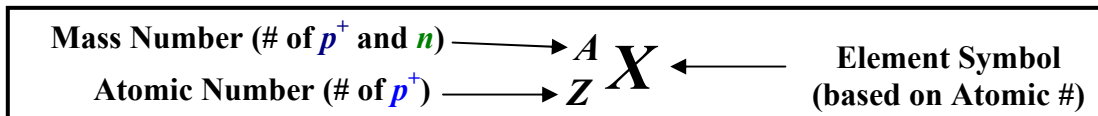


Chapter 23: Nuclear Chemistry23.1: The Nature of Nuclear Reactions

**Nucleons:** - the particles that make up a nucleus of an atom (**protons**, ( ${}^1_1p^+$  or  ${}^1_1H$ ) and **neutrons**, ( ${}^1_0n$ )).

**Isotopes:** - atoms that have different mass number but the same atomic number or number of protons.

**Nuclide:** a particular atom or isotope containing specific numbers of protons and neutrons



**Radioactivity:** - the particles and/or electromagnetic radiation that are emitted due to unstable nuclei.  
- all elements having atomic number 84 (Polonium) and greater are radioactive.

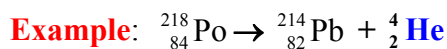
**Nuclear Transmutation:** - a process where radioactivity is resulted from the bombardment of nuclei by neutrons, protons or other nuclei.  
- in most cases, heavier elements are synthesized from lighter elements.

History of Radioactivity

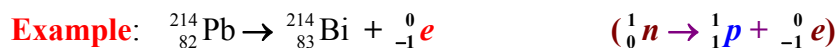
- In 1896, **Wilhelm Roentgen** discovered X-ray by examining ray emitting from the outside of the cathode ray glass tube. It has the capability of passing through solid materials, but can be blocked by denser matters. It can also be exposed to photographic plate, resulting from an image of “seeing through” an container made of less dense material.
- In the same year, **Antoine Becquerel** discovered that uranium emits a ray onto a photographic plate in the absence of sunlight or other forms of energy.
- A few years later, **Marie and Pierre Curie** demonstrated that radiation can be emitted by other elements. They discovered two new elements (polonium and radium) based on their tendency to emit radiation (**radioactivity**).

Types of Radioactive Particle and Decay

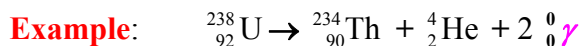
1. **Alpha Particle ( $\alpha$  particle):** - basically a helium nucleus ( ${}^4_2He$ ), commonly found during radioactive decay from heavier nuclide (the net result is to **increase the neutron to proton ratio** – more explanation in the next section).



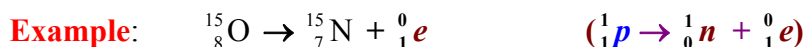
2. **Beta Particle ( $\beta$  particle):** - basically an electron ( ${}^0_{-1}e$  or  ${}^0_{-1}\beta$ ) that is emitted when the neutron to proton ratio is higher than the zone of stability (**a neutron is transformed to a proton and an electron as a result** – more explanation in the next section).  
- electrons have a mass number of 0 and an atomic number assignment of -1, due to its charge.



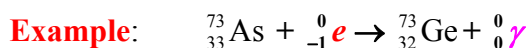
3. **Gamma Ray ( $\gamma$  ray)**: - also known as a high-energy photon ( ${}^0_0\gamma$ ) that is usually a by-product of an alpha-particle decay.  
- photon has no mass and no atomic number.



4. **Positron ( $e^+$ )**: - an antimatter of electron ( ${}^0_1e$  or  ${}^0_1\beta$ ) that is emitted when the neutron to proton ratio is lower than the zone of stability (**a proton is transformed to a neutron** as a result - more explanation in the next section).  
- positrons have a mass number of 0 and an atomic number of 1, due to its charge.  
- when a positron and an electron collide, they **annihilate** themselves to produce energy (**matter-antimatter reaction**).



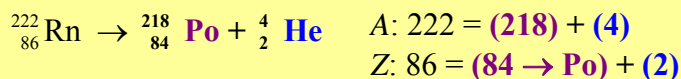
5. **Electron Capture**: - an inner-orbital electron is “captured” by the nucleus to **increase neutron to proton ratio**. It is usually accompanied by an emission of gamma ray.



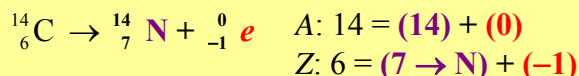
**Balancing Nuclear Equations:** - the total atomic number (Z) and the total atomic mass (A) have to balance on both sides.

**Example 1:** Balance the following nuclear equations.

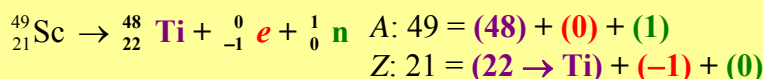
- a.  ${}^{222}_{86}\text{Rn}$  produces an  $\alpha$  particle.



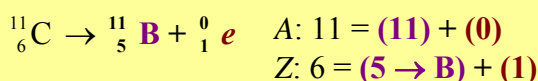
- b.  ${}^{14}_6\text{C}$  produces a  $\beta$  particle.



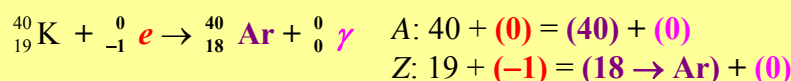
- c.  ${}^{49}_{21}\text{Sc}$  produces a  $\beta$  particle and a neutron.



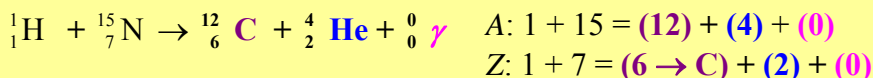
- d.  ${}^{11}_6\text{C}$  produces a positron.



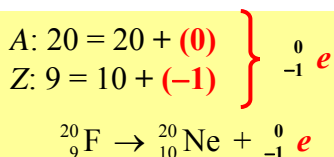
- e.  ${}^{40}_{19}\text{K}$  captures an electron to produce  $\gamma$  ray



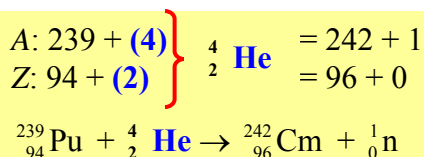
- f.  ${}^1_1\text{H}$  reacts with  ${}^{15}_7\text{N}$  to produce an  $\alpha$  particle with  $\gamma$  ray.



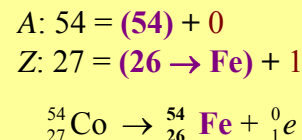
- g.  ${}^{20}_9\text{F} \rightarrow {}^{20}_{10}\text{Ne} + \underline{\hspace{2cm}}$



- h.  ${}^{239}_{94}\text{Pu} + \underline{\hspace{2cm}} \rightarrow {}^{242}_{96}\text{Cm} + {}^1_0n$



- i.  ${}^{54}_{27}\text{Co} \rightarrow \underline{\hspace{2cm}} + {}^0_1e$

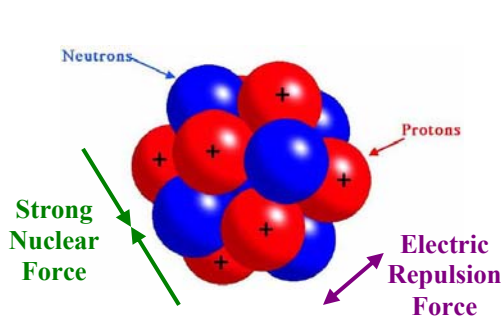


## 23.2: Nuclear Stability

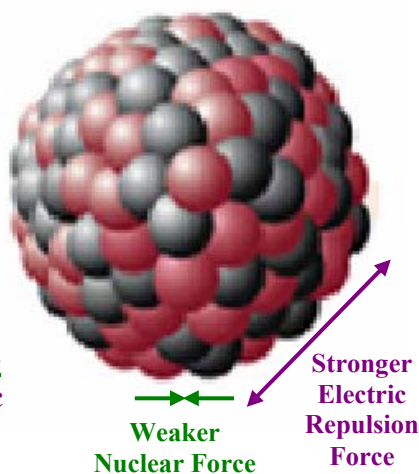
**Strong Nuclear Force:** - a force of attraction that is present over extremely short distance ( $1 \times 10^{-15}$  m) between all nucleons (protons and neutrons).  
 - it is much stronger than electromagnetic force in short distances. However, electromagnetic force is more significant over longer distances.

