Chapter Five

(Radioactivity)

Radioactive decay is the process in which an unstable nucleus spontaneously loses energy by emitting ionizing particles and radiation. This decay, or loss of energy, results in an atom of one type, called the parent nuclide, transforming to an atom of a different type, named the daughter nuclide. The three principal modes of decay are called the alpha, beta and gamma decays.

The radioactive decay is statistical in nature, and we can only describe the evolution of the expectation values of quantities of interest, for example the number of atoms that decay per unit time. If we observe a single unstable nucleus, we cannot know when it will decay to its daughter nuclide. The time at which the decay happens is random, thus at each instant we can have the parent nuclide with some probability p and the daughter with probability 1-p. This process can only be described in terms of the quantum mechanical evolution of the nucleus. However, if we look at an ensemble of nuclei, we can predict at each instant the average number of parent and daughter nuclides. If we call the number of radioactive nuclei N, the number of decaying atoms per unit time is dN/dt. It is found that this rate is constant in time and it is proportional to the number of nuclei themselves:

$$\frac{dN}{dt} \propto N$$

$$\frac{dN}{dt} = -\lambda N(t)$$

The constant of proportionality λ is called the decay constant = probability of a nucleus decaying per second. We can also rewrite the above equation as:

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

The fact that this probability is a constant is a characteristic of all radioactive decay. It also leads to the exponential law of radioactive decay:

$N(t)= N(0)e^{-\lambda t}$

$N(0)=N(t=0)\equiv N_o$, which is the number of nuclei at t=0 (the time of manufacture)

We can also define the mean lifetime:

$\tau =1/\lambda$

and the half-lifetime:

$t_{1/2} = \ln(2)/\lambda = 0.693/\lambda$

Which is the time it takes for half of the atoms to decay. And the activity is:

$A(t)= |dN/dt|=\lambda N_o e^{-\lambda t} =\lambda N(t)$

$A(t)=A_o e^{-\lambda t}$

Where A_o is the activity at t=0 (the time of manufacture)

Units of activity: 1 Becquerel (Bq) = 1decay/second

1 Curie (Ci) = 3.7 x 10^{10} decays/sec (Bq) = Activity (1g of radium)

A common situation occurs when the daughter nuclide is also radioactive. Then we have a chain of radioactive decays, each governed by their decay laws. For example, in a chain $N_1 \rightarrow N_2 \rightarrow N_3$, the decay of N_1 and N_2 is given by:

$dN_1 = -\lambda_1 N_1 dt$, $\quad dN_2 =+\lambda_1 N_1 dt - \lambda_2 N_2 dt$

Another common characteristic of radioactive decays is that they are a way for unstable nuclei to reach a more energetically favorable (hence stable) configuration. In α and β decays, a nucleus emits a α or β particle, trying to approach the most stable nuclide, while in the γ decay an excited state decays toward the ground state without changing nuclear species.

For nuclei which decompose by two types, i.e. the emission of alpha particles and gamma rays together, the activity of source are:

$-dN=dN_\alpha+dN_\gamma$, $A(t) = A_o e^{-(\lambda_\alpha+\lambda_\gamma)t}$ or $N(t) = N_o e^{-\lambda_{tot} t}$

Where $\lambda_{tot}=\lambda_\alpha+\lambda_\gamma$, $A_{tot}=A_\alpha+A_\gamma$

And the ratio $\frac{A_\alpha}{A_{tot}} = \frac{\lambda_\alpha}{\lambda_{tot}}$ is called Branching Ratio.

(5-1) Alpha decay

The decrease in binding energy at high mass number (A) is due to Coulomb repulsion. Coulomb repulsion grows in fact as Z^2, much faster than the other nuclear force which is $\propto A$. This could be thought as a similar process to what happens in the fission process: from a parent nuclide, two daughter nuclides are created. In the α-decay we have specifically:

$${}^{A}_{Z}P_{N} \rightarrow {}^{A-4}_{Z-2}D_{N-2} + \alpha + Q_{\alpha}$$

where α is the nucleus of He-4 (${}^{4}_{2}He_{2}$) as shown in figure below.

