CHAPTER III

Experimental Results

1. Gamma Gamma Angular Correlation in As\(^{75}\):

a) Introduction:

The radioactive decay of Se\(^{75}\)(\(T_\beta=120\) days) to the levels of As\(^{75}\) has been studied by various workers.\(^1\)-\(^12\)

The level scheme of As\(^{75}\) as shown in fig. 3.1 can be considered as well established from these investigations. There remain, however, discrepancies\(^1\)-\(^3\),\(^13\)-\(^15\) as far as multipole admixtures are concerned. Schardt and Walker\(^1\) from their internal conversion coefficients measurements, conclude that 121 keV, 136 keV and 265 keV gamma rays are all \(E_1\) and 260 keV gamma ray is pure \(E_2\). But the later measurements of conversion coefficients\(^3\) conclude that 121 keV and 136 keV transitions are pure \(E_1\), 265 keV transition is pure \(M_1\) and that 260 keV transition a mixture of \(M_1\) and \(E_2\). The value of the mixing parameter \(|\delta|\) for the 260 keV transition lies between 0.33 and 0.44 from the conversion coefficients of Metzer and Todd.\(^1\)

Edwards and Gallagher\(^3\) have corrected this value to 0.42\(^\pm\)0.14. Decroes and Backstrom\(^3\) value for the mixing parameter for the same transition is 0.80\(^\pm\)0.19 and Edwards and Gallagher\(^3\) obtain the value of the mixing parameter as 0.51\(^\pm\)0.14. Schart and Walker\(^1\) and Kelly and Wiedenbeck\(^5\) from their angular correlation measurements, obtain the value of \(|\delta|\) for 260 keV transition as 0.44\(^\pm\)0.11 and
Fig. 31

Decay Scheme of $^{75}$Se
respectively, while Van Den Bold et al. have obtained the value of the mixing parameter $|\xi|$ for the 280 keV transition as $0.75^{+0.10}_{-0.09}$ and for 265 keV transition as $0.18^{+0.06}_{-0.06}$. There appear to be discrepancies in the values of the mixing parameters for 265 keV and 280 keV transitions from various angular correlation measurements as well as those obtained from angular correlation measurements and internal conversion coefficient measurements. So it was considered worthwhile to reinvestigate the angular correlation of 121-280 keV and 136-265 keV cascades. In addition, the present investigations were also extended to check the spin for 199 keV level and to get information about the amount of the multipole admixtures present in the various gamma rays by the angular correlation measurements. Special attention was paid for the angular correlation of weaker cascades 66-199 keV, 136-66 keV and 136-199 keV.

do Sholit has proposed a core coupling model to explain some of the nuclear properties of the odd-even nuclei. They have pointed out that the excited states in odd-even nuclei are not the single particle states due to the last odd nucleon but they are due to the coupling of the single particle low lying state of the last odd nucleon with the $2^+$ even-even core. The ground state of these odd-even nuclei is due to the coupling of the single particle low lying state of the last nucleon with the $0^+$ ground state of even-even core. Therefore the enhancement of $E2$ transition from the excited
states to the ground state in odd even nuclei should nearly be the same as that of the first $2^+ \rightarrow 0^+ E2$ transition in neighbouring even even nuclei. As this isotope appears to be interesting from the theoretical point of view, we have discussed the properties of the states in the light of single particle core coupling model.

b) Experimental Techniques and Source Preparation:

Se$^{75}$ which was in the form of Selenium Chloride in dil. \( \text{SeCl}_2 \) was obtained from the Isotope Division of the Atomic Energy Establishment, Trombay, India. The gamma gamma coincidences were recorded with the help of two identical scintillation spectrometers having 14" x 2" NaI(Tl) crystals mounted on 6292 photomultiplier tubes and conventional slow fast coincidence circuit of resolving time $2\tau=0.15$ microseconds. The singlespectrum is shown in fig. 3.2. Coincidence measurement confirmed the decay scheme proposed by Schardt and Walker.\(^1\)

For the angular correlation work the source which was in the form of selenium chloride in dil. \( \text{SeCl}_2 \) was taken in a source holder which consisted of a thin perspex rod with a hole of 1/10 inch in diameter and about ½ inch in length. The source was placed at 10 cms from each crystal. The coincidences were recorded from 90 to 270 degrees at an interval of 22.5 degrees. The strength of the source was so adjusted that the true to chance coincidence ratio was quite high in all the measurements. The data after subtracting the chance coincidences was least square fitted.
Fig 32
Singles Spectrum of S. Arrows on the 265 and 2
phoiopeak show the centre of the gates for case
by the method of Bose\textsuperscript{17} and the solid angle correction\textsuperscript{17) was applied.

\begin{itemize}
  \item[(c)] \textit{Angular Correlation of 121-280 keV and 136-265 keV Cascades.-}

  The gamma gamma directional correlation of the unresolved 121-280 keV and 136-265 keV cascades in Ag\textsuperscript{75} have been studied by Schardt and Walker\textsuperscript{1}) Kelly and Wiedenbeck\textsuperscript{15} and Van Den Bold et al.\textsuperscript{2}) In the present case we have followed the method of Schardt and Walker\textsuperscript{1}) for studying the above correlations and hence it is described briefly.

  The directional correlations were measured for three different settings of the single channel discriminators

(a) One discriminator was set on the unresolved 121-136 keV peak and the other on the unresolved 265-280 keV peak. The window width in each case was approximately equal to the width of these lines at their base.

(b) The discriminator setting on the 265-280 keV peak was increased and the discriminator setting on the 121-136 keV peak was decreased in such a way so as to favour more of the 121-280 keV cascade. The window widths in these settings for the two peaks were one fourth as wide as in the previous case.

(c) In the same way the settings on the two discriminators were adjusted so as to favour more of the 136-265 keV cascade.
In the case (b) and (c) the channels were set on the sloping portion of the composite photopeaks. As a result of this the counting rate in the channels was very much sensitive to the small shifts in the pulse heights. For this purpose a number of readings were taken at every angle for a fixed time. The deviation of these from the average value was used in calculating the errors in A_2 and A_4 instead of statistical deviations. When the channels were set as described in case (b) the maximum deviation of different readings from the average value for different angles was 4.3% in comparison with the statistical error of 3% in each reading. In case (c) when the settings were adjusted to favour the 136-265 keV cascade the statistical error was 2.5% and the maximum deviation due to fluctuations in the channels was 3.2%.

