Measurements, Results and Discussion:

Chapter 4.1 The Decay of $^{103}$Ru

4.1.1 Introduction

The negaton decay of $^{103}$Ru to $^{103}$Rh with a half life of 39.6 days has been extensively studied by several workers using the various techniques of beta and gamma ray spectroscopy. These investigations have resulted in a generally accepted level scheme of $^{103}$Rh with excited levels at 40, 93, 297, 362, 538 and 650 keV. The first excited level at 40 keV is an isomeric state with a half-life of 57 minutes. About a dozen gamma transitions between these levels, following the decay of $^{103}$Ru, have been reported by the various investigators. There is an agreement amongst the various workers about the existence of prominent gamma rays of 53, 498 and 610 keV. Recent investigations also support the existence of 297, 445 and 557 keV weak gamma rays. The existence of other weak gamma rays of energies 65, 112, 176, 322 and 362 keV is, however, still controversial. Of these, the 112, 176, and 322 keV gamma rays have been proposed as a weak triple cascade between the levels at 650, 538, 362 and 40 keV respectively. These weak gamma rays could not, however, be confirmed by the later workers.

The K-shell internal conversion coefficient of the 53 keV transition $\xi_K(53)$ has been measured by the KX-ray peak-to-gamma peak method by several workers. The various values reported for $\xi_K(53)$ namely $1.2 \pm 0.3^3, 2.74 \pm 0.13^6$ and $1.77 \pm 0.03^7$ are, however, in poor agreement. A knowledge of the $\xi_K(53)$ is desirable for a correct interpretation of the directional correlation measurements of the 445-53 and 557-53 keV cascades.
Definite spin-parity assignments have been made to the ground state and the excited states at 40, 297 and 362 keV of $^{103}\text{Rh}$. The spin of the ground state of $^{103}\text{Rh}$ has been measured to be $1/2$ using atomic-beam absorption techniques. This is consistent with a $3p_{1/2}$ orbital for the last proton on shell-model considerations. Such an orbital requires the parity of the state to be negative. Therefore, the ground state of $^{103}\text{Rh}$ has a $1/2^-$ character. The 40 keV transition from the isomeric level has been classified as E3 on the basis of K/L, L-sub shell internal conversion ratios and lifetime considerations. An E3 nature of the 40 keV transition is also supported by an observed E3 Coulomb excitation of the isomeric level. Such a classification of the 40 keV transition requires a character $7/2^+$ for the 40 keV isomeric level. The 297 and 362 keV levels have been assigned spin-parities $3/2^-$ and $5/2^-$ on the basis of Coulomb excitation experiments.

Spin-parity assignments for the 93, 538 and 650 keV levels have been attempted on the basis of angular correlation measurements, conversion data, the log ft values of beta groups feeding the 538 and 650 keV levels and the branching ratios of the gamma rays de-exciting the 538 and 650 keV levels. This has, however, resulted in conflicting spin-parity assignments to these three levels. The various proposed assignments are $7/2^+$ and $9/2^+$ for the 93 keV level, $3/2^+$, $5/2^+$, $7/2^+$, $7/2^-$ and $9/2^+$ for the 538 keV level and $5/2^+$, $7/2^+$, $7/2^-$ and $9/2^+$ for the 650 keV level.

In view of the above inconsistencies, the present investigations were undertaken. It was felt that the main reason for these inconsistencies is the low intensity of the gamma transitions. In the present investigations, high efficiency sum-peak coincidence spectrometer in $4\pi$-geometry and the
modified sum-coincidence spectrometer (as discussed in chapter 3) have been utilized in the study of these transitions. The relative gamma ray intensities have been determined by a single-crystal scintillation spectrometer. The gamma-gamma coincidence measurements have also been performed to study the cascading relations between the various gamma rays. Gamma-gamma directional correlations for the 445-53 and 557-53 keV cascades have been measured to assign spin-parity to the 93, 538 and 650 keV levels. The results of these measurements are presented below.

4.1.2 Source preparation

The radio-isotope $^{103}$Ru, in the form of RuCl$_3$ dissolved in dilute hydrochloric acid was obtained from Bhabha Atomic research Centre, Bombay, India. The radio-isotope was prepared from the distillation of fission products of natural uranium which was irradiated for a short time. A few drops of this active solution were put and dried in a perspex source holder. For sum-peak coincidence studies a very weak source on cellophane was prepared.

The source for gamma-gamma directional correlation measurements was prepared in a cylindrical perspex holder with a vertical central cavity of 2 mm dia x 6 mm depth, in the form of a dilute aqueous solution. The source in dilute solution form was taken in order to minimize any possible attenuation of the angular correlation functions of the 445-53 and 557-53 keV cascades due to a long half-life $T_{1/2} = 1.0 \pm 0.5$ n-sec. of the 93 keV intermediate level.

4.1.3 Singles gamma ray spectrum

The 'singles' gamma ray spectra of $^{103}$Ru were studied using the 2" x 2" NaI(Tl) crystal at source-to-crystal distances of 10 and 20 cm. The spectra were corrected for background counts and analysed by the usual
'peeling off' procedure\textsuperscript{24}). From the analysed spectrum, the energy and the relative intensity of the various gamma rays were found to be: 53 keV (0.6\pm0.2)\%, 297 keV (0.4\pm0.2)\%, 445 keV (0.8\pm0.3)\%, 496 keV (100)\%, 557 keV (1.4\pm0.2)\% and 610 keV (6.7\pm1.0)\%. The relative intensities have been corrected for absorption in the window of the crystal and also for iodine K\alpha-ray escape\textsuperscript{25}) from the crystal for the 53 keV peak. It may be mentioned that the present values of the relative intensities are in fair agreement with the results of other workers\textsuperscript{2,3,6,7}. In the analysis of any of the singles spectra observed in the present study, no indication for a gamma ray of 362 keV could be observed in contradiction with the results of Mukerji et al.\textsuperscript{6})

4.1.4 Gamma-gamma coincidence spectra

The gamma-gamma coincidence measurements were made using the fast-slow coincidence setup of fig. 3.2. The resolving time (T) of the setup was 50 nsec. The source was viewed by the two 2" x 2" NaI(Tl) crystals with their axes at 90° to each other, and was placed at a distance of 7 cm from either detector. A graded lead shield was used to avoid crystal-to-crystal scattering.

Figure 4.1.1 (a) shows a gamma ray coincidence spectrum (corrected for random coincidences) obtained by selecting a gate on the prominent 53 keV photopeak. Two clear peaks at 445 and 557 keV are observed in the coincidence spectrum. A comparison of the areas of the two photopeaks corrected for peak efficiencies and absorption in the window of the detector shows that the 445 keV transition is 50\% as intense as the 557 keV transition.

A coincidence spectrum obtained by gating in the 65 keV region is shown in fig. 4.1.1(b). A prominent peak at 297 keV is observed indicating
FIG. 4.1: GAMMA RAY COINC SPECTRA OF $^{103}$Rh WITH GATES SET AT (a) 53 KeV, (b) 65 KeV & (c) 322 KeV REGIONS.

FIG. 4.12: SUM-COINC SPECTRA OF $^{103}$Rh WITH SUM GATES SET AT (a) 498 & (c) 362 KeV.
a coincidence relationship between the 65 and 297 keV gamma rays. This coincidence relation was also verified by studying the coincidence spectrum by gating at 297 keV. A weak peak at about 65 keV was observed in the coincidence spectrum, providing a satisfactory evidence for the existence of a 65 keV transition in the decay of $^{103}$Ru.

Figure 4.1.1 (c) shows a coincidence spectrum obtained by selecting a gate in the 322 keV region. Peaks at 112 and 176 keV are observed. This spectrum supports the existence of a 112-176-322 keV triple cascade proposed by Zoller and Walters$^{10}$.

4.1.5 Sum-coincidence spectra

The cascade relationship between the various gamma rays indicated in the gamma-gamma coincidence measurements of section 4.1.4 were further investigated by sum-coincidence studies, utilizing the set up of fig. 3.3(b). The detectors, 2" x 2" NaI(Tl) crystals, laterally shielded with graded lead cylinders, were set at 90° to each other. A graded lead shield was put at 45° to either detector to eliminate crystal-to-crystal scattering. The source was set at a distance of 7cm from the face of either crystal.

The use of the setup of fig. 3.3(b), incorporating a fast-slow coincidence circuit with a resolving time ($T$) = 50 nsec., reduced the accidental coincidence rate due to the intense 498 keV gamma ray appreciably. This set-up also eliminated the sum-peak from the sum-coincidence spectrum. The removal of the sum-peak from the spectrum is desirable in the present investigations. The difference in the energy of the sum-peak and the higher energy component of the cascades being small ($\leq$ 65 keV) the two peaks are not well separated. The weak cascade constituent will be masked by the high intensity sum-peak arising due to the intense cross-over transition.
After equalising the gains of the two detectors the sum-gates were successively set at 610, 498 and 362 keV with gate widths of ~1.5% of the gate energies. The observed sum-coincidence spectra corrected for random coincidences are shown in fig. 4.1.2 (a), (b) and (c) for sum-gates set at 610, 498 and 362 keV, respectively. These measurements convincingly confirm the existence of the 557-53, 445-53 and 297-65 keV cascades in the decay of $^{103}$Ru. It may be mentioned that the 445 keV transition could not be observed by Naqvi and Hogg in their sum-coincidence studies as it was lost in the intense 498 keV peak which has been eliminated in the present measurements.

### 4.1.6 Sum-peak coincidence spectra

A zero bias and a 80 keV bias sum-peak coincidence spectrum obtained with the 2" x 2" NaI(Tl) detectors in 4T" geometry are shown in figs. 4.1.3(a) and (b) respectively. The zero bias spectrum shows peaks at 53, 297, 362, 498 and 610 keV whereas the 80 keV bias spectrum shows peaks at 297, 498 and 610 keV only. By raising the bias to 80 keV the contribution of the 65-297 keV cascade in the 362 keV sum-peak (observed in the zero bias spectrum) is eliminated. A 362 keV cross-over transition, if present, could still give a sum-peak at 362 keV in the 80 keV bias spectrum through 'cross-talk' phenomena. The absence of the 362 keV peak in the 80 keV bias spectrum indicates the non-existence of a cross-over transition from the 362 keV level to the ground state of $^{103}$Rh. An estimate on the upper limit of the intensity of a 362 keV cross-over transition is obtained by comparing the 297 keV peak in the zero and 80 keV spectra and any variation over Compton continuum in the 362 keV region in the latter spectrum. This analysis gives an upper limit of $< 0.01\%$ for the intensity of this transition.
FIG 4-13 a- ZERO BIAS SUM-PEAK COINC. SPECTRUM OF $^{103m}$Ru CRYSTALS IN 4M GEOMETRY

FIG 4-13 b- 80KeV BIAS SUM-PEAK COINC. SPECTRUM OF $^{103m}$Ru CRYSTALS IN 4M GEOMETRY.
Figure 4.1.3 (c) shows the adder spectrum obtained in the same geometry. By a comparison of the areas of the 498 and 610 keV peaks in the zero-bias sum-peak coincidence and adder spectra the attenuation factors for the 498 and 610 keV peaks are determined to be 0.062 and 0.086 respectively. The corresponding values of attenuation factors for non-coincident single gamma rays of energies 498 and 610 keV are 0.060 and 0.070 respectively (fig. 3.5). These values together with the experimentally determined photopeak efficiencies (fig. 3.5) determine the cross-over to cascade ratio, according to equation 3.9 and 3.10. A simple calculation gives that the 610 keV cross-over transition is 18 times as intense as the 557-53 keV competing cascade and the 498 keV cross-over transition is 190 times as intense as the 445-53 keV competing cascade.

4.1.7 K-shell internal conversion coefficient of the 53 keV transition

The K-conversion coefficient of the 53 keV transition was measured by selecting a gate on the 557 keV gamma ray with a 2" x 2" NaI(Tl) crystal and recording the coincidence spectrum with the help of a 1/4" x 1/4" NaI(Tl) crystal using the 256-channel pulse-height analyzer. The effective resolving time (\(\tau\)) of the fast-slow coincidence set up was 100 nsec.

Figure 4.1.4 shows a typical coincidence spectrum, (corrected for random coincidences) obtained with the gate set at 557 keV. The spectrum shows a Rh KX-ray peak at 20 keV and a gamma ray peak at 53 keV. The decay of the source was followed over a period of two half-lives to check the purity of the source. The ratio of the areas under the KX-ray and the gamma ray peaks was found to be constant within 4\% (table 4.1.1) during this period, indicating an absence of impurities in any significant proportion in the radioisotope. The K-shell conversion coefficient was calculated from the ratio of the number of counts under the KX-ray and gamma-ray peaks. The two
FIG. 4.15: THE EXPERIMENTAL ANGULAR CORRELATION FOR
(a) 557-53 (b) 445-53

Key CASCADE

180° 120° 0°

0 60 80 T 0 60 80

CHANNEL NUMBER

RUN FOR 2 MIN.

ENERGY IN KEV

FIG. 4.13(C) ADDER SPECTRUM OF $^{103}_{\text{Ru}}$ CRYSTALS IN 4$\pi$-GEOMETRY.

FIG. 4.5: THE EXPERIMENTAL ANGULAR CORRELATION FOR
(3) 557-53 (b) 445-53 keV CASCADEx
Fig. 4:1.4: Gamma ray coinc. spectrum of $^{103}_{\text{Ru}}$. Gate set at 557 keV.
Table 4.1.1: Parameters of the measurement of $\alpha_K$ for the 53 keV transition in Rh.

<table>
<thead>
<tr>
<th>d (cm)</th>
<th>Counts in</th>
<th>$I_K/I_\gamma$</th>
<th>Escape and absorption corrected $I_K/I_\gamma$</th>
<th>$\alpha_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross spectrum</td>
<td>Chance spectrum</td>
<td>True spectrum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X-ray peak</td>
<td>Y-ray peak</td>
<td>X-ray peak</td>
<td>Y-ray peak</td>
</tr>
<tr>
<td>7</td>
<td>3760±61</td>
<td>3571±60</td>
<td>74±19</td>
<td>691±18</td>
</tr>
<tr>
<td>7</td>
<td>2475±49</td>
<td>2376±49</td>
<td>227±15</td>
<td>216±15</td>
</tr>
<tr>
<td>5</td>
<td>245±50</td>
<td>2313±48</td>
<td>116±11</td>
<td>116±11</td>
</tr>
</tbody>
</table>

Average $\alpha_K$ = 1.90±0.06

d = source to detector distance

$I_K/I_\gamma$ = KX-ray intensity/γ-ray intensity.
areas were corrected for attenuation in the source holder and the window of the display crystal. These areas were further corrected for iodine escape peak\(^{25}\) for the 53 keV photopeak, K-shell fluorescence yield for rhodium\(^{27}\) and variation of detection efficiency with gamma ray energy\(^{28}\). Since the escape peak of the 53 keV gamma ray lies under the 20 keV KX-ray photopeak, the area of the KX-ray peak was also corrected for this contribution. An average of three measurements yielded a value of \(\delta_{\text{K}}(53) = 1.90 \pm 0.06\) (table 4.1.1). This value is in fair agreement with the value reported by Potnis et al.\(^{7}\) but is in disagreement with the values of Saraf\(^{3}\) and Mukerji et al.\(^{6}\).

4.1.8 Gamma-gamma directional correlation measurements

The directional correlation measurements were carried out using the set up of fig. 3.6. Two of the detectors were the identical 2" x 2" NaI(Tl) crystals and the third one was a \(1\frac{1}{2}\)" dia x \(\frac{1}{4}\)" thick NaI(Tl) crystal mounted on a RCA 6342 photomultiplier tube. These three detectors were mounted in a horizontal plane with their axes passing through the centre where the source was kept. The source-to-crystal distance was 10 cm in each case. The 2" x 2" NaI(Tl) crystals were kept fixed while the thinner crystal was moved between the angular positions 90° to 180° with respect to the fixed crystals. The singles rate of the movable detector was constant within 0.5% at different angular positions. The detectors were shielded with graded lead cylinders. Graded lead cones were put in front of the fixed detectors to avoid crystal-to-crystal scattering. Two separate fast-slow coincidence arrangements with resolving time \(\tau = 50\) nsec, for either of them were set up to simultaneously observe the coincidences between the pulses from the thinner crystal and either of the 2" x 2" NaI(Tl) crystal. In this way two sets of the observations at complementary angles were
obtained simultaneously. This enabled us to obtain double the normal coincidence counting rate. The \( \frac{1}{2} \)" x \( \frac{1}{2} \)" thick NaI(Tl) crystal was used to detect the 53 keV radiations. The use of a thinner crystal for the detection of the 53 keV gamma rays minimised the detection of high intensity 498 keV radiations in it, resulting in an improvement in the true-to-chance ratio for the cascades studied.

The coincidence counts were corrected for random coincidences and normalized by the singles counting rates of the detectors. The resulting data were analysed by the least-squares method \(^{29} \) to obtain correlation coefficients. These coefficients were corrected for finite angular resolution of the detectors using the correction factors given by Yates \(^ {30} \) and Stanford \(^ {31} \).

(A) The 557-53 keV cascade

The 557-53 keV cascade was studied by gating at the higher-energy half of the 498 keV photopeak selected in the two \( 2" \) x \( 2" \) NaI(Tl) crystals and the 53 keV photopeak selected in the thinner crystal. Coincidences at seven angles between 90° and 180° at intervals of 15° each were recorded. The experimental points with the least-squares fitted curve are shown in fig. 4.1.5(a). The correlation function corrected for finite angular resolution of the detectors is found to be,

\[
W(\theta) = 1 - (0.114 \pm 0.007)P_2(\cos \theta) - (0.047 \pm 0.011)P_4(\cos \theta).
\]

The present correlation function is in good agreement with the results of earlier workers \(^ {11-13} \).

(B) The 445-53 keV cascade

The 445-53 keV cascade was studied by gating at the lower-energy half of the 498 keV peak selected in the two \( 2" \) x \( 2" \) NaI(Tl) crystals and the 53 keV radiations selected in the thinner crystal. The experimental
points with the least-square's fitted curve are shown in fig. 4.1.5 (b). The solid angle corrected correlation function is found to be,

\[ W(\theta) = 1 + (0.114 \pm 0.019)P_2(\cos \theta) + (0.057 \pm 0.028)P_4(\cos \theta). \]

This correlation is influenced by the 557-53 keV cascade due to the Compton contribution of the 557 keV gamma ray falling in the gate set at the 445 keV peak. This interference is estimated to be (9.0 \pm 1.8)\% from the coincidence spectrum of fig. 4.1.1 (a). Correcting for this interference, the true correlation function for the 445-53 keV cascade is found to be

\[ W(\theta) = 1 + (0.137 \pm 0.021)P_2(\cos \theta) + (0.067 \pm 0.031)P_4(\cos \theta). \]

This correlation function is in agreement with the results of George et al.\(^{13}\).

4.1.9 Analysis of the angular correlation functions

The ground and the 40 keV isomeric levels of \(^{103}\)Rh have spins and parities 1/2\(^+\) and 7/2\(^+\) respectively\(^{12,17}\). From our conversion coefficient measurements, the K-conversion coefficient of the 53 keV transition \(K(53)\) has been found to be 1.90 \pm 0.06. A comparison of the experimental conversion coefficient with the theoretical values\(^{32}\) for M1 and E2 transitions shows that the 53 keV gamma ray is predominantly M1 in character with 1 \pm 1\% admixture of E2. This conclusion is in agreement with the results obtained ( \(\leq 1\%\) E2 admixture) from a comparison of the L sub-shell ratios of Manthrihil et al.\(^{8}\) with the theoretical values obtained from the tables of Hager and Seltzer\(^{32}\). A predominantly M1 character of the 53 keV transition requires spin-parity assignments 5/2\(^+\), 7/2\(^+\) or 9/2\(^+\) for the 93 keV level.