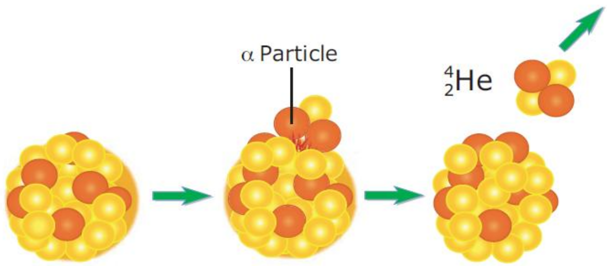

Figure (5-1): Alpha decay schematic.

Energetics:

In analyzing a radioactive decay (or any nuclear reaction) an important quantity is Q, the net energy released in the decay:

$Q_{\alpha}=(m_P-m_D-m_{\alpha})c^2=931.5[m(A,Z)-m(A-4,Z-2)-m_{\alpha}]=-S_{\alpha}$

This is also equal to the total kinetic energy of the fragments, here $Q=T_D+T_{\alpha}$ (here assuming that the parent nuclide is at rest). When Q>0 energy is release in the nuclear reaction, while for Q<0 we need to provide energy to make the reaction happen. As in chemistry, we expect the first reaction to be a spontaneous reaction, while the second one does not happen in nature without intervention. (The first reaction is exo-energetic the second endo-energetic). Q give the quality of the reaction, i.e. how energetically favorable, hence probable, it is. For example in the alpha-decay,$\log(t_{1/2}) \propto \frac{1}{\sqrt{Q_{\alpha}}}$, which is the Geiger-Nuttall rule (1928).

The alpha particle carries away most of the kinetic energy (since it is much lighter) and by measuring this kinetic energy experimentally it is possible to know the masses of unstable nuclides. We can calculate Q using the SEMF, Then:

$$Q_\alpha = B({}^{A-4}_{Z-2}Y) + B({}^{4}_{2}He) - B({}^{A}_{Z}X) = B(A-4, Z-2) - B(A,Z) + B({}^{4}_{2}He)$$

Since we are looking at heavy nuclei, we know that Z≈0.41A (instead of Z≈A/2) and we obtain:

$$Q_\alpha \approx -36.68 + 44.9A^{-1/3} + 1.02A^{2/3}$$

Where the second term comes from the surface contribution and the last term is the Coulomb term.

Then, the Coulomb term, although small, makes Q increase at large A. We find that Q ≥ 0 for A≥150, and it is Q ≈ 6MeV for A=200. Although Q>0, we find experimentally that α-decay only arise for A≥200. Further, take for example Francium-200(${}^{200}_{87}Fr_{113}$). If we calculate Q_α from the experimentally found mass differences we obtain Q_α≈7.6MeV (the product is ^{196}At).

Example:

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

m_U=238.050784u, m_{Th}=234.043593u, m_α=4.002602u

$Q_\alpha=(m_P-m_D-m_\alpha)c^2=(m_U-m_{Th}-m_\alpha)931.5=0.004589x931.5=4.275$MeV

Note that:

1. Most of the energy (Q) is KE of α
2. Decay occurs if Q > 0 (energy released)
3. Spontaneous decay does not occur if Q < 0
4. Conservation of momentum (daughter + alpha) and Energy gives:
   Q = KE(α)+ KE(daughter)
5. KE(α)=Q($\frac{A-4}{A}$)

For ^{238}U KE(α)=4.275x(234/238)=4.2MeV

Energy spectrum of Alpha particle:

Alpha particles have a linear spectrum of energy as shown in figure below:

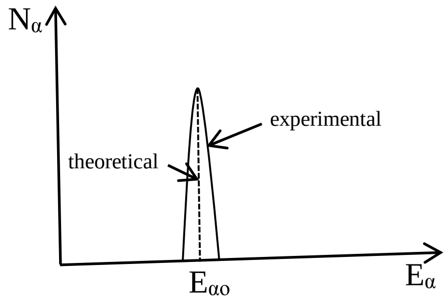

Figure (5-2): spectrum of alpha particles.

