Nuclear Physics

IB 12

Nuclide:

Nucleon:

Atomic number (Z) (proton number):

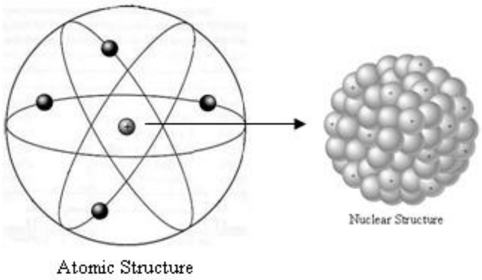
Mass number (A) (nucleon number):

Neutron number (N):

Isotopes:

Unified atomic mass unit (u):

Atomic mass



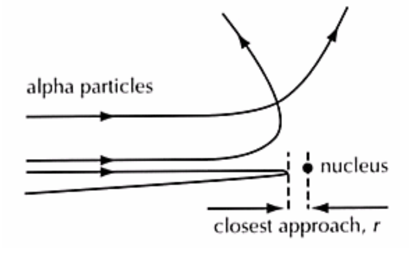
- 1 u =
- 1 u =
- 1 u =

$^{A}_{Z}X$	$^{56}_{26}Fe$	$^{27}_{13}Al$	$^{12}_{6}C$	$^{14}_{6}C$
Atomic Number				
Mass Number				
Neutron Number				
Atomic Mass				
Molar Mass				

How big are atomic nuclei?

How do we know this?

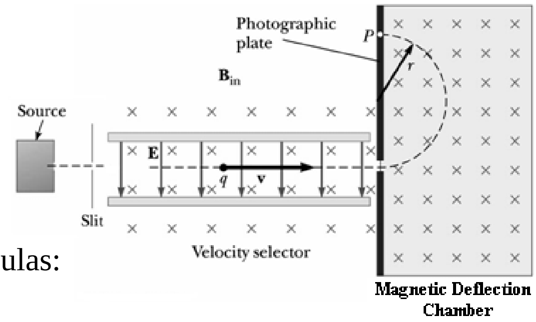
Formulas:



Note that most nuclei have approximately the same . . .

How do we know that neutrons exist?

How do we know that isotopes exist?



Formulas:

Nuclear Stability

What interactions exist in the nucleus?

1. **Gravitational:** (long range) attractive but very weak/negligible
2. **Coulomb or Electromagnetic:** (long range) repulsive and very strong between protons
3. **Strong nuclear force:** (short range) attractive and strongest – between any two nucleons
4. **Weak nuclear force:** (short range) involved in radioactive decay

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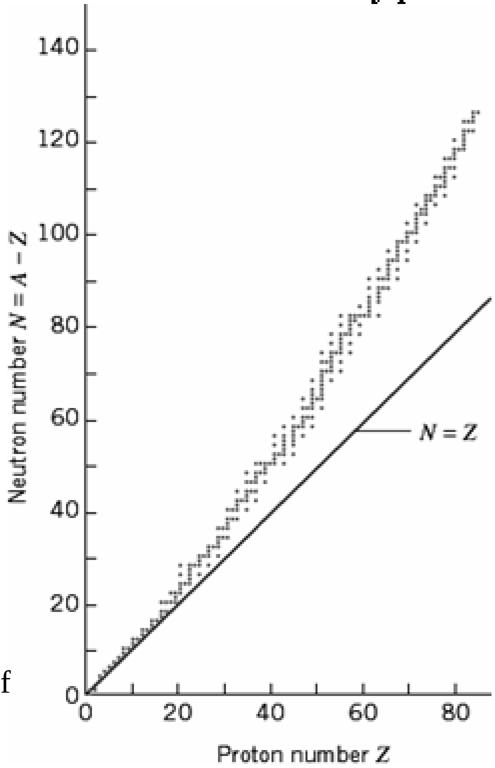
Why are some nuclei stable while others are not?

Nuclear stability plot



The Coulomb force is a long-range force which means that every proton in the nucleus repels every other proton. The strong nuclear force is an attractive force between any two nucleons (protons and/or neutrons). This force is very strong but is short range (10^{-15} m) which means it only acts between a nucleon and its nearest neighbors. At this range, it is stronger than the Coulomb repulsion and is what holds the nucleus together.

Neutrons in the nucleus play a dual role in keeping it stable. They provide for the strong force of attraction, through the exchange of gluons with their nearest neighbors, and they act to separate protons to reduce the Coulomb repulsion.

Each dot in the plot at right represents a stable nuclide and the shape is known as the “band (or valley) of stability.” With few exceptions, the naturally occurring stable nuclei have a number *N* of neutrons that equals or exceeds the number *Z* of protons. For small nuclei (Z < 20), number of neutrons tends to equal number of protons (N = Z).

As more protons are added, the Coulomb repulsion rises faster than the strong force of attraction since the Coulomb force acts throughout the entire nucleus but the strong force only acts among nearby nucleons. Therefore, more neutrons are needed for each extra proton to keep the nucleus together. Thus, for large nuclei (Z > 20), there are more neutrons than protons (N > Z).
After Z = 83 (Bismuth), adding extra neutrons is no longer able to counteract the Coulomb repulsion and the nuclei become unstable and decay in various ways.

