CHAPTER - 3

NEUTRON SHIELDING
3.1 Introduction to Polymers

Polymers are complex and giant molecules and are different from low molecular weight compounds. Polymers are made up of repeating units called ‘monomers’. Polymers can be converted into strong solid articles, flexible rubber-like materials and so on. They can be used to bond objects, seal joints, bear loads and fill cavities infact any thing from clothing to powering a space vehicle to even replace human organ.

Classification of Polymers:

Polymer is a generic name given to a vast number of materials of high molecular weight. Polymers can have different chemical structures, physical properties mechanical behaviors, thermal characteristics etc., The polymers can be classified in different ways as follows:

1. Natural and synthetic polymers
2. Organic and inorganic polymers
3. Thermoplastic and thermosetting polymers
4. Plastics, elastomers, fibres and liquid resins.
1. **Natural and synthetic polymers:**

   Depending on their origin, polymers can be classified as natural or synthetic. The polymers obtained from natural materials are known as natural polymers. Silk, cotton, wood, rubber, cellulose, cellophane and leather are some examples of natural polymers. Polymers synthesized from low molecular weight compounds are known as synthetic polymers. Polyethylene, polypropylene, PVC, nylon and terylene are some examples of synthetic polymers.

2. **Organic and inorganic polymers:**

   In an organic polymer, the backbone chain is made up of carbon atoms. The atoms attached to the side valencies of the backbone carbon atoms are usually hydrogen, oxygen, nitrogen etc. The majority of synthetic polymers is organic. The number and variety of organic polymers are so large that when refer to 'polymers', normally mean organic polymers. The molecules of inorganic polymers generally contain no carbon atom in their backbone chain. Glass and silicone rubber are some examples of inorganic polymers.
3. **Thermoplastic and thermosetting polymers:**

On heating some polymers become soft and can be converted into any shape that they can retain on cooling. Such polymers, that soften on heating and stiffen on cooling are known as ‘thermoplastic’. Polyethylene, PVC, and nylon are some examples of thermoplastic polymers. Thermosetting polymers undergo some chemical changes on heating and convert themselves into an infusible mass.

4. **Plastic, Elastomers, Fibres and Liquid resins:**

Depending on the ultimate form and use, polymers can be classified as plastic, elastomer, fibre and liquid resin. When a polymer is shaped into hard and tough utility articles by the application of heat and pressure, it is used as a ‘plastic’. Polystyrene, PVC and polymethyl methacrylate are some examples of plastic. When vulcanized into rubbery products exhibiting good strength and elongation, polymers are used as “Elastomers”. Rubber is a typical example of elastomer. Fibres can be drawn into long filament like materials. Nylon and terylene are typical examples of fibres. The liquid resins can be used as adhesives, sealants, potting compounds etc., in a liquid form. Commercial epoxy adhesives and polysulphide sealants are some examples of liquid resins.
Phase:

A phase is simply a part of a system separated from the other parts of the same system by an interface. The different phases within the same system differ with regard to the order of molecular arrangement.

Polymer substances can exist in two phases viz, crystalline and liquid. In the crystalline state, the individual molecules of polymer do not exhibit molecular mobility but vibrate about their mean positions. A definite and repetitive molecular pattern is observed over distances which are hundred and thousand times the size of individual molecules. In the liquid state, there is not repetitive pattern of molecules over long distances. Due to aggregation, molecules in their vicinity of any given molecule can exhibit short range orderly arrangement. In the liquid phase there are two possibilities; first where molecular mobility is frozen, and second where molecular mobility is activated. In both the cases, no long range order is observed. Depending on whether a polymer possesses long range order or not, it can be exist in the solid (glassy or crystalline), rubbery or liquid molten state. A polymer is said to be amorphous when it does not possess long range order. The amorphous polymer may exist in the glassy, rubbery or liquid state.
Due to the absence of molecular mobility, at low temperatures, amorphous polymer exists as a glassy solid. On heating beyond a certain temperature, segmental mobility originates and the polymer becomes rubbery. The temperature corresponding to transition of polymer from its glassy state to a rubbery state is known as “glass transition” temperature $T_g$. If temperature is increased much above $T_g$, the polymer starts flowing because of molecular mobility at this temperature the polymer becomes highly viscous liquid, known as viscofluid. The temperature at which transition of polymer from its rubbery state to viscofluid state takes place known as “Flow temperature” ($T_f$).

