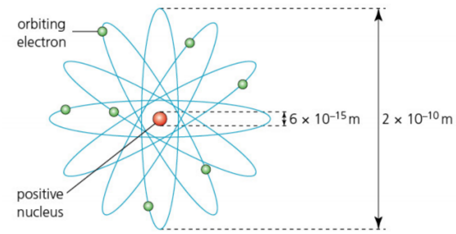
Nuclear Physics – Part I

Nuclide: a particular type of nucleus

Nucleon: a proton or a neutron

$${}^{A}_{Z}X$$



A nitrogen atom

Atomic number (Z) (proton number): number of protons in nucleus

Mass number (A) (nucleon number): number of protons + neutrons

Neutron number: number of neutrons in nucleus (A – Z)

Isotopes: nuclei with same number of protons but different numbers of neutrons

Unified atomic mass unit (u): 1/12th the mass of a carbon-12 atom

- 1 u = 1.661×10^{-27} kg
- 1 u = 931.5 MeV/c^2
- 1 u = 1 g/mol

Nuclide name	Iron-56 (Fe-56)	Carbon-12 (C-12)	Carbon-14 (C-14)	Uranium-238 (U-238)
Nuclide symbol	${}^{56}_{26}Fe$	${}^{12}_{6}C$	${}^{14}_{6}C$	${}^{238}_{92}U$
Atomic Number	26	6	6	92
Mass Number	56			
Neutron Number	30			
Atomic Mass	56 u			
Molar Mass	56 g			

n = number of moles of a substance

N = number of particles (atoms, molecules) in a substance

N_A = Avogadro's number = 6.02×10^{23} mol^{-1} = number of particles in one mole of a substance

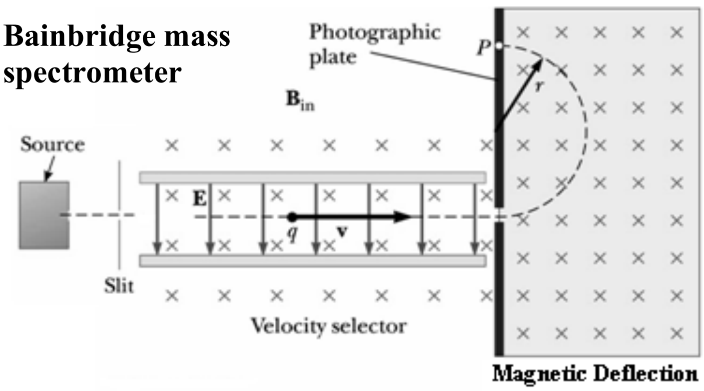
Relationships:

1. How many carbon atoms are in 2.5 moles of carbon-12?

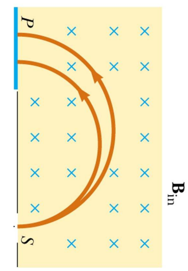
2. How many carbon atoms are 2.5 kg of carbon-12?

3. How do we know the masses of nuclei?

Bainbridge mass spectrometer



Conclusion: Different mass values for the same type of nuclide give evidence for the existence of isotopes.



4. How big are nuclei?

Size of atom: Size of nucleus:

5. How do we know the sizes of nuclei?

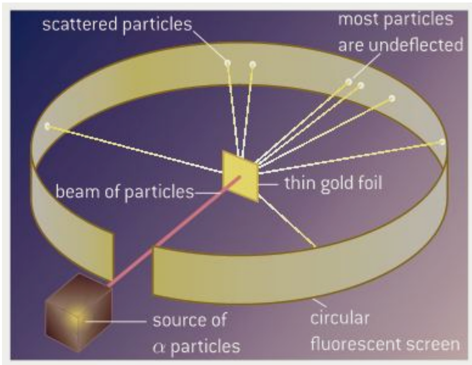
a)

Also known as:

Method: Alpha particles from a radioactive source are directed at a thin gold foil. Scattered alpha particles were detected as flashes on a fluorescent screen.

Results:
i) most particles went straight through or were deflected at small angles

ii) a few were deflected at very large scattering angles

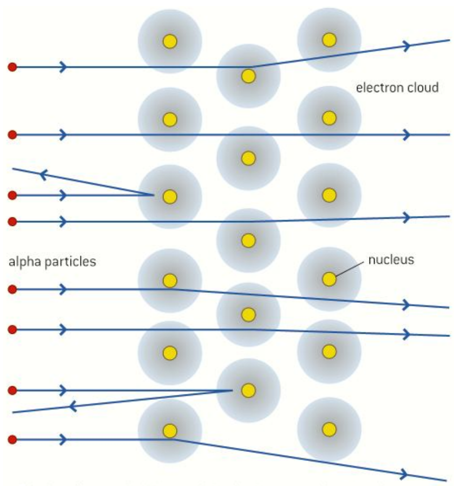


The Rutherford–Geiger–Marsden apparatus.

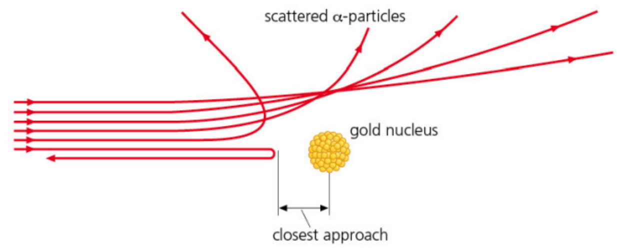
Conclusions:
i) most of the atom is empty space

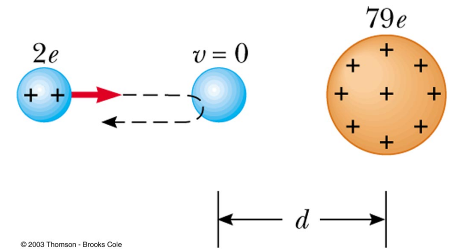
ii) all positive charge and most of the mass is concentrated in a very small space

Alpha particles are fired at a speed of 2.00×10^7 m/s at a gold nucleus (atomic number = 79) as shown. Determine the "distance of closest approach."



Paths of several alpha particles in the scattering experiment.



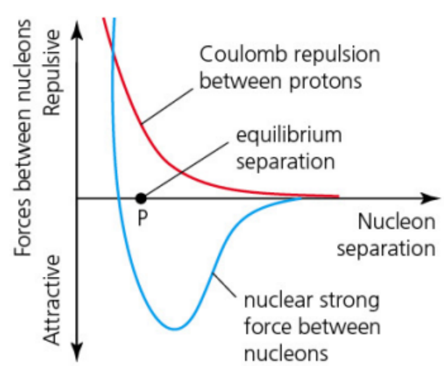


Conclusion:

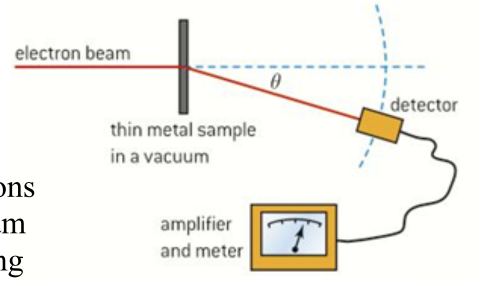
Fundamental Forces and their Properties

Force	Range	Relative strength	Roles played by these forces in the universe
Gravitational	∞	1	binding planets, solar system, sun, stars, galaxies, clusters of galaxies
Weak nuclear	$\approx 10^{-18}$ m	10^{24}	(W^+, W^-): transmutation of elements (W^0): breaking up of stars (supernovae)
Electromagnetic	∞	10^{35}	binding atoms, creation of magnetic fields
Strong nuclear	$\approx 10^{-15}$ m	10^{37}	binding atomic nuclei, fusion processes in stars

Deviations from Rutherford scattering: The scattering experiments performed by Rutherford, Geiger, and Marsden were limited by the energies of the alpha particles emitted by the radioactive sources available to them. When their experiments are repeated using more energetic alpha particles it is found that, at these higher energies, the Rutherford scattering relationship does not agree with experimental results. At higher energies the alpha particles were able to approach the target nucleus so closely that the strong nuclear attractive force overcomes the electrostatic repulsion. The method of closest approach gives an *approximation* of the size of a nucleus. More reliable values for the size of a nucleus can be from using . . .



Comparing Coulomb repulsion to the nuclear strong force b)



(a) outline of experiment

Using the scattering of high-energy electrons to investigate nuclei

Method: Electrons are accelerated through a potential difference to high energies. This beam of high-energy electrons is directed toward a sample. The intensity of the electron beam passing through the sample at various angles is measured using a detector and a graph is plotted.

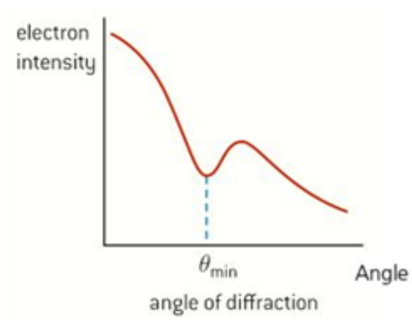
Why are high-energy electrons used?

i) electrons are not subject to the strong nuclear force since they are leptons (only hadrons experience the strong force)

ii) electron beams are easily produced and controlled

iii) electrons can be accelerated to such high energies that they will be diffracted by the nuclei since their de Broglie wavelength is on the order of magnitude of the size of the nuclei

What potential difference should be used to accelerate an electron so that it has a de Broglie wavelength of 5×10^{-15} m?



(b) typical results

Variation of electron intensity with angle

Results: The intensity of the electron beam is plotted versus diffraction angle. The angle of the first diffraction minimum can be seen from the graph.