The coincidence counting rate at various angles after subtracting the chances were normalised at 90 degrees. The least square fitted curves to the experimental points are shown in fig. 3.3 and the angular correlation coefficients after applying correction for the finite geometry, by the method due to Rose^1), are given in table 1. As the gamma rays 121 keV, 136 keV as well as 265 keV and 260 keV are unresolved, the true correlation coefficients were calculated from these measured directional correlation coefficients. The formulas used for calculating the true correlation coefficients were the same as discussed in detail by Schardt and Walker.^1)
Fig 3.3 Least square fitted curves to the experimental points of the angular correlation data. Curve (a), (b) and (c) correspond to the channels set to include both the 121 280 keV and 136-265 keV, to favour 121-280 keV cascade & to favour 136-265 keV cascade respectively.
Table I
Experimental results of the angular correlation measurements

<table>
<thead>
<tr>
<th>Channel position</th>
<th>Coefficient of $F_2(\cos \theta)$</th>
<th>Coefficient of $F_4(\cos \theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_2$</td>
<td>$A_4$</td>
</tr>
<tr>
<td>Case (a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel set to include both the cascades</td>
<td>-0.114 ± 0.006</td>
<td>-0.002 ± 0.008</td>
</tr>
<tr>
<td>Case (b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel set to favour 121-280 keV cascade</td>
<td>-0.351 ± 0.016</td>
<td>-0.012 ± 0.023</td>
</tr>
<tr>
<td>Case (c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel set to favour 136-265 keV cascade</td>
<td>-0.046 ± 0.013</td>
<td>+0.010 ± 0.018</td>
</tr>
</tbody>
</table>

In the calculations we need the ratio of the disintegrations through the mode 121-280 keV and through the mode 136-265 keV at each channel setting as in case (a), (b) and (c). These mixing ratios were determined from the analysis of the composite photopeaks. The relative intensities used for this purpose were taken from Edwards and Gallagher. We find experimentally for our case:

$$\frac{N_2}{N_1} = 2.252 \pm 0.15$$ (1)
where $n_1$ and $n_2$ are disintegrations per second of the 401 keV level through the node 121-280 keV and 136-265 keV respectively. By putting these values of mixing ratios, in the following formulas the true angular correlation coefficients for the 121-280 keV and 136-265 keV cascades were calculated:

$$A_{11} = \frac{\left[ (1 + \beta_b)A_{1b} - (1 + \beta_c)A_{1c} \right]}{(\beta_b - \beta_c)}$$

$$A_{12} = \frac{\left[ (\beta_c(1 + \beta_b)A_{1b} - \beta_b(1 + \beta_c)A_{1c} \right]}{(\beta_b - \beta_c)}$$

where $A_{11}, A_{12}, A_{21}, A_{22}$ and $A_{1c}$ are coefficients of Legendre's Polynomials in correlation function $W(\theta)$ and 1 and 2 subscripts of $A_{11}$ refer to true correlation coefficients of 121-280 keV and 136-265 keV cascades respectively, while $b$ and $c$ subscripts on $A_{11}$ and $\beta$'s refer to the channels set to favour 121-280 keV and 136-265 keV cascades respectively and

$$\beta = \frac{N_{01} \cdot N_{13} \cdot N_{22}}{N_{02} \cdot N_{23} \cdot N_{11}}$$

where $N_{01}$ and $N_{02}$ correspond to counting rate in the channel of first detector due to 121 keV and 136 keV gamma rays respectively. $N_{13}$ and $N_{23}$ correspond to the counting rate in the channel of second detector due to 265 keV and 280 keV gamma rays respectively. The following results were obtained for the true correlation coefficients.
for the 121-280 keV cascade,

\[ w(\Theta) = 1 - (0.395 \pm 0.020)P_2(\cos \Theta) - (0.015 \pm 0.026)P_4(\cos \Theta) \]

for the 136-265 keV cascade,

\[ w(\Theta) = 1 - (0.035 \pm 0.015)P_2(\cos \Theta) + (0.012 \pm 0.020)P_4(\cos \Theta) \]

Spins 5/2, 5/2, and 3/2 are established\(^1,^2\) for the excited levels at 401 keV, 280 keV and 265 keV respectively.

The spin and parity of the ground state of As\(^{75}\) is 3/2.\(^-\)

Therefore the cascades 121-280 keV and 136-265 keV follow the spin sequence 5/2(D\(_{1/2}\),Q)5/2(D\(_{5/2}\),Q)3/2 and 5/2(D\(_{3/2}\),Q)3/2(D\(_{5/2}\),Q)3/2 respectively.

The point of interest is the amount of the quadrupole contents in the various gamma rays. So we have analysed the directional correlation data graphically. The quadrupole admixtures in these gamma rays have been estimated by the method of Arns and Wiedenbeck.\(^1^8\)

(1) 121-280 keV cascade.

Fig. 3.4 shows the graphical analysis of eq. 5 in terms of spin sequence 5/2(D\(_{1/2}\),Q)5/2(D\(_{5/2}\),Q)3/2. From the analysis it is clear that the 280 keV gamma ray is \(E_1^+E_2\) irrespective of the fact whether we take 121 keV gamma ray as pure \(E_1\) or not. From the internal conversion data\(^3,^6\) and half life data\(^1^9,^2^0\) 121 keV gamma ray seems to be almost pure \(E_1\) allowing only a very small amount of
Fig. 3.4
Analysis of the 121-280 keV angular correlation in terms of a $\frac{3}{2} (0,0) \frac{3}{2} (0,0) \frac{3}{2}$ spin sequence.
admixture. With $q_1 = 0$ for the 121 keV gamma ray, fig. 3,4 gives a quadrupole content of 260 keV gamma ray as

$$0.090 \leq q_2 \leq 0.153$$

$$0.594 \leq q_2 \leq 0.686$$

and with $q_1 = 0.01\%$ (the maximum allowed quadrupole admixture by half life data 4,19), the values of $q_2$ are

$$0.086 \leq q_2 \leq 0.173$$

$$0.567 \leq q_2 \leq 0.694$$

The higher values of $q_2$ in both the above cases are ruled out on the basis of other supplementary data, namely internal conversion coefficients measurements 3) and polarization correlation measurements 2). Therefore an admixture $q_2 = (13.0 \pm 4.3)\%$ is possible. Thus the 260 keV gamma ray is estimated to contain $(87.0 \pm 4.3)\%$ $\gamma_1$ and $(13.0 \pm 4.3)\%$ $\gamma_2$. Internal conversion coefficient measurements by Edwards and Gallagher 3) however allow an admixture of $(20.8 \pm 8.9)\%$.

