

CHAPTER II

EXPERIMENTAL TECHNIQUES

1. Spectrometer Setting:

   a) Mounting of the NaI(Tl) crystals:

   The mounting of NaI(Tl) crystals plays an important part in nuclear spectroscopy techniques. The resolution of the spectrometer depends on the careful mounting of the crystals. The cylindrical NaI(Tl) crystals in particular discs were purchased from Harshaw Chemical Company in the form of raw blanks. The polishing and mounting of the crystals were done in a specially constructed dry box at a humidity of 8%. The crystals were made clear by rubbing them with the zero grade grinding paper so that the layer exposed to moisture and free iodine is removed. One side of the crystal, which was to be coupled to the face of the photomultiplier, was then polished by successively rubbing the crystal on a tissue paper after making it wet with the acetone. The crystals were mounted in thin Aluminium cans. A coating of about 10 mg/cm² of Al₂O₃ was uniformly sprayed on the unpolished sides in order to minimise the Compton scattering in the housing of the crystal. The polished crystal face was optically coupled with the perfectly plane thin glass plates using DC-200 silicone oil. The crystals were then sealed against moisture with the araldite adhesive applied at the corners. The mounted crystals
were then optically coupled with the lumon 6292 photomultiplier tubes by using the IX-200 silicone oil. The resolution of these crystals was 9% for the 662 γ-ray of Cs$^{137}$. The anthracene crystals were polished in the same manner and then coupled to the photomultiplier tubes using thin aluminium foil as a reflector and light shield. To minimize the spurious counts the crystal cans and mu-magnetic shields were properly earthed.

b) **Linear Amplifiers**

Two LA 600B type linear amplifiers were purchased from Eldorado Electronics Corporation U.S.A. These amplifiers are designed on the pattern of DD2 type "Non blocking double line linear pulse amplifier". The amplifiers have the maximum gain of 40,000 and accept the RC tail-end pulses. The amplifier converts these tail off pulses to the positive pulses. These pulses are immediately followed by their negative reflections. This type of double differentiation eliminates base line shift which generally occurs in an RC coupling network when the positive area is not equal to the negative area. The delay lines provide such type of shaping of the input pulses. Its high gain, good stability, wide gain control range, good linearity at all gain settings and counting rates, low noise, variable band width, and the ability to operate under high duty cycle conditions make it a suitable instrument in scintillation and proportional counter spectrometry.
The amplifier also contains a D-13 type discriminator which accepts the positive pulses from the amplifier. It was designed to receive a positive pulse with approximately 0.5 μsec rise time and a pulse width of 1.2 μsec. The linear amplifier provides the proper pulse shape for the D-13 discriminator.

c) **White Cathode Followers**

Two white cathode followers were designed to match with the LA 600B amplifiers. These cathode followers provide long tail pulses (≈100 μsec at the base) of either polarity, which is the input requirement of the LA 600B amplifiers. The output impedance of the cathode follower (about 200 ohm) also matches with the amplifier. The output of these cathode followers has minimum nonlinearity, distortion and noise. The circuit diagram of the cathode follower along with the base connections of the photomultiplier tube is shown in fig.2.

d) **High Voltage Power Supplies**

As the gain of the photomultiplier tubes depends upon the voltage on its dynodes, the high voltage power supplies with good stability, low noise and ripple are essential for scintillation spectrometers. Two high voltage power supplies type 200 were purchased from Bhabha Atomic Research Centre, Trombay, Bombay, India. These were found stable for continuous runs. The variation in the output voltage was less than 0.05% for the input variation from 160 to 250 volts.
Fig. 21