### Properties of Neutrons:

1. **Neutrons** serve as “*nuclear cement*”, gluing neighbouring protons together despite the electric repulsion of positive charges, but only **over short distances**.
2. At large distances, strong nuclear force become less significant. Hence, **the MORE Protons in the nucleus (Heavier Atoms), the MORE Neutrons are needed to hold them together**. Sometimes this means for every 1 proton, there are 1.5 times to twice as many neutrons.
3. **SMALLER Atomic Nuclei usually have the SAME Number of Protons as Neutrons.**
4. **A Single Neutron** is rather **UNSTABLE**. It will **CONVERT** itself to a **Proton and an Electron**.



**For Small Nucleus, Strong Nuclear Force is MORE significant compared to electric repulsive force between protons due to small distances between nucleons.**



**For Large Nucleus, Electric Repulsive Force between Protons is MORE significant compared to strong nuclear force because of the large distances between nucleons. Hence, they are inherently unstable and likely undergo alpha decay (see below).**

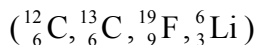
**Radioactive Decay:** - when a heavier nucleus loses nucleons to become a smaller but more stable nucleus. In the process, it gives off radiation products like alpha-, beta- particles and/or gamma rays.

**Zone of Stability:** - a graph that depicts the relationship between the number of neutrons versus the number of protons, and the area where there are stable nuclides.

**Common Observations of Radioactive Decay**

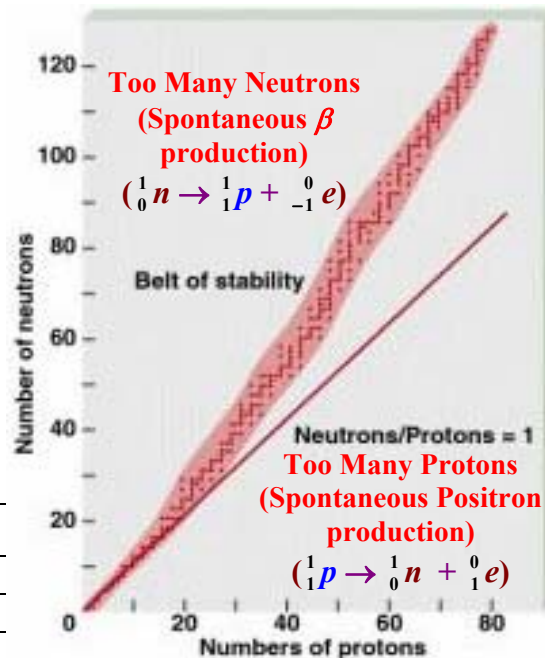
1. When a nuclide has **84 or more protons** ( $Z \geq 84$ ), it tends to be **unstable** and likely undergo **radioactive decay**.
2. **Lighter nuclides are stable when  $Z = n$**  (or  $n : p^+$  ratio = 1). However, **heavier nuclides are stable only when  $Z < n$**  (or  $n : p^+$  ratio  $> 1$ ).
3. Nuclides with **even # of  $p^+$  with even # of  $n$**  are **more stable** than nuclides with **odd # of  $p^+$  and odd # of  $n$** .

**Example:** Most Stable to Least Stable Nuclides



Nuclide	${}^{12}_6\text{C}$	${}^{13}_6\text{C}$	${}^{19}_9\text{F}$	${}^6_3\text{Li}$
# of $p^+$	6 (even)	6 (even)	9 (odd)	3 (odd)
# of $n$	6 (even)	7 (odd)	10 (even)	3 (odd)

**Stability:** Most  $\longrightarrow$  Least



4. **Magic Numbers of protons or neutrons (2, 8, 20, 28, 50, 82 and 126) results in very stable nuclides.**

**Thermodynamic Stability:** - amount of potential energy inside a nucleus versus total potential energy of all nucleons.  
 - the difference in energy can be calculated using Einstein's equation ( $\Delta E = \Delta mc^2$ ), where  $\Delta m$  is referred to as mass defect.

**Mass Defect ( $\Delta m$ ):** - the change in masses during a nuclear transformation. ( $\Delta m = m_{\text{products}} - m_{\text{reactants}}$ )  
 - sometimes masses for subatomic particles is measured in amu (atomic mass unit)  
 (1 kg =  $6.022 \times 10^{26}$  amu , or 1 g =  $6.022 \times 10^{23}$  amu = 1 mole amu).

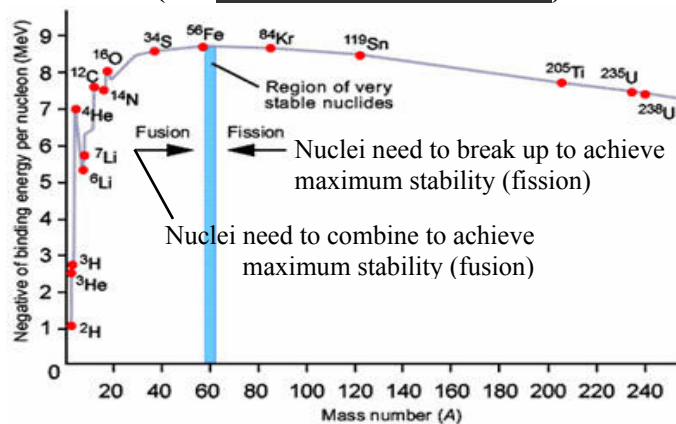
Subatomic Particle	Mass (kg)	Atomic Mass Unit (amu)
Neutron	$1.67497 \times 10^{-27}$	1.008665
Proton	$1.67357 \times 10^{-27}$	1.007825

**Binding Energy ( $\Delta E_{\text{bind}}$ ):** - the amount of energy released during a nuclear transformation because of a mass defect. It is used to bind the nucleons in the reactant nuclide.  
 - we often convert the unit to **electron volt** (1 eV =  $1.69 \times 10^{-19}$  J or 1 MeV =  $1.69 \times 10^{-13}$  J).  
 - **higher the  $\Delta E_{\text{bind}}$  per nucleon means more mass is turned into pure energy to bind the nucleons together.** Hence, bigger  $\Delta E_{\text{bind}}$  means more stable nuclei (the **most stable nuclei is  ${}^{26}\text{Fe}$** ).

**Einstein's Mass-Energy Conversion**

$$\Delta E_{\text{bind}} = -\Delta mc^2$$

$\Delta E_{\text{bind}}$  = Binding Energy  
 $\Delta m$  = mass defect (kg)  
 $c$  = speed of light ( $3.00 \times 10^8$  m/s)



**Example 1:** Calculate the binding energy for carbon-13 (13.003355 amu) in J/nucleon and MeV/nucleon.

$$m \text{ of } {}^{13}_6\text{C} = 13.003355 \text{ amu}$$

$$m \text{ of } (6p^+ \text{ and } 7n) = 6(1.007825 \text{ amu}) + 7(1.008665 \text{ amu}) = 13.107605 \text{ amu}$$

$$\Delta m = m \text{ of } {}^{13}_6\text{C} - m \text{ of } (6p^+ \text{ and } 7n) = 13.003355 \text{ amu} - 13.107605 \text{ amu} \quad \Delta m = -0.104250 \text{ amu}$$

$$\Delta E = -\Delta mc^2 = -(-0.104250 \text{ amu}) \left( \frac{1 \text{ kg}}{6.022 \times 10^{26} \text{ amu}} \right) (3.00 \times 10^8 \text{ m/s})^2 = 1.5580372 \times 10^{-11} \text{ J}$$

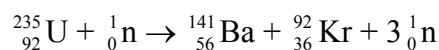
$$\Delta E_{\text{bind per nucleon}} = \frac{1.5580372 \times 10^{-11} \text{ J}}{13 \text{ nucleons}}$$

$$\Delta E_{\text{bind}} = 1.20 \times 10^{-12} \text{ J/nucleon}$$

$$\Delta E_{\text{bind}} = 1.20 \times 10^{-12} \text{ J/nucleon} \times \frac{1 \text{ MeV}}{1.69 \times 10^{-13} \text{ J}}$$

$$\Delta E_{\text{bind}} = 7.09 \text{ MeV/nucleon}$$

**Example 2:** Calculate the energy released per mole of  ${}^{235}_{92}\text{U}$  reacted when it undergoes nuclear fission:



$$({}^{235}_{92}\text{U} = 235.0439 \text{ amu}; {}^{141}_{56}\text{Ba} = 140.9144 \text{ amu}; {}^{92}_{36}\text{Kr} = 91.9262 \text{ amu})$$

$$m_{\text{initial}} \text{ of } {}^{235}_{92}\text{U} + {}^1_0\text{n} = 235.0439 \text{ amu} + 1.00899 \text{ amu} = 236.05289 \text{ amu}$$

$$m_{\text{final}} \text{ of } {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3 {}^1_0\text{n} = 140.9144 \text{ amu} + 91.9262 \text{ amu} + 3(1.00899 \text{ amu}) = 235.86757 \text{ amu}$$

