Study Material - Sem. 4 - CGT

- Radioactivity & Alpha Decay - Dr. T. Kar

Chapter Eleven

RADIOACTIVITY I

11.1 Introduction

Nuclear physics may be said to begin with the discovery of radioactivity by Becquerel and the Curies. During his experiments on fluorescence of uranium, the French physicist Henry Becquerel in 1896 was amazed to notice that a photographic plate, wrapped in black paper for protection, was affected by the salts of uranium kept outside it. In tracing the origin and nature of this invisible radiation, *radioactivity* – the phenomenon of emission of such radiation – was discovered, thanks to the monumental and pioneering work carried out in the field by Mme Curie and Pierre Curie, Ernst Rutherford, Fredric Soddy and others. The Curies were awarded jointly with Becquerel, the Nobel Prize in physics in 1903 for this discovery. In 1911 Mme Curie was again awarded the Nobel Prize in chemistry for her painstaking efforts in isolating the radioactive element, now called, radium.

11.2 Radioactivity

Radioactivity is the phenomenon of *spontaneous disintegration,* attended with emission of corpuscular or electromagnetic radiations, of *heavy* atomic nuclei like uranium, radium etc. at a *constant rate* unaffected by any physical or chemical changes or influences such as temperature, pressure etc. to which the atom (nucleus) may be subjected. It is a *nuclear property* of the active element and in all radioactive processes, a *transmutation* (change from one element to another) of the element occurs – an altogether new nucleus is formed. Radioactivity is in fact the first nuclear phenomenon to be discovered.

The radiations from different radioactive substances were classified as α-rays and β-rays by Rutherford from a study on the penetrating power of these radiations. Subsequently, a third type of radiation – γ-rays – which is a very energetic form of electromagnetic waves was added to the list by Paul Villard. In the case of α and β-emission processes, either the atomic number Z or the mass number A or both Z and A of the nucleus change leading to a new nucleus (transmutation).

In γ-emission process, no transmutation occurs, the nucleus makes only a transition from a quantum state of higher energy (excited state) to another of lower energy. Any nuclide that undergoes a change in its structure by shedding nuclear particles such as α and β, and gives off γ-rays is called a *radioactive nucleus.* It has been found that there are 272 stable nuclei of naturally occurring elements (they are non-radioactive); the rest are all unstable, and hence radioactive, and are known as *radio-isotopes.*

11.3 Radioactive decay law

Experimental studies, as conducted by Rutherford and Soddy, show that

(i) On emission of α or β-rays, which is usually but not invariably accompanied by γ-emission, the emitting parent nuclide transforms into a new daughter element; the daughter element again is radioactive so that the process of successive disintegration continues till the original active parent nuclide gets transformed into a stable one, usually lead (Pb).

(ii) The *rate of radioactive disintegration,* that is, the number of atoms (nuclides) that

break up at any instant of time t is *directly proportional to the number N_t of active nuclides present* in the sample under study *at that instant.*

Decay equation — Let N_t be the number of active nuclides present in the sample at any instant t. Then, we have, experimentally

$$-\frac{dN_t}{dt} \propto N_t$$

$$\text{or,} \quad \frac{dN_t}{dt} = -\lambda N_t \tag{i}$$

where λ, the constant of proportionality, is known as the *decay constant* – a characteristic constant of the element (nuclide). The negative sign hints at the fact that N_t decreases with t.

Re-arranging (i), $$\frac{dN_t}{N_t} = -\lambda dt \tag{ii}$$

Integrating (ii), $$\ln N_t = -\lambda t + A \tag{iii}$$

where A is the constant of integration.

At $t = 0$, $N_t = N_0$, the initial number of nuclides. So from (iii), we obtain, $A = \ln N_0$.

$\therefore$ From (iii), finally, $$\ln(N_t/N_0) = -\lambda t$$

$$\text{or,} \quad N_t = N_0 e^{-\lambda t} \tag{iv}$$

The above is the radioactive *decay law* or *decay equation.* It shows that the number of active nuclides decreases exponentially with time (Fig.11.8).

According to the decay law, therefore, an infinite time is theoretically needed for the radioactivity to disappear *completely* and in this respect, all radio-elements are the same. So to distinguish one radio-element from another, a quantity called *half-life* $T_{\frac{1}{2}}$ is more often used.