The assignments proposed by the various workers for the 650 keV level are 5/2\(^+\), 7/2\(^+\), 9/2\(^+\) or 7/2\(^-\). Assuming the above mentioned spin...
assignments for the 40, 93 and 650 keV levels, the possible spin sequences for the 557-53 keV cascade are:

\begin{align*}
  \text{a)} & \quad \frac{5}{2} \, (1,2) \, \frac{5}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{b)} & \quad \frac{7}{2} \, (1,2) \, \frac{5}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{c)} & \quad \frac{9}{2} \, (2,3) \, \frac{5}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{d)} & \quad \frac{5}{2} \, (1,2) \, \frac{7}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{e)} & \quad \frac{7}{2} \, (1,2) \, \frac{7}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{f)} & \quad \frac{9}{2} \, (1,2) \, \frac{7}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{g)} & \quad \frac{5}{2} \, (2,3) \, \frac{9}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{h)} & \quad \frac{7}{2} \, (1,2) \, \frac{9}{2} \, (1,2) \, \frac{7}{2}, \\
  \text{i)} & \quad \frac{9}{2} \, (1,2) \, \frac{9}{2} \, (1,2) \, \frac{7}{2}.
\end{align*}

The spin sequences (b), (e) and (h) require the theoretical correlation coefficient $\lambda_{4}$ to be positive whereas experimentally it has a definite negative value. This therefore rules out these spin sequences leaving (a), (c), (d), (f), (g) and (i) as the possible spin sequences for the 557-53 keV cascade.

The results of the directional correlation of the 557-53 keV cascades were analysed in terms of the spin sequences (a), (c), (d), (f), (g) and (i) using the method of Arns and Middeke. The quadrupole fraction in the 557 keV transition is determined consistent with the restriction that the quadrupole admixture in the 53 keV transition is $0 \leq Q_{53} \leq 0.02$. Fig. 4.1.6 shows a typical analysis of the angular correlation results for the spin sequences (a) (c), (d), (f), (g) are summarized in table 4.1.2. From the table it is clear that the present results for the angular correlation of the 557-53 keV cascade are consistent with the measured K-shell conversion coefficient of the 557 keV transition for the spin sequences (i) and (ii) 9/2 (1,2) 9/2 (1,2) 7/2. The spin sequence (i) requires the 557 keV transition to be pure E3 whereas spin sequence (ii) requires this transition to be E1 + M2. Since the 93 keV level has a positive parity, therefore,
FIG 4.6: THE ANALYSIS OF THE 557-53 keV CASCADE FOR THE SPIN SEQUENCES \( \frac{3}{2} - \frac{3}{2} - \frac{7}{2} \) & \( \frac{5}{2} - \frac{9}{2} - \frac{7}{2} \).
Table 4.1.2
Summary of the multipole admixture analysis of the directional correlation coefficients of the 557-53 keV cascade in $^{103}$Rh.

<table>
<thead>
<tr>
<th>Spin sequence for the 557-53 keV cascade</th>
<th>$q_{557} = \frac{\delta^2}{\delta_1^2 + \delta_2^2}$</th>
<th>Possible assignment</th>
<th>From 557-53 keV ( q_e(557) ) correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 5/2 - 5/2 - 7/2</td>
<td>$0 \leq q_1 \leq 0.05$</td>
<td>E1+M2</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.75 \leq q_2 \leq 0.78$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.610 \leq q \leq 0.820$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>c) 9/2 - 5/2 - 7/2</td>
<td>$0.03 \leq q_1 \leq 0.06$</td>
<td>E2+M3</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.54 \leq q_2 \leq 0.59$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>d) 5/2 - 7/2 - 7/2</td>
<td>$0 \leq q_1 \leq 0.05$</td>
<td>E1+M2</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.95 \leq q_2 \leq 1.00$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.610 \leq q \leq 0.820$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>f) 9/2 - 7/2 - 7/2</td>
<td>$0.01 \leq q_1 \leq 0.02$</td>
<td>E1+M2</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.99 \leq q_2 \leq 1.00$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.610 \leq q \leq 0.820$</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>g) 5/2 - 9/2 - 7/2</td>
<td>$0 \leq q_1 \leq 0.04$</td>
<td>E2+M3</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.96 \leq q_2 \leq 1.00$</td>
<td></td>
<td>Yes for $q_2$ and $\gamma$ 557 taken as pure E3</td>
</tr>
<tr>
<td></td>
<td>$0.136 \leq q \leq 0.218$</td>
<td>or pure E3</td>
<td></td>
</tr>
<tr>
<td>i) 9/2 - 9/2 - 7/2</td>
<td>$0.01 \leq q_1 \leq 0.07$</td>
<td>E1+M2</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$0.49 \leq q_2 \leq 0.68$</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>$0.610 \leq q \leq 0.820$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The values of $q_{557}$ in column 3 are calculated losing the $ife(557)$ taken from Manthruthil et al. 8 and table of Hager and Seltzer 32.
either nature of the 557 keV transition requires a negative parity for
the 650 keV level. An E3 multipolarity for γ 557 requires the lifetime
of the 650 keV level to be $1 \times 10^{-6}$ sec, by Weisskopf's estimate. In
estimating this life-time, the branching ratio of the 557 and 610 keV
transitions was taken into consideration. The 610 keV gamma transition is,
however, known to be in prompt coincidence with the 112 keV beta branch
feeding the 650 keV level. Thus the $5/2^-$ (E3) $9/2^+$ (M1,E2) $7/2^+$ spin
sequence is also ruled out. Therefore, the 557-53 keV cascade follows
the spin sequence $9/2^-$ (E1,M2) $9/2^+$ (M1,E2) $7/2^+$, with a M2 admixture
in γ 557 to be $0.49 \leq q_{557} \leq 0.68$.

The assignments proposed by various workers for the 538 keV level
are $3/2^-$, $5/2^-$, $7/2^+$, $9/2^+$ and $7/2^-$. Assuming these assignments for the
538 keV level and $9/2^+$, $7/2^+$ characters for the 93 and 40 keV levels respec-
tively the various possible spin sequences for the 445-53 keV cascade are:

1) $3/2 (3,4) 9/2 (1,2) 7/2$
2) $5/2 (2,3) 9/2 (1,2) 7/2$
3) $7/2 (1,2) 9/2 (1,2) 7/2$
4) $9/2 (1,2) 9/2 (1,2) 7/2$.

The spin sequence (i) requires the life-time of the 538 keV level
to be $10^{-6}$ sec. The life-time of 538 keV level is however known to
be $(5.6 \pm 1.9) \times 10^{-11}$ sec. So the spin sequence (i) is ruled out.
The spin sequences (ii) and (iv) are also incompatible with the observed $A_4$
correlation coefficient, for the 445-53 keV cascade. These sequences require
the $A_4$ term to be negative whereas experimentally it has a finite positive
value. Therefore, the only possible spin sequence for this cascade is
$7/2 (1,2) 9/2 (1,2) 7/2$.

Figure 4.1.7 shows a graphical analysis of the results of the 445-53
keV cascade in terms of the spin sequence $7/2 (1,2) 9/2 (1,2) 7/2$ with the
restriction that the quadrupole fraction in the 53 keV transition is
FIG 41.7: THE ANALYSIS OF THE 445-53 KeV CASCADE FOR THE SPIN SEQUENCE $\frac{3}{2}-\frac{3}{2}-\frac{1}{2}$
This analysis shows that the quadrupole fraction in the 445 keV transition is either $0.01 \leq Q_{445} \leq 0.02$, or $0.91 \leq Q_{445} \leq 1.00$.

The K-conversion coefficient of the 498 keV transition compared with the theoretical conversion coefficients due to Hager and Seltzer\textsuperscript{32)} shows the 498 keV transition to be an admixture of El + M2. This requires a negative parity for the 538 keV level. Therefore from the above analysis the 445 keV transition is either dominantly El with less than 2% M2 fraction or dominantly M2 with less than 9% El fraction. The conversion coefficient of the 445 keV transition\textsuperscript{8)} does not help in deciding whether this transition is predominantly El or M2.

4.1.10 Transition probabilities and retardation and enhancement factors for the gamma transition in $^{103}$Rh.

The branching ratios for the various transitions de-exciting a level were calculated by using the relative intensity data of Potnis et al.\textsuperscript{7)} and the theoretical conversion coefficients taken from the tables of Hager and Seltzer\textsuperscript{32)}. These branching ratios, along with the mixing ratios determined either in the present work or calculated using the measured K-conversion coefficients of Manthirthil et al.\textsuperscript{8)} were used to determine the absolute gamma ray transition probabilities of various gamma rays of $^{103}$Rh. The total conversion coefficients required for these calculations were taken from the theoretical tables\textsuperscript{32)}. Further, the half-lives of the respective excited states used in these calculations were taken from literature\textsuperscript{14-16)}.

The theoretical estimates for the transition probabilities can be obtained from Mosskopf's Estimates\textsuperscript{34)}. The appropriate statistical factors required for these calculations were calculated using the formulae given by Mosskowski\textsuperscript{34)}. 

$0 \leq Q_{53} \leq 0.02$. This analysis shows that the quadrupole fraction in the 445 keV transition is either $0.01 \leq Q_{445} \leq 0.02$, or $0.91 \leq Q_{445} \leq 1.00$. 

The K-conversion coefficient of the 498 keV transition\textsuperscript{8)} compared with the theoretical conversion coefficients due to Hager and Seltzer\textsuperscript{32)} shows the 498 keV transition to be an admixture of El + M2. This requires a negative parity for the 538 keV level. Therefore from the above analysis the 445 keV transition is either dominantly El with less than 2% M2 fraction or dominantly M2 with less than 9% El fraction. The conversion coefficient of the 445 keV transition\textsuperscript{8)} does not help in deciding whether this transition is predominantly El or M2.

4.1.10 Transition probabilities and retardation and enhancement factors for the gamma transition in $^{103}$Rh.

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The theoretical estimates for the transition probabilities can be obtained from Mosskopf's Estimates\textsuperscript{34)}. The appropriate statistical factors required for these calculations were calculated using the formulae given by Mosskowski\textsuperscript{34)}.
The experimental transition probabilities ($T_{\text{exp}}$) and the transition probabilities obtained on single particle estimates ($T_{\text{sp}}$) are given in table 4.1.3. A comparison of the experimental and single particle transition probabilities is made and an estimate of the hinderance factors ($H$) and enhancement factors ($E$) obtained. The results for the calculations are given in table 4.1.3.

<table>
<thead>
<tr>
<th>Transition Energy $K$(keV)</th>
<th>Multipolarity and Mixing ratio</th>
<th>$T_{\text{exp}}$</th>
<th>$T_{\text{sp}}$</th>
<th>Hinderance factors $H$ or enhancement factors $E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>0.99±0.01 M1</td>
<td>$2.3\times10^8$</td>
<td>$5.8\times10^9$</td>
<td>$H(M1); (25±12)$</td>
</tr>
<tr>
<td></td>
<td>0.01±0.01 E2</td>
<td>$4.6\times10^5$</td>
<td>$1.5\times10^4$</td>
<td>$E(E2); (31±34)$</td>
</tr>
<tr>
<td>445</td>
<td>EL</td>
<td>$4.2\times10^7$</td>
<td>$1.3\times10^{14}$</td>
<td>$H(EL); (2.6±0.8)\times10^8$</td>
</tr>
<tr>
<td></td>
<td>or M2</td>
<td>$5.2\times10^7$</td>
<td>$3.2\times10^7$</td>
<td>$E(M2); (1.6±0.5)$</td>
</tr>
<tr>
<td>498</td>
<td>0.51±0.06 EL</td>
<td>$7.2\times10^9$</td>
<td>$1.8\times10^{14}$</td>
<td>$H(EL); (2.5±1.0)\times10^8$</td>
</tr>
<tr>
<td></td>
<td>or M2</td>
<td>$5.1\times10^9$</td>
<td>$5.7\times10^7$</td>
<td>$E(M2); (90±36)$</td>
</tr>
</tbody>
</table>
Discussion of the results

The conclusions drawn from present investigations are incorporated in the decay scheme of $^{103}$Ru shown in fig. 4.1.8. These studies have definitely established the 65-297 keV cascade besides the 445-53 and 557-53 keV cascades. A triple cascade 112-176-322 keV between the 650 and 40 keV levels has been confirmed. A 362 keV transition from the level at 362 keV has been estimated to be $\leq 0.01\%$ if it at all exists. Spin-parities $9/2^+, 7/2$ and $9/2^-$ have been assigned to the 93, 538 and 650 keV levels of $^{103}$Rh on the basis of the result of directional correlations of the 445-53 and 557-53 keV cascades and the conversion coefficient data.

The 112 and 225 keV beta groups feeding the 650 and 538 keV levels have log $ft$ values 5.7 and 5.6 respectively. The beta transitions with log $ft$ values $< 5.8$ from nuclei with atomic number $Z < 80$ are of 'allowed' nature. The assignments $7/2^-$ and $9/2^-$ to the 538 and 650 keV levels respectively and the 'allowed' nature of the beta groups feeding these levels require a $7/2^-$ or $9/2^-$ character for the ground state of $^{103}$Ru. The spin-parity assignment to the ground state of $^{103}$Ru has been attempted on the basis of stripping reactions. From the deuteron stripping reaction $^{102}$Ru(d,p)$^{103}$Ru, using an enriched target of $^{102}$Ru, Mason et al. concluded that the angular distribution of the emitted protons could be fitted utilizing the Butler stripping theory with $l_n = 2$ or $l_n = 3$. This suggests spin-parity assignments $3/2^+$ or $5/2^+$ for $l_n = 2$ and $5/2^-$ or $7/2^-$ for $l_n = 3$, for the ground state of $^{103}$Ru. Mason et al. tentatively assigned a character $5/2^+$ to the ground state of $^{103}$Ru on the basis of allowed nature of the beta group feeding the 538 keV level and a supposed $7/2^-$ character for the 538 keV level. The presently assigned $7/2^-$ character to the 538 keV level prefers a $7/2^-$ assignment to the ground state of $^{103}$Ru. The log $ft$
FIG. 4.18: DECAY SCHEME OF $^{103}\text{Ru}$ BASED ON RESULTS OF EARLIER WORKERS AND PRESENT WORK.
values of other beta groups from the ground state of $^{103}\text{Ru}$ are not in contradiction with an assignment $7/2^-$ to the ground state of $^{103}\text{Ru}$. As pointed out by Menthurthil et al., a remeasurement of the $^{102}\text{Ru}(d,p)^{103}\text{Ru}$ stripping reaction with refined techniques can help in deciding between the assignments $5/2^+$ and $7/2^-$ for the ground state of $^{103}\text{Ru}$.

As already mentioned the ground state of $^{103}\text{Rh}$ is classified as a $3p_{1/2}$ orbital on the basis of shell model. The $40$ keV state may be described corresponding to $[(p_{1/2})^2p_0(\varepsilon_{9/2}^27/2)^{5p}]7/2$ or $[(p_{1/2})^1h(\varepsilon_{9/2}^27/2)^{7p}]7/2$ for the seven protons in excess of the 38 which completely fill the lower orbitals. The $93$ keV excited state seems also to correspond to similar configurations as the $53$ keV transition from this level does not show appreciable collective effects (table 4.1.3). The $297$ and $362$ keV levels have been interpreted as core-excitation states, arising due to the interaction of the $2^+$ state of an even-even core and the last nucleon in the $3p_{1/2}$ orbital. The $538$ and $650$ keV levels have been reached occasionally in Coulomb excitation experiments but not as often as the $297$ and $362$ keV levels. This indicates some collective effects in the excitation of the $538$ and $650$ keV levels as well.
References

CHAPTER 4.2

The Decay of $^{110m}_{\text{Ag}}$

4.2.1 Introduction

The 253 day positron decay of $^{110m}_{\text{Ag}}$ to $^{110}_{\text{Cd}}$ has been studied extensively by several workers$^{1,2}$, using various aspects of beta and gamma ray spectroscopy. The salient features of the decay scheme, shown in fig. 4.2.1, may be considered as fairly well established. In addition to the gamma rays shown in the fig. 4.2.1, a number of weak gamma transitions have been reported in literature$^{3-5}$. From a study of the conversion electron spectrum, Cork et al.$^{3}$ reported weak gamma transitions of 437, 471, 499, 541 and 575 keV. Gustova et al.$^{4}$ using a gamma-ray hodoscope obtained evidence for gamma rays of 1760, 1910, 2090, 2220 and 2460 keV. A gamma ray of 1760 keV was also observed in singles scintillation spectrum$^{5}$. None of these weak transitions could however be confirmed in the subsequent investigations$^{1,2}$.

The conversion coefficient data$^{2,6}$ establish the transitions between the strongly excited levels of $^{110}_{\text{Cd}}$ (fig. 4.2.1) to be of E2 or M1+E2 multipolarity. This assigns a positive parity to all the strongly excited states of $^{110}_{\text{Cd}}$. The directional correlation measurements$^{7-12}$ supplemented by internal conversion data$^{2,6}$ have led to unique spin assignments to all but the 2220 keV level of $^{110}_{\text{Cd}}$. No unique spin assignment for this level is possible from the presently available conversion coefficient data$^{2,6}$.

On the basis of the measured internal conversion coefficients for the 706 and 1565 keV transitions it is hard to decide whether the spin of the 2220 keV level is 3$^+$ or 4$^+$. So far no attempt has been made to assign a spin to this level on the basis of directional correlation measurements.
FIG. 4-2-1: DECAY SCHEME OF $^{110}_{\text{m}}\text{Ag}$ TO $^{110}_{\text{c}}\text{Cd}$ AS GIVEN IN REF. 1

FIG. 4-2-2: GAMMA RAY SPECTRUM OF $^{110}_{\text{m}}\text{Ag}$ CRYSTAL $\text{NaI}(T)$ SOURCE DISTANCE 40 cm.
Although the conversion coefficient measurements\textsuperscript{2,6} establish all the gamma transitions in $^{110}\text{Cd}$ to be E2 or M1+E2, yet it is difficult to know the multipole admixtures in the various transitions from the data. This is because of the fact that the theoretical values of the conversion coefficients\textsuperscript{13} corresponding to M1 or E2 multipolarities are very close to each other. The directional correlation measurements are very useful in the determination of mixing ratios in such cases. It was, therefore, thought worthwhile to undertake the present investigations. The directional correlations of the 1565-658 and 706-1565 keV cascades have been measured in order to assign a spin to the 2220 keV level. In addition to this the directional correlations of the 764-1505, 1505-658, 1384-884, 937-884, 884-658 and 446-(937)-884 keV cascades have been measured to determine the multipole admixtures of the various gamma transitions involved in these cascades. The directional correlation measurements of the 706-1565, 1565-658 and 446-(937)-884 keV cascades have been attempted for the first time.

A careful study of the singles spectrum of $^{110}\text{mAg}$ was made to check the existence of a 1760 keV gamma ray. Also sum-coincidence spectrum of $^{110}\text{mAg}$ has been studied in 3π - geometry to look for the existence of other weak gamma rays. The results of the above-mentioned investigations are presented below.