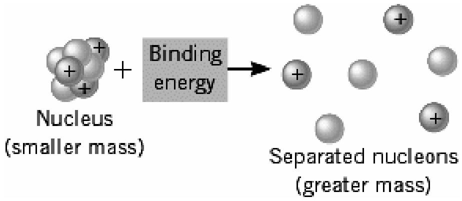
Nuclei above (to the left of) the band of stability have too many neutrons and tend to decay by alpha or beta-minus (electron) emission, both of which reduce the number of neutrons in the nucleus.

Nuclei below (to the right of) the band of stability have too few neutrons and tend to decay by beta-plus (positron) emission which increases the number of neutrons in the nucleus.

Binding Energy

The total mass of a nucleus is always less than the sum of the masses its nucleons. Because mass is another manifestation of energy, another way of saying this is the total energy of the nucleus is less than the combined energy of the separated nucleons.

Mass defect (mass deficit) (Δm)



Nuclear binding energy (ΔE)

Formulas:

1. energy _______________ when a nuclide is ________________ from its individual components

2. energy _______________ when a nuclide is ________________ from its individual components

Different nuclei have different total binding energies. As a general trend, as the atomic number increases . . .____.

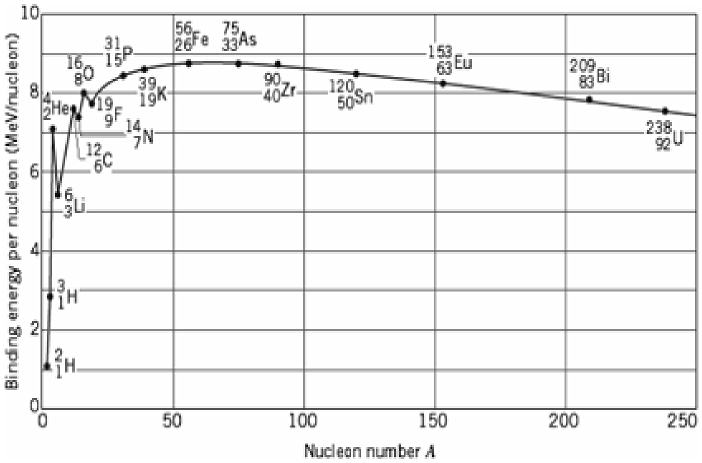
Particle	Electric Charge (e)	Electric Charge (C)	Rest Mass (kg)	Rest Mass (u)	Rest Mass (MeV/c^2)
Proton	+1	+1.60 x 10^{-19}	1.673 x 10^{-27}	1.007276	938
Neutron	0	0	1.675 x 10^{-27}	1.008665	940
Electron	-1	-1.60 x 10^{-19}	9.110 x 10^{-31}	0.000549	0.511

1. The most abundant isotope of helium has a ${}_{2}^{4}\mathrm{He}$ nucleus whose mass is 6.6447×10^{-27} kg. For this nucleus, find the mass defect and the binding energy.

2. Calculate the binding energy and mass defect for ${}_{8}^{16}\mathrm{O}$ whose measured mass is 15.994915 u.

Binding Energy per Nucleon

To see how the nuclear binding energy varies from nucleus to nucleus, it is useful to compare the binding energy for each nucleus on a per-nucleon basis, as shown in the graph below.



Binding energy per nucleon plot

Your Turn

a) This graph is used to compare the energy states of different nuclides and to determine what nuclear reactions are energetically feasible. As binding energy per nucleon increases so does the stability of the nucleus. ______________ binding energies represent ______________ energy states since more energy was released when the nucleus was assembled.

b) Binding energy per nucleon increases up to a peak at ________ then decreases, so ________ is the most stable nuclide. Most nuclides have a binding energy per nucleon of about _________. Lighter nuclei are held less tightly than heavier nuclei.

c) Nuclear reactions, both natural (radioactive decay) and artificial/induced (fission, fusion, bombardments) occur if they increase the binding energy per nucleon ratio. ___________ occurs for light nuclei (below $_{26}^{56}$Fe) and ______________ occurs for heavy nuclei (above $_{26}^{56}$Fe).

d) For both natural and induced nuclear reactions, the total rest mass of the products is less than the total rest mass of the reactants since energy is released in the reaction. Also, the products are in a lower energy state since energy was released in the reaction and so the products have a greater binding energy per nucleon than the reactants.

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1. Use the graph above to estimate the total binding energy of an oxygen-16 nucleus.

Types of Nuclear Reactions

1) Artificial (Induced) Transmutation: A nucleus is bombarded with a nucleon, an alpha particle or another small nucleus, resulting in a nuclide with a different proton number (a different element).

2) Nuclear Fusion: Two light nuclei combine to form a more massive nucleus with the release of energy.

3) Nuclear Fission: A heavy nucleus splits into two smaller nuclei of roughly equal mass with the release of energy.