$$\Delta m = m_{\text{final}} - m_{\text{initial}} = 235.86757 \text{ amu} - 236.05289 \text{ amu} \quad \Delta m = -0.18532 \text{ amu}$$

$$\Delta E = -\Delta mc^2 = -(-0.18532 \text{ amu}) \left( \frac{1 \text{ kg}}{6.022 \times 10^{26} \text{ amu}} \right) (3.00 \times 10^8 \text{ m/s})^2 = 2.76964464 \times 10^{-11} \text{ J/nucleus}$$

$$\Delta E_{\text{bind}} = 2.76964464 \times 10^{-11} \text{ J/nucleus} \times (6.022 \times 10^{23} \text{ nucleus/mol}) = 1.66788 \times 10^{13} \text{ J/mol}$$

$$\Delta E_{\text{bind}} = 1.67 \times 10^{10} \text{ kJ/mol} = 16.7 \text{ TJ/mol}$$

$$1 \text{ TJ (Tera-Joules)} = 1 \times 10^{12} \text{ J}$$

### Assignment

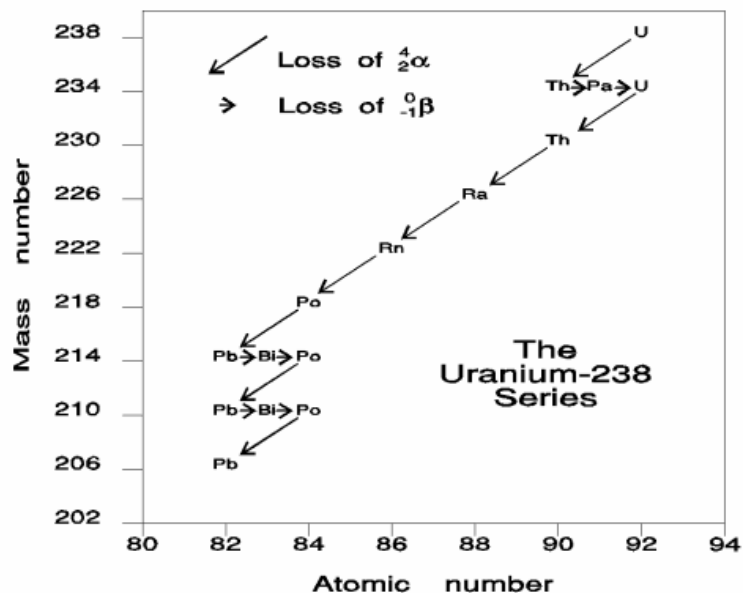
23.1 pg. 994–995 #1 to 6, pg. 996 #55

23.2 pg. 995 #7, 8, 11, 12, 14, 16, 18 to 20; pg. 998 #80

### 21.3: Natural Radioactivity

**Decay Series:** - a succession of decays from a particular radioactive nuclide until the formation of a stable nuclide.

**Rate of Decay:** - the rate at which a given radioactive nuclide decays over time.  
- the negative of the change in the number of nuclides per unit of time (measured in reciprocal time unit).



**Kinetic Stability:** - sometimes called **radioactive decay** (a process where a nucleus decomposes into a different nucleus to achieve more stability).

**Non-Calculus Explanation:**

$N = N_0 e^{-kt}$  (Continuous Exp Decay)

$\frac{N}{N_0} = e^{-kt}$  (Solving for  $-kt$ )

$\ln\left(\frac{N}{N_0}\right) = \ln(e^{-kt})$  (Natural log both sides)

$\ln\left(\frac{N}{N_0}\right) = -kt \ln e$  ( $\ln e = 1$ )

**Derivation Using Calculus:**

$Rate = -\frac{\Delta N}{\Delta t} = kN$

$\frac{1}{N} \Delta N = -k \Delta t$

$\int_{N_0}^N \frac{1}{N} dN = -k \int_0^t dt$

$\ln N - \ln N_0 = -kt$

( $k =$  Rate Constant,  
 $N =$  Amount of Nuclide)  
(Rearrange for Integration,  
 $\Delta N = dN$ ;  $\Delta t = dt$ )

(Integrate Both Sides:  $\int \frac{1}{x} dx = \ln x$ )

(Use Logarithm Law:  
 $\log A - \log B = \log\left(\frac{A}{B}\right)$ )

$\ln\left(\frac{N}{N_0}\right) = -kt$  (Radioactive Decay Equation)

**Half-Life ( $t_{1/2}$ ):** - the amount of time it takes to half the amount of radioactive nuclides.

- at **half-life,  $t_{1/2}$** , the amount of radioactive nuclides  $\frac{1}{2} N_0 = N$ :

$\ln\left(\frac{N}{N_0}\right) = -kt \Rightarrow \ln\left(\frac{\frac{1}{2} N_0}{N_0}\right) = -kt_{1/2} \Rightarrow \ln\left(\frac{1}{2}\right) = -kt_{1/2} \Rightarrow \ln(2) = kt_{1/2}$

$t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k}$

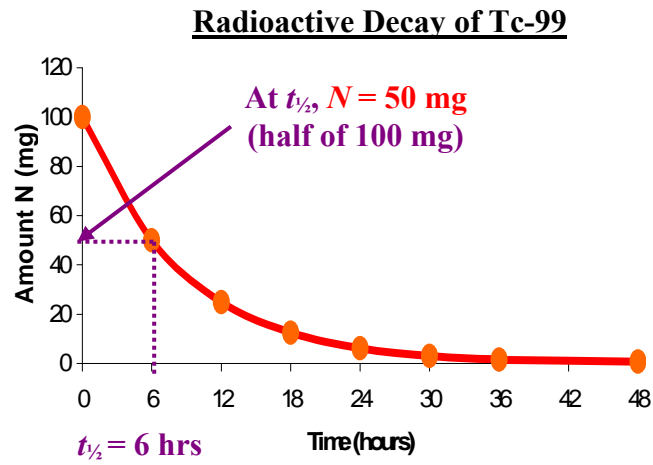
**Radioactive Decay Equations**

$\ln\left(\frac{N}{N_0}\right) = -kt$        $t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k}$        $N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$

$N =$  Amount of Nuclide at time  $t$        $N_0 =$  Amount of Nuclide at time 0  
 $k =$  Rate Constant ( $s^{-1}$ ,  $min^{-1}$ ,  $hr^{-1}$ ,  $day^{-1}$ ,  $yr^{-1}$ )       $t =$  total decay time       $t_{1/2} =$  half-life

**Example 1:** Technetium-99, the first synthetic element in the Table, is used as a radiotracer for many organs such as heart, liver and lungs. It has a half-life of 6.0 hours. Draw a graph showing how 100 mg of  $^{99}_{43}Tc$  decays over time. What is the radioactive amount of  $^{99}_{43}Tc$  after 2.00 days?

<p><math>N_0 = 100</math> mg  <math>t_{1/2} = 6.0</math> hrs  <math>t = 2.00</math> days = 48.0 hrs  <math>N = ?</math></p> <p><math>N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}</math></p> <p><math>N = (100 \text{ mg}) \left(\frac{1}{2}\right)^{\frac{48.0 \text{ hrs}}{6.0 \text{ hrs}}}</math></p> <p style="text-align: center; border: 1px solid red; border-radius: 50%; padding: 5px;"><math>N = 0.391</math> mg</p>	<p><math>t_{1/2} = \frac{\ln 2}{k}</math></p> <p><math>k = \frac{\ln 2}{t_{1/2}} \quad k = \frac{\ln 2}{6 \text{ hr}}</math></p> <p><math>\ln\left(\frac{N}{N_0}\right) = -kt \quad \frac{N}{N_0} = e^{-kt}</math></p> <p><math>N = N_0 e^{-kt}</math></p> <p><math>N = (100 \text{ mg}) e^{-\frac{\ln 2}{6 \text{ hr}}(48.0 \text{ hr})}</math></p> <p style="text-align: center; border: 1px solid red; border-radius: 50%; padding: 5px;"><math>N = 0.391</math> mg</p>
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**Example 2:**  $^{131}_{53}\text{I}$  is a radiotracer used to detect thyroid activity. The half-life of  $^{131}_{53}\text{I}$  is 8.1 days.