(ii) 136-265 keV cascade.

Eq. 6 is analysed in terms of $5/2(\nu,\gamma)3/2(D,\gamma)3/2$ spin sequence for 136-265 keV cascade. The half life data 4,19) allow a maximum admixture of $0.01\%$ $\gamma_2$ in 136 keV gamma ray. Thus taking $q_1 = 0.01\%$ we get, for the 265 keV gamma ray, the following values of the admixture $q_2$ from fig. 3.5.

$$0.012 \leq q_2 \leq 0.019$$

$$0.873 \leq q_2 \leq 0.987$$
The higher values of $Q_2$ are excluded on the basis of internal conversion data$^3$ as well as polarization correlation data.$^2$ Therefore the estimated value of the admixture in 265 keV gamma ray is $Q_e=0.016 \pm 0.003$. In other words 265 keV gamma ray contains $(98.4 \pm 0.3)\%$ $\gamma_1$ and $(1.6 \pm 0.3)\%$ $\gamma_2$ radiation. This value is in good agreement with the value obtained from the conversion coefficient measurements.$^3$

\(d\) Angular correlation of 66-199 keV, 136-199 keV and 136-66 keV cascades:

In the single's spectrum shown in fig. 3.2, 199 keV gamma ray peak is surrounded by the two intense composite photopeaks one due to 136 and 136 keV and the other due to 265 keV and 260 keV gamma rays. So the coincidences with 199 keV gamma ray are not straightforward and any gate channelled at 199 keV peak will, therefore, contain some contribution from these two composite photopeaks. Their contribution to the true angular correlations was taken into account in the following way.

The coincidence counts for a fixed time were obtained with a narrow gate of about 20 keV set at the centre of 199 keV peak. The gate was then moved to the lower energy side by an amount approximately equal to the gate width and the coincidences for half of the previous time were noted and were subtracted from the previous reading.
Finally the gate was displaced to the high energy side of the first position by the same amount and the coincidences for half of the time were noted and again subtracted from the first reading. This gate subtraction method assumes that the unwanted coincidences in the first gate is an arithmetic mean of the low energy side and high energy side gates. The chance coincidences were subtracted separately from three set of readings obtained at three different channel settings. The coincidence spectrum obtained in this way is shown in fig. 3.6. This spectrum shows gamma ray in coincidence with 159 keV gamma ray and is also free from background coincidences due to other gamma ray cascades. From the spectrum it is clear that 199 keV gamma ray is in coincidence with 66 keV and 136 keV gamma rays. For the angular correlation measurements of 66-199 keV cascade the fixed counter was set at 66 keV gate and the counts coincident with 199 keV gamma ray at five equispaced angles between 50 and 270 degrees were recorded in the same manner as described above. Nagvi and Dilly have adopted the same method as is stated above, but they have not subtracted the chance coincidences separately. Their procedure does not seem to be right as it is quite likely that the chance coincidences in the three different settings of the channels of the same width may not be equal.

The solid angle corrected correlation function after applying least square fit to the data is,

\[ e(\theta) = 1 - (0.019 \pm 0.020)(\cos \theta) + (0.008 \pm 0.025)(\cos \theta) \]  

(7)

The spins of 265 keV level and the ground state of As are both 3/2. The spin 1/2 has been suggested for 199 keV.
Gamma ray spectrum in coincidence with 199 keV Gamma-ray.
level of $^{75}\text{As}^{1,2}$. As the theoretical values of $A_2$ and $A_4$
for $3/2(D_Q)1/2(D_Q)3/2$ spin sequence are both zero, the
present directional correlation coefficients which are nearly
zero, also support spin $1/2$ for the $199$ keV level.

(ii) 136-199 keV cascade.

The contribution due to interfering cascades was
taken into account in a similar manner as discussed in
section 4 (i). The skipped angular correlation function
after applying the solid angle correction is,

$$\kappa(\theta) = 1 - (0.015 \pm 0.018)P_2(\cos \theta) + (0.008 \pm 0.025)P_4(\cos \theta)$$

These correlation coefficients which are again nearly
zero, are consistent with the spin $1/2$ for the $199$ keV level
as the skipped correlation coefficients $A_2$ and $A_4$ for $5/2(D_Q)3/2$
$(D_Q)1/2(D_Q)3/2$ spin sequence are both zero. Thus the spin
$1/2$ of the $199$ keV level is consistent with the angular
correlation measurements of $66-(97)$ keV and $136-199$ keV cascades.

(iii) 136-66 keV cascade.

To remove the contribution of the high energy
coincident gamma rays the gate subtraction coincidence
technique as described earlier was applied to the $66$ keV gamma
ray and the other detector was fixed at the sloping portion
of the $121-136$ keV peak so as to collect more of the $136$ keV
gamma rays.

The least square fitted correlation function after
applying solid angle correction is,

\[ w(\theta) = 1 + (0.019 \pm 0.010)P_2(\cos \theta) - (0.003 \pm 0.014)P_4(\cos \theta) \]

... (8)

The spins 5/2 and 3/2 for the excited levels at 401 keV and 265 keV respectively are well established. The 199 keV level has the spin 1/2. Therefore the cascade 136-66 keV follows the spin sequence 5/2(1/2)3/2(3/2)1/2. Fig. 3.7 shows the graphical analysis of equation (8) in terms of 5/2(1/2)3/2(3/2)1/2 spin sequence. From the analysis it is clear that 66 keV gamma ray is \( \xi_1+\xi_2 \) irrespective of the 136 keV gamma ray being either a pure \( \xi_1 \) or having a small admixture. Thus taking \( Q_1 = 0.01\% \), the maximum allowed admixture in 136 keV gamma ray, by the half life data, \(^{14,19}\) we get the following values of the admixture \( Q_2 \) for the 66 keV gamma ray,

\[ 0.009 \leq Q_2 \leq 0.048 \]
\[ 0.827 \leq Q_2 \leq 0.911 \]

The higher values of \( Q_2 \) are ruled out on the basis of internal conversion data. Therefore an admixture \( Q_2 = 0.029 \pm 0.019 \) is possible. Thus the 66 keV gamma ray contains \((97.1 \pm 1.9)\% \xi_1 \) and \((2.9 \pm 1.9)\% \xi_2 \) which is in good agreement with the internal conversion data. \(^3\)