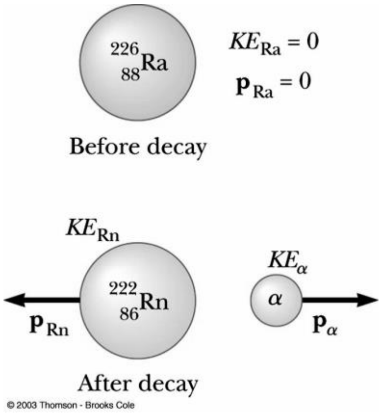
4) Natural Radioactivity: When an unstable (radioactive) nucleus disintegrates spontaneously, the nucleus emits a particle of small mass and/or a photon.

Release of energy in nuclear reactions:

Binding energy per nucleon:

Radioactive Decay Reactions

Alpha Decay



Alpha particle:

Example reaction: $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He + energy$

General equation:

Where does the kinetic energy come from?

Result:

1. A radium nucleus, initially at rest, decays by the emission of an alpha particle into radon in the reaction described above. The mass of $_{88}{}^{226}$Ra is 226.025402 u and the mass of $_{86}{}^{222}$Rn is 222.017571 u and the mass of the alpha particle is 4.002602 u.

   a) Calculate the energy released in this decay.

   b) Compare the momenta, speeds, and kinetic energies of the two particles produced by this reaction.

   c) If the kinetic energy of the alpha particle is 4.77 MeV, calculate its speed.

   d) Calculate the recoil speed of the radon nucleus.

Beta Decay

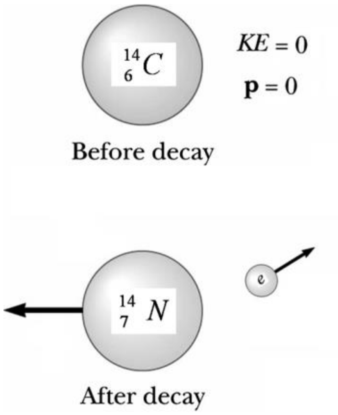
Beta-minus particle:

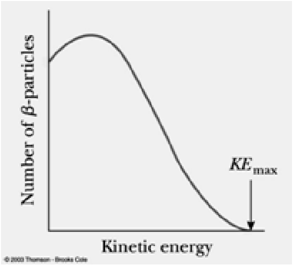
Beta-plus particle:

Consider the following two "mysterious" results of beta decay:

a) Observe the before and after picture of beta decay. What's wrong?

b) Inspect the graph of kinetic energy carried away by the beta particles. Why are so few beta particles leaving with the majority of the kinetic energy? Where did this missing kinetic energy go?





Continuous spectrum of beta particles in beta decay

Conclusion:

Neutrino and anti-neutrino:

Beta-minus decay

Example reaction:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + ^{0}_{0}\overline{\nu} + energy$$

General equation:

How does this happen?

Beta-plus decay

Example reaction:

$$^{12}_{7}N \rightarrow ^{12}_{6}C + ^{0}_{+1}e + ^{0}_{0}\nu + energy$$

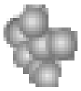
General equation:

How does this happen?

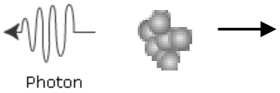
Gamma Decay

Gamma particle:

Example reaction: $^{12}_{6}C^{*} \rightarrow ^{12}_{6}C + \Upsilon + energy$



Before Decay



After Decay

General equation:

Where does the photon (energy) come from?

Energy Spectra of Radiation

The nucleus itself, like the atom as a whole, is a quantum system with allowed states and discrete energy levels. The nucleus can be in any one of a number of discrete allowed excited states or in its lowest energy relaxed state. When it transitions between a higher energy level and a lower one, it emits energy in the form of alpha, beta, or gamma radiation. When an alpha particle or a gamma photon is emitted from the nucleus, only discrete energies are observed. *These discrete energy spectra give evidence that a nucleus has energy levels*. (However, the spectrum of energies emitted as beta articles is continuous due to its sharing the energy with a neutrino or antineutrino in any proportion.)

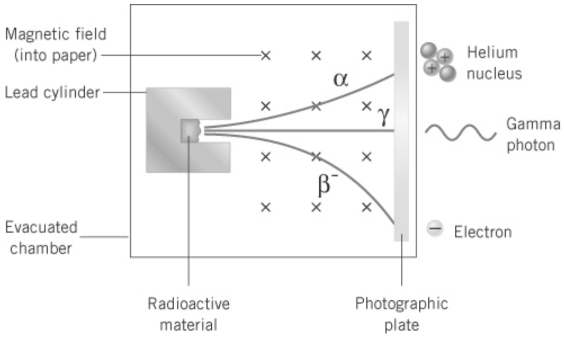
Importance:

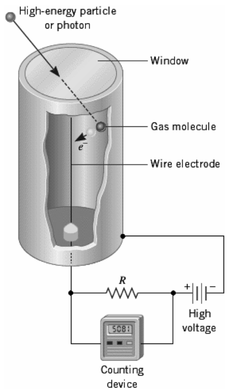
Alpha spectra	**Beta spectra**	**Gamma spectra**

Ionizing Radiation

Ionizing Radiation – As this radiation passes through materials, it "knocks off" electrons from neutral atoms thereby creating an ion pair: ______________________ and _________________________. This **ionizing property** allows the radiation to be detected but is also dangerous since it can lead to mutations in biologically important molecules in cells, such as DNA.