- Determine the rate constant of  $^{131}_{53}\text{I}$ .
- How long will it take a patient to have her initial dosage of  $^{131}_{53}\text{I}$  to decrease to 1.00 % of its initial value?

$$t_{1/2} = 8.1 \text{ days}$$

$$\frac{N}{N_0} = 0.01$$

$$k = ?$$

$$t = ?$$

$$\text{a. } t_{1/2} = \frac{\ln 2}{k} \quad k = \frac{\ln 2}{t_{1/2}}$$

$$k = \frac{\ln 2}{8.1 \text{ days}} \quad k = 0.086 \text{ day}^{-1}$$

$$\text{b. } \ln\left(\frac{N}{N_0}\right) = -kt$$

$$t = \frac{\ln\left(\frac{N}{N_0}\right)}{-k} = \frac{\ln(0.01)}{-\left(\frac{\ln 2}{8.1 \text{ days}}\right)} = 53.815 \text{ days}$$

$$t = 54 \text{ days}$$

$$N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} \rightarrow \frac{N}{N_0} = \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

$$\log\left(\frac{N}{N_0}\right) = \frac{t}{t_{1/2}} \log\left(\frac{1}{2}\right)$$

$$\frac{t_{1/2} \log\left(\frac{N}{N_0}\right)}{\log\left(\frac{1}{2}\right)} = t$$

$$t = \frac{(8.1 \text{ days}) \log(0.01)}{\log(0.5)} = 53.815 \text{ days}$$

$$t = 54 \text{ days}$$

**Example 3:**  $^{222}_{86}\text{Rn}$  is a natural alpha particle producer. Due to its noble gas characteristic, it can cause damage to tissues as it can be easily inhaled into the body.  $^{222}_{86}\text{Rn}$  can be found quite easily in uranium mine because it is a decay product of  $^{238}_{92}\text{U}$ . In an analysis 50.0 mg  $^{222}_{86}\text{Rn}$  decayed to 45.7 mg in 24.0 hours. Determine the half-life of  $^{222}_{86}\text{Rn}$  and its rate constant.

$$N_0 = 50.0 \text{ mg}$$

$$N = 45.7 \text{ mg}$$

$$t = 24.0 \text{ hrs}$$

$$t_{1/2} = ?$$

$$k = ?$$

**Solving  $k$  first:**

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

$$k = \frac{\ln\left(\frac{N}{N_0}\right)}{-t} = \frac{\ln\left(\frac{45.7 \text{ mg}}{50.0 \text{ mg}}\right)}{-24.0 \text{ hrs}}$$

$$k = 0.00375 \text{ hr}^{-1}$$

**Then, solve for  $t_{1/2}$ :**

$$t_{1/2} = \frac{\ln 2}{k} = \frac{\ln 2}{0.0037468628 \text{ hr}^{-1}}$$

$$t_{1/2} = 185 \text{ hours} = 7.71 \text{ days}$$

**Solving  $t_{1/2}$  first:**

$$N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} \rightarrow \frac{N}{N_0} = \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

$$\log\left(\frac{N}{N_0}\right) = \frac{t}{t_{1/2}} \log\left(\frac{1}{2}\right)$$

$$t_{1/2} = \frac{t \log\left(\frac{1}{2}\right)}{\log\left(\frac{N}{N_0}\right)} = \frac{(24.0 \text{ hrs}) \log(0.5)}{\log\left(\frac{45.7 \text{ mg}}{50.0 \text{ mg}}\right)}$$

$$t_{1/2} = 185 \text{ hours} = 7.71 \text{ days}$$

**Then solve for  $k$ :**

$$t_{1/2} = \frac{\ln 2}{k} \quad k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{185 \text{ hrs}}$$

$$k = 0.00375 \text{ hr}^{-1}$$

**Radiocarbon Dating:** - sometimes called **carbon-14 dating**.  $^{14}_6\text{C}$  can be found naturally in organic material and the atmosphere. It decays as soon as the organism dies ( $^{14}_6\text{C} \rightarrow ^0_{-1}\text{e} + ^{14}_7\text{N}$ ).  
 - uses the known ratio of  $^{14}_6\text{C}/^{12}_6\text{C}$  of similar organic sample of the day with the ratio in the artefact and the half-life of  $^{14}_6\text{C}$  being 5730 years to determine the age of the artefact.

**Example 4:** An ancient wooden artefact found in China has a  $^{14}_6\text{C}$  decay rate of 5.2 counts per minute per gram of carbon. A comparison to a freshly cut piece of wood has a count of 13.6 counts per minute per gram of carbon. Given the rate of carbon-14 decay is 5730 years, determine the age of this artefact.

$$\frac{\text{Final Rate at } t}{\text{Initial Rate at } t=0} = \frac{kN}{kN_0} = \frac{5.2 \text{ counts}/(\text{min} \cdot \text{g})}{13.6 \text{ counts}/(\text{min} \cdot \text{g})} \quad t_{1/2} = 5730 \text{ yrs} \quad t = ?$$

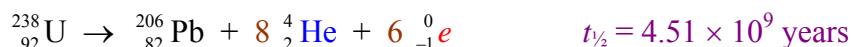
First, we solve for  $k$ .

$$t_{1/2} = \frac{\ln 2}{k} \rightarrow k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{5730 \text{ yrs}} \quad k = 1.209680943 \times 10^{-4} \text{ yr}^{-1}$$

Next, we solve for  $t$ .

$$\ln\left(\frac{N}{N_0}\right) = -kt \rightarrow t = \frac{\ln\left(\frac{N}{N_0}\right)}{-k} = \frac{\ln\left(\frac{5.2}{13.6}\right)}{-\left(\frac{\ln 2}{5730 \text{ yrs}}\right)} = 7947.642495 \text{ yrs} \quad t = 7948 \text{ years}$$

**Uranium-238 Dating:** - due to its lengthy half-life ( $4.5 \times 10^9$  years), it is used to date rocks and other ancient inorganic material.  $^{238}_{92}\text{U}/^{206}_{82}\text{Pb}$  ratio is used as  $^{238}_{92}\text{U}$  eventually decays to stable  $^{206}_{82}\text{Pb}$ .



**Example 5:** A piece of ore containing  $^{238}_{92}\text{U}$  and  $^{206}_{82}\text{Pb}$  was found. The ratio between  $^{206}_{82}\text{Pb}$  to  $^{238}_{92}\text{U}$  is 0.432. Suppose that no  $^{206}_{82}\text{Pb}$  was originally present. Determine the age of the ore given that the half-life of  $^{238}_{92}\text{U}$  is  $4.5 \times 10^9$  years.

$$\frac{N \text{ of } ^{206}_{82}\text{Pb at } t}{N \text{ of } ^{238}_{92}\text{U at } t} = 0.432 = \frac{432}{1000} \Rightarrow \frac{N}{N_0} = \frac{N \text{ of } ^{238}_{92}\text{U still present}}{N \text{ of } ^{238}_{92}\text{U before}} = \frac{^{238}_{92}\text{U now}}{^{238}_{92}\text{U} + ^{206}_{82}\text{Pb}} = \frac{1000}{1000 + 432} = \frac{1000}{1432}$$

$$t_{1/2} = 4.5 \times 10^9 \text{ yrs} \quad t = ?$$

First, we solve for  $k$ .

$$t_{1/2} = \frac{\ln 2}{k} \rightarrow k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{4.5 \times 10^9 \text{ yrs}} \quad k = 1.54032707 \times 10^{-10} \text{ yr}^{-1}$$

Next, we solve for  $t$ .

$$\ln\left(\frac{N}{N_0}\right) = -kt \rightarrow t = \frac{\ln\left(\frac{N}{N_0}\right)}{-k} = \frac{\ln\left(\frac{1000}{1432}\right)}{-\left(\frac{\ln 2}{4.5 \times 10^9 \text{ yrs}}\right)} = 2,331,141,717 \text{ yrs} \quad t = 2.3 \text{ billion years}$$

**Potassium-40 Dating:** - used mainly in geochemistry to determine the age a metal ores. Its main mode of decay via electron capture  $^{40}_{19}\text{K}$  turns it into  $^{40}_{18}\text{Ar}$  with a half-life of  $1.2 \times 10^9$  years. Using a mass spectrometer, we can easily measure the amount of  $^{40}_{18}\text{Ar}$  trapped inside the lattice mineral. By calculating the  $^{40}_{18}\text{Ar} / ^{40}_{19}\text{K}$ , we can determine the age of a metal ore.