We assumed that the parent nuclide is at rest i.e. $P_P=0$

From the conservation law of linear momentum:

$P_\alpha=P_D \rightarrow m_\alpha v_\alpha=m_D v_D$

$T=1/2\ mv^2 = m^2v^2/2m=P^2/2m$

$T_D = P_D^2/2m_D\ ,\ T_\alpha = P_\alpha^2/2m_\alpha$

$P_\alpha=P_D \ \rightarrow \ \dfrac{T_D}{T_\alpha} = \dfrac{m_\alpha}{m_D}$

This equation means that the two particles share of energy available to them by the inverse proportional with its masses.

Rewrite the last equation:

$$\frac{T_D}{T_\alpha}+1=\frac{m_\alpha}{m_D}+1 \quad \rightarrow \frac{T_D+T_\alpha}{T_\alpha}=\frac{m_\alpha+m_D}{m_D}$$

$$\because Q_\alpha = T_\alpha + T_D$$

$$\therefore T_\alpha = \frac{Q_\alpha m_D}{m_\alpha + m_D}$$

$\because Q_\alpha, m_\alpha, m_D$ are constant values, therefore T_α is a constant quantity, i.e. the alpha particles have the same energy and linear spectrum. By approximation the masses:

$$m_\alpha + m_D \approx A$$

$$\therefore T_\alpha = \frac{A-4}{A} Q_\alpha$$

H.W.: Calculate Q_α , T_α and T_D for emission of alpha particle from Radium, Radon and Polonium, where the masses of ^{224}Ra, ^{220}Rn and ^{216}Po are 224.020217u, 220.01140u and 216.001927u respectively, note that m_α=4.002603u and m(^{212}Pb)=211.991903u, then give your comment on the result.

Range of alpha particle in materials:

It is the distance which alpha particle moving in the material until loses all of its energy.

$$R_\alpha = 0.318\, T_\alpha^{3/2} \qquad \text{(experimentaly equation)}$$

Where T_α in MeV, R_α in cm which is the range of alpha particle in air under pressure 76 cm.Hg at room temperature.

(5-2) Beta decay

The beta decay is a radioactive decay in which a proton in a nucleus is converted into a neutron (or vice-versa). Thus A is constant, but Z and N change by one. In the process the nucleus emits a beta particle (either an electron or a positron) and quasi-massless particle, the neutrino.

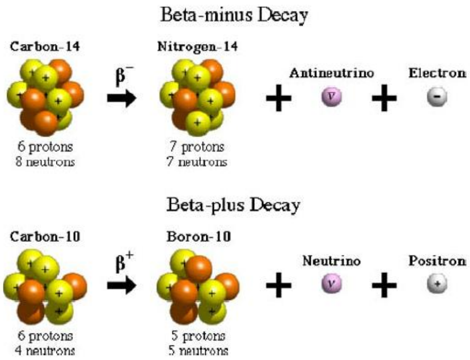

Figure (5-3): beta decay schematics.

There are 3 types of beta decay:

$${}^{A}_{Z}X_{N} \rightarrow {}_{Z+1}^{A}Y_{N-1} + e^{-} + \bar{\upsilon}$$

This is the β^- decay (or negative beta decay). The underlying reaction is:

$n \rightarrow p + e^{-} + \bar{\upsilon}$

That corresponds to the conversion of a neutron to proton with the emission of an electron and an anti-neutrino. There are two other types of reactions, the β^{+} reaction is:

$${}^{A}_{Z}X_{N} \rightarrow {}_{Z-1}{}^{A}Y_{N+1} + e^{+} + \upsilon \Leftrightarrow p \longrightarrow n + e^{+} + \upsilon$$

Which sees the emission of a positron (the electron anti-particle) and a neutrino, while the electron capture:

$${}^{A}_{Z}X_{N} + e^{-} \rightarrow {}_{Z-1}{}^{A}Y_{N+1} + \upsilon \Leftrightarrow p + e^{-} \longrightarrow n + \upsilon$$