Note. The decay constant is also called *disintegration constant, transformation constant* or the *radioactive constant.* It depends on the energy that is available for the nuclear transformation and on the characteristics of the parent and daughter nuclei. It is *independent* of the external conditions and the age of the sample.

Half-life — The *half-life* or the *half-value period* of a radioactive nuclide is defined as the *time* $T_{\frac{1}{2}}$ in which the original amount of radioactive atoms is *reduced* by way of disintegration *to half* its value.

Substituting N_t by $N_0/2$ in eq. (iv) $T_{\frac{1}{2}}$ is given by

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{\frac{1}{2}}}$$

$$\therefore \quad T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{2.303 \log 2}{\lambda} = \frac{0.693}{\lambda} \tag{v}$$

$$\text{or,} \quad \lambda T_{\frac{1}{2}} = 0.693 = \text{const.} \tag{vi}$$

So, $T_{\frac{1}{2}}$ is *independent* of the instant from which it is measured. Depending on the radioactive nuclide, its value may range from 10^{10} years to 10^{-7}s.

Average life — The fundamental law of radioactive decay is a **statistical law.** It gives that the *probability* of decay of a given nuclide in a short time interval dt at time t is $|dN_t/N_t| = \lambda dt$ which is *independent* of the age of the nuclide. It *does not state* anything about the decay of an individual atom. Of the N_t nuclides which one would disintegrate at any instant t is completely at the mercy of chance. From the decay law, we can only infer that the decay rate will be proportional to N_t. From this probabilistic interpretation of the decay law, it is apparent that among the nuclides, some may disintegrate almost immediately after they are formed, while others may exist for an infinitely long time. We do not know why it is so. The possible time of existence (actual life) of a nuclide thus may vary from 0 to ∞ and all radio-elements are the same in this respect. We can however speak of an *average* or *mean life* $\bar{T}$ of a radio-element.

The *average* or *mean life* $\bar{T}$ of a radioelement is the *average lifetime* of all the atoms in the given sample and is defined as the ratio of the *total lifetime* of all the atoms to the *total number of atoms.*

$$\therefore \quad \bar{T} = \frac{t_1 dN_1 + t_2 dN_2 + \cdots}{dN_1 + dN_2 + \cdots} = \frac{\Sigma t dN}{\Sigma dN}$$

where dN_1 atoms have a lifetime t_1, dN_2 atoms a lifetime t_2 and so on.

Stated in the notation of integral calculus,

$$\bar{T} = \frac{\int_{t=0}^{\infty} t dN}{\int_{N_0}^{0} dN} = \frac{\int_{t=0}^{\infty} t dN}{-N_0}$$

But, we have, $dN = d(N_0 e^{-\lambda t}) = -\lambda N_0 e^{-\lambda t} dt$

$$\therefore \quad \bar{T} = \lambda \int_0^\infty t e^{-\lambda t} dt$$

$$= \lambda \left[-\frac{t}{\lambda} e^{-\lambda t} + \frac{1}{\lambda} \int_0^\infty e^{-\lambda t} dt \right]$$

$$= \lambda \left[-\frac{t}{\lambda} e^{-\lambda t} - \frac{1}{\lambda^2} e^{-\lambda t} \right]_0^\infty$$

$$= \frac{1}{\lambda}$$

$$\therefore \quad \text{Mean or average life, } \bar{T} = \frac{1}{\lambda} \qquad \text{(vii)}$$

The mean or average life of a radioactive element is thus *not* the same as its half-life. The mean life is the reciprocal of the decay constant, that is, the *decay probability per second* and is greater than the half-life.

Note. Since the actual life of an atom extends from 0 to infinity, the mean life $\bar{T}$ is not of much physical importance. From practical point of view the decay constant λ and the half-life $T_{\frac{1}{2}}$ are comparatively more significant quantities than $\bar{T}$.

We can now write how the three constants of radioactivity – the *decay constant*, the *half-life* and the *mean life* – are related to each other.

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda} = 0.693\bar{T}. \qquad \text{(viii)}$$

Caution ! The decay equation $N_t = N_0 e^{-\lambda t}$ applies to the behaviour of a single, pure radioactive element. Mixtures of radioactive substances and radio-samples having products of initial disintegrations that are themselves radioactive *do not obey* the above decay law.

