Chapter 4

Radioactive Decays – transmutations of nuclides

Radioactivity means the emission of alpha (α) particles, beta (β) particles, or gamma photons (γ) from atomic nuclei. **Radioactive decay** is a process by which the nuclei of a nuclide emit α, β or γ rays. In the radioactive process, the nuclide undergoes a **transmutation**, converting to another nuclide.

> *A scientist must question dogma and authority, because they are frequently wrong*
> Arthur Holly Compton

The variation of radioactivity over time is called **decay kinetics**. The characteristics of kinetics are expressed in **decay constant** and **half life**. Variations of radioactivity in mixtures of radioactive nuclides and consecutive decays are often considered, and decay kinetics serves science and technology in many applications.

In radioactive decay processes, some of the things are conserved, meaning they do not change. The number of nucleons before and after the decay is the same (conserved). So are electric charges and energy (including mass). The relationship between nuclides is best seen in a chart based on the number of neutrons and the number of protons. Such a chart clearly shows relationships among isobars, isotopes, isotones, and isomers.

The mass number of a nuclide does not change in β and γ decays, but it decreases by 4 in α decay due to the emission of a helium nucleus. Thus, there are four families of radioactive series based on mass numbers starting with ^{232}Th, ^{237}Np, ^{238}U, and ^{235}U respectively. Masses of their family members are in the 4*n*, 4*n* +1, 4*n* +2, 4*n* +3 categories, where *n* is an integer. Sources of natural radioactive materials such as radium, radon, and polonium, came from the natural occurring radioactive nuclides ^{235}U, ^{238}U, and ^{232}Th, whereas ^{237}Np is a man made nuclide, because this nuclide no longer exists in the planet Earth.

Studies of radioactive decays led to theories of nuclear stability and nuclear structure. Some of these theories will be examined as we take a closer look at atomic nuclei. Concepts such as energy states of nucleons, angular momentum, parity of nuclear energy state *etc*. will be introduced. These concepts and theories provide the tools for the discussion of energy in radioactive decays.

We will look at radioactivity and decay kinetics, look at transmutation of nuclides in radioactive decay, the nuclide chart, which is used to discuss the four families of radioactive decay, look at atomic nuclei closely, and look at the energy aspect in radioactive decays.

Radioactivity and Decay Kinetics

The emission of alpha (α), beta (β) or gamma (γ) rays by a sample of substance is called **Radioactivity**. A sample may emit one or more types of radioactive ray. The number of α, β or γ rays emitted per unit time is called the **decay rate**. The study of radioactive material requires the identification of types of rays emitted, decay rates, changes in decay rates, and the nuclides in the sample that emit the rays. The variation of decay rates over time from a fixed amount of nuclide is called **decay kinetics**, which is an important topic in the study of radioactivity.

Radioactivity Units, Decay Constants and Half Lives

The **decay rate** is measured in decays per unit time, and the SI unit for radioactivity is **becquerel** (Bq) which is 1 decay or disintegration per second (dps)*. The widely used unit **curie** (Ci) defined as the decay rate of 1.0 g of radium earlier is 3.700×10^{10} Bq.

- How are decay rates related to the amounts of radioactive nuclide?
  How do decay rates vary over time?
- Do chemical states of a radioactive nuclide (element) affect its decay rate?

A Summary of Decay Kinetics

N_o is number of nuclei at $t = 0$,
N is the number of nuclei at t.
A is the Radioactivity.

$$A = -\frac{dN}{dt} = \lambda N$$

Integration gives

$$N = N_o\, e^{-\lambda t}$$

$$\ln N = \ln N_o - \lambda t$$

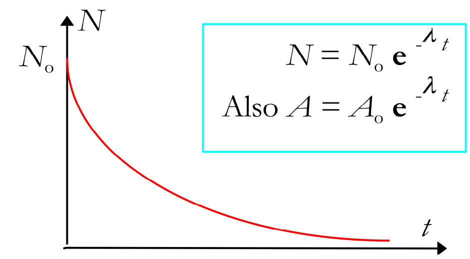
Samples containing the same amount of uranium and thorium have very different decay rates. A radioactive source contains one or more radioactive nuclides. The decay rate of a sample is proportional to the amount of radioactive nuclide present. Decay rate of a nuclide is unaffected by its chemical or physical state, studies have shown.

The amount of radioactive nuclide can be expressed in unit g, mole, or number of nuclei (N). The disintegration rate of N nuclei (called activity, A, or in mathematical notation $-dN/dt$) at any given time is proportional to N. The proportional constant is called the **decay constant**, λ. A summary of decay kinetics is given in the text box.

* Long before SI units were established, radioactivity was compared to a quantity called **curie** (Ci), which was originally the radioactivity of 1.0 g of radium. One Ci is now defined as the quantity of any radioactive material that gives 3.700×10^{10} dps or Bq. Thus, Ci is considered a cgs (cm, gram & second) unit, and 1 Ci = 3.700×10^{10} Bq.

Because of radioactive decay, the number of nuclei (N) decreases exponentially with time. The period of time required for half of the nuclei to decay is called **half-life**, ($t_{½}$). The decrease of N as a function of time, t, is shown here. The product of half-life, $t_{½}$, and the decay constant λ is a constant (ln 2 = 0.693):

Variation of N as a function of time *t*



$$t_{½}\,\lambda = 0.693\ .$$

This relationship indicates that the faster a nuclide decays, the shorter its half-life and vice versa. Since the radioactivity, A, is proportional to N, the radioactivity of a sample also decreases exponentially. The variation of A with time is the same as the variation of N with time. If A_0 is the initial radioactivity, $A_0/2$ is the radioactivity after one half-life, and the radioactivity is reduced to $A_0/4$ after two half-lives.

The average life expectancy of radioactive nuclei is larger than the half-life. The average life called **life-time, τ,** is the average life-time of all nuclei, and it can be shown that

$$\tau = 1/\lambda = 1.44\ t_{½}.$$
$$\text{At } t = \tau = 1/\lambda,\ A = A_o/\mathbf{e} = 0.368\ A_o$$

Since the variation of N or A with time t is not linear, proportionality should not be used to evaluate the activity at various times. Exponential functions

$$N = N_o\,\mathbf{e}^{-\lambda t}$$
$$A = A_o\,\mathbf{e}^{-\lambda t}$$

or logarithms

$$\ln N = \ln N_o - \lambda\,t$$
$$\ln A = \ln A_o - \lambda\,t$$

should be used. These equations shows the real relationship between N (or A) and time, t. From these equations, you know that plots of ln N, log N, ln A, or log A against time, t, are straight lines. For example, when $t = ½\ t_{½}$, $N = 0.707\ N_o$, not 0.75 N_o. Similarly, you can confirm that $A = 0.354\ A_o$, when $t = {}^{3}/_{2}\ t_{½}$.

Skill Building Questions:

1. *The half-life for ^{14}C has been determined to be 5730 years. What is the decay constant λ?*
   What is its average life, τ? (λ = ln(2)/5730 = 1.21×10^{-4} /y.)

2. *How many nuclei are present in 1.0 g of ^{14}C?* ($N = 6.023 \times 10^{23} / 14 = 4.302\times10^{22}$ nuclei.)
   What is the radioactivity of 1.0 g of ^{14}C? ($A = \lambda N = 5.20\times10^{18}$ d. per year (d./y) = 1.42×10^{16} d.

per day = 5.94×10^{14} d. per hour = 9.90×10^{12} d. per minute = 1.65×10^{11} Bq = 4.5 Ci, very high radioactivity.)
Plot the radioactivity A and log N of 1.g of ^{14}C over 20000 years. (Do the plots)

3. *What is the radioactivity of one gram of ^{238}U, whose half-life is 4.46×10^{9} y.?* (0.34 mCi)
Plot the radioactivity A and log N of 1.g of ^{238}U over 20000 years. (Do the plots)

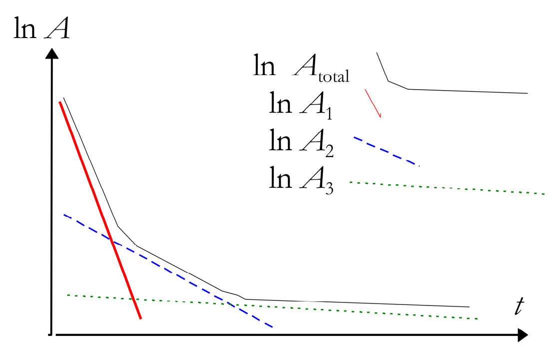
4. *Suppose that 1.0 Ci of radium ($^{226}Ra \rightarrow {}^{222}Rn + {}^{4}\alpha$) was isolated in 1900, what was its radioactivity then and what is its radioactivity now? (The half-life of nuclide ^{226}Ra is 1600 y?*
Plot the radioactivity A and log N of 1.g of ^{226}Ra over 20000 years. (Do the plots)

Mixtures of Radioactive Nuclides

If a sample contains two or more radioactive nuclides, each will decay according to its own half-life or decay constant. In the case of a mixture of unrelated radioactive nuclides, the **apparent or total radioactivity** is the sum of all the activities, and a plot of total radioactivity versus time is not very informative to reveal each component, because they are all curves. A better way to analyze this type of data is to plot the logarithm of the radioactivity against time, since

$$\ln A_{total} = \ln A_1 + \ln A_2 + \ln A_3 + \ldots$$
$$= (-\lambda_1 N_1 - \lambda_2 N_2 - \lambda_3 N_3 - \ldots)\, t.$$

Apparent Radioactivity of 3 Nuclides



Thus, if the λ's are very different, the variations of ln A's will also be very different. Such a graph can easily be decomposed into all its components. When three radioactive nuclides are present in a sample, the plot of logarithms of the activities is sketched in a diagram shown here. The decay constants can be evaluated from the slopes of some sections in the curve of $\ln A_{total}$ at various times. The sketch is made with $\lambda_1 > \lambda_2 > \lambda_3$. Of course, the shapes are related to amounts of radioactive nuclides.

Radioactive mixtures can be of the same element with two or more isotopes or two or more different elements. Separation of elements can be done by chemical methods, but isotopes cannot be separated by ordinary chemical methods. Plots of ln A versus time are useful for showing the number of radioactive nuclides, determining the decay constants (or half lives), and confirming the number of radioactive nuclides in the sample.

Both natural occurring and synthetic radioactive materials are usually mixtures of radioactive nuclides. Chemical and physical means are required to purify samples of radioactive nuclides.

Skill Building Questions:

1. *The radioactivity of a sample measured at every 10 min interval are: 9876, 8465, 7258, 6222, 5333, 4572, 3919, 3359 …. Determine the half-life for the nuclide contained in the sample.*

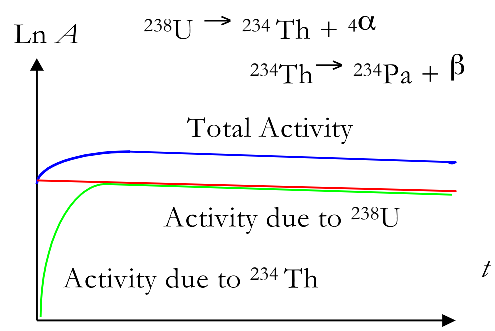
2. *A sample containing 10^{-6} g each of ^{222}Ra and ^{226}Ra, whose half-lives are 38 s and 1600 y respectively. What are the decay rates at t = 2, 6, 10, 20, 40, 80, 160, 1000, 10,000 min for each of the two radioactive nuclides?*
   What is the total radioactivity?
   Plot the data according to methods described above.

Consecutive Decay and Growth

Alpha decay of ^{238}U, actually leads to a beta emitting radioactive nuclide thorium, ^{234}Th, whose half-life is 24.1 days.

$$^{235}\text{U} \rightarrow {}^{234}\text{Th} + {}^{4}\alpha$$
$$^{234}\text{Th} \rightarrow {}^{234}\text{Pa} + \beta$$

Radioactivity of Decay Product



Since the half-life of ^{238}U is 4.47x10^{9} years, its decay rate remains constant over hundreds of years. However a freshly prepared ^{238}U sample will immediately start to decay at its rate of producing thorium, ^{234}Th. As soon as ^{234}Th nuclei are produced, they begin to emit β particles according to their decay constant. Thus, the β radioactivity of ^{234}Th will begin to grow until the rate of producing Th (which is equal to the rate of U decay) equals to the rate of its own decay; $\lambda_U N_U = \lambda_{Th} N_{Th}$. At such time, the activity due to Th is equal to the activity of U, and the total activity is twice that due to U. The amount of Th at this equilibrium state is a constant, $N_{Th} = (\lambda_U/\lambda_{Th}) N_U$. Since λ_U is very small compared to λ_{Th}, N_{Th}/N_U is a small fraction. In this consecutive decay scheme, U is called the **parent** and Th the **daughter** nuclide.

In case the daughter *D* has a long half-life compared to that of the parent *P*, the decrease of radioactivity due to *P* follows that of a single radioactive nuclide. The growth of radioactivity due to *D* is rather rapid, and reaches a maximum at time $t_m = \dfrac{1}{\lambda_D - \lambda_A} \ln \dfrac{\lambda_D}{\lambda_P}$. Eventually when the radioactivity of *P* becomes insignificant, the total activity is that of the daughter.

Actually, the decay of ^{234}Th to ^{234}Pa is not the end of the decay chain, because ^{234}Pa is a beta emitter with a half life 6.75 hours. In fact, many generations following ^{234}Pa are radioactive and a natural uranium mineral consists of a number of radioactive nuclides. The details of the transmutation will be described later, but this is mentioned here to show that the nature is very complicated.

This model describes some simple growth and decay cases, but natural growth and decay cases can be much more complicated. For an analysis of nature, much more complicated models are required. Mathematical skills are useful, but we will not get into this type at the present time.

Skill Building Questions:

1. *How many ^{234}Th nuclei are present in 1.0 g of ^{238}U when the rate of producing Th equals to its decay?*

2. *Discuss the growth of daughter nuclide D if the half-life of the parent nuclide P is 10 min. whereas the half-life of D is 100 min. Sketch a diagram to show the total activity, activities due to P and D respectively. Discuss the growth of daughter nuclide D if the half-life of the parent nuclide P is 100 min. whereas the half-life of D is 10 min. Sketch a diagram to show the total activity, activities due to P and D respectively.*

3. *You have a mixture of two radioactive nuclides X and Y and the radioactivity is 1000 Bq each. The half-life for X is 10 minutes, and that of Y is 100 minutes. Plot the total activity, the activity of X and activity of Y separately. Discuss the plots in view of the previous question.*

Applications of Decay Kinetics

Half-life of radioactive nuclides ranges from a microsecond for $^{219}Th^{90}$ to $4.46x10^9$ years for $^{238}U^{92}$. Measurements of both short and long half-life are difficult, the former requires a great speed, whereas the latter requires very sensitive instruments. As instruments become more and more sophisticated, shorter and longer half-lives have been measured. When the half-life is short, radioactivity of a small amount of the nuclide can be very high. However, the radioactivity is quickly reduced to undetectable level. Radioactivity of a long-lived nuclide lasts a long time, but a large amount is required for a reasonable level of radioactivity.