4.2.2 Experimental arrangements and procedure

The radioactive isotope $^{110}\text{mAg}$ in the form of silver nitrate dissolved in dilute nitric acid was obtained from Rhabba Atomic Research Centre, Bombay, India. A few drops of this active solution were put and dried in a perspex source holder to prepare a strong source. A source prepared on cellulose mounted on aluminium holder was used for sum-coincidence studies. For gamma-gamma directional correlation measurements, a moderately
strong liquid source was prepared in a cylindrical perspex holder with a vertical central cavity of 1.5 mm dia. x 4 mm depth.

The gamma rays were detected in two identical Harshaw integral line assemblies with 3" dia. x 3" thick NaI(Tl) crystals. These detectors have a resolution of about 7.8% for 662 keV photons. Coincidence measurements were carried out with a fast-slow coincidence set up (fig. 3.2) having an effective resolving time $\tau = 50$ nsec. The sum-coincidence measurements were carried out with the setup of fig. 3.3(b).

The directional correlation measurements were carried out with both the detectors shielded from each other with anti-Compton graded lead cylinders and lead cones. The source was symmetrically located 14 cm from each crystal at the point of intersection of the axes of the two crystals. The source could be centered within 1% variation in the 'singles' counting rate of the movable detector at different angular positions. The coincidence counts were recorded at seven angles between 90° to 180°, at intervals of 15° each. The random coincidences were determined by introducing a delay of ~500 nsec, in one of the channels of the fast-coincidence circuit. The true-to-chance ratio was about 12 : 1 for all cascades studied. The total number of true coincidence counts collected at each angle were about 40,000 in case of strong cascades and more than 12,000 in case of weak cascades. The singles counts in the movable and the fixed detectors were also recorded, simultaneously with the coincidence counts.

The data, after correction for random coincidences and normalisation by the singles counting rates of the two detectors were fitted by the least-squares' method\textsuperscript{14) to extract the correlation coefficients. These coefficients were corrected for finite geometry of the detectors using the correction factors calculated by Yates\textsuperscript{15) .}
In most cases the cascades studied have interfering contributions from neighbouring cascades. These contributions were estimated by using the relative intensity data of Moragues et al. obtained with Ge(Li) detectors. The errors in the relative intensities have been taken into consideration in finally calculating the errors in the correlation coefficients.

The detectors used in the present directional correlation measurements are larger in size and have better resolution than the detectors used in the earlier studies. This has resulted in a better detection efficiency, lesser interference between neighbouring cascades and a considerably reduced Compton background of higher energy gamma rays under the photopeaks of the lower-energy gamma rays. As a consequence the corrections for interfering cascades are appreciably reduced.

In the analysis of the correlation functions to obtain the spin sequences and mixing ratios, method of Arns and Wiedenbeck and tables of Taylor and McPherson were used.

4.2.3 Gamma ray singles spectra

The singles gamma ray spectra of $^{110m}_{\text{Ag}}$ were studied using the 3" x 3" NaI(Tl) crystal at source-to-crystal distance of 40 cm. These spectra were analysed by the usual 'peeling off' method. One of the analysed spectrum is shown in fig. 4.2.2. The average value of the relative gamma ray intensities obtained from these spectra are given in table 4.2.1, along with the results of previous workers. A composite value of the intensity is given for those gamma rays which could not be resolved by the scintillation detectors. Comparison indicates that the present values are in fair agreement with the results of earlier investigators except for gamma rays, which could not be fully resolved.
Table 4.2.1
Energies and relative intensities of the gamma rays in the decay of $^{110m}$Ag

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Knipper (11)</th>
<th>Anton'yeve et al. (19)</th>
<th>Voinova et al. (20)</th>
<th>Moregues et al. (2)</th>
<th>Present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>446</td>
<td>7</td>
<td>7±1</td>
<td>6±1</td>
<td>3.5±0.4</td>
<td>8±2</td>
</tr>
<tr>
<td>620</td>
<td>10</td>
<td>4±1</td>
<td>5±1</td>
<td>2.9±0.5</td>
<td>10±3</td>
</tr>
<tr>
<td>658</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>677</td>
<td>-</td>
<td>10±1</td>
<td>9±1</td>
<td>12.1±1.8</td>
<td>-</td>
</tr>
<tr>
<td>686</td>
<td>-</td>
<td>7±2</td>
<td>15±2</td>
<td>7.5±1.5</td>
<td>-</td>
</tr>
<tr>
<td>707</td>
<td>32</td>
<td>21±2</td>
<td>18±2</td>
<td>16.8±1.1</td>
<td>28±5</td>
</tr>
<tr>
<td>744</td>
<td>-</td>
<td>-</td>
<td>5±2</td>
<td>4.7±0.8</td>
<td>-</td>
</tr>
<tr>
<td>764</td>
<td>24</td>
<td>24±2</td>
<td>24±1</td>
<td>23.5±1.5</td>
<td>26±5</td>
</tr>
<tr>
<td>818</td>
<td>6</td>
<td>10±2</td>
<td>6±1</td>
<td>7.5±0.7</td>
<td>10±3</td>
</tr>
<tr>
<td>835</td>
<td>75</td>
<td>71±5</td>
<td>75±1</td>
<td>79.1±3.0</td>
<td>72±6</td>
</tr>
<tr>
<td>937</td>
<td>25</td>
<td>34±3</td>
<td>33±2</td>
<td>35.7±2.0</td>
<td>35±5</td>
</tr>
<tr>
<td>1384</td>
<td>20</td>
<td>20±2</td>
<td>24±1</td>
<td>27.6±1.1</td>
<td>24±3</td>
</tr>
<tr>
<td>1476</td>
<td>-</td>
<td>3.6±1</td>
<td>4±1</td>
<td>4.4±0.20</td>
<td>2±1</td>
</tr>
<tr>
<td>1505</td>
<td>13</td>
<td>10±1</td>
<td>13±1</td>
<td>14.5±0.7</td>
<td>16±2</td>
</tr>
<tr>
<td>1565</td>
<td>-</td>
<td>1.2±0.2</td>
<td>1.34±0.10</td>
<td>1.8±0.4</td>
<td></td>
</tr>
<tr>
<td>1760</td>
<td>-</td>
<td>0.05</td>
<td>-</td>
<td>~0.08</td>
<td></td>
</tr>
</tbody>
</table>
The existence of weak gamma rays of energies higher than 1565 keV was checked by studying the singles spectrum of $^{110m}\text{Ag}$. To reduce the summing effects appreciably, the singles spectrum was studied with a source-to-detector distance of 100 cm. To keep the background low the detector was covered with 6" of lead on all sides. A large number of counts were accumulated to improve overall statistical accuracy. Figure 4.2.3 shows a typical spectrum corrected for background counts. A clear peak is indicated at 1760 keV whose intensity is estimated to be ~0.08%. The spectrum was also studied by filtering the gamma radiations through a lead absorber 1 cm thick. The intensity of the 1760 keV peak was observed to decrease by (40±5)%. A single gamma ray of 1760 keV is expected to be reduced by ~42%. This indicates that the 1760 keV photopeak is due to a single gamma ray of the same energy. The singles spectrum was reinvestigated twice in the same geometry during one half-life of the source after the first experiments. These studies indicated that the 1760 keV gamma ray belongs to the decay of $^{110m}\text{Ag}$.

4.2.4 Sum-coincidence spectrum

The sum-coincidence spectrum of $^{110m}\text{Ag}$ was recorded with the matched pair of 3" x 3" NaI(Tl) crystals utilising the set up of fig. 3.3(b). The crystals were placed face-to-face with a lead shield of 6 mm thickness to eliminate crystal-to-crystal scattering. A source of moderate intensity was placed in a hole made in the centre of the shield. The geometry of the experiment is shown in the insert of fig. 4.2.4.

A sum-coincidence spectrum (corrected for random coincidences) obtained with the sum-gate set at 2926 keV is shown in fig. 4.2.4. A number of sum-coincidence peaks are observed, most of which fit in with the expected cascades involving two or more gamma rays. A possible
FIG. 4-2: GAMMA RAY SPECTRUM OF $^{110m\text{Ag}}$. CRYSTAL = $^{3\times10^3}\text{NaI(TL)}$. SOURCE DISTANCE = 100 cm.
combination of the coincident gamma rays which could lead to the observed spectrum is shown in table 4.2.2. It is noted that all the observed sum-peak except the 200 and 2720 keV peaks are explained on the level scheme of fig. 4.2.1. The two peaks are, however, not explained on the level scheme of fig. 4.2.1. The full-width at half-maximum of these peaks as observed in the spectrum are not too much off from the expected widths of the peaks for such energies in the sum-coincidence spectrum. These peaks were investigated with and without lead shields in between the two crystals to check the contributions of the back-scattering processes in the formation of these two peaks.

Table 4.2.2
Possible combination of the gamma rays giving sum-coincidence peaks in the 2926 keV sum-coincidence gate spectrum.

<table>
<thead>
<tr>
<th>Sum-coinc. peaks (keV)</th>
<th>Possible Cascades (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>446, 2475 (446; 937 + 884 + 658)</td>
<td>658, 2276 (658; 1505 + 764), (658; 884 + 1384)</td>
</tr>
<tr>
<td>742, 2178 (706; 744 + 1476), (706; 677 + 884 + 658), (764; 1505 + 658), (764; 687 + 1476).</td>
<td>873, 2050 (818; 658 + 744 + 706), (818; 658 + 687 + 764), (834; 1384 + 658)</td>
</tr>
<tr>
<td>1114, 1835 (446 + 658; 937 + 884)</td>
<td>1384, 1565 (1384; 884 + 618), (706 + 677; 884 + 658), (764 + 620; 884 + 658), (446 + 937; 884 + 658).</td>
</tr>
<tr>
<td>1467, 1467 (1476; 742 + 705), (658 + 818; 687 + 764).</td>
<td>200, 2720 (200; Sum of two or more gamma rays)</td>
</tr>
</tbody>
</table>
FIG. 42: SUM-COINC. SPECTRUM OF $^{110m}_{\text{Ag}}$. GATE SET AT 2926 KEV.
It was observed that the widths of these peaks in the sum-coincidence spectrum studied with lead shield are closer to the expected values than the widths in the sum-coincidence spectrum studied without lead shields. It is, therefore, felt that the major contribution in the 200 keV photopeak is due to a 200 keV gamma ray which could have been missed because it happens to be in the region of back-scattering.

4.2.5 Gamma-gamma angular correlations

A gamma ray scintillation spectrum of $^{110m}$Ag obtained with the $3" \times 3"$ NaI(Tl) crystal with a source-to-crystal distance of 14 cm is shown in fig. 4.2.5. The gates used for directional correlation measurements of various cascades are shown in the figure. These positions were chosen to eliminate or minimize the interference from neighbouring cascades.

1) The directional correlation of the 764-1505 keV cascade

The 764-1505 keV correlation was measured with gate 1 accepting the high-energy of the 1505 keV photopake (1505-1590 keV) and the gate 2 accepting the 764 keV photopake (730-780 keV). With these gates the only interference is from the 1565-706 keV cascade. This interference is estimated to be $\leq 0.5\%$ and was therefore neglected. The corrected correlation function is:

$$W(\theta) = 1 - (0.1736 \pm 0.0089)P_2(\cos \theta) - (0.0039 \pm 0.0023)P_4(\cos \theta).$$

The present correlation coefficients are in good agreement with the results of previous workers (table 4.2.3).

The 658, 2162 and 2926 keV levels are having spins $2^+$, $3^+$ and $5^+$ respectively. Therefore, the 764-1505 keV cascade follows the spin sequence $5(1) 3(0,2) 2$. A mixing ratio analysis (fig. 4.2.6) of the $A_2$ expansion coefficient in terms of this spin sequence (assuming a pure $E2$ character for $\gamma_{764}$) shows that the quadrupole content in the 1505 keV transition is either $(9.0 \pm 1.8)\%$ or $(73.2 \pm 3.1)\%$. The observed $A_4$ coefficient,
FIG. 4-2: ANALYSIS OF THE 764-KeV CASCADE IN TERMS OF THE SPIN SEQUENCE $S(Q) \rightarrow D(Q) \rightarrow 2$.
Summary of the angular correlation results of the gamma ray cascades in 110Cd.

<table>
<thead>
<tr>
<th>Cascade (keV)</th>
<th>Reference</th>
<th>$A_2$</th>
<th>$A_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>764-1505</td>
<td>Knipper (11)</td>
<td>-0.16 ±0.02</td>
<td>+0.01 ±0.03</td>
</tr>
<tr>
<td></td>
<td>Funk and Wiedenbeck (10)</td>
<td>-0.17 ±0.05</td>
<td>+0.02 ±0.05</td>
</tr>
<tr>
<td></td>
<td>Taylor and Frisk (8)</td>
<td>-0.1627 ±0.0063</td>
<td>-0.0031 ±0.0098</td>
</tr>
<tr>
<td></td>
<td>Capeller and Genssuage (9)</td>
<td>-0.098 ±0.213</td>
<td>+0.004 ±0.115</td>
</tr>
<tr>
<td></td>
<td>Münich et al. (7)</td>
<td>-0.137 ±0.075</td>
<td>+0.0075 ±0.0065</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>-0.1736 ±0.0089</td>
<td>+0.0039 ±0.0023</td>
</tr>
<tr>
<td>1505-658</td>
<td>Knipper (11)</td>
<td>-0.14 ±0.07</td>
<td>-0.12 ±0.09</td>
</tr>
<tr>
<td></td>
<td>Funk and Wiedenbeck (10)</td>
<td>-0.40 ±0.13</td>
<td>-0.03 ±0.04</td>
</tr>
<tr>
<td></td>
<td>Münich et al. (7)</td>
<td>-0.395 ±0.033</td>
<td>-0.032 ±0.02</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>-0.406 ±0.049</td>
<td>-0.049 ±0.02</td>
</tr>
<tr>
<td>1565-658</td>
<td>Present study</td>
<td>+0.120 ±0.027</td>
<td>+0.010 ±0.003</td>
</tr>
<tr>
<td>706-1565</td>
<td>Present study</td>
<td>-0.295 ±0.063</td>
<td>-0.053 ±0.021</td>
</tr>
<tr>
<td>1384-884</td>
<td>Knipper (11)</td>
<td>-0.238 ±0.022</td>
<td>-0.048 ±0.014</td>
</tr>
<tr>
<td></td>
<td>Funk and Wiedenbeck (10)</td>
<td>-0.308 ±0.033</td>
<td>-0.009 ±0.020</td>
</tr>
<tr>
<td></td>
<td>Taylor and Frisk (8)</td>
<td>-0.2337 ±0.0068</td>
<td>-0.0318 ±0.0096</td>
</tr>
<tr>
<td></td>
<td>Capeller and Genssuage (9)</td>
<td>-0.221 ±0.019</td>
<td>-0.062 ±0.022</td>
</tr>
<tr>
<td></td>
<td>Sakai et al. (12)</td>
<td>-0.1335 ±0.028</td>
<td>+0.0114 ±0.0306</td>
</tr>
<tr>
<td></td>
<td>Münich et al. (7)</td>
<td>-0.284 ±0.011</td>
<td>-0.0374 ±0.0090</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>-0.2708 ±0.0073</td>
<td>-0.0092 ±0.0084</td>
</tr>
<tr>
<td>937-884</td>
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<td>-0.02 ±0.03</td>
</tr>
<tr>
<td></td>
<td>Funk and Wiedenbeck (10)</td>
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<td>-0.006 ±0.036</td>
</tr>
<tr>
<td></td>
<td>Taylor and Frisk (8)</td>
<td>+0.091 ±0.023</td>
<td>-0.035 ±0.036</td>
</tr>
<tr>
<td></td>
<td>Capeller and Genssuage (9)</td>
<td>+0.117 ±0.028</td>
<td>-0.035 ±0.032</td>
</tr>
<tr>
<td></td>
<td>Sakai et al. (12)</td>
<td>+0.0377 ±0.0286</td>
<td>-0.0366 ±0.0308</td>
</tr>
<tr>
<td></td>
<td>Münich et al. (7)</td>
<td>+0.093 ±0.012</td>
<td>+0.0148 ±0.0058</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>+0.101 ±0.011</td>
<td>+0.03 ±0.007</td>
</tr>
<tr>
<td>446-(937) -884</td>
<td>Funk and Wiedenbeck (10)</td>
<td>+0.073 ±0.014</td>
<td>-0.019 ±0.020</td>
</tr>
<tr>
<td></td>
<td>Sakai et al. (12)</td>
<td>+0.115 ±0.0316</td>
<td>-0.0031 ±0.0339</td>
</tr>
<tr>
<td></td>
<td>Münich et al. (7)</td>
<td>+0.1004 ±0.0087</td>
<td>+0.0036 ±0.0046</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>+0.094 ±0.0024</td>
<td>+0.0074 ±0.0036</td>
</tr>
<tr>
<td>446-(937) -884</td>
<td>Present study</td>
<td>-0.322 ±0.048</td>
<td>-0.129 ±0.038</td>
</tr>
</tbody>
</table>
however, favours a dominantly dipole character for the 1505 keV gamma transition. Therefore, the 1505 keV transition is $(9.4_2,1.8)_E^2$ and $(91.0_2,1.8)_M^2$ with $S_{1505} = -0.32 \pm 0.04$.

ii) The directional correlations of the 1505-658, 1505-658 and 706-1565 keV Cascades

The 1505 and 1565 keV photopeaks are not resolved in the scintillation spectrum. Similarly, the 658, 706 and 764 keV photopeaks are not resolved. The directional correlations of the above cascades were, therefore, studied by making three measurements with different gates:

a) Measurement (A)

One of the discriminators was set on gate 1 (1505-1590 keV) and the second discriminator was set on gate 3 (630-680 keV). The evaluation of experimental data, after solid angle correction yields,

$$ W_A(e) = 1 - (0.350 \pm 0.008)P_2 (\cos \theta) - (0.042 \pm 0.008)P_4 (\cos \theta) \ldots 1) $$

b) Measurement (B)

One of the discriminators was put on gate 3 (630-680 keV) and the second discriminator was put on gate 4 (1565-1670 keV). The solid angle corrected correlation function is,

$$ W_B(e) = 1 - (0.194 \pm 0.010)P_2 (\cos \theta) - (0.026 \pm 0.004)P_4 (\cos \theta) \ldots 2) $$

c) Measurement (C)

One of the discriminators was set on gate 4 (1565-1670 keV) and the second discriminator was set on gate 5 (680-740 keV). The evaluation of experimental data after solid angle correction gives,

$$ W_C(e) = 1 - (0.243 \pm 0.017)P_2 (\cos \theta) - (0.035 \pm 0.010)P_4 (\cos \theta) \ldots 3) $$

In case of measurements (B) and (C), the discriminators were set on the sloping portions of the composite photopeaks. As a result of this the counting rates in both the channels were sensitive to even small shifts
in pulse heights. To overcome this difficulty the counting period at each angle was decreased and the coincidences collected in a larger number of sweeps than in other measurements.