The crystalline polymer can have solid phase state and liquid phase state. The temperature corresponding to transition of crystalline polymer from its solid phase state to liquid phase state is called the “melting point” ($T_m$).

It is very difficult to get pure crystalline polymers. Many of the polymers are semicrystalline polymers. The semicrystalline polymers have both the crystalline regions and the amorphous regions. Therefore, the semicrystalline polymers have both the glass transition temperature and the melting point. The amorphous regions of semicrystalline polymer exists in the glassy state and the crystalline regions in the crystalline state below $T_g$. The amorphous
region pass from glassy state to rubbery state at $T_g$, but, the crystalline regions continue to be in the crystalline state. At $T_m$, the crystalline regions melt and pass on to the liquid state, therefore they continue to be in the rubbery state. Beyond $T_m$, both the amorphouse and the crystalline regions pass on to the liquid state.

The glass transition has been attributed to a second order transformation. The glass transition is due to the onset of motion of chain segments in the amorphous region of a polymer. The glass transition is accompanied by abrupt changes in the thermal-expansion coefficient and specific heat$^{[3.01]}$. The glass transition is a characteristic property of any amorphous substance$^{[3.02]}$.

**Crystallinity of polymers:**

Regularity in the structure of polymer favours crystallinity, because the chains can pack close together. Crystallinity of a polymer sample can be expressed in terms of that fraction of the sample which is crystalline. Many polymers are semicrystalline, that is they have both crystalline and amorphous regions. The crystalline regions are called crystallites. Where the chains are arranged in a ordered manner. The amorphous regions are completely disordered. The crystallites vary in size and shape and
are much smaller than the crystals of normal organic compounds. An individual crystallite has dimension of the order of $10^3$ Å. In the semicrystalline polymer, crystalline and amorphous regions can coexist. Because of the coexistence of crystalline and amorphous regions, X-ray diffraction patterns of semicrystalline polymers consist both broad as well as sharp bands. The broad bands indicate the existence of amorphous regions and the sharp bands indicate the existence of crystalline regions. The crystallinity is generally related with polymers which have a relatively high degree of molecular order. For a given polymer a 100% crystalline sample has the highest density and a 100% amorphous sample has the lowest density. Densities of semicrystalline polymers lie between those of their amorphous and crystalline components. The degree of crystallinity of given semicrystalline polymer sample can be calculated by using the equation:

$$X_v = \frac{d - d_a}{d_c - d_a}$$  \quad (3.01)

Where $X_v$ is the degree of crystallinity by volume and $d$, $d_a$ and $d_c$ are the density of the sample, the fully amorphous and fully crystalline components.
The crystalline and amorphous components influence polymer properties. Polymers that have more and larger crystalline components are stiffer and stronger and are more useful for many applications. The polymer properties such as density, permeability and heat capacity depend on the percentage of crystallinity. The density of crystalline regions will be higher than that of the amorphous regions. Permeability depends on the rate and extent of penetration of liquid or vapour molecules through the polymer which in turn depend on the physical structure of the polymer. The crystalline regions are far less permeable than the amorphous regions, because the crystalline regions offer stiffer resistance to a penetrating molecule than the amorphous regions. Permeability and hence crystallinity play important role in the chemical degradation of polymers. In the whole mass of a polymer, the amorphous regions are more rapidly attacked by oxygen than the crystalline regions.

Melting in polymers takes place over a range of temperature since crystallisable polymers consist of regions of crystallites surrounded by amorphous regions with the crystallites having a range of sizes. The melting point is usually taken as the peak temperature since this indicates the point that most closely approximates the loss of crystallinity.
The fraction of crystallinity of given semicrystalline polymer can be calculated as follows\[3.03\]

\[
X = \frac{\Delta H_f^+}{\Delta H_f^0} \quad (3.02)
\]

Where \( x \) is the fraction of crystallinity, \( \Delta H_f^+ \) is the heat of fusion of the sample and \( \Delta H_f^0 \) is the heat of fusion of 100% crystalline phase. If the degree of crystallinity of a polymer is known by x-ray diffraction or infrared analysis. Then the heat of fusion of the polymer in a hypothetically perfect crystalline state can be determined from the observed heat of fusion.