The present results are summarized in table 2 along with the correlation functions reported by other investigators.
Analytical of the 136-66 KeV angular correlation in terms of a \( \frac{1}{2} \) (D,\( \alpha \)) \( \frac{3}{2} \) spin sequence.
### Table II
Summary of $^{75}$As angular correlation data

<table>
<thead>
<tr>
<th>Cascade energies (keV)</th>
<th>Correlation coefficients</th>
<th>Assigned spin sequence</th>
<th>Mixing ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_2$</td>
<td>$A_4$</td>
<td></td>
</tr>
<tr>
<td>121-280</td>
<td>-0.40 ± 0.03$^a$</td>
<td>-0.013 ± 0.017$^a$</td>
<td>5/2$(D,Q)5/2(D,Q)3/2</td>
</tr>
<tr>
<td></td>
<td>-0.41 ± 0.03$^b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.53 ± 0.06$^c$</td>
<td>-0.035 ± 0.08$^c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.46 ± 0.02$^d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.39 ± 0.02$^e$</td>
<td>-0.015 ± 0.02$^e$</td>
<td></td>
</tr>
<tr>
<td>136-265</td>
<td>-0.19 ± 0.02$^a$</td>
<td>-0.012 ± 0.012$^a$</td>
<td>5/2$(D,Q)3/2(D,Q)3/2</td>
</tr>
<tr>
<td></td>
<td>+0.016 ± 0.03$^b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+0.04 ± 0.05$^e$</td>
<td>-0.06 ± 0.05$^e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.035 ± 0.015$^e$</td>
<td>+0.012 ± 0.020$^e$</td>
<td></td>
</tr>
<tr>
<td>66-199</td>
<td>-0.19 ± 0.020$^e$</td>
<td>+0.008 ± 0.025$^e$</td>
<td>3/2$(D,Q)1/2(D,Q)3/2</td>
</tr>
<tr>
<td>136-199</td>
<td>-0.15 ± 0.018$^c$</td>
<td>+0.008 ± 0.025$^c$</td>
<td>5/2$(D,Q)3/2(D,Q)3/2</td>
</tr>
<tr>
<td>136-66</td>
<td>+0.019 ± 0.010$^e$</td>
<td>-0.003 ± 0.014$^e$</td>
<td>5/2$(D,Q)3/2(D,Q)3/2</td>
</tr>
</tbody>
</table>

a) ref. 1; b) ref. 15; c) ref. 2(coefficients of $\cos^2 \phi$ and $\cos^4 \phi$); d) ref. 3; e) Present investigations
e) Transition Rates

(1) Branching ratios of transitions from $^{75}$As levels.

The branching ratio $a(E)$ defined as the ratio between the intensity of a specific transition and the sum total of intensities of all the transitions from the same level, was calculated for each transition according to the formula

$$a(E) = \frac{I_\gamma(E) [1 + \kappa(E)]}{\sum_i I_\gamma(E_i) [1 + \kappa(E_i)]}$$  \hspace{1cm} (9)

where $I_\gamma(E)$ and $\kappa(E)$ are the intensity and the conversion coefficient of the specific transition and $I_\gamma(E_i)$ and $\kappa(E_i)$ are the intensities and conversion coefficients of the other transitions from the same level. The values of $a(E)$ are given in column 2 of table III. The intensities of various transitions have been taken from ref. 12).

(ii) Experimental transition probabilities.

The experimental gamma decay transition probability is obtained from the observed half life ($T_{1/2}^{obs}$) of the decaying level, the branching ratio $a(E)$ of the specific transition and the total internal conversion coefficient $\kappa(E)$, according to

$$T_{\exp}(E) = 0.6931 \frac{a(E)}{[\sum_i a(E_i) [1 + \kappa(E_i)]]^{1/2}}$$  \hspace{1cm} (10)

The calculated $T_{\exp}(E)$ values in sec$^{-1}$ units are given in column 3 of table III.
(iii) Transition probabilities of single proton.

Transition probabilities $T_{S\alpha p}$ of a single proton were estimated from the Weiskopf formulae\(^{21}\) taking the statistical factor $\delta = 1$. The estimated $T_{S\alpha p}$ for $H_1$, $L_1$, and $L_2$ transitions are given in columns 4, 5, and 6 of table III.

(iv) Retardation and enhancement factors.

From the estimated transition probabilities $T_{S\alpha p}$ and the experimental gamma decay transition probabilities $T_{\text{exp}}$, the retardation and enhancement factors can be evaluated by employing the mixture ratio $\delta^2$. The retardation and enhancement factors for different transitions are

$$B(H_1) = (1+\delta^2) T_{S\alpha p}(H_1)/T_{\text{exp}}$$
$$B(L_1) = (1+\delta^2) T_{S\alpha p}(L_1)/T_{\text{exp}}$$
$$E(L_2) = \delta^2 T_{\text{exp}}/(1+\delta^2) T_{S\alpha p}$$

where $B(H_1)$ and $B(L_1)$ are the retardation factors for $H_1$ and $L_1$ transitions and $E(L_2)$ is the enhancement factor for $L_2$ transitions. The results are given in columns 9 and 10 of table III. The $\delta^2$ values employed are given in column 7 of the same table. For the 66 keV, 265 keV, and 280 keV transitions we used our $\delta^2$ values obtained from angular correlation measurements. For the pure $L_1$ and $L_2$ transitions we have taken $\delta^2 = 1$.