	α	β	γ
Particle			
Penetration ability			
Material needed to absorb it			
Path length in air			





Detection of Radiation: the Geiger-Muller tube (Geiger counter)

The Geiger counter consists of a gas-filled metal cylinder. The *α*, *β*, or *γ* rays enter the cylinder through a thin window at one end. Gamma rays can also penetrate directly through the metal. A wire electrode runs along the center of the tube and is kept at a high positive voltage (1000-3000 V) relative to the outer cylinder.

When a high-energy particle or photon enters the cylinder, it collides with and ionizes a gas molecule. The electron produced from the gas molecule accelerates toward the positive wire, ionizing other molecules in its path. Additional electrons are formed, and an avalanche of electrons rushes toward the wire, leading to a pulse of current through the resistor *R*. This pulse can be counted or made to produce a "click" in a loudspeaker. The number of counts or clicks is related to the number of disintegrations that produced the particles or photons.

Biological Effects of Ionizing Radiation

Alpha and beta particles have energies typically measured in MeV. To ionize an atom requires about 10 eV so each particle can potentially ionize 10^5 atoms before they run out of energy. When radiation ionizes atoms that are part of a living cell, it can affect the ability of the cell to carry out its function or even cause the cell wall to rupture. In minor cases, the effect is similar to a burn. If a large number of cells that are part of a vital organ are affected then this can lead to death. Alternatively, instead of causing the cell to die, the damage done by ionizing radiation might just prevent cells from dividing and reproducing. Or, it could be the cause of the transformation of the cell into a malignant form. If these malignant cells continue to grow then this is called cancer.

The amount of harm that radiation can cause is dependent on the number and energy of the particles. When a gamma photon is absorbed, the whole photon is absorbed so one photon can ionize only one atom. However, the emitted electron has so much energy that it can ionize further atoms, leading to damage similar to that caused by alpha and beta particles.

On a positive note, rapidly diving cancer cells are very susceptible to the effects of radiation and are more easily killed than normal cells. The controlled use of the radiations associated with radioactivity is of great benefit in the treatment of cancerous tumors.

Mathematical Description of Radioactive Decay

Radioactive decay:

1) **Random process**: It cannot be predicted when a particular nucleus will decay, only the probability that it will decay.
2) **Spontaneous process:** It is not affected by external conditions. For example, changing the pressure or temperature of a sample will not affect the decay process.
3) **Rate of decay decreases exponentially with time:** Any amount of radioactive nuclei will reduce to half its initial amount in a constant time, independent of the initial amount.

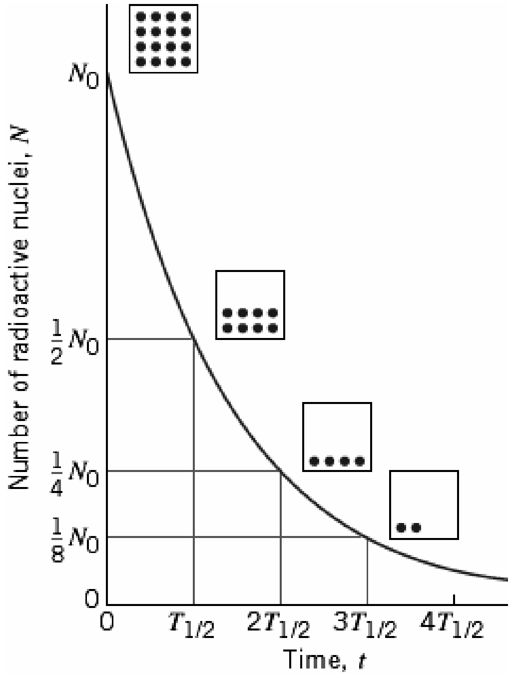
Half-life ($T_{1/2}$) Units:

-

-

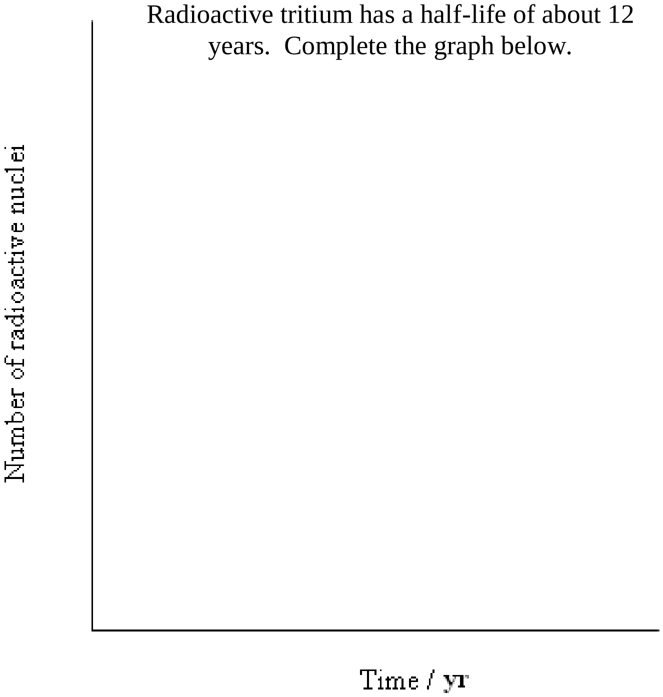
N_0 =

N =



Your Turn

Radioactive tritium has a half-life of about 12 years. Complete the graph below.