Other method for calculating degree of crystallinity without using heats of fusion is as follows:

\[
X = \frac{(C_p - C_p)}{(C_p - C_p_s)} \quad (3.03)
\]

Where \( C_p \) is the measured specific heat of the semicrystalline polymer and the subscripts \( l \) and \( s \) signify the amorphous and perfectly crystalline states, respectively. Eq. (3.03) is not suitable when the specific heat of the crystalline and amorphous phases are very nearly equal. Another condition is that the specific heat measurements be made in a temperature range in which the
crystallinity remains constant. If this condition is not met, then Eq. (3.03) must be corrected by adding the term.

\[-\Delta H_f^o \frac{dx}{dt} / (C_{pl} - C_{ps}) \rightarrow (3.04)\]

Here \(dx/dt\) represents the variation of degree of crystallinity with temperature.

### 3.2 Attenuation of Am-Be (\(\alpha, n\)) Neutrons

Significant amount of data is available in literature on neutron transmission measurement several materials have been developed with respect to their shielding characteristics when subjected to the passage of neutron beam. Wherever neutrons are generated in measurable intensities there is also production of radioactive radiations. Therefore attention must be given to shielding material. The composite shielding for health protection in an operation involving neutrons consequently is designed to reduce neutrons and gamma radiations in working area to acceptable values. As most powerful source of neutrons, nuclear reactors have been developed, the intensities of the radioactive radiations have increased. Heavy ion accelerators are being used in various fields such as nuclear physics and high energy physics research, material science and solid state physics studies. The reactions of heavy ion
projectiles on thick targets generate neutrons in considerable quantity. High energy X-ray beams used in the treatment of cancer patients are contaminated with neutrons as a result of x-ray photon interactions with bremsstrahlung target, shielding materials, collimators and flattering filters. Neutrons are also emitted during the process of photo fission reactions with heavier elements like bismuth or depleted uranium when bombarded with electrons or photons in the energy range used in radiotherapy. The primary consideration is that attenuation of neutrons in shielding is very nearly exponential with a characteristic attenuation length. The adequate and complete shielding becomes difficult problem as the neutron energy becomes higher than some 3 to 10 MeV.

The present work deals with the evaluation of attenuation characteristics of certain polymers, lead, iron and some composite shields made up of polymers, lead and iron for neutrons as a function of shield thickness. For this purpose, cross section measurements are done using 16ci, Am-Be neutron source, donated by BARC, Mumbai. The significance of above considered shields for neutron shielding is to be investigated as they can replace the conventional boron and ordinary concrete. Standard foil detectors were employed for studying the attenuation characteristics of shields. Attenuation characteristics as determined by foil detectors
are essential for determining the effectiveness of shield materials. In studying the variation of several integral parameters associated with the neutron attenuation as a function of shield thickness an often used concept is the total attenuation cross section. Of all the neutron cross sections the total attenuation cross section can be determined most easily and accurately. The results of experimental study of a nuclear cross section can be expressed in terms of the number of processes which take place under the conditions of the experiment or in terms of the cross section for the reaction.

**Foil Activation:**

Foil activation technique is the most reliable method of neutron flux detection\(^{[3,04]}\). Foil activation detectors are one of the type of passive detectors for the measurement of neutron flux, have very good discrimination properties against other types of radiations. The foil activation detectors are useful, where the energy of the neutron is fixed but not necessarily monoenergetic. In this technique spectral measurement of neutrons is based on the existence of energy threshold for certain neutron induced reactions with target nuclei. These detectors cover large threshold values which enables one to know the spectral quality in different energy regions, e.g., up to 14 MeV in this present case. In this technique a
foil detector of known threshold is exposed to a flux of neutrons. Nuclei of the irradiated foil detector become radioactive. Many of these radioactive nuclei decay through beta and subsequent gamma emission, and the gamma rays are characteristic of that particular decay process. A set of foils is irradiated with neutrons and activity induced in the foil is determined using gamma spectroscopy. To achieve a high degree of precession, foil materials are chosen which have large cross section for a neutron induced reaction which leads to a measurable radioactivity. The thickness of the foil material must be kept small to prevent perturbing the neutron flux, because the mean free path of neutrons in materials of high cross section is quite small. Methods based on the absorption of alpha and beta particles in matter have found wide spread use in the determination of foil thickness and foil uniformity. Collimated beams of monoenergetic alpha or low energy beta particles are used. If the alpha particles reaching the detector are near the end of their range. Then slight changes in interposed thickness cause large change in counting rate. Alpha and beta gauzes are particularly simple to use for relative measurements and uniformity checks.