Photomultiplier, Dynode voltage divider and cathode follower circuit.
The circuit diagram of the coincidence circuit is shown in fig.12. The negative input pulses (output of the LA 600B amplifiers) were inverted and amplified by one tube inverter amplifier to trigger the negative biased blocking oscillator\(^2\) comprising the tubes \(V_2\) and \(V_3\). The cathode of the tube \(V_3\) provides the pulse of standard shape and size. These pulses were fed to the grid of a 6BB6 gated beam coincidence tube\(^3\) through a cathode follower and IN3\# crystal diode. Both the channels are exactly similar except a variable lumped delay line consisting of twelve steps, each having a delay of 0.05 \(\mu\) sec. To remove the small distortions caused by the delay the pulses in the second channel were again shaped with the blocking oscillator and then applied to the limited grid of the 6BB6 coincidence tube through a cathode follower and a crystal diode. The 6BB6 tube is initially in non-conducting state due to the positive cathode voltage determined by the 2.5\(\Omega\) potentiometer. But when the pulses at its two grids overlap in time, it starts conducting and consequently a negative coincident pulse is formed at the anode. The resolving time of the coincidence circuit was set equal to \(27=0.15\) \(\mu\) sec. by proper adjustment of the width of the input pulses and by changing the operating point of 6BB6 tube by means of cathode bias. The output pulse was taken through a 6AK5 cathode follower. The coincidence circuit was tested by the random coincidence method and also by introducing variable known delay in one of the
channels. When the coincidence spectrum was analysed by the twenty channel analyzer the coincidence output was inverted and amplified by means of 6AK5 tube to trigger a 6J6 univibrator. By the proper adjustment of the bias of the univibrator, an output pulse of about 25 volt and 2 μsec. width was obtained. This satisfies the input requirement of the twenty channel analyzer. The block diagram of the circuitary is shown in fig.13.

2. Analysis of the Scintillation Spectrum-

The gamma ray passing through NaI(Tl) crystals interacts mainly by three processes, the photo-electric effect, the Compton scattering and pair production. Therefore the scintillation spectra due to a monoenergetic source may contain a distinguished features like photopeak, Compton continuum, back scattered peak and escape peak. The complicated spectrum arising due to various gamma rays from the same source may be analysed with the help of known monoenergetic sources of gamma rays. The contribution due to various gamma rays in a definite channel width is obtained by the analysis of the spectrum after applying corrections due to photopeak efficiency and absorption due to crystal casing.

Due to the statistical nature of the light emission of photons from the phosphor and the subsequent variations in the emission of photoelectrons from photomultiplier tube there results a distribution...
Fig. 23
Block Diagram of Electronic Circuitry.
monoenergetic gamma ray source. So the photopeak follows a Poisson distribution. The full width at half the maximum height of the photopeak divided by the pulse size of the photopeak is defined as the resolution and varies inversely as the square-root of the incident energy.\(^3\)

When a certain gamma ray escapes after Compton scattering, the energy given to the electron gives rise to a Compton edge, the energy of which is \(^4\)

\[
E_c = E_{\text{inc}} \left[ 1 + \frac{m_e^2}{2E_{\text{inc}}} \right]^{-1}
\]

where \(E_c\) is the energy of the Compton edge and \(E_{\text{inc}}\) is energy of the incident gamma ray. If at the same time the Compton scattered gamma ray is also simultaneously absorbed in the crystal then the pulse will fall under the photopeak. If the surrounding material scatters back the Compton scattered gamma ray, the back scattered peak will be formed whose energy will be \(^4\)

\[
E_{\text{bs}} = E_{\text{inc}} - E_c
\]

The intensity of the Compton edge can be reduced by using large crystals and the intensity of the back scattered peak can be reduced by keeping minimum amount of substance around the crystal and selecting the surrounding material to be of low Z.

One more important thing which should be taken into account in the analysis of the spectra is the existence of the
escape peak. The energy of the escape peak is \( E = 28.4 \) keV in NaI(Tl) crystals and is due to the escape of the Iodine K-X-ray. The ratio of the intensity of the escape peak to the photopeak mainly depends upon the energy of the gamma ray, the size of the crystal and the geometry of the detector. This peak is relatively broad due to the escape of K-X-rays of different energies \( (K_x = 26 \) keV, \( K_\beta = 31 \) keV). Its relative contribution decreases rather fast with energy and the size of the crystal. It is almost unimportant above 150 keV.