The measured correlation functions $W_A(\theta)$, $W_B(\theta)$ and $W_C(\theta)$ can be represented by the following equations in terms of the correlation functions $W_{764-1505}(\theta)$, $W_{1505-658}(\theta)$, $W_{1565-658}(\theta)$ and $W_{706-1565}(\theta)$ of the 764-1505, 1505-658, 1565-658 and 706-1565 keV cascades.

\[
W_A(\theta) = a_1 W_{764-1505}(\theta) + b_1 W_{1505-658}(\theta) + c_1 W_{1565-658}(\theta) + d_1 W_{706-1565}(\theta)
\]

\[
W_B(\theta) = a_2 W_{764-1505}(\theta) + b_2 W_{1505-658}(\theta) + c_2 W_{1565-658}(\theta) + d_2 W_{706-1565}(\theta)
\]

\[
W_C(\theta) = a_3 W_{764-1505}(\theta) + b_3 W_{1505-658}(\theta) + c_3 W_{1565-658}(\theta) + d_3 W_{706-1565}(\theta)
\]

where $a_i$, $b_i$, $c_i$ and $d_i$ ($i = 1,2,3$) are the relative contributions of the 764-1505, 1505-658, 1565-658, and 706-1565 keV cascades respectively in the three measurements (A), (B) and (C). These constants were estimated from a careful examination of the scintillation spectrum at gate positions 1, 3, 4 and 5 by using the relative intensity data of Moragues et al.\(^2\) and are given below:

\[
a_1 = (0.019 \pm 0.001), \quad b_1 = (0.882 \pm 0.040), \quad c_1 = (0.099 \pm 0.005)
\]

and $d_1 = 0$

\[
a_2 = (0.018 \pm 0.001), \quad b_2 = (0.507 \pm 0.022), \quad c_2 = (0.374 \pm 0.018)
\]

and $d_2 = (0.102 \pm 0.005)$

and $a_3 = (0.241 \pm 0.012), \quad b_3 = (0.111 \pm 0.005), \quad c_3 = (0.089 \pm 0.005)$

and $d_3 = (0.566 \pm 0.022)$. 


Using these constants and the measured correlation functions $W_A(\theta)$, $W_B(\theta)$ and $W_C(\theta)$, the true correlation functions for the 1505-658, 1565-658 and 706-1565 keV cascades were evaluated by solving the equations 4, 5, and 6. The correlation functions for these cascades are as follows:

- $W_{1505-658}(\theta) = 1 - (0.406 \pm 0.049)P_2(\cos \theta) - (0.049 \pm 0.020)P_4(\cos \theta)$,
- $W_{1565-658}(\theta) = 1 + (0.120 \pm 0.017)P_2(\cos \theta) + (0.010 \pm 0.003)P_4(\cos \theta)$,

and

- $W_{706-1565}(\theta) = 1 - (0.295 \pm 0.063)P_2(\cos \theta)$.

Of the cascades discussed above, only measurements for the 1505-658 keV cascade have been reported previously (table 4.2.3). None of these authors have made a correction for the interference from the 1565-658 keV cascade which is quite significant as is clear from the above analysis. Further, the interference of the 764-1505 keV cascade in the 1505-658 keV cascade has been reduced from about 10% as reported by Munnich et al.\(^7\) to 1.9% in our case, due to the bigger size and better resolution of our detectors.

Spins $3^+$ and $0^+$ have been assigned\(^7\) to the levels 2162 and 658 keV and the ground state of $^{110}$Cd. Therefore the 1505-658 keV cascade follows the spin sequence $3(D,Q)\ 2(Q)\ 0$. A mixing ratio analysis (fig. 4.2.7) of the experimental $A_2$ coefficient in terms of the above spin sequence shows the 1505 keV transition to be either $(19.5 \pm 6.8)\%$ E2 and $(81.5 \pm 6.8)\%$ M1 or $(92.0 \pm 4.8)\%$ E2 and $(8.0 \pm 4.8)\%$ M1. The $A_4$ term does not favour either of the quadrupole admixtures. However, the lower value of the quadrupole fraction
FIG. 4.2.1: ANALYSIS OF THE 1505-658 KEV CASCADE IN TERMS OF SPIN SEQUENCE 3(D, Q) 2(0, 0).

FIG. 4.2.2: ANALYSIS OF THE 1505-658 KEV CASCADE IN TERMS OF THE SPIN SEQUENCE 4(Q, O) 2(Q, O).
viz, (19.5±6.8)% E2 is chosen on the basis of the directional correlation of the 764-1505 keV cascade. The mixing ratio for Y1505 from the above quadrupole admixture is $S_{1505} = 0.49 \pm 0.11$. This value of $S_{1505}$ is higher than the value determined from the angular correlation of the 764-1505 keV cascade. The reversal of the sign of $S_{1505}$ as determined from the 1505-658 and 764-1505 keV cascade is expected because of a change in order of 1505 keV γ-ray in the two cascades.

The 2220 keV level is connected to the 2926 keV level of spin 5+, the 1542 keV level of spin 4+ and the 658 keV level of spin 2+ by the 706, 677, and 1565 keV gamma transitions respectively. These gamma transitions are known to be E2 or M1 + E2. This requires the spin of the 2220 keV level to be 3+ or 4+. Therefore, the possible spin sequences for the 1565-658 keV cascade are (i) 3(Q,0)2(Q,0) or (ii) 4(Q,0)2(Q,0). Assuming spin sequence (i) the theoretical $A_4$ term is expected to be negative for any value of the quadrupole fraction in the 1565 keV transition. This is in contradiction with the definite positive value of the experimental $A_4$ coefficient ($A_4 = 0.010 \pm 0.003$). Therefore, the only other possible spin sequence that could be considered for this cascade is 4(Q,0) 2(Q,0). The theoretical expansion coefficients for such a spin sequence are $A_2 = 0.1020$ and $A_4 = 0.0091$ (assuming a pure E2 character for $Y_{1565}$) which agree fairly well with the observed coefficients for this cascade. Thus we conclude that the only possible spin assignment for the 2220 keV level is 4+. An analysis (fig. 4.2.8) of the observed $A_2$ and $A_4$ coefficients in terms of the spin sequence 4+ (E2, M3)2+ (E2)0+ shows that the 1565 keV transition has less than 0.1% M3 admixture. This is in agreement with our assumption of a pure quadrupole character for $Y_{1565}$ in calculating the theoretical expansion coefficients.
The spin assignment to the 2220 keV level is also checked by the angular correlation study of the 706-1565 keV cascade. Assuming spins $3^+$ or $4^+$ for the 2220 keV level, the two possible spin sequences for this cascade are (i) $5(Q)\,3(D,Q)2$ or (ii) $5(D,Q)\,4(Q)2$. For either spin sequence the value of the theoretical $A_4$ coefficient is either zero or negative. However, the maximum negative value of the theoretical $A_4$ coefficient for spin sequence (i) and (ii) are $-0.0136$ and $-0.0589$ respectively. A comparison of the observed $A_4$ coefficient ($-0.053 \pm 0.021$) with the theoretical values favours the spin sequence $5(D,Q)4(Q)2$ for the 706-1565 keV cascade. This again assigns a $4^+$ character for the 2220 keV level, in agreement with the results of the 1565-658 keV cascade. A mixing ratio analysis (fig. 4.2.9) of the experimental $A_2$ and $A_4$ coefficients for the 706-1565 keV cascade in terms of the spin sequence $5(D,Q)4(Q)2$ shows that the 706 keV transition is $(91.0^{7.0\%}_{9.2\%})E2$ and $(9.0^{7.5\%}_{9.5\%})M1$ with $\Sigma_{706} = 3.18 \pm 1.36$.

### iii) The directional correlation of the 1384-884 keV cascade

This correlation was measured using gates 6(1340-1480)keV and 7(830-938 keV). The solid angle corrected correlation function is

$$W(\theta) = 1 - (0.2708 \pm 0.0073)P_2(\cos \theta) - (0.0092 \pm 0.0084)P_4(\cos \theta).$$

This cascade is free from interfering contributions from other cascades. The reason is that the gamma rays of energies 1476, 1505 and 1565 keV are in coincidence with gamma rays of energies less than or equal to 764 keV. The profile of $\gamma_{764}$ is, however, not included in the gate 7, set at the 884 keV photopeak. Therefore, these results need no further correction. The present coefficients are in good agreement with the results of previous workers (table 4.2.3).

The 1384-884 keV cascade follows the spins sequence $5(D,Q)4(Q)2$. A mixing ratio analysis (fig. 4.2.10) of the observed coefficients in terms
FIG. 4-0: ANALYSIS OF THE 1384-884 KeV CASCADE IN TERMS OF SPIN SEQUENCE $S(D,Q)4(Q)2$

FIG. 4-9: ANALYSIS OF THE 706-1565 KeV CASCADE IN TERMS OF SPIN SEQUENCE $S(D,Q)4(CQ)2$
of this spin sequence shows that \( Y_{1384} \) is \((9.5 \pm 1.0)\% \) E2 and \((90.5 \pm 1.0)\% \) M1 with \( \delta_{1384} = +0.32 \pm 0.02 \).

iv) The directional correlation of the 884-658 keV cascade

The 884-658 keV correlation was measured using gates 8(620-658 keV) and 9(835-884 keV). The solid angle corrected correlation function is

\[
W(\theta) = 1 + (0.0521 \pm 0.0016) P_2(\cos \theta) + (0.0029 \pm 0.0023) P_4(\cos \theta).
\]

This cascade is influenced by all other high energy cascades and needs further corrections. A second correlation with gates 10(1060-1110 keV) and 8 was measured and subtracted from the original correlation. This subtraction corrected the original correlation for contributions due to the coincidences of Compton of higher energy gamma rays under the 884 keV photopeak with the 658 keV gamma ray and the contributions of the 706 and 764 keV gamma radiations under the gate 8. Other corrections were estimated to be small. A least-squares fit of the subtracted data after solid angle corrections gives,

\[
W(\theta) = 1 + (0.0949 \pm 0.0024) P_2(\cos \theta) + (0.0074 \pm 0.0036) P_4(\cos \theta).
\]

The present correlation coefficients are in good agreement with the results of previous investigators (table 4.2.3).

The 884-658 keV cascade follows the spin sequence \( 4(Q,0)2(Q)0^+ \). A mixing ratio analysis of the observed correlation coefficients in terms of the above spin sequence shows \( Y_{884} \) to be pure E2 with \( \delta_{884} = 0.010 \pm 0.005 \) i.e. the octupole admixture in the 884 keV radiation is less than 0.1%.

(v) The directional correlation of the 937-884 keV cascade

This correlation was measured using gates 7(830-938 keV) and 11(884-990 keV). The solid angle corrected correlation function is
This correlation is strongly influenced by the 1384-884 keV cascade. In the gates used for studying this cascade the contribution of the 1384-884 keV cascade was estimated to be $(16.9 \pm 1.2)\%$ using the relative intensity data of Homaga at al. [2]. There was no interference of the 764-1505 keV cascade as the 764 keV gamma ray is not selected in gate 7. Correcting for the 1384-884 keV cascade by using results of section 4.2.5 (iii), the correlation function for the 937-884 keV cascade is,

$$W(\theta) = 1 + (0.0379 \pm 0.0068)P^2 \cos \theta + (0.0088 \pm 0.0044)P^4 \cos \theta. $$

The 937-884 keV cascade follows the spin sequence $6(\Lambda) 4(\Lambda) 2(\Lambda)^7$. The theoretical expansion coefficients for such a sequence are $A_2 = 0.1020$ and $A_4 = 0.0091$, in agreement with the observed coefficients for this cascade. An analysis of the observed coefficients in terms of the above spin sequence and using $S_{934}$ as determined in previous section shows that the 937 keV gamma ray is pure E2 with less than $0.1\%$ M3 admixture.

vi) The directional correlation of the 446-(937)-884 keV cascade

This correlation was measured using gates 7 and 12 (395-455 keV). The solid angle corrected correlation functions is

$$W(\theta) = 1 - (0.122 \pm 0.009)P^2 \cos \theta - (0.043 \pm 0.007)P^4 \cos \theta. $$

This correlation is influenced by the other high energy cascades. The correlation was corrected for coincidences between the Compton distributions of higher energy gamma rays under the 884 and 446 keV photopeaks by measuring a second correlation with the discriminators set on gates 12 and 10 and subtracting it from the original correlation. A least-squares fit of the subtracted data, after solid angle correction yields,

$$W(\theta) = 1 - (0.092 \pm 0.010)P^2 \cos \theta - (0.048 \pm 0.010)P^4 \cos \theta. $$
This correlation still has interfering contributions from the coincidencies of Compton distributions of $^{138}\gamma$ and $^{65}\gamma$ under the 446 keV photopeak with the 884 keV photopeak. From a careful examination of the scintillation spectrum at gate position 12, these contributions were estimated to be $(54.4 \pm 2.2)\%$ due to the 884–658 keV cascade and $(5.4 \pm 2.2)\%$ due to the $^{138}\gamma$–884 keV cascade. The interference from the 446–937 keV cascade was estimated to be less than 0.5\% and was therefore, neglected. The true correlation function for the 446–(937)–884 keV cascade, after accounting for these interferences from the results of section 4.2.5 (iii) and (iv) is found to be:

$$W(\theta) = 1 - (0.322 \pm 0.048)P^2(\cos \theta) - (0.129 \pm 0.038)P^4(\cos \theta).$$

The 446–(937)–884 keV cascade follows the spin sequence $5(D,Q)6(Q)4$ in which the 937 keV intermediate transition between the levels with spins 6 and 4 is unobserved. The experimental correlation coefficients $A_2$ and $A_4$ can be written as:

$$A_k = A_k(446) U_k(937) A_k(884); \ k = 2 \text{ and } 4;$$

where $U_k(937)$ is the correction factor for the unobserved intermediate transition of 937 keV and can be determined from a knowledge of the mixing ratio, multipole order of the intermediate transition and the spins of the levels between which the transition occurs. A simple calculation gives $U_2 = 0.9000$ and $U_4 = 0.6861$.

With these values of $U_k$ and the values of $A_k(884)$ calculated using the mixing ratio of 884 determined in section 4.2.5 (iv), the value of $A_k(446)$ are calculated to be $A_2 = 0.801 \pm 0.120$ and $A_4 = 0.581 \pm 0.172$. A mixing ratio analysis (fig. 4.2.11) of $A_2(446)$ in terms of the spin sequence $5(0,4)6$ yields two values of quadrupole fractions in 446 viz. $Q_1 = 0.097 \pm 0.063$ and $Q_2 = 0.582 \pm 0.058$. An analysis of the $A_4(446)$ shows that the quadrupole
FIG. 4-2.11: ANALYSIS OF THE 446-884 KeV CASCADE IN TERMS OF THE SPIN SEQUENCE 5(D) + (Q) 4(Q) 2

FIG. 4-2.12: DECAY SCHEME OF $^{105}$Nd BASED ON SOME OF THE EARLIER RESULTS & RESULTS OBTAINED IN THE PRESENT STUDY.
4.2.6 Discussion of Results:

The singles spectrum studies of $^{110}\text{Cd}$ suggest the existence of a weak gamma ray of 1760 keV. This transition cannot be accommodated in the presently accepted level scheme of fig. 4.2.1 and needs introduction of a level at 1760 keV. This level may be directly fed by a weak beta group or from higher excited levels notably the 2162 and 2220 keV through other weak transitions namely 437, 477 keV reported by Cork et al.\textsuperscript{3).}

Cookson and Darcey\textsuperscript{19) have studied the energy levels of $^{110}\text{Cd}$ by inelastic proton scattering and have reported levels at 1740, 1790 and 1820 keV besides other levels. The presently reported level at 1760 keV may be identified with the 1740 or 1790 keV levels reported by these authors\textsuperscript{19).}

The sum-coincidence studies suggest the existence of a level at 1720 keV fed by a 200 keV gamma transition from the 2926 keV level. The gamma ray of 499 keV reported by Cork et al.\textsuperscript{3) when subtracted from 2720 keV leads to 2221 keV. This is worthy of note and seems to suggest that the 2720 keV level decays to the 2220 keV level through a 499 keV gamma transition.

A level scheme of $^{110}\text{Cd}$ incorporating the results of the present investigations is given in fig. 4.2.12. From the results of the directional correlation measurements of the 1565-658 keV and 706-1565 keV cascade it has been possible to assign a unique spin 4\textsuperscript{+} to the 2220 keV level.

A spin assignment of 4\textsuperscript{+} to this level has also been favoured by Moragues et al.\textsuperscript{2) on the basis of K-conversion coefficient of the 706 keV gamma ray. However, the errors in the experimental conversion coefficients\textsuperscript{2,6)
being large and the differences between the corresponding theoretical values for M1 and E2 transition being small\(^{13}\), it is difficult to know the mixing ratio or the nature of the transitions on conversion data alone. It has been possible to infer the mixing ratio of some of the transitions in \(^{110}\)Cd from the present angular correlation studies. The results of mixing ratio analysis of the observed \(^\alpha_2\) and \(^\alpha_4\) expansion coefficients in terms of their respective spin sequences are summarized in table 4.2.4. The 446 keV gamma transition between the states with spin 5 and 6 has a dominant E2 character instead of the expected M1 dominant character. Further the 1384 keV and 706 keV gamma rays originating from the 2926 keV (5\(^+)\) level and feeding the first and second 4\(^+\) levels at 1542 and 2220 keV respectively have quite different mixing ratios viz \(\alpha_{1384} = 0.32 \pm 0.02\) and \(\alpha_{706} = 3.18 \pm 1.36\) indicating that a different set of selection rules is valid for the two transitions.

The even-even nucleus \(^{110}\)Cd lies in the spherical mass region. The properties of the low lying states of such nuclei have been described by a collective vibrational model of the nucleus\(^{20,21}\). The model predicts the ratio \(B(E2,2^+\rightarrow 2)/B(E2,2^+\rightarrow 0)\) to be 2. The level structure of \(^{110}\)Cd has been recently studied through Coulomb excitation by Milner et al.\(^{22}\). These authors observed that there is an appreciable magnetic dipole transition between the second 2\(^+\) and the first 2\(^+\) levels in contradiction with the predictions of the model requiring this transition to be pure E2. Further the experimentally measured ratio \(B(E2, 2^+\rightarrow 2)/B(E2,2^+\rightarrow 0) = 1.08 \pm 0.29\) is smaller than the predicted value for this ratio on this model. Therefore, as pointed out by Milner et al.\(^{22}\), a simple vibrational model picture is inadequate to explain the low-lying states of \(^{110}\)Cd.

