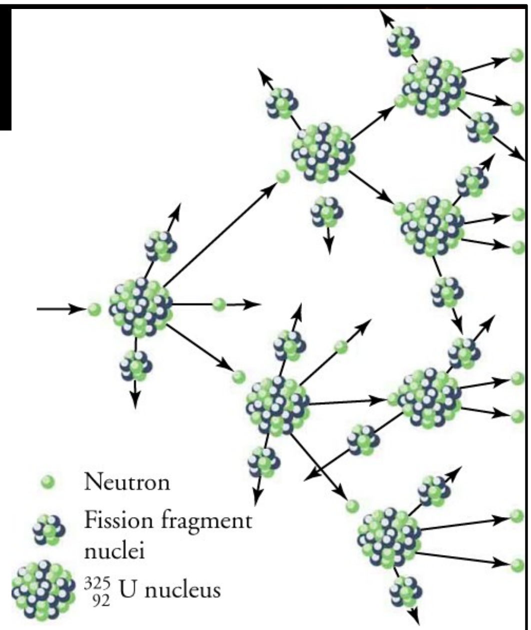
13-03 Nuclear Fission

- 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



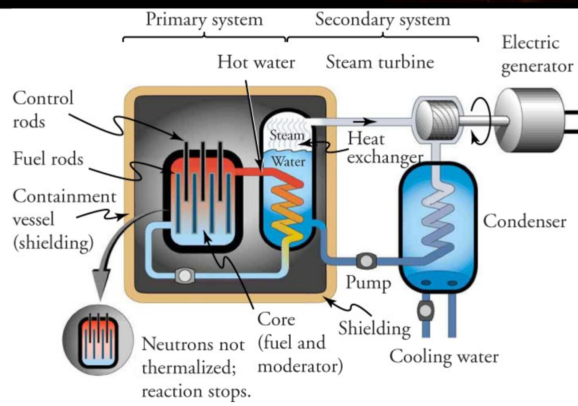
13-03 Nuclear Fission

- 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
  - ${}^{235}\mathrm{U}$: 235.0439299 u
  - ${}^{141}\mathrm{Ba}$: 140.9144035 u
  - ${}^{92}\mathrm{Kr}$: 91.926173094 u

Find change in mass:

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

Covert the mass into energy

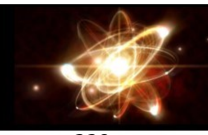
$$0.186023306\,u\left(\frac{931.5\,\frac{\mathrm{MeV}}{\mathrm{c}^2}}{1\ \mathrm{u}}\right) = 173.28\,\frac{\mathrm{MeV}}{\mathrm{c}^2}$$

$$E = mc^2$$

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

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.

$$\left(\frac{1000\ g}{239.05\,\frac{\text{g}}{\text{mol}}}\right)\left(\frac{6.022\times10^{23}\text{ atoms}}{1\text{ mol}}\right) = 2.519\times10^{24}\text{ atoms of }^{239}\text{Pu}$$

Find the energy

$$(2.519\times10^{24}\ atoms)\left(211.5\,\frac{MeV}{atom}\right)\left(\frac{1\times10^{6}\ eV}{1\ MeV}\right)\left(\frac{1.60\times10^{-19}\ J}{1\ eV}\right)$$

$$= 8.525\times10^{13}\ J$$

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

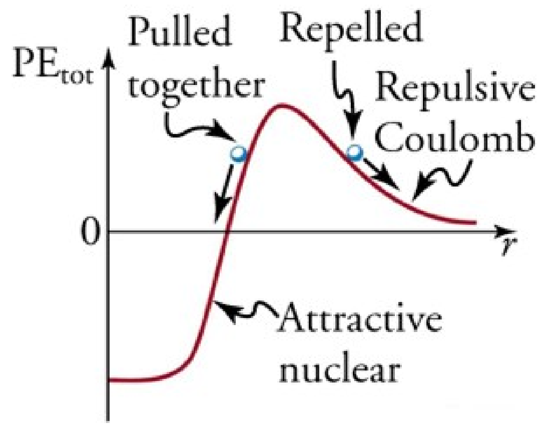
OpenStax High School Physics 22.4
OpenStax College Physics 2e 32.5

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

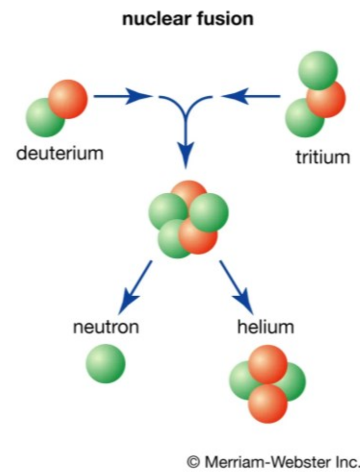
- Why fusion is difficult
  - The parent products must have enough kinetic energy to overcome the electrical force forcing the positive protons apart
    - Use high temp to make the KE
  - Once the parent elements are close enough the strong nuclear force does work pulling the pieces together into one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



13-04 Nuclear Fusion

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

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

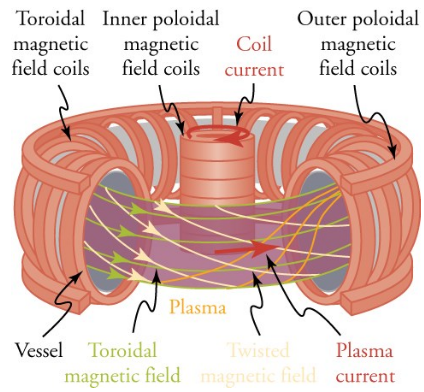


e^+ is positron
ν_e is a electron neutrino

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

13-04 Nuclear Fusion

- 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.