Nuclide	Half life
$^{219}Th^{90}$	1 μs
$^{26}Na^{11}$	1s
$^{40}Cl^{17}$	1.4 min
$^{32}P^{15}$	14.3 d
$^{14}C^{6}$	5730 y
$^{235}U^{92}$	$7.04x10^8$ y
$^{238}U^{92}$	$4.46x10^9$ y

The half-life is specific for a nuclide, unaffected by the chemical or physical state of the element. It can be used for the radioactive nuclide identifications. Half-life measurements are often done in order to identify the nuclide present. As pointed out in the previous two sections, sometimes the variation of apparent radioactivity gives us a hint about the sample. Apparent radioactivity of a radioactive nuclide mixture differs from that of consecutive decay and growth.

As we shall discuss later, some nuclides have more than one mode of decay. For example, a sample of ^{237}Ac is a source of alpha and beta particles, and this type is often called **branch decay**. Thus, applications based on decay kinetics should be done with care.

Anthropologists, biologists, chemists, diagnosticians, engineers, geologists, physicists, and physicians often use radioactive nuclides in their respective work. In these applications, decay kinetics is always an important factor to be considered. For example, when a physician requires a short-lived radioactive nuclide for his or her diagnosis of a patient, the sample must be manufactured in a nearby facility. A long-lived radioactive waste needs to be stored away for a long time before its radioactivity is reduced to a harmless level.

Dating is a process to determine the age of something since its creation. For example, the age of archaeological remains is often determined (dated) by measuring the radioactivity of ^{14}C in the sample. This is an application of ^{14}C decay kinetics. However, many other factors should be considered in this application in order to produce reliable data. We will discuss this application again after you have acquired more concepts.

Review Questions:

1. *Sodium-24 ^{24}Na is a β^- emitting nuclide with half life 15.02 h. It decays to give a stable nuclide ^{24}Mg. A medical preparation dated January 15, 2000 contains 0.1 Ci. How much radioactive ^{24}Na should there be on Feb. 15, 2000, when a physician used it for a patient?*

2. *A 1-Ci ^{235}U (half-life 7.08×10^8 y) waste has been stored in a waste dump on January 1, 1900. How much ^{235}U is left today?*
   What is the total radioactivity due to the decay of ^{235}U and nuclides derived from its decays?

3. *A plutonium bomb used 500 kg of ^{239}Pu in 1959. This bomb is sitting in a warehouse silo in the US desert. How much ^{239}Pu is left in the bomb today?* (The overall half-life for ^{239}Pu is 24400 y, and it has several decay modes)

4. *A hydrogen bomb used 5 kg of ^{3}T in 1959. This bomb is sitting in a warehouse silo in the US desert. How much ^{3}T is left in the bomb today?* (The half-life for ^{3}T is 12.26 y)

Transmutation of Nuclides in Radioactive Decay

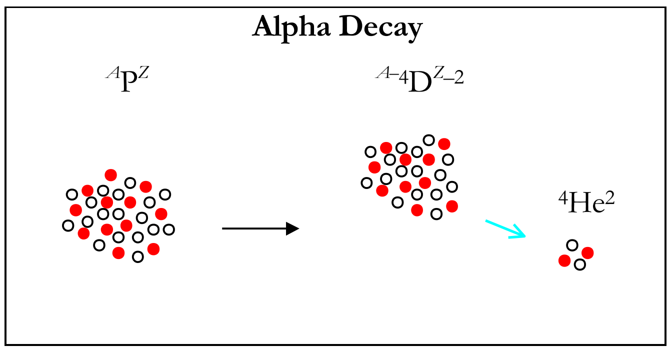
As you have seen that a nuclide converts a different nuclide when it emits a particle, α or β. This type of conversion is called **transmutation.** Depending on the charge and mass of the emitting rays, the mass number, *A*, or the atomic number, *Z*, or both may change. When *Z* changes, the parent nuclide is converted to a different element. In a γ photon decay, the energy and other properties of the nuclide change, but neither *A* nor *Z* changes.

In the transmutation, energy (including mass), charge, linear and angular momenta, and number of nucleons are conserved; their total values before and after the decay processes remain the same.

Transmutation of Nuclides in Alpha Decays

In an **alpha-decay process**, a helium nuclei, $^4\alpha^2$, is emitted from the nucleus. When it pick up two electrons, it forms a helium atom.

- What happens to the parent nuclide in an alpha decay process?



A helium nucleus consist of 2 protons and 2 neutrons (*A* = 4, and *Z* = 2). After an alpha emission, mass number *A* of the parent nucleus, *P*, decreases by 4 and its atomic number *Z* decreases by 2 to give a daughter nuclide *D*

$$^AP^Z \rightarrow {}^{A-4}D^{Z-2} + {}^4He^2$$

Most alpha emitters are elements with *Z* greater than 82 (*Z* for lead, Pb). This number is considered magic because there are four stable lead isotopes. The two heaviest stable nuclides ^{209}Bi and ^{208}Pb have 126 neutrons, and the number 126 is considered a magic number. Note that the number of electrons before and after the radioactive decay remains the same.

The following examples of α decay are given to illustrate the transmutation of nuclides in α decay, with their half-lives given in the parentheses:

$$^{235}U^{92} \rightarrow {}^{231}Th^{90} + {}^4\alpha^2 \ (t_{1/2},\ 7.13\times10^8\ y)$$
$$^{238}U^{92} \rightarrow {}^{234}Th^{90} + {}^4\alpha^2 \ (t_{1/2},\ 4.51\times10^9\ y)$$
$$^{208}Po^{84} \rightarrow {}^{204}Pb^{82} + {}^4\alpha^2 \ (t_{1/2},\ 2.9\ y)$$

It should be pointed out that some heavy nuclides have many decay modes. For example, ^{249}Bk (berkelium, $t_{1/2}$ = 314 d) has all three modes of decay: α (5.42 MeV), β (0.125 MeV), and γ (0.32 MeV). If one thinks of the alpha particle being the atomic nucleus of helium, the equations as written seem have an unbalanced numbers of electrons, but the conservation of the number of electrons is implicit in these equations.

Some light nuclides such as ^{5}He, ^{5}Li, ^{6}Be, ^{8}Be, ^{8}Li, and ^{9}Li, emit α particles due to the extreme stability of the helium nuclei:

$^5He \rightarrow {}^1n^0 + {}^4\alpha^2$ ($t_{1/2}$, 2×10^{-21} s),
$^5Li \rightarrow {}^1p^1 + {}^4\alpha^2$ ($t_{1/2}$, $\sim10^{-21}$ s),
$^8Be \rightarrow 2\,{}^4\alpha^2$ ($t_{1/2}$, 2×10^{-16} s).

Some rare earth (^{144}Nd, ^{146}Sm, ^{147}Sm, ^{147}Eu, ...^{174}Hf) are α emitters:

$^{144}Nd \rightarrow {}^{140}Ce + {}^4\alpha^2$ ($t_{1/2}$, 5×10^{15} y),
$^{174}Hf \rightarrow {}^{170}Yb + {}^4\alpha^2$ ($t_{1/2}$, 2×10^{15} y).

Skill Building Questions:

1. *Is it possible for the nuclide $^{238}U^{92}$ to convert to $^{206}Pb^{82}$ through a series of alpha decay? Depending on how you view this question, you may have yes or no as an answer. Give the reasons to support your answer.*

2. *After ^{235}U emits 7 α particles consecutively, what is the mass number of the resulting nuclide?*

3. *Write the decay equations for ^{8}Li, ^{9}Li, ^{146}Sm, ^{147}Sm, and ^{177}Eu.*

Transmutation of Nuclides in Beta Decays

The emission of a negative electron, β^-, a positive electron (positron), β^+ or the capture of an atomic orbital electron (EC) is called a **beta decay process**.

- What happens to the nuclide in a beta decay process?

In any of the three beta decays, the mass number, *A*, of the parent nuclide, *P*, does not change. Its atomic number, *Z,* changes, because the numbers of neutrons and protons change to give the daughter nuclide *D*. Nuclides with the same mass number are called **isobars**, and **beta decays cause transmutations among isobars**.

In a β^- emission, the atomic number *Z* increases by 1. The daughter nuclide has an atomic number *Z* + 1. The conservation of energy, number of leptons, linear and angular momentum calls for the emission of an antineutrino $\bar{\nu}$ or the absorption of a neutrino ν,

$$^AP^Z \rightarrow {}^AD^{Z+1} + \beta^- + \bar{\nu} \qquad \text{(Electron emission)}$$

or

$$^{A}P^{Z} + \nu \rightarrow {}^{A}D^{Z+1} + \beta^{-} \text{ (antineutrino ignored).}$$

Positron emission and electron capture decrease the atomic number by one. Accompanying these processes are neutrino emissions, or antineutrino absorptions.

Positron emission is represented by

$$^{A}P^{Z} \rightarrow {}^{A}D^{Z-1} + \beta^{+} + \nu$$

or

$$^{A}P^{Z} + \bar{\nu} \rightarrow {}^{A}D^{Z-1} + \beta^{+}.$$

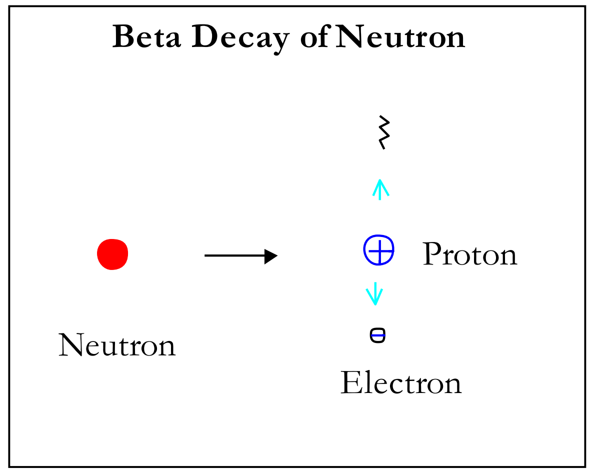
Typical electron capture is represented by

$$^{A}P^{Z} + e^{-} \rightarrow {}^{A}D^{Z-1} + \nu$$

or

$$^{A}P^{Z} + e^{-} + \bar{\nu} \rightarrow {}^{A}D^{Z-1} + \nu$$

A neutron outside a nucleus is not stable, and it converts to a proton with the emission of a β^{-} particle plus an antineutrino. The energy of decay is 0.78 MeV, and its half-life is12 minutes. The equation is



Beta Decay of Neutron

$$^{1}n^{0} \rightarrow {}^{1}p^{1} + \beta^{-} + \bar{\nu}$$

There are many natural β^{-} emitting nuclides. Carbon-14, ^{14}C, produced in nature by cosmic ray bombardment of nitrogen nuclei, is a beta emitter with half life 5720 y. Nuclides $^{40}K^{19}$, $^{50}V^{23}$, $^{87}Rb^{37}$, and $^{115}In^{49}$ are still present due to their long half lives.

$$^{14}C^{6} \rightarrow {}^{14}N^{7} + \beta^{-} + \bar{\nu} \qquad (t_{1/2}, 5720 \text{ y})$$
$$^{40}K^{19} \rightarrow {}^{40}Ca^{20} + \beta^{-} + \bar{\nu} \quad (1.27\times10^{9} \text{ y})$$
$$^{50}V^{23} \rightarrow {}^{50}Cr^{24} + \beta^{-} + \bar{\nu} \quad (6\times10^{15} \text{ y})$$
$$^{87}Rb^{37} \rightarrow {}^{87}Sr^{38} + \beta^{-} + \bar{\nu} \quad (5.7\times10^{10} \text{ y})$$
$$^{115}In^{49} \rightarrow {}^{115}Sn^{50} + \beta^{-} + \bar{\nu} \quad (5\times10^{14} \text{ y})$$

Here are some synthetic (man made) beta* emitters, although we will discuss the process of synthesizing nuclides in the Chapter on Nuclear Reactions:

* Many radioactive nuclides have been observed to emit more than one β particle before becoming stable. Theoretical consideration indicated that the probability of simultaneous or double beta decay was extremely small, but it has been observed. Transmutation of nuclides in double beta decay follows the same pattern as those in beta decay, except that the atomic number increases by 2 when 2 beta particles are emitted.

$^{90}\text{Sr}^{38} \rightarrow {}^{90}\text{Y}^{39} + \beta^- + \bar{\nu}$ ($t_{½}$, 29 y)
$^{116}\text{In}^{49} \rightarrow {}^{116}\text{Sn}^{50} + \beta^- + \bar{\nu}$ (54 m)

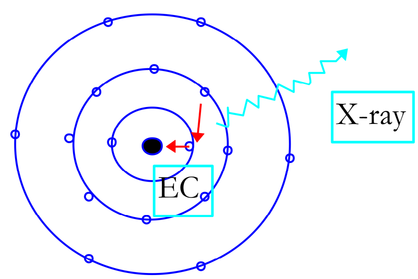
Properties of positrons are the same as those of electrons, but positions have positive instead of negative charges. Soon after the discovery of positions, positron emission was detected. There are no natural positron emitters, and the first observed positron decay was also the first observed case of artificial radioactivity by I. and F. Joliot-Curie in 1934. After bombarding a fluorine compound with α particles, a trace radioactive nuclide $^{22}\text{Na}^{11}$ was isolated. They identified the emitted particles from $^{22}\text{Na}^{11}$ as positrons and the reaction is,

$^{22}\text{Na}^{11} \rightarrow {}^{22m}\text{Ne}^{10} + \beta^+ + \nu,$ ($t_{½}$, 2.6 y).

The neon isomer, ^{22m}Ne, emits (1.28 MeV) γ rays with a half life of 10^{-11} s. Some other positron emitters are:

$^{21}\text{Na}^{11} \rightarrow {}^{21}\text{Ne}^{10} + \beta^+ + \nu$ ($t_{½}$, 22s)
$^{30}\text{P}^{15} \rightarrow {}^{30}\text{Si}^{14} + \beta^+ + \nu$ (2.5 m)
$^{34}\text{Cl}^{17} \rightarrow {}^{34}\text{S}^{16} + \beta^+ + \nu$ (1.6 s)
$^{116}\text{Sb}^{51} \rightarrow {}^{116}\text{Sn}^{50} + \beta^+ + \nu$ (60 m)

Electron Capture and X-ray Emission

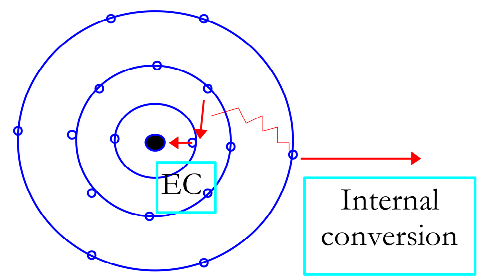


Even before the discovery of positron emission, Fermi and his coworkers had considered the possibility of reducing the nuclear charge by electron capture (EC). Luis Alvarez (1938), among researchers, looked for EC evidences. Both EC and positron emission lead to the same nuclide. Thus, β^+ decay and EC compete with each other. An EC process will consume an electron in the inner shell of an atom. When an outer electron fills its place, a characteristic X-ray photon will be emitted. X-rays are similar to γ rays, and as a result Alvarez measured the ratio of X-rays to positrons in the decay of many radioactive nuclides, which were synthesized by bombardments of α, proton or deuterium particles. In particular, he found the radioactive decay of ^{48}V to be a 1:1 split between β^+ emission and EC. The characteristic X-ray ^{48}V has a wavelength of 0.27 nm.