Formula: Where:

D =

Note:

A beam of electrons whose energy is 420 MeV is being used to measure the size of the nucleus of calcium-40. The first diffraction minimum is detected at an angle of 18.6^{o}. Determine:

i) the de Broglie wavelength of the electrons used.

ii) the nuclear radius of calcium-40.

Conclusion:

Electron diffraction experiments:

a) measuring the size of atoms (10^{-10} m, keVs) – atomic diffraction

b) measuring the size of nuclei (10^{-15} m, 100s of MeVs) – elastic scattering – nuclear diffraction

c) probing the quark structure of nuclei (10^{-18} m – 10^{-19} m, 10s or 100s of GeV) – deep inelastic scattering – Note that this type of scattering provides direct evidence for the quark modle of nucleons, that is, provides direct evidence that protons and neutrons are made of quarks.

---

6. What is the density of a nucleus?

The volume (V) of a nucleus should be proportional to . . .

Therefore the radius (R) of a nucleus should be proportional to . . .

Formula:

Where:

What is the radius of a calcium-40 nucleus?

Nuclear density:

Conclusion: Nuclear densities are . . .

Note: The only macroscopic objects with the same density as nuclei are . . .

Conversion between Mass and Energy

Mass of proton	Speed of light in a vacuum	Charge on electron
1.67262×10^{-27} kg	2.99792×10^{8} m/s	1.60218×10^{-19} C

1. Use the information above to determine the energy equivalent of a proton.
   a) Express your answer in joules.

   b) Convert your answer to electronvolts and megaelectronvolts.

New units of mass:

Energy	Mass

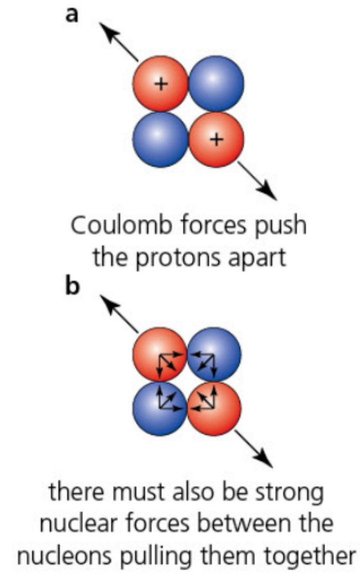
Conversion factor:

2. How much energy would be released if a neutron were converted completely to energy?

3. The mass of an alpha particle is 4.002 u. How much energy would be released if an alpha particle were converted completely to energy?

Nuclear Stability

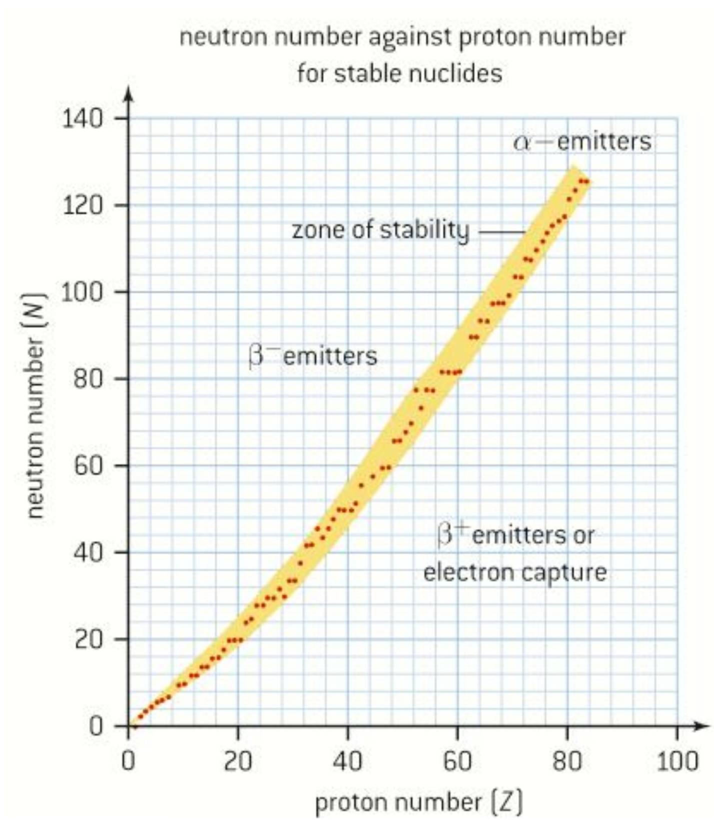
Why are some nuclides stable while others are not?



The Coulomb force is a long-range force of repulsion 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 ($N = Z$).



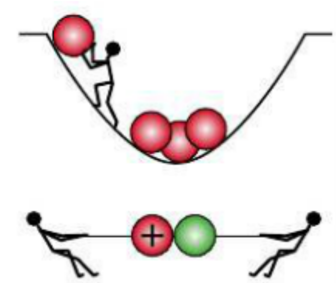
As more protons are added, the Coulomb repulsion rises faster than the strong force of attraction since the Coulomb force acts throughout the entire nucleus but the strong force only acts among nearby nucleons. Therefore, more neutrons are needed for each extra proton to keep the nucleus together. Thus, 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 beta-minus (electron) emission which reduces 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 or electron capture , either of which increases the number of neutrons in the nucleus.

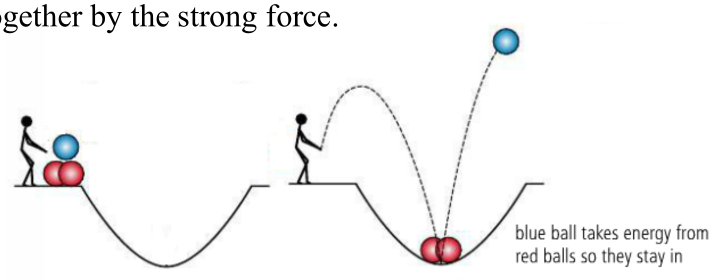
The heaviest nuclides emit alpha particles since that reduces both the numbers of neutrons and protons, which reduces the neutron-proton ratio and brings the overall mass down.

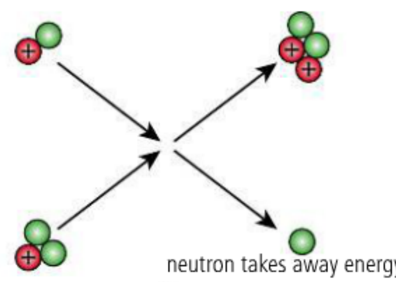
Because the strong force holds the nucleons together in a nucleus, work would need to be done to separate the nucleus into its individual parts. This means that the system is in a lower energy state when the nucleons are together than it would be if they were apart.


Pulling a nucleus apart (work done).

The energy that would need to be supplied to pull the nucleus apart is called the . . .

Similarly, separate nucleons which are in a higher energy state need to have energy removed to be bound together by the strong force.

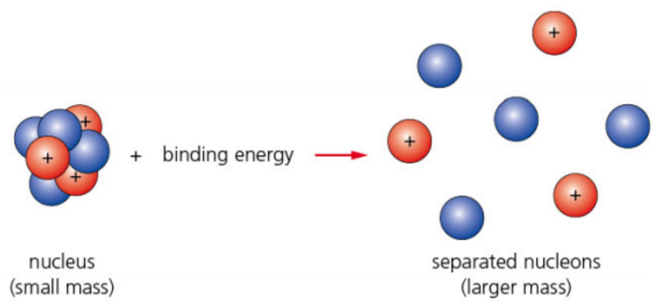




The energy that would be released when the nucleus forms is called the . . .

Because mass is another manifestation of energy, another way of saying this is the total mass of the nucleus is less than the combined mass of the separated nucleons.

The difference between the masses is called the . . .



Binding energy is needed to separate nucleons; this example is lithium-7

Nuclear binding energy (ΔE)

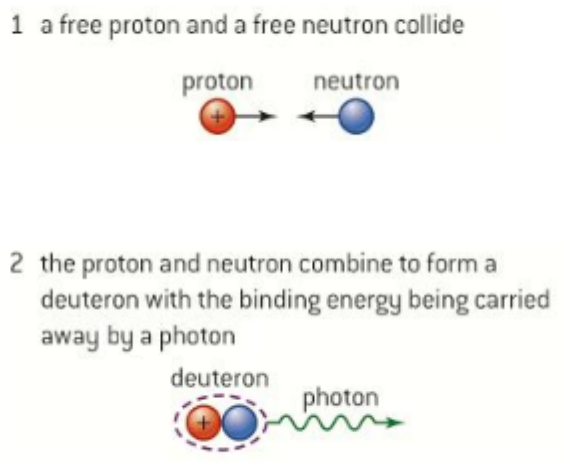
a) energy released when a nuclide is assembled from its individual components

b) energy required when nucleus is separated into its individual components

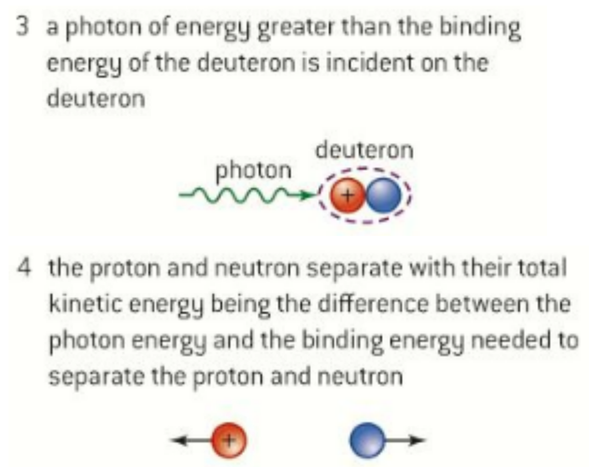
Mass defect (mass deficit) (Δm)