Note 1. As λ increases, $T_{\frac{1}{2}}$ decreases and conversely. From the decay law, as λ increases (i.e., $T_{\frac{1}{2}}$ decreases), the number of radioactive atoms decreases more rapidly. Conversely, if λ is small ($T_{\frac{1}{2}}$ large), the number of radioactive atoms decreases very slowly, e.g., uranium and thorium. The half-lives of U and Th are very long so that their λ-values are very small.

Note 2. The λ and $T_{\frac{1}{2}}$ are characteristic constants of a radioactive substance (Fig. 11.8). The number of radioactive atoms is reduced by a factor $\frac{1}{2}$ after a time $T_{\frac{1}{2}}$. Plainly, it would be reduced by a factor $(\frac{1}{2})^2$ i.e., $\frac{1}{4}$ after a time $2T_{\frac{1}{2}}$. In general, the number would be reduced by $(\frac{1}{2})^n$ or $\frac{1}{2^n}$ after a time $nT_{\frac{1}{2}}$, that is, after n half-lives.

11.4 Activity or strength

Differentiating the decay equation $N_t = N_0 e^{-\lambda t}$

$$\frac{dN_t}{dt} = -\lambda N_0 e^{-\lambda t} \qquad \text{(i)}$$

When $t = 0$, $\left(\frac{dN_t}{dt}\right)_0 = -\lambda N_0$. Hence from the relation (i) above,

$$\frac{dN_t}{dt} = \left(\frac{dN_t}{dt}\right)_0 e^{-\lambda t}$$

$$\text{or,} \qquad A_t = A_0 e^{-\lambda t} \qquad \text{(ii)}$$

where $A_t = dN_t/dt$ and $A_0 = (dN_t/dt)_0$.

A_t is called the *activity* or the *strength* of the sample and is proportional to the rate of disintegration. The graph of the equation (ii) is shown in Fig. 11.8.

The *activity* or *strength* A_t of a radioactive sample at any instant t is thus defined as the number of disintegrations occurring in the sample in unit time at t, that is,

$$\text{Activity, } A_t = \left|\frac{dN_t}{dt}\right| = \lambda N_t$$

The activity per unit mass of a sample is called its **specific activity.**

Units of activity — The customary unit of radioactivity is called the **curie** (Ci). It is defined as the activity of any radioactive substance that disintegrates at the rate of 3.7×10^{10} disintegrations per second.

A thousandth part of a curie is called a **millicurie** (mCi). Still smaller unit is the **microcurie** (μCi). So, by definition,

$$1 \text{ Ci} = 1 \text{ curie} = 3.7 \times 10^{10} \text{ disint/sec}$$
$$1 \text{ mCi} = 10^{-3} \text{ curie}$$
$$1 \ \mu\text{Ci} = 10^{-6} \text{ curie}$$

A second unit of strength of radioactivity has come into use and is known as **rad.** It is a measure of the energy deposited per unit mass of matter by α, β or γ-rays traversing the matter.

$$1 \text{ rad} = 100 \text{ erg/g} = 0.01 \text{ J/kg.}$$

Another unit of activity is the **rutherford** (rd) which is defined as the activity of a radioactive substance that disintegrates at the rate of 10^6 disintegrations per second. There are smaller such units called milli-rutherford (mrd) and micro-rutherford (μrd) defined as one-thousandth rutherford ($= 10^3$ disintegrations/s) and 10^{-6} rutherford ($= 1$ disint/s).

Note 1. A_0 $[= (dN_t/dt)_0]$ is the initial activity of the sample. The half-life may be defined in terms of activity as well. It is the time in which the activity drops to one-half of the initial activity, see Fig. 11.8.

Note 2. Originally, 1 curie was defined as the number of disintegrations that occur per second in 1 g of Ra-226 by α-emission. The number, as measured carefully by a number of workers, has a value close to 3.7×10^{10} disint/s, but does not always give consistent results, so the new definition replaced the old one in 1950.

11.5 Radioactive radiations

Soon after the discovery of radioactivity, Rutherford, Curies and other workers carried out a thorough investigation of the radioactive radiation and discovered that it was not homogeneous in character but was composed of **three different and distinct types** of radiations. We describe here an experiment to that effect.