$^{48}\text{V} \rightarrow {}^{48}\text{Ti} + + \beta^+ + \nu$ (50%)
$^{48}\text{V} + e^- \rightarrow {}^{48}\text{Ti} + \nu$ (+ X-ray) (50%)

Instead of emitting X-rays, energy may also be used to eject an electron from the atomic orbital, and these electrons are called **internal conversion** electrons, which could be mistaken as β^- particles. In the same paper, Alvarez also checked results of other published data, and commented on the following EC process.

Electron Capture and Internal Conversion



$^{40}K + e^- \rightarrow {}^{40}Ar + \nu$ (+X-ray)
(also β^- decay; half life, 1.27×10^9 y)

$^{65}Zn + e^- \rightarrow {}^{65}Cu + \nu$ (+X-ray)
(also β^+ decay; 245 d)

$^{7}Be + e^- \rightarrow {}^{7}Li + \nu$ (+X-ray) (245 d)

These discoveries well establish the EC process. A gold atom ^{195}Au becomes a platinum atom ^{195}Pt due to an EC process:

$$^{195}Au^{79} + e^- \rightarrow {}^{195}Pt^{78} + \nu \text{ (+ X-ray)} \quad \text{(192 d)}$$

Skill Building Questions:

1. *What are isobars?*
   How do isobars convert into each other?

2. *Describe the three decay modes of the beta process: beta emission, positron emission, and electron capture.*

3. *How can electron capture be detected?*

4. *Is it possible for a nuclide to be both a beta emitter and a positron emitter?*
   (This question will be discussed later.)

Transmutation of Nuclides in Gamma Decay

. Gamma rays are high-energy photons emitted from atomic nuclei.

- What type of nuclides are likely gamma-ray emitters?

Nuclei having excess energy after α or β decay emit γ-ray photons to release the excess energy. This may take place at the same time as β emission:

$^{60}Co \rightarrow {}^{60}Ni + \beta + \bar{\nu} + \gamma$ ($t_{½}$, 5.24 y)

$^{24}Na \rightarrow {}^{24}Mg + \beta + \bar{\nu} + \gamma$ (2.75 MeV, $t_{½}$, 15 h).

A nuclide not releasing the excess energy immediately is called an **isomer**, which is often marked with a letter m after the mass number in the superscript. High-energy isomers undergo **isomeric transitions** (IT), by which, photons are released. For example,

$^{99m}Tc \rightarrow {}^{99}Tc + \gamma$

$^{60}Co \rightarrow {}^{60m}Ni + \beta + \bar{\nu}$

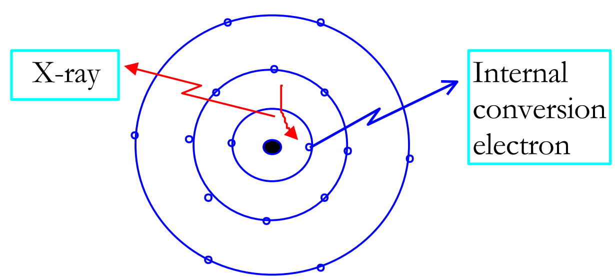
$^{60m}Ni \rightarrow {}^{60}Ni + \gamma$.

Not all beta decay leads to gamma emission. For example, the following is decay has no gamma emission:

$^{32}P \rightarrow {}^{32}S + \beta + \bar{\nu}$ (no gamma) ($t_{½}$, 14.3 d).

Another form of isomeric transition is **internal conversion**, a process by which a nucleus releases its extra energy by ejecting an electron from an atomic orbital. These electrons from the atomic orbital differ from β^- particles from atomic nuclei. Gamma decay includes internal conversion of atomic electrons.

Internal Conversion Electron and X-ray Emission



An internal conversion leaves a vacancy in the inner electron shell, and an electron from an outer shell will fill its place. The excess energy of the outer electron is used to emit an X-ray photon, or to emit yet another electron from an atomic orbital. This latter process is known as the **Auger effect**, and electrons so emitted are called **Auger electrons**.

Skill Building Questions:

1. *What are isomers? How do isomers release excess energy?*

2. *What happens to the parent nuclide in gamma decays?*

3. *Explain the following terms: internal conversion, Auger effect, Auger electron.*

Transmutations in Other Decay Processes

Radioactivity commonly refers to α, β, and γ decays. However, some other decay processes have been detected in the past few decades. Thus, we should also know how the nuclides change in these decay modes. As transmutations in α, β, and γ decays, the number of nucleons and charges remain the same before and after the decay.

Proton Decay: Proton emission reduces both atomic number and mass number by 1. Proton emission is not favorable, but proton emission has been observed in 1970 for the excited isomer ^{53m}Co. One and half percent (1.5 %) of $^{53m}Co^{27}$ ($t_{1/2}$ 0.24 s) emit protons, whereas the majority (98.5 %) of its nuclei emits β^+. These reactions are represented as follows (Friedlander *et al*, 1981):

$$^{53m}Co^{27} \xrightarrow{(1.5\ \%)} {}^{52}Fe^{26} + {}^{1}p^{1}$$
$$\xrightarrow{(98.5\ \%)} {}^{53}Fe^{26} + \beta^+ + \nu.$$

Spontaneous Fission: Some nuclides spontaneously split into two halves plus some neutrons. However, these nuclides also emit alpha particles. A few nuclides such ^{235}U, ^{238}U, ^{231}Th, ^{208}Po, $^{258}Fm^{100}$, $^{256}Fm^{100}$, $^{254}Cf^{98}$, $^{254}Fm^{100}$, $^{252}Fm^{100}$ and $^{250}Cm^{96}$ do undergo spontaneous fission. For example, ^{235}U undergoes spontaneous fission with a partial half life of 2×10^{17} years (compared to a half life of 4.5×10^{9} for α decay), and ^{254}Cf has a 60-day half life for spontaneous fission. Both nuclides are α emitters and their nuclei are more likely to undergo an alpha, α, decay than spontaneous fission.

Energy from 150 to 200 MeV is released as the fragments fly apart during spontaneous fission. Let us look at a particular example of spontaneous fission:

$$^{256}Fm^{100} \rightarrow {}^{140}Xe + {}^{112}Pd + 4\ n + \text{energy}$$

The products Xe and Pd are not unique. Other types of fragmentation are also possible. In addition to the list given above, high rates of spontaneous fission have been observed for $^{236,238}Pu$, $^{240,\ 242,\ 244,\ 246}Cm$, ^{249}Bk, $^{246,\ 248,\ 249,\ 250,\ 252}Cf$, $^{253,\ 254}Es$, and ^{254}Fm. All these are artificially made using accelerators.

Beta-delayed Alpha and Proton Emissions: Some light positron emitters produce daughters at excited states which are unstable with respect to alpha, proton, or neutron emission. For example, the following beta decays give an unstable nuclide ^{8m}Be, which splits into two alpha particles:

$$^{8}B \rightarrow {}^{8m}Be + \beta^+ + \nu \quad (t_{1/2},\ 0.78\ s)$$
$$^{8}Li \rightarrow {}^{8m}Be + \beta^- + \bar{\nu} \quad (t_{1/2},\ 0.82\ s)$$
$$^{8m}Be \rightarrow 2\,\alpha$$

These processes are called $\beta^+\alpha$, and $\beta^-\alpha$ decays respectively. Another example of $\beta^+\alpha$ is,

$$^{20}Na \rightarrow {}^{20}Ne + \beta^+ + \nu \quad (t_{1/2},\ 0.39\ s)$$
$$^{20}Ne \rightarrow {}^{16}O + \alpha$$

In a few cases, the daughter from positron emission will emit a proton. One such example is

$$^{111}Te \rightarrow {}^{111}Sb + \beta^+ + \nu \ (t_{1/2}, 19.5\ s)$$
$$^{111}Sb \rightarrow {}^{110}Sn + p^+.$$

This double emission can be represented by β^+p.

Double-beta decay: Double beta decay releases two beta particles simultaneously from a nucleus. Two antineutrinos are also released. Recently, the double-beta decay process is intensely studied for their neutrino emission.

Skill Building Questions:

1. *What is spontaneous fission?*
   Give some example nuclides that undergo spontaneous fission.

2. *What are beta-delayed proton emission and beta delayed alpha emission?*
   Use examples to illustrate these processes. What do $\beta^+\alpha$ and $\beta^-\alpha$ represent?

3. *What is double-beta decay process?*
   What are the products in a double beta decay of ^{100}Mo?
   Why is it intensely studied?

The Nuclide Chart for Nuclear Data

We have used the term **nuclide** to mean a type of nuclei with a specific numbers of protons and neutrons. A **chemical element** contains many isotopes. Not all isotopes have the same nuclear properties. Nuclear properties are unique for each nuclide. An excellent way to organize nuclear properties is a **nuclide chart** designed by D. T. Goldman of the General Electric Company when the information was not extensive. The Chart contains nuclear properties of all nuclides and shows relationship among nuclides. Today more information about a nuclide is known, and details are given in handbooks of isotopes, a term meaning nuclides here.

A Chart of Light Nuclides

In radioactive laboratories, a nuclide chart on the wall is a source of quick reference. Such a chart is too large to put in a book or shown on the computer screen. A small portion containing some light nuclides is given here to illustrate its organization and the information therein.

Be **4**			^{6}Be, ? p 6.019725	^{7}Be, 53.3 d EC 0.86 7.01928	^{8}Be, 0.06 fs 2 α 0.86 8.005305	^{9}Be, 100% 9.012182	^{10}Be, 1.6x10^{6} y β 0.5
Li **3**			^{5}Li, 0.18 s p or α 5.01254	^{6}Li, 7.42% 6.015121	^{7}Li, 92.5% 7.016003	^{8}Li, 0.85 s α & β 16 8.022485	
He **2**		^{3}He,0.0001% 3.01603	^{4}He,100% 4.0026	^{5}He,? n, α 5.01222	^{6}He 0.81s β 3.51 6.018886	^{7}He	^{8}He, 1s β, β,n, 14 8.03392
H **1**	^{1}H,99.99 % 1.007825	^{2}H, 0.015% 2.0142	^{3}H, 12.26y β 0.0186 3.014102		Symbol, abundance or half-life, (fs =10^{-15}s, second, minute, year)		
N **0**		^{1}n^{0,} 12 m β, 0.78 1.008665			Decay mode: α, β, γ energy MeV, Mass in amu		
↑ p # → n #	**0**	**1**	**2**	**3**	**4**	**5**	**6**

Chart of some light nuclides with a key in the large square.

For detailed information on the properties of nuclides, please consult the *Handbook of Chemistry and Physics* or the *CRC Table of Isotopes*. The simplified nuclide chart summarizes some commonly used properties. Today, here is more information for each and every nuclide.

Each nuclide has its own story and character. Each piece of the data was obtained with careful experiments and intelligent interpretation.

The **neutron** ($^1n^0$, discovered by Chadwick) is not a real nuclide, but its properties are as important as those of a nuclide. Chadwick and Goldhaber (1935) found its mass greater than that of a hydrogen atom, and they observed the decay of neutron into a proton and electron, which was confirmed experimentally by Snell and Miller (1948). Using a pair of electrodes, they detected current flow due to electrons and protons in a *clean* neutron beam. Three years later, using a rather elaborate set up in Chalk River, Ontario, Canada, Robson (1951) further showed the simultaneous production of electrons and protons from a neutron beam, confirming the radioactive decay of neutron into a proton (p^+) and β^- particle, with a maximum energy of 782 KeV. We do not know if neutrons lose their identity inside a nucleus, but if they do neutrons in a nucleus are very different from free neutrons. The Nuclide Chart gives free neutrons' half-life, decay mode (β^-), decay energy (0.78 MeV), and mass (1.008665).

On the Nuclide Chart, look at the three isotopes; $^1H^1$ and $^2H^1$ (deuterium ^2D), and $^3H^1$ for hydrogen (Z = 1). The first two are stable, with natural abundance shown for ^1H (99.985%) and ^2H (0.015 %). The isotope $^3H^1$ (tritium ^3T) is a β emitter with a half life of 12.26 years and a decay energy 0.0186 MeV. Other properties such as masses can be added to the Nuclide Chart.

To illustrate the usage of data on the Chart, let us assume that all the deuterium is tied up in D_2O rather than HDO. We may estimate the amount of water required for the extraction of 1 ml (1 c.c., equivalent to 1 gram) of heavy water from the abundance data for $^1H^1$ and $^2H^1$:

1 ml x 99.985 / 0.015 = 6666 ml = 6.7 liters.

In reality, it takes much more water to extract 1 mL of D_2O.

Helium (Z = 2) has two stable isotopes, ^3He (daughter of ^3T beta decay, abundance 0.013 %) and $^4He^2$ (almost 99.99%). Helium gas constantly emerges from the ground, due to α decay of uranium and thorium. The isotope $^5He^2$ is a neutron or alpha emitter, but $^6He^2$ and $^8He^2$ are beta emitters. The nuclides ^7He and ^8He have half lives of 0.5 micro seconds and 0.122 seconds respectively. Both have α and β decay modes. There is no stable isobar with mass number 8, and both ^8Li and ^8Be are radioactive.

The Chart shows that ^6He is a β emitter with a half-life of 0.81 seconds, but ^6Be decays by emitting a proton to give ^5Li, which emits another proton and becomes a stable ^4He nucleus. Thus, the Nuclide Chart provides a convenient reference for tracing the relationship in nuclide transmutation.

Note that ^6Li, ^7Li and ^9Be are stable nuclides, and their properties given.

The Chart can be extended to include all nuclides, but we only illustrate the way of organizing the information of nuclides here.