Another model which has been successful in an interpretation of the level structure of even-A nuclei is the non-axial rotor model of Davydov and coworkers\(^{23-25}\). It is interesting to compare the measured ratios of the
Table 4.2.4: Summary of the mixing ratio analysis for directional correlation data in $^{110}$Cd

<table>
<thead>
<tr>
<th>Cascade (keV)</th>
<th>$A_2$</th>
<th>$A_4$</th>
<th>Possible spin sequence</th>
<th>Multipole admixture(%) and mixing ratio (S')</th>
</tr>
</thead>
<tbody>
<tr>
<td>764-1505</td>
<td>$-0.1736 \pm 0.0089$</td>
<td>$-0.0039 \pm 0.0033$</td>
<td>5(E2)3(M1,E2)2</td>
<td>$\gamma_{1505} : 9.0 \pm 0.8$, 91.0$\pm 1.0$ M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{1505} : 0.32 \pm 0.04$</td>
</tr>
<tr>
<td>1505-658</td>
<td>$-0.406 \pm 0.049$</td>
<td>$-0.049 \pm 0.030$</td>
<td>3(M1 E2)2(E2)0</td>
<td>$\gamma_{1505} : 19.5 \pm 6.8$, 81.5$\pm 6.8$ M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{1505} : 0.49 \pm 0.11$</td>
</tr>
<tr>
<td>1565-658</td>
<td>$+0.120 \pm 0.017$</td>
<td>$+0.010 \pm 0.003$</td>
<td>4(E2,M3)2(E2)0</td>
<td>$\gamma_{1565} : ^{+}100$E2, $\leq 0.1$ M3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{1565} : +0.02 \pm 0.01$</td>
</tr>
<tr>
<td>706-1565</td>
<td>$-0.295 \pm 0.063$</td>
<td>$-0.053 \pm 0.021$</td>
<td>5(M1,E2)4(E2)2</td>
<td>$\gamma_{706} : 91.0$, E2, 9.0, M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-9.5$, E2, 9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{706} : +3.18$</td>
</tr>
<tr>
<td>1384-884</td>
<td>$-0.2706 \pm 0.0073$</td>
<td>$-0.0092 \pm 0.0084$</td>
<td>5(M1,E2)4(E2)2</td>
<td>$\gamma_{1384} : 9.5 \pm 1.0$, E2, 90.5$\pm 1.0$ M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{1384} : +0.32 \pm 0.02$</td>
</tr>
<tr>
<td>884-658</td>
<td>$+0.0949 \pm 0.024$</td>
<td>$+0.004 \pm 0.0036$</td>
<td>4(E2,M3)2(E2)0</td>
<td>$\gamma_{884} : ^{+}100$E2, $\leq 0.1$ M3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{884} : 0.01 \pm 0.005$</td>
</tr>
<tr>
<td>937-884</td>
<td>$+1.101 \pm 0.011$</td>
<td>$+0.013 \pm 0.007$</td>
<td>6(E2,M3)4(E2)2</td>
<td>$\gamma_{937} : ^{+}100$E2, $\leq 0.1$ M3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{937} : 0.00$</td>
</tr>
<tr>
<td>446-(937)</td>
<td>$-0.322 \pm 0.048$</td>
<td>$-0.129 \pm 0.038$</td>
<td>5(M1,E2)6(E2)4(E2)2</td>
<td>$\gamma_{446} : 81.2$, E2, 18.8, M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-8.7$, E2, 18.8, M1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\delta_{446} : -2.68$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$=0.40$</td>
</tr>
</tbody>
</table>
reduced transition probabilities \(^{22}\) with the predictions of this model \(^{23,24}\).

This is done by calculating the non-axiality parameter \(\nu_0\) from the energies of the second and first \(2^+\) excited states. The value of \(\nu_0\) thus obtained is \(26.1^\circ\). This value of \(\nu_0\) is used to calculate the reduced transition probabilities and the following results are obtained:

\[
\frac{B(E2,2^+ \rightarrow 2)}{B(E2,2^+ \rightarrow 0)} = 21.3 \quad \text{and} \quad \frac{B(E2,2^+ \rightarrow 0)}{B(E2,2^+ \rightarrow 0)} = 1.08.
\]

These values are in excellent agreement with the following experimental ratios measured by Milnor et al. \(^{22}\):

\[
\frac{B(E2,2^+ \rightarrow 2)}{B(E2,2^+ \rightarrow 0)} = 24.05 \pm 7.71 \quad \text{and} \quad \frac{B(E2,2^+ \rightarrow 0)}{B(E2,2^+ \rightarrow 0)} = 1.08 \pm 0.29.
\]

The non-axial rotor model also predicts the energy levels of a nucleus as a function of non-axiality parameter \(\nu_0\). The predicted energy levels of \(^{110}\)Cd calculated using \(\nu_0 = 26.1^\circ\) are given along with the experimental values in table 4.2.5. It is noted that the predicted excitation ratios are higher than the experimental values. However, a better agreement with the experiment is obtained if one takes into account the rotation-vibration interaction either on the Mallman model \(^{26}\) or Davydov-Chaban model \(^{25}\). Squares and Aisenberg \(^ {27,28}\) have calculated the level structure of \(^{110}\)Cd on the basis of these models \(^{25,26}\). The results of these authors \(^{27,28}\) are summarized in table 4.2.5. The predictions of the either model are in broad agreement with the experimental level structure of \(^{110}\)Cd.

It may be noticed that the calculations on the basis of Davydov-Chaban model \(^{25}\) give a better fit with the experimental level structure of \(^{110}\)Cd.
Table 4.2.5

Comparison of the level structure of $^{110}$Cd with theoretical predictions.

<table>
<thead>
<tr>
<th></th>
<th>$E_2'/E_2$</th>
<th>$E_4'/E_2$</th>
<th>$E_3/E_2$</th>
<th>$E_6/E_2$</th>
<th>$E_5/E_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
<td>2.24</td>
<td>3.29</td>
<td>3.37</td>
<td>3.77</td>
<td>4.45</td>
</tr>
<tr>
<td><strong>D.F.Model</strong></td>
<td>2.24</td>
<td>2.77</td>
<td>3.24</td>
<td>5.52</td>
<td>5.21</td>
</tr>
<tr>
<td><strong>Mallman</strong></td>
<td>2.24*</td>
<td>2.34*</td>
<td>3.02*</td>
<td>4.67*</td>
<td>3.77*</td>
</tr>
<tr>
<td><strong>D.C.Model</strong></td>
<td>2.17**</td>
<td>2.32**</td>
<td>2.81**</td>
<td>3.91**</td>
<td>3.80**</td>
</tr>
</tbody>
</table>

* From ref. 27.
** From Ref. 28.

This model predicts the second $4^+$ level at 2573 keV which is in fair agreement with the experimentally observed second $4^+$ level at 2220 keV.

From the above discussion it appears that non-adiabatic non-axial rotor model\textsuperscript{25} explains reasonably well the known experimental level structure of $^{110}$Cd.
References


The Decay of $^{124}\text{Sb}$

4.3.1 Introduction

The radioisotope $^{124}\text{Sb}$ decays to $^{124}\text{Te}$ by negaton emission with a half-life of 60 days. Several authors$^1$ have investigated this decay scheme extensively using magnetic and scintillation spectrometers. These investigations led to a generally accepted level scheme of $^{124}\text{Te}$ with excited levels at 603, 1247, 1326, 1901, 1962, 2295, 2693 and 2865 keV (fig. 4.3.1). The decay of $^{124}\text{Sb}$ has been studied by Stelson$^2$ using a Ge(Li) detector in singles and slow-fast coincidence modes together with NaI(Tl) crystals or an anthracene crystal. On the basis of these investigations, Stelson$^2$ reported a number of additional levels at 2038, 2090, 2108, 2183, 2323, 2524 and 2773 keV. Recently Zirnheld and Henck$^3$ have also studied the gamma ray spectrum of $^{124}\text{Sb}$ using Ge(Li) detectors in singles and slow-fast coincidence modes. Of the above mentioned new levels reported by Stelson$^2$, these authors$^3$ confirmed the levels at 2038 and 2773 keV only. They are, however, in agreement with Stelson$^2$ about the absence of levels at 1901 and 2865 keV in $^{124}\text{Te}$.

Spin-parity assignments to some of the levels in $^{124}\text{Te}$ have been attempted on the basis of angular correlation measurements and internal conversion data$^1,2,4-12$, but the results are inconsistent. Rama-Mohan et al.$^7$ have measured the angular correlation of the 1361-603 keV cascade in order to assign a spin to the 1962 keV level. These authors$^7$ seem to have neglected the interference from the strong 1370-(722)-603 keV cascade. Thus the spin assignment 3 for the 1962 keV level as proposed by these authors$^7$ is doubtful. Similarly in the angular correlation measurement of the 967-722 keV cascade, by Rama-Mohan et al.$^7$, the interferences
from the 1370-722 keV cascade and other neighbouring cascades have been neglected, rendering the conclusions based on these measurements as ambiguous.

Dorikens-Vanpraet et al. have measured the angular correlation of a number of cascades in $^{124}$Te. Of the various cascades studied by these workers, the 2260-603 and 1540-722 keV cascades have not been observed by the later workers. On the basis of angular correlation measurements of the 645-603 keV cascade, Dorikens-Vanpraet et al. proposed a spin assignment of $3^+$ for the 1248 keV level. This assignment is in contradiction with the conclusions of other workers and the known systematics of spin-sequences for the nuclei in this mass region. The value of the mixing ratio $\delta$ for the 722 keV transition between the second and first $2^+$ states is also controversial.

An interpretation of the angular correlation measurements of the various gamma ray cascades in $^{124}$Te is made difficult by the presence of significant interfering contributions from neighbouring cascades. Dorikens-Vanpraet et al. have corrected for such contributions using the relative intensity data based on scintillation spectrometers. However, with the availability of the recent relative intensities data from Ge(Li) detectors, these contributions can be estimated more accurately and accounted for.

In view of the above inconsistencies and the more precise information about the intensities of the various gamma rays available from Ge(Li) detector measurements the present investigations were undertaken. The level scheme of $^{124}$Te has been studied using scintillation spectrometers in singles, fast-slow, sum-and sum-peak coincidence modes. The directional correlations of a number of gamma ray cascades have been
studied in order to assign spins and parities to some of the levels and to know the nature of some of the gamma rays in $^{124}$Te. The results of these measurements are presented below.

### 4.3.2 Source preparation

The radioisotope $^{124}$Sb in the form of antimony chloride dissolved in dilute hydrochloric acid was obtained from Bhabha Atomic Research Centre, Bombay, India. A few drops of this active solution were put and dried in a perspex source holder to prepare a strong source. A weak source prepared on cellulose was used for 4$\pi$ sum-peak coincidence studies. For gamma-gamma directional correlation measurements a moderately strong liquid source was prepared in a cylindrical perspex holder with a vertical central cavity of 1.5 mm dia. x 4 mm depth.

### 4.3.3 Singles gamma ray spectrum

The singles gamma ray spectra of $^{124}$Sb were studied using the 3" x 3" NaI(Tl) crystal at a source-to-crystal distance of 40 cm. The spectra were recorded on the RCL 256-channel analyser. The spectra were analysed using the usual 'peeling off' method. Figure 4.3.2 shows a typical analysed spectrum. The relative intensities of the various gamma rays obtained from these spectra, after correcting for absorption in the window of the detector are given in the table 4.3.1, along with the results of previous workers. The present values are in fair agreement with the results of previous workers except for those gamma rays which could not be resolved from other close lying gamma rays. A composite value of intensity is quoted for such gamma rays. It may be remarked that we could not observe a 2260 keV gamma ray in the present spectra. However a weak gamma ray of about 2300 keV was observed in the present spectra. The observed intensity of this gamma ray is not fully accounted for by the
Table 4.3.1
Relative intensities of gamma rays observed in the decay of $^{124}$St.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Nuclear Data</th>
<th>Present study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1) Stelson</td>
<td>2) Zirnheld and Henck 3)</td>
</tr>
<tr>
<td>602.5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>645.1</td>
<td>7.2</td>
<td>$9.5 \pm 1$</td>
</tr>
<tr>
<td>709.0</td>
<td>-</td>
<td>$1.8 \pm 0.3$</td>
</tr>
<tr>
<td>713.3</td>
<td>3.7</td>
<td>$2.8 \pm 0.5$</td>
</tr>
<tr>
<td>722.3</td>
<td>10.5</td>
<td>$12.5 \pm 1$</td>
</tr>
<tr>
<td>790.2</td>
<td>-</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>967.8</td>
<td>2</td>
<td>$2.3 \pm 0.3$</td>
</tr>
<tr>
<td>1044.9</td>
<td>2</td>
<td>$2.0 \pm 0.3$</td>
</tr>
<tr>
<td>1325.5</td>
<td>2</td>
<td>$1.6 \pm 0.3$</td>
</tr>
<tr>
<td>1354.0</td>
<td>1</td>
<td>$1.2 \pm 0.2$</td>
</tr>
<tr>
<td>1368</td>
<td>2.5</td>
<td>$3.0 \pm 0.4$</td>
</tr>
<tr>
<td>1434</td>
<td>2.0</td>
<td>$1.4 \pm 0.2$</td>
</tr>
<tr>
<td>1445</td>
<td>-</td>
<td>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>1483</td>
<td>-</td>
<td>$0.8 \pm 0.2$</td>
</tr>
<tr>
<td>1525</td>
<td>1.7</td>
<td>$0.5 \pm 0.1$</td>
</tr>
<tr>
<td>1690</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>1720</td>
<td>-</td>
<td>$0.15 \pm 0.04$</td>
</tr>
<tr>
<td>1921</td>
<td>-</td>
<td>$0.07 \pm 0.02$</td>
</tr>
<tr>
<td>2040</td>
<td>-</td>
<td>$0.05 \pm 0.01$</td>
</tr>
<tr>
<td>2091</td>
<td>6.3</td>
<td>$6.0 \pm 0.5$</td>
</tr>
<tr>
<td>2103</td>
<td>-</td>
<td>$0.03 \pm 0.03$</td>
</tr>
<tr>
<td>2183</td>
<td>-</td>
<td>$0.030 \pm 0.007$</td>
</tr>
<tr>
<td>2294</td>
<td>-</td>
<td>$0.030 \pm 0.007$</td>
</tr>
<tr>
<td>2682</td>
<td>-</td>
<td>$0.002$</td>
</tr>
<tr>
<td>2694</td>
<td>-</td>
<td>$0.002$</td>
</tr>
</tbody>
</table>
summing of the 603 and 1690 keV gamma rays. Thus the present studies indicate the existence of a weak gamma transition of about 2300 keV.

4.3.4 Gamma-gamma coincidence spectra

Gamma-gamma coincidence measurements were made using a fast-slow coincidence spectrometer (fig. 3.2) having a resolving time $t = 50$ nsec. The source was viewed by two 3" x 3" NaI(Tl) crystals with their axes at 90° to each other and a source-to-crystal distance of 10 cm. The crystals were shielded laterally with graded lead cylinders. A graded Compton shield was used to avoid crystal-to-crystal scattering. For each run the single-channel analyser was set on a principal gamma ray photopeak and the coincidence spectrum recorded on the RCL 256-channel analyser.

Figure 4.3.3 shows the gamma ray spectrum in coincidence with the gate set at the composite photopeak of the 603 and 645 keV gamma rays. The spectrum was analysed by the 'peeling off' method. The analysed spectrum shows peaks at 603, 645, 722, 968, 1045, 1368, 1440, 1525, 1690 and 2090 keV. No indication for gamma rays of energies 1298 and 2260 keV was found in the present spectrum. The 603 keV peak is due to the 645 keV photopeak and the Comptons of higher energy gamma rays falling in the gate. The peaks at 645, 722, 968, 1045, 1368, 1440, 1525, 1690 and 2090 keV confirm the coincidences of these gamma rays with the 603 or 645 keV gamma rays. It may be added that the Compton contributions of higher energy gamma rays in the gate were estimated to be small and needed no correction in the coincidence spectrum.

The gamma ray spectrum coincident with the higher energy half of the 722 keV photopeak is shown in fig. 4.3.4. This gate setting does not contain any contribution from the 645 keV gamma ray. The analysed spectrum shows peaks at 603, 640, 715, 968, 1368 and ~1440 keV in coincidence.
FIG. 4.3.3  GAMMA RAY COINC. SPECTRUM OF $^{124}\text{Sb}$ WITH GATE AT 603 KeV.

FIG. 4.3.4  GAMMA RAY COINC. SPECTRUM OF $^{124}\text{Sb}$ WITH GATE AT 722KeV.
with the gate energy. The peak at 640 keV cannot be completely explained as arising due to the Compton contributions of the 1050 and 1450 keV gamma rays and the photopeak of the 714 keV gamma ray falling in the gate (fig. 4.3.1). This indicates the presence of a gamma ray of about 640 keV in coincidence with the 722 keV transition. This gamma ray can be accommodated between the 1962 and 1326 keV levels.

Similarly the peak at 715 keV is not fully accounted for by the Compton contributions of the 968 and 1368 keV gamma rays (fig. 4.3.2) falling in the gate. This discrepancy is at once explained if the 715 keV gamma ray is in coincidence with the 722 keV gamma ray. This requires the introduction of a level at 2040 keV. This level also accommodates the 1440 keV gamma ray observed in coincidence with the 603 keV gamma ray (fig. 4.3.3).

A weak gamma ray of 1440 keV is also present in the coincidence spectrum of fig. 4.3.4, obtained with the gate set at the higher-energy half of the 722 keV photopeak. The gate does not contain any contribution from the 603 and 645 keV gamma rays. Therefore, this 1440 keV gamma ray cannot be identified with the 1450 keV transition from the 2691 keV level (fig. 4.3.1) or the 1440 keV gamma ray observed in the coincidence spectrum of fig 4.3.3. Thus the 1440 keV gamma ray observed in coincidence with the 722 keV photopeak requires an additional level at 2775 keV. A level at 2775 keV also accommodates the 1525 keV gamma ray observed in coincidence with the gate set at the composite photopeak of the 603 and 645 keV gamma rays (fig. 4.3.3).

Figure 4.3.5 shows the gamma ray spectrum in coincidence with the gate set at the 1368 keV photopeak. This gate setting includes contributions from the 1326, 1354 and 1368 keV gamma rays. Peaks at 603, 640, 722, 968, 1326 and 1368 keV are observed in the coincidence spectrum.
Fig 435: Gamma ray coincidence spectrum of $^{124}$Sb with gate at 1368 KeV.

Fig 436: Zero bias vs. sum-peak coincidence spectrum of $^{124}$Sb.
This spectrum shows that the 1326 and 1368 keV gamma rays are in coincidence with each other. The 1326 and part of the 603 and 722 keV peaks are due to the 1368 keV gamma ray being in the gate whereas the 968, 1368 and part of the 640 and 722 keV peaks are due to the 1326 keV gamma ray being in the gate. The coincidence peak at 603 keV has also contributions from the 1354-603 keV cascade.

Coincidence spectra were also studied with the gates set at 1690 and 2090 keV photoeaks. Both these spectra show coincidence peaks at 603 keV only. The present coincidence study does not support the existence of a 396-1690 keV cascade proposed by Rao et al. from their sum-coincidence spectra.

4.3.5 Sum-peak coincidence spectra

The sum-peak coincidence spectra of $^{124}$Sb were studied using the set-up of fig. 3.4. The two 3" x 3" NaI(Tl) crystals were put in 4-W'-geometry with a weak source of $^{124}$Sb sandwiched between them. The spectra were studied with different biases. Fig. 4.3.6 shows a sum-peak coincidence spectrum with zero bias. The highest sum-peak in this spectrum is at 2730 keV. This peak is due to the de-excitation radiations from the 2693 keV level. The energy of the sum-peak is higher than the actual sum-energy by the expected amount $^{15}$. Fig. 4.3.7 (a) and (b) show the sum-peak coincidence spectra with 680 and 1570 keV biases respectively. The highest sum-peak in either spectrum is again at 2730 keV. No peak corresponding to a 2865 keV level is observed in any of these spectra. This, therefore, indicates the absence of a 2865 keV level in $^{124}$Te.

This conclusion is also supported by the absence of a 2260 keV gamma ray in the coincidence spectrum obtained with a gate set at the 603 keV gamma ray (fig. 4.3.3.).
FIG 4:3 7-4π SUM-PEAK COINC. SPECTRA OF $^{124}$Sb WITH (a) 680 & (b) 1570 KeV BIASES

FIG 4:3 8-ZERO BIAS SUM-PEAK COINC. SPECTRUM. SOURCE DISTANCE = 8 CM.
By raising the bias to 1570 keV the contribution of all cascades in the 2730 keV sum-peak are eliminated and only a cross-over transition could contribute in the sum-peak at 2730 keV. The presence of a 2730 keV sum-peak in the 1570 keV bias spectrum (fig. 4.3.7(b), therefore, indicates the presence of a cross-over transition from the 2693 keV level.