Care should be taken to select foils, which have reaction responses in the energy range of neutron source. The induced activity grows with time and approached saturated value for
infinitely long irradiation time. The specific activity of any
threshold detector is given by

\[ A = N \lambda C \int_{E_{th}}^{\infty} \phi (x, E) \sigma (E) \, dE. \] (3.05)

Where \( C = (1 - e^{-\lambda t}) \) \( e^{-\lambda td} \), the correction factor for irradiation and decay times.

\( N = \) number of atoms in the foil per gram of the material

\( \sigma (E) = \) microscopic cross-section in barns

\( \phi(x,E) = \) incident flux

\( t_i = \) irradiation time

\( t_d = \) decay time, \( \lambda = \) disintegration or decay constant.

\( \phi (x, E) = \bar{\phi} \cdot S (x,E) \) where \( \bar{\phi} \) is the total integral flux and \( S (x,E) \) is the shape of the curve.

\[ A = \lambda NC \bar{\phi} \int_{E_{th}}^{\infty} S (x, E) \sigma (E) \, dE \] (3.06)

\[ A = \lambda NC \bar{\phi} \bar{\sigma} \sigma_{eff}. \] (3.07)

Where \( \bar{\sigma} \sigma_{eff} \) is spectrally averaged effective cross section for activation which is generally a function of shield thickness. Since spectral shape varies with the shield thickness. When the neutron
spectrum reaches the equilibrium, $\sigma_{\text{eff}}$ becomes very nearly constant and gives

$$\phi = \frac{A}{\lambda N.C \ \sigma_{\text{eff}}} \quad (3.08)$$

Thus the integral flux $\phi$ is proportional to specific activity. The activation cross sections were taken from the handbook on nuclear activation cross sections.$^{[3.05]}$

**Primary Considerations:**

In the ideal transmission experiment, the neutron flux observed after a beam of neutrons has passed through thickness $x$ of shield material is given by

$$\phi_{\text{calculated}} = \phi_o \exp (-\mu_{\text{Rem}} \cdot x) \quad (3.09)$$

Here, $\phi_o$ is the neutron flux incident on the material and $\mu_{\text{Rem}}$ the macroscopic removal cross section.

The above equation valid only in the ideal transmission measurement, where the detector observes only neutrons which pass undeviated through the shield. In the actual measurement error in
the count rate is due to the fraction of neutrons scattered into the
detector by air, walls, floors and other scattering materials. There
are also the corrections for neutrons scattered many times in the
shield. The validity of the Eq.(3.09) mainly depends upon

i) Geometry

ii) Thickness of the shield

With the increase in thickness of shield between the source
and detector the multiple scattering increases the probability of low
energy neutrons to reach the detector along with incident neutrons
so in this case the Eq.(3.09) becomes invalid. To keep the validity
of the equation it is necessary to apply correction term C, then
equation becomes

\[ \phi_{\text{measured}} = C \phi_{0} \exp(-\mu_{\text{Rem.}} x) \] (3.10)

The increase in thickness of shield between neutron source
and detector is responsible for the increases of multiply scattered
neutrons.

The correction term is given by

\[ C = \frac{\phi_{\text{measured}}}{\phi_{\text{calculated}}} \]
It is found that the $\phi_{\text{measured}}$ is always greater than $\phi_{\text{calculated}}$. This implies that the values of $C$ are always greater than unity. For all the solid angles up to a particular shield thickness after which the value of $C$ increases. Because, number of multiply scattered neutrons increases with increasing shield thickness, the value of $C$ increases with increase in solid angle, which is due to the fact that for greater solid angle the exposed area of the detector to the scattered neutrons is large, therefore more number of neutrons are detected thereby increasing the value of $\phi_{\text{measured}}$ which results in the increase in the value of $C$. By making an arrangement of very narrow beam geometry, the value $C$ can be obtained almost equal to unity.