Skill Building Questions:

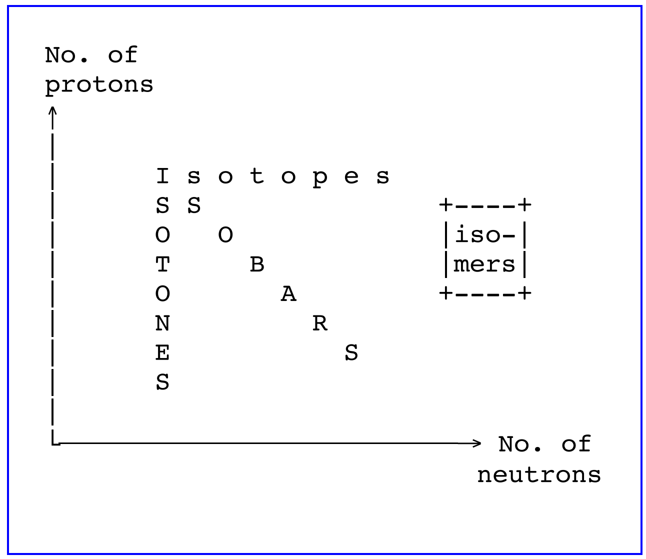
1. *From the masses for neutrons and hydrogen atoms in the Chart given above, show that the energy of beta decay of a neutron is 0.78 MeV.*

2. *What are stable isotopes of lithium, and what are their abundances?*

3. *Write an equation for the decay of* $^{8}Be^{4}$. *Evaluate is the energy of decay from the information on the Nuclide Chart?*

Isotopes, Isotones, Isobars and Isomers

A Nuclide Chart interestingly correlates the nuclides in terms of isotopes, isotones, isobars and isomers. We have already used these terms in the discussion of nuclide transmutation. **Isotopes** have the same number of protons, and they appear horizontally on the Chart. **Isobars** have the same number of nucleons, and these nuclides are located in a diagonal fashion. **Isotones** have the same number of neutrons, and they are arranged vertically. Isomers are the same nuclide, and they occupy the same square. An **isomer** is a nuclide containing excess energy for gamma ray decay, and it is usually marked by a superscript m, for example ^{60m}Co.



- Why are the terms isotope, isobar, isomer, and isotone required? Any use?

These terms refer to classes of nuclides. A class may share some common properties. For example, isotopes have common chemical properties, and beta decay converts nuclides among isobars. The Nuclide Chart for isobars with 6 nucleons shows that only ^{6}Li is stable, one of the few stable nuclei having odd numbers of protons and neutrons (3 and 3).

Skill Building Questions:

1. *Discuss the transmutation of isobars* ^{14}C, ^{14}N, and ^{14}O.

2. *What are isomers and what are their decay modes?*

Families of Radioactive Decay Series

The ancestral relationship of radioactive nuclides forms a **family of radioactive decay series**. Because only the alpha decay changes the mass number by 4 and proton emission is very rare, we usually consider 4 families of radioactive decay series. Radioactive nuclides are related to each other according to the mass relationship. If we divide the mass number by 4, the remainders are 0, 1, 2, or 3. Thus, these are called 4*n*, 4*n*+1, 4*n*+2, and 4*n*+3 families (*n* is an integer).

The 4*n* +2 Series: The transmutations of $^{238}U^{92}$, and generations of its offspring form the 4*n*+2 radioactive decay series. The $^{238}U^{92}$ is an alpha emitter.

$$^{238}U^{92} \rightarrow {}^{234}Th^{90} + {}^{4}\alpha^{2} \qquad \text{(half-life of } 4.5\times10^{9}\text{ y)}$$

The daughter, $^{234}Th^{90}$, emits a beta and becomes protactinium,

$$^{234}Th^{90} \rightarrow {}^{234}Pa^{91} + \beta^{-} + \bar{\nu} \qquad \text{(half-life of 24.1 d)}$$

Further β decay of $^{234}Pa^{91}$ produces a uranium isotope.

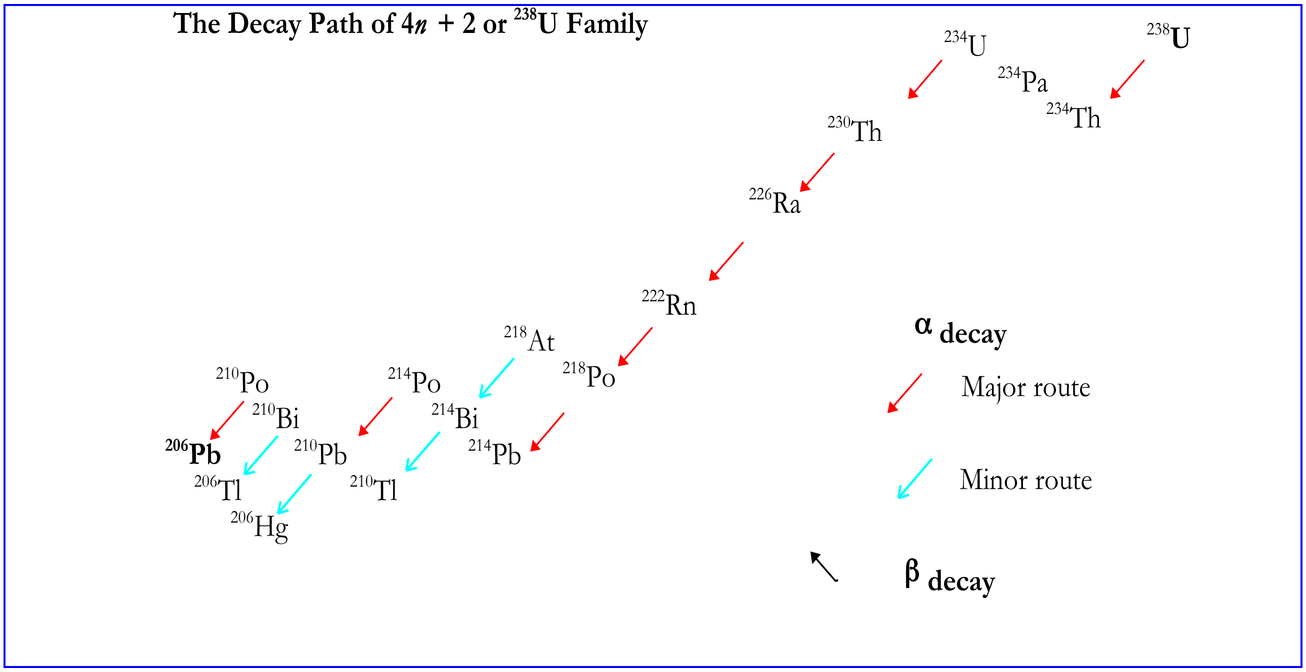
$$^{234}Pa^{91} \rightarrow {}^{234}U^{92} + \beta^{-} + \bar{\nu} \qquad \text{(half-life of 6.7 h)}$$

Thus, $^{234}U^{92}$ is a third generation decay product of $^{238}U^{92}$, and yet $^{234}U^{92}$ is also an alpha emitter ($t_{½} = 2.5\times10^{5}$ y). This isotope is present only in trace amounts due to its short half life compared to those of $^{238}U^{92}$ and $^{235}U^{92}$.

- How many generations of offspring of heavy nuclides are radioactive?
  What stable nuclides do these heavy radioactive nuclides eventually become?

- Is there any ancestral relationship for all heavy radioactive nuclides?

Actually, the transmutation of ^{238}U continues until it becomes an isotope of lead, ^{206}Pb, as shown using a Chart on the next page.



There are a few interesting points regarding the family of radioactive decay series.

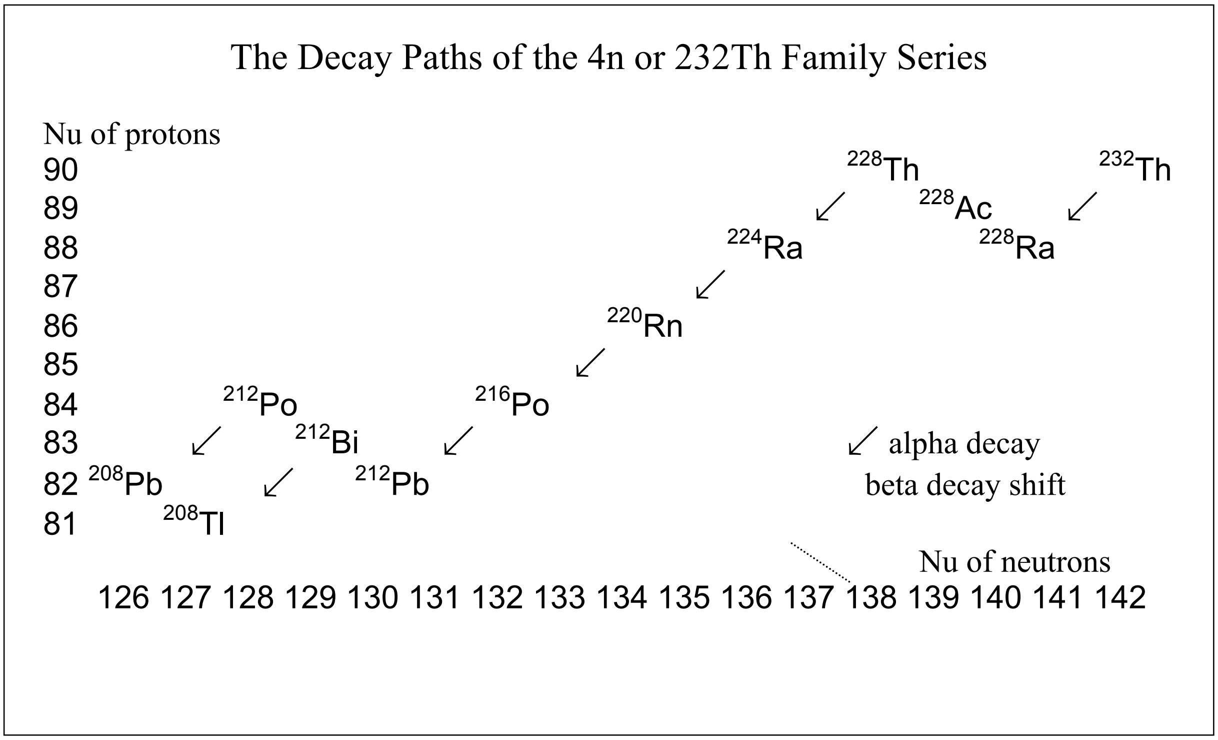
Both α and β decays occur in the decay series. Beta decays transform nuclides into isobars.

Many nuclides have more than one mode of decay, α and β decays. Gamma emission usually accompanies α and β decays. The major path is marked by heavy arrows (➔), and minor paths are marked by light arrows →.

Regardless of the decay path a nucleus transforms from ^{238}U to ^{206}Pb by emitting the same numbers of α and β particles. The number of alpha particles emitted (N_α) is equal to the difference of mass numbers divided by 4, because each alpha decay decreases the mass number by 4. In the $^{238}U^{92}$ to $^{206}Pb^{82}$ series, $N_\alpha = (238\text{-}206)/4 = 8$. If Z_i and Z_f are the atomic numbers of the initial and final nuclides, then the number of beta particles (N_β) is $2\, N_\alpha – (Z_I - Z_f)$. For the $^{238}U^{92}$ to $^{206}Pb^{82}$ series, $N_\beta = 2x8 - (92\text{-}82) = 6$.

This decay series gives three isotopes of lead: ^{206}Pb, ^{210}Pb and ^{214}Pb; 3 polonium isotopes, ^{210}Po, ^{214}Po, and ^{218}Po; 2 isotopes each of uranium (U), thorium (Th), bismuth (Bi) and thallium (Tl); and one isotope of At, Rn, Ra, and Pa.

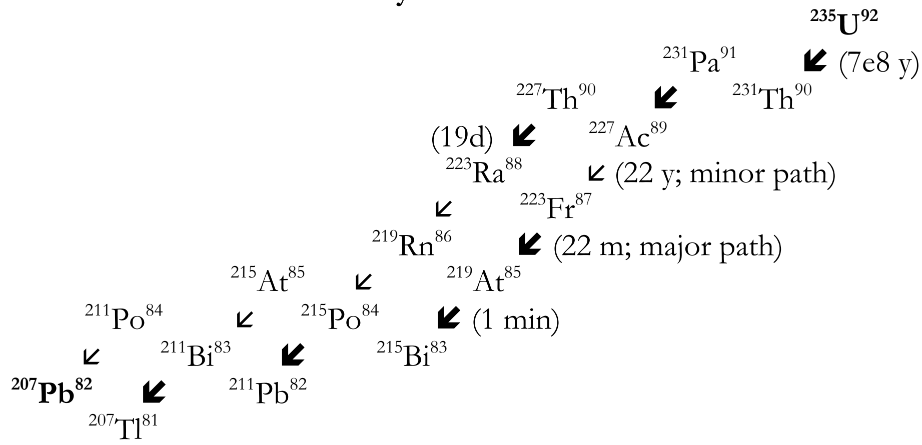
The 4*n* Series: The 4*n* series begins with ^{232}Th, which has a half life of 1.4×10^{10} y, 3.1 times longer than 4.5×10^{9} y of ^{238}U. The major transmutation of the 4*n* series is given here in a manner as the 4n + 2 series. The emission of α and β particles are implied in the diagram shown next.



There are fewer β^- emitting members in the ^{232}Th family than the ^{238}U family, members of both have even numbers of nucleons. Emission of a beta particle from an even-even nuclide results in an odd-odd nuclide. Most members in the 4*n* family have a single mode of decay as shown, except $^{212}Bi^{83}$ which is also an α emitter. Thus, there is a minor path of $^{212}Bi^{83}$ -(, α)$\rightarrow$ $^{208}Tl^{81}$ -(, β) $\rightarrow$ $^{208}Pb^{82}$. The half life of 6.7 y for ^{228}Ra is the longest of all offsprings of the Th family.

The half-life is a partial indication of the comparative stability of the nuclide. Whether a nuclide decays by emitting an alpha or a beta particle depends on the relative stability of the daughter nuclide. Nuclides in the 4*n* and (4*n* + 2) radioactive decay families either have even or odd numbers of protons and neutrons. The distributions of the nuclei in these two families suggest a preference for the even-even type over the odd-odd type.

The Decay Paths of the 4*n* + 3 or $^{235}U^{92}$ Family Series



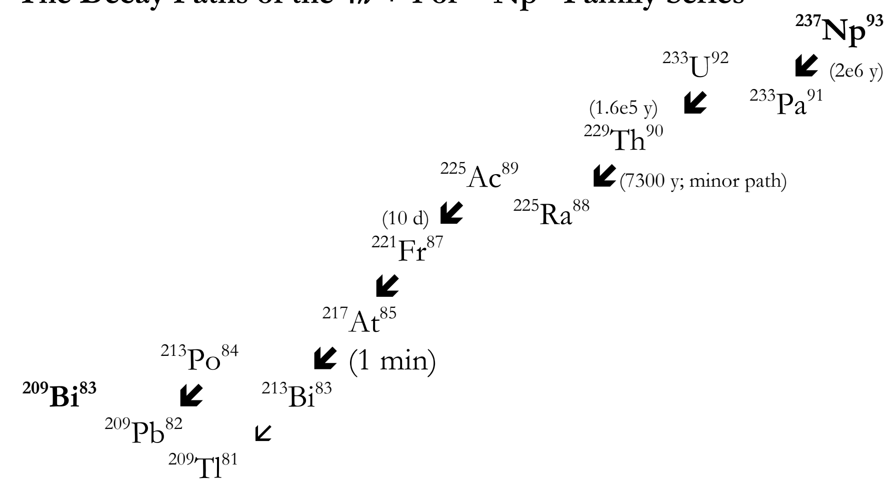
The 4*n*+3 family: All nuclides in the 4*n*+3 or ^{235}U family series have odd numbers of nucleons and they are both α and β emitters. Branch decay is common among nuclides in this series. The half life of 3.4×10^4 y for ^{231}Pa is the longest of all off springs of the ^{235}U family. The next longest half life is 22 y for ^{227}Ac; all others have half-lives in the range between days and milliseconds (ms).