As the axial sources placed at the intersection of the axes of two counters and perpendicular to the plane of the axes of the counters give best geometry for the angular correlation work, the sources were always prepared in perspex cells with cylindrical cavity.

3. Angular Correlation Studies

For the angular correlation studies one detector was fixed and the other detector was made moveable. The detectors along with the table carrying the detectors were kept away from all the scattering materials. The radioactive source which was generally in the liquid form was placed in a source holder made of perspex rod. The source holder was placed at the intersection of the axes of the two crystals. The singles counting rates at different angles were always found constant. The source strength was so chosen that the true to chance coincidence ratio was very high. The coincidence counts were
recorded at different angles varying from 90° to 270° between
the axes of the detectors for a definite interval. The
chance coincidences were always subtracted from the coincidence
counts. The coincidence rate at each angle was normalised
by the 180° counts by dividing with the single counting rates
N1 and N2 and multiplying by the counting rates at 180°. The
normalisation of the counting rate takes account of the decaying
of the source during the observations, source alignment and
any slight drift in the single counting rates. As the
experiments were performed with the liquid sources, the effect
of the extra nuclear field on the angular correlation pattern
was assumed to be very small. The effect due to time dependent
fields is negligible because of the slow coincidence circuitry
(2 T = 0.15 μ sec.) employed. Before starting the actual
measurement, the whole set-up was tested for Co60.

a) Least square fit of the data:

The method of least square fit applied to the
angular correlation data for the determination of angular
correlation coefficients A2 and A4 has been formulated by
Rose. 17 We give below a short discussion on the procedure of
computation of A2 and A4 on the basis of Rose's formulation.

The Aν coefficients which are the most probable
values for the given data are obtained from 17)

$$\sum \omega_i \left( \mu_i - \sum \kappa_\lambda A_{i\lambda} \right)^2 = \min.$$  \hspace{1cm} (3)

where \(\mu_i\) are the normalized coincidence counting rates and \(\omega_i\)
give the statistical weights to be attached to the \(\mu_i\).
for a fixed time of counting and is also equal to the inverse of the squared standard deviation i.e. \( \omega^2 = \frac{1}{\sigma_{\omega}^2} \)

and \( A_{\lambda} \) is the \( \lambda \)th Legendre Polynomial of \( \lambda \)th angle.

The required normal equations, which express the condition that the first derivative of each variable should be zero, are

\[
\sum_i \omega_i \left( \mu_i - \sum_{\lambda} \alpha_{\lambda} A_{\lambda} \right) A_{\lambda} = 0
\]

(4)

These are the three equations containing three unknown variables \( \alpha_0, \alpha_1 \) and \( \alpha_2 \) and can be solved to obtain three unknown coefficients. Putting these values in the following equation the least square fitted curve can be obtained.

\[
\omega(\theta) = \sum_{\nu=0}^{\infty} \alpha_{\nu} P_{\nu}(\cos \theta)
\]

(5)

b) Calculation of the errors

The systematic errors in the angular correlation coefficient measurements are calculated by the method due to Bose.\(^{17}\) We are giving this procedure for five values of the angle \( \theta \) viz. \( 180^\circ \), \( 157.5^\circ \), \( 135^\circ \), \( 112.5^\circ \) and \( 90^\circ \). The normalized coincidence rate corrected properly form a column matrix

\[
\mu = \begin{pmatrix}
\mu(180) \\
\mu(157.5) \\
\mu(135) \\
\mu(112.5) \\
\mu(90)
\end{pmatrix}
\]