Difference between the mass of the nucleus and the sum of the masses of its individual nucleons

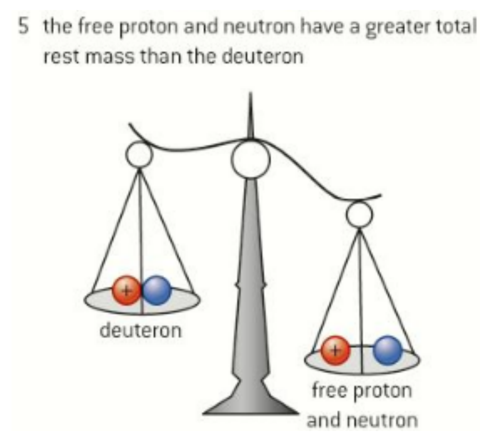
Formulas:



Energy released when a nucleus is formed



Energy supplied to separate a nucleus



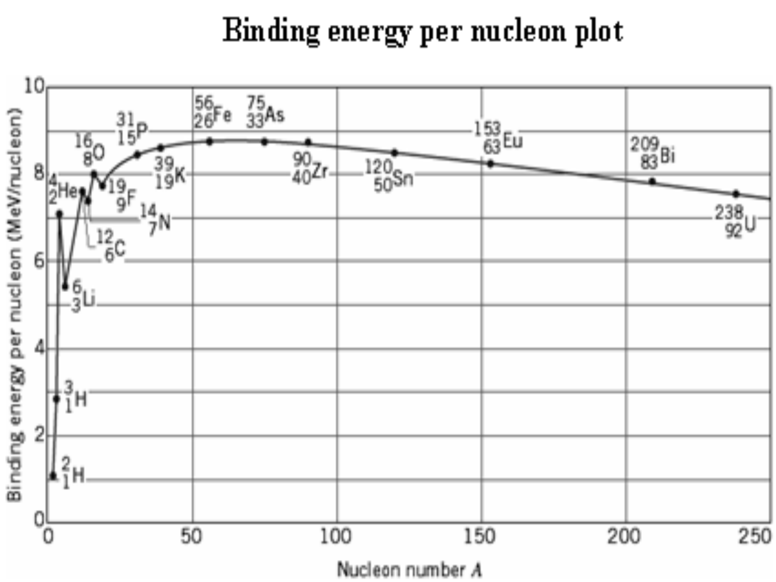
1. The rest mass of a deuteron is 1876 MeV c^{-2}.
   Determine its binding energy and mass defect.

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

3. Determine the binding energy and mass defect of lithium-7 whose nuclear mass is 6534 MeV c^{-2}.

4. Calculate the total binding energy, binding energy per nucleon, and mass defect for ${}^{16}_{8}O$ whose measured mass is 15.994915 u.

5. The mass of a potassium-40 (${}^{40}_{19}K$) nucleus is 37216 MeV c^{-2}. Determine the binding energy per nucleon of K-40.



5. Estimate the total binding energy of an oxygen-16 nucleus.

1. As a nucleus gains more nucleons,

   a) its total binding energy . . .

   b) while its binding energy per nucleon . . .

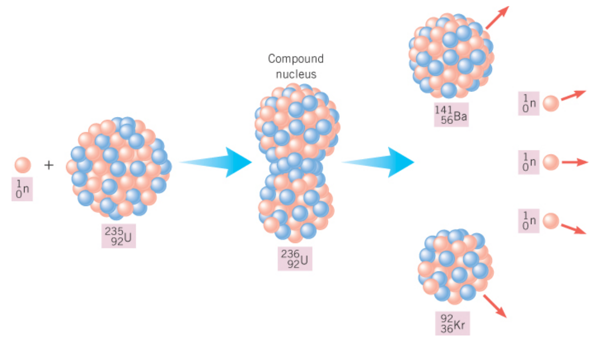
2. Most nuclei have a binding energy per nucleon . . .

3. As the binding energy per nucleon increases, the nucleus . . .

4. The most stable common nucleus is . . .

Nuclear Processes

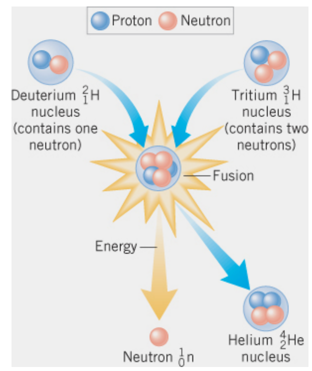
Nuclear Fission: A heavy nucleus splits into two smaller nuclei of roughly equal mass with the release of energy.



Important occurrences of fission:

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

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

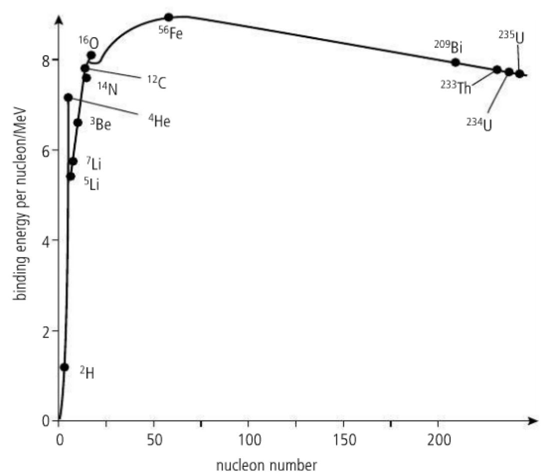


$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Important occurrence of fusion:

---

1. Mark and label fission and fusion processes on the accompanying plot of binding energy per nucleon.



2. Fission and fusion reactions . . .

   a)

   b)

   c)

   d)

Fission/fusion reactions:

3. Energy is usually released in the form of . . .

4. Where does this energy come from?

Rest mass of neutron = 1.0087 u
Rest mass of uranium-235 = 235.0439 u
Rest mass of barium-144 = 143.9229 u
Rest mass of krypton-89 = 88.9178 u

5. One possible fission reaction for uranium-235 is shown below.

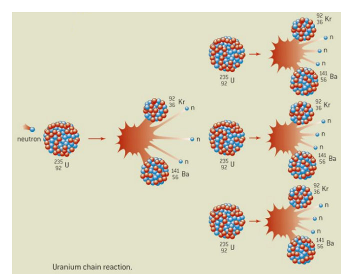
$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3{}^{1}_{0}n + \text{photons}$$

a) Determine how much energy is released in this reaction.

b) Based on your answer to part (a), how much energy is released from the fissioning of one kilogram of uranium-235?

c) What are the characteristics of the initial neutron that bombards the uranium-235 nucleus for fission to occur?

d) What is significant about the reaction producing three neutrons?



Uranium chain reaction.

---

6. One possible fusion reaction is shown below.

$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n$$

Rest mass of hydrogen-2 = 2.0141 u
Rest mass of helium-3 = 3.0161 u
Rest mass of neutron = 1.0086 u

a) Determine how much energy is released in this reaction.

b) Based on your answer to part (a), how many joules of energy will be released if 5.0 grams of hydrogen-2 fuse in this manner?

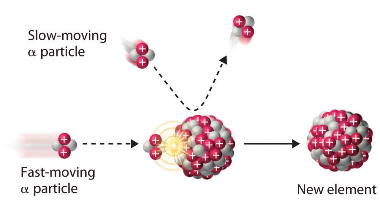
c) In order for these two positively charged nuclei to fuse together, they must have …

d) The major reason that fusion power plants are not yet in use today is . . .

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).

For example, in 1919, Ernest Rutherford discovered that when nitrogen gas is bombarded with alpha particles, oxygen and protons are produced.

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$



Importance: artificial radioactive isotopes are produced which may be used in medical tests and therapies

Requirement: the bombarding particle must have sufficient kinetic energy to overcome the Coulomb repulsion

Artificial transmutation reactions:

7. Neutron bombardment of lithium can produce the radioactive isotope of hydrogen known as tritium.

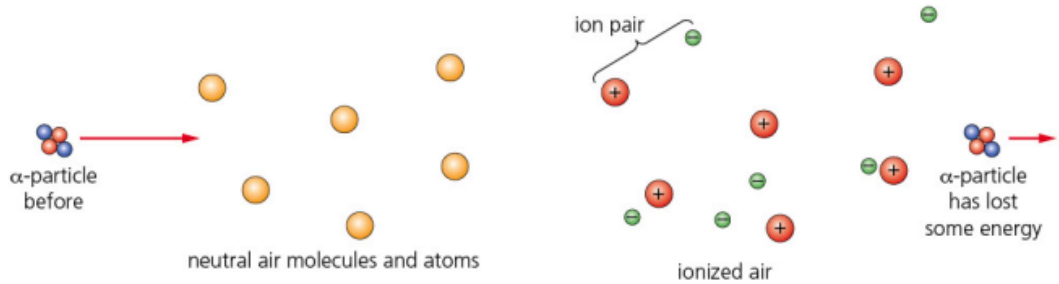
$$^{7}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}He + ^{1}_{0}n$$

Rest mass of lithium-7 nucleus	=7.0160u
Rest mass of tritium nucleus	=3.0161u
Rest mass of He nucleus	=4.0026u

Determine the minimum initial kinetic energy the bombarding neutron must have to initiate this artificial transmutation.