A nuclide X has a half-life of 10 s. On decay the stable nuclide Y is formed. Initially a sample contains only atoms of X. After what time will 87.5% of the atoms in the sample have decayed into nuclide Y?

Activity

Activity (A) –

Units:

Formula:

Standard units:

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1. A sample originally contains 8.0 x 10^{12} radioactive nuclei and has a half-life of 5.0 seconds. Calculate the activity of the sample and its half-life after:

a) 5.0 seconds   b) 10. seconds   c) 15 seconds

2. Samples of two nuclides X and Y initially contain the same number of radioactive nuclei, but the half-life of nuclide X is greater than the half-life of nuclide Y. Compare the initial activities of the two samples.

Activity

The Radioactive Decay Law: The rate at which radioactive nuclei in a sample decay (the activity) is proportional to the number of radioactive nuclei present in the sample at any one time.

[As the number of radioactive nuclei decreases, so does the average rate of decay (the activity).]

Initial Activity

The initial activity (A_0) is directly related to the number of radioactive nuclei originally present (N_0) in the sample.

3. The isotope Francium-224 has a half-life of 20 minutes. A sample of the isotope has an initial activity of 800 disintegrations per second. What is the approximate activity of the sample after 1 hour?

Decay constant (λ)

Units:

–

-

Deriving the Radioactive Decay Law	**Relating the Decay Constant and Half-life**

1. The half-life of a certain radioactive isotope is 2.0 minutes. A particular nucleus of this isotope has not decayed within a time interval of 2.0 minutes. What is the probability of it decaying in:

   a) the next two minutes   b) the next one minute   c) the next second

2. A sample of a radioactive isotope X has the same initial activity as a sample of the isotope Y. The sample of X contains twice the number of atoms as the sample of Y. If the half-life of X is T_X then the half-life of Y is $0.5\ T_X$

3. The half-life of a radioactive isotope is 10 days. Calculate the fraction of the sample that will be left after 15 days. 35%

4. The half-life of a radioactive substance is 10 days. Initially, there are 2.00 x 10^{26} radioactive nuclei present.

a) What is the probability of any one particular nucleus decaying?

b) What is the initial activity?

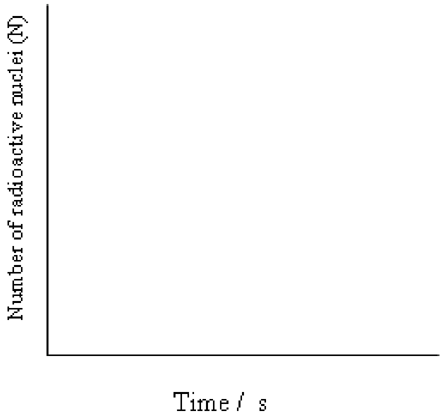
c) How many radioactive nuclei are left after 25 days?

d) What is the activity of the sample after 25 days?

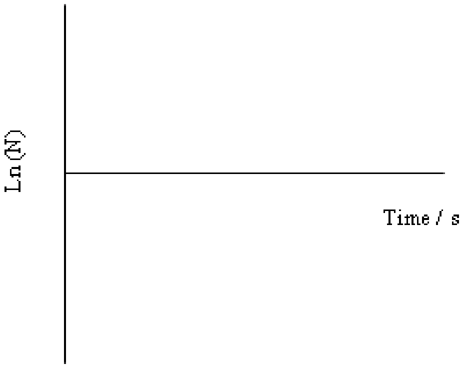
e) How long will it take for the activity to fall to 1.0 x 10^{24} dy^{-1}?

Graphs of Radioactive Decay

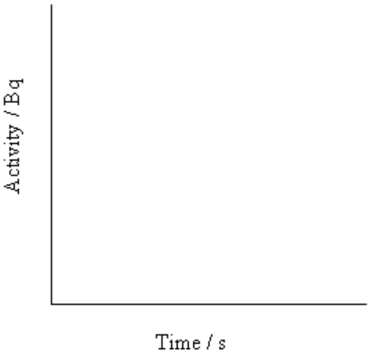
Radioactive nuclei vs. time



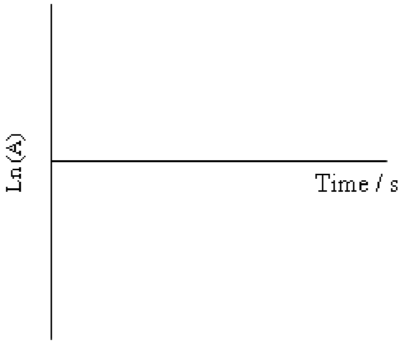
Straightening by natural log



Activity of sample vs. time



Straightening by natural log



Methods of Determining Half-life

If the half-life is short, then readings can be taken of activity versus time using a Geiger counter, for example. Then, either