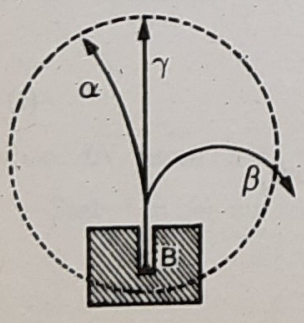

Fig.11.1 Radioactive radiations : α,β and γ-rays

Experimental set-up — The experimental arrangement (Fig. 11.1) described here is due to Mme Curie. A small quantity of radium preparation (either the element or its salt) is placed in a small hole drilled in a block of lead B. The block is housed in a chamber (not shown) evacuated to a very high degree to prevent absorption of the radiations by air inside the chamber. A strong magnetic field is applied at right angles to the plane of the paper and directed inward (that is, away from the reader).

Observations — The radiations emerging from the radium preparation are found to be divided into *three* distinct groups: one bent to the left, the second bent to the right and the third proceeding undeviated. Further, it is observed that the magnitude of the deflection of the first group is much smaller compared to that of the second.

Conclusion — On applying the left hand rule, it is concluded that (i) the first group consists of *positively charged* particles, (ii) the second group of *negatively charged* particles and (iii) the third group of *uncharged* radiations.

Further, the magnitudes of deflection indicate that the particles of the first group are more *massive* compared to those of the second. The three groups are named as α, β and γ-rays respectively.

Note. The heterogeneity of the radiations from a radioactive substance may also be established by subjecting them, instead of a magnetic field, to a strong electrostatic field which has a similar effect on the radiations.

11.6 General properties of α, β and γ-rays

We enumerate below, without proofs, some of the important properties of the α, β and γ-rays.

α-rays — The α-rays consist of *material* particles with a mass four times the protonic mass and a *positive charge* twice that of the proton. These particles are identified as the *helium nuclei*. They can ionise gases and penetrate matter as has been seen in the α-ray scattering experiments of Rutherford. The velocities with which α-particles are ejected from a radioactive substance are very high, ranging from $0.03\,c$ to $0.07\,c$ where $c = 3 \times 10^8$ m/s, the velocity of light in free space.

β-rays — The β-rays also consist of *material* particles but with a *negligible mass* and a *negative charge*. The q/m-value (the *specific charge*) of β-rays agree with that of the electrons and the β-rays are, in fact, identified as *electrons*. They can ionise gases, affect photographic plate and penetrate matter. The penetrating power is about 100 times greater than that of the α-particles. Because of the low mass, the ionising power is only about 1/100th of that of the α-particles. The velocity of the emitted β-rays from radioactive sources however depends on the source and is so high as to sometimes approach close to the velocity of light in vacuo.

γ-rays — These are *non-material* and *uncharged* in character, being totally unaffected by electric and magnetic fields. In fact, these consist of *electromagnetic radiations* of very small wavelength, smaller than even the shortest x-rays. Like the α-and β-rays, these also affect photographic plates, ionise gases through which they pass and penetrate matter. In penetrating power they are 10–100 times more effective than β-rays. But the ionising power is proportionately much weaker.

13.3 Range of α-particles

The most important property of α-particles is their ability to ionise the material (solid, liquid or gas) through which they pass. Let an α-particle course through a gas. As it moves, it ionises the gas particles by multiple collisions and thereby loses its energy gradually. Finally, its energy falls below the ionisation potential of the gas when it stops ionising and gets converted, by capturing two electrons, into neutral helium atom.

Range — The distance through which an α-particle travels in a specified material before stopping to ionise it is called its *range* in that material. The *range is* thus *a sharply defined ionisation path-length.*

Blackett demonstrated such ranges of α-particles beautifully in his cloud chamber photographs (Fig. 13.3). Naturally, the range is highest in gases, less in liquids and the least in solids due to more and more dense packing of the particles.

Plainly, in a gas, the *range depends on* (i) the *initial energy* of the α-particle, (ii) the *ionisation potential* of the gas and (iii) the *chances of collision* between the α-particles and the gas particles, that is, on the *nature* and the *temperature* and *pressure* of the gas. With increase of pressure, the range decreases; it increases if the temperature of the gas is increased.