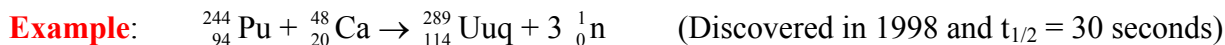
### Assignment

23.3 pg. 995 #21, 23 to 26, 28, 29; pg. 997–998 #66 to 68, 85

**23.4: Nuclear Transmutation**

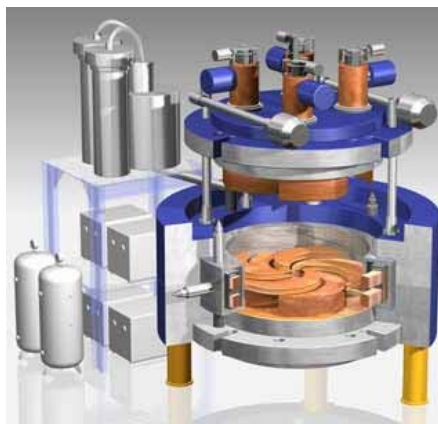
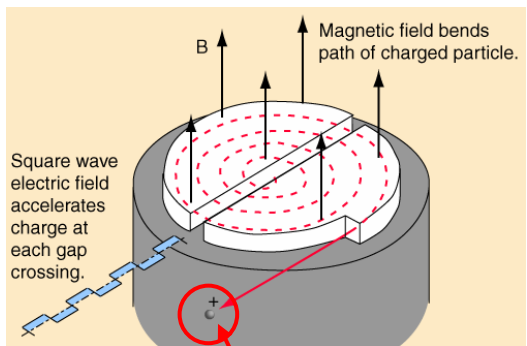
**Nuclear Transmutation:** - the reaction where one element is converted to another element by changing the number of protons.

**Transuranium Elements:** - elements that have been synthesized by nuclear transformation after the last natural element, uranium.



**Particle Accelerator:** - a device that alternates electric field to speed up a particle to add into a target nuclide.

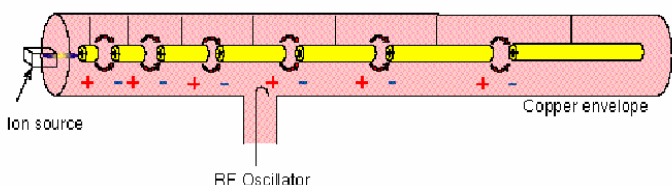
**a. Cyclotron:** - a type of particle accelerator that utilizes a changing electric field along with a magnetic field to increase the speed of an ion around a disc before hitting a target nuclide.



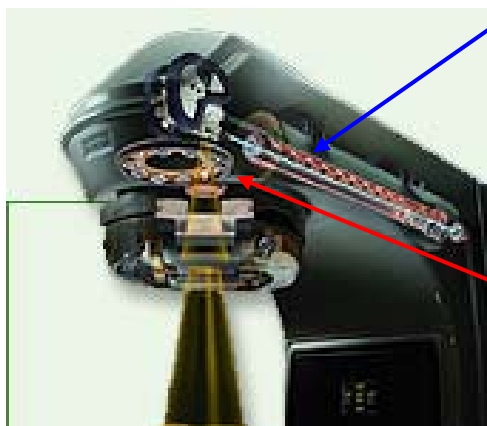
**COMET:** A medical superconducting cyclotron. It is used to generate thallium-201 (coronary arteries) and gallium-67 (soft-tissue tumors). It can also produce radio-pharmaceutical needed for PET and SPECT scans

Schematic of Accelerated charged particle a Cyclotron to collide with target nuclide

**b. Linear Accelerator:** - a particle accelerator that speeds up a particle by using an alternating electric field at different segment of a linear tube to add an ion into a target nuclide.



Left: Schematic of a Linear Accelerator  
Right: Stanford Linear Accelerator

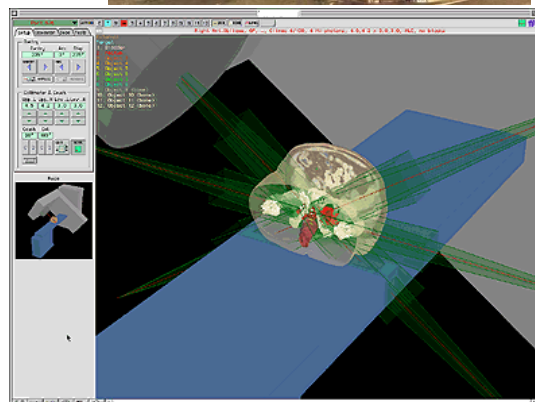


Linear Accelerator

Multileaf Collimeter to shape the beam

Schematic of a Medical Linear Accelerator

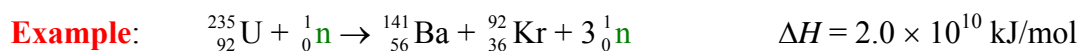
Computer Program is used to control radiotherapy treatment by a medical linear accelerator



**Assignment**  
**23.4 pg. 996 #33 to 36**

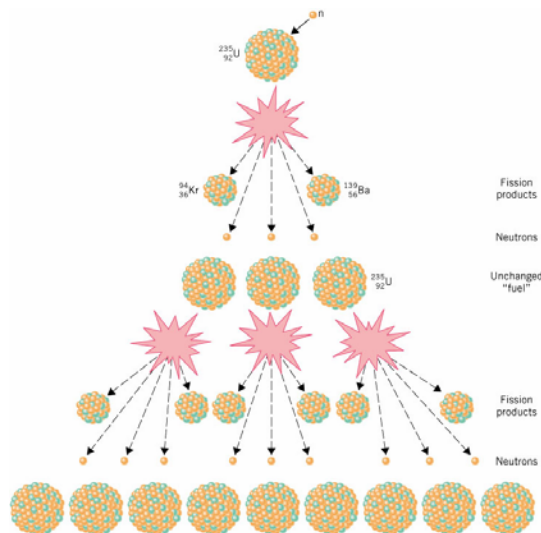
**23.5: Nuclear Fission**

**Nuclear Fission:** - the breaking up of a heavier nucleus into two nuclei with small mass number.



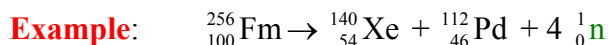
**Chain Reaction:** - when the nuclear fission is self-sustaining.

- Subcritical:** - when there is on average, less than one neutron produced per  ${}_{92}^{235}\text{U}$  is consumed. The fission will eventually stop.
- Critical:** - when there is on average, exactly one neutron produced per  ${}_{92}^{235}\text{U}$  consumed. The fission can then be self-sustaining at the same level.
- Supercritical:** - when there is one average, more than one neutron produced per  ${}_{92}^{235}\text{U}$  is consumed. The fission can increase its rate rapidly and a violent explosion can result.



**Critical Mass:** - the minimum mass of fissionable material required for the generation of a self-sustaining nuclear chain reaction.

**Spontaneous Fission:** - when a heavy nuclide splits into two lighter nuclides and sometimes neutrons.

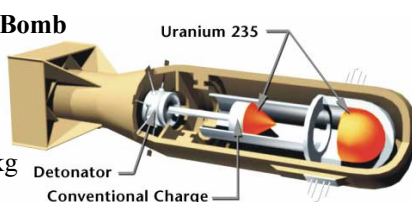


**Atomic Bomb:** - an uncontrolled nuclear fission device that releases large amount of energy.

- in 1939, just before WWII, Einstein and other scientists wrote to President Roosevelt that Nazi Germany was researching ways to purify U-235 for the purpose of an atomic bomb. This led to the US initiation of the “Manhattan Project” (a secret project to develop the atomic bomb by the US).
- the first atomic bomb test was conducted at Jemez Mountains in northern New Mexico on July 16, 1945 at 5:29:45 AM (Mountain War Time). Less than a month later, an atomic bomb (code name: Little Boy) was dropped on Hiroshima, Japan on Aug 6. It had a yield of 15 kilotons of TNT ( $6 \times 10^{10} \text{ kJ} \approx 750 \text{ g of U-235}$ ) and it killed an estimated 80,000 people with 60,000 died later of radiation poisoning. Three days later, another atomic bomb (code name: Fat Man) was dropped on Nagasaki. It had a yield of 21 kilotons of TNT ( $8 \times 10^{10} \text{ kJ} \approx 1 \text{ kg of Pu-239}$ ) and killed 74,000 people with several hundred thousands died from disease due to radiation.
- the “gun-type assembly” design detonation starts with conventional TNT explosion at one end of the device, pushing half the U-235 / Pu-239 subcritical mass into another half of the U-235 / Pu-239 subcritical mass located at the other end of the bomb. When the two masses connect, a supercritical chain reaction takes place and releases a large amount of heat energy. The “implosion” design involves detonate surrounding TNT to ignite a nuclear fission core.