The sum-peak coincidence spectrum of $^{124}$Sb was also studied at a source-to-crystal distance of 8 cm. A moderately strong source of $^{124}$Sb was viewed by the two 3" x 3" NaI(Tl) crystals with their axes at 90° to each other. A graded lead shield was put at 45° to either crystal to avoid crystal-to-crystal scattering. Figure 4.3.8 shows a zero bias sum-peak coincidence spectrum of $^{124}$Sb recorded in this geometry. Sum-peaks at 1248, 1323, ~1460, 2330 and 2730 keV are observed. The sum-peak at about 1460 keV, which cannot be due to a cross-over transition, gives further support to the existence of a 715-722 keV cascade in $^{124}$Te.

4.3.6 Sum-coincidence spectra

The sum-coincidence spectra were recorded with a matched pair of 3" x 3" NaI(Tl) crystals utilizing the set up of fig. 3.3.(b). The two detectors were set at 90° to each other with a source-to-crystal distance of 8 cm. The crystals were laterally shielded with graded lead cylinders. A graded lead shield was put at 45° to the crystals to avoid crystal-to-crystal scattering.

A sum-coincidence spectrum with the sum-gate set at 2693 keV is shown in fig. 4.3.9. The spectrum shows three pairs of coincidence peaks at energies 603-2090, 722-1970 and 1326-1368 keV. The peak at 1970 keV is due to the summing of 1368-603 keV cascade in the display crystal. This spectrum shows that the 2693 keV level de-excites through the 2090-603, 1368-1326 and 1368-722-603 keV cascades.
FIG 4.5: SUM COINC SPECTRUM OF 124SB WITH GATE AT 2293 KEP.

FIG 4.6: SUM COINC SPECTRUM OF 124SB WITH GATE AT 2101 KEP.

ENERGY IN KEP

CHANNEL NUMBER

COUNTS/CHANNEL

COUNTS/CHANNEL

2293
2101
124SB
124SB
A sum-coincidence spectrum with the sum-window set at 2293 keV is shown in fig. 4.3.10. The spectrum shows three pairs of coincidence peaks at energies 603-1690, 968-1325 and 1045-1248 keV. A major portion of the 1248 keV peak is due to the summing of the 645, 603 keV cascading gamma rays in the display crystal. This spectrum confirms the existence of the 1690-603, 968-1325 and 1045-645-603 keV cascade from the 2293 keV level.

4.3.7 The level scheme of $^{124}\text{Te}$

The level scheme of $^{124}\text{Te}$ incorporating the results of present investigations is shown in fig. 4.3.11. The spin assignments are based on directional correlation measurements to be described later in section 4.3.8. The levels at 603, 1248, 1325, 1960, 2293 and 2693 keV are consistent with the results of previous workers (fig. 4.3.1). The levels at 1901 and 2865 keV (fig. 4.3.1) are not supported by our measurements. The various sum-peak coincidence spectra and the gamma-gamma coincidence spectrum with the 603 keV gamma ray in the gate clearly indicate the absence of a 2865 keV level. There is also no indication of a 1298 keV gamma ray in coincidence with the 603 keV gamma ray, indicating the absence of a 1901 keV level.

Present measurements support the existence of levels at 2040 and 2775 keV proposed by Stelson and Zimheld and Honch. The coincidences observed between the 722-715 and 603-1440 keV gamma rays are good evidences for placing a level at 2040 keV. The coincidences observed between the 722 and 1440 and 645 and 1525 keV gamma rays indicate a level at 2775 keV.

A weak cross-over transition from the 2693 keV level is indicated from the 1570 keV bias sum-peak coincidence spectrum studied in 4.
FIG-43-II: DECAY SCHEME OF $^{124}\text{Sb}$ BASED ON RESULTS OF EARLIER WORKERS & PRESENT WORK

FIG-43-I: GAMMA RAY SPECTRUM OF $^{124}\text{Sb}$. SOURCE DISTANCE: 14 cm.
geometry. A cross-over transition from the 2293 keV level is indicated from the singles spectrum. A transition between the 1960 and 1325 keV level is confirmed by the observed coincidences between the 722-640 keV gamma rays.

4.3.8 Directional correlation measurements

The directional correlations were measured for nine gamma ray cascades in $^{124}$Te. Two 3" x 3" NaI(Tl) crystals were used in these measurements. These detectors were surrounded by cylindrical graded lead absorbers and had graded lead cones over the front of each to avoid crystal-to-crystal scattering. The source was in liquid form and was symmetrically located 14 cm from each crystal at the point of intersection of the axes of the two crystals. The source could be centered within less than 0.8° variation in the singles rate of the movable detector at different angular positions. The coincidence counts were recorded at seven angles between 90° to 180° at intervals of 15° each. The true-to-chance coincidence ratio was about 10 : 1 for all cascades studied. The total number of true coincidence counts collected were more than 50,000 for strong cascades, and about 10,000 in case of weak cascades. All the correlation functions were obtained by a least-squares analysis and were corrected for finite geometry of the crystals using the correction factors calculated by Yates. The interfering contributions of the neighbouring cascades were estimated using a weighted average of the relative intensity data of Stelson and Zirnheld and Henck. The errors quoted in the correlation coefficients include statistical errors and those resulting from corrections for interfering cascades.

In the analysis of angular correlation functions to obtain spin sequences and mixing ratios the tables of Taylor and McPherson and the method of Arns and Wiedenbeck were used.
A gamma ray scintillation spectrum of $^{123}$Sb obtained with the $3'' \times 3''$ NaI(Tl) crystal with a source-to-crystal distance of 14 cm is shown in fig. 4.3.12. The spectrum was analysed using the usual 'peeling off' method. The peak at 2300 keV is mainly due to the summing of the 1690-603 keV cascade in the crystal. The gates used for the various directional correlation measurements are shown in this figure. These positions were chosen to eliminate or minimize the interference from the neighbouring cascades. In some measurements the gates were set on the sloping portions of the photo-peaks. In such cases the counting rates are sensitive to even small shifts in pulse-heights. To overcome this difficulty the counting period at each angle was decreased and the coincidences were collected in a larger number of sweeps than in other measurements.

4.3.8 (1) The 2090-603 keV correlation

The 2090-603 keV correlation was measured using gates 1 and 2. The measured correlation function after solid angle correction is

$$W(\theta) = 1 - (0.064 \pm 0.006)P_2(\cos \theta) - (0.004 \pm 0.002)P_4(\cos \theta).$$

The present correlation coefficients are in good agreement with the results of the previous workers (table 4.3.2).

The spins and parities of the ground and first excited states of even-even nucleus $^{124}$Te are $0^+$ and $2^+$ respectively. The 222 keV beta group from the $3^-$ ground state of $^{124}$Sb and feeding the 2693 keV level has a value of $\log f_t = 6.9^{(2)}$. This $\log f_t$ value classifies the beta group as either of allowed or non-unique first forbidden type. Therefore, the probable spin values for the 2693 keV level are 2, 3 and 4. The 2090 keV transition has been classified as E1 on the basis of internal pairs produced by it. Therefore, the 2090-603 keV cascade follows the spin
Table 4.3.2
Summary of the results on angular correlation measurements in $^{124}\text{Te}$

<table>
<thead>
<tr>
<th>Cascade (KeV)</th>
<th>Reference</th>
<th>$A_2$</th>
<th>$A_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2090-603$</td>
<td>Lindqvist et al. (4)</td>
<td>-0.034±0.006</td>
<td>+0.007±0.012</td>
</tr>
<tr>
<td></td>
<td>Hayashi (5)</td>
<td>-0.052±0.006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weitkamp (6)</td>
<td>-0.053±0.005</td>
<td>+0.006±0.005</td>
</tr>
<tr>
<td></td>
<td>Rama Mohan et al. (7)</td>
<td>-0.042±0.006</td>
<td>+0.006±0.006</td>
</tr>
<tr>
<td></td>
<td>Dorikens-Vanpraet et al. (8)</td>
<td>-0.052±0.012</td>
<td>+0.037±0.018</td>
</tr>
<tr>
<td></td>
<td>Present study</td>
<td>-0.064±0.006</td>
<td>-0.004±0.002</td>
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<tr>
<td>$1690-603$</td>
<td>Lindqvist et al. (4)</td>
<td>-0.063±0.003</td>
<td>+0.008±0.008</td>
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<td>Hayashi (5)</td>
<td>-0.064±0.008</td>
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<tr>
<td></td>
<td>Rama Mohan et al. (7)</td>
<td>-0.059±0.0072</td>
<td>+0.0082±0.0048</td>
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<td>-0.009±0.006</td>
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<tr>
<td></td>
<td>Meder et al. (9)</td>
<td>-0.078±0.005</td>
<td>-0.007±0.005</td>
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<td></td>
<td>Stelson (2)</td>
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<td></td>
<td>Present study</td>
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<td>$1368-1326$</td>
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<tr>
<td>$1368-722$</td>
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<td>-0.043±0.008</td>
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<td></td>
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<td>+0.048±0.007</td>
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<td>$645-603$</td>
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<td>-0.020±0.007</td>
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<td>Glaubman et al. (10)</td>
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<tr>
<td>$1368-603$</td>
<td>Lindqvist et al. (4)</td>
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<td>-0.001±0.007</td>
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<tr>
<td>$722-603$</td>
<td>Glaubman et al. (10)</td>
<td>+0.128±0.007</td>
<td>+0.24±0.09</td>
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<td>+0.03±0.007</td>
<td>+0.13±0.01</td>
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<td></td>
<td>Stelson (2)</td>
<td>+0.14±0.03</td>
<td>+0.26±0.04</td>
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<td></td>
<td>Present study</td>
<td>+0.12±0.010</td>
<td>+0.23±0.012</td>
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sequence either (i) $2(1,2)2(2)0$ or (ii) $3(1,2)2(2)0$. The observed $a_2$
coefficient appears to be consistent with the sequence (i) only with a
quadrupole admixture of either $\sim 15.5\%$ or $\sim 100\%$ in the 2090 keV tran-
sition. The theoretical values of the $a_4$ coefficient for spin sequence
(i) for the above two values of the quadrupole admixtures are $+0.051$ and
$+0.327$ respectively. Both of these values are incompatible with the
experimental $a_4 = -(0.004 \pm 0.002)$, which is nearly zero. Therefore,
the only spin sequence that could be assigned to this cascade is $3(1,2)
2(2)0$. A mixing ratio analysis of the observed correlation coefficients in
terms of the above spin sequence shows the 2090 keV transition to be pure
$E1$ with $\delta_{2090} = -(0.012 \pm 0.007)$ i.e. the $M2$ admixture in the 2090 keV
radiation is less than 0.04%.

4.3.8(c) The 1690-603 keV correlation

The 1690-603 keV correlation was measured using gates 2 and 3.
The measured correlation function after solid angle correction is,

$$W(\theta) = 1 - (0.064 \pm 0.003)P_2(\cos \theta) - (0.005 \pm 0.003)P_4(\cos \theta).$$

The interference from the 2090-603 keV cascade in this correlation
is estimated to be less than 1\% and was, therefore, neglected. The present
correlation coefficients are in good agreement with the results of the
previous workers (table 4.3.2).

The 2293 keV level has been assigned spin-parity $3^-$ on the basis
of the log $ft$ value of the 622 keV beta group feeding the level, a pure
$E1$ nature of the 1690 keV gamma ray and an absence of a strong cross-over
transition from this level. Therefore, the 1690-603 keV cascade follows
the spin sequence $3(1,2)2(2)0$. A mixing ratio analysis of the observed
correlation coefficients in terms of the above spin sequence shows the
1690 keV transition to be pure $E1$ with $\delta_{1690} = -(0.012 \pm 0.005)$ i.e.
4.3.8(3) The 1368-1326 keV correlation

The 1368-1326 keV correlation was measured with both the channels positioned on the 1326 and 1368 keV composite photopeak (gate 4). A least-squares fit of the data after solid angle correction yields:

\[ W(\theta) = 1 - (0.066 \pm 0.010)P_2(\cos \theta) + (0.004 \pm 0.003)P_4(\cos \theta). \]

This cascade contains \( \leq 3\% \) interference from the 1440-1326 keV cascade. No correction could be applied for this interference because the correlation function for the 1440-1326 keV cascade is not known.

The 1325 keV level is fed by a beta group with a value of \( \log ft = 10.2 \). This classifies the beta group as either of allowed or 'first-forbidden' type\(^\text{21}\). The 722 keV gamma transition connecting the 1325 keV level of the \( 2^+ \) first excited level is known to be of M1+E2 multipolarity\(^8\). The 1325 keV level, therefore, may be assigned spin-parities \( 2^+ \) or \( 3^+ \). The presence of a fairly strong cross-over transition\(^2,3\) from this level to the ground state rejects the latter assignment. Therefore, we conclude that the 1325 keV level has spin and parity \( 2^+ \). Thus, the 1368-1326 keV cascade follows the spin sequence \( 3(1,2)2(2)0 \). A mixing ratio analysis of the observed correlation coefficients in terms of this spin sequence shows the 1368 keV transition to be pure E1 with \( S_{1368} = -(0.01 \pm 0.015) \); i.e., the M2 admixture in the 1368 keV transition is less than 0.07%.

4.3.8 (4) The 1368-722 keV correlation

The 1368-722 keV correlation was measured using gate 5 accepting the lower-energy half of the 1368 keV photopeak and gate 6 set on the 722 keV photopeak. The measured correlation function after solid angle correction is,
This correlation does not contain any interference from the 1354-603, 1368-(722)-603 keV cascades as the profile of Y 603 is not included in gate 6. Interferences from the 715-1326, 1440-722 and 1368-1326 keV cascades were estimated using the recent relative intensity data\textsuperscript{2,3} and the gate position 6. These interferences were estimated to be 0.5%, 0.2% and 2% for the 715-1326, 1440-722 and 1368-1326 keV cascades respectively. Correcting for the interference from the 1368-1326 keV cascade from the results of section 4.3.8(3) and neglecting other interfering contributions the correlation function for the 1368-722 keV cascade is found to be,

\[ W(\theta) = 1 + (0.046 \pm 0.006)p^2 (\cos \theta) + (0.005 \pm 0.006)p^4 (\cos \theta). \]

The present correlation coefficient \( \lambda_2 \) has about the same magnitude but opposite sign to that reported by Dorikens-Vanpraet et al. (table 4.3*3).

The 2293, 1325 and 603 keV levels have been discussed to have spins-parities 3\(^{-}\), 2\(^{+}\) and 2\(^{+}\) respectively (refer section 4.3.8(2),(3)). The 1368-1326 keV correlation (section 4.3.8(3) shows the 1368 keV transition to be pure El. Therefore, the 1368-722 keV cascade follows the spin sequence 3(1)2(1,2).2.

A mixing ratio analysis of the observed correlation coefficients in terms of the spin sequence shows that the 722 keV gamma transition has either \( \delta_722 = -(0.32 \pm 0.16) \) or \( \delta_722 = -(3.6 \pm 1.2) \). The \( \lambda_4 \) term does not favour the either mixing ratio. The K-shell conversion coefficient of the 722 keV transition because of the large uncertainty in the reported values is not helpful in deciding the mixing ratio of the 722 keV.
However, the value \( S_{722} = -3.6^{+1.2}_{-0.8} \) can be selected as being consistent with the results of Glaubman and Oberholtzer\(^{10}\), Stelson\(^{2}\) and Paul\(^{11}\). This choice of mixing ratio \( S = 3.6^{+1.2}_{-0.8} \) is also supported by the known systematics\(^{22}\) of the mixing ratios of the \( 2^+ \rightarrow 2^+ \) transitions between the second and first \( 2^+ \) excited states for even nuclei in this mass region. Therefore, the 722 keV transition is \( (92.8^{+2.7}_{-5.1})^\% E2 \) and \( (7.2^{+2.7}_{-5.1})^\% M1 \). The sign of \( S_{722} \) as presently determined is opposite to that quoted by Stelson\(^{2}\) and Glaubman and Oberholtzer\(^{10}\) due to the fact that in their case \( S_{722} \) was determined from the 722-603 keV cascade in which \( \gamma \) 722 is the first transition, whereas in our case it is determined from the 1368-722 keV cascade in which \( \gamma \) 722 is the second transition. Therefore, a reversal of the sign of mixing ratio is expected (refer chap. 2).

4.3.8(5) The 968-1326 keV correlation

The 968-1326 keV correlation was measured using gates 4 and 7. The solid angle corrected correlation function is,

\[
W(\theta) = 1 - (0.065 \pm 0.015)P_2 (\cos \theta) + (0.003 \pm 0.002)P_4 (\cos \theta).
\]

This correlation has interference from the 1368-1326 keV cascade. An analysis of the gate positions and the relative intensity data\(^{2,3}\) shows this interference to be \( (30.5 \pm 6)^\% \). Interference from the 1440-1326 keV cascade was estimated to be small and was therefore neglected. Correcting for the interference of the 1368-1326 keV cascade from the results of section 4.3.8(3), the correlation function for the 968-1326 keV cascade is

\[
W(\theta) = 1 - (0.065 \pm 0.023)P_2 (\cos \theta) + (0.003 \pm 0.004)P_4 (\cos \theta).
\]
The 2293, 1325 keV and the ground state of $^{125}$Te are having spins $3^-$, $2^+$ and $2^+$ respectively (refer section 4.3.8 (2) and (3)). Therefore, the 968-1326 keV cascade follows the spin sequence $3(1,2)2(2)0$. A mixing ratio analysis of the observed correlation coefficients in terms of the above spin sequence shows that the 968 keV transition has a mixing ratio $\Delta 968 = -0.010 \pm 0.030$, i.e. the 968 keV transition is pure $E1$ with less than 0.2% $M2$ admixture.

4.3.8(6) The 968-722 keV correlation

The 968-722 keV cascade was measured using gates 7 and 8. The measured correlation function after solid angle correction is,

$$W(\theta) = 1 + (0.025 \pm 0.004)P_2(\cos \theta) + (0.009 \pm 0.008)P_4(\cos \theta).$$

This correlation is influenced by the interfering contributions from the 1368-1326, 1368-722, 968-1326 and 1440-1326 keV cascades. There is no interference from the 1045-645 keV cascade as the profile of $\gamma 645$ is not included in gate 8. The correlation was corrected for the contributions of the 1368-1326, 1368-722 and 1440-722 keV cascades by measuring a second correlation with the discriminators set on gates 8 and 9 and subtracting it from the first correlation. A least-squares fit of the subtracted data after solid angle corrections yields,

$$W(\theta) = 1 + (0.036 \pm 0.006)P_2(\cos \theta) + (0.004 \pm 0.008)P_4(\cos \theta).$$

This correlation still has interfering contributions from the 968-1326 keV cascade. A careful examination of the gates used and the relative intensity data shows that this interference is $(10.4 \pm 1.5)\%$. Correcting for this interference from the results of section 4.3.8 (5), the correlation function for the 968-722 keV cascade is found to be

$$W(\theta) = 1 + (0.048 \pm 0.008)P_2(\cos \theta) + (0.0 \pm 0.009)P_4(\cos \theta).$$
The 2293, 1325 and 603 keV levels have been discussed in earlier sections to have characters $3^-$, $2^+$ and $2^+$ respectively. The 968-1326 keV correlation (section 4.3.8(5)) shows the 968 keV transition to be almost pure $E1$. Therefore the 968-722 keV cascade follows the spin sequence $3(1)2(1,2)2$. A mixing ratio analysis of the observed correlation coefficients in terms of the spin sequence $3(1)2(1,2)2$ shows that the 722 keV transition has mixing ratio either $\mathcal{S}_{722} = (0.82 \pm 0.20)$ or $\mathcal{S}_{722} = -(3.6 \pm 0.5)$. The latter value of $\mathcal{S}_{722}$ is selected on the basis of arguments given in section 4.3.8(4).