The $\delta^2$ value for the 199 keV transition has been taken from ref. 25.
<table>
<thead>
<tr>
<th>E (keV)</th>
<th>Branching Ratio a(E)</th>
<th>T_{exp} (sec^{-1}) b</th>
<th>T_{S.P.} (E_{1}) (sec^{-1}) b</th>
<th>T_{S.P.} (E_{2}) (sec^{-1}) b</th>
<th>T_{M.G.} (E_{1}) mixing ratio</th>
<th>B(E_{1})</th>
<th>B(E_{2})</th>
<th>E(E_{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>0.0226 ± 0.0007</td>
<td>6 ± 335 x 10^9</td>
<td>2.95 x 10^4</td>
<td>-</td>
<td>0.0597 ± 0.0207</td>
<td>0.0507</td>
<td>(9.2 ± 0.4) x 10^2</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>0.065 ± 0.0022</td>
<td>(2.3 ± 0.1) x 10^7</td>
<td>2.10 ± 10^5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(9.7 ± 0.2) x 10^2</td>
</tr>
<tr>
<td>121</td>
<td>0.162 ± 0.006</td>
<td>(0.8 ± 0.221) x 10^8</td>
<td>-</td>
<td>3.25 ± 10^12</td>
<td>1.2 ± 10^12</td>
<td>-</td>
<td>(3.9 ± 0.2) x 10^5</td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>0.012 ± 0.0180</td>
<td>(2.75 ± 0.743) x 10^8</td>
<td>-</td>
<td>4.27 ± 10^12</td>
<td>1.4 ± 10^12</td>
<td>-</td>
<td>(1.625 ± 0.435) x 10^4</td>
<td></td>
</tr>
<tr>
<td>199 X000</td>
<td>(2.56 ± 0.186) x 10^8</td>
<td>2.26 x 10^{11}</td>
<td>5.30 ± 10^6</td>
<td>-</td>
<td>0.19 ± 0.15</td>
<td>(3.6 ± 10^3) x 10^4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>245</td>
<td>(9.8 ± 0.1259)</td>
<td>(5.6 ± 0.152) x 10^9</td>
<td>5.39 ± 10^11</td>
<td>3.05 ± 10^9</td>
<td>0.01 ± 0.0015</td>
<td>(9.6 ± 0.569) x 10^2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>1.96 ± 0.0014</td>
<td>(2.46 ± 0.141) x 10^8</td>
<td>6.36 ± 10^11</td>
<td>4.03 ± 10^2</td>
<td>0.33 ± 0.0570</td>
<td>(3.6 ± 0.30) x 10^2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>401</td>
<td>0.240 ± 0.0010</td>
<td>(6.46 ± 1.7466) x 10^7</td>
<td>-</td>
<td>1.24 ± 10^14</td>
<td>-</td>
<td>(1.7 ± 10^2) x 10^6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) These values were calculated using the following T_{2} observed.

265 keV level: = (1.5 ± 0.2) x 10^{-11} sec (ref. 19, 23)
280 keV level: = (1.8 ± 0.2) x 10^{-10} sec (ref. 22)
401 keV level: = (1.5 ± 0.2) x 10^{-2} sec (ref. 19, 22)
304 keV level: = 0.017 sec (ref. 6)
199 keV level: = (9.0 ± 1.0) x 10^{-10} sec (ref. 23)

b) Transition probabilities were calculated from single-particle model.
f) Discussion

Our results of the angular correlation of the 121-280 keV cascade give the value of the mixing parameter $\delta$ for 280 keV gamma ray as $-0.38 \pm 0.08$. This value is in good agreement with the internal conversion data$^{3,14}$ and also with the values of other angular correlation measurements$^{1,15}$. But this value is in distinct disagreement with the value $-0.75 \pm 0.10$ obtained by Van Den Bold et al.$^2$ from their angular correlation measurements. Later on Edwards and Gallagher$^3$ have pointed out that the error limits in the value of Van Den Bold et al.$^2$ were incorrectly assigned and the corrected value of the mixing parameter should be $-0.74 \pm 0.26$. This value is still not in good agreement with our measurements. This may probably be due to uncertainty in the assignments of their errors.

As regards the 265 keV transition the value of the mixing parameter $|\delta|$ from the internal conversion coefficient measurements of Edwards and Gallagher$^3$ is $0.06 \pm 0.06$ while our value is $0.12 \pm 0.02$. Metzer and Todd$^{14}$ obtained the value as $0.06 \pm 0.04$. The three measurements$^{1-2,15}$ of this angular correlation give values for $|\delta|$ as: $-0.12 \pm 0.13$, $0.16 \pm 0.06$ and $0.16 \pm 0.02$. Thus our value is in good agreement with the other reported values. The value of the mixing parameter $|\delta|$ for the 66 keV gamma ray from the internal conversion coefficient measurements by Edwards and Gallagher$^3$ is $0.21 \pm 0.07$ while our value is $0.16 \pm 0.07$. 
It should be noted that our values of the mixing parameters of various gamma rays give better limits than the other reported values. The small anisotropy in the angular correlation measurements of 66-199 keV and 136-199 keV cascades is consistent with the spin \( \frac{1}{2} \) for the 199 keV level.

As required by the single particle core coupling model\(^{16}\), the single particle low lying state of As\(^{75}\) should be coupled to the even-even core of Ge\(^{74}\) nucleus. The ground state of As\(^{75}\) may be described as being formed by the coupling of a \( p_{3/2} \) proton with the \( 0^+ \) ground state of even-even core. The states having spins \( 1/2^+, 3/2^+, 5/2^- \) and \( 7/2^- \) will result from the coupling of the first \( 2^+ \) excited state of Ge\(^{74}\) with the \( p_{3/2} \) proton.

The value of \( B(E2; 2 \rightarrow 0) \) from the first excited state to the ground state of Ge\(^{74}\) has been reported by Stelson and McGown\(^{26}\) as \((4.317 \pm 0.032) \times 10^{-4}\) e\(^+\) which corresponds to an \( E2 \) enhancement of \( 33.9 \pm 3.4 \). From the table III the \( E2 \) enhancement of the 199 keV, 265 keV and 280 keV transitions from the \( 1/2^- \), \( 3/2^- \) and \( 5/2^- \) states to the ground state of As\(^{75}\) respectively is nearly of the same order as in the even mass core of Ge\(^{74}\). This is in agreement with the prediction of deShalit\(^ {16}\) that the transitions from the excited states to the ground state in odd-even nuclei should be enhanced by the same order as in the neighbouring even-even nuclei.
As far as the $N_1$ transitions are concerned the single particle core coupling model predicts that the ground state transitions (199 keV, 255 keV and 280 keV) from the three members of the $2^+$ core single particle coupled states should have the transition probability for $N_1$ transitions as zero and therefore the $N_1$ portion of these transitions should be highly hindered. Experimentally it is not so, as is clear from table III. Also the enhancement of the 280 keV transition is smaller than predicted. This appears to be due to the mixing of the core single particle coupled states as being formed from the coupling of odd particle with the $0^+$ and $2^+$ even mass core. This mixing will make the $N_1$ transitions a bit allowed and reduce the enhancement of the $E2$ transitions.