The multiple scattering cross section where the neutron scattered $m$ times is proportional to $(\sigma_s/\sigma_t)^m$. If total microscopic cross selection $\sigma_t$ is greater than scattering cross section $\sigma_s$, the probability of multiple scattering is reduced specially for large $m$. If $\sigma_s < \ll \sigma_t$, multiply scattering corrections can be neglected. When $\sigma_s/\sigma_t$ is small, the thickness of the shield should be chosen to give $\mu_{\text{Rem}} \cdot x \approx 1$. 

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The transmission measurement gives the apparent cross section. If the cross section contains unresolved resonance structure, the apparent cross section decreases with increasing shield thickness. The shield thicknesses are usually such that they have transmissions from 0.3 to 0.7. The upper limit arises from the fact that there is poor accuracy in determining total macroscopic mass removal cross section $\mu_{\text{Rem}}$ when transmission is equal to 1. The lower limit is set by the necessity of distinguishing the background counts from the transmitted flux. The lower background achieved with well designed shielding can enable to obtained transmission data down to $T=0.01$.

In order to minimize the correction of air scattered neutrons, a dimensionless parameter $x$ is defined. To correct for neutrons, distance is measured in terms of $x$. Actual distance is $x\lambda$, where $\lambda$ is the mean free path of neutron in air. The shielding usually working at a distance of the order of one meter from the neutron source, distance of interest for the comparison are represented by value of $x$ in the range 0.002 to 0.10.

Then the ratio of air scattered neutron flux to direct neutron flux $R=e^x - 1$ is the very nearly equal to $x$. The walls and floors of
the room and other scattering materials are kept as far away as possible to reduce background neutrons.

**Effect of skyshine:**

In the radiation shield design, one must consider the dose rate due to skyshine. When there is ordinary roof over the radiation area of radiation source located in a building, there is a significant probability that radiation reflected from the roof will exceed the dose limits in the vicinity of the source. This reflected radiation is known as “skyshine”.

The adequate expression for the neutron skyshine intensity around the neutron source is given by the empirical relation

\[
\phi(r) = \frac{Q e^{-\lambda r}}{4\pi r^2} \tag{3.11}
\]

Where \( r \) is the distance from the neutron source, \( Q \) is an effective source strength and \( \lambda \) is an effective absorption length. From the above empirical relation, one can conclude that the neutron skyshine intensity decreases at least as fast as does the inverse square of the distance from the source \( r \).
Materials:

Iron ($\rho = 7.87 \text{ gm/cm}^3$)

Lead ($\rho = 11.35 \text{ gm/cm}^3$)

Concrete ($\rho = 2.40 \text{ gm/cm}^3$)

Polypropylene ($\rho = 0.91 \text{ gm/cm}^3$)

Polyacrylic acid ($\rho = 1.34 \text{ gm/cm}^3$)

Table (3.01) shows the chemical composition (% by weight) of Polypropylene and Polyacrylic acid. Table (3.02) shows atomic and physical properties of iron and lead used in this present work.

Experimental Arrangement and Method:

Experimental arrangement for studying the attenuation characteristics of given shield for neutrons is shown in the Fig(3.01). This arrangement provides a narrow collimated beam of neutrons and is spoken of as “good geometry”. The implication of good geometry is that the neutron detector subtends a small solid angle from the neutron source and the shield. The thick lead shielding blocks separated by a narrow space act as the collimator. The detector used to detect neutrons, shield and collimator are surrounded by thick concrete block to absorb extraneous neutrons.
which might otherwise be scattered in to the detector and counted. In the ‘good geometry’ experimental setup, neutrons are removed from the beam either by absorption or by scattering. A neutron which undergoes scattering with a nucleus in the shield may be deflected enough so that it does not reach the detector and is lost from the beam, just as through it had actually been absorbed.