Ionizing Radiation

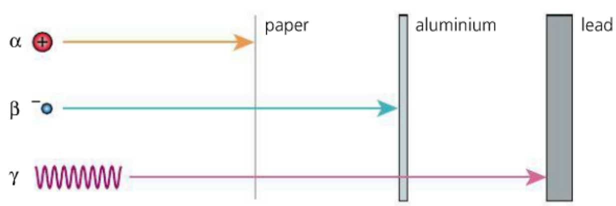
Ionization: removal of an electron from an atom/molecule leaving it positively charged



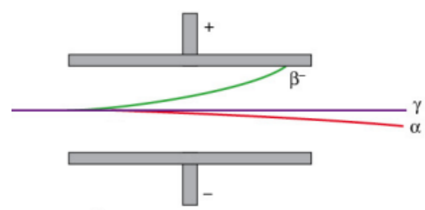
Formation of ion pairs by alpha particles from molecules in the air

Ionizing Radiation – As this radiation passes through materials, it "knocks off" electrons from neutral atoms thereby creating an ion pair: free electrons and a positive ion. 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.

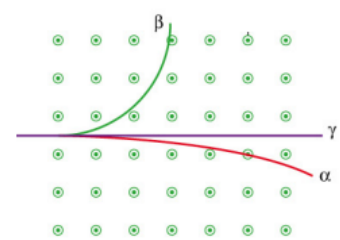
Properties of some common ionizing radiations



Absorption/penetrating characteristics (Range)



Behaviour of ionizing radiations in an electric field



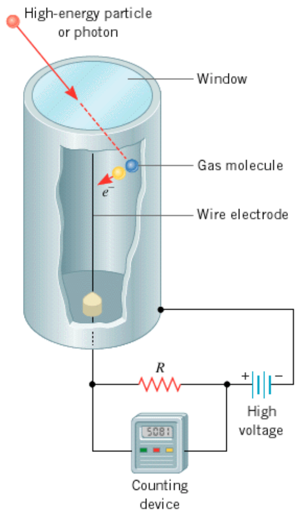
Behaviour of ionizing radiations in a magnetic field

Emission	Composition	Range	Ionizing ability
α	a helium nucleus (2 protons and 2 neutrons)	low penetration, biggest mass and charge, absorbed by a few centimetres of air, skin or thin sheet of paper	very highly ionizing
β	high energy electrons	moderate penetration, most are absorbed by 25 cm of air, a few centimetres of body tissue or a few millimetres of metals such as aluminium	moderately highly ionizing
γ	very high frequency electromagnetic radiation	highly penetrating, most photons are absorbed by a few cm of lead or several metres of concrete few photons will be absorbed by human bodies	poorly ionizing – usually secondary ionization by electrons that the photons can eject from metals

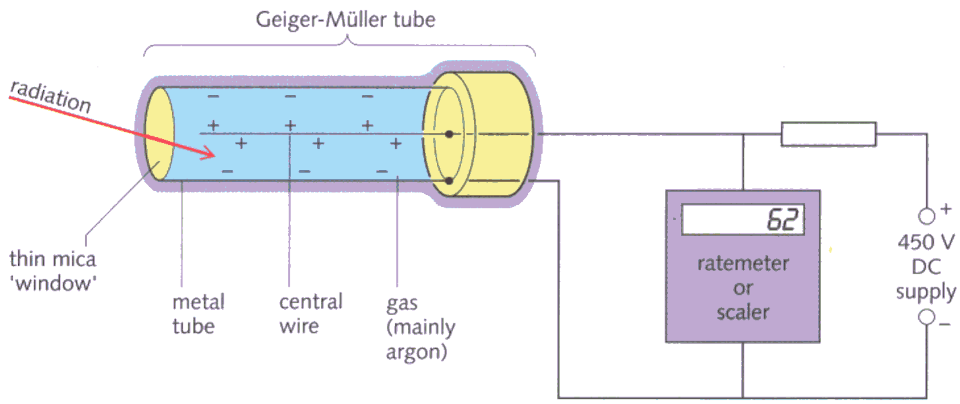
1. Which type of radiation has the greatest penetrating ability? Why?

2. Which type of radiation has the greatest ionizing ability? Why?

3. How can ionizing radiations be detected?



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



A Geiger-Muller tube is a type of ionization chamber which contains a low-pressure gas. When gas molecules are ionized by radiation passing through, current flows between two electrodes and produces an audible "click." A counter also keeps track of the number of ionizations that occur.

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.

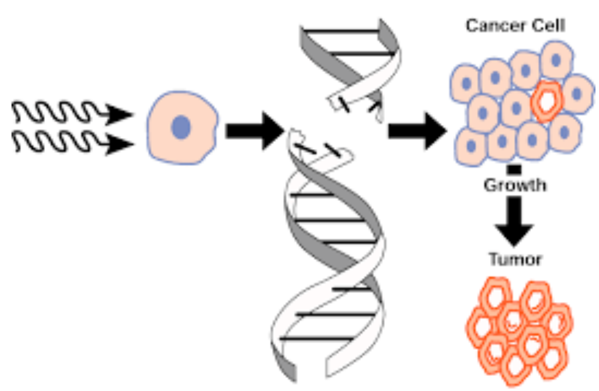
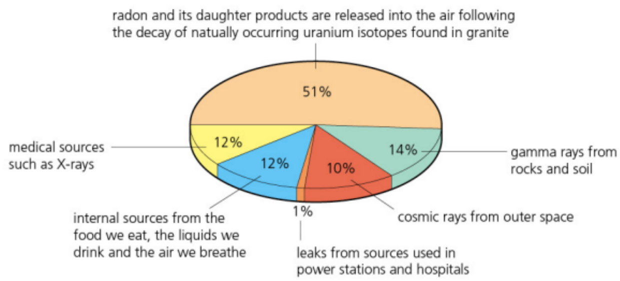


Figure 1. Development of cancer from mutation produced by ionizing radiation.

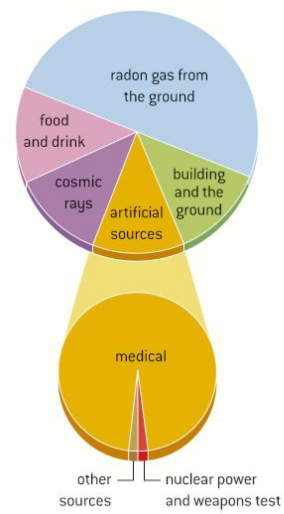
The amount of harm that radiation can cause is dependent on the number and energy of the particles. When a gamma photon is absorbed, the whole photon is absorbed so one photon can ionize only one atom. However, the emitted electron has so much energy that it can ionize further atoms, leading to damage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

On a positive note, rapidly dividing 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.

Background Radiation: We are exposed to ionizing radiation all the time from naturally-occurring sources. This is called *background radiation.*



Sources of background radiation in the UK



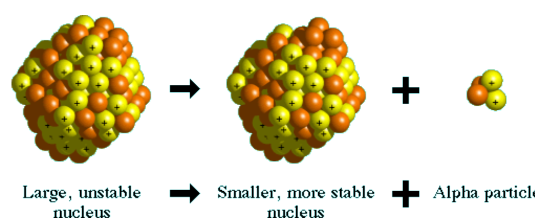
Radioactive Decay: when an unstable nucleus drops to a lower energy state by emitting one or more particles and energy

The particles emitted during radioactive decay are . . ..

Types of Radioactive Decay

I. Alpha Decay

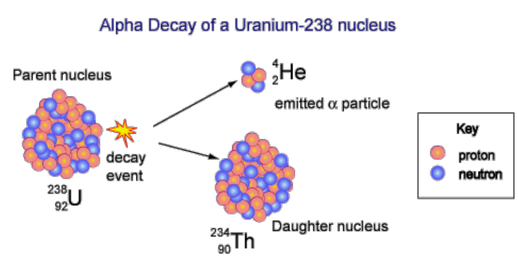
Alpha particle:



General reaction:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + energy$$

Example reaction:



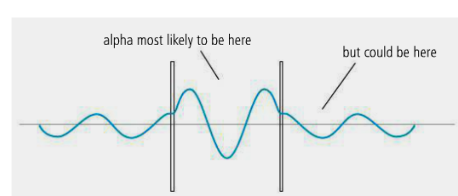
$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

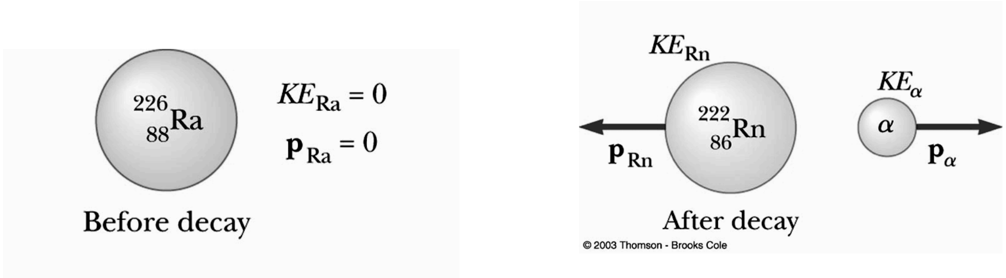
Radioactive decay reactions:

1. In what form is the released energy?

2. Where does the kinetic energy come from?

3. How does alpha decay occur?





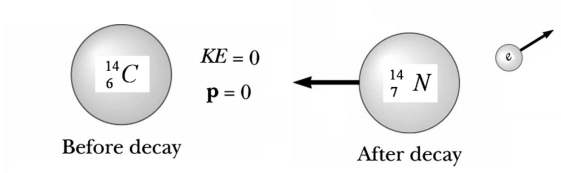
5. A radium nucleus, initially at rest, decays by the emission of an alpha particle into radon in the reaction described above. The mass of $_{88}{}^{226}$Ra is 226.025402 u and the mass of $_{86}{}^{222}$Rn is 222.017571 u and the mass of the alpha particle is 4.002602 u.