As the neutrino is hard to detect, initially the beta decay seemed to violate energy conservation. Introducing an extra particle in the process allows one to respect conservation of energy. The Q value of a beta-decay is given by the usual formula:

$$Q_{\beta^{-}} = [m_N({}^{A}_{Z}X) - m_N({}_{Z+1}{}^{A}Y) - m_e]c^2$$

Using the atomic masses and neglecting the electron's binding energies as usual we have:

$$Q_{\beta^{-}} = \{[m_A({}^{A}_{Z}X) - Zm_e] - [m_A({}_{Z+1}{}^{A}Y) - (Z+1)m_e] - m_e\}c^2$$

$$= [m_A({}^{A}_{Z}X) - m_A({}_{Z+1}{}^{A}Y)]c^2$$

i.e. $Q_{\beta^{-}} = [m_A(A,Z) - m_A(A,Z+1)]931.5 = T_{\beta^{-}} + T_{\bar{\upsilon}}$

since $T_D \approx 0$

As the same method, we get the equations for β^{+} and electron capture as follows:

$$Q_{\beta^{+}} = [m_A(A,Z) - m_A(A,Z-1) - 2m_e]931.5 = T_{\beta^{+}} + T_{\upsilon}$$

$$Q_{E.C} = [m_A(A,Z) - m_A(A,Z-1)]931.5 = T_D + T_{\upsilon} = T_{\upsilon}\,,(T_D \approx 0)$$

The kinetic energy (equal to the Q) is shared by the neutrino and the electron (we neglect any recoil of the massive nucleus). Then, the emerging electron (remember, the only particle that we can really observe) does not have a fixed energy, as it was for example for the alpha particle or gamma photon. But it will exhibit a spectrum of energy (or the number of electron at a given energy) as well as a distribution of momenta, for examples:

$$
{}^{64}_{29}\mathrm{Cu} \begin{array}{l} \nearrow \\ \searrow \end{array} \begin{array}{ll} {}^{64}_{30}\mathrm{Zn} + e^{-} + \bar{\nu}, & Q_{\beta} = 0.57MeV \\ {}^{64}_{28}\mathrm{Ni} + e^{+} + \nu, & Q_{\beta} = 0.66MeV \end{array}
$$

The neutrino and beta particle ($\beta^{\pm}$) share the energy. Since the neutrinos are very difficult to detect (as we will see they are almost massless and interact very weakly with matter), the electrons/positrons are the particles detected in beta-decay and they present a characteristic continuous energy spectrum (see Fig. 5-4)

The difference between the spectrums of the $\beta^{\pm}$ particles is due to the Coulomb repulsion or attraction from the nucleus and the continuous spectrum of β decay is due to the random distribution of energy to β particle and neutrino as shown in figure below.

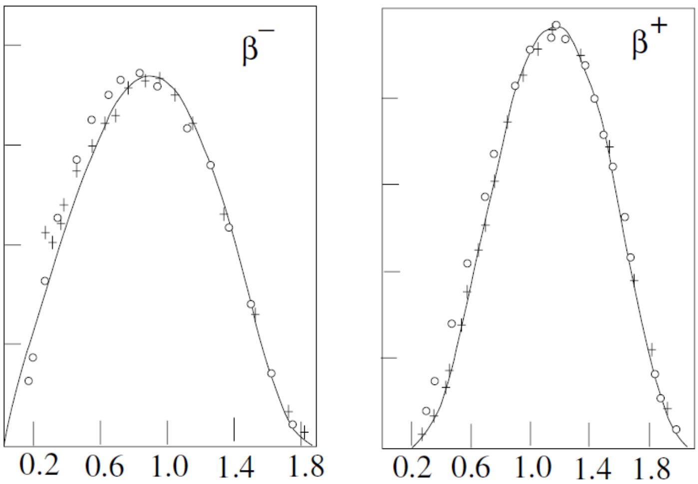

Figure (5-4): The β^{-} and β^{+} spectra of ^{64}Cu. The suppression of the β^{+} spectrum and enhancement of the β^{-} at low energy due to the Coulomb effect is seen.

Notice that the neutrinos also carry away angular momentum. They are spin-1/2 particles, with no charge (hence the name) and very small mass. For many years it was actually believed to have zero mass. However it has been confirmed that it does have a mass in 1998. Other conserved quantities are:

1-Momentum and Energy: The momentum and energy is also shared between the electron and the neutrino. Thus the observed electron momentum or energy ranges from zero to a maximum possible transfer.