4.3.8(7) The 645-603 keV correlation:

The 645-603 keV correlation was measured using gates 10 and 11, the two gates accepting the lower-energy half and higher-energy half of the 603 keV and 645 keV photopeaks respectively. The measured correlation function after solid angle correction is,

$$ W(\theta) = 1 + (0.087 \pm 0.006)P_2(\cos \theta) + (0.032 \pm 0.015)P_4(\cos \theta). $$

This correlation is influenced by all other high energy cascades and needs further corrections. A second correlation with gates 10 and 12 was measured and subtracted from the first correlation. The position of gate 12 was selected to have contribution from $\gamma_{722}$ in this gate, equal to that in gate 10. This subtraction corrects the correlation for coincidences between the Compton distribution of higher energy gamma rays under the 645 keV photopeak with the 603 keV transition. Other corrections were estimated to be small.

A least-squares' fit of the subtracted data after solid angle correction gives;

$$ W(\theta) = 1 + (0.092 \pm 0.008)P_2(\cos \theta) + (0.030 \pm 0.018)P_4(\cos \theta). $$
The present correlation coefficients are in agreement with those reported by earlier workers except Dorikens-Vanperet et al. (table 4.3.3.).

The 645-603 keV cascade is between the 1248, 603 keV levels and the ground state of $^{124}\text{Te}$. The 1668 keV beta group from the $3^-$ ground state of $^{124}\text{Sb}$ and feeding the 1248 keV level has a value of log ft = 10.5 $^2$. This classifies the 1668 keV beta group as either of allowed or first forbidden nature. Therefore, the probable spin assignments for the 1248 keV level are 1, 2, 3, 4 or 5. The absence of a cross-over transition from the 1248 to be ground state of $^{124}\text{Te}$, rules out spins 1 and 2 as possible assignments for the 1248 keV level. The 645 keV gamma ray from the 1248 keV level to the $2^+$ first excited state is of multipolarity E2 or M1 + E2, if its K-conversion coefficient is compared with the theoretical values taken from the tables of Hager and Seltzer. Such a nature of the 645 keV transition rules out 5 as a possible assignment for the 1248 keV level. Consequently, there are two possible spin sequences for the 645-603 keV cascade, namely (i) 3(1,2)2(2)0 or 4(2,3)2(2)0. The observed $A_2$ coefficient appears to be consistent with the sequence (i) only with a quadrupole admixture in the 645 keV transition of either $\sim 4.6\%$ or $\sim 85.2\%$. However, in both these cascades the finite positive value (0.030 ± 0.013) of the observed $A_4$ coefficient cannot be accounted for, since the spin sequence (i) requires $A_4 \leq 0$ for any value of quadrupole admixture. Therefore, the only possible spin sequence that could be assigned to this cascade is 4(2,3)2(2)0.

The theoretical correlation coefficients for such a spin sequence are $A_2 = 0.1020$ and $A_4 = 0.0091$ (if one assumes a pure E2 character for the 645 keV transition) which agree fairly well with the observed correlation.
coefficients. An analysis of the observed correlation coefficients in terms of the spin sequence $4(2,3)2(2)0$ shows that the 645 keV transition has a mixing ratio $\delta_{645} = +0.017 \pm 0.013$, i.e. the 645 keV transition is pure E2 with less than 0.1% M3 admixture.

4.3.8(8) The 1354-603 keV correlation

The 1354-603 keV correlation was measured using gates 4 and 10. The measured correlation function after solid angle correction is,

$$W(\theta) = 1 - (0.042 \pm 0.003)P_2(\cos \theta) + (0.010 \pm 0.003)P_4(\cos \theta).$$

This correlation is strongly influenced by the other high-energy cascades. In the gate positions used for studying this correlation, the contributions of the various cascades, estimated using the weighted average of the relative intensity data of Stelson and Zirnheld and Henck, are found to be,

- 1690 - 603 keV cascade (69.8 ± 4.9)%
- 2090 - 603 keV cascade (7.2 ± 0.4)%
- 1368 - (722) - 603 keV cascade (15.5 ± 1.5)%
- 1354 - 603 keV cascade (6.7 ± 0.6)%

and less than 1% of other perturbing cascades.

The 1368-(722)-603 keV cascade is placed between the 2693, 1325, 603 keV levels and the ground state of $^{124}\text{Te}$. These levels have spins $3^-, 2^+, 2^+$ and $0^+$ respectively. The 1368 keV transition has been shown to be pure E1 (section 4.3.8(3)) and the 603 keV transition is known to be pure E2\(^{-1}\). The mixing ratio of the 722 keV unobserved intermediate transition has been measured to be $\delta_{722} = -(3.6^{+1.2}_{-0.8})$ (section 4.3.8(4)). Therefore, the 1368-(722)-603 keV cascade follows the spin sequence $3(1)2(1,2)2(2)0$. From the known nature of the various transitions, one can calculate the expected correlation coefficients for the 1368-(722)-603
keV cascade using eqns. 2.12, 2.13 and 2.8. A simple calculation gives
\[ A_2 = 0.012 \pm 0.001 \] and \[ A_4 = 0. \]

Correcting for the contributions of the 2090-603 and 1690-603 keV cascades from the results of section 4.3.8(1) and (2) and for the 1368-(722)-603 keV cascade from the calculated coefficients given above, the correlation function for the 1354-603 keV cascade is found to be,
\[ W(\theta) = 1 + (0.119 \pm 0.017)P_2(\cos \theta) + (0.035 \pm 0.005)P_4(\cos \theta). \]

The 1354-603 keV cascade is placed between the 1960, 603 keV levels and the ground state of \(_{124}^{212}\text{Te}\). The 1960 keV level is fed by a 959 keV beta group from the 3\(^{-}\) ground state of \(_{124}^{212}\text{Sb}\)\(^{2}\). This beta group has a value of \(\log f_t = 9.6\)\(^2\) and can be classified as either of 'allowed' or 'first-forbidden' type\(^{21}\). Therefore, the probable spin values for the 1960 keV level are 1, 2, 3, 4 or 5. The absence of a cross-over transition from the 1960 keV level to the ground state rules out spins 1 and 2 as possible assignments for the 1960 keV level. Consequently, there are three possible spin sequences for the 1354-603 keV cascade namely (i) 3(1,2)2(2)0, (ii) 4(2,3)2(2)0, and (iii) 5(3,4)2(2)0. The spin sequence (i) requires the \(A_4\) term to be zero or negative for all values of the mixing ratio of the 1354 keV gamma ray. This is incompatible with the definite positive value of the observed \(A_4\) coefficient and hence spin sequence (i) is ruled out. The observed correlation coefficients appear to be consistent with the sequence (iii) only with a mixing ratio \(\delta_{1354} \approx 0.11\) for the 1354 keV transition. From this value of the mixing ratio of the 1354 keV transition and its branching ratio determined from the recent relative intensity data\(^{2,3}\), the lifetime of the 1960 keV level can be estimated on the single particle model\(^{24}\) for a \(L = 4\) multipolarity of the 1354 keV transition. From these
considerations, the life-time of the 1960 keV level is estimated to be $\sim 0.5 \times 10^{-3}$ sec. The 959 keV beta group is, however, to be in prompt coincidence with the 1354 keV gamma ray from the 1960 keV. Thus the spin-sequence (iii) is also ruled out and the only possible spin sequence that could be assigned to the 1354-603 keV cascade is $4(2,3)2(2)0$. The 712 keV gamma ray between the 1960 and 1243 keV levels is classified as $E2$ (or less probably $M1 + E2$) on the basis of its $K$-conversion coefficient and the corresponding theoretical values taken from the tables of Hager and Seltzer. Therefore, the 1960 keV level has a positive parity. The 1354 keV radiation is then of multipolarity $E2 + M3$. A mixing ratio analysis of the observed correlation coefficients of the 1354-603 keV cascade in terms of the spin sequence $4(E2,M3)2(E2)0$ show that the 1354 keV transition has a mixing ratio $-0.16 < S_{1354} < 0.09$, i.e., the $M3$ admixture in the 1354 keV radiation is less than 2.5%. 

4.3.8(9) The 715-(722)-603 keV correlation

The 715-(722)-603 keV correlation was measured using gates 3 and 10. The measured correlation function after solid angle correction is given by

$$W(\theta) = 1 + (0.090 \pm 0.004)P_2(\cos \theta) + (0.131 \pm 0.006)P_4(\cos \theta).$$

This correlation is influenced by the other high-energy cascades and needs corrections. A second correlation with gates 10 and 13 was measured and subtracted from the original correlation. This subtraction corrects the correlation for coincidences between the Compton distribution of higher-energy gamma rays under the 722 keV photopeak with the 603 keV transition. The width of gate 13 was adjusted to have about the same contributions from $\gamma 968$ and $\gamma 1045$ in the two gates 8 and 13.
A least-squares fit of the subtracted data yields after solid angle corrections:

$$W(\theta) = 1 + (0.128 \pm 0.010)P_2(\cos \theta) + (0.235 \pm 0.012)P_4(\cos \theta).$$

This correlation contains contributions from the following cascades:

1. $722-603$ keV cascade
2. $715-(722)-603$ keV cascade
3. $710-(645)-603$ keV cascade
4. $792-(645)-603$ keV cascade

The contributions from $710-645$, $792-645$ and $715-722$ keV cascades are negligibly small, as gate 10 is positioned on the valley of the $645$ keV gamma ray. An analysis of the gate positions and the relative intensity data shows that the contributions for various cascades are:

1. $722-603$ keV cascade = $74.9 \pm 7.7\%$
2. $715-(722)-603$ keV cascade = $15.8 \pm 3.1\%$
3. $710-(645)-603$ keV cascade = $9.4 \pm 1.9\%$
4. $792-(645)-603$ keV cascade $\leq 2\%$.

The $722-603$ keV cascade follows the spin sequence $2(1,2)2(2)0$. The correlation coefficients for this cascade can be calculated from the known mixing ratio of the $722$ keV transition $\delta_{722} = (3.6^{1.2}_{-0.8})$. It should be remembered that the sign of $\delta_{722}$ in the present case is positive, because of reversal of order of $\gamma_{722}$ in this cascade compared to the $1368-722$ keV cascade. A simple calculation gives for the correlation coefficients of the $722-603$ keV cascade:

$$A_2 = 0.136 \pm 0.022$$ and $$A_4 = 0.303 \pm 0.136$$

The $712-(645)-603$ keV cascades follows the spin sequence $4(2)4(2)2(2)0$ in which the $645$ keV intermediate transition is unobserved. The expected correlation coefficients for such a cascade are:

$$A_2 = -0.118$$ and $$A_4 = +0.152$$
Correcting for the 722-603 and 710-(645)-603 keV and neglecting the contributions of the 792-(645)-603 keV cascade, the true correlation coefficients for the 715-(722)-603 keV cascade are found to be,

\[ A_2 = 0.222 \pm 0.140 \quad A_4 = -0.032 \pm 0.664 \]

The 715-(722)-603 keV cascade is between the levels 2040, 1325, 603 keV and the ground state of \(^{124}\text{Te}\). The 2040 keV level is fed by a 870 keV keV beta group having a value of \(\log ft = 9.3^2\). This beta group can be classified as either of allowed or first forbidden type. On this basis, the probable spin values for the 2040 keV level are 1, 2, 3, 4 or 5. The spins 4 and 5 are excluded because of the presence of a cross-over transition to ground state. The spin assignment 4 is also excluded because it requires the correlation coefficients (spin sequence \(4(2)2(1,2)2(2)0\)) to be \(A_2 = -0.017\) and \(A_4 = +0.002\), which are in contradiction with the experimental results. Spin assignments 1, 2 or 3 require the 715 keV transition to be an admixture of dipole-quadrupole radiations. A proper choice of the mixing ratio of the 715 keV transition can yield values of the theoretical correlation coefficients compatible with the experimental \(A_2\) correlation coefficients for any one of the three assignments. Thus any of the three spin assignments 1, 2 or 3 is compatible with the present measurements.

4.3.9 Summary of the angular correlation measurements and the resulting spin assignments and mixing ratios

From the results of directional correlation measurements of the 645-603 and 1354-603 keV cascades it has been possible to assign spin and parities \(4^+\) to the 1248 and 1960 keV levels. On the basis of the 715-(722)-603 keV cascade it has been possible to limit the possible spin assignments to the 2040 keV level to 1, 2 or 3. The results of
present measurements are summarized in table 4.3.3. From the present measurements it has not been possible to make spin assignments to the 2040 and 2775 keV l.v.'s. Directional correlation measurements of the 1525-645, 1440-722 and 1440-1326 keV cascades and 715-722 keV cascade using NaI(Tl) crystal with a Ge(Li) detector, can help make these assignments.

4.3.10 Discussion

The even-even vibrational nuclei are characterised by a triplet of quadrupole vibrational states with spins $0^+$, $2^+$ and $4^+$ at an excitation energy twice that of the first state. (We denote by $2^+$ the second $2^+$ state). In these nuclei $2^+ \rightarrow 0^+$, $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$ and the E2 part of the $2^+ \rightarrow 2^+$ transitions are all enhanced and the M1 part of the $2^+ \rightarrow 2^+$ transitions is retarded with respect to the single particle estimates. The spins and parities of the first four excited states in $^{124}$Te, as discussed below, suggest that this nucleus can be considered as a vibrational nucleus.

The ratio of the excitation energies of the second and the first $2^+$ state is 2.2. This value is in fair agreement with the predicted value 2.00 and is the same as the average experimental value 2.2 observed for other vibrational nuclei.

It is instructive to compare the experimental transition probabilities with the corresponding single particle estimates. Akkerman et al. have measured the mean-life of the 603 keV level to be $(6.3 \pm 0.3)$ psec, by resonance scattering method. A comparison of the experimental and single-particle transition probabilities shows that the 603 keV E2 transition is enhanced by a factor of about 44 over single particle estimates.
### Table 4.3.3
Summary of the mixing ratio analysis of the directional correlation data in $^{124}$Te.

<table>
<thead>
<tr>
<th>Cascade (keV)</th>
<th>$A_2$</th>
<th>$A_4$</th>
<th>Possible spin sequence</th>
<th>Multipole admixture (%) and Mixing ratio($\delta$)</th>
</tr>
</thead>
</table>
| 2090-603     | -0.064| -0.004| $3^+(E_1,M_2)2^+(E_2)0^+$ | $2090: 100E_1, \leq 0.04M_2$  
$2090: \leq 0.012, 0.007$ |
| 1690-603     | -0.064| -0.005| $3^+(E_1,M_2)2^+(E_2)0^+$ | $1690: 100E_1, \leq 0.03M_2$  
$1690: \leq 0.012, 0.005$ |
| 1368-1326    | -0.068| +0.004| $3^+(E_1,M_2)2^+(E_2)0^+$ | $1368: 100E_1, \leq 0.07M_2$  
$1368: \leq 0.010, 0.015$ |
| 1368-722     | +0.048| +0.005| $3^+(E_1)2^+(M_1,E_2)2^+$ | $722 : 7.2^2E_1M_1, 92.8^2E_2$  
$722 : -3.6, 1.2, -0.8$ |
| 968-1326     | -0.065| +0.003| $3^+(E_1,M_2)2^+(E_2)0^+$ | $968: 100E_1, \leq 0.2M_2$  
$968: \leq 0.015, 0.030$ |
| 968-722      | +0.048| 0     | $3^+(E_1)2^+(M_1,E_2)2^+$ | $722 : -7.2M_1, -92.8E_2$  
$722 : -3.6, 1.5, -1.0$ |
| 645-603      | +0.092| +0.030| $4^+(E_2,M_3)2^+(E_2)0^+$ | $645: 100E_2, \leq 0.1M_3$  
$645: \leq 0.017, 0.013$ |
| 1354-603     | +0.119| +0.015| $4^+(E_2,M_3)2^+(E_2)0^+$ | $1354: 97.5E_2, \leq 2.5M_3$  
$1354: -0.15, < 0.09$ |
| 715-722      | +0.222| -0.032| Only spins 1,2,3 are possible for the 2040 keV level.  
| 715-603      | +0.150| +0.064|                                      |
The half-life of the 1325 keV level is known to be 0.6 ps eV\(^2\). Using a weighted average of the relative intensity data\(^2,3\) and the presently determined mixing ratio of the 722 keV transition, the experimental transition probabilities of the M1 and E2 part of the 722 keV transition can be calculated and compared with single particle estimates\(^2,4\) to get the enhancement or hinderance factors. The results of these calculations are given below:

<table>
<thead>
<tr>
<th>Transition Probabilities of the 722 keV transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>E2</td>
</tr>
</tbody>
</table>

These calculations show that the E2 part of the 722 keV transition is enhanced by a factor of \(101 \pm 10\) whereas M1 part is retarded by a factor of \(155 \pm 33\) over the single particle transition probabilities.

The ratio of the reduced transition probabilities \(B(E2, 2^{-} \rightarrow 0^{+})/B(E2, 2^{+} \rightarrow 2^{+})\) can be calculated using the following relation,

\[
\frac{B(E2, 2^{-} \rightarrow 0^{+})}{B(E2, 2^{+} \rightarrow 2^{+})} = \frac{\text{Cross-over Intensity}}{\text{Cascade Intensity}} \times \frac{1 + \delta^2}{\delta^2} \times \left[ \frac{E \gamma (2^{-} \rightarrow 2^{+})}{E \gamma (2^{+} \rightarrow 0^{+})} \right]^5
\]

where \(\delta\) is the mixing ratio of the \(2^{+} \rightarrow 2^{+}\) transition, \(E \gamma (2^{+} \rightarrow 2^{+})\) and \(E \gamma (2^{+} \rightarrow 0^{+})\) are the energies of the stop-over and cross-over transitions from the \(2^{+}\) level. From the presently available experimental data this ratio has been calculated to be \(0.0079 \pm 0.0010\). This value
is in agreement with the corresponding values obtained in other vibrational nuclei.

The above discussion shows that the isotope $^{124}$Te may be regarded as a vibrational nucleus. On this model the 603(2$^+$) keV level is regarded as one-phonon quadrupole vibrational state and the 1248(4$^+$) and 1354(2$^+$) keV levels as two-phonon quadrupole vibrational states. The 1960 and 2040 keV levels may then be regarded as members of a three-phonon quadrupole vibration quintet. If such is the case, then the 712 and 1354 keV gamma rays from the 1960 keV level correspond to one-phonon and two phonon transitions respectively. Therefore the former transition should be enhanced compared to the latter transition in analogy with the enhancement of the 2$^+ \rightarrow 2^+$ transition compared to 2$^+ \rightarrow 0^+$ transition. Taking both the 712 and 1354 keV gamma rays as E2, the ratio of the reduced transition probabilities for the two modes of de-excitation of the 1960 keV levels is,

$$B(E2, 4^+ \rightarrow 2^+) / B(E2, 4^+ \rightarrow 4^+) = 0.19 \pm 0.02.$$ 

Thus the 712 keV transition is enhanced over the 1354 keV transition. But the enhancement is not as large as expected for a vibrational nucleus. Therefore, it appears that the 1960 keV level is not a pure three-phonon state and has other excitations also mixed into it.