   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.

II. Beta Decay



Beta-minus particle:

Beta-plus particle:

Positron:

Neutrino and anti-neutrino:

Symbols:

Beta-minus decay

Example reaction:

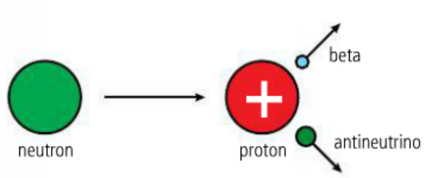
$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + ^{0}_{0}\bar{\nu} + energy$$

General equation:

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + ^{0}_{-1}e + ^{0}_{0}\bar{\nu} + energy$$

How does this happen?

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e + ^{0}_{0}\bar{\nu} + energy$$



Beta-plus decay

Example reaction:

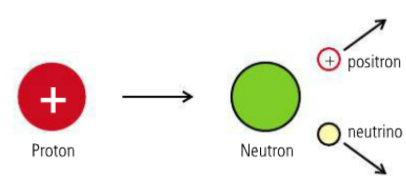
$$^{12}_{7}N \rightarrow ^{12}_{6}C + ^{0}_{+1}e + ^{0}_{0}\nu + energy$$

General equation:

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + ^{0}_{+1}e + ^{0}_{0}\nu + energy$$

How does this happen?

$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}e + ^{0}_{0}\nu + energy$$



III. Electron Capture

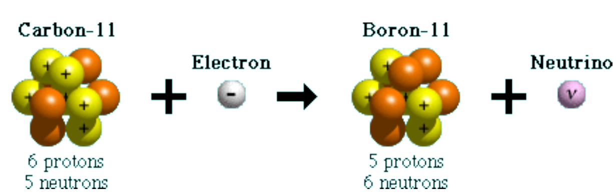
Electron capture is the opposite of beta emission. The capture of an electron allows a proton to turn into a neutron. In addition, both neutrinos and high-energy photons (gamma, X-ray) are emitted.

General equation:

$$^{A}_{Z}X + ^{0}_{-1}e \rightarrow ^{A}_{Z-1}Y + ^{0}_{0}\nu + energy$$

Example reaction:

$$^{11}_{6}C + ^{0}_{-1}e \rightarrow ^{11}_{5}B + ^{0}_{0}\nu + energy$$

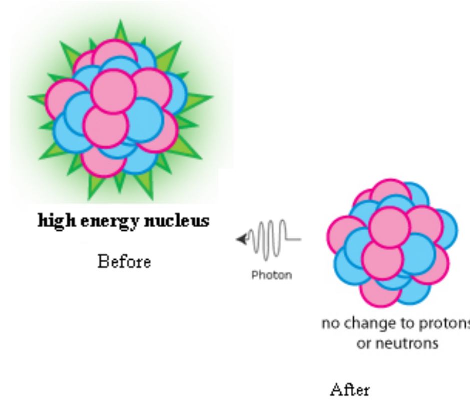


IV. Gamma Decay

Gamma particle:

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

General equation: $${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \Upsilon + energy$$



Where does the photon (energy) come from?

Complete the missing information in each reaction and state the type of reaction it is.
Include any particles that are missing from the reaction.

a) ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} +$ _____ Type: ________________

b) ${}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} +$ ______ Type: ________________

c) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} +$ ____________ Type: ________________

d) ${}^{105}_{47}\mathrm{Ag} +$ ______ $\rightarrow {}^{105}_{46}\mathrm{Pd}$ Type: ________________

e) ${}^{40}_{19}K \rightarrow$ _____ $+ {}^{40}_{20}\mathrm{Ca}$ Type: ________________

f) ${}^{244}_{94}\mathrm{Pu} \rightarrow {}^{240}_{92}U +$ _______ Type: ________________

g) ${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow$ ___________ $+ {}^{1}_{0}\mathrm{n}$ Type: ________________

h) ${}^{32}_{15}\mathrm{P} \rightarrow {}^{32}_{16}S +$ _______ Type: ________________

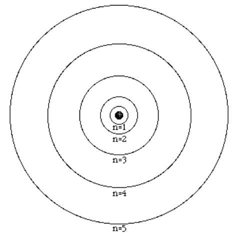
i) ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} +$ __________ Type: ________________

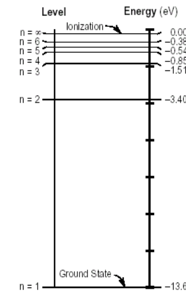
j) ${}^{14}_{6}C \rightarrow {}^{14}_{7}N +$ ______ Type: ________________

Energy Spectra

Atomic Energy Levels

Cause:



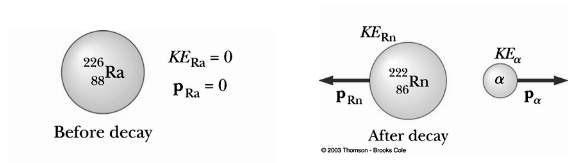


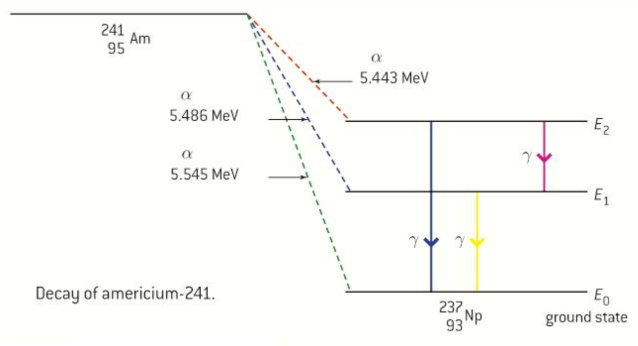
Energy Levels for the Hydrogen Atom

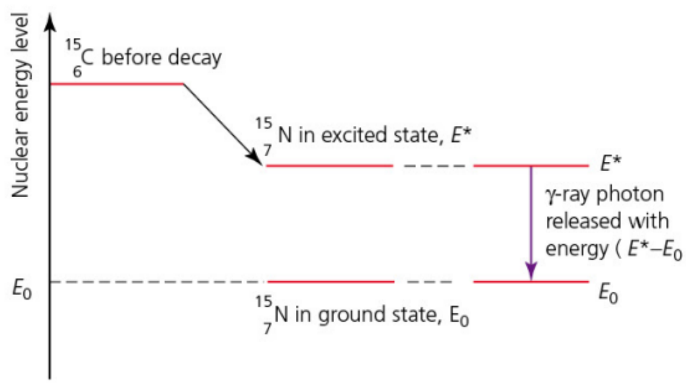
Nuclear Energy Levels

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.

Cause:







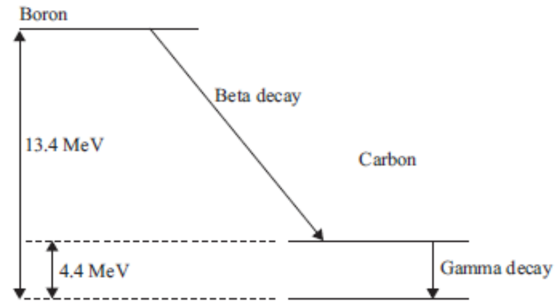
Rules for drawing nuclear energy level diagrams:

a) Alpha and beta decays are drawn to the side

b) Gamma decays are drawn vertically down

1. A nucleus of the isotope bismuth-212 undergoes α-decay into a nucleus of an isotope of thallium. A γ-ray photon is also emitted. Draw a labeled energy level diagram for this decay.

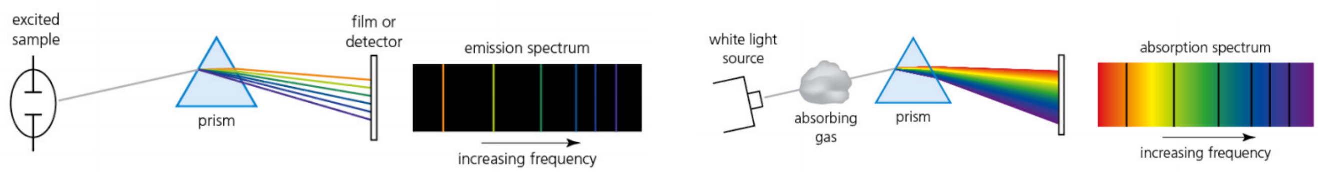
2. The diagram shows some of the nuclear energy levels of the boron isotope B-12 and the carbon isotope C-12. Differences in energy between the levels are indicated on the diagram. A particular beta decay of boron and a gamma decay of carbon are marked on the diagram.



a) Calculate the wavelength of the photon emitted in the gamma decay.

b) Calculate the maximum kinetic energy of the beta particle emitted in the beta decay indicated.

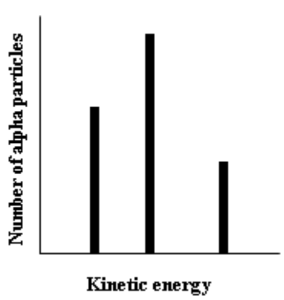
3. Evidence for atomic energy levels:

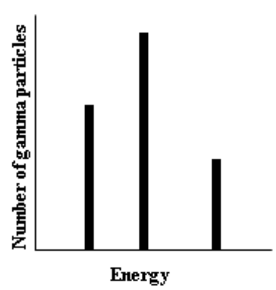


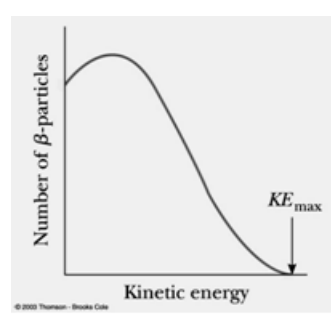
4. Evidence for nuclear energy levels:

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.)