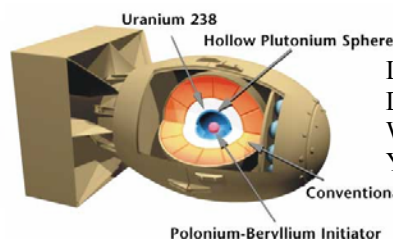
**Uranium “Gun” Atomic Bomb (Little Boy)**

Length: 10 ft / 3 m  
Diameter: 28 in / 71.1 m  
Weight: 9,700 lbs / 4,400 kg  
Yield: 15 kilotons



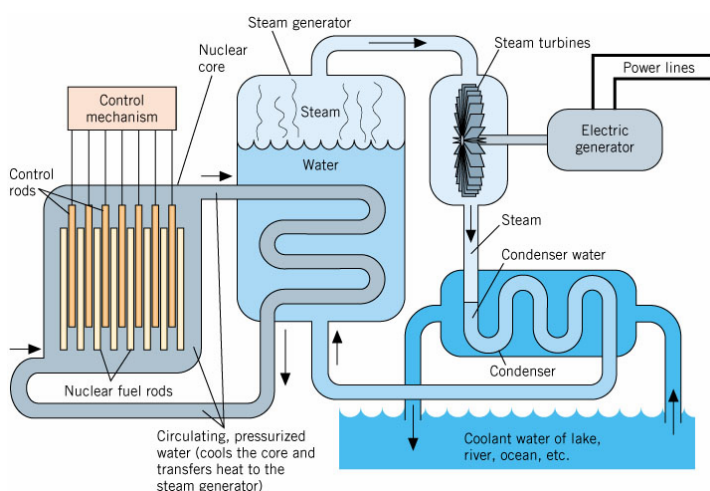
**Plutonium Implosion Atomic Bomb (Fat Man)**

Length: 10.7 ft / 3.25 m  
Diameter: 5 ft / 1.5 m  
Weight: 10,265 lbs / 4,656 kg  
Yield: 21 kilotons



**Nuclear Reactors:** - fission reactors where enriched  $^{235}_{92}\text{U}$  is placed in the **reactor core**. The heat is generated in the reactor is used to heat water. This water also acts as the moderator (a substance that slows down neutrons emitted and reduces their kinetic energy). **Control rods (usually made of carbon, cadmium, or boron to absorb extra neutrons)** can be lifted or lowered to control the rate of the fission process. The super-heated moderator water from the reactor core heats another tank of water, but the moderator water is recycled back into the reactor. As the water in the tank is heated into steam, it turns the steam turbine to generate electricity. This water is then cooled in a cooling tower and recycled (the hot water cannot be discharged into nearby lake or stream to avoid thermal pollution). Since large amount of cold water is needed for the cooling process of steam, most nuclear power plants are built near a large river or lake.

- the by-products of  $^{235}_{92}\text{U}$  fission have a very long half-lives and can remain radioactive for a long time. Great efforts are needed to dispose of the wastes properly. The danger of a nuclear meltdown is also a constant danger as in the cases of Three Mile Island, Pennsylvania in 1979 and Chernobyl, Ukraine in 1986.



Bruce Power Nuclear Plant at Tiverton (Lake Huron), Canada

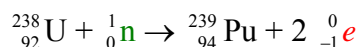
**Light Water Reactor:** - uses light water (regular  $\text{H}_2\text{O}$ ) as moderator.

- all US nuclear reactors are light-water reactors and they use cadmium or boron control rods.  
 - since light water is a good absorber of neutrons, the uranium fuel used has to be enriched (the same initial process is used to make weapon-grade uranium,  $^{235}\text{U}$ ).

**Heavy Water Reactor:** - uses heavy water ( $\text{D}_2\text{O}$  – deuterium water -  $^2_1\text{H}_2\text{O}$ ) as moderator.

-  $\text{D}_2\text{O}$  does not absorb neutrons as well as  $\text{H}_2\text{O}$  (it has a neutron in the hydrogen atom already). Hence, the nuclear reactor is more efficient (more neutrons are left to do more fission collisions). As a result, uranium enrichment is not necessary. This eliminates the potential of a country to develop nuclear weapons.  
 -  $\text{D}_2\text{O}$  can be expensive to produce due to the amount of water needed for operating a nuclear power plant. Currently, Canada is the only country that uses heavy water reactor (CANDU reactor).

**Breeder Reactor:** - due to the limited resources of enriched uranium  $^{235}_{92}\text{U}$ , the excess neutrons in the fission reactor can be used to convert uranium-238 to plutonium-239 to be used as an alternate nuclear fuel.



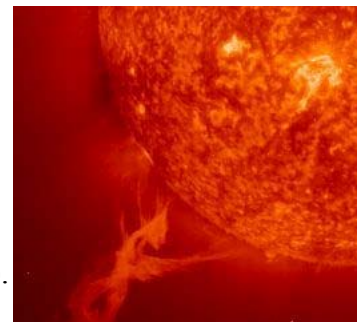
- it is the most expensive type of reactor due to its technical aspects. Currently, only Russia and France have a handful of breeder reactors.

### 23.6: Nuclear Fusion

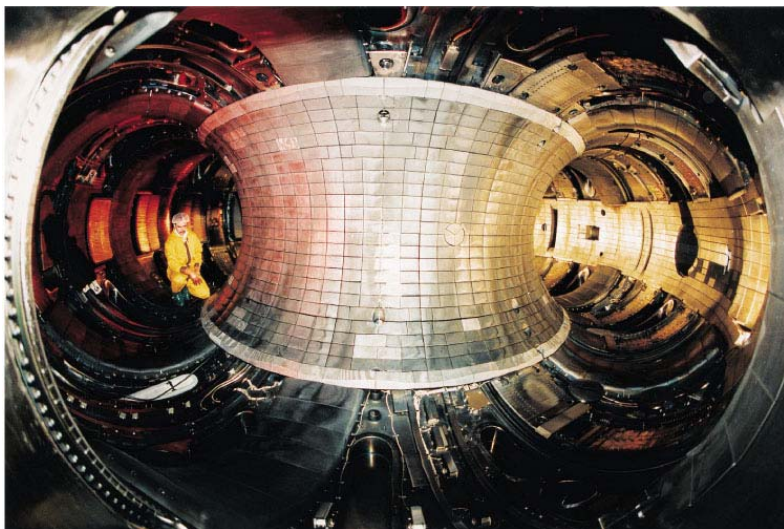
**Nuclear Fusion:** - the combining of two light nuclei into a heavier and more stable nucleus.



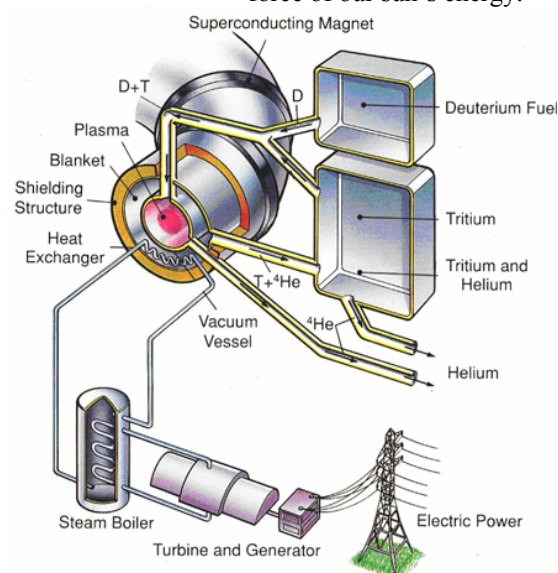
- the availability of hydrogen isotopes, deuterium ( ${}^2_1\text{H}$ ) and tritium ( ${}^3_1\text{H}$ ), in sea water and the harmless product,  ${}^4_2\text{He}$ , makes nuclear fusion an environmental friendly alternative to generate power.
- however, fusion reactions such as the one above usually require an initial temperature above  $4 \times 10^7 \text{ K}$  to overcome the strong electrostatic repulsion between the two protons (the release of significant binding energy can only achieve when the distance between the two protons is approximately  $10^{-15} \text{ m}$ ). High-powered laser and heating by electric currents are being studied as methods to attain this high temperature to initial a control fusion reaction.