2- Angular momentum: both the electron and the neutrino have spin 1/2.

3- Parity: It turns out that parity is not conserved in this decay. This hints to the fact that the interaction responsible violates parity conservation (so it cannot be the same interactions we already studies, electromagnetic and strong interactions).

Thus the neutrino hypothesis is required to satisfy the energy, linear and angular momentum conservation laws.

Consider for example ^{22}Na and ^{36}Cl. They both decay by β decay:

$$^{22}_{11}\mathrm{Na}_{11} \rightarrow ^{22}_{10}\mathrm{Ne}_{12} + \beta^+ + \nu, \qquad Q = 0.22\mathrm{MeV}, \quad T_{\frac{1}{2}} = 2.6\mathrm{years}$$

$$^{36}_{17}\mathrm{Cl}_{19} \rightarrow ^{36}_{18}\mathrm{Ar}_{18} + \beta^- + \bar{\nu} \qquad Q = 0.25\mathrm{MeV}, \quad T_{\frac{1}{2}} = 3 \times 10^5\mathrm{years}$$

Classification of beta decay:

1- Charge: there is two type of beta particle; β^- and β^+

2- Spin momentum ($\overrightarrow{S_\beta}$): there is two type as follow:

a- Fermi decay (F)

In this type of decay, the direction of spin momentum for beta particle is opposite to that for neutrino i.e.

$$\overrightarrow{S_\beta} = \overrightarrow{s_\beta} + \overrightarrow{s_\upsilon} = 0$$

b- Gammow-Teller decay (G.T.)

In this type of decay, the direction of spin momentum for beta particle is the same to that for neutrino i.e.

$$\overrightarrow{S_\beta} = \overrightarrow{s_\beta} + \overrightarrow{s_\upsilon} = 1$$

3- Orbital angular momentum $\overrightarrow{L_\beta}$:

a- If $\overrightarrow{L_\beta} = 0$, the decay is called (allowed decay)

b- If $\overrightarrow{L_\beta} = 1$, the decay is called (1st forbidden decay)

c- If $\overrightarrow{L_\beta} = 2$, the decay is called (2nd forbidden decay)

d- For $I_i=I_f=0$, i.e. the transition 0→0, the decay is called (forbidden decay)

Note that the 1st and 2nd forbidden decays, not means there are not happened, but the probability of their decay are very small due to the large values of $\overrightarrow{L_\beta}$ which lead to increasing in half life time ($t_{1/2}$) for the exited state, which making the decay in small probability.

Selection rules for beta decay:

1- momentum conservation:

$$\vec{I}_P = \vec{I}_D + \vec{S}_\beta + \vec{L}_\beta \Rightarrow \Delta I = \vec{I}_P - \vec{I}_D = \vec{S}_\beta + \vec{L}_\beta$$

Where $\vec{I}_\beta = \vec{S}_\beta + \vec{L}_\beta$

And $\left|\vec{I}_P - \vec{I}_D\right| \le \Delta I \le \vec{I}_P + \vec{I}_D$ or $\left|\vec{I}_i - \vec{I}_f\right| \le \Delta I \le \vec{I}_i + \vec{I}_f$

2- parity conservation:

$$\pi_P.\pi_D = (-1)^{L_\beta} \quad \text{or} \quad \pi_i.\pi_f = (-1)^{L_\beta}$$

<u>Example:</u> classify the following beta decays:

1. the transition $2^- \rightarrow 1^+$, 2. the transition $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$, 3. the transition $0^+ \rightarrow 0^+$

<u>Solution:</u>

1. for $2^- \rightarrow 1^+$: $\pi_i.\pi_f = -.+ = (-1)^{L_\beta} \Rightarrow L_\beta = 1,3,5,\ldots$
2. for $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$: $\pi_i.\pi_f = +.+ = (-1)^{L_\beta} \Rightarrow L_\beta = 0,2,4,\ldots$

1. $1 \le \Delta I \le 3 \Rightarrow \Delta I = 1,2,3$

2. $0 \le \Delta I \le 1 \Rightarrow \Delta I = 0,1$

For the higher probability of decay, we must take the lowest value of L_β to correspond to ΔI value.