Regarding the $9/2^+$ and $5/2^+$ states we can say that they result from the coupling of the $2^+$ state of $^{74}$Ge with the $\pi_9/2$ proton. Therefore one should expect that the transitions starting from the $5/2$ state to $5/2^−$, $3/2^−$ and ground state of $^{75}$As should be $L$-forbidden as well as "core forbidden" and hence must be highly retarded. From the table III it is clear that the 121 keV, 136 keV and 402 keV transitions, which take place from 401 keV $5/2^+$ level, are highly retarded which support the above mentioned interpretation.
References

20. NDS Nuclear Data Sheets, Nuclear Data Group, Oak Ridge National Laboratory Oak Ridge, Tennessee, USA.
2. Gamma Gamma Angular Correlation in $^{82}$Kr

a) Introduction

The radioactive beta-decay of $^{82}$Kr to the levels of $^{82}$Kr has been studied by various workers over the past decade. The presently accepted decay scheme is shown in fig.3,5. Dzhelepov et al. have reported a 1652 keV gamma transition but they were unable to fit it into the decay scheme. Recent studies have confirmed the existence of 1652 keV gamma ray leading to the first excited state at 777 keV and thereby place a highly excited state at 2429 keV. Recently Etherton and Kelly and Reaman et al. have studied the energy level structure of $^{82}$Kr using high resolution Ge(Li) detectors and permanent magnet electron spectrometers. They suggest the possible spin values for the 2429 keV level as 2, 3 and 4. The present measurements on the directional correlation of 1652-777 keV cascade were performed in order to assign a unique spin value to the 2429 keV level and to find the multipole admixture in 1652 keV gamma transition. In addition the angular correlation measurements have been made on 1317-777 keV, 619-1475 keV, 554-1475 keV and 554-1317 keV gamma cascades in order to estimate the amount of multipole admixture in various other gamma transitions.

The experimental gamma transition probabilities are calculated from the observed half lives. The results are compared with the theoretical estimates for the single proton
Decay Scheme for $\text{Br}^{82}$
model. Retardation and enhancement factors calculated from the results are discussed.

b) Experimental Techniques and Source Preparation -

The isotope Br$^{82}$ ($T_1 = 35$ hours) for these investigations was obtained from the isotope division of Bhabha Atomic Research Centre, Trombay, India. To remove the presence of 4.4 h Br$^{80}$ activity, the source was allowed to decay for a period of 3 days before the investigations were performed. All the coincidences and directional correlation measurements were carried with the help of two identical scintillation spectrometers having 1 x 2" NaI(Tl) crystals and conventional slow-fast coincidence circuit of resolving time $2 \gamma = 0.15$ microseconds.

The source was taken in dry form in a source holder which consisted of a thin perspex rod with a hole of 1/10 inch in diameter and 1/5 inch in length. The source was placed at a distance of 10 cms from each crystal. For the angular correlation work the coincidences were recorded from 90° to 270° at an interval of 22.5 degrees. The gamma ray spectrum is shown in fig. 3.9. From the coincidence measurements it was found that 1652 keV gamma ray is in coincidence with 777 keV gamma ray. Other coincidences with strong gamma rays are in agreement with the established decay scheme shown in fig. 3.8.

c) Measurements -

(1) Angular correlation of 1652-777 keV cascade.

In this cascade there were no interfering
Singles Spectrum of $^{82}$Br
coincidences from other gamma rays. The correlation function for this cascade after applying solid angle correction was found to be

$$W(\theta) = 1 + (0.037 \pm 0.016)P_2(\cos \theta) - (0.035 \pm 0.025)P_4(\cos \theta) - (1)$$

The first excited state of $^{82}$Kr has been shown to be at 777 keV by coulomb excitation$^{16}$ and nuclear resonance fluorescence$^{17}$. The spins and parities of the ground state and the first excited state are $0^+$ and $2^+$ respectively. From internal conversion coefficient measurements,$^8$ 777 keV gamma ray is found to be pure $E2$. So the possible spin sequences for the cascade 1652-777 keV are the following:

(i) $2(\Omega, Q)2(Q)0$
(ii) $3(\Omega, Q)2(Q)0$
(iii) $4(Q)2(Q)0$

The spin sequence (iii) is not compatible with equation (1) because the theoretical correlation coefficients for this sequence are $A_2 = 0.1020$ and $A_4 = 0.0091$. If we consider the spin sequence (i) for the cascade, the value of $A_2$ allows in 1652 keV gamma ray either 92.6% dipole and 7.4% quadrupole or 97.9% quadrupole and 2.1% dipole radiations. But in both the above cases it is found that the value of $\delta$ is not compatible with the -ve value of $A_4$. So the only spin sequence which is now left to fit in the data is $3(\Omega, Q)2(Q)0$. From the graphical analysis of the observed $A_2$ coefficient shown in fig. 3,10, the quadrupole content of 1652 keV gamma ray is $Q_{1652} = (0.9057 \pm 0.0136)$ or $(0.0210 \pm 0.0070)$. Therefore the 1652 keV gamma ray is either
Fig. 3:10  
Analysis of 1652-777 KeV angular corn terms of 3(D,θ)2(θ)0 spin sequence.
predominantly dipole in character having quadrupole content of (2.1 ± 0.7)% or predominantly quadrupole in character with a dipole admixture of (9.4 ± 1.3)%. If the mixing ratio analysis is made of the $A_{2}$ coefficient it favours a predominantly dipole character for the 1652 keV gamma ray. This result is in agreement with the results of Koch et al.\textsuperscript{12} but it is in quite disagreement with the result of Banas et al.\textsuperscript{16} who prefer a predominantly quadrupole character for this transition from their angular correlation measurements.

(i) 1317-777 keV cascade.

In this gamma gamma cascade there was a negligible contribution (≤ 2.0%) of the higher gamma cascades mainly due to 1652-777 keV. The measured correlation function after applying the solid angle correction is

$$W(\theta) = 1 - (0.025 \pm 0.006)R_2(\cos \theta) - (0.067 \pm 0.012)R_4(\cos \theta)$$

(2)

As the spin of the 3094 keV level is established to be $3^+$, this correlation function is analysed in terms of the spin sequence $3(\Omega, \Omega)2(\Omega, \Omega)$. It is found from figure 3.11 that 1317 keV gamma ray is mostly quadrupole in character and contains a dipole admixture of (5.0 ± 0.3)%). This is in agreement with the results of Atherton and Kelly.\textsuperscript{8}

(iii) 629-1475 keV and 554-1475 keV cascades.