Measured in unit of *length*, the range in solids and liquids is very small $\sim 10^{-3}$ mm for α of few MeV. In a gas, it is few cm in length. The range can also be expressed in unit of the *mass* of the material. Let a cylinder of unit cross-section and length equal to the range R be drawn in the substance. The amount of matter in it is $R\rho$, where ρ is the density of the substance. In this case, the unit of the range is mass per unit area ($kg.m^{-2}$). If expressed in this unit, the range is of the same order of magnitude in different substances : solid, liquid or gas.

The range of α-particles obviously will depend on their initial velocity (kinetic energy), and accurate measurement of ranges of particles having different velocities gives the relation between these two quantities : $R = R(v)$. In fact, Geiger showed from his experimental studies that for monoenergetic α-particles of velocity v, the range R in standard air is proportional to v^3.

$$\therefore \quad R \propto v^3$$

$$\text{or,} \quad R = av^3 \tag{i}$$

where a is a constant. The relation (i) is known as the **Geiger law,** which is valid only in a limited velocity range.

Since $R \propto v^3$, and the energy $E = \frac{1}{2}mv^2$, the range-energy relationship is

$$R \propto E^{3/2} \Rightarrow R = bE^{3/2} \tag{ii}$$

This relation (ii) is *another form* of the empirical *law of Geiger.*

The values of the constants a and b of eq. (i) and (ii) respectively are

$$a = 9.416 \times 10^{-24}; \quad b = 3.15 \times 10^{-3},$$

if R is expressed in meter and E in MeV.

13.4.1 Straggling of range : Stopping power

The α-particles of the same initial energy have more or less the same range in matter. However, a small spread in the values of ranges about a mean value is observed. This phenomenon is known as the **straggling of the range.**

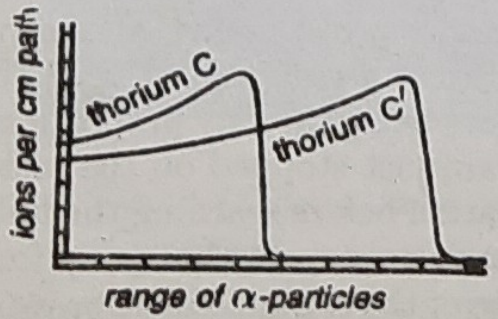

Fig.13.8 Bragg curves for the range of α-particles

If we measure the number of ions produced along the path of an α-particle and plot these values against the distance from the source, curves similar to those shown in Fig.13.8 are obtained. Towards the end of each curve, the number of ions reaches a maximum and then steeply drops down to zero. The curves are called **Bragg curves** after W.H. Bragg, and the maximum of the curve the **Bragg hump.** Thus the maximum number of ions is produced immediately before the particles stop ionising. The point at which the ion-density sharply drops to zero value gives the range. The Bragg curve

shows that the ionisation is fairly constant over the initial part and rises to the hump towards the end when the speed of the α-particles is diminished. Finally, when the energy of the particles falls below the ionisation potential of the gas, the curve steeply falls down. But the x-axis is not met abruptly. Near the end of the path it *tails off*. This is **straggling.**

The straggling of range occurs mainly due to *two reasons* : (i) there is a *statistical fluctuation in the number of collisions* (which is a random process) suffered by the different particles about a mean value in travelling over a given distance, and (ii) there is also a *statistical fluctuation* about a mean value in the *energy loss per collision.*

There are *other factors* as well contributing to straggling. They may be multiple scattering of the particles during collisions, inhomogeneity in density of the absorber and capture of electrons.

Note. It is to be noted that straggling of the range may also occur with other charged particles as well, e.g. β-particles.

Stopping power — The energy of α-particles progressively decreases as they pass through increasing thicknesses of matter (Kapitza). The amount of energy-loss of an α-particle per unit path length in the absorber is called the *stopping power* of the absorber.

The *air-equivalent* of an absorber is the *thickness*, t_a, of *standard air* that produces the same energy loss of α-particles as does a given thickness, t, of the absorber placed in the path. The ratio t/t_a is called the *equivalent stopping power*, t_e. The *equivalent stopping power is thus the thickness of the absorber that produces the same energy loss* in the α-particle *as does unit thickness of standard air*, for since

$$\therefore t_e = t/t_a, \text{ we obtain } t_e = t, \text{ when } t_a = 1.$$

The *relative stopping power*, S, is the ratio $1/t_e$. It is thus the ratio of the energy loss (of the α-particle) in traversing unit distance in the absorber to that in traversing unit distance in standard air.