1. $\Delta I = \vec{S}_\beta + \vec{L}_\beta \Rightarrow 1 = 0 + 1 \Rightarrow \vec{S}_\beta = 0$ and $\vec{L}_\beta = 1$

Therefore the beta decay for $2^- \rightarrow 1^+$ transition is 1st forbidden in Fermi decay

2. $\Delta I = \vec{S}_\beta + \vec{L}_\beta \Rightarrow 0 = 0 + 0 \Rightarrow \vec{S}_\beta = 0$ and $\vec{L}_\beta = 0$

Therefore the beta decay for $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ transition is allowed in Fermi decay

3. If we have $0^+ \to 0^+$ transition, this decay is forbidden to beta decay.

(5-3) Gamma decay

In the gamma decay the nuclide is unchanged, but it goes from an excited to a lower energy state. These states are called isomeric states. Usually the reaction is written as:

$${}^{A}_{Z}X^{*}_{N} \rightarrow {}^{A}_{Z}X_{N} + \gamma$$

Where the star indicates an excited state, we will study that the gamma energy depends on the energy difference between these two states, but which decays can happen depend, once again, on the details of the nuclear structure and on quantum-mechanical selection rules associated with the nuclear angular momentum.

Gamma ray spectroscopy is a basic tool of nuclear physics, for its ease of observation (since it's not absorbed in air), accurate energy determination and information on the spin and parity of the excited states.

$Q_\gamma=[M^*(A,Z) - M(A,Z)]931.5= E_i - E_f=E_\gamma$

Where $T_D=0$

Since the gamma decay produces two types of particles, gamma ray (electromagnetic radiation or photons) and daughter nuclide, therefore the energy spectrum for gamma ray is linear spectrum as shown in the figure below.

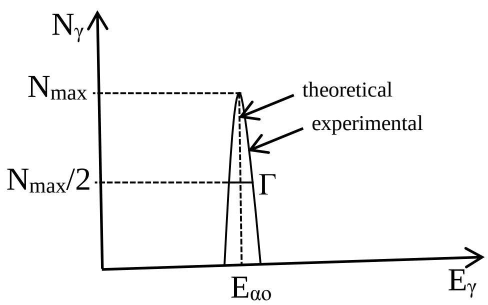

Figure (5-5): spectrum of gamma ray.

The percentage ratio between the full width at half maximum (FWHM=Γ) and the gamma energy E_γ is called Energy Resolution (R).

$R=\Gamma/E_\gamma$ (%)

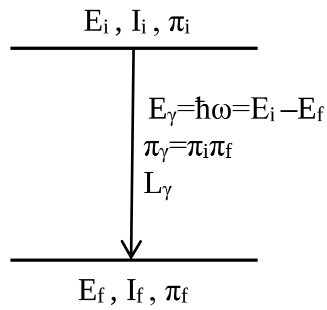

Figure (5-6): Schematics of gamma decay.

(5-3-1) nuclear multipole moments

The nuclide has electric multipole moments due to its positive charge, non-spherical shape and the energy levels arrangement. The ranking of the electric moment is determined based on the orbital angular momentum value and is equal to:

$P=2^L$ (number of poles)

if L=1 → P=2 → 2 poles → electric dipole moments≡E1

if L=2 → P=4 → 4 poles → electric quadrupole moments≡E2

if L=3 → P=8 → 8 poles → electric octapole moments≡E3

And due to the vibration of the charges, there is an electromagnetic radiation emitting which called electric multipole radiation.