(6)
We know the squared standard deviation $(\sigma_{\lambda\lambda}^2)$ from the experimental errors, which gives the weights to be attached to the $\lambda_{\mu}^{i\lambda}$ for a fixed time of counting, as $W(\theta) = \frac{1}{\sigma_{\lambda\lambda}^2(\theta)}$ is given as a diagonal matrix

$$W = \begin{pmatrix}
W(180) & 0 & 0 & 0 & 0 \\
0 & W(157.5) & 0 & 0 & 0 \\
0 & 0 & W(135) & 0 & 0 \\
0 & 0 & 0 & W(112.5) & 0 \\
0 & 0 & 0 & 0 & W(90)
\end{pmatrix} \quad (7)$$

However, this weight refers to the statistical weight of the data and does not take into account the systematic errors. Rosen has discussed the method for the estimation of such errors. The expression for the systematic errors is

$$\sigma_{\lambda\lambda}^2(\theta) = S_\xi \frac{\cos \lambda}{|\xi|}, \quad (8)$$

where a matrix $G$ is now formed as

$$G = \tilde{A} W A \quad (9)$$

where the tilde over $A$ means the transposed matrix and $A$ is given by

$$A = \begin{pmatrix}
P_o(\cos 180) & P_o(\cos 180) & P_o(\cos 180) \\
P_o(\cos 157.5) & P_o(\cos 157.5) & P_o(\cos 157.5) \\
P_o(\cos 135) & P_o(\cos 135) & P_o(\cos 135) \\
P_o(\cos 112.5) & P_o(\cos 112.5) & P_o(\cos 112.5) \\
P_o(\cos 90) & P_o(\cos 90) & P_o(\cos 90)
\end{pmatrix}$$
Further $\xi_1 = \Lambda_{ij}^\mu$ (from eqns. 6, 7 and 10) when $\alpha = c^{-1} \xi_1$, $c^{-1}$ being formed from eqn. 9 as another matrix whose $(i,j)^{th}$ element is the co-factor of $C_{ij}$ in the determinant $|C|$, and divided by $|C|$ as $s^2_\varepsilon$ is the residual variance of the least square fitted curve and is a goodness of fit parameter.\(17\)

For the particular directional correlation experiment, it is defined by the following equation

$$s^2_\varepsilon = \frac{1}{m-2} \sum_i (\varepsilon_i - \varepsilon_i)$$

(11)

where $m$ is the no. of measured data points and $\varepsilon$ stands for the number of coefficients. $(\varepsilon_i - \varepsilon_i')$ represents the difference between the observed counting rate and least square fitted counting rate at the $i^{th}$ position. For the three angle data we cannot compute the systematic errors. We write $\alpha$ as

$$\alpha = \begin{pmatrix}
\alpha_0 \\
\alpha_2 \\
\alpha_4
\end{pmatrix}$$

(12)

Now the squared standard deviation is formed from determinant $\varepsilon$, as

$$\varepsilon = \begin{pmatrix}
1 & 1 & 1 \\
1 & 0.781 & 0.343 \\
1 & 0.25 & -0.406 \\
1 & -0.261 & -0.086 \\
1 & -0.50 & 0.375
\end{pmatrix}$$

(10)
\begin{equation}
\sigma^2 = \begin{pmatrix}
\sigma_f^2 & \text{Cofactor } C_{11} = k_0 \\
\sigma_e^2 / c & \text{Cofactor } C_{22} = k_2 \\
\sigma_e^2 / c & \text{Cofactor } C_{33} = k_4 
\end{pmatrix}
\end{equation}

one can now write down from eqn 12 and 13 the value of

\[ A_2 \pm \Delta A_2 = \frac{\alpha_2}{\alpha_o} \pm \frac{\sqrt{k_2}}{\alpha_o} \]

and

\[ A_4 \pm \Delta A_4 = \frac{\alpha_4}{\alpha_o} \pm \frac{\sqrt{k_4}}{\alpha_o} \]

Eqn. 14 gives the most probable values of \( A_2 \) and \( A_4 \) as obtained from the experimental data.

c) Corrections to be applied:

The variation of the coincidence counting rate as a function of angle \( \theta \) between the two counters corresponds to the theoretical correlation function \( k(\theta) \) only when the following conditions are satisfied:

1. The sources should be centred point sources.
2. The detectors should be ideal point detectors.
3. No scattered radiations are present.