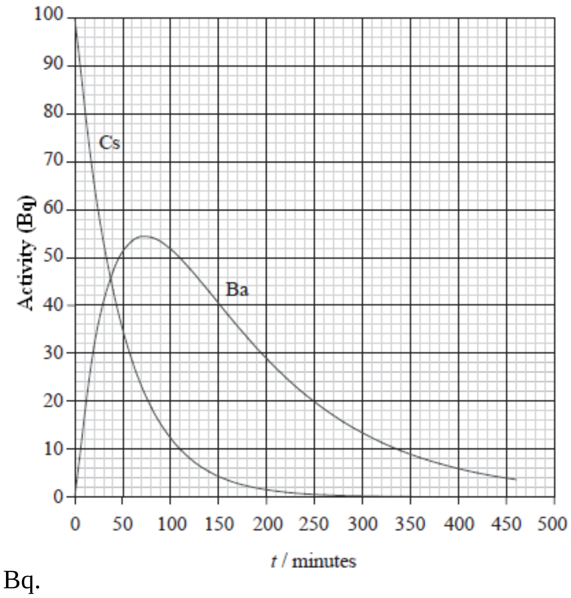
1. A graph of activity versus time would give the exponential shape and several values for the half-life could be read from the graph and averaged.

OR

2. A graph of ln (activity) versus time would be linear and the decay constant can be calculated from the slope.

If the half-life is long, then the activity will be effectively constant over a period of time. If a way could be found to calculate the number of nuclei present chemically, perhaps using the mass of the sample and Avogadro's number, then the activity relation or the decay equation could be used to calculate half-life.

1. Cesium-138 decays into an isotope of barium. Measurements of the activity of a particular sample of cesium-138 were taken and graphed at right.



a) Suggest how the data for this graph could have been obtained.

b) Use the graph to estimate the half-life of cesium-138.

c) Use the graph to estimate the half-life of the barium isotope.

2. A 2.0 mg sample of carbon-14 is measured to have an activity of 6.5 x 10^{10} Bq.

a) Use this information to determine the half-life of carbon-14 in years.

b) A student suggests that the half-life can be determined by taking repeated measurements of the activity and analyzing the data graphically. Use your answer to part (a) to comment on this method of determining the half-life.

3. The radioactive isotope potassium-40 undergoes beta decay to form the isotope calcium-40 with a half-life of 1.3 x 10^9 yr. A sample of rock contains 10 mg of potassium-40 and 42 mg of calcium-40.

a) Determine the age of the rock sample.

b) What are some assumptions made in this determination of age?

Nuclear Fission

Nuclear Fission: A heavy nucleus splits into two smaller nuclei of roughly equal mass with the release of energy.

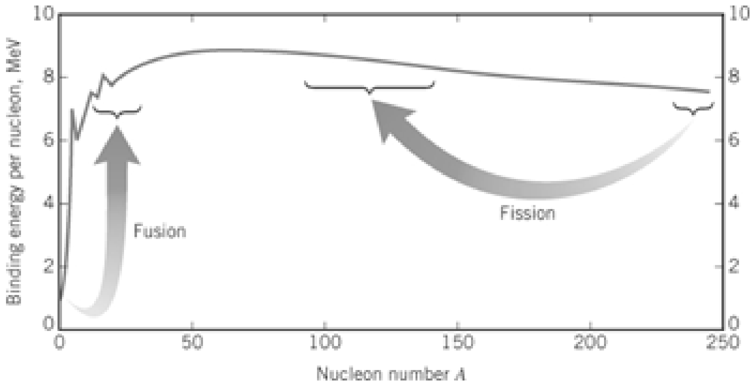
Nuclear Fusion: Two light nuclei combine to form a more massive nucleus with the release of energy.

Release of energy in nuclear reactions:

Energy is usually released in the form of . . .

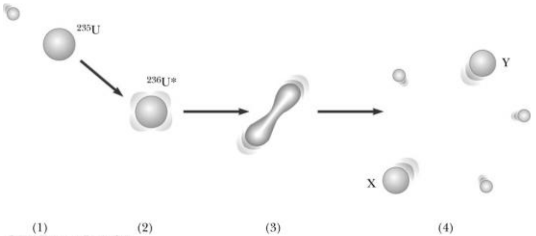
Binding energy per nucleon:

Binding Energy per Nucleon Plot



One Common Fission Reaction

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U^{*} \rightarrow X + Y + \text{ neutrons}$$



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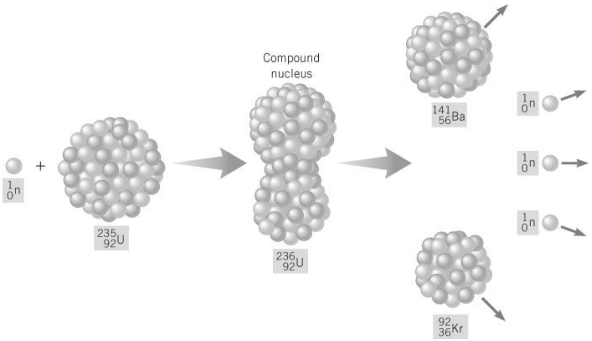
There are about 90 different daughter nuclei (X and Y) that can be formed.
Here is a typical example:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$



1. Estimate the amount of energy released when a uranium nucleus fissions.

2. A neutron collides with a nucleus of plutonium and the following fission reaction occurs. Determine the number of neutrons produced and calculate the amount of energy released.