Look at the energy spectra shown below for three types of radioactive decay.



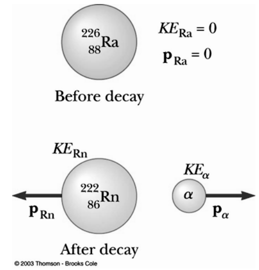




5. Which energy spectra are continuous and which are discrete?

6. Which energy spectra give evidence for the quantization of nuclear energy levels?

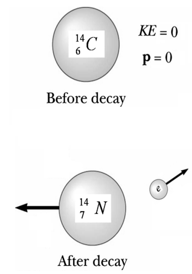
7. How does the discrete nature of the energy spectra for alpha and gamma decay give evidence for quantized nuclear energy levels?

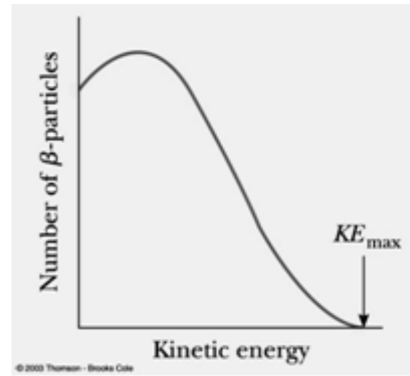


Since only one particle is ejected it carries with it all the kinetic energy from the nuclear energy level transition. Thus, if the KE of the alpha particle is quantized, so is the transition and so are the energy levels.

8. Why does the continuous spectrum of beta decay **not** show evidence for nuclear energy levels?

Since two particles are ejected, the KE can be split between them in any proportion so the spectrum is continuous and thus the quantization of the nuclear energy levels is not demonstrated.





9. Why is there a maximum to the kinetic energy of the emitted beta particles?

10. Why are so few beta particles emitted with the maximum kinetic energy?

Evidence for Atomic and Nuclear Structure

Atomic Feature	Evidence
Size of nuclei (nuclear radii)	Measurements made from charged particle scattering experiments such as the Geiger-Marsden experiment (Rutherford alpha particle scattering experiment)
Nuclear masses	Measured using a Bainbridge mass spectrometer
Existence of isotopes	Evidence provided by the results of Bainbridge mass spectrometer measurements: two atoms of the same atomic number (same number of protons) land at a different spot and so have a different mass, therefore must have a different number of neutrons.
Atomic energy levels (electrons energy levels)	Emission and absorption spectra (line spectra)
Nuclear energy levels	Discrete energy spectra of alpha particles in alpha decay Discrete energy spectra of gamma rays in gamma decay

Nuclear Physics - Part II

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

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.

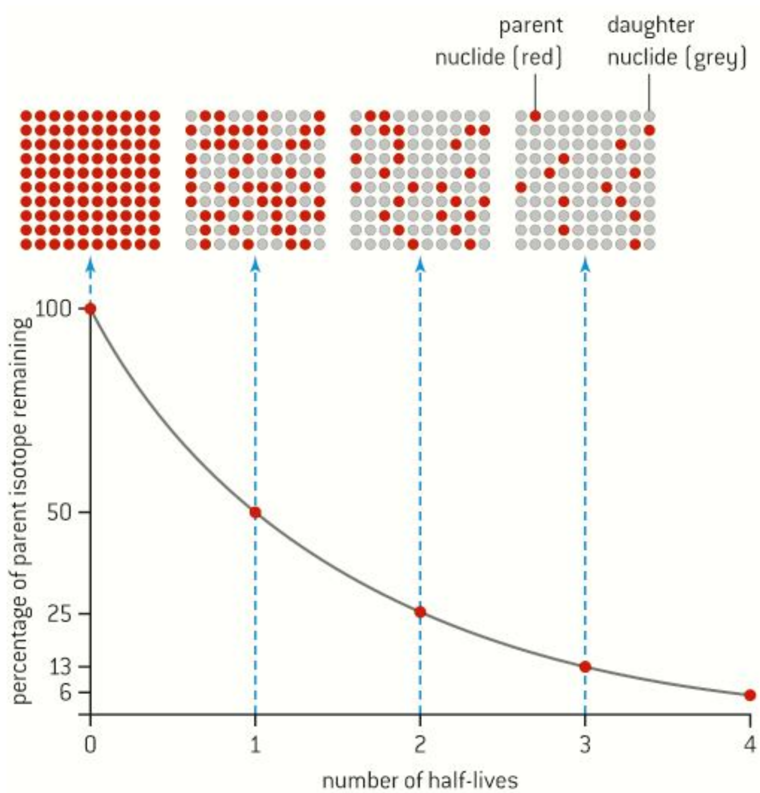
3) **Rate of decay decreases exponentially with time:** Any amount of radioactive nuclei will reduce to half its initial amount in a constant time, independent of the initial amount.

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

Units:

1. Determine the fractions of decayed and non-decayed nuclides after:

Number of Half-lives	Non-decayed Nuclides	Decayed Nuclides
1		
2		
3		
4		



Formula:

Where x =

2. Oxygen-15 is radioactive and decays by positron emission (beta+ decay) with a half-life of 0.10 seconds.

   a) How much of the sample will remain radioactive after 0.30 seconds?

   b) How much of the sample will have decayed after 0.30 seconds?

   c) How much of the sample will remain radioactive after 0.45 seconds?

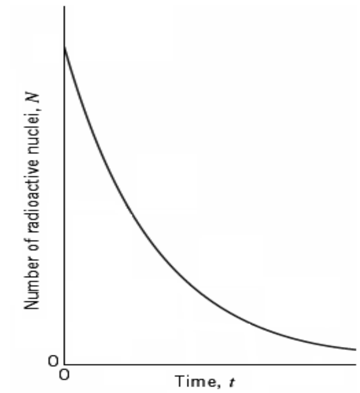
Activity (decay rate) (A) –

Formula: **Units:** **Standard units**:

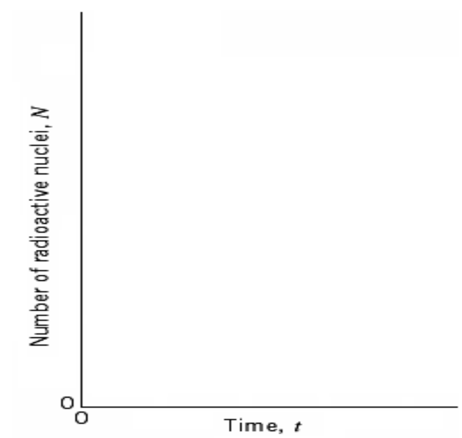
2. a) How can the activity of a radioactive sample be determined from a graph of radioactive nuclei vs. time?

   b) What happens to the activity of the sample over time?

   c) What happens to the half-life of the sample over time?



3. 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. Sketch graphs for both nuclides.



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.

Activity: **Initial Activity:**

Decay constant (λ) **Units:**

-

-

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

4. 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 fraction of it decaying in:

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

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

- the time taken for ½ of the radioactive nuclides in a sample to decay
- the time taken for the activity of a sample to decrease to ½ of its initial value

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

a) Calculate the decay constant for this nuclide.

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

c) How long will it take for 90% of the nuclei to decay?

d) What is the probability per unit time that a single radioactive nucleus in the sample will decay in the next ten days?

e) What is the probability per unit time that a single radioactive nucleus in the sample will decay in the next day?

NOTE:

6. The half-life of a radioactive isotope is 15 seconds. Calculate the percentage of the sample that will be left after 25 seconds.

7. 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?

8. Plutonium-239 (Pu-239) has a half-life of 2.4×10^4 years. Calculate the time taken for the activity of freshly-prepared sample of Pu-239 to fall to 0.1% of its initial value.

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

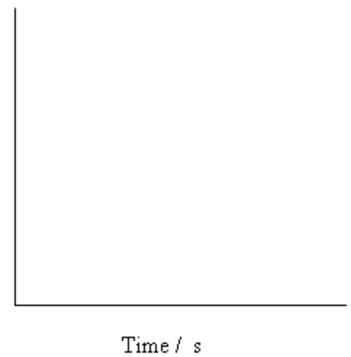
a) What is the initial activity?

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

c) How long will it take for the activity to fall to 1.00×10^{24} dy^{-1}?