The Earth still has abundant nuclei of ^{238}U, ^{235}U and ^{232}Th. Members of their decay families are present wherever they are found, and these decay products give rise to natural radioactivity in addition to their own decay. Radium and radon are widely known source of radioactivity, and ^{223}Ra, ^{224}Ra, and ^{226}Ra belong to families of ^{235}U, ^{232}Th, and ^{238}U respectively. These radium isotopes produce ^{219}Rn, ^{220}Rn, and ^{222}Rn isotopes, which causes the air to be radioactive, because radon is an inert gas. The half-life of 1620 y for ^{226}Ra is the longest of Ra isotopes, and the daughter from its alpha decay ^{222}Rn has the longest half live (3.823 d) of all radon isotopes. Radon is bad for health, because its decay products are no longer inert gases. They will remain in the human body for a long time.

A curious mind would seek the predecessor for ^{238}U. Purely counting the number of nucleons would lead one to conclude that the following nuclides ^{242}Pu, ^{246}Cm, ^{250}Bk and ^{254}Es or even ^{258}Md are the predecessors. However, all these heavy nuclides have short half lives, the longest one being 3.8×10^5 years for ^{242}Pu. Even if they were present when the Earth was formed, they would have exhausted long ago due to radioactive decay. It should be pointed out that successive decays provide α, β and γ rays in the uranium salt, which Becquerel had used. What darkened his photographic plates was probably not a single type of radioactivity.

The 4*n*+1 family: All members of the (4*n* + 1) series have vanished from the Earth, because they have short half lives, the longest being 2.2×10^6 years for ^{237}Np. This nuclide was eventually artificially made, completing the four families of radioactive decay series.

The Decay Paths of the 4*n* + 1 or $^{237}Np^{93}$ Family Series



All members in the 4*n* + 1 family of radioactive decay series have relatively short half-lives compared to the three families of natural radioactive series. The radium isotope ^{225}Ra of the neptunium series has a half life of 14.8 days, which is short when compared to ^{233}U (1.6 x 10^5 y) and ^{229}Th (7300 y). This isotope is only a β^- emitter, and hence no radon (Rn) isotope is produced.

Another interesting point about the artificial (4*n* + 1) series is that the stable product is an isotope of bismuth $^{209}Bi^{83}$ rather a lead (Z = 82) isotope, as is the case for all the other three series. No nuclide with atomic number greater than 83 is stable. The nuclide $^{209}Bi^{83}$ has 126 (209 - 83 = 126) neutrons, and the stability has been attributed to the magic number, 126, of neutrons.

There are four stable isotopes for the element 82, (lead) ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb, their natural abundance being 1.48 %, 23.6 %, 22.6 % and 52.3 % respectively. In terms of number of nucleons, ^{204}Pb and ^{208}Pb belong of the 4*n*+2 type. Isotopes ^{206}Pb and ^{207}Pb belong to the 4*n* and 4*n*+3 types respectively.

It is perhaps interesting to point out that M. Curie isolated the short lived isotope radium $^{226}Ra^{88}$ (half-life 1622 y), the 88th element on the Periodic Table. The nuclide $^{226}Ra^{88}$ is a member of the ^{238}U family.

Nuclides of four families of radioactive series belong to either the main groups or the actinides. Elements thallium (Tl), lead (Pb), bismuth (Bi), polonium (Po), astatine (At), francium (Fr), radon (Rn), and radium (Ra) belong to the **main groups** whereas actinium (Ac), thorium (Th), protactinium (Pa), uranium (U), and neptunium (Np) are **actinides**. The actinides have properties similar to those of **rare-earths** (from lanthanum (La) to lutetium (Lu)). The chemical properties of radium (Ra) are similar to those of barium (Ba) or calcium (Ca), and if ingested, they are likely to take the place of calcium in the bone structure.

Since the synthesis of ^{237}Np, heavier nuclides such as ^{241}Am (458 y), ^{245}Bk (4.95 d) ^{249}Cf (360 y) and ^{253}Es (2 h) have been successfully made. These nuclides are all alpha emitters and they could be considered as extended ancestors of the (4*n* + 1) series, but historically neptunium is considered as the first ancestor of this series due to its long half-life.

Review Questions:

1. *How many alpha and how many beta particles are emitted when* $^{232}Th^{90}$ *is converted to the stable nuclide* $^{208}Pb^{82}$*?*
   What principle is used for this deduction?

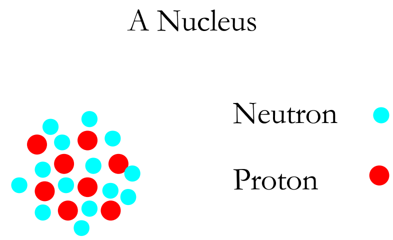
2. *Generations of decay products from the nuclide* ^{241}Am *are radioactive. To which family will the generation belong?*
   What stable nuclide will the final product be?
   How many alpha and how many beta particles will be emitted in the entire decay process?

3. *What are the implications of having 3 natural families of decay series?*

A Closer Look at Atomic Nuclei

We take a closer look at the atomic nuclei in order to understand the decay process and decay energy. Thus, components of atomic nuclei and theories regarding the structures of nuclei are interesting.

Protons and neutrons are components of atomic nuclei, and they are called **nucleons**. Free nucleons are called **baryons**. The number of protons in the atomic nucleus is the **atomic number** *Z*, and the **mass number** *A* is total number of nucleons. Considering protons and neutrons as components of nuclei is convenient for the interpretation of nuclear decay and nuclear reactions. However, the standard model further suggests quarks being components of protons and neutrons.



Interconversion of protons and neutrons results in emitting **leptons** (β decay). Emitting of nucleons gives proton and alpha decays. Isomers lower their energy by emitting photon (gamma decay). Some theories have been devised for the nuclei to explain these phenomena, and we will briefly explain them in this section.

Properties of Subatomic Particles

Protons, neutrons, electrons, neutrinos and their antiparticles are components of nuclei. Nuclear technology deals with subatomic particles, and their fundamental properties are importance.

- What are the basic properties of baryons and leptons?
  How do these properties affect the radioactive decay process?

Protons are nuclei of hydrogen atoms. Neutrons outside nuclei emit β^- particles and antineutrino $\bar{\nu}$.

Masses of free particles can be deduced from physical measurement. Furthermore, quantum mechanical properties such as magnetic moment, spin, and wave nature have been discussed. The values have been measured carefully. Their masses are considered fundamental constants, which are given at the beginning of this book.

Basic properties are carefully evaluated and kept by the Particle Data Group. The data are kept in several places, and some universal resource locations (URL) are:
http://mesa.lbl.gov/1996/contents.html)
http://www.nndc.bnl.gov/nndcscr/masses/.

Fundamental properties for protons, neutrons, electrons, and neutrinos are given below:

Properties of Baryons and Leptons

	Proton	Neutron	Electron	Neutrino	Units
Rest	1.00727647	1.0086649	5.485799×10^{-4}	$<10^{-10}$	amu
Mass	938.2723	939.5653	0.51899	$<5 \times 10^{-7}$	MeV
Charge*	1	0	–1	0	e^-
Spin	½	½	½	½	$(h/2\pi)$
Magnetic moment*	2.7928474 μ_N	-1.9130428 μ_N	1.00115965μ_B	?	

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* Charges and magnetic moments of antiparticles have opposite signs..

To illustrate the applications and consistence of these data, let us consider the masses of neutron and proton. Subtracting the mass of proton from that of neutron gives 0.0013884 amu or 1.2927 MeV. This is 2.491 times the mass of electron

$$\begin{aligned} m_n - m_p &= 1.0086649 - 1.00727647 \\ &= 0.0013884 \text{ amu (or 1.2927 MeV)} \\ &= 2.491\ m_e \end{aligned}$$

The mass of $^1H^1$ is 1.007825 amu, (= 1.00727647 amu + 0.00054856 amu). The mass difference between a neutron and a hydrogen is

$$1.0086649 - 1.007825 \text{ amu} = 0.000840 \text{ amu } (= 0.783 \text{ MeV})$$

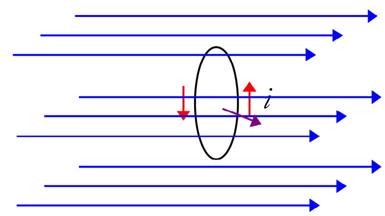
The beta decay energy of a neutron is 0.783 MeV.

The rest masses of nuclei are not the sum of rest masses of protons and neutrons. Therefore, free neutrons and protons are different from those within a nucleus.

Whether a neutrino has a mass or not is a fundamental problem. If neutrino has a mass, some scientific theories will have to be modified. Currently, the rest mass of a neutrino has been set to a limit of less than 0.5 eV, and its study is continuing in research centers around the world. The studies include measurements of β^- energy in the rare neutrinoless double-beta decay of nuclides ^{76}Ge, ^{48}Ca, and ^{100}Mo.

It is well known that a loop carrying a current behaves like a magnet. Experimentally, electrons, neutrons and protons behave as if they are tiny magnets when placed in a magnetic field. These phenomena have been attributed to their intrinsic spin with angular momenta of ½ (in units of $^{h}/_{2\pi}$). Thus the quantum number ½ is assigned to them as the **spin quantum number** (s). All particles with spin ½ are called **fermions**.

A close-loop current in a uniform magnetic field experiences a torque if the plane of the loop is not perpendicular to the magnetic field.



The spin of a charge gives rise to a magnetic moment. Theoretically, the magnetic moment μ_B of an electron equals to its charge e times the Planck constant h and divided by $4\pi\ m_e\ c$, where m_e and c are the mass of electron and the velocity of light respectively. This is a fundamental constant, and its value depends on the unit.

$$\begin{aligned}\mu_B &= e\ h\ /\ 4\pi m_e\ c\\ &= 9.27400899\text{x}10^{-24}\ \text{J T}^{-1}\\ &= 5.788381749\text{x}10^{-5}\ \text{eV T}^{-1}\\ &= 1.399624624\times10^{10}\ \text{Hz T}^{-1}\quad \text{(Bohr magneton)}\end{aligned}$$

This quantity is called a **Bohr magneton**. The measured magnetic moment of an electron is actually slightly larger 1.00115965 μ_B, but in excellent agreement. Willis Eugene Lamb and Polykarp Kusch independently confirmed these values, and they received the Nobel Prize for physics in 1955.

Similar to the electron, the proton is supposed to have a magnetic moment of a **nuclear magneton**, μ_N, which is defined similar to the Bohr magneton of an electron but using the proton mass m_p,

$$\begin{aligned}\mu_N &= e\ h\ /\ 4\pi m_p\ c\\ &= 5.0507832\times 10^{-27}\ \text{J T}^{-1}\\ &= 3.152454124\times 10^{-8}\ \text{eV T}^{-1}\\ &= 7.622\ 593\ 964\ (31)\ \text{MHz T}^{-1}\end{aligned}$$

The nuclear magneton is $^{1}/_{1840}$ of Bohr magneton. However, the magnetic moments μ_p and μ_n experienced by protons and neutrons respectively are more than a nuclear magneton. They are almost 2 to 3 times larger, 2.7928474 μ_N and -1.9130428 μ_N respectively. The negative sign for neutrons indicates that the spin and magnetic moment are in opposite direction with respect to the proton. Even though the neutron has no charge, it has a magnetic moment suggesting a complicated structure.

The magnetic moments of protons, neutrons, and electrons contribute to the magnetic properties of materials as well as to their spectroscopic properties.

The presence of a spin of ½ for neutrinos is inferred from the principle of conservation of spin in beta decay, and so far no contradiction has been observed.

A basic wave property for nucleons and nuclei is **parity**, which has something to do with their wave functions being symmetric or asymmetric. This is often referred to as even and odd. An even state is represented by +1 and an odd state by –1. We will discuss parity further later. Since only relative parity is measurable, **the states of protons, neutrons, electrons, and neutrinos are assigned +1 as their intrinsic parity**.
See: http://www.atlantic.net/~elifritz/nature.htm

Review Questions:

1. *What are the rest masses of neutrons, protons, electrons, and $^1H^1$?*
   From their rest masses, calculate the amount of energy required to convert a hydrogen atom into a neutron, if this is possible.

2. *How can a particle experience a torque when placed in a uniform magnetic field?*
   Draw on an analogy between current and magnetism in your explanation.

3. *Explain the spin quantum number of ½ for a proton, neutron, electron, and neutrino.*
   How can spin states be observed experimentally?
   (Further reading in general physics or general chemistry is helpful).

4. *What are fermions?*

Nuclear Models

A **nuclear model** is a theory proposed to explain the nuclear phenomena. Since radioactive decays involve protons, neutrons, and electrons, most nuclear models consider these subatomic particles as components of nuclei. Each model explains some aspects of nuclear decays.

- If nuclei are composed of protons and neutron, what force holds them together and how are they arranged in atomic nuclei?

- What are some of the models for the description of nuclei?

Radius of a nucleus, R, with mass number A is approximately $R = 1.2\,A^{1/3}$ fm

Liquid Drop Model: **Bohr** proposed the **liquid drop model.** The **strong force**, which is only effective at very short distances in the order of fermi (1 fm = ~10^{-15} m), hold neutrons and protons together like molecules in a drop of liquid. This model partially explains nuclear fission, by which a nucleus split into two pieces plus some neutrons. If nuclei are spherical, the liquid drop model suggests that nuclear radii R of mass number A are proportional to $A^{1/3}$. More precisely, $\mathbf{R = 1.2\,A^{1/3}}$ **fm**.

Gas Model: Fermi proposed a **gas model**. Gaseous nucleons are confined in a nucleus by mutual attractions. Nucleons on the surface experience an imbalance attraction due to other nucleons. All nucleons move around as molecules in a gas, and are loosely coupled, not as tight as the liquid drop model.

Shell Model: Robert Hofstadter proposed the shell model in 1950s. Since nucleons experience a net force towards the nucleus center, they move about in a nucleus similar to electrons moving about in a Bohr atom. The shell model treats neutrons and protons separately. They have separate energy states. Because they have spins, neutron pairs with neutron and proton pairs with proton in each quantum state. The lowest energy levels are filled first. When the number of protons or neutrons equals 2, 8, 20, 28, 50, 82, or 126 a closed shell is formed making these nuclides stable. Thus, these are called **magic numbers**. Nuclides having these number of protons and neutrons are said to be **magic-number nuclides**.

Quantum mechanics is the basis for the shell model. In a quantum mechanical view, nucleons confined in the small space of a nucleus have energy states restricted to some definite levels called **quantum states**, each having a set of unique **quantum numbers**, n, l, m_j and s.