The stopping power divided by ρ, the density of absorber, is called **mass stopping power,** and the mass stopping power divided by the number of atoms per c.c. of the material is known as the **atomic stopping power.**

Note. The contents of this sub-section is valid if the energy loss of α-particles is small, as is the case with thin radioactive films.

13.5 Geiger-Nuttall law

An important *quantitative relation* between the range R of the α-particles and the decay constant λ of the emitting nuclei was experimentally discovered by Geiger and Nuttall (1911) and is called the **Geiger-Nuttall law.** The relation runs as :

$$\ln \lambda = A + B \ln R \qquad \text{(i)}$$

where A and B are constants having values different for different radioactive series. According to this law, α-particles emitted by substancces having larger λ (or shorter half-lives) have longer ranges and vice versa.

A plot of '$\ln \lambda$' against '$\ln R$' would thus give a straight line, the slope of which gives the value of B. For different radioactive series, different straight lines are obtained. They are essentially parallel to one another so that the value of B is the same for all of them, but A is different for different series. These graphs are often utilised to find λ (hence the half-life) of a radio-nuclide by evaluating R experimentally.

In the diagram, as shown in Fig.13.9, the line (1) corresponds to U-series, the line (2) to Th-series and (3) to Ac-series.

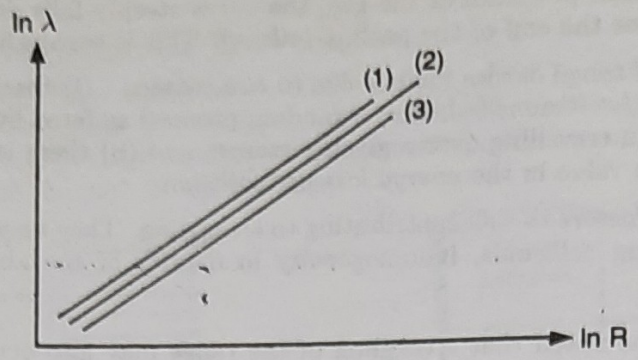

Fig.13.9 Variation of $\ln\lambda$ with $\ln R$: Geiger-Nuttall law

Since $R \propto E^{3/2}$, the equation (i) may also be written in the form

$$\ln\lambda = C + D\ln E \qquad \text{(ii)}$$

where C, D are two constants. This relation may be looked upon as an *alternative form* of Geiger-Nuttall law.

Since the half life $T_{\frac{1}{2}} = \ln 2/\lambda$, one can as well express the Geiger-Nuttall law by relating the variation of $\log T_{\frac{1}{2}}$ with $\log R$ or $\log E$. In this case also, straight lines will be obtained but with negative slopes.

Note 1. The once empirical equation (i) was put on a sound theoretical basis by George-Gamow in his quantum mechanical explanation of the **tunnel effect** (see later).

Note 2. The Geiger-Nuttall relation however is *not very exact.* More accurate relations have subsequently been obtained. For example, the $\log\lambda$-values of different isotopes of a given element (Z = constant) and the reciprocal of the velocities of the particles emitted from their nuclei are directly related. They represent straight lines for even-even nucleus. These relations can be obtained using quantum mechanics.

13.6 α-decay : α-disintegration energy : Fine structure of α-rays

Let us examine a single decay process, represented by the following equation, leading to the emission of an α-particle.

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He} \qquad \text{(i)}$$

The ejected α-particle can be identified as a He-nucleus by both chemical and physical means and the product nucleus Y chemically. The kinetic energies of the emitted α-particles are of the order of few MeV. This shows that the process is a *nuclear transformation.*

The Q-value (*Read* Art 15.6) of the decay process (i), known as the *α-disintegration energy* is the total energy released in the disintegration process and is given by

$$Q_\alpha = (M_\mathrm{X} - M_\alpha - M_\mathrm{Y})c^2 \qquad \text{(ii)}$$

where M's are the masses of the particles and c the velocity of light in vacuo.