In order to compare the experimental data with the theoretical functions, we would have to apply the corrections for the deviations from such an ideal arrangement. These corrections have been discussed in detail by Fraunfelder and
AeppeU et al. 18)

If the decay scheme of the radioactive isotope under study is not too complicated and is well known, then only satisfactory interpretation of the measured data can be obtained. But generally the other radiations from the same source or the other source are present besides the cascades to be investigated. If these radiations are not in coincidence with the cascade radiations, then they only give rise to accidental counts and do not change the anisotropy. But if they also give rise to true coincidences then they may appreciably change the anisotropy and a correction must be applied. This correction is usually applied by knowing percentage of coincident counts due to other radiations obtained from the analysis of the singles and coincident spectra 10).

We define the coincidence rate CR(θ) as the ratio of the true coincidence counts to the true single counts in the movable detector. Therefore the coincidence rate is independent of the source strength and need not be corrected for the decay of radioactive isotope during the measurements.

The source strength should be chosen in such a way so that the true to chance coincidence ratio is very high. The chance coincidences should be subtracted from the observed coincidence counts.

Small changes in efficiency are corrected by using the coincidence rate CR(θ) for the calculation of W(θ).
If the moveable detector registers different single counts at different angles, then coincidences from an isotopic source vary with the single counting rate $N_s$. It is corrected by dividing the coincidence rate $CH(\theta)$ by the single counts $N_s$ of the moveable detector. 19)

The spurious coincidences due to scattering can be minimised by keeping away the table carrying the detectors away from all the scattering materials and shielding the side and front of the detectors with lead cones.

The finite size of the detectors also reduces the anisotropy. Hence the experimentally measured correlation coefficients $\lambda_k^{\text{Exp}}$ should be corrected for the finite solid angle of the detectors. Neglecting the correction for the extension of the source and using the theory developed by Frankel 20) we obtain for the corrected coefficients $\lambda_k$ as

$$\lambda_k = \frac{\lambda_k^{\text{Exp}}}{\eta_k}$$

(15)

In order to determine the factor $\eta_{kk}$ it is assumed that the efficiency of the detector is a function only of the angle $\Theta$ between the counter axis and direction of propagation of energy $'E'$ of the radiation. These detectors are called cylindrically symmetric or circular detectors. Scintillation counters come in the same category.

For such type of detectors in general the correction factor $\eta_{kk}$ can be expressed as product of two factors.
where \( Q_k(1) \) is the correction factor due to the counter no. 1 and \( Q_k(2) \) is the correction factor due to counter no. 2. In general

\[
Q_k = Q_k(1) \cdot Q_k(2) \tag{16}
\]

with

\[
Q_k(1) = \frac{J_k(1)}{J_0(1)} \tag{17}
\]

Here \( \alpha \) is the angular radius of the detector following Rose's notation. The value of \( \alpha \) for a circular detector is \( 4 \pi \).

These correction factors can be determined in various ways.

1. The angular efficiencies of the two detectors are determined experimentally by using a well collimated gamma ray beam. A numerical integration then gives \( Q_k \).

2. For gamma rays the efficiency \( \mathcal{E}(E, \Theta) \) is well represented by

\[
\mathcal{E}(E, \Theta) = 1 - e^{-\tau(E)} X(\Theta)
\]

where \( \tau(E) \) is the total absorption coefficient in the crystal for gamma rays of energy \( E \) and \( X(\Theta) \) is the distance traversed by the radiation in the crystal at an angle \( \Theta \) with respect to the axis of the cylindrical detector. These correction
factors have been evaluated for various sizes of the Sodium Iodide detectors at various distances $h$ from the source. \textsuperscript{17)}

In the present case we have taken the values of $Q_k(1)$ and $Q_k(2)$ from the table of Marion. \textsuperscript{14)}
References

20. S. Frankel, Phys. Rev. 63 (1951) 673.