> n = *integer*; the principal quantum number; most important for energy
> l = 0, 1, 2, … n - 1; the orbital angular momentum quantum number
> s = ½ or -½; the spin quantum number of protons or neutrons

The angular momentum of a nucleon in a nucleus is the **resultant** (vector sum) of its spin angular momentum and orbital angular momentum. This is often referred to as the **coupling** between orbital (l) and spin (s). Corresponding to this phenomena is a **total angular momentum quantum number** j, representing the vector sum of spin and orbital angular momentum,

$$j = l + s.$$

A nucleon can be in any of all possible sums of l and s (maximum value of l + ½). As a result, there are 2j + 1 states, each accommodating 2 protons or neutrons., 2(2j+1) nucleons. A set of quantum numbers uniquely defines a state is represented by m_j,

$$m_j = -j, -j+1, \ldots, j - 1, j.$$

The m_j represents the projection of the combined angular momentum on a certain direction. For example, for $l = 2$, $j = {}^5/_2$, and $m_j = {}^5/_2, {}^3/_2, ½, -½, -{}^3/_2, -{}^5/_2$. There are 6 states ($2({}^5/_2) + 1 = 6$) to accommodate 12 nucleons.

Following a set of quantum mechanical rules resulted in energy level **notation** given in the diagram on the next page. The diagram shows the relative energy level, but not to scale. The order of energy levels may change slightly, because there are other complications. The parities of the states are noted, even by + and odd by – respectively following the j values. Parity will further be discussed in the next section.

The energy with $n = 1$ is the lowest, and energy increases as the n increase. For the same n, the energy decreases as l increases. Energy levels split further for different j values. For simplicity, these splits are not shown in the diagram. Observations of nuclide properties indicate that some energy gaps are large, leading to the concept of shells separated by these gaps. The **shell total** is the number of nucleons required to fill all lower energy sub shells. The shell total numbers 2, 8, 20, 28, 50, 82 and 126 are known as **magic numbers**. Nuclides with these numbers of protons or neutrons are relatively stable. Helium, ^{4}He, with 2 protons and 2 neutrons is a double-magic-number nuclide. It is extremely stable. The stability of ^{12}C or ^{16}O has also been attributed to 3 or 4 alpha particles respectively, but ^{8}Be is unstable, disintegrating into 2 α particles. Other double-magic number nuclides are $^{16}O^{8}$, $^{40}Ca^{20}$.

Energy Level Diagram of Nucleons

n	l	j	↓ Notation	$(2j+1)$	Shell total
7	6	$^{13}/_{2}+$	1i	14	~126
6	0	½–	3p	2	
6	1	$^{3}/_{2}-$	3p	4	
6	2	$^{5}/_{2}-$	2f	6	
6	3	$^{7}/_{2}-$	2f	8	
6	4	$^{9}/_{2}-$	1h	10	
6	5	$^{11}/_{2}-$	1h	12	~82
5	0	½+	3s	2	
5	2	$^{3}/_{2}+$	2d	4	
5	3	$^{5}/_{2}+$	2d	6	
5	4	$^{7}/_{2}+$	1g	8	
5	4	$^{9}/_{2}+$	1g	10	~50
4	0	½–	2p	2	
4	1	$^{3}/_{2}-$	2p	4	
4	2	$^{5}/_{2}-$	1f	6	
4	3	$^{7}/_{2}-$	1f	8	~28
3	0	½+	2s	2	~20
3	1	$^{3}/_{2}+$	1d	4	
3	2	$^{5}/_{2}+$	1d	6	
2	0	½–	1p	2	~8
	1	$^{3}/_{2}-$	1p	4	
1	0	½+	1s	2	~2

Energy states of all nucleons in a nucleus are uniquely represented by a set of quantum numbers. Since protons and neutrons are different, they are treated separately. Quantum numbers of a proton may be the same as one of neutrons and vice versa.

Skill Building Questions:

1. *Based on the liquid drop model, how do the densities of the nuclei of nuclides vary as the number of nucleons increase? The atomic radii and nuclei radii are approximately 10^{-10} m and 10^{-15} m respectively. From these values, compare densities of nuclei to those of ordinary material.*

2. *Describe the liquid drop model, gas model, and shell model for the structure of nuclei.*

3. *How many nucleons can have the principle quantum number of 3?*

Parity of Nuclear States

Quantum mechanics* treats particles as waves. Particles are represented by wavefunctions. Only standing waves can be confined in space, and their energies are limited to some discrete levels. A wave that is the same as its mirror image is symmetric and its parity is even, or +1. An

* We often refer to quantum mechanical methods or results in the discussion of nuclear and atomic worlds, not because we believe it writes the rules for these small worlds, but because these worlds behave as if they were poems written in the quantum mechanical language.

asymmetric wave differs from its mirror image, and its parity is odd or –1. Parity of the states depends on the quantum number *n*, +1 when *n* is odd, and –1 when *n* is even.

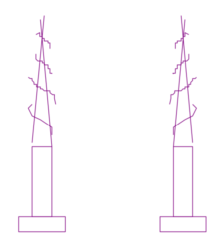
Waves do not have the shapes of gloves, but surgical and garden gloves that are not specific to left and right hands have even parity or +1. Baseball and dress gloves are specific for left and right hands. They have odd parity or -1.

When a nuclide undergoes γ decay, the energy corresponds to transitions between energy levels of different parity, observed by Laporte in 1924. In order for parity to conserve in γ decay, Wigner suggested photon has an odd parity (-1). Since then, the principle of conservation of parity has widely been applied to nuclear transitions, and at the same time, it has been scrutinized.

Parity is conserved in γ and other nuclear transitions involving nucleon-nucleon strong interaction. However, Lee and Yang questioned its validity in the 1960s, and predicted that parity was not conserved in beta decay. Experimentally, Wu observed that when the source is placed in a magnetic field, the beta particles is favored in certain direction, indicating that parity was not conserved. Parity is an important property of nuclear states.

As pointed out earlier, the **intrinsic parity** of fermions (spin ½) is assigned +1. The parity corresponds to one of two rotational directions, clockwise and counter clockwise. By the way, do you know the difference between left-hand and right-hand screws?

Right and Left Hand Screws



With respect to spin and parity Dirac's theory requires **particles and antiparticles to have opposite spins and parities**.

Skill Building Questions:

1. *What is the difference between a left-hand screw and a right-hand screw?*

2. *Draw a right hand and a left hand. What is the relationship between the two? How can you transfer one into the other?*

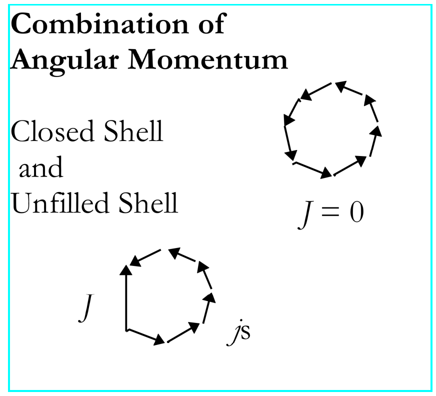
Excited Energy Levels of Nuclides

Nucleons fill the lowest energy states according to the **Pauli exclusion principle,** which states that each proton or neutron has a unique set of quantum numbers. A nuclide with nucleons at the lowest possible states is at the **ground state**. However, nucleons may be excited to a higher energy level. Such a nuclide is at an **excited state**. Excited nuclide is called **isomer**.

A relative energy level diagram has been shown earlier. However, relative energy levels for nuclides with large numbers of nucleons varies slightly because both orbital and spin angular momentum of nucleons combine (couple) with each other affecting the relative heights of energy levels.

In nuclides with many nucleons, the total angular momenta of spin and orbital are represented by yet another quantum number J, which is a vector sum of all j_n of all nucleons,

$$J = j_1 + j_2 + \cdots + j_{n-1} + j_n.$$



Nuclides with closed shells (having magic numbers) of protons and neutrons, the J values are 0. The J values are determined by nucleons outside the closed shells. Since values for j are half inters, J values are integers for nuclides with even numbers of nucleons. They are half integers for nuclides with odd numbers of nucleons. An energy level is usually labeled with J followed by the parity of + or –.

J values change as one or more nucleons are excited to higher energy states. As an example, states of the ^{7}Li nuclide are given here. The J values are multiples of half. The energies in MeV above the ground state are also given, but the positions of the lines are not to scale. Parities and J are obtained theoretically and experimentally too complicate to describe at this level, but they are given so that you know what they are. The energy gaps are also obtained by nuclear spectroscopy.

Some Excited States of the ^{7}Li Nuclide

½ +	6.54 MeV
$^7/_2$ +	4.64
½ –	0.478
$^3/_2$ –	Ground State

Skill Building Questions:

1. *How energy can be put into atomic nuclei and how do excited nuclei get rid of the extra energy?*

2. *What are used to label the energy levels in a nuclide?*
   What is the quantum number J for the ground state of ^{16}O and ^{4}He?

3. *What are the ground states of ^{5}Li and ^{17}O?*

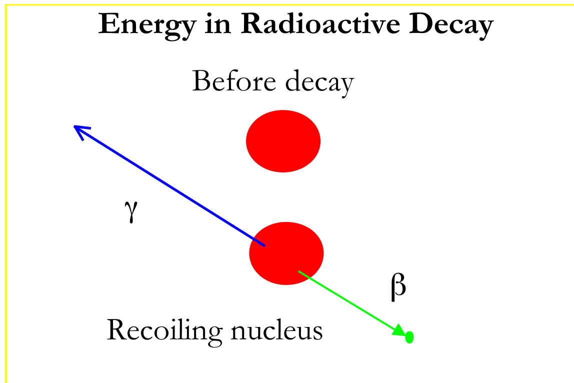
Radioactive Decay Energy

Alpha and beta rays are energetic particles whereas gamma rays are energetic photons, all emitted from atomic nuclei. Amounts of energy in nuclear decay come from the expense of mass. **The law of conservation of energy (including mass)** apply however. When mass and energy are included, the total amount of energy and mass before decay must be the same as that after decay. The total mass of reactants, $M_{reactants}$ should equal the total mass of products, $M_{Products}$ plus the mass equivalence of the decay energy Q,

$$M_{reactants} = M_{products} + Q$$

or

$$Q = M_{reactants} - M_{products},$$



The energy of decay is distributed between α, β or γ rays and the recoil nuclei due to the conservation laws.

The distribution of energies among the particles or photons from a source is called a **spectrum**. Usually, a spectrum is a plot of the intensity versus the energy of the particles. Each radioactive nuclide gives a specific spectrum Spectra provide information nuclear structure. Their characteristics are required for applications in analytical chemistry, medicine, engineering, and other nuclear technology.

Energy in Gamma Radiation

Gamma, γ, rays are electromagnetic radiation emitted from atomic nuclei. The bundles of energy emitted are called **photons**.

- How do nuclei get the energy for photon emission?
  What is the energy distribution among the photons in γ rays and why?

- How is energy of decay related to the half life of a nuclide?

An excited nucleus (called **isomer**) de-excites by emitting γ photons ($h\nu$)* in a process called **isomeric transition** (IT). The photon energy is the difference of energy E between the initial and final states represented by E_i and E_f respectively,

$$h\nu = E_i - E_f$$

* The same symbol ν is used to represent both a neutrino and the frequency of photons.

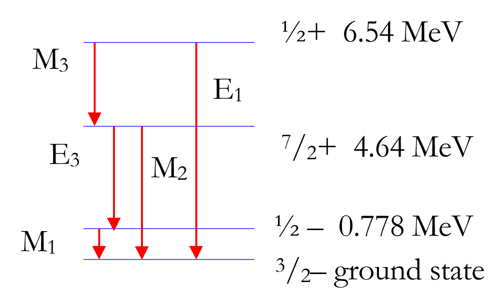
Isomeric transitions change the spin, parity, and energy of nuclides. These transitions are classified as electric, E, or magnetic, M, by analogy to classical radiation from a radiating electric dipole or magnetic dipole. They are further classified by changes in the quantum number J ($\Delta J = |J_{\text{initial}} - J_{\text{final}}|$) and in parity ($\Delta\pi$) between initial and final states. They are designated as $E_{\Delta J}$, and $M_{\Delta J}$ by these rules:

Types of Isomeric Transitions and their Ranges of Half-life

Radiation Type	Symbol	ΔJ	$\Delta\pi$	Partial half life t_γ (s)
Electric dipole	E_1	1	Yes	$5.7 \cdot 10^{-15}\, E^{-3}\, A^{-2/3}$
Magnetic dipole	M_1	1	No	$2.2 \cdot 10^{-14}\, E^{-3}$
Electric quadrupole	E_2	2	No	$6.7 \cdot 10^{-9}\, E^{-5}\, A^{-4/3}$
Magnetic quadrupole	M_2	2	Yes	$2.6 \cdot 10^{-8}\, E^{-5}\, A^{-2/3}$
Electric octupole	E_3	3	Yes	$1.2 \cdot 10^{-2}\, E^{-7}\, A^{-2}$
Magnetic octupole	M_3	3	No	$4.9 \cdot 10^{-2}\, E^{-7}\, A^{-4/3}$
Electric 2^4-pole	E_4	4	No	$3.4 \cdot 10^{4}\, E^{-9}\, A^{-8/3}$
Magnetic 2^4-pole	M_4	4	Yes	$1.3 \cdot 10^{5}\, E^{-9}\, A^{-2}$

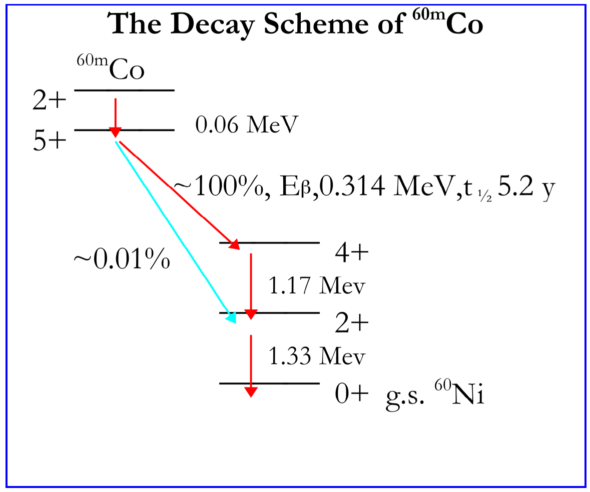
A nuclide may emit gamma rays of different energies by a number of radiation types. Transition is favored if ΔJ is small, and if the energy of transition is high. This trend is called the selection rule of transition. Favored transitions have short partial half lives, and unfavorable transitions either do not occur or have long partial half lives. When several modes of transition are possible, those with short half lives dominate. The apparent half life for the isomer is approximately the short partial half life. For ^{7}Li, the excited states have been shown before. Various hypothetical gamma transitions and their classification are illustrated here. Of course, only nuclei excited to the various levels will be able to emit γ rays. Having the energy level but no nucleon occupying it does not lead to any emission.