For heavy nuclei, Q_α is positive; so the decay can occur spontaneously as it does. We may evaluate the kinetic energy T_α of the ejected α-particle from the Q-value by the application of the laws of conservation of momentum and energy. Assuming the nucleus to be at rest during decay and that kinetic energies can be treated non-relativistically, we may write

$$0 = M_\alpha v_\alpha - M_\mathrm{Y} v_\mathrm{Y} \qquad \text{(iii)}$$

$$\text{and} \quad Q_\alpha = \tfrac{1}{2}M_\alpha v_\alpha^2 + \tfrac{1}{2}M_\mathrm{Y} v_\mathrm{Y}^2 \qquad \text{(iv)}$$

From (iii) and (iv), therefore, $Q_\alpha = \frac{1}{2}M_\alpha v_\alpha^2 \left(1 + \frac{M_\alpha}{M_Y}\right) = T_\alpha \left(1 + \frac{M_\alpha}{M_Y}\right)$

$$\therefore \quad T_\alpha = \frac{Q}{1 + M_\alpha/M_Y} \tag{v}$$

The experimental values of T for the α-particles from a number of nuclei show that the maximum value of the energy always agrees with eq. (v). But, for a given decay, there exists a *discrete spectrum* of α-particle energies, with groups of particles having slightly different energies, lower than that given by eq. (v). The α-particles thus exhibit a *fine structure* in their energies. The phenomenon has been confirmed experimentally by Rosenblum using 180° magnetic spectrograph. The observed fine structure in α-particles is attributed to the existence of *discrete energy levels* in nuclei and can be explained in reference to the diagram shown in Fig. 13.10. It represents the α-decay of the ground state (g.s.) of X(^{212}Bi). The full line arrows

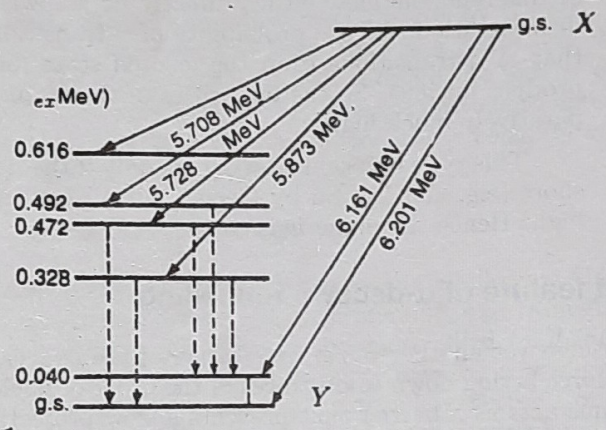

Fig.13.10 Fine structure of α-particles and discrete energy levels

indicate transitions leading to ejection of an α-particle with energies shown against each, while dashed arrows show emission of γ-rays. Like electrons, nuclei also have discrete spectra of excited states so that the α-decay process would leave the nucleus Y either in the ground state (g.s.) or one of the allowed states of excitation. The kinetic energy T_α must thus have discrete values — the energy difference between the g.s. of X and a particular state in Y. When, however, Y falls from an excited state to its g.s. through an electromagnetic transition, the energy difference of the states appears as a γ-ray. The γ-rays are therefore found to be associated with α-decay. There exists also a correlation between the differences in the energies of the groups of α-particles emitted by the parent nucleus and the energies of the γ-photons emitted by the daughter.

$\therefore$ Energy of the γ-ray, $E_\gamma = Q_\alpha - (T_\alpha + T_Y)$

$$= Q_\alpha - T_\alpha(1 + T_Y/T_\alpha)$$

$$= Q_\alpha - T_\alpha(1 + M_\alpha/M_Y)$$

($\because$ $T_Y/T_\alpha = \frac{1}{2}M_Y v_Y^2 / \frac{1}{2}M_\alpha v_\alpha^2 = M_Y M_\alpha^2 / M_\alpha M_Y^2 = M_\alpha/M_Y$ for $M_\alpha v_\alpha = M_Y v_Y$, from conservation of momentum)

Note. The presence of a small number of α-particles with energies much in excess of that of the main group of particles is the so-called *long range α-particles.*

The α-particles emitted by radio-nuclides are usually monoenergetic which fact implies that they are emitted from a definite energy state of the parent to a definite state of the product. However, some radio-nuclides emit groups of α-particles, each group of a definite