The 2040 keV level decays to both the first and second 2$^+$ states. The ratio of the reduced transition probabilities for the two modes of de-excitation of the 2040 keV level is 

$$B(E2, J^+ \rightarrow 2^+) / B(E2, J^+ \rightarrow 2^+) = 0.015 \pm 0.006.$$ 

This value is comparable to the expected value for the transition in vibrational nuclei. The members of the three phonon quintet have spins $0^+$, $2^+$, $3^+$, $4^+$ and $6^+$. The spin of the 2040 keV level has been
limited to the values 1, 2, 3. If the 1960 keV level is regarded as the 4+ member of the quintet, the 2040 keV level may be the 2+ or 3+ member of the same quintet.

The 3\(^{-}\) spin states at 2293 keV and 2693 keV may be regarded as collective octupole vibrational states. Such an interpretation is supported by the Coulomb excitation experiments of Hansen and Nathan\(^{23}\) at least for the 2293 keV level. These authors\(^{23}\) have observed a octupole state at \(\sim 2250\) keV in \(^{124}\)Te which has been shown to have an enhancement of 70 for \(B(E3)\) over corresponding single particle estimates. This Coulomb excited state may be identified with the 2293 keV level observed in the decay of \(^{124}\)Sb to \(^{124}\)Te.
References

19. H.W. Taylor and R. McPherson, Gamma Gamma directional correlation coefficients $A_{\gamma}$ and $a_{\gamma}$ as functions of the mixing ratio (privately circulated tables, 4Sept. 1960).


Chapter 4.4
The Decay of $^{134}$Cs

4.4.1 Introduction

The 2.1 year negaton decay of $^{134}$Cs which leads to the excited levels of $^{134}$Ba has been studied extensively by many workers using various aspects of beta and gamma ray spectroscopy. These investigations have resulted in a generally accepted level scheme of $^{134}$Ba with excited levels at 605, 1168, 1401, 1643 and 1970 keV. Besides these well established levels, conflicting reports are present in the literature about the existence of weakly excited levels at about 1580 and 1773 keV. In a recent study of the gamma ray spectrum of $^{134}$Cs, using Ge(Li) detectors, Nagpal has introduced a level at 1580 keV in $^{134}$Ba to accommodate a gamma ray of the same energy. Such a level is in contradiction with the results of most of the earlier workers.

The conversion coefficient data show that the gamma transitions between the strongly excited levels of $^{134}$Ba are of E2 or M1 + E2 multipolarity. This assigns a positive parity to all the strongly excited levels of $^{134}$Ba. The directional correlation measurements supplemented by internal conversion data have been used to assign spins to the excited levels of $^{134}$Ba. These investigations have led to unique spin assignment to all but the 1643 and 1970 keV levels.

The reported assignments for the 1643 keV level are 2, 3, and 4. In a recent study, Rama Mohan et al. have proposed a spin 3 for the 1970 keV level, on the basis of the directional correlation of the 802-1168 keV cascade. A spin assignment 3 to the 1970 keV level is in contradiction with the results of previous workers.
In view of these inconsistencies, it was thought worthwhile to investigate the gamma ray spectrum following the decay of $^{134}$Cs. The directional correlations of 302-1168, 1365-605 and 1038-605 keV cascades in $^{134}$Ba have been measured to assign spins to the 1643 keV and 1970 keV levels in $^{134}$Ba. The results of these measurements are presented below.

4.4.2 Source preparation

The radio-isotope $^{134}$Cs in the form of cesium chloride dissolved in dilute hydrochloric acid was obtained from Bhabha Atomic Research Centre, Bombay, India. A few drops of this source were put and dried in a perspex holder to prepare a strong source. For gamma-gamma directional correlation measurements a moderately strong liquid source was prepared in a cylindrical perspex source holder with a vertical central cavity of 1.5 mm dia. x 4 mm depth. The same source was used for gamma ray coincidence measurements.

4.4.3 'Singles' gamma ray spectrum

The singles gamma ray spectra of $^{134}$Cs were studied using the 3" x 3" NaI(Tl) crystal at a source-to-crystal distance of 40 cm. The face of the crystal was covered with 1" of perspex to absorb the beta rays of $^{134}$Cs. These spectra were analysed by the usual 'peeling off' method. The analysed spectra showed peaks at 475, 569, 605, 800, 1038, 1170 and 1365 keV. From these spectra the relative intensities of these gamma rays were calculated and were observed to be in good agreement with the values quoted by previous workers.

To check the existence of a weak 1580 keV gamma ray the singles spectrum of $^{134}$Cs was carefully studied with a source-to-crystal distance of 100 cm using the same crystal and absorber. In this spectrum no indication of any peak around 1580 keV was observed.
FIG. 4.4: GAMMA RAY SPECTRUM OF $^{134}C\alpha$. SOURCE DISTANCE = 14.1 cm.
FIG 442: GAMMA RAY COINC. SPECTRUM OF $^{134m}$Cs. GATE AT 1168 KEV PEAK.

FIG 443: DECAY SCHEME OF $^{134m}$Ba INCORPORATING THE RESULTS OF THE PRESENT INVESTIGATIONS.
A 1580 keV gamma ray if present with the same intensity as reported by Nagpal\textsuperscript{11}) would have definitely showed up in the spectrum. From the present studies it was estimated that a 1580 keV gamma ray, if at all present, has an intensity less than 0.001%.

4.4.4 Gamma-gamma coincidence spectra

Gamma-gamma coincidence measurements were made by using a fast-slow coincidence set up of fig. 3.2 having a resolving time $T = 50$ nsec. The source was viewed by two 3" x 3" NaI(Tl) crystals with their axes at 90° to each other. A graded Compton shield was used at 45° to either crystal to avoid crystal-to-crystal scattering. For an individual run the single-channel analyser was set on a principal gamma ray peak and the coincidence spectra recorded on RCL 256-channel analyser. The source was placed at a distance of 14 cm from the face of either crystal to minimise summing effects of cascading gamma rays in the gating crystal.

Figure 4.4.1 shows an analysed singles spectrum of $^{134}Ba$ obtained in the above geometry. The areas (a) and (b) show the gates selected on the 1168 keV and 1365 keV peaks. Figure 4.4.2 shows the gamma ray spectrum in coincidence with the 1168 keV peak. The spectrum was run for 24 hours. After correcting for random coincidences, the analysed spectrum shows peaks at 475 keV, 605 and 802 keV. The 605 keV peak in this spectrum has contributions from the 1365-605 keV cascade due to the Compton of the 1365 keV gamma ray falling in the gate set at the 1168 keV peak. This contribution was carefully estimated from the coincidence spectrum obtained with gate 'a' set on the 1365 keV peak and the Compton contribution of the 1365 keV gamma ray in the gate 'b' set on the 1168 keV peak (fig. 4.4.1). From this analysis it was estimated that only about 50% of the 605 keV peak is due to the 1365-605 keV...
cascade. It is, therefore, quite convincing that there are real coincidences between the 1168 and 605 keV gamma rays. This, therefore, confirms the existence of a level at 1773 keV in $^{134}$Ba.

The gamma-gamma coincidence spectra of $^{134}$Cs were also studied with the gates set at 605, 800 and 1038 keV photopeaks. The spectra so observed are in agreement with the results of other workers.

4.4.5 Gamma-gamma directional correlation measurements:

The directional correlation measurements in $^{134}$Ba were carried out using a fast-slow coincidence set up of fig. 3.2, having an effective resolving time ($\tau$) of 50 nsec. The gamma rays were detected in two 3" x 3" NaI(Tl) crystals. Both the detectors were shielded from each other with anti-Compton graded lead cylinders and lead cones. The source was symmetrically located 14 cm from each crystal at the point of intersection of the axes of the two crystals. The source could be centered within 0.5% variation in the singles counting rate of the movable detector at different angular positions. The coincidence counts were recorded at seven angles between 90° to 180°, at intervals of 15° each. The random coincidences were determined by introducing a delay of 500 nsec. in one of the channels of the fast-coincidence circuit. The true-to-chance ratio was about 12 : 1 for the cascades studied in the present work. The correlation functions were obtained by least-squares' analysis and were corrected for finite geometry of the crystals using the correction factors calculated by Yates. The interfering contributions of neighbouring cascades were estimated using Ge(Li) detector data.

In the analysis of angular correlation functions to obtain spin sequences and mixing ratios, the tables of Taylor and McPherson were used.
A gamma ray scintillation spectrum of $^{134}\text{Cs}$ obtained with $3'' \times 3''$ NaI(Tl) with a source-to-crystal distance of 14 cm is shown in fig. 4.4.1. The gates used in the correlation measurements are shown in this figure. These positions were chosen to eliminate or minimize the interference from neighbouring cascades. Whenever the gates were set on the sloping portions of the photopaks the counting period at each angle was decreased and coincidence counts were collected in a larger number of sweeps than in the other measurements.

4.4.5(1) The 802-1168 keV correlation

This correlation was measured using gates 1 and 2. The crystal selecting a gate on the 1168 keV peak was covered with about 7 mm of lead to reduce the summing of the 563-605 keV cascade in this crystal. This geometry reduced the detection of the 563-605 keV cascade sum to less than 2% compared to the detection of the 1163 keV cross-over transition. The solid angle corrected correlation function is found to be:

$$W(\theta) = 1 + (0.112 \pm 0.003)P_2(\cos \theta) + (0.010 \pm 0.0066)P_4(\cos \theta).$$

This cascade does not contain any interfering contributions from the 1365-605 keV cascade, as 605 keV gamma ray is not selected in gate 1.

The 802-1168 keV correlation was also measured by sum-peak coincidence spectrometer using the set up of fig. 3.4. The crystals and the geometry was the same as before, except that in this case the face of either crystal was covered with 7 mm of lead to reduce summing of the 563-605 keV cascade. The integral biases of the two single-channel analysers were set at 700 keV to completely bias out the 605 keV gamma ray. The sum-peak coincidence spectrum was recorded on the 256-channel analyser. This spectrum after subtraction of random coincidences showed a sum-peak
at 1970 keV which corresponds to the summing of 802 and 1168 keV cascading gamma rays. The solid angle corrected correlation function from this data is,

\[ W(\theta) = 1 + (0.1022 \pm 0.0040)P_2(\cos \theta) + (0.0082 \pm 0.0050)P_4(\cos \theta). \]

A weighted average of the above two measurements gives,

\[ W(\theta) = 1 + (0.1081 \pm 0.0025)P_2(\cos \theta) + (0.0091 \pm 0.0040)P_4(\cos \theta). \]

4.4.5(ii) The 1365-605 keV correlation

This correlation was measured using gates 3 and 4. In this case also the face of the crystal selecting a gate on the 1365 keV peak was covered with about 1 cm of lead to reduce the summing of the 569-796 keV cascade in this crystal.

The solid angle corrected correlation function is found to be,

\[ W(\theta) = 1 + (0.0980 \pm 0.0038)P_2(\cos \theta) + (0.0097 \pm 0.0034)P_4(\cos \theta). \]

This correlation does not contain any interference and needs no further corrections.

4.4.5(iii) The 1038-605 keV correlation

This correlation was measured using gates 5 and 6. The gate 5 was set on the higher-energy half of the 605 keV peak so as to avoid contributions from the 475 keV gamma transition in this gate. The measured correlation function after solid angle correction is,

\[ W(\theta) = 1 + (0.094 \pm 0.007)P_2(\cos \theta) + (0.006 \pm 0.004)P_4(\cos \theta). \]

This cascade is influenced by the 1365-605 keV and 802-1168 keV cascades and needs further corrections. Segaert et al.⁴ and Rama Mohan et al.¹⁷ have made directional correlation measurements for this cascade and have reported the correlation functions without taking account
of these interfering contributions. Their uncorrected correlation functions compare well with our results given above.

The interfering contributions of the 1365-605 keV and 802-1168 keV cascades were evaluated using Ge(Li) detector relative intensity data\(^7\)\(^,\)\(^10\)\(^,\)\(^11\) and gate positions 5 and 6. The relative contributions of the 1038-605, 1365-605 and 802-1168 keV cascades were estimated to be (71.2 \pm 10.6)\%, (25.3 \pm 3.8)\% and (3.5 \pm 0.5)\% respectively. Correcting for the interference of the 1365-605 keV and 802-1168 keV cascades, the true correlation function for the 1038-605 keV cascade is found to be

\[ W(\theta) = 1 + (0.092 \pm 0.012)P_2(\cos \theta) - (0.02 \pm 0.006)P_4(\cos \theta). \]

4.4.6 Analysis of directional correlation data:

The spin and parity of ground state of even-even nucleus \(^{134}\)Ba is \(0^+\). The K-conversion coefficient of the 605 keV transition\(^3\)\(^,\)\(^6\)\(^,\)\(^7\)\(^,\)\(^11\) shows this transition to be pure E2 in character. This requires a spin assignment \(2^+\) to the 605 keV first excited state. This assignment is also in conformity with the systematics\(^22\) of even-even nuclei.

The K-conversion coefficient of the 1168 keV transition\(^3\)\(^,\)\(^6\)\(^,\)\(^7\)\(^,\)\(^11\) shows the transition to be pure E2 in character. This requires an assignment \(2^+\) to the 1168 keV level of \(^{134}\)Ba.

The ground state of odd-odd nucleus \(^{134}\)Cs has a \(4^+\) character\(^1\). The 86 keV beta group from the ground state of \(^{134}\)Cs has a value of \(\log f_t = 6.2\)\(^3\). Therefore, this beta group is either an allowed transition having \(I = 0\) or 1 and no parity change or a first forbidden transition with the same change in angular momentum but having a change in parity. Thus the probable spin values for the 1970 keV level are \(3^+, 4^+, 5^+, 3^-, 4^-, 5^-\). The 569, 802 and 1365 keV gamma transitions from the 1970 keV level to the \(4^+, 2^+\) and \(2^+\) levels at 1401, 1168 and 605 keV are of multi-
polarity E2 or E2+M1^,^,^,'1~1'). Therefore, the 1970 keV level should have positive parity. Therefore, only possible assignments for this level are 3^+, 4^+ and 5^+. The lifetime considerations for this level, however, rule out the 5^+ assignment leaving only two possibilities 3^+ or 4^+.

Consequently there are two possible spin sequences for the 802-1168 keV cascade, namely (i) 3(D,Q)2(Q)0 or (ii) 4(Q,0)2(Q)0. Assuming spin sequence (i), the theoretical A^\_4 coefficient is expected to be zero or negative for any value of the quadrupole fraction in the 802 keV transition. This is incompatible with observed definite positive value of the experimental A^\_4 coefficient (A^\_4 = 0.009±0.004). Therefore, the only possible spin sequence for this cascade is 4(Q,0)2(Q)0. Thus we conclude that the spin assignment for the 1970 keV level is 4^+. An analysis of the observed coefficients in terms of the above spin sequence shows that the 802 keV is pure E2 with \( Q_{802} < -0.01 \) i.e. the M3 admixture in \( \gamma_{802} \) is less than 0.01%. This conclusion is in agreement with the results based on internal conversional coefficient \( ^7,^{11} \) of the 802 keV transition which shows this transition to be pure E2.

The spin assignment to the 1970 keV level is also checked by the directional correlation measurement of the 1365-605 keV cascade. Assuming spin 3^+ or 4^+ for the 1970 keV level the two possible spin sequences for the 1365-605 keV cascade are (i) 3(D,Q)2(Q)0 and (ii) 4(Q,0)2(Q)0. Here again a definite positive value of the observed A^\_4 coefficient (A^\_4 = 0.0087±0.0034) rules out (i) as a possible spin sequence. Therefore, the 1365-605 keV cascade follows the spin sequence 4(Q,0)2(Q)0. This confirms a spin assignment 4^+ for the 1970 keV level of \(^{134}\)Ba. A mixing ratio analysis of the observed correlation
Coefficient shows the 1365 keV transition to be pure E2 with i.e. the M3 admixture in 1365 is less than 0.1%. This conclusion is also supported by the internal conversion data\(^3,6,7,11\) for the 1365 keV transition.

The level at 1643 keV is connected to the first and second \(2^+\) excited levels at 605 and 1168 keV by 1038 keV and 475 keV transitions respectively. These transitions are known to be of E2 or M1+E2 multipolarity\(^7\). Therefore, the probable spin values for the 1643 keV level are \(0^+,1^+,2^+,3^+\) and \(4^+\). This level is fed by a beta group of energy 410 keV with log ft. value of about 10\(^3\). This beta group may be classified as of allowed or first forbidden type\(^{22}\). Spin assignments \(0^+,1^+,2^+\) are incompatible with either nature of the beta group and a known \(4^+\) character of the ground state of \(^{134}\)Cs. Spin assignments \(1^+\) and \(2^+\) for the 1643 keV level are also ruled out because of the absence of a transition from this level to the \(0^+\) ground state of \(^{134}\)Ba. Consequently, there are two possible spin sequences for the 1038-605 keV cascade namely (i) \(3(0,1)2(2,0)\) and (ii) \(4(1,0)2(2,0)\). The observed correlation coefficient \(A_4\) was analysed in terms of these spin sequences and the mixing ratio of the 1038 keV transition was determined. The mixing ratios are used to compute the expected \(A_4\) coefficient for each spin sequence. The results of this analysis are summarized in table 4.4.1. A comparison of the observed \(A_4\) coefficient \((A_4 = -0.012 \pm 0.006)\) with the calculated values of \(A_4\) given in table 4.4.1, favour the spin sequence \(3(0,1)2(2,0)\) for the 1038-605 keV cascade. This assigns a \(3^+\) character to the 1643 keV level in \(^{134}\)Ba.
Table 4.4.1: Analysis of the results of the directional correlation of the 1038-605 keV cascade in $^{134}\text{Ba}$.

<table>
<thead>
<tr>
<th>Possible spin sequence</th>
<th>Mixing ratio $\delta_{1038}$ determined from the experimental $A_2$ Coefficient.</th>
<th>Corresponding expected $A_4$ Coefficient for the mixing ratio $\delta_{1038}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(D,Q)2(Q)0</td>
<td>$\delta_{1038} = \sim -0.25$</td>
<td>$A_4 = \sim -0.005$</td>
</tr>
<tr>
<td></td>
<td>$\delta_{1038} = \sim -2.40$</td>
<td>$A_4 = \sim -0.069$</td>
</tr>
<tr>
<td>4(Q,0)2(Q)0</td>
<td>$\delta_{1038} = \sim +0.035$</td>
<td>$A_4 = \sim +0.014$</td>
</tr>
<tr>
<td></td>
<td>$\delta_{1038} = \sim -1.7$</td>
<td>$A_4 = \sim -0.034$</td>
</tr>
</tbody>
</table>

4.4.7 Discussion of Results:

The decay scheme of $^{134}\text{Cs}$ incorporating the results of present investigations is shown in fig. 4.4.3. Present measurements support the existence of a level at 1773 keV. This level may be fed by a weak beta group or by a 200 keV gamma transition from the 1970 keV level as suggested by Trehan et al. A level at 1580 keV, proposed recently by Nagpal, is not supported by our measurements.

The directional correlation measurements of the 802-1168 keV and 1365-605 keV cascade assign spin $4^+$ to the 1970 keV level. The directional correlation measurements of the 1038-605 cascade favour a spin assignment $3^+$ for the 1643 keV level of $^{134}\text{Ba}$. A spin assignment $3^+$ to the 1643 keV level has also been favoured by recent workers on the basis of conversion data.

The level structure of $^{134}\text{Ba}$ has been discussed on a number
of nuclear models by many investigators. These investigations show that the experimental level structure of $^{134}$Ba is predicted reasonably well by the generalized asymmetric rotor model.
References