Various Gamma Transitions in ^{7}Li



Because the angular momentum of the photon is 1, γ transition cannot take place if the change in angular momentum $\Delta J = 0$. Angular momentum must be conserved. Thus, transitions from $J_i = 0$ to $J_f = 0$ ($0 \rightarrow 0$) states are forbidden. In these cases, internal conversion of electrons and positron emission (E must be greater than 1.02 MeV for the latter) rather than gamma emission takes place. The energy and angular momentum in an **internal conversion** are transferred from a nucleus to an electron in the atomic orbital. The converted electron will have kinetic energy equal to the energy of nuclear transition less the binding energy of the electron to the atom.

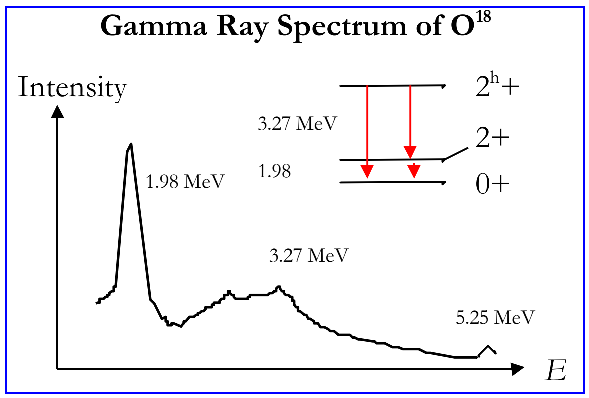
The transition of isomer ^{60m}Co from state 2+ to 5+ has a half life of 10.5 min. The γ -ray spectrum from a ^{60m}Co sample has an intense peak at 0.06 MeV, ($^{60m}Co \rightarrow {}^{60}Co + \gamma$, M_3). The nuclide ^{60}Co is a beta emitter ($^{60}Co \rightarrow {}^{60}Ni + \beta$), and the majority of the decay goes to the 4+ state of Ni. The excited Ni nuclei decay by emitting γ rays as shown in the decay scheme. The γ transitions for Ni are E2 and the half lives for both are so short that the emission of gamma is almost immediate.



Bombardment by subatomic particles and photons also produce high-energy isomers. For example, bombarding ^{17}O by a high-energy deuteron, ^{2}D, an isomer ^{18m}O is produced. The bombardment also produce protons:

$$^{17}O + {}^{2}D \rightarrow {}^{18m}O + {}^{1}H.$$

The excited energy levels of ^{18}O can be studied from the γ ray spectrum coincident with the emission of the proton. In a study to reveal high-energy levels, some lines were observed corresponding to the simplified energy levels, (Moreh, 1967). The peaks at 1.98, 3.27 and 5.25 MeV in the spectrum correspond to the 2+ → 0+, 2^h+ → 2+, and 2^h+ → 0+ transitions respectively. Intensities of the peaks are related to the population of the excited state as well as the half life of the transition. Some other energy levels between those indicated were omitted for clarity, and the peaks due to other transitions are unlabelled.



Skill Building Questions:

1. *Which one of the gamma transitions in the diagram for Li^7 is the most favorable?*
   What types of transitions take place between energy levels ½+ and ½–?
   (Check the energy level from the previous diagram and apply the rules to classify the isomeric transitions).

2. *Classify the transitions for O^{18}.*
   Qualitatively, what do you expect the half life of these transitions to be, very fast, fast, intermediate, or slow?

3. *What are the three means by which isomers de-excite?*
   (Emission of photons, simultaneous emission of electron and positron, and internal conversion)

4. *What is the wavelength for a gamma ray with energy 1.98 MeV?*
(Apply $E = h\,v = h\,c\,/\,\lambda$ to evaluate the wavelength)

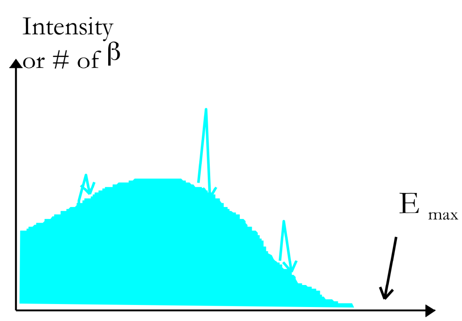
Energy in Beta Decay

The beta decay processes consist of β^+ and β^- emissions as well as electron capture (EC).

- What is the energy distribution of β^+ and β^- particles?

- How is energy of decay related to the half life?

A Typical Beta Spectrum



Early investigators noticed some intense peaks at certain energies and continuous distribution in β^- spectra as shown here. These spectra were difficult to explain. The intense peaks were eventually recognized as due to internal conversion and Auger electrons. In the continuous spectrum, few β particles have the maximum energy E_{max}, some have zero energy, and numbers of β particles with energy E vary continuously between 0 and E_{max}. The fact that some have zero energy is due to Coulomb attraction between electrons and the nuclei when the electrons leave the nuclei, reducing their energy; some to zero. Depending on the atomic number, Z, the distribution and the number of β^- particles with energy E near 0 vary. The numbers of β^- particles with zero energy increase with atomic number of the nuclides.

If identical nuclei of parent nuclide P^Z decay to identical nuclei of daughter nuclide D^{Z+1}, the energy of β^- decay, E_{decay}, should be the difference between mass of P, M_P, and mass of D, M_D, in the decay process:

$$P^Z \rightarrow D^{Z+1} + \beta^- + \bar{\nu} + E_{decay}.$$

Note that the rest mass of β^- has already been included in the mass of D^{Z+1}, because the daughter nuclide needs an additional electron for its atomic orbital. The rest mass for $\bar{\nu}$ is considered zero. Thus we have

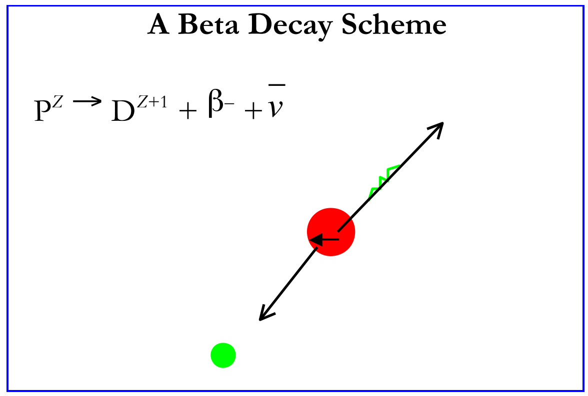
$$E_{decay} = M_P - M_D. \qquad \text{(Masses and energy are expressed in the same units)}$$

All β^--particles are expected to have energy E_β, which is equal to the decay energy, E_{decay}, minus the recoil energy of the daughter nuclei, E_{recoil}, and the Coulomb attraction energy E_C:

$$E_\beta = E_{decay} - E_{recoil} - E_C.$$

E_β is expected to be the same as the E_{max}.

Parent nuclei are identical, so are daughter nuclei. Yet, some beta particles have less energy than E_β and these observations violated the principle of conservation of energy. Furthermore, electrons, neutrons and protons all have a spin ½. The spins before and after the decay do not add up in the decay of a neutron into a proton and an electron. The decay violates the principle of conservation of angular momentum. An explanation to preserve these principles of conservation was made by Wolfgang Pauli (1900-1958) in 1931, who suggested that a **neutrino** (ν, little neutron) with spin ½ is emitted simultaneously with the beta particle. The elusive neutrino caries away the missing energy, missing linear momentum and angular momentum in the beta decay. The energy of beta decay is unevenly divided among recoil nuclei, β, and the antineutrino. Thus, we should have



$$E_{max} = E_\beta + E_{\bar{\nu}}$$

or

$$E_\beta = E_{max} - E_{\bar{\nu}}$$

The β^- decay can be pictured in a scheme shown here. The recoiling daughter nucleus, the beta particle, and the antineutrino go off three different directions. This explanation is based on classical Newtonian physics. An antineutrino $\bar{\nu}$ is emitted at the same time a beta particle leaves the nuclide, but it was called neutrino originally. The antineutrino concept has been described in the section

The ^{32}P beta spectrum is not complicated by Auger electron peaks, and it has a continuous distribution of β particles with a E_{max} of 1.71 MeV. The synthesis of ^{32}P and the discovery of this spectrum by Jensen *et al.*, (1952) confirmed the internal conversion and Auger electron theory, but the mystery of neutrinos and antineutrinos was solved much later, because their detection had been very difficult.

When a positron, β^+, is emitted, an atomic orbital electron must also be released from the atom. Thus, the decay energy E_{decay} is equal to the mass of the parent, M_P, subtracting the mass of the daughter, M_D, and minus the rest mass of two electrons, $2m_e$, since the mass of positron is the same as that of electron.

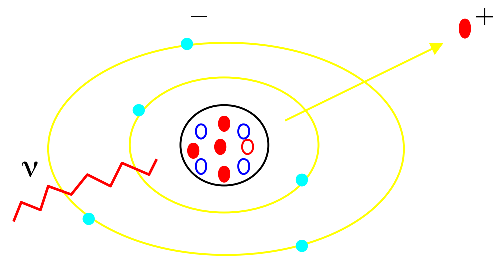
$$P^Z \rightarrow D^{Z-1} + \beta^+ + e^- + \nu + E_{decay}.$$

$$E_{decay} = M_P - M_D - 2\, m_e. \qquad \text{(Masses and energy are expressed in the same units)}$$

The neutrino is considered to have zero rest mass. Thus, **the mass difference between M_P and M_D must be greater than twice the rest mass of the electron, 1.02 MeV for β^+ particle emission**. Positrons are repelled by their nuclei as they leave. Thus, there are no β^+ particles with zero kinetic energy. The Coulomb interaction contributes to the kinetic energy of β^+ particles. Note, however, that the β^+ and e^- (perhaps from elsewhere) will annihilate each other producing two photons.

Studies of β^+ kinetic energy distribution also call for the simultaneous emission of neutrinos, (as opposed to antineutrinos in the β^- emission). Furthermore, recoil energy must also be considered in the estimate of β^+ kinetic energy.

Positron Emission



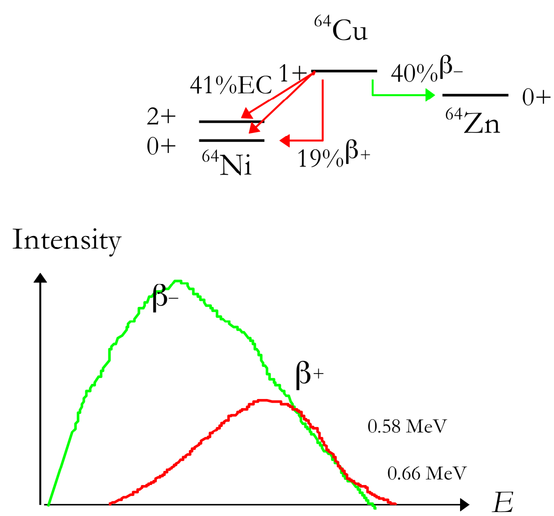
When the energy of the parent nuclide is insufficient for positron (β^+) emission, electron capture (EC) is an alternate mode of decay. In this case, the energy released is

$$E_{\mathrm{EC}} = M_P - M_D - E_{\mathrm{be}}$$

This process was first suggested by Yukawa and Sakata in 1935, and found by Alvarez in 1938.

The nuclide $^{64}Cu^{29}$ has all three decay modes: 40% β^- decay to $^{64}Zn^{30}$ (E_{decay}=0.58 MeV); 40% EC and 19% β^+ decay to the ground state of $^{64}Ni^{28}$ (E_{decay} =1.68 MeV); and 1% decay to an excited (2+) state of $^{64}Ni^{28}$. The decay scheme and a sketch of the beta spectrum are shown, ignoring the Auger electrons. The kinetic energy of β^- ranges from 0 to a maximum E_{max}= 0.58 MeV, but the number of β^- particles (intensity) varies continuously as a function of energy E. The similar β^+ spectrum is shifted, but its maximum energy is (1.68 - 1.02) = 0.66 MeV. The differences between the two spectra are due to the percentage of decay and Coulomb interaction towards β^- and β^+.

A Typical Beta Spectrum

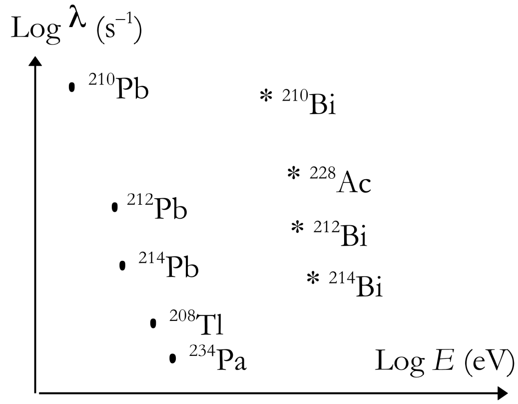


The nuclide $^{64}Cu^{29}$ has odd numbers of protons and neutrons. Both products ^{64}Ni and ^{64}Zn have even numbers of protons and neutrons, and they are at lower energy states than ^{64}Cu. This is one of the nuclides that have all three modes of beta decays. The odd and even numbers of protons and neutrons are important factors governing the stability of nuclides, which will be discussed in another Chapter.

The half lives of beta decay vary widely. The relationship between half lives and decay energies E_{decay} (maximum β^- energy E_{max}) depend on changes in quantum states, angular momenta, atomic numbers, mass numbers, and parity.

When decay constants ($\lambda = 0.693/t_{1/2}$) were plotted against E_{max} by Sargent for natural occurring β^- emitters, he found the plot fell into two curves. Actually, he used log scales for both because they have wide ranges. He called the emission of nuclides on the curve corresponding to shorter half lives **allowed**, and the emission of the other group **forbidden**. Such a sketch is shown here, and the scale is omitted because we are only interested in the idea of analysis and classification.