In this good geometry experimental setup, the first slab of the shielding material is mounted in line with the neutron source. The subsequent slabs are successively placed below the slabs already present. In this way the shielding thickness could be increased. The foil detectors were mounted directly on the shields located at their centres and also the central line of the neutron source.

The activity measurements were carried out with foil detectors Fe$^{56}$ and Al$^{27}$. The basic criterion for choosing these detectors was that the induced activities should be significant after irradiating for a reasonable time with the 16ci, Am-Be neutron source. Because of the smaller cross-section, the threshold foil detectors were larger than thermal neutrons detectors. The aluminium sheets with a purity of 99.8%, and iron foils were cut from steel straps of rectangular shape. A single set of aluminium foils will give results for both (n, p) and (n, α) reactions.
<table>
<thead>
<tr>
<th>Polymer</th>
<th>Density (gm/cm³)</th>
<th>Structural Formula</th>
<th>Composition (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Carbon</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.91</td>
<td>[C₃H₆]ₙ</td>
<td>85.6290</td>
</tr>
<tr>
<td>Polyacrylic</td>
<td>1.34</td>
<td>[CH₂ CH (CO₂H)]ₙ</td>
<td>50.0018</td>
</tr>
</tbody>
</table>

Table (3.01)

Chemical Composition (% by weight) of Polypropylene And Polyacrylic Acid
### Atomic And Physical Properties of Lead And Iron

<table>
<thead>
<tr>
<th>Property</th>
<th>Lead</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic weight</td>
<td>207.19</td>
<td>55.85</td>
</tr>
<tr>
<td>Atomic Number</td>
<td>82</td>
<td>26</td>
</tr>
<tr>
<td>Melting point (i)</td>
<td>327.5°C</td>
<td>1539 °C</td>
</tr>
<tr>
<td>Boiling point (i)</td>
<td>1750°C</td>
<td>2800 °C</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>11.35</td>
<td>7.87</td>
</tr>
</tbody>
</table>

**Table (3.02)**

Atomic And Physical Properties of Lead And Iron
Fig. (3.01)

Experimental Arrangement
The foils were irradiated for period of two days. Activities of irradiated foils were measured using standard NaI(Tl) scintillation spectrometer. The mechanism of scintillation production in NaI(Tl) scintillation spectrometer is reliable and hence it offers a high-efficiency detection. The energy resolution of the spectrometer was found to be 10% for Cs-137 (662 keV) at operating voltage 750 V. using the standard gamma sources namely, Co-60 (117 keV, 1332 keV), Ba-133(360 keV) and Cs-137 (662 keV) the linearity of the NaI(Tl) spectrometer was checked and was found to be excellent. A period of 24 hours was allowed for the spectrometer to attain stability condition. To minimize the electronic drifts, the AC main voltage was stabilized with good stabilizer. The activity measurements were conducted in the well-ventilated room during night to minimize thermal noise. The many pulse heights produced by decay processes were displayed on the MCA (AC 5058A) in the histogram style. Before connecting the NaI(Tl) spectrometer, the MCA was calibrated for the both energy and efficiency. The set of foils used, reactions and their physical characteristics related to the experiment are given in the Table (3.03)
<table>
<thead>
<tr>
<th>Foil</th>
<th>Abundance (%)</th>
<th>Reaction</th>
<th>Threshold Energy and Cross-Section</th>
<th>Product half-life</th>
<th>Gamma Energy (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>100</td>
<td>Al\textsuperscript{27}(n,\textit{p}) Mg\textsuperscript{27}</td>
<td>3.3 MeV 62 mb</td>
<td>9.45 min</td>
<td>840</td>
</tr>
<tr>
<td>Iron</td>
<td>91-68</td>
<td>Fe\textsuperscript{56}(n,\textit{p}) Mn\textsuperscript{56}</td>
<td>7.5 MeV 53 mb</td>
<td>2.57 h</td>
<td>840</td>
</tr>
<tr>
<td>Aluminium</td>
<td>100</td>
<td>Al\textsuperscript{27}(n,\textit{\alpha}) Na\textsuperscript{24}</td>
<td>8.7 MeV 115 mb</td>
<td>15.05 h</td>
<td>1369</td>
</tr>
</tbody>
</table>