As 554 keV and 629 keV gamma ray peaks are not resolved there will be some interference of the triple cascade 554(629)1475 keV, however there were practically no contribution in the angular correlation measurement of 629-1475 keV cascade.
Analysis of 1317-1777 KeV angular correlation in terms of $3(D,\alpha)2(\alpha)0$ Spin Sequence.
due to Compton coincidences. At the channel settings and energy windows used for 619 - 1475 keV cascade angular correlation the contribution of 55^b(619)1475 keV cascade was found to be (5.6 ± 1.0)% and the angular correlation function after applying solid angle correction is

\[ w(\theta) = 1 - (0.119 \pm 0.004) P_2(\cos \theta) - (0.031 \pm 0.009) P_4(\cos \theta) \]  

Similarly, when the channels were set for 55^b-1475 keV angular correlation the main interference was due to 619-1475 keV cascade. Its contribution at the channel settings and energy windows used was estimated to be (6.9 ± 1.1)% and the angular correlation function after applying the solid angle correction is

\[ w(\theta) = 1 - (0.037 \pm 0.008) P_2(\cos \theta) + (0.001 \pm 0.007) P_4(\cos \theta) \]  

From equations (3) & (4) the true angular correlation functions for 619-1475 keV and 55^b-1475 keV cascades can be calculated. The values obtained are:

For 619-1475 keV cascade,

\[ w(\theta) = 1 - (0.110 \pm 0.004) P_2(\cos \theta) - (0.028 \pm 0.010) P_4(\cos \theta) \]  

For 55^b-1475 keV cascade

\[ w(\theta) = 1 - (0.041 \pm 0.009) P_2(\cos \theta) + (0.026 \pm 0.014) P_4(\cos \theta) \]  

As the spin of the 1475 keV level is 2^+, the 619-1475 keV cascade follows the spin sequence 3(0,1)2(\gamma)0. As shown in fig. 3.12, the correlation function given by the eq. (5) has been found to be consistent with the spin sequence 3(0,1)2(\gamma)0 with a dipole admixture of
Fig. 3.12

Analysis of 619-1475 keV angular correlation in terms of $3(D,0)2(Q)0$ spin sequence.
(16.74 ± 0.46)% in 619 keV gamma ray. These results are in agreement with the previous results.\textsuperscript{2-3,8)}

As the spin of 264\,\textit{keV} level is \(\text{4}^\text{\textit{g}}\), the 554(619) 1475 keV cascade follows the spin sequence \(4\,^{\text{P}}_1\,^{\text{Q}}_2\,0\,^{\text{Q}}_2\,\text{O}\). Taking the quadrupole content in the 619 keV gamma ray as \((16.74 ± 0.46)\%\), the quadrupole content in the 554 keV gamma ray was found to be \((27±0.5)\%. This skipped angular correlation has been analyzed by the method given in ref. 19) and the graphical analysis is shown in fig. 3.13.

(iv) 554-1317 keV cascade.

For this cascade the correlation function, after applying the correction for solid angle was found to be.

\[
W(\theta) = 1 - (0.079 ± 0.010)\cos^2\theta + (0.002 ± 0.010)\cos^4\theta
\]  

(7)

In the above correlation function the interfering coincidences are present due to the following cascades:

1. 554 - 1475 keV cascade
2. 619 - 1475 keV cascade
3. 1317 - 777 keV cascade

Their contributions towards the coincidences were estimated to be \((7.2±1.0)\%\), \((6.4±1.2)\%\) and \((6.9±1.0)\%\) of the total coincidence counts respectively. Corrections for these interferences are made from their measured angular correlations. The angular correlation function after applying correction for these interferences becomes
Analysis of 554(619)1475 keV angular correlation in terms of 4(D, Q)3(D, Q)2(\theta)0 spin sequence.
\[ w(\theta) = 1 - (0.074\pm 0.012) \cos^2 \theta + (0.007\pm 0.020) \cos \theta \] (7)

The 554 keV cascade follows the spin sequence \( ^4(\nu,\gamma) ^3(E,\gamma) ^2 \). Taking the quadrupole content in the 1317 keV gamma ray as \( (5.08\pm 0.33) \% \), it was found by the graphical analysis, as shown in figure 3.14, that 554 keV gamma ray is mostly dipole in character and contains \( (3.6\pm 0.5) \% \) quadrupole content.

d) Transition Rates

The branching ratios for various transitions have been calculated by the formula given in Chapter III page 53. The values of intensities used are taken from ref. 14) and the values of internal conversion coefficients used are taken from ref. 6). The values of the branching ratio \( a(E) \) are given in column 2 of table 2.

The experimental transition probabilities have been calculated by the formula given in Chapter III page 53, using the above calculated branching ratios and conversion coefficients. The half life data is taken from ref. 9) and 17). The calculated \( T_{\text{exp}}(E) \) values in sec\(^{-1}\) units are given in column 3 of the same table.

Transition probabilities of single proton were estimated from the Weisskopf formula\(^ {20} \) taking the statistical factor \( S=1 \). The calculated \( T_{\text{exp}}(E) \) for \( ^4 \nu, E_1 \) and \( E_2 \) transitions are given in column 4, 5 and 6 of the same table.
Fig. 3.14

Analysis of the 554-1317 keV angular correlation in terms of a (D,Q)3(0,0)2 spin sequence.

\[ Q_2 = 0.949 \pm 0.008 \]
\[ 0.036 \leq Q_1 \leq 0.041 \]
### TABLE 1

Transition Probabilities \( (T) \), retardation factors \( (B) \) and enhancement factors \( E \)