A Sargent Diagram

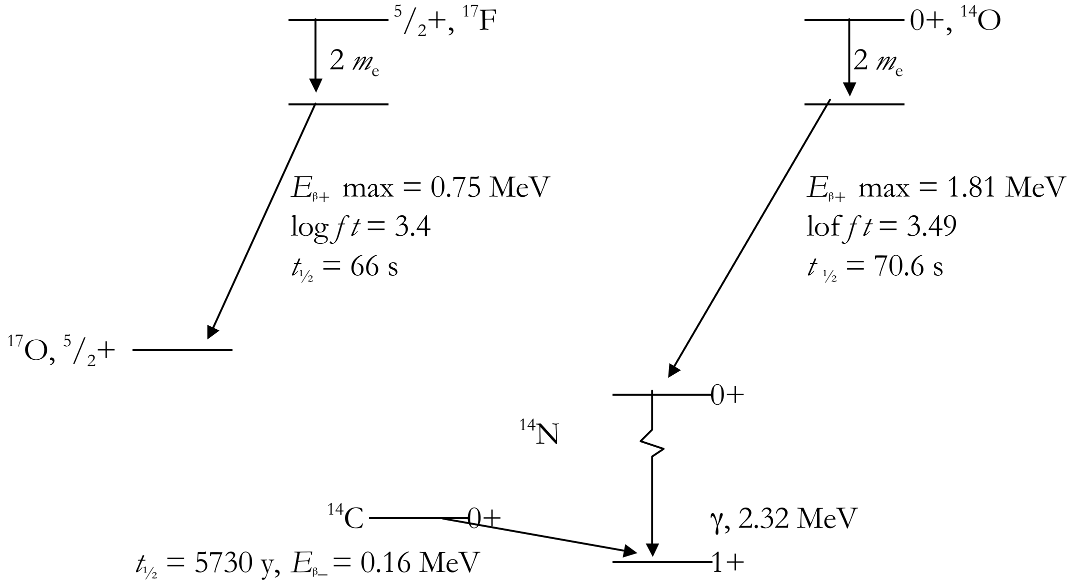


In order to compare rates of decay, a **comparative half life, $f\,t$**, has been used. The factor f is a function of atomic number Z and decay energy E_{decay}. This factor has not taken the changes in angular momenta ΔJ and parity, $\Delta\pi$, into account. Based on $f\,t$ values, beta (β^-, β^+ and EC) decay nuclides fall into several categories. **Transitions corresponding to shortest, short, medium and long comparative half lives are called super allowed, allowed, first forbidden, and second forbidden.** The rules for the classification are given below:

Classification of Beta Decays

Class	$\lvert\Delta J\rvert$	$\Delta\pi$	Log $f\,t$	Representative nuclides
Super allowed	0 or 1	no	2-4	n→H, ^{3}H→He, ^{7}Be→Li, ^{11}C→B, ^{13}N→C
Allowed	0 or 1	no	4-7	^{14}C→N, ^{35}S→Cl, ^{60}Co→Ni, ^{69}Zn→Ga
First forbidden	0 or 1	yes	6-8	$^{141}Ce^{58}$→Pr^{59}($t_{1/2}$ = 32.5 d)
Second forbidden	2	yes	11-13	$^{36}Cl^{17}$→Ar^{18} ($t_{1/2}$ = 300000 y), ^{135}Cs→Ba
Higher order forbidden	3, 4		12-23	$^{40}K^{19}$→Ca^{20} ($t_{1/2}$ = 1.3x10^{9} y)

The superallowed transitions occur mostly for light nuclides. In the transition n → H + e, J and π do not change. The neutron, n and H are called **mirror nuclides,** whose number of neutrons and number of protons are interchanged. Another transition between mirror nuclides $^{17}F^{9} \rightarrow {}^{17}O^{8}$ can be represented by the following diagram:



There is no angular momentum change, $\Delta J = 0$, in transmutations $^{14}O^{8} \rightarrow {}^{14}N^{7}$ and $^{14}O^{8} \rightarrow {}^{14}N^{7}$ by β^+ emission. These are supper-allowed transitions and their half-lives are approximately 70 min. On the other hand, the transition for the transition, $^{14}C^{6} \rightarrow {}^{14}N^{7}$ has an angular momentum change, $|\Delta J| = 1$, and this is an allowed transition. Its half life is 5730 years instead of seconds.

Beta transitions have been extensively studied. For example, Lee and Yang suggested that parity is not conserved, and this has been shown to be true experimentally. In general, the higher the decay energy, the shorter the half life, but the transition is complicated by changes in angular momentum and parity, leading to a large range of half lives* .

Before neutrinos were detected, their characteristics have been predicted from the study of beta decay. Neutrinos are speculated to react with protons, p, in a reverse reaction of beta decay to produce neutrons n and positrons, β^+ in a rare reaction:

$$p + \nu \rightarrow n + \beta^+$$

The neutron so produced can be absorbed by cadmium, and the positron will be annihilated with an electron producing two gamma photons, which fly apart from each other. An experiment was designed according to suggestions by Reines and Cowan, and the detection of neutrino was published in 1959.

Skill Building Questions:

1. *The exclusive beta decay of ^{60}Fe (state 0+) to ^{60m}Co (state 2+) has a decay energy of 210 keV. The half-life of ^{60m}Co (2+ to 5+) is 10.5 m. Sketch beta and gamma spectra for these transitions.*

* There is much more information on this subject than we can cover in this book, but for an introductory level, we reviewed the energy aspect of the beta transition.

2. *How is the energy of beta decay distributed among various particles?*

3. *What are mass numbers of stable isotopes of copper, Cu?* (Consult other literature for information). *The mass of ^{64}Zn, ^{64}Cu, and ^{64}Ni are 63.929145, 63.929765, and 63.027968 amu, calculate the decay energy. Comment on the fact that ^{64}Cu has three modes of beta decay.*

4. *What is comparative half life? Give a qualitative description.*

5. *What are mirror nuclides?*
   Give at least 4 examples. Are beta transitions between mirror nuclides supper-allowed or allowed?

6. *Draw a diagram to show the configuration of protons and neutrons for the ^{17}F and ^{17}O pair. The term configuration here means the lowest energy levels occupied by the protons and neutrons. The order of energy levels has been given in the section on Shell Models.*

Energy in Alpha Decay

The transition of nuclides in alpha decay has been described. The energy and half life for some α emitting nuclides were mentioned. Let us take a closer look at the energy of alpha particles from a source.

- Why α particles instead of protons or other groups of nucleons are emitted?

- How is alpha energy evaluated and determined?
  What is a typical alpha spectrum and why?

Energy consideration indicates that α particles (^{4}He atoms) are much more stable than hydrogen, deuterium, and other light nuclides. The average nucleon mass of ^{4}He (1.00065 amu) is much lower than those of comparable masses: ^{2}D, ^{3}T, ^{3}He, ^{5}He, and ^{5}Li, as seen in the accompanying Table. The stability is evident either from the *average mass* or the *mass excess.*

Comparing Average Nucleon Masses

Nuclide	*Mass* amu	*Mass / A* amu
^{1}H	1.007825	1.007825
^{1}n	1.008665	1.008665
^{2}D	2.01420	1.00710
^{3}T	3.01605	1.00535
^{3}He	3.01603	1.00535
^{4}He	4.00260	**1.00065**
^{5}He	5.01222	1.002444
^{5}Li	5.01254	1.00251

The **average mass** of nucleons is the *mass* divided by the mass number *A*,

average mass = mass / A.

The ***mass excess*** is obtained by subtracting the mass number *A* from the rest *mass*

mass excess = mass - A.

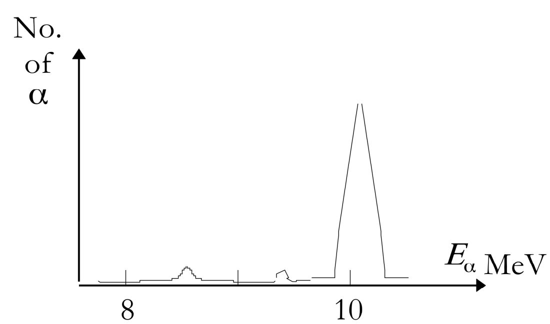
If the average mass is greater than 1, ignoring the integer portion before the decimal point of the *mass* is the *mass excess*. For example the *mass excess* for ^{4}He is of 0.00260 amu. The *mass excess* and the *average mass* are related. Both *mass excess* and *average mass* for ^{4}He are the lowest for nuclides of comparable masses, indicating that its nucleons are at a lowest energy state among those in the Table. The atomic nucleus ^{4}He or α particle is energetically very stable, and it is also emitted by radioactive decay. Some even ventured to suggest that α particles are components of atomic nuclei, instead of protons and neutrons.

In order to show an alpha spectrum, energies of α particles must be determined. Soon after the discovery of radioactivity, oil chambers were used to observe the paths of alpha particles. The entire distance travel by alpha particles is called the ***range***. Experiments show that the *range* depends on the energy. On the other hand, modern instruments can measure the energy more accurately.

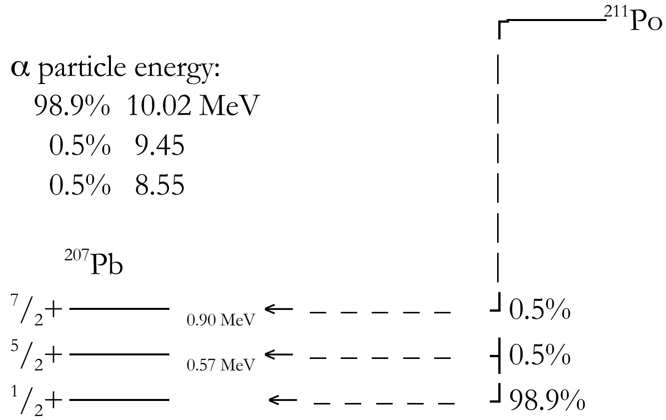
Typical α energies range from 1 to 11 MeV, with most of them between 4 and 8 MeV. The three natural occurring families of radioactive decay series have many α emitters, and they provide a good source for the study of α particles. As early as 1911, Geiger and Nuttall plotted the decay constant λ versus the *ranges* of nuclides in these families. They observed three lines for these families, and the lines are very close together. They established a relationship between the decay energy and the half life: In general, **the higher the energy of α decay, the shorter the half life,** but there are other factors to be considered.

Careful measurements and analyses revealed that not all α particles from a radioactive nuclide have the same energy. A hypothetical spectrum is shown here. As pointed out earlier, there are several energy states in a nuclide. A nuclide transforming to various states of the daughter nuclide resulting in alpha particles having some discrete energy.

An Ideal Alpha Spectrum



Spectra of α particles should be examined together with the daughters' γ ray spectra. Not all α decays will result in the ground state of the daughter nuclide, but some to higher energy levels. A simple example is the decay of ^{211}Po to the various energy levels of ^{207}Pb as shown below:



Thus, 98.9% of α particles from ^{211}Po have a kinetic energy of 10.02 MeV, but 0.5% of them have 9.5 MeV and another 0.5%, 8.55 MeV. Under ideal conditions, this alpha spectrum should have three sharp peaks as sketched above. The gamma spectrum consists of peaks at 0.90, 0.57, and 0.33 MeV, corresponding to the difference of the energies for the alpha lines in the spectrum.

Skill Building Questions:

1. *The masses for ^{15}O, ^{16}O, ^{17}O are 15.003065, 15.994915, and 16.99131 respectively. What are the average masses of nucleons and mass excess for the three species?*
   Compare and discuss these values with those of ^{4}He.
   (The mass excess and average mass per nucleon will be further discussed in the topic dealing with nuclear fusion.)

2. *The α particle energies and intensities of ^{238}U given in the CRC Handbook of Chemistry and Physics are: 4.039 MeV, 0.23%; 4.147 MeV, 23%; and 4.196 MeV, 77%.*
   Draw a diagram to show the decay scheme.
   What are the γ ray energies from this decay scheme?

Exercises

1. Define and explain the following terms: becquerel; curie, isotope, isobar, isotone, isomer, nucleus, nuclide, and transmutation. Give some examples if possible in your explanation.

2. One mole (about 226 g) of radium has an Avogadro's number of nuclei. Calculate the number of nuclei in one gram of ^{226}Ra. Calculate the decay constant and the half-life from the fact that one gram ^{226}Ra gives a decay rage of 3.7×10^{10} Bq. (The half life is about 1600 y).

3. If the alpha decay energy of ^{226}Ra is 4.8 MeV α particle, what is the energy released per second by 1.00 g of ^{226}Ra due to radiation? Express the rate of energy release in MeV, J, and cal. (1.8×10^{11} MeV/s, 2.9×10^{-2} J/s and 6.9×10^{-3} cal/s)

4. Calculate the weight of 1.0 Ci ^{222}Rn in g, which has a half life of 3.8235 d. This isotope of radon has the longest half life of all radon isotopes. (6.50×10^{-6} g)

5. A sample of radioactive water containing tritium has an activity of 0.1 Bq per gram of water. How many ^{3}T nuclei are present per gram of water? What is the mass of these ^{3}T nuclei? What is the weight percentage of ^{3}T? The half-life for ^{3}T is 12.26 y.

6. How these elements got their names: argon, boron, europium, francium, germanium, helium, mercury, neptunium, oxygen, polonium, promethium, technetium, and uranium.

7. Confirm the mass excess per nucleon of ^{3}He, ^{4}He, and ^{5}Li as 2.57, 7.07 and 5.33 MeV respectively. Use data given in the Chart of Light Nuclides.

8. Calculate the energy released when a deuterium is synthesized from a hydrogen atom and a neutron. (1.11 MeV per nucleon, using data given in the Chart of Light Nuclides.).

9. Using the format of the Chart of Light Nuclides, draw a diagram to show the transmutations of nuclides in α, β and γ decay processes.

10. How do the nuclide transform in the α, β and γ decay processes? Give a short description and then some examples for each process.

11. Describe characteristics of the α, β and γ spectra (from a nuclide).

12. Describe the three modes of beta decay. What are the characteristics of a β spectrum, *i.e.*, the energy distribution of beta particles), say from $^{14}C \rightarrow ^{14}N + \beta$? Check out the energies of decay and energy levels of nuclides involved from a handbook. Knowing where the information is available and knowing what information is present are an asset for you.

13. The nuclide ^{64}Cu has all three modes of beta decay, β^- and β^+ and EC. Explain why? What are the characteristics of the β^- and β^+ spectra from this nuclide? Justify their differences?

14. The (4*n* + 1) series in the four families of radioactive decay series starts with ^{237}Np^{93} (neptunium) and ends at a stable ^{209}Bi^{83}. How much energy is released per neptunium atom in its entire process decaying to a stable isotope? (Per Np atom, 40.03 MeV are released in the decay of 7 alpha, 4 beta, and gamma photons. The energy is estimated by 237.04800 - (208.9804 + 7*4.0026)*931.5 MeV. Note that the mass of the beta particles is not involved in this estimate.)

15. What is the abundance of ^{234}U if its half-life is the same as that of ^{238}U?

16. How many α and β particles are emitted when ^{237}Np becomes a stable nuclide ^{209}Bi in its entire decay process? Are the numbers dependent on the path of transmutation? Why? Do the same for the other three families of radioactive nuclides.

17. Assume the nuclide ^{238}U follows the main decay route (marked by dark arrows in the diagram depicting the decay paths of 4*n* + 2 family series), write out all the steps in the tranmutation processes by which ^{238}U converts to ^{206}Pb.

18. How many helium atoms are produced from each ^{238}U atom when it has become ^{206}Pb at the end of its decay process? (8 He atoms)

19. Radon is usually described as a deadly radioactive gas usually found in basements by the medium. Is the description correct? Why? What radon isotopes are likely to be found in basements? Describe the transmutations of ^{222}Rn.

Further Reading and Work Cited

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Useful Internet Sites

- http://www-highspin.phys.utk.edu/~bingham/p34198a.html Introductory Nuclear Physics.
- http://www-highspin.phys.utk.edu/~bingham/py341rev.html A List of topics in the above given for review purpose
- http://www.pgs.ca/pages/nl/nlalpenv.htm Alpha Particles in the Environment.
- http://t2.lanl.gov/data/astro/astro.html Nuclear Astrophysics.
- http://www.dne.bnl.gov/CoN/index.html Nuclide Chart for Query

Film

The nucleus - alpha, beta, and gamma rays (W MP16 25 m)