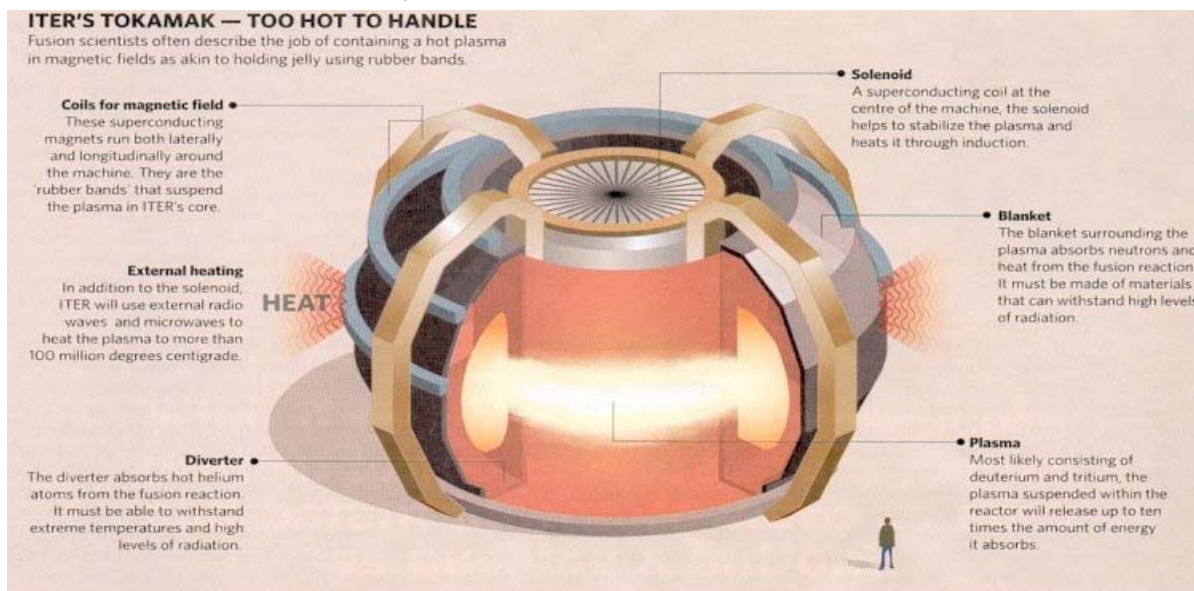
Fusion reaction is the driving force of our sun's energy.



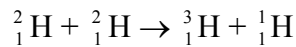
European Tokamak Fusion Test Reactor Vacuum Vessel employs the design of a toroid with a super strength magnetic field to contain plasma without having it touch the wall of the reactor. A similar experimental fusion reactor can also be found at Princeton, USA.



Propose Schematic of a Fusion Reactor to Generate Electricity

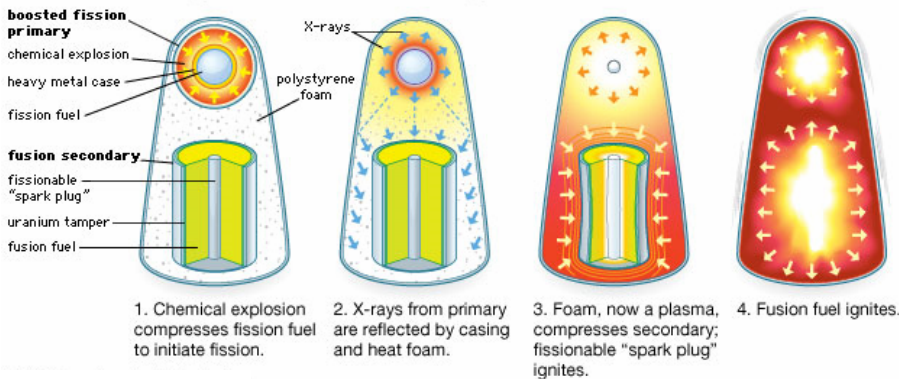


**Hydrogen Bomb:** - also called a thermonuclear bomb that uses fusion reaction to destroy a large target area.  
 - the device contains solid lithium deuteride ( $\text{LiD}$  or  $\text{Li}_2\text{H}$ ) which can be packed tightly. The detonations involve a fission reaction to generate the initial heat to start the fusion reaction.



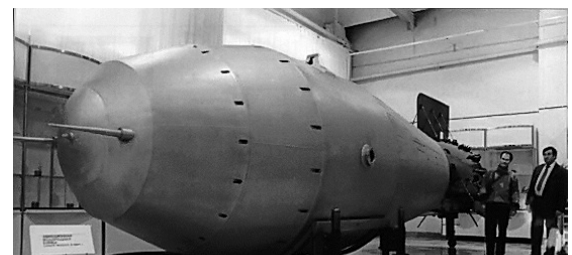
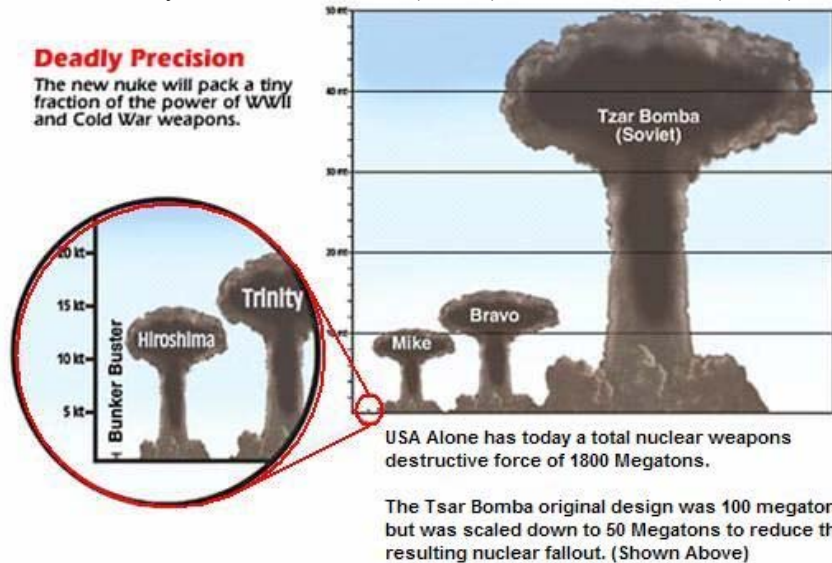
- fusion reaction is not limited by a critical mass as in fission reaction. Hence, the size of the explosion depends on the amount of fusion material.
- besides the intense heat to incinerate a large area, the damaging radiation effects come from the products of the fission starter and the product of the fusion reaction, tritium, has a half-life of 12.5 yrs. However, other radioactive material with longer half-life, such as Co-59, can be used to spread harmful radiations.

**Teller-Ulam two-stage thermonuclear bomb design**



Length: 18.8 ft / 5.7 m  
 Diameter: 5 ft / 1.5 m  
 Weight: 39,600 lbs / 18,000 kg  
 Yield: 13.5 megatons

Differences in yields between atomic (fission) and thermonuclear (fusion) bombs



**Thermonuclear Hydrogen Bomb (Tsar Bomba)**  
 Length: 26.6 ft / 8 m Weight: 59,400 lbs / 27,000 kg  
 Diameter: 6.6 ft / 2 m Yield: 50 megatons  
 Tested on Oct 30, 1961 at Novaya Zemlya Island, (north of the Russia)

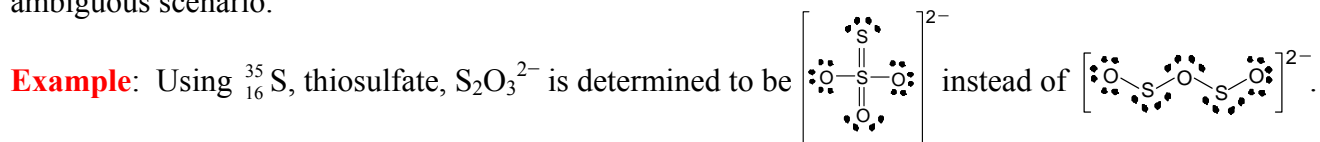
See Tsar Bomba explosion:  
<http://www.youtube.com/watch?v=FfoQsZa8F1c> and  
<http://www.youtube.com/watch?v=BmQIkDkZ7sk>



**Assignment**  
 23.5 & 23.6 pg. 996 #38, 40, 41, 44 to 46

**23.7 & 23.8: Uses of Isotopes & Biological Effects of Radiation****Some Uses of Isotopes:**

1. **Structural Determination**: - when a molecular or polyatomic ion structure is difficult to determine, an isotope of an element in the chemical can be used to study the mechanism of decomposition. This in addition of Infrared Spectral Analysis, we can determine the correct chemical structure of otherwise an ambiguous scenario.



**Radioactive Tracers**: - radioactive elements that leave a path of radiation that can be imaged to determine how the material is taken up by an organism.

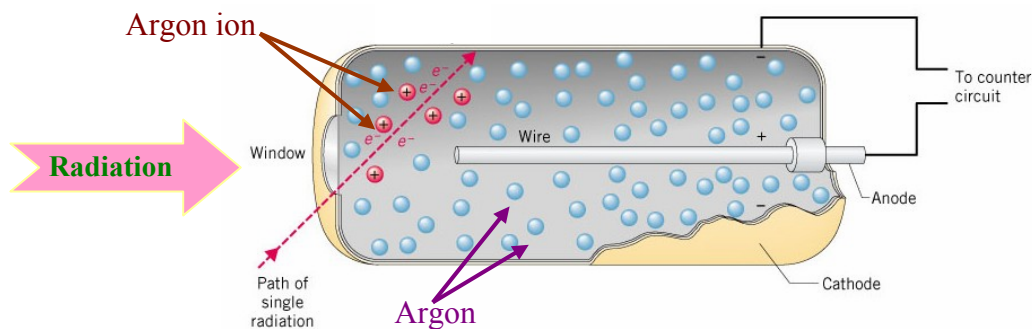
2. **Study of Photosynthesis**: - radioactive tracers like  $^{14}\text{C}$  and  $^{18}\text{O}$  can be included in determine the path of carbon and oxygen during the process of photosynthesis and other nutrient uptakes
3. **Isotopes in Medicine**: - compound that contain a radioactive tracer (**carrier compound**), can be introduced to a patient. An device that can pick up radiation produces an image for the purpose of diagnosis (**medical imaging**).