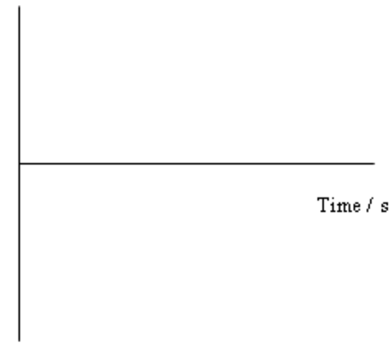
Graphs of Radioactive Decay

Math Model



Radioactive nuclei vs. time

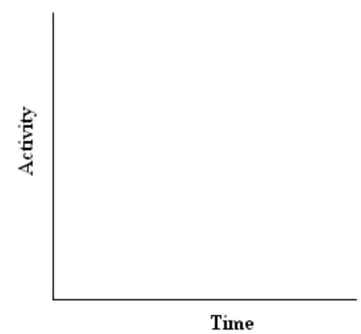
Activity of sample vs. time



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 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 so a different method is required.

a) First, the activity can be measured with a Geiger counter,

b) then the number of atoms might be determined chemically,

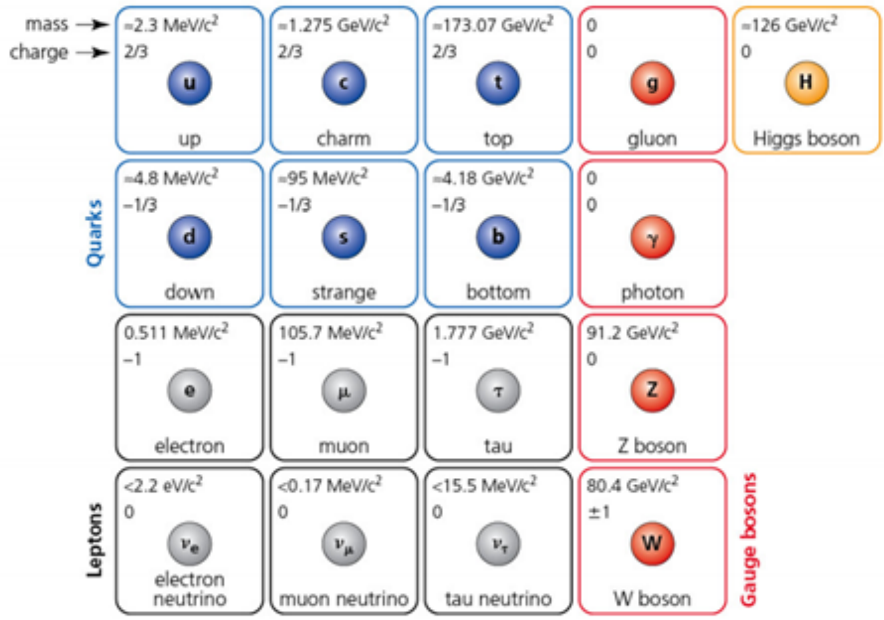
c) then the decay constant can be calculated

d) and thus the half-life can be calculated.

10. A 400 mg sample of carbon-14 is measured to have an activity of 6.5×10^{10} Bq. Use this information to determine the half-life of carbon-14 in years. Can the half-life graphically be determined by repeated measurements of the activity?

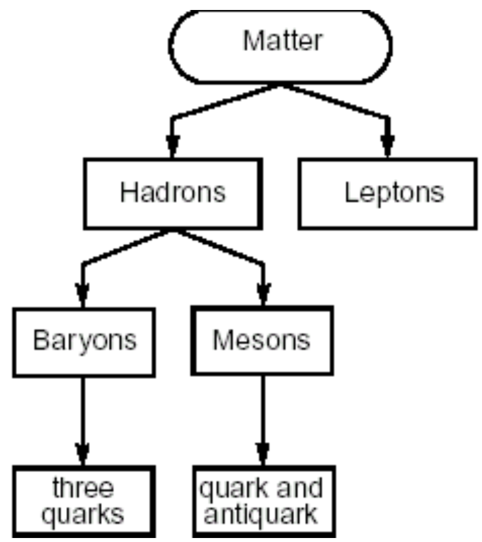
The Standard Model

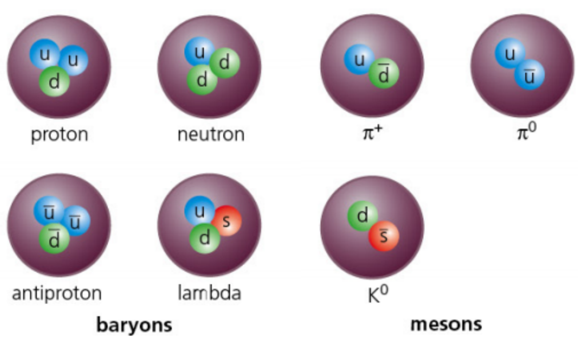
The Standard Model of particle physics is the theory that says all matter is composed of combinations of six types of quarks (and six antiquarks) and six types of leptons (and six antileptons), as well as four types of gauge bosons (exchange particles) that mediate the four fundamental forces, and the Higgs boson. This is the currently accepted theory. Each of these particles is considered to be fundamental (or elementary) which means that they have no internal structure, that is, that they are not made out of smaller constituents. Gravity is not explained by the Standard Model.



The Standard Model

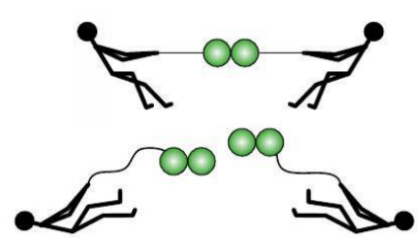
According to the Standard Model, all matter particles can be classified according to the scheme shown at right.





Examples of some hadrons

Quark Confinement – Isolated quarks cannot be observed. If sufficient energy is supplied to a hadron in an attempt to isolate a quark, the energy supplied will produce more hadrons or mesons rather than isolated quarks since the strength of the strong interaction increases with distance.



Higgs Boson - According to original versions of the Standard Model, quantum mechanical calculations predicted that quarks and leptons (as well as the W and Z bosons) should have no mass, but measurements showed that they did. One solution to this problem would be if mass was not a property of the particle itself but a property of space. This is known as the Higgs field and the particle associated with it is called the Higgs boson. A particle with properties matching that of the Higgs boson was detected at the LHC in 2012.

Particle properties

Charge	Quarks			Baryon number		Charge	Leptons		
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$		-1	e	μ	τ
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$		0	υ_e	υ_μ	υ_τ
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1						All leptons have a lepton number of 1 and antileptons have a lepton number of −1			

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

Quantum Numbers - Every particle has certain properties that are assigned a number, such as:

a) c)

b) d)

NOTE: Antiparticles have same mass as corresponding particles but all quantum numbers are opposite.

NOTE: An antiparticle is usually denoted by a bar over the symbol. Three leptons are exceptions:

a) Electron (beta- particle): e^- and the antielectron (positron, beta+ particle): e^+
b) Mu particle (mu lepton, muon): μ^- and the antimuon (positive muon): μ^+
c) Tau particle (tau lepton, tauon): τ^- and the antitau (positive tau): τ^+

1. State the type and quantum numbers of each of the following particles:

Particle	Quark Contents	Type	Electric Charge	Baryon Number	Lepton Number	Strange-ness
Up	-					
Anti-bottom	-					
Strange	-					
Electron	-					
Beta+ particle	-					
Tau neutrino	-					
Proton						
Anti-neutron						
Lambda (Λ^o)	uds					
Antimuon (μ^+)	-					
Pion (π^+)	$u\bar{d}$					
Omega(Ω^-)	sss					
B-zero (B^o)	$d\bar{b}$					
Kaon (K^+)	$u\bar{s}$					

Conservation Laws - In all particle reactions, these four quantum numbers are conserved.

Exception: Strangeness is conserved in strong and electromagnetic interactions, but not when a particle containing a strange quark or antiquark decays by the weak interaction.

2. Determine if the following particle reactions are possible:

$$n \rightarrow p + e^- + \overline{v}$$

a)

Charge				
Baryon #				
Lepton #				
Strangeness				

Possible?

$$p \rightarrow n + e^+ + v$$

b)

Charge				
Baryon #				
Lepton #				
Strangeness				

Possible?

$$n + p \rightarrow e^- + \overline{v}$$

c)

Charge				
Baryon #				
Lepton #				
Strangeness				

Possible?

$$\mu^- \rightarrow e^- + \gamma$$

d)

Charge			
Baryon #			
Lepton #			
Strangeness			

Possible?

$$p + \tau^- \rightarrow n + \pi^0$$

where π^0 is $u\overline{u}$

e)

Charge				
Baryon #				
Lepton #				
Strangeness				

Possible?

$$p + \pi^- \rightarrow K^0 + \Lambda^0$$

Which is: $uud + \overline{u}d \rightarrow d\overline{s} + uds$

f)

Charge				
Baryon #				
Lepton #				
Strangeness				

Possible?

$$K^- + p \rightarrow K^0 + K^+ + \Omega^-$$

Which is:

g)

Charge					
Baryon #					
Lepton #					
Strangeness					

Where . .

Particle	Quark structure
K^-	$s\overline{u}$
K^+	$u\overline{s}$
K^0	$d\overline{s}$

Possible?

Force	Range	Relative strength	Roles played by these forces in the universe
Gravitational	∞	1	binding planets, solar system, sun, stars, galaxies, clusters of galaxies
Weak nuclear	$\approx 10^{-18}$ m	10^{24}	(W^+, W^-): transmutation of elements (W^0): breaking up of stars (supernovae)
Electromagnetic	∞	10^{35}	binding atoms, creation of magnetic fields
Strong nuclear	$\approx 10^{-15}$ m	10^{37}	binding atomic nuclei, fusion processes in stars

3. Rank the four fundamental forces/interactions from strongest to weakest:

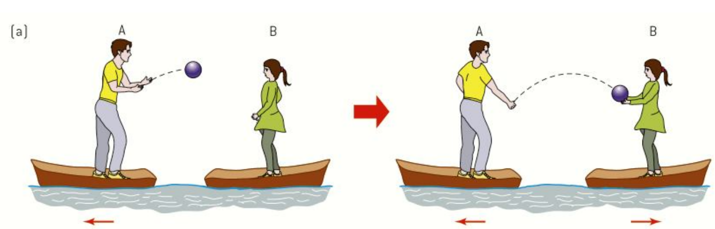
The only interaction in which a quark can change into another quark (or a lepton into another lepton) is the . . .

The interaction that involves neutrinos is the . . .