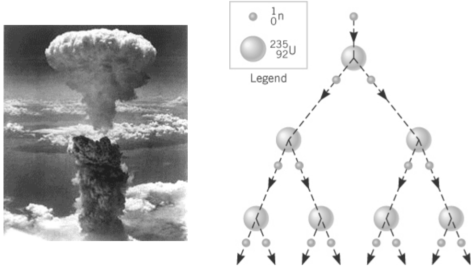
$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{140}_{56}Ba + ^{96}_{38}Sr +$$

Masses:

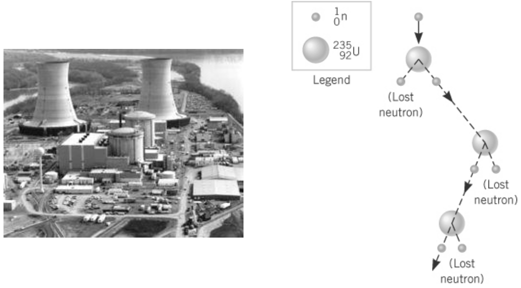
$^{239}_{94}$Pu = 239.052157 u
$^{96}_{38}$Sr = 95.921750 u
$^{140}_{56}$Ba = 139.910581 u
$^{1}_{0}$n = 1.008665 u

Chain Reactions

Chain Reaction – neutrons released from one fission reaction go on to initiate further reactions



Uncontrolled Chain Reaction



Controlled Chain Reaction

Uncontrolled nuclear fission:

Controlled nuclear fission:

1)

2)

Critical Mass:

Thermal Neutron:

Naturally Occurring Isotopes of Uranium:

1) Uranium-238:

2) Uranium-235:

Fuel Enrichment:

1)

2)

3)

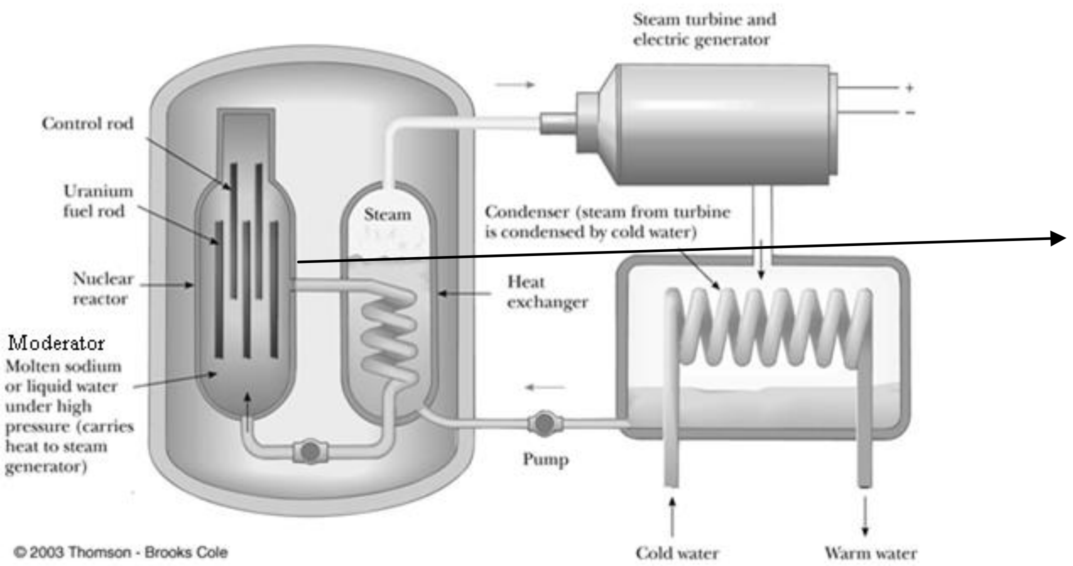
Advantage:

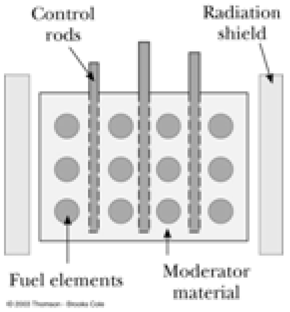
Disadvantage:

Nuclear Reactors

Most nuclear reactors:

Main components of a pressurized-water reactor (PWR)





Nuclear Reactor "Core"