**Some Common Radioactive Tracers and their Usages:**

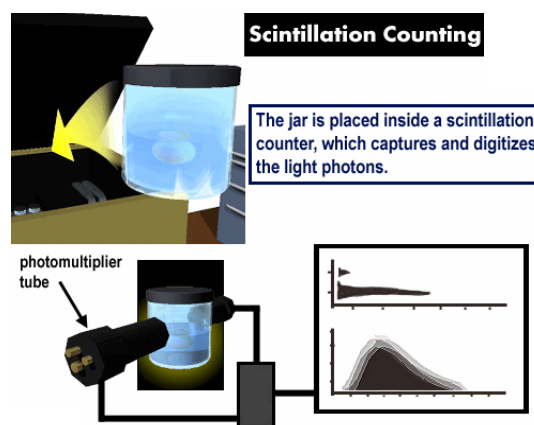
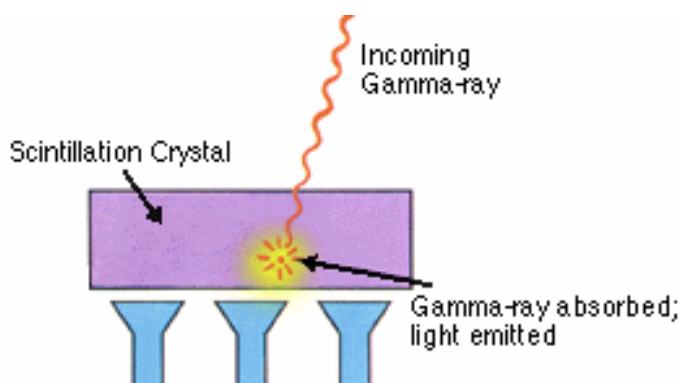
Radiotracers	Area of the Body Examine / Treatment	Other Usages
$^{131}_{53}\text{I}$	Thyroid	
$^{59}_{26}\text{Fe}$ and $^{51}_{24}\text{Cr}$	Red Blood Cells, Metabolism	Metallic Welds, Corrosion Mechanisms, Engine Wears
$^{252}_{98}\text{Cf}$	Cervical and Brain Cancer Treatments	Detections of Metal Fatigue and Explosives
$^{32}_{15}\text{P}$	Eyes, Liver, Tumours	Path and Rate of Adsorption of Plant Nutrients
$^{60}_{27}\text{Co}$	Radiation Source of Radiotherapy	Food Irradiation, Sterilization of Medical Equipment
$^{192}_{77}\text{Ir}$	Localize Prostate and Cervical Cancer Treatments	Metal Integrity Tests
$^{87}_{38}\text{Sr}$ and $^{47}_{20}\text{Ca}$	Bones	
$^{99}_{42}\text{Mo}$	Parent Generator of $^{99}_{43}\text{Tc}$	
$^{99}_{43}\text{Tc}$	Brain, Myocardium, Thyroid, Lungs, Liver, Gallbladder, Kidneys, Skelton, Blood Flow and Tumours	Equipment Calibration and Nanoscale Nuclear Batteries
$^{241}_{95}\text{Am}$		Smoke Detection
$^{133}_{54}\text{Xe}$	Heart, Lungs, Brain and Blood Flow	
$^{24}_{11}\text{Na}$	Extracellular Fluids, Circulatory System	Detection of Leaky Pipes

Detecting Radiations:

1. **Geiger-Müller Counter:** - sometimes refer to as the **Geiger Counter**. (Hans Geiger worked with Rutherford on his gold-foil experiment. The counter was invented to count the number of  $\alpha$ -particles.)  
 - argon gas becomes ionized and when struck by high-energy particle from radioactive decay. The resulting electric potential is amplified and the current can show as the intensity of the radioactivity.



2. **Scintillation Counter:** - zinc sulfide and other substances give off light when struck by high-energy particle from radioactive decay. A photocell measures the intensity of the light produced and gives the measure as the number of decay events per unit of time.



**Radiation Damages:** - high-energy particles generated by nuclear decays can cause damage to organisms. Depending on the doses, it can be shown either immediately or years after exposure.

- a. **Somatic Damage:** - radiation damage to the organism's tissues or cell structures causes sickness or death.

**Examples:** Sunburn, hear rash, cancer, and cataracts

- b. **Genetic Damage:** - radiation damage to the genetic code or reproduction process of the organism, which causes mutations in the offspring.

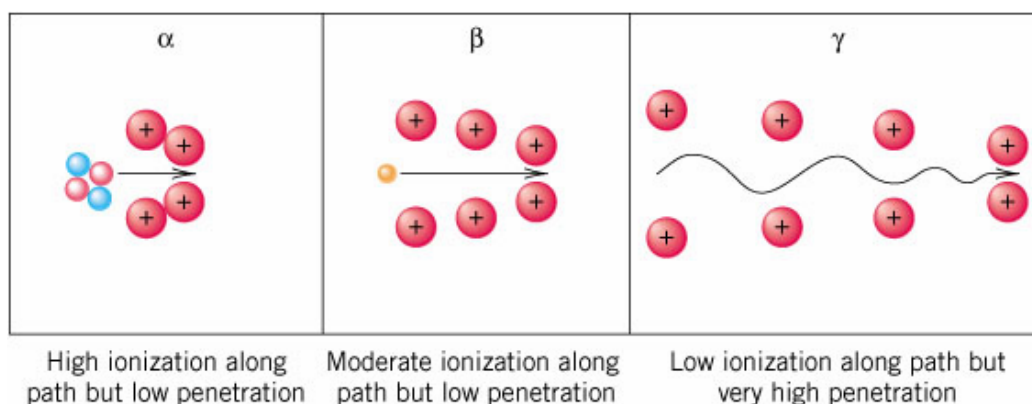
**Examples:** Genetic and DNA mutations

**Sources of Radiation:**

- Natural Radiations:** - small amounts of radiation happened naturally from the environment.
  - **Cosmic radiation** from outer space and the sun (amounts vary by elevation from sea level).
  - **Ground radiation** from Earth's interior that is responsible from heat of hot springs and geyser to the molten core of the planet. It is also present in organic food and water, building material such as bricks and wood products.
  - **Air radiation** from radon-222 (inert gas from natural uranium deposits); easily inhaled from basement cracks. Radon-222 is also found in tobacco smoke (man-made radiation).
  - **Human tissues** contains about 20 mg of potassium-40 that emit pulses of radioactivity over time.
- Man-Made Radiations:** - radiations that are artificially created (intentional and unintentional).
  - **Medical procedures** such as X-ray and radiotherapy and radio-diagnostic procedures.
  - **Consumer products** like television tubes.
  - **Proximity to Power Generators** like nuclear and coal power plants.
  - **Aviation** from airline travels.
  - **Nuclear Weapon Testing Fallout** can travel all around the globe.

**Biological Effects from Radiation**

- Radiation Energy Level:** - the higher the energy levels (doses), the more the severe are the damages.
  - radiation doses are measured in *rads* (radiation absorbed doses – now an obsolete unit), 1 rad = 10 mJ.
  - *rems* (roentgen equivalent in man), measures the ability to radiation to cause harm biologically.
  - it takes 500 rems to be considered lethal radiation dosage if it was given in a short period of time.
  - smaller radiation on a body can be measured in *millirems*. (1000 millirems = 1 rem)
- Penetrating Ability:** - the lighter the particles, the more penetrating they can be. In terms of penetrating ability:  **$\gamma$  ray is the strongest, followed by  $\beta$  particles and  $\alpha$  particle is the least penetrating.**
- Ionization Ability:** - as high-energy particles pass through tissue, it can cause ionization that is damaging to the organism.  **$\alpha$  particles ionize the most along its path whereas  $\gamma$  ray does not.** Therefore,  **$\alpha$  particle** producers like plutonium and radon can cause severe radiation damage if ingested or inhaled.



- Radiation Source's Chemical Properties:** - the length of the half-life of a radioactive nuclide can also affect radiation damage. Generally, **the longer the half-life, the more damage it can cause.** This is because it can reside in the organism for a longer period of time. This is why most radiotracers used in medical diagnosis have half-lives that are at most in days.

**Assignment**  
23.7 & 23.8 pg. 996 #50