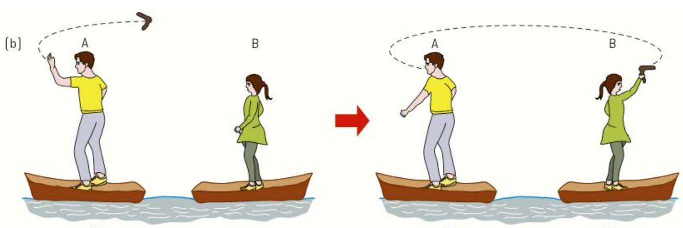
Force	Exchange particle	Acts on
Gravitational	gravitons (undiscovered)	all particles
Weak nuclear	W^+, W^- and Z^0 bosons	quarks and leptons
Electromagnetic	photons	electrically charged particles
Strong nuclear	gluons (and mesons)	quarks and gluons (and hadrons)

4. What are "exchange particles" or "gauge bosons?"

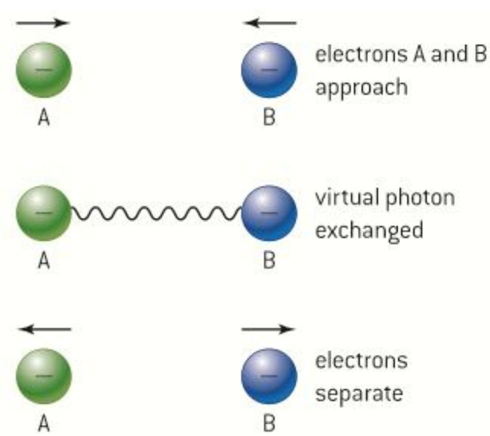
NOTE:



Analogy of an exchange particle mediating a repulsive force between two objects



Analogy of an exchange particle mediating an attractive force between two objects



Exchange of a virtual photon that mediates the electromagnetic force of repulsion between two electrons

Feynman Diagrams - These are graphical representations, developed by the American physicist Richard Feynman, that represent interactions between particles. It isn’t supposed to show the paths of the particles, just the nature of the interactions. These diagrams can be used to find the probability of an interaction occurring as well as to predict new interactions.

Rules for constructing Feynman diagrams

a) The x-axis represents time, going from left to right, and the y-axis represents space. NOTE: Sometimes these two axes are reversed.

b) Quarks or leptons are shown by solid lines with arrows.

c) Exchange particles are shown either by wavy or broken lines (photons, W and Z bosons) or a curly lines (gluons).

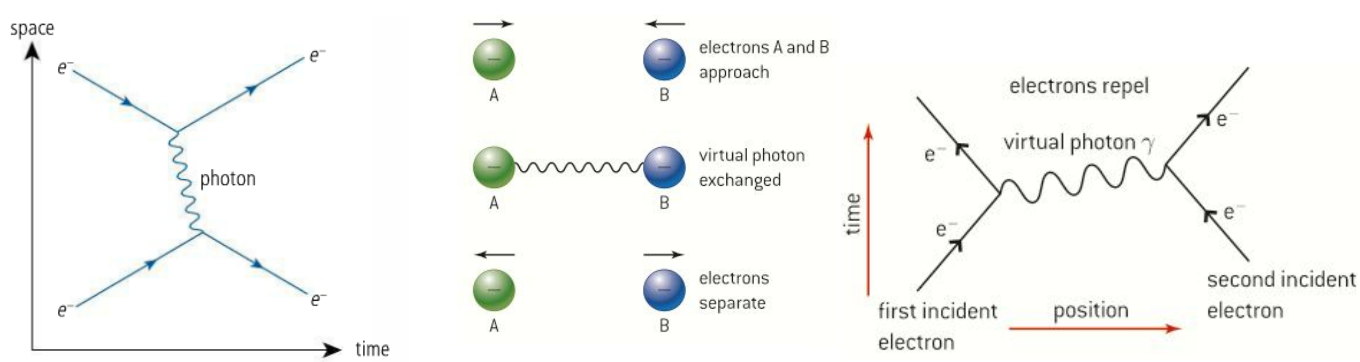
d) Time flows from left to right. Arrows from left to right represent particles travelling forward in time. Arrows from right to left represent antiparticles travelling forward in time.

e) A junction or vertex (point where lines meet) is made up of two solid lines (two particles) and one wavy/dashed/curly line (exchange particle). Each vertex has one arrow going in and one arrow going out.

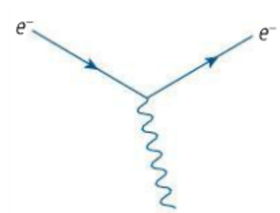
f) Vertices represent interactions so at each vertex all the conservation laws must apply.

Examples of Feynman Diagrams

1. Electromagnetic interaction between two electrons, shown using both possible sets of axes.

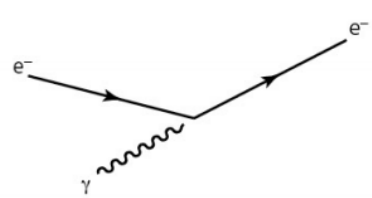


2.



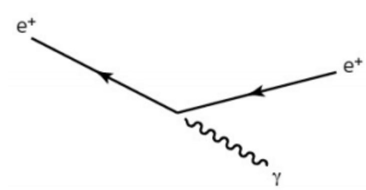
an electron emits a photon

3.



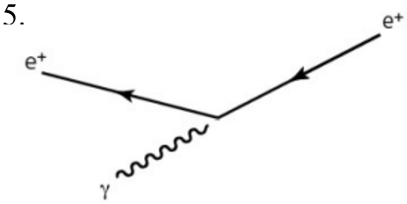
an electron absorbs a photon

4.



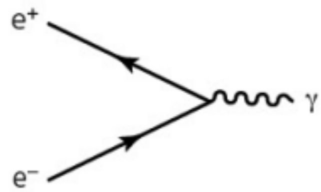
a positron emits a photon

5.



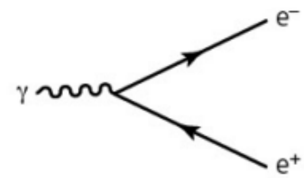
a positron absorbs a photon

6.



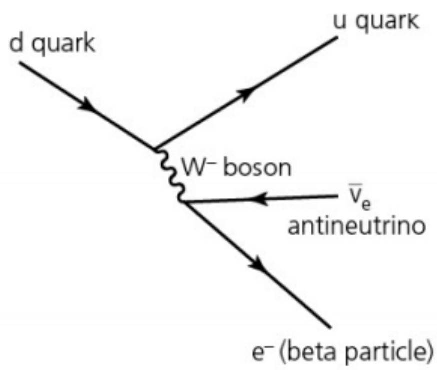
"Pair annihilation": an electron and positron annihilate into a photon

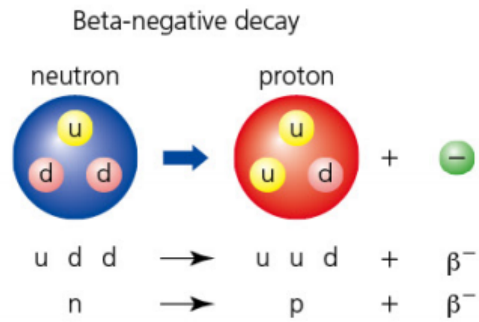
7.



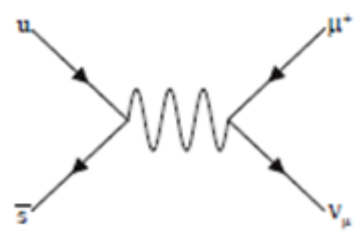
"Pair production": a photon spontaneously produces an electron and positron

8. Beta-minus decay



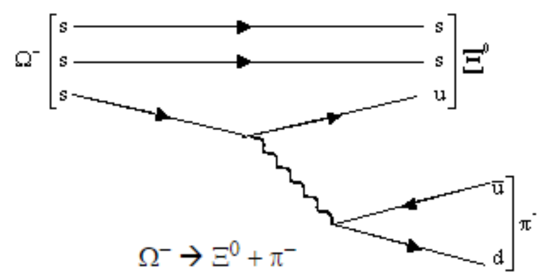


9.



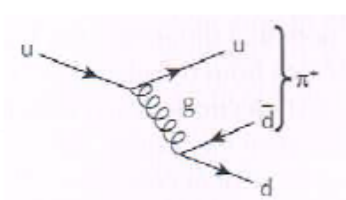
The kaon ($K^+ = u\bar{s}$) decays into an antimuon and a neutrino

10.



A omega minus (sss) decays into a xsi zero (uss) and a pi minus.

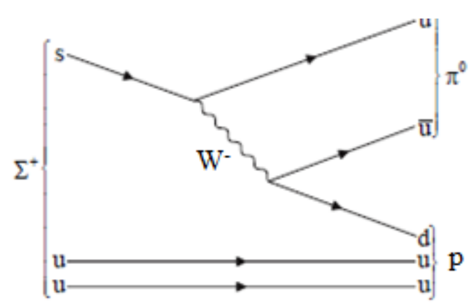
11.



An up quark (in a proton) emits a gluon which in turn tranforms into a down/antidown quark pair. This reaction could take place as a result of a proton-proton collision:

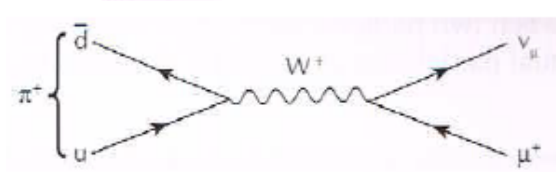
$$p + p \rightarrow p + n + \pi^+$$

12.



A Σ^+ particle decays into a π^0 particle and a proton

13.



Pion decay: The quark and antiquark annihilate to produce a W^+ particle. This decays into an antimuon and a muon neutrino.