It also may happen that; rotation of the charges in closed paths (Loops) to make magnetic multipole moments and emitting an electromagnetic radiation which called magnetic multipole radiation.

if L=1 → P=2 → 2 poles → magnetic dipole moments≡M1

if L=2 → P=4 → 4 poles → magnetic quadrupole moments≡M2

if L=3 → P=8 → 8 poles → magnetic octapole moments≡M3

We must know that the probability of emitting the multipole radiation is as follow:

E1>M1>E2>M2>E3>M3…

(5-3-2) Selection Rules

1- conservation of energy

$E_\gamma = E_i - E_f$

2- conservation of angular momentum

The angular momentum must be conserved during the decay. Thus the difference in angular momentum between the initial (excited) state and the final state is carried away by the photon emitted.

$$\vec{I}_i = \vec{I}_f + \vec{L}_\gamma + \vec{S}_\gamma \Rightarrow \Delta I = \vec{I}_i - \vec{I}_f = \vec{L}_\gamma + 1$$

Where $S_\gamma = 1$ for bosons (gamma ray)

$$\left|\vec{I}_i - \vec{I}_f\right| \leq \Delta I \leq \vec{I}_i + \vec{I}_f$$

$$\vec{L}_\gamma = \left|\vec{I}_i - \vec{I}_f\right| \cdots \left|\vec{I}_i + \vec{I}_f\right|$$

Since $L_\gamma \neq 0$, because of, if $L_\gamma=0$ the number of polarities which is $P=2^L$ was equal 1 , i.e. there is a one or a single pole and that is impossible, then there is no multipol momentum and no energy emitting.

$\Delta I=0,\pm 1$ and $I_i=0 \rightarrow I_f=0$ is forbidden to gamma decay

3- conservation of parity

The parity of the gamma photon is determined by its character, either magnetic or electric multipole, we have:

$\pi_i . \pi_f = (-1)^L$ for Electric multipole

$\pi_i . \pi_f = (-1)^{L+1}$ for Magnetic multipole

This of course limits the type of multipole transitions that are allowed given an initial and final state, the character (magnetic or electric) of the multipole is found by looking at the parity. In general then, the most important transition will be the one with the lowest allowed L. Higher multipole are also possible, but they are going to lead to much slower processes.

Table (5-1): Angular momentum and parity of the gamma multipole.

Multipolarity	Angular Momentum L	Parity π	Multipolarity	Angular Momentum L	Parity π
M1	1	+	E1	1	-
M2	2	-	E2	2	+
M3	3	+	E3	3	-
M4	4	-	E4	4	+
M5	5	+	E5	5	-

(5-3-3) Dominant Decay Modes

In general we have the following predictions of which transitions will happen:

1. The lowest permitted multipole dominates
2. Electric multipole is more probable than the same magnetic multipole by a factor $\approx 10^2$ (however, which one is going to happen depends on the parity)

$$\frac{\lambda(EL)}{\lambda(ML)} \approx 10^2$$

3. Emission from the multipole L+1 is 10^{-5} times less probable than the L multipole emission.

$$\frac{\lambda(E,L+1)}{\lambda(EL)} \approx 10^{-5} \quad , \quad \frac{\lambda(M,L+1)}{\lambda(ML)} \approx 10^{-5}$$

4. Combining 2 and 3, we have:

$$\frac{\lambda(E,L+1)}{\lambda(ML)} \approx 10^{-3} \quad , \quad \frac{\lambda(M,L+1)}{\lambda(EL)} \approx 10^{-7}$$

Thus E2 competes with M1 while that's not the case for M2 vs. E1

Attenuation or absorption of gamma ray

When the gamma rays fall on a substance and transmitted, the intensity will be reduced according to the equation:

$I=I_o e^{-\mu x}$

Where x is a thickness and μ is a linear absorption coefficient of the substance.

Note that the thickness of any substance which reduces the intensity to the half of its value was called a half thickness $x_{1/2}$.

$x_{1/2}=0.693/\lambda$

(5-4) Spontaneous fission

Some nuclei can spontaneously undergo fission, even outside the particular conditions found in a nuclear reactor. In the process a heavy nuclide splits into two lighter nuclei, of roughly the same mass.

(5-5) Branching Ratios

Some nuclei only decay via a single process, but sometimes they can undergo many different radioactive processes, that compete one with the other. The relative intensities of the competing decays are called branching ratios. Branching ratios are expressed as percentage or sometimes as partial half-lives. For example, if a nucleus can decay by beta decay (and other modes) with a branching ration b_β, the partial half-life for the beta decay is $\lambda_\beta = b_\beta \lambda$.