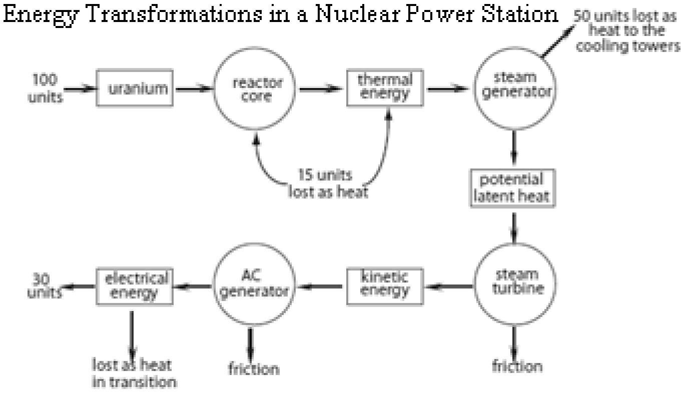
Fuel Rods:

Moderator:

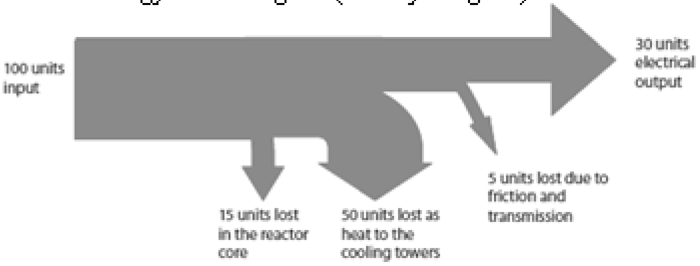
Control Rods:

Heat Exchanger:

Energy Transformations in a Nuclear Power Station



Energy Flow Diagram (Sankey Diagram)



Neutron Capture and Plutonium-239

Uranium-238 is a non-fissionable isotope but is considered “fertile”

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np +$$

Neutron capture and Beta-minus decay

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu +$$

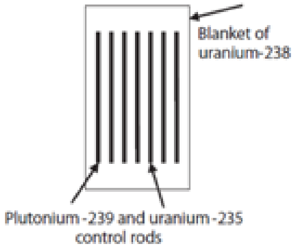
Beta-minus decay

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{140}_{56}Ba + ^{96}_{38}Sr +$$

Fission reaction

Advantage:

Disadvantage:



Core of a Breeder Reactor

Safety Issues and Risks in the Production of Nuclear Power

Uranium Mining:

Thermal Meltdown:

Nuclear Waste:

Nuclear Weapons Manufacture:

1. Suppose the average power consumption for a household is 500 W per day. Estimate the amount of uranium-235 that would have to undergo fission to supply the household with electrical energy for a year. Assume that for each fission, 200 MeV is released.

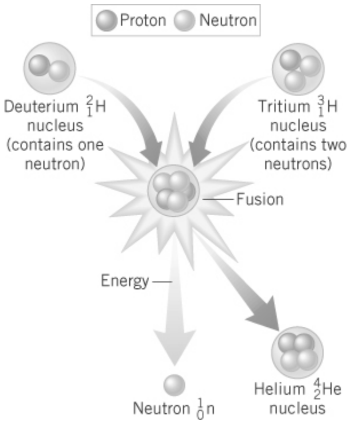
2. A fission reaction taking place in a nuclear power station might be

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Estimate the initial amount of uranium-235 needed to operate a 600 MW reactor for one year assuming 40% efficiency and 200 MeV released for each fission reaction.

Nuclear Fusion

Nuclear Fusion: Two light nuclei combine to form a more massive nucleus with the release of energy.



$_1^2$H (deuterium, 2.0141 u)
$_1^3$H (tritium, 3.0161 u)
$_2^4$He (4.0026 u)
neutron (1.0087 u)

1. Write the reaction equation for the fusion reaction shown at right.

2. Calculate how much energy is released in this fusion reaction.

3. Calculate the energy released per nucleon and compare this with a fission reaction.

Important occurrence of fusion:

Suggested Mechanism:

$$^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1e + \nu$$

$$^1_1H + ^2_1H \rightarrow ^3_2He + \gamma$$

Then either:

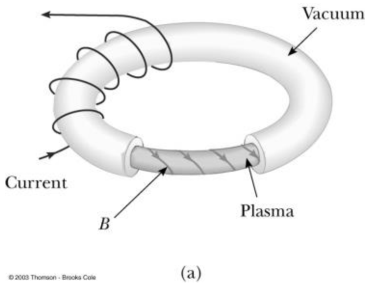
$$^1_1H + ^3_2He \rightarrow ^4_2He + ^0_1e + \gamma$$

Or:

$$^3_2He + ^3_2He \rightarrow ^4_2He + ^1_1H + ^1_1H$$

Fusion Reactor

Plasma:



Magnetic confinement:

Heating Plasma:

Problems with current fusion technology:

Artificial (Induced) Transmutation

Artificial (Induced) Transmutation: A nucleus is bombarded with a nucleon, an alpha particle or another small nucleus, resulting in a nuclide with a different proton number (a different element).

Requirement:

1. In 1919, Ernest Rutherford discovered that when nitrogen gas is bombarded with alpha particles, oxygen and protons are produced. Complete the equation for this reaction.

$$^{14}_{7}N + ^{4}_{2}He \rightarrow$$

2. Neutron bombardment of lithium can produce the radioactive isotope of hydrogen known as tritium. Complete the reaction.

$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H +$$

NOTE:

Importance: