CHAPTER 4

RADIATION AND LIFE

"Radiation is like everything in life"
"Good or Bad"
"Love is the radiation of goodness"
"Misery is the radiation of evil"

A. OSCILLATIONS AND WAVES

In this chapter we are going to study the properties of different radiations and waves and their impact on the human being. Two kinds of waves exist, namely, mechanical waves and electromagnetic waves. Mechanical waves, such as sound waves, need a medium through which they travel. But electromagnetic waves, like those coming from the Sun, do not need any medium and they travel in free space.

A.1. Sound waves

Sound waves are longitudinal waves travelling through various media with speeds depending on the properties of the medium. The particles of the medium vibrate in a simple harmonic motion to produce density and pressure changes along the direction of the wave. This is in contrast to a transverse wave, where the particle motion is perpendicular to the direction of wave propagation. The longitudinal displacements of individual molecules from their equilibrium positions result in a series of high and low pressure regions called **condensations and rarefactions,** respectively. The mathematical description of harmonic sound waves is identical to that of the simple harmonic motion. Fig. 4.1 shows the density changes in air due to the propagation of a sound wave. Wherever the density of molecules is higher than normal, the pressure is also higher than normal.

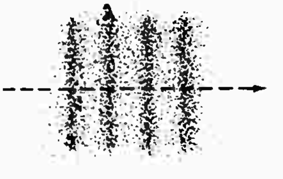


Fig. 4.1. Density changes in air in a sound wave.

The range of frequencies audible to the human ear extends from 20 to 20,000 Hz. These limits are somewhat variable depending, e.g. on age. Elder people are less sensitive to high frequencies.

The intensity of sound is the power transported by the sound of wave front. The units of intensity are watt/m^2. The intensity of sound is usually expressed on a logarithmic scale called **intensity level**, the unit of which is called **the decibel.**

As a sound wave spreads out of its source, its intensity, I, falls off according to an inverse square law of distance from the source, r; we have:

$$I_2 = I_1 \; (r_1^2 \,/\, r_2^2)$$

This law is derived directly from the fact that the total energy, E, emitted from the sound source is incident on the surfaces of the two spheres r_1 and r_2 (see Fig. 4.2).

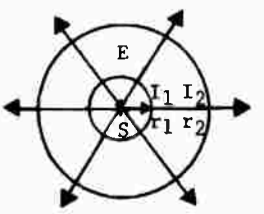


Fig. 4.2

A.2. Wave propagation and simple harmonic motion

The motion of particles in a medium through which a sound wave is propagating, is a periodic or oscillatory motion, similar to the motion of a mass on a spring, or the motion of a pendulum. The molecules oscillating about their equilibrium positions transmit the sound energy. In the following section we deal with the simple harmonic motion of an object oscillating between two spatial positions for an infinite period of time, without any loss of energy. If energy is lost during oscillation the motion is called **damped**, tending to a stand still after some time. If an external force is applied such that the energy loss is balanced by the energy provided by the force, we call the motion **a forced motion.**

A.2.1. The free simple harmonic motion

The oscillation of a mass on a spring is a good example of a simple harmonic motion. Fig. 4.3 shows a mass attached to a spring hanged vertically from a fixed point. We suppose that air friction is negligible and the vibration is made freely without any loss of energy. If the mass has a marking pen attached to it, and is set in motion while a sheet of paper is moved horizontally as shown, then the pen will trace out a sinusoidal wave. The displacement, x, from equilibrium, varies with time according to the relationship:

$$x = A \cos(\omega t + \delta)$$

where A is the amplitude of motion, ω is the angular frequency, δ is a constant of motion called the phase angle. The constants δ and A tell us what the displacement was at the time $t = 0$. The displacement, x, is periodic and repeats itself when (ωt) increases by (2π) radians.

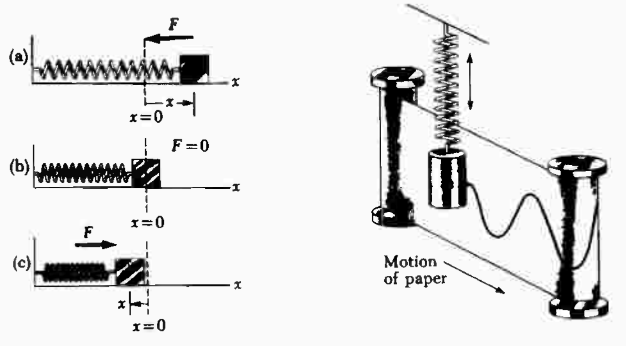


Fig. 4.3. The simple harmonic motion.

The inverse of the period is called the frequency of motion, it represents the number of oscillations made per second:

$$f = 1 / T = \omega / 2\pi$$

The velocity of the simple harmonic motion is obtained by differentiating the displacement with time:

$$v = dx / dt = - \omega A \sin (\omega t + \delta)$$

The acceleration is give by:

$$a = dv / dt = - \omega^2 A \cos (\omega t + \delta) = - \omega^2 x$$

We can understand these equations qualitatively if we consider that when the mass is displaced a small distance, x, from equilibrium, the spring exerts a force on the mass, m, given by Hooke's law:

$$F = - k x$$

where k is the force constant of the spring. This force, F, is always directed towards the equilibrium position, i.e. opposite to the displacement. Applying Hooke's second law of motion we get:

$$F = - k x = m a$$

The acceleration is thus: $a = - k x / m$

i.e. it is proportional to the displacement of the mass from equilibrium and is in the opposite direction. It also shows that the ratio (k/m) is the square of the angular velocity:

$$\omega^2 = k / m = (2\pi / T)^2$$

Thus: $$T = 2\pi \sqrt{m / k}$$

and $$f = \frac{1}{2\pi} \sqrt{k / m}$$

The energy of the harmonic oscillator described above is conserved, i.e. the sum of the potential and kinetic energies at any moment is constant.

The elastic potential energy, U, stored in the spring for an elongation, x, is given by $[(1/2)\, k\, x^2]$. The kinetic energy, K, is $[(1/2)\, m\, v^2]$. The total energy, T, is:

$$T = \frac{1}{2} k x^2 + \frac{1}{2} m v^2$$

$$= \frac{1}{2} K A^2 [\sin^2 (\omega t + \delta) + \cos^2 (\omega t + \delta)]$$

$$= \frac{1}{2} k A^2$$

That is, the total energy (T) of the harmonic oscillator is proportional to the square of the amplitude of motion.

At x = ± A, the velocity is zero and the whole energy is potential. Whereas, at x = 0, the velocity of motion is maximum and the whole energy is kinetic. Plots of the kinetic energy, K, and potential energy, U, are shown in Fig. 4.4.

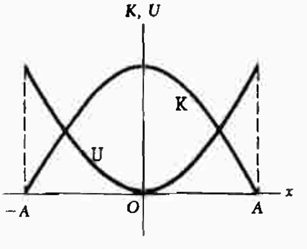


Fig. 4.4. Kinetic energy and potential energy versus time for a simple harmonic motion.

A.2.2. The simple pendulum

The simple pendulum is another mechanical system that forms a simple harmonic oscillator for small displacements. The pendulum consists of a light string, L, fixed from one end and a point mass, m, is suspended from the other end. The forces acting on the mass are the tension, T, acting along the string, and the weight, mg . When the mass is displaced slightly by an angle, θ, the tangential force component (mg cos θ), is a restoring force. Thus the equation of motion is:

$$F = m a = - m g \sin \theta$$

Thus, the acceleration is:

$$a = -(g / L) \sin \theta$$

Approximating ($\sin \theta$) to be θ, for small amplitudes of vibration, then we get:

$$\omega^2 = g / L$$

ω being the angular frequency, and the period of motion is:

$$T = 2\pi / \omega = 2\pi \sqrt{L / g}$$

We come back to the above equation of motion of the pendulum when we treat nonlinear and chaotic behavior of dynamical systems, but without making the approximation: $\sin \theta$ nearly equal θ .

A.2.3. Damped oscillations

Real dynamic systems experience dissipative forces, such as friction, which retard the motion of the system. Consequently, the total energy of the system will not remain constant but will diminish in time. The vibration is said to be **damped**. This viscous action adds to the restoring force ($-kx$), a term ($-bv$), equation of force could thus be written as:

$$F = m a = -k x - b v$$

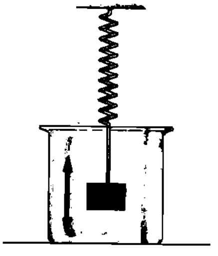
i.e.

$$m \frac{d^2x}{dt^2} = -k x - b \frac{dx}{dt}$$

The solution of this differential equation gives a displacement:

$$x = A e^{-bt/2m} \cos(\omega t + \delta)$$

with an amplitude decaying with time as shown in Fig. 4.5.



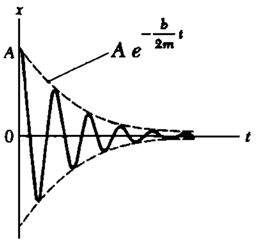


Fig. 4.5. Graph of the displacement versus time, for a damped wave.

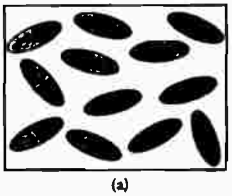
A.2.4. Ultrasonic waves and applications (Sonography)

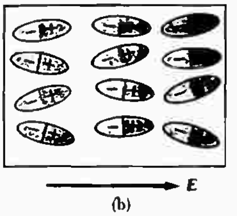
The upper audible limit of sound waves to the human ear is of the order of 20,000 Hz. This limit is variable and depends on factors such as the age. Frequencies above that limit are called **ultrasound.** Ultrasonic waves of very high frequency do not propagate very well through air, because of their dissipation by air molecules. However, these waves propagate readily through liquids and solids, and this has led to the development of some useful applications of ultrasonic waves. For instance, such waves are now used in place of X-rays to take pictures of the interior of the human body. It is used to examine the fetus in the body of a pregnant woman and so we avoid the damage that X-rays might do to the very sensitive tissues of the fetus. The ultrasonic cameras, called **Sonar**, that take such pictures employ sound waves of a frequency of about one mega Hertz (1 MHz). Further development of this technique has led to the construction of acoustic microscopes using frequency of about 1000 MHz. The wavelength of sound waves of such very high frequency is about 10^{-6} m, which is comparable with the wavelength of ordinary light waves. The micrographs made by experimental ultrasonic microscopes compare very well with micrographs made by ordinary optical microscopes.

A.2.5. Sources of ultrasonic waves (Polarizability)

The atomic and molecular structure of all solids contain negative charges, -electrons, and positive charges, cores of the atoms. The negative and positive charges in each part of a dielectric crystal can be considered to be centered at the same point. In this case the molecules forming the crystal are neutral. But, when an electric field is applied to the dielectric crystal, the centers of the positive charges are slightly displaced in the direction of the applied field and the centers of negative charges are slightly displaced in the opposite direction. This produces local dipoles throughout the crystal, and the process of inducing such dipoles in the crystal is called **polarization.**

The dipole moment is the product of the charge into the distance between the opposite charges ($p = q.d$). The ratio of the induced dipole moment to the effective field is called **the polarizability of the atom** (or molecule).





(a) (b)

Fig. 4.6. (a) Dipole moments of polar molecules are randomly oriented in zero electric field. (b) Molecules tend to align in an external electric field, but the alignment is not complete because of thermal agitation.

There are some crystals made of complex ions or molecules already possess permanent dipole moments. In the absence of any external electric field, the centers of symmetry of the positive and negative charges in each molecule do not coincide. When an external field is applied, the existing dipoles tend to rotate and orient themselves parallel to the field direction. In the absence of the field the dipoles are randomly oriented because of their thermal motion, so that the crystal has zero moment. The polarization of such polar crystals is strongly temperature dependent, since even in the presence of an applied field, thermal motion tends to randomize the dipole orientations. Figs. 4.6 and 4.7 show schematically how an external electric field force the alignment of the dipoles in the field direction, and how a surface charge is formed on the faces of the dielectric crystal placed in the field of a charged parallel plate condenser.

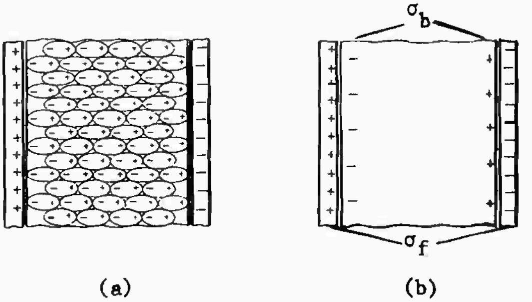


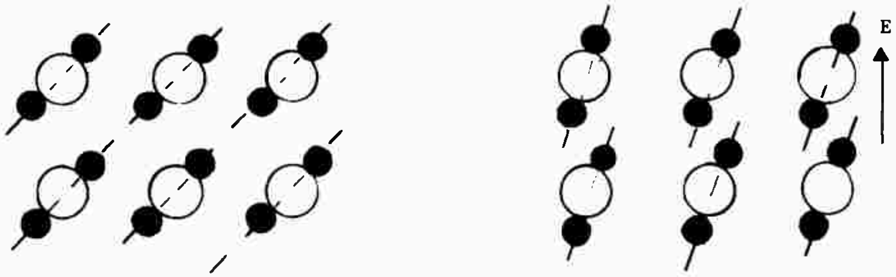
Fig. 4.7. (a) A dielectric slab is polarized in the uniform field of a parallel-plate capacitor. (b) A surface charge density (σ_b) is formed on the faces of the dielectric adjacent to the plates.

A.2.6. Piezoelectricity

Let us now consider the effect of a mechanical stress applied to the crystal. In the case of crystal with a centrosymmetric structure, as shown in Fig. 4.8, composed of positively and negatively charged ions, the atoms are slightly displaced, but the ionic displacements are symmetrical about the symmetry centers. The charge distribution inside the crystal is not appreciably altered by the applied stress.

Next, consider the acentric crystal structure shown in Fig. 4.9. The ions are arranged in pairs forming dipoles. When such a crystal is deformed by an applied stress, the ions are displaced from each other in an asymmetric way. So, the original balance of moments in the crystal is altered. This is called **the piezoelectric effect**, and it is observed in crystals that have non-centrosymmetric structures. A typical example of a piezoelectric crystal is quartz which has wide applications in practice.

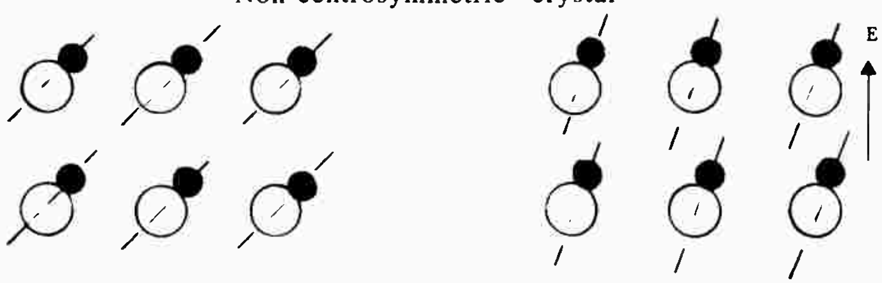
Centrosymmetric crystal



No field Electric field applied

Fig. 4.8

Non-centrosymmetric crystal



No field Electric field applied

Fig. 4.9

Consider a piezoelectric crystal placed between two metal plates, as shown in Fig. 4.10. If the crystal is compressed by an applied stress it will produce a polarization in the crystal whose density is proportional to the applied stress. The charges created on the two metal plates will form an electric field. Now, if we do the reverse, i.e. we apply an electric field to the plates of the condenser, then the dimension of the crystal will change accordingly due to the piezoelectric effect, which is a reversible phenomenon. If an alternating electric field is applied, the crystal dimension will experience a periodic strain with the same frequency as that of the field of force. When the natural frequency of the piezoelectric crystal is adjusted to be equal to that of the force, resonance takes place, and the crystal will produce ultrasound through its mechanical vibrations. An oscillator circuit is usually used to produce the electric field with the suitable frequency to excite the crystal.

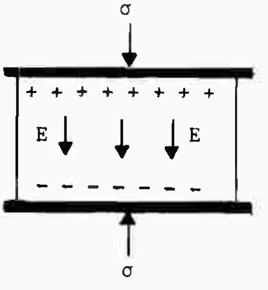


Fig. 4.10

B. ELECTROMAGNETIC WAVES

B.1. The decline of the Newtonian universe

Newton's physics can be thought of as the rules according to which atoms move. The general worldview - atomic materialism coupled with Newton's physics - dominated science for more than two centuries. Then Maxwell and Hertz introduced electromagnetic waves, showing that they can travel through free space. They were physically real as light. The most convincing argument for the reality of electromagnetic fields comes from the conservation of energy. Suppose that a radio transmitter sends a message, i.e. an electromagnetic wave, to a receiver far away in space. Energy must travel from the sender to the receiver in order to respond. Where is this energy during the time between sending and receiving the message? Not in the sender. Not in the receiver. And energy never just vanishes, so it must be in the space between the sender and receiver, in the electromagnetic field.

Because physicists could not contemplate that energy might exist apart from the tiny particles of a medium, they developed the idea of a hypothetical medium called ether filling all space. Light and electromagnetic waves could then be explained mechanically, in terms of the motions of material ether particles, thus keeping with Newtonian mechanics.

Einstein, early this century, broke this idea, and his work showed that the ether theory had to be rejected. After Einstein's work, electromagnetic fields could no longer be interpreted as properties of a material substance.

Although the Newtonian worldview still dominates the minds of many scientists who think of the universe like a mechanical clock, yet it is now definite that this mechanical universe is seriously out of tune with the contemporary physics of the twentieth century. Relativity theory and quantum theory contradict both the specific predictions of Newtonian physics. Physics is still in the middle of the post-Newtonian-revolution, and it is not clear what new overall scientific worldview will emerge from it. But it is clear that the Newtonian assumption have broken down.

B.2. The electromagnetic spectrum

Hertz and Maxwell discovered that accelerating electric charges generated a new kind of waves. These waves consisted of oscillating electric and magnetic fields, which are at right angles to each other and also at right angles to the direction of wave propagation. Such electromagnetic waves are transverse in nature, and they cover wide range of frequencies. For instance, radio waves are electromagnetic waves of frequency about 10^7 Hz, and are produced by oscillating currents in a radio tower's transmitting antenna. Light waves are another form of electromagnetic radiation of frequency about 10^{14} Hz, and are produced by oscillating electrons within atomic systems. Fig. 4.11 is a representation of an electromagnetic wave travelling in the positive x-direction with velocity of light, c. The electric field component, E, is perpendicular to the magnetic field component, B. The relative magnitudes of E and B in empty space is given by

$$c = E / B$$

If λ is the wavelength, and f is the frequency then:

$$c = \lambda f = 3 \times 10^8 \text{ m/s}$$

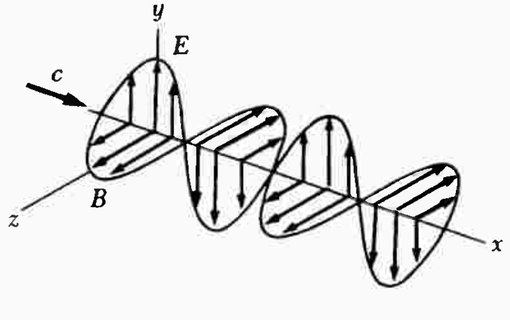


Fig. 4.11. The electromagnetic wave. Note that the electric and magnetic fields are perpendicular.

Most of us heard about X-rays and their use as a diagnostic tool in medicine and as a treatment for certain forms of cancer. X-rays are one type of electromagnetic waves with shorter wavelengths than light. Gamma rays also belong to the electromagnetic spectrum. The various types of electromagnetic waves, their frequencies and wavelengths, are given in Fig. 4.12.

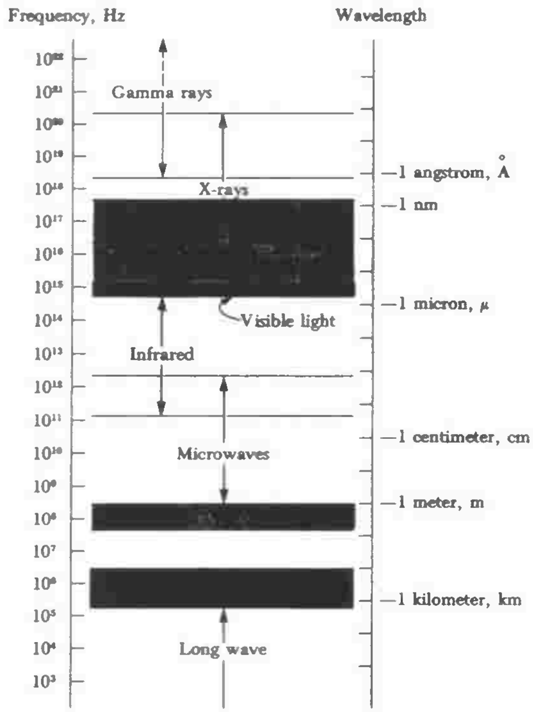


Fig. 4.12. The electromagnetic spectrum. Note the wide range of frequencies and wavelengths.

In the following section we give a short description of the various types of waves in the electromagnetic spectrum in the order of decreasing wavelength. We start with radio and radar waves.

B.3. The ac circuit

An ac circuit consists of combinations of resistors, inductances, capacitances and a generator for providing the alternating current (Fig. 4.13). The instantaneous values of the voltage and the current are given by:

$$V = V_m \sin \omega t \qquad ; \qquad I = I_m \sin \omega t$$

where V_m is the peak voltage of the ac generator, or the voltage amplitude, and I_m is the current amplitude. The angular frequency ω is given by:

$$\omega = 2\pi f = 2\pi / T$$

where f is the frequency of the source and T is the period.

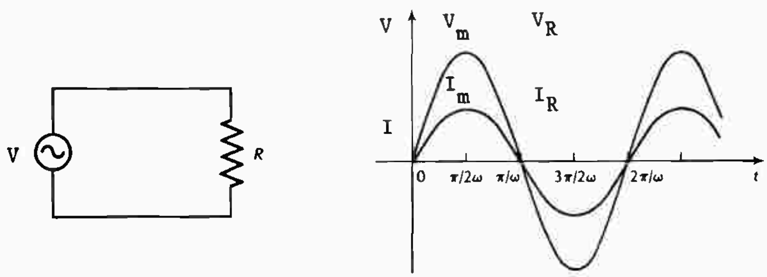


Fig. 4.13. Plots of the current and voltage across a resistor in an ac circuit. The current is in phase with the voltage.

The ac current is different from the dc current in that its magnitude changes sinusoidally between $\pm I_m$, and the electric power at any instant is P where:

$$P = V.I = V_m I \sin \omega t = V_m I_m \sin^2 \omega t$$

Thus, the power changes in ac circuits between its maximum value ($P_m = V_m I_m$) and zero. The average power is equal to half the maximum power since:

$$\frac{1}{T}\int_0^T \sin^2 \omega t \; dt = \frac{1}{2}$$

Therefore, the average value over one whole cycle is:

$$P = \frac{1}{2} V_m I_m = \frac{1}{2} V_m^2 / R = V_{rms}^2 / R = I_{rms}^2 R$$

We substituted by:

$$V_{rms} = V_m / \sqrt{2} \qquad \text{and} \qquad I_{rms} = I_m / \sqrt{2}$$

where V_{rms} and I_{rms} are called the root mean square values of voltage and current respectively. So, when we say that the mains voltage is 220 volts we mean that $V_{rms} = 220$ volts, and accordingly, the maximum instantaneous voltage will be $\sqrt{2}\, V_{rms}$, i.e. $\sqrt{2} \times 220 =$ 331 volts.

B.3.1. Inductance in the ac circuit

Consider an ac circuit consisting of a coil of self-inductance, L, connected to the terminals of an ac generator as shown in Fig. 4.14. The ac current is always changing with time, and accordingly, the magnetic flux created by the current while passing through the first loop of wire of the coil, will cut the second loop of wire. An induced current in the second loop will thus oppose the direction of the original current. This effect is called **self-induction** since the changing flux through the circuit arises from the circuit itself. The self-induced e.m.f. is proportional to the time rate of change of the current. This induced e.m.f. opposes the original current, and just as ohmic resistance is a measure of the opposition to current we assign "self inductance" of the coil to the measure of the opposition of the ac current by the coil.

Faraday's law states that: "the induced e.m.f. is given by the negative time rate of change of the magnetic flux, ϕ, which is proportional to the magnetic field, which in turn is proportional to the current in the circuit". Therefore, the induced e.m.f., E, is given by:

$$E = -N \frac{d\phi_m}{dt} = -L \frac{dI}{dt}$$

where L is a proportionality constant called the inductance, of the coil whose number of turns is N. Thus:

$$L = N \frac{\phi_m}{I} = -\frac{E}{(dI/dt)}$$

Because of this opposition to the current by induction effects, the current is out of phase with the voltage. The voltage reaches its peak value at a time that is one quarter of a period before the current reaches its peak value (see Fig. 4.14).

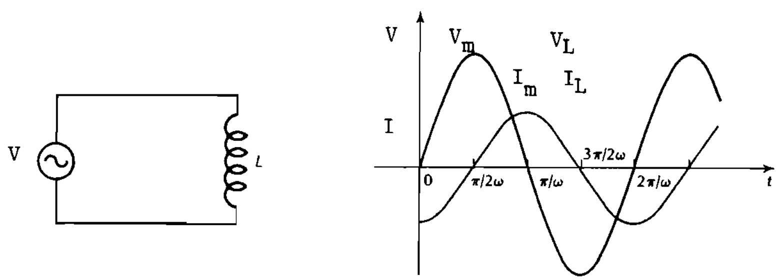


Fig. 4.14. Plots of the current and voltage across an inductance as a function of time. For a sinusoidal applied voltage the current always lags behind the voltage across the coil by 90°. This shows that V_L reaches its maximum value when the current is zero.

If V_L is the instantaneous voltage across the coil, then

$$V = -V_L = L \frac{dI}{dt} = V_m \sin \omega t$$

By integration we get the current as a function of time:

$$I_L = -(V_m / \omega L) \cos \omega t$$

$$= (V_m / \omega L) \sin (\omega t - \frac{\pi}{2})$$

The maximum current is:

$$I_m = V_m/\omega L = V_m/X_L$$

where X_L is called the inductive reactance, and is given by:

$$X_L = \omega L$$

B.3.2. Capacitance in the ac circuit

Consider now a capacitance, C, connected across the terminals of an ac generator, Fig. 4.15. The instantaneous drop across the capacitor is:

$$V_C = V_m \sin \omega t = Q / C$$

Q being the charge on the condenser plates. Therefore,

$$Q = C V_m \sin \omega t$$

But, $i = dQ/dt$, thus the instantaneous current is

$$i_C = dQ / dt = \omega C V_m \cos \omega t = \omega C V_m \sin (\omega t + \frac{\pi}{2})$$

The current is not in phase with the voltage, but here the voltage lags behind the current by 90^o. The current reaches its peak value one quarter of a period sooner than the voltage reaches its peak value. The maximum current is given by:

$$I_m = \omega C V_m = V_m / X_C$$

where X_C is called the capacitive reactance

$$X_C = 1 / \omega C$$

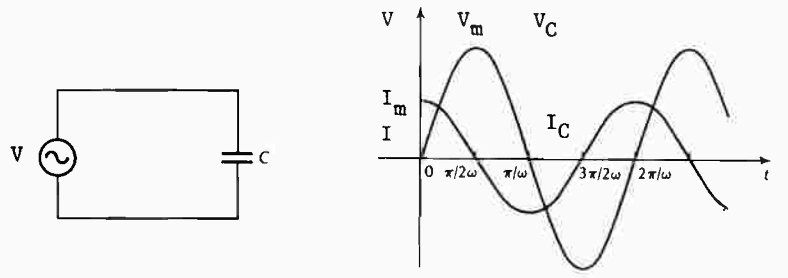


Fig. 4.15. Plots of the current and voltage across the capacitance as a function of time. The voltage lags behind the current by 90°.

B.3.3. The RLC circuit

Consider now a series circuit consisting of a resistor, an inductor and a capacitor connected to an ac generator. The ac current at all points of the circuit has the same amplitude and phase. Using vector analysis and what is called phasor diagram the total voltage V_m is given by:

$$V_m = \left[V_R^2 + (V_L - V_C)^2\right]^{1/2} = \sqrt{I_m^2 R^2 + (I_m X_L - I_m X_C)^2}$$

Therefore: $V_m = I_m \left[R^2 + (X_L - X_C)^2\right]^{1/2}$

The impedance Z of the circuit is thus defined as

$$Z = \left[R^2 + (X_L - X_C)^2\right]^{1/2}$$

The maximum voltage is thus: $V_m = I_m \cdot Z$

B.3.4. The resonance circuit

A series RLC circuit is said to be in resonance when the current has its peak value. The rms current is given by

$$I_{rms} = \frac{V_{rms}}{[R^2 + (X_L - X_C)^2]^{1/2}} = \frac{V_{rms}}{Z}$$

The impedance depends on frequency, so is the current. It is clear that the current reaches its maximum when $X_L = X_C$. The frequency ω_o at which this occurs is called **the resonance frequency of the circuit**. To find ω_o we use:

$$\omega_o L = 1 / \omega_o C \qquad \text{or} \qquad \omega_o^2 = 1 / L C$$

It is also important to calculate the average power as a function of frequency. We have:

$$P_{av} = I_{rms}^2 \cdot R$$

$$= \frac{V_{rms}^2 \cdot R}{Z^2} = \frac{V_{rms}^2 \cdot R}{[R^2 + (X_L - X_C)^2]^{1/2}}$$

Knowing that: $X_L = \omega L$; $X_C = 1/\omega C$; and $\omega_o^2 = 1/LC$, we get:

$$(X_L - X_C)^2 = \frac{[L^2(\omega^2 - \omega_o^2)^2]}{\omega^2}$$

This gives: $$P_{av} = \frac{V_{rms}^2 R \omega^2}{[R^2\omega^2 + L^2(\omega^2 - \omega_o^2)^2]}$$

A plot of the power versus frequency yields a peaked curve with its peak value at resonance conditions, namely, when $\omega = \omega_o$. For this reason this curve is called the resonance curve of the RLC circuit. The sharpness of the resonance curve is usually described by a dimensionless parameter known as the **quality factor**. The width of resonance depends on the dissipative losses in the circuit (see Fig. 4.16).

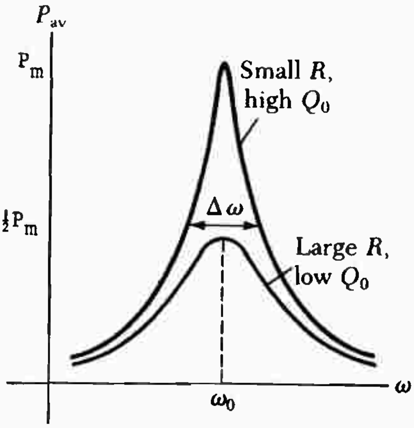


Fig. 4.16. Plot of average power versus frequency for a resonance circuit. Increasing the resistance and the dissipation in the circuit increases the width of resonance.

B.4. Production of electromagnetic radiations

Hertz was the first to find that when an oscillatory voltage of high frequency is connected to two plates of a condenser, some of the oscillatory energy travelled in space around the condenser. This was the first discovery of the electromagnetic radio waves. Radio waves do not travel far from the transmitting aerial unless their frequency is very high. In order to produce radio waves for radio broadcasting and for other reasons, we need oscillator circuits that produce alternating voltages in the mega Hertz frequency range.

The basic oscillatory circuit of an oscillator is formed of a capacitor and a coil. When an electrical disturbance is made in the capacitor the circuit will oscillate with its natural frequency, f, give by:

$$\omega_0 / 2\pi = f = 1 / 2\pi \sqrt{L\ C}$$

L being the self-inductance of the coil, and C is the condenser capacity. The physical reason for the oscillations is the constant interchange of energy between the capacitor and the coil. The capacitor is fully charged at one instant, and the energy is thus stored as electrostatic energy. Following to the instant, the condenser is discharged through the coil and the energy is wholly in the magnetic field (see Fig. 4.17).

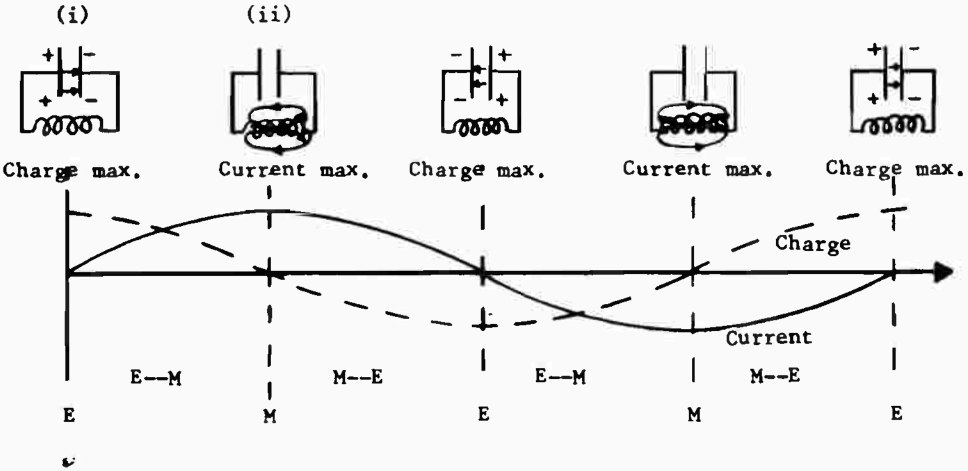


Fig. 4.17. Electrical oscillations - energy exchanges. At the instant (i) all energy is stored in the electric field, and since the current is zero there is magnetic energy. At the instant (ii) the current is maximum, and the energy has become magnetic energy stored in the inductor. The potential energy is the agency which causes the transfer of energy.

B.4.1. The radio-frequency oscillator

In order to understand how high frequency oscillations are maintained in the coil of the oscillatory circuit, the triode valve oscillator circuit shown in Fig. 4.18 illustrates the principle of the method. The oscillatory circuit is connected in the grid-cathode circuit of the valve; a coil L_1 is mutually coupled with the coil L of the oscillatory circuit and a high tension battery is applied to the valve. The oscillating potential difference across the capacitor C, is amplified by the valve and the oscillatory current in the anode circuit will pass through the coil L_1 . By mutual induction between the two coils, some energy is fed back to the oscillator circuit. This feed back current will help to maintain the oscillations of current in the oscillatory circuit. This oscillator will produce a radio wave of constant amplitude.

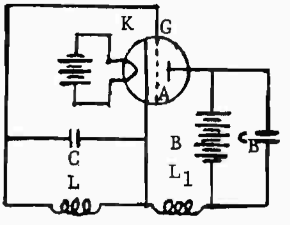


Fig. 4.18. Triode as oscillator.

At broadcasting stations, speech or music are fed through a microphone into the oscillatory circuit. The radio waves are thus modulated with an amplitude that varies exactly as the audio-frequency sound imposed. The modulated wave, being still a radio wave, will have the property of being transmitted over long distances. The antenna's of the radio receivers will pick-up this modulated radio wave, filters it from the high frequency, leaving only the audio-frequency variations which can be heard by means of a loudspeaker.

B.4.2. Microwaves and radar

Microwaves have shorter wavelengths than radio waves. Their wavelengths range between 1 mm and 30 cm and are also generated by electronic devices as LC oscillators in which charges are accelerated through conducting wires. The long wavelengths of radio waves allow them to be used in radio and television communication systems. Because of the shorter wavelengths of microwaves, they are well suited for the radar systems used in aircraft navigation and for studying the atomic and molecular properties of matter. Microwave ovens are also extensively used in domestic applications for cooking purposes. During war times microwaves are used in radar systems to announce in advance the possible attack of the enemies by aircraft and bombers, in order to give ample time for the counter forces for a defence action.

B.5. X-rays

B.5.1. Emission of X-rays

X-rays are electromagnetic radiation with wavelength of the order of one Angstrom (1 Å). The most common source of X-rays is the deceleration of high-energy electrons bombarding a metal target. X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer. A missadvantage of using X-rays is the damage it causes to the living tissues and organisms. Thus, care must be taken to avoid unnecessary exposure or overexposure. X-rays have useful applications in the study of crystal structure, since X-ray wavelengths are comparable to the atomic separation distances in solids.

X-rays have the property of producing fluorescence in a zinc sulphide screen. Accordingly, if a human - or other body - is placed between X-ray tube and a fluorescent screen, the shadows of the bones can be seen on the screen, because they absorb X-rays more than flesh does. Foreign bodies,' weapons, explosives, etc., are searched for in bags and suitcases in airports, bone fractures, or porosity in castings in metal industry.

B.5.2. The X-ray tube

The modern X-ray tube is an evacuated bulb. The electrons are provided by thermionic emission from a white-hot tungsten filament. Electrons are accelerated to the target, or anode, through a high dc potential of about 100,000 volts imposed across the anode filament. The heat generated at the target by electronic bombardment is so great that the target must be cooled artificially by circulating water or oil.

The loss of kinetic energy of the electrons at the target is used in two ways other than heat generation, namely, production of white X-radiation and characteristic X-radiation of the target.

If V is the voltage drop across the tube, and if the whole electron energy, eV, is converted into X-radiation, then the shortest wavelength which will be emitted from the target will be given by Einstein's formula:

$$eV = hc/\lambda$$

where λ is the wavelength of the emitted X-rays, c is the speed of light, and h is Plank's constant. Substitution of numerical values in this equation gives:

$$\lambda = 12.4 / V$$

with λ in Angstrom and V in kilovolts.

When the accelerating voltage is too high, then characteristic X-radiation of the element of the target may be emitted. Such radiation depends on the electron energy levels of the target atoms. The transition of electrons between these levels results in the absorption or emission of energy. The energy emitted in this case will have a sharply defined wavelength. The characteristic X-ray spectrum from a metal is usually superimposed on a background of continuous white radiation. Fig. 4.19 illustrates the characteristic lines, K_α and K_β , of a metal target. It should be noted that the wavelengths of these lines are independent of the potential difference across the X-ray tube, they are characteristic of the metal.

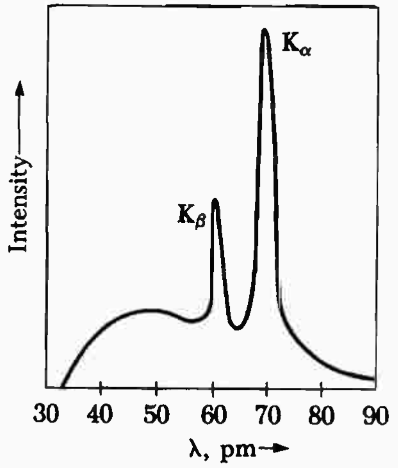


Fig. 4.19. X-ray characteristic lines and background.

B.5.3. Crystal diffraction and Bragg's law

A X-ray beam passing over an atom of a solid sets each electron of the atom into oscillation because of the oscillating electric field of the beam. The atomic electrons then scatter the beam in all directions without change in wavelength. The superposition of the scattered X-rays by individual atoms in a crystal results in diffraction. The amplitude of the scattered wave is a maximum in a direction such that the contributions from each atom of the crystal structure differ in phase only by integral multiple of 2π .

Suppose that a monochromatic beam of X-rays, of wavelength, λ, is reflected from a system of atomic plane (hkl), rich in atoms, and the interatomic spacing is d(hkl), Fig. 4.20.

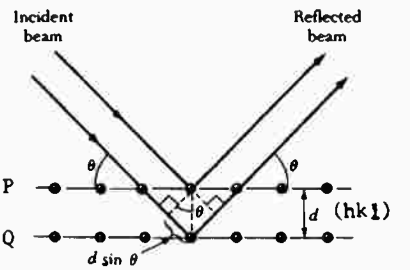


Fig. 4.20. Reflection at crystal atomic planes.

The beam interacts with atoms such as A, B, C, D in an atomic plane P. Each atom scatters X-rays. If θ is the grazing angle of the incident wavefront, then a reflected wavefront is formed with an equal angle to the atomic plane. The intense reflected beam produced by the crystal is made of the wavelets scattered from all atomic planes and which are in phase with each other.

The path difference between the rays marked (1) and (2) is the length abc = 2 ab = 2d sin θ , (see Fig. 4.20). Thus an intense X-ray beam is reflected when the path difference is an integral multiple of wavelengths, i.e. when:

$$2\,d(hkl)\;\sin\theta = n\,\lambda \qquad n = 1,2,3,\ldots$$

This is known as **Bragg's law**. It is clear that, λ, d, and θ must have simultaneous values to satisfy the diffraction condition.

Laue, in 1913, was the first to visualize that the regular array of atoms forming the crystalline solid, behave like a diffraction grating with respect to X-rays. In this way, the Laue X-ray diffraction pattern might identify the interatomic spacings of the crystal structure, if the wavelength of the incident X-radiation is known. The job of the crystallographer is to find the angles θ, hence he can determine d(hkl) for the most important planes of the crystal, accordingly, the structure might be identified.

B.5.4. Moseley's law

Moseley studied the characteristic K radiation for many metals. He found a correlation between the frequency of the line and the atomic number of the element. When a graph between the atomic number, Z, and the square root of the frequency, i.e. $f^{1/2}$, was plotted, an almost perfect straight line was obtained, from which Moseley gave his empirical relation:

$$f = a(Z - b)^2$$

where a and b are constants. From this relation Moseley was able to discover the elements with atomic numbers 43, 61, 72 and 75, which were missing from the graph at that time, and which were later discovered.

C. NUCLEAR RADIATIONS

C.1. The nucleus and radioactivity

The discovery of radioactivity was made by Becquerel in the year 1896. Rutherford showed that the emitted radiation was of three types, which were called **alpha, beta and gamma rays.** These are classified according to the nature of the electric charge they possess and according to their ability to penetrate matter. The way these rays respond to electric or magnetic fields shows that alpha rays are positively charged, beta rays are negatively charged and gamma rays are uncharged (see Fig. 4.21).

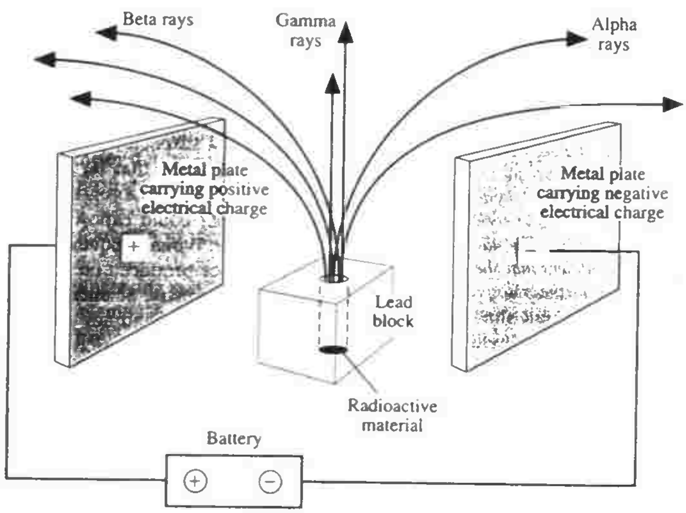


Fig. 4.21. Effect of electric field on radioactive rays.

These rays are created in one of two types of spontaneous nuclear processes, known as radioactive decay processes.

In the alpha decay, the radioactive nucleus sends out a particle called **an alpha particle** that is identical with the nucleus of helium: two protons and two neutrons bonded together by a strong nuclear force, $_2He^4$. Once an alpha particle escapes into its surroundings, it soon slows down due to collisions with the surrounding particles, and picks up two electrons from nearby atoms to become a normal helium atom.

In beta decay, a radioactive nucleus sends out an electron which soon slows down due to collisions and is captured by some nearby atom to become an ordinary orbital electron. This electron emitted from the nucleus of an atom is called **a beta particle.**

Gamma rays are high energy photons.

C.2. Half life and radioactive dating

The rate at which a particular decay process occurs in a radioactive sample is proportional to the number of radioactive nuclei present, that have not yet decayed. If N is the number of radioactive nuclei at some instant, the rate of change of N is:

$$dN / dt = - \lambda N$$

where λ is called **the decay constant,** or disintegration constant. The minus sign is because N is decreasing with time, t. Integrating the above equation gives us the decay equation:

$$N = N_0 \exp(- \lambda t)$$

The constant N_0 represents the number of radioactive nuclei at zero time. The decay rate [R = dN/dt] can be obtained by differentiating the above equation with respect to time, i.e.

$$R = dN / dt = N_0 \lambda \exp(- \lambda t) = R_0 \exp(- \lambda t)$$

$R_0 = N_0 \lambda$ is the decay rate at zero time (t = 0), and $R = \lambda N$ is the decay rate of a sample is often referred to as its activity.

It is now possible to predict roughly what fraction of the radioactive atoms will decay in any particular period of time, even though it is impossible to predict exactly which nuclei will decay and which ones do not. The plot of N versus t shown in Fig. 4.22 illustrates the exponential decay law.

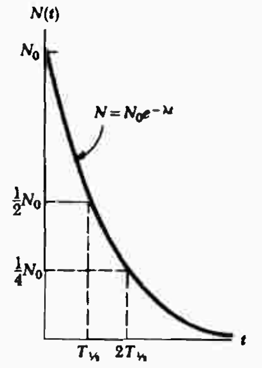


Fig. 4.22. Plot for the law relating the number of radioactive nuclei with time. The time $T_{1/2}$ is the half life of the sample.

Another useful parameter used to characterize the decay of a particular nucleus is the half life time, $T_{1/2}$. The half life of a radioactive substance is the time it takes in order that half of a given number of radioactive nuclei to decay. Setting $N = N_0/2$ and $T = T_{1/2}$, in the decay equation, we get:

$$\frac{1}{2} N_0 = N_0 \exp(-\lambda T_{1/2})$$

Taking the natural logarithm, therefore:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

The following table gives half-lives of some radioactive isotopes and the decay process.

Isotope	Name of element	Decay process	Half-life, $T_{1/2}$
$^{14}_{6}C$	carbon	beta	6000 years
$^{90}_{38}Sr$	strontium	beta	30 years
$^{131}_{53}I$	iodine	beta	8 days
$^{137}_{55}Cs$	ceasium	beta	30 years
$^{214}_{84}Po$	polonium	alpha	0.00016 second
$^{226}_{88}Ra$	radium	alpha	1600 years
$^{238}_{92}U$	uranium	alpha	4.5×10^9 years
$^{239}_{94}Pu$	Plutonium	alpha	24000 years

The unit of activity is the **Curie (Ci)**, defined as:

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/second}$$

This unit was selected because it is the approximate activity of 1 g of radium. The SI unit of activity is called **the Becquerel (Bq)**, defined as:

$$1 \text{ Bq} = 1 \text{ decay/second}$$

Therefore: $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$

Radioactive dating

Radioactive decay is a kind of clock. If we know how much of a substance has decayed, we can get the elapsed time from the decay curve. Carbon dating is one example. Carbon has two stable isotopes, ^{12}C and ^{13}C. But there is also a radioisotope ^{14}C, which has half life of 6000 years. It is formed in the Earth's atmosphere due to cosmic rays coming from the outer space colliding with atmospheric nitrogen, transforming the nitrogen nucleus into carbon 14. Because all living organisms in the biological world make use of the air of the atmosphere, then about the same ratio of this ^{14}C exists in living bodies and is maintained constant until a living organism dies. Then the ^{14}C gradually decays. The time elapsed since death can be determined by measuring the amount of ^{14}C remaining. Comparing the amount of ^{14}C that remained in the fossil, with the normal amount we always have in air, then we know the time since that fossil was alive. For example, if an old piece of wood has only a quarter of the normal amount of ^{14}C, then the tree from which this piece of wood came must have died two half-lives ago, i.e. 12,000 years.

C.3. The decay processes

A radioactive nucleus decays via three processes, namely, alpha decay, beta decay and gamma decay.

C.3.1. Alpha decay

An alpha particle is a helium nucleus containing two protons and two neutrons. If a nucleus emits an alpha particle, then N decreases by 2 and Z decreases by 2, and A decreases by 4. The disintegrating nucleus is called **parent nucleus** and the resulting one is called **daughter nucleus.** As an example, uranium 238 is an alpha emitter and decays according to the scheme:

$$^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$$

The daughter nucleus of thorium (Th) is less by 4 in its atomic mass number (A) than that of the parent nucleus. Likewise, Z is reduced by 2. This process is called **spontaneous decay**. As a rule, the sum of mass numbers A must be the same on both sides of the decay equation, similarly the sum of charge numbers Z must also be the same.

The mass of the daughter nucleus plus the particle(s) emitted is usually less than the mass of the parent nucleus. The energy equivalent of this mass difference is called the disintegration energy. This residual energy appears in the form of kinetic energy of the daughter nucleus and the alpha particle.

C.3.2. Beta decay

In a process of beta decay, the daughter nucleus has the same number of nucleons as the parent nucleus but the charge number is changed by one. It should also be noted here that both the nucleon number and total charge are both conserved in these decays.

The energy balance between the initial and final states of a nuclear disintegration in the alpha decay is exact. But this is not so in the beta decay. Experimentally, it was found that the beta particles are emitted over a continuous range of energies. However, the disintegration energy, Q, must be the same for each decay. Then, how come the emitted electrons have different kinetic energies? To account for that, Pauli in 1930, proposed that there exists a particle, the neutrino, which is electrically neutral but have little rest mass smaller than that of an electron. The neutrino, υ, has spin of 1/2 and interacts very weakly with matter. By this proposal the principles of conservation of angular momentum (spin) and conservation of energy are not violated.

C.3.3. Gamma decay

Sometimes, a nucleus is left in an excited state after a radioactive decay process. A second decay might then takes place to the ground state, by emitting a gamma photon. The energy of the gamma photon, hf, is very high relative to the energy of visible light. For this reason gamma rays have high penetrating power through materials.

C.4. Natural radioactivity

The disintegration of radioactive elements usually follow a sequence of events passing through different radioactive elements until finally it reaches a stable nucleus. This sequence of events is called **radioactive nuclei.** There are three series of naturally occurring radioactive nuclei, which begin with the isotopes ^{238}U, ^{235}U and ^{232}Th. The corresponding stable end products are three isotopes of lead, namely, ^{206}Pb, ^{207}Pb and ^{208}Pb. Fig. 4.23 shows the successive decays for the uranium-238 (^{238}U) series.

C.5. The use of isotopes in medicine

Atoms with the same number of protons but with different numbers of neutrons are called isotopes. Most of the isotopes are unstable, i.e. they decay by a spontaneous nuclear reaction and transmute themselves into another, more stable element. Radio-isotopes might emit alpha rays, beta rays, or gamma rays. The isotope of cobalt-60 (^{60}Co), which is used in the cobalt bombs frequently used in hospitals, is a gamma and beta emitter:

$$^{60}Co \longrightarrow {}^{60}Ni + \text{beta } (\beta^-) + \text{gamma } (\gamma)$$

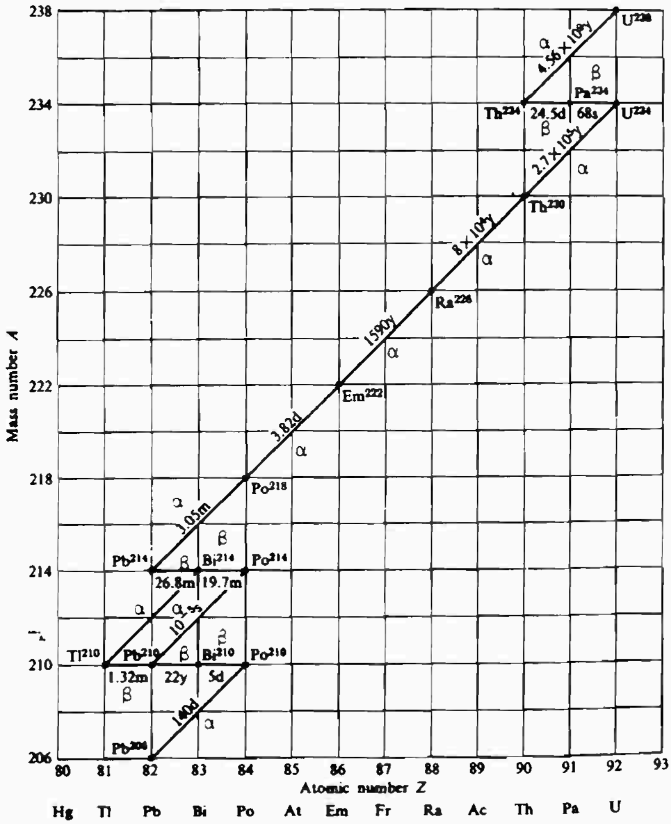


Fig. 4.23. Successive decays for the uranium-238 (^{238}U) series.

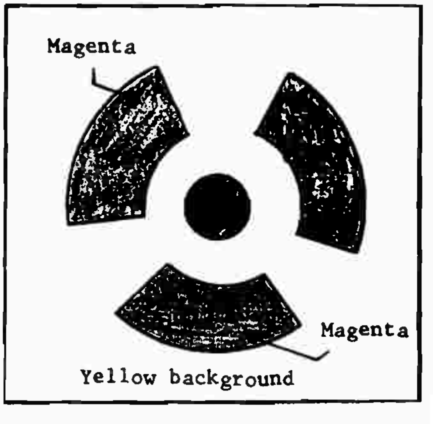


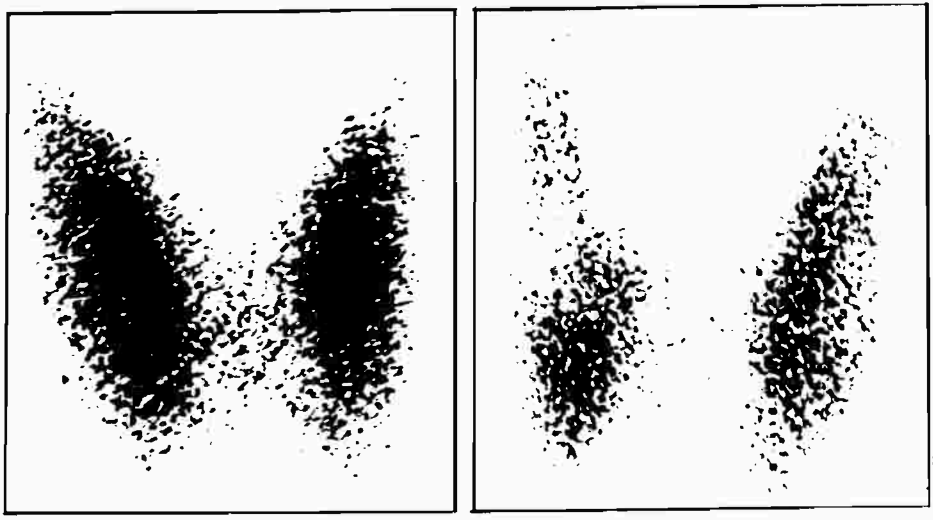
Fig. 2.24. The warning sign for dangerous nuclear sources.

In medical practice, cobalt bombs are used both for diagnosis and for therapy. Nuclear sources that have strength more than 10^{-6} Curies, are considered dangerous. [one Curie (1 Ci) = 3.7×10^{10} disintegration per second (dps/s)]. Health authorities require that such sources be handled only by qualified people. A warning sign (Fig. 4.24) is usually found in magenta on a yellow background.

Radioactive iodine forms one of the important uses of isotopes in medicine. It is used both as tracer to investigate diseased organs, also, as a source of radiation for curing malignant tumors. ^{131}I is an artificially produced isotope of iodine. Iodine is a necessary nutrient for our bodies. It is obtained largely through the intake of iodized salt and seafood. The thyroid gland plays a major role in the distribution of iodine throughout the body. In order to evaluate the performance of the thyroid, the patient drinks a very small amount of radioactive sodium iodide. Two hours later, the amount of iodine in the thyroid gland is determined by measuring the radiation intensity at the neck area. The radioactive iodine will concentrate in the thyroid gland, which will thus glow in its gamma ray radiation. In the presence of a tumor, the radiograph will show an area of low concentration, see Fig. 4.25.

Brain scans can be made either with ^{131}I or with ^{99}Tc which is the daughter of ^{99}Mo. These isotopes are incorporated in certain protein molecules (albumin) that are not absorbed by the normal brain tissue. However, if there exists a tumor in the brain, the diseased parts will absorb the radioisotope, and hence the tumor will emit gamma rays and become visible on a scan, see Fig. 4.26.

Scans of other organs, lungs, heart, liver, kidneys, bones, can be made with appropriate radioisotopes.



(a) (b)

Fig. 4.25. a) Scan of normal thyroid showing uniform concentration of iodine-131 (^{131}I). b) Scan of abnormal thyroid. The left lobe displays a focal area of low concentration of ^{131}I, indicating the presence of tumor.

(a) (b)

Fig. 4.26. a) Scan of normal human brain. b) Scan of abnormal brain with several tumors as secondaries of breast cancer.

C.6. Traces and agriculture

The tracer technique is also useful in agriculture research. Suppose one wishes to find the best method of fertilizing a plant. A certain element in a fertilizer, such as nitrogen, can be tagged with one of its radioactive isotopes. The fertilizer is then sprayed on a group of plants, sprinkled on the ground for a second group, and raked into the soil for a third. After the plant grows, a Geiger counter could be used to track the nitrogen through the three types of plants. Thus, it could be judged how much did the plant benifit from the fertilizer in the three cases.

Radiotracers could also be used to amount of underground water present in a certain locality. Radiotracer is to be injected in the well. After some time, to allow for the diffusion of the isotope in the underground water, a sample of the water is tested. From the remaining activity, the estimation of water volume could be made.

C.7. Human exposure to ionizing radiations

Electromagnetic radiations of short wavelengths, such as X-rays, as well as nuclear emanations: alpha. beta and gamma rays, damage biological cells. The damage is done when these high energy photons and particles pass like bullets through a cell, ionizing some of the cell's molecules, accordingly, they are called ionizing radiations.

Ionization changes a molecule's chemistry. Any change in the biological cell is likely to be for the worse. The cell's functions can be altered depending on which molecules are ionized. The most important effects results from the damage of a cell in a DNA molecule, because DNA carries the biological information inherited by other cells.

The biological damage effected by ionizing radiations in humans is measured in a unit called the **rem**, for Roentgen Equivalent Man. If a person receives ionizing radiation, the number of rems received is a direct measure of the number of the damaged cells. On the average, a human receives every year from all sources about 0.3 rems, whereas, a sudden dose of 1000 rems causes death within 30 days.

There are three main types of biological damage to humans:

1. An acute short-term effects on red blood corpuscles and the blood-forming cells of the bone marrow and the cells that line the intestinal wall. A dose between 25 and 100 rems causes short-term changes in blood that the person might not be aware of. At 100 to 300 rems, the effects on the blood and intestines produce typical symptoms of radiation sickness: fever, vomiting, damaged red blood cells, reduced white blood cells and platelets, loss of hair, spontaneous internal and external bleeding from weakened blood vessels. Above 500 rems causes death within days but 10,000 rems causes death within hours. The most severe examples have been the nuclear bombs dropped on Hiroshima and Nagasaki and the Chernobyl nuclear reactor accident.

2. The second hazard for nuclear radiation is mutation, which is an inheritable alteration of the genetic material in a sperm or egg cell. Mutations can produce successive generations of altered offspring. However, sometimes mutation is advantageous when scientists uses it in the process of biological evolution.

3. The third form of damage is cancer in ordinary body cells. The rate of certain cancers observed in nuclear bomb survivors is far above normal. It was four times greater than the normal rate of leukemia, and more than double the normal rate for many other forms of cancer. It is now believed that smaller exposures have more effects in producing cancer.

Radioactive strontium-90 (^{90}Sr) is a cancer-causing isotope produced by nuclear weapon explosions and nuclear reactors. After a nuclear explosion, radioactive isotopes attach themselves to atmosphere dust particles that eventually fall to Earth as "Radioactive Fallout". Strontium is chemically similar to calcium, so if we breathe or eat the strontium isotope, it will do what calcium does, i.e. it migrates to the bone marrow and stay there damaging the bone marrow and causing leukemia.

Figure 4.27 shows the sources of radioactive risk, the relative contributions from various sources: natural and man-made. It could be seen that the natural sources provide about 82%, while the non-natural sources provide 18% of the average total dose that a human being commonly receives. The largest artificial source is medical. Most of the average dose comes from radon, which comes from the alpha decay of radium in the ground.

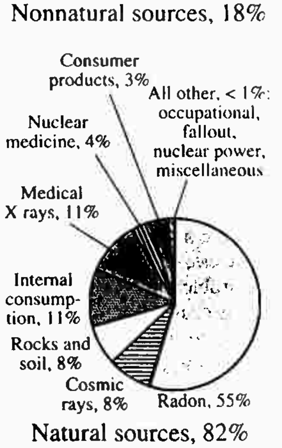


Fig. 4.27

C.8. Radiation detectors

Various devices have been developed for radiation detection. These devices are used in medical diagnosis, measurement of background radiation, and many other purposes.

The Geiger counter, Fig. 4.28, is the most common device used to detect radiation. It consists of a cylindrical metal tube filled with gas at low pressure and a long wire along the axis of the tube. High positive potential is imposed on that wire (about 1000 volts) with respect to the tube. When an ionizing radiation enters the tube through a thin window at one end, ionization of the gas takes place. The electrons removed from the atoms are attracted toward the positive wire. A current pulse will thus be observed at the output of the tube. The pulse might be amplified and then used to trigger an electronic counter, which clicks each time a particle is detected.

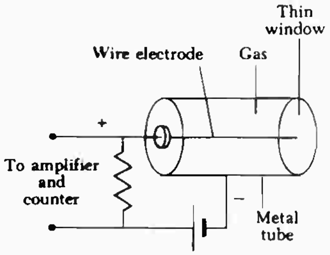


Fig. 4.28. Diagram of a Geiger counter.

The scintillation counter is another device which uses a solid or liquid material whose atoms are easily excited by the incoming radiation. The excited atoms emit photons when they return to their ground state. When such a material is attached to one end of a photomultiplier tube, see Fig. 4.29, the photons from the scintillation crystal, created by the incoming particle, will produce electrons by the photoelectric effect. Many more electrons are ejected when the initial electrons strike some other electrodes, whose potentials are increased in succession along the length of the tube. Accordingly, one particle striking the scintillator produces a sizeable electric pulse in the output of the photomultiplier tube, and this pulse is in turn sent to an electronic counter. This device is much more sensitive than the Geiger counter.

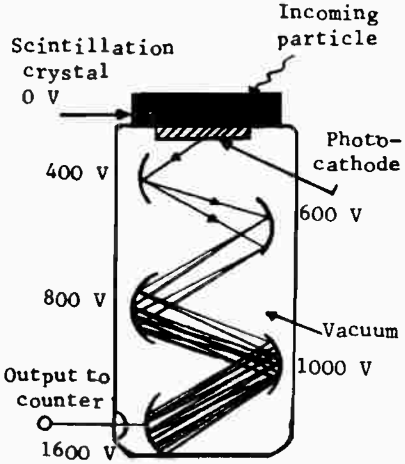


Fig. 4.29. Diagram of a scintillation counter connected to a photo-multiplier tube.

Wilson cloud chamber is another device for detecting nuclear radiations. It contains a gas that has been supercooled to just below its usual condensation point. The vapor pressure of the gas is greater than the saturation vapor pressure at the ambient temperature. When a nuclear radiation, such as alpha, beta, or gamma, ray enters the chamber, ionization takes place along the track of the particle. The produced ions form centers on which the gas condenses. An incident beam of light could thus be scattered from the liquid droplets making them visible even with the naked eyes. The tracks could be photographed, and from the length of these tracks a measure of the particle energy could be determined.

Photographic emulsions are also commonly used as nuclear detectors. The emulsions are much thicker than those used in ordinary photography, and the concentration of silver bromide in gelatine is many times greater than in ordinary photography. Protons, neutrons, and alpha-particles can be detected in such emulsions by the tracks they produce as silver granules in the emulsion. After the plate is developed the track might be observed microscopically or otherwise. This type of radiation detection is very commonly used in badge dosimeters. In nuclear plants and power stations, the total dose that a person gets during his work should not exceed a certain value otherwise he is harmed. For this reason every person is asked to wear a badge dosimeter to test overdosage. The dosimeter is a photographic emulsion which is developed every week and a record is made for all personals working in the station.