**Table (3.03)**

**Characteristics of Activation Foil Detectors Used**
The low background laboratory was established. Precaution was taken to obtain good, reliable measurements. For the activity measurements, the background, measured with no source present was eliminated by increasing the detector efficiency. The non-peak background per percent efficiency decreases per percent of detector efficiency. This is because the peak- to-compton ratio increases with increasing detector efficiency. As the peak-to-compton ratio increases, the non-peak background decreases. This means that the most dominant background component is Compton scatter from specific lines then from a cosmic background continuum. Thus peak-to-compton ratio is the key indicator of a detector ability to distinguish low-energy peaks in the presence of high-energy sources. The peak-to-compton ratio was obtained by dividing the height of the 1.33 MeV peak by the average of Compton plateau between 1.040 and 1.096 MeV. Higher peak-to-compton value was obtained with better value of energy resolution. The primary effect of improved energy resolution was better ability to discriminate one nuclide peak from a close neighbouring peak. The minimum detectable activity was reduced by the improved energy resolution. When the two peaks interfere, one acts as background to the other. Thus, when the interference was eliminated, the minimum detectable activity was reduced. The peak-to-compton ratio
multiplied by the value of resolution was found to be constant. The shielding of the detector was found to be essential for reducing ambient background radiation. The detector was surrounded by low radiogenic lead to eliminate the contributions from the number of naturally occurring radio nuclides, cosmic ray induced background, and man made radionuclides Cs-137 and Co-60.

The detector produces light as it absorbs energy the light flash results in the release of proportionate number of photoelectrons at the cathode of photomultiplier tube. The photomultiplier tube amplifies this signal, producing a current pulse that is larger in amplitude at each of its successive dynodes. A long cable connection between the detector and the preamplifier adds input capacity and also makes the electronics more susceptibility to picking up environmental noise. Both effects can cause a degradation of the energy resolution and the timing performance. The primary function of preamplifier is to extract the signal from the detector without significantly degrading the intrinsic signal-to-noise ratio. Therefore, the preamplifier was located as close as possible to the detector. The discriminator was adjusted to reject the low amplitude noise. The events were recorded using the MCA consisting of 8k ADC, a histogramming memory, and a visual display of the histogram recorded in the memory. The analog pulse
at the input of the ADC was converted into digital output. The
digital output from the ADC was fed to dedicated memory known as
channel and sorted into a histogram to record the number of events
counted in each pulse-height interval. The spectrum of input pulse
heights represented by the histogram was connected to a computer
for displaying the spectrum.
Results and discussion:

Threshold foil detectors were used as neutron detectors. The foil activation method was found to be reliable method for the detection of neutrons and study the attenuation characteristics of shield materials. The neutron source was well shielded by low radiogenic lead in order to minimize the background neutron flux in the laboratory. The main uncertainty in this method is the accuracy of determining the position of foil to be irradiated and the reproduction of this position from experiment to experiment. The precaution was taken to select the position of foil to be irradiated. To determine the activity of irradiated foil, counts under the photopeak area were considered. The correction for multiply scattered neutrons was avoided by the good geometry setup. Further the multiply scattered neutron effect was reduced by applying well known theoretical concept $\mu_{\text{Rem}} \cdot t \approx 1$. Table (3.04) shows the macroscopic removal cross section $\mu_{\text{rem}}$ of different shield materials for Am-Be (α, n) neutrons measured using different threshold detectors. It is very interesting to note that macroscopic removal cross section is maximum for iron, followed by lead, polypropylene and polyacrylic acid and minimum for concrete. It can be
concluded that the macroscopic removal cross section is independent of density of material. Table (3.05) shows the weight of material in gm/cm$^2$ required to reduce the flux of neutrons to half of its initial value. It is minimum for polypropylene, followed by polyacrylic acid, concrete, iron and maximum for lead. The main errors arised due to the counting statistics. Counting statistics gave an uncertainty of ± 5% for the iron foils and ±7% percent for the aluminium foils. The error due to the calibration of the NaI(Tl) detector was of the order of ±7%.
<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu_{\text{Rem}}\text{ (cm}^{-1}\text{)}$ measured using foil detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminium $\text{Al}^{27}(n,p)\text{Mg}^{27}$</td>
</tr>
<tr>
<td>Iron</td>
<td>0.1723</td>
</tr>
<tr>
<td>Lead</td>
<td>0.1117</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.1024</td>
</tr>
<tr>
<td>Polyacrylic acid</td>
<td>0.0794</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.0783</td>
</tr>
</tbody>
</table>

Table (3.04)

Macroscopic Removal Cross-Section For Different Shield Materials
Measured Using Activation Foil Detectors
<table>
<thead>
<tr>
<th>Material</th>
<th>Weight in gm/cm² required to reduce the flux of neutrons to half of its initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{27}$Al(n,p) $^{27}$Mg</td>
</tr>
<tr>
<td>Iron</td>
<td>31.6536</td>
</tr>
<tr>
<td>Lead</td>
<td>70.4167</td>
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<tr>
<td>Polypropylene</td>
<td>6.1585</td>
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<tr>
<td>Polyacrylic acid</td>
<td>11.6955</td>
</tr>
<tr>
<td>Concrete</td>
<td>21.2414</td>
</tr>
</tbody>
</table>

Table (3.05)
Weight of Material (gm/cm²) Required To Reduce The Flux of Neutrons To Half of Its Initial Value
Production of High Energy Gamma Rays:

Am-Be(α, n) neutron source is the radioactive neutron source. The reaction responsible for the neutron emission is Be⁹ (α, n) C^{12}. This is exoergic reaction with Q value 5.708 MeV. The final nucleus C^{12} can be left in its ground state or in the 4.43 MeV or 7.63 MeV excited states. The transition from 7.65 MeV excited state to 4.43 MeV state is accompanied by gamma rays of energy 3.2 MeV and transition from 4.43 MeV state to the ground state is accompanied by 4.43 MeV gamma rays. The direct transition from 7.65 MeV state to the ground state is forbidden by selection rule.

Experimental setup is shown in the Fig.(3±2) Am-Be(α, n) neutron source was mounted on a support 150 cm above the floor level. The source was surrounded by the 3cm thick paraffin wax. NaI (Tl) detector head and assembly was placed in front of the source at a constant distance of 50 cms. The NaI (Tl) detector was surrounded by a concrete castle in order to minimize extraneous gammas reaching the detector. Gamma spectra were taken on the MCA for two different configurations.
1) With the neutron source enclosed by 3 cm thick paraffin wax.

2) 3 cm thick paraffin wax and 3 cm iron plate surrounding the neutron source.

Analysis of Results:

Neutron of different energies from Am-Be(α, n) neutrons source were thermalized in the paraffin wax. These neutron interact with the hydrogen of the paraffin wax and give rise to 2.23 MeV gamma rays, which is shown in the Fig.(3.03). The peak is well resolved and distinctly seen. This results from capture of neutron by hydrogen. Also in the Fig.(3.03) one can see three peaks at 3.2 MeV, 3.9 MeV and 4.43 MeV which result from the Be⁹ (α, n) C¹² reaction in the neutron source. 3.2 MeV peak is the photopeak corresponding to the transition of excited C¹² nucleus from its 7.65 MeV state to the 4.43 MeV state. 4.43 MeV peak is the photopeak corresponding to the transition of excited C¹² nucleus from 4.43 MeV state to its ground state. 3.9 MeV peak is the pair production peak due to the interaction of 4.43 MeV gamma rays with NaI (Tl) crystal. Fig.(3.04) shows gamma ray peak due to iron radiator. Thermal neutron captured by Fe⁶⁶ give rise to intense peak with the energy of 7.64 MeV. However the 4.43 MeV peak is more intense than the 7.64 MeV peak. Hence in order to obtain the iron peak it is necessary to carry out the counting for nearly 8 hours.
Experimental Setup For Studying The Production of High Energy Gamma Rays
Fig. 3.03

Gamma Ray Spectrum From Neutron Source (Surrounded With Paraffin Wax)
Fig. 3.04
Gamma Ray Spectrum From Neutron Source (Surrounded With Paraffin Wax and Iron)