| \( E_r \) (keV) | Branching Ratio \( (B) \) | \( T_{exp} \) \((\text{Sec}^{-1})^a\) | \( T_{sp} (M_1) \) \((\text{Sec}^{-1})^b\) | \( T_{sp} (K_1) \) \((\text{Sec}^{-1})^b\) | \( T_{sp} (E_2) \) \((\text{Sec}^{-1})^b\) | Mixing Ratio \( \delta^2 \) | \( B(M_1) \) \(|\) | \( B(E_2) \) \(|\) |
|------------|----------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|
| 554 | 0.7520 | > 1.3021x10^9 | 4.930x10^12 | 3.208x10^14 | 1.375x10^9 | \( E_1 \) | - | < 2.4637x10^5 |
| 619 | 0.6105 | > 7.0436x10^9 | 6.877x10^12 | - | 2.395x10^9 | 4.975x10^9 | < (5.6370±0.1673)x10^3 | - | > 2.4487±0.0141 |
| 696 | 0.6094 | < 5.0633x10^11 | 9.665x10^12 | - | 4.365x10^9 | 9.0±2.97 | > (1.9406±0.5764)x10^2 | - | (19.415±3.089) |
| 777 | 1.0000 | < (1.43±0.23)x10^16 | - | - | 7.463x10^9 | \( E_2 \) | - | - |
| 828 | 0.2480 | > 4.2943x10^8 | - | 3.334x10^14 | - | \( E_2 \) | - | < 6.2295x10^5 |
| 1044 | 1.0000 | > 1.1547x10^10 | - | - | 3.269x10^10 | \( E_2 \) | - | > 0.3530 |
| 1316 | 0.3695 | > 4.496x10^9 | 6.625x10^13 | - | 1.047x10^11 | 16.785±1.267 | < 16.785±1.267 | - | < 0.408±0.001 |
| 1475 | 0.3906 | < 3.2633x10^11 | - | - | 1.84±10^11 | \( E_2 \) | - | < 1.777 |

---

**a)** These values were calculated using the following \( T \) observed:

- 777 keV level: = (4.78±0.76) ps. (ref. 17)
- 1475 keV level: > 0.83 ps. (ref. 17)
- 1821 keV level: < 0.06 ns. (ref. 9)
- 2094 keV level: < 0.06 ns. (ref. 9)
- 2648 keV level: < 0.4 ns. (ref. 9)

**b)** Transition probabilities were calculated from single particle model.
Retardation and enhancement factors are evaluated using the formula given in Chapter III page 574. The results are given in columns 8 to 10 of the table 1. The $\delta^2$ values employed are given in column 7 of the same table. For the 619 keV and 1317 keV transitions we have used our values of $\delta^2$ obtained from angular correlation measurements. For the pure $E_1$ and $E_2$ transitions we have taken $\frac{\delta^2}{1+\delta^2} = 1$. The $S^2$ values for the 698 keV transition has been taken from the measurements of Atherton and Kelly. 8)

e) Discussion

From the angular correlation measurements on the cascade 1652-777 keV the spin of 2429 keV level comes out to be 3 and the 1652 keV gamma ray is predominantly dipole in character. This is in agreement with the measurement of Koch et al. 12) but is in disagreement with the result of Bann et al. 16) who prefer the predominant quadrupole character of this transition.

The 554 keV gamma ray is found to be almost pure $E_1$ having only very small amount of quadrupole admixture from the angular correlation measurements of 554-1475 keV and 554-1317 keV cascade.

The energy levels in Kr$^{82}$ constitute a rotational band. The $2^+$ and $4^+$ levels at energies 777 keV and 1821 keV respectively along with the $0^+$ ground state of Kr$^{82}$ constitute a ground state band with $K = 0$. The $2^+$ and $3^+$ levels at at energies 1475 keV and 2094 keV are due to
γ-band with band head K=2 at 1475 keV. Obstner[21] has plotted the retardation factors for all K-allowed and K-forbidden transitions as a function of |Δk|. We have compared our retardation as well as enhancement factors with the range of values obtained in other cases for the same type of transitions. We find that our values for most of the transitions lie within the limits of retardation factors for other nuclei as shown in Table II.
### TABLE II
Change in quantum number (Δk), retardation factors (B) and enhancement factors $B_e$.

<table>
<thead>
<tr>
<th>$E_s$ (keV)</th>
<th>Δk</th>
<th>$B(M_1)$</th>
<th>$B(S_1)$</th>
<th>$B(S_2)$</th>
<th>$B(M_1)^a$</th>
<th>$B(S_1)^a$</th>
<th>$B(S_2)^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>554</td>
<td>2</td>
<td>$&lt;2.46 \times 10^5$</td>
<td>-</td>
<td>-</td>
<td>$\sim 10^4$ to $10^8$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>619</td>
<td>0</td>
<td>$(5.64 \pm 1.7) \times 10^3$</td>
<td>-</td>
<td>$&gt;2.45 \pm 0.2$</td>
<td>$\sim 10^2$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>698</td>
<td>2</td>
<td>$(1.94 \pm 0.5) \times 10^2$</td>
<td>-</td>
<td>$&lt;1.55 \pm 0.7 \times 10^2$</td>
<td>$\sim 10^2$ to $10^5$</td>
<td>-</td>
<td>$\sim 10^{-2}$ to $10^3$</td>
</tr>
<tr>
<td>777</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>$&lt;1.02 \pm 0.09$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>828</td>
<td>4</td>
<td>$&lt;8.23 \times 10^5$</td>
<td>-</td>
<td>-</td>
<td>$\sim 10^9$ to $10^{11}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1044</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>$&gt;0.35$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1318</td>
<td>2</td>
<td>$(16.75 \pm 1.27)$</td>
<td>-</td>
<td>$&gt;1.3 \pm 0.1$</td>
<td>$\sim 10^2$ to $10^5$</td>
<td>-</td>
<td>$\sim 10^{-2}$ to $10^3$</td>
</tr>
<tr>
<td>1475</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>$&lt;1.77$</td>
<td>-</td>
<td>-</td>
<td>$\sim 10^{-2}$ to $10^3$</td>
</tr>
</tbody>
</table>

*a* The approximate value (ranges) of the retardation factors for $E_1$, $M_1$ and $S_2$ transitions, taken from reference 71.

14
References

12. J. Koch et al., Zeit fur Naturforch 20a (1965) 245.
3. Gamma Gamma Angular Correlation in Er\textsuperscript{166}.

a) Introduction

The radioactive decay of short lived \( \text{Ho}\textsuperscript{166} \) (27 \(^{\text{h}}\)) has been investigated by various authors.\(^{1-11}\) The presently accepted decay scheme is shown in Fig. 3.15. The ground state of \( \text{Er}\textsuperscript{166} \) and the first excited state \( \text{Er}\textsuperscript{166} \) at 61 keV are fed by the main fraction of the beta-transitions. Only a very small percentage of beta-transitions populates the 787 keV, 1460 keV, 1654 keV and 1830 keV levels. From the 1654 keV and 1460 keV levels, 1573-61 keV and 1380-81 keV cascades go to the ground state. The angular correlation of 1573-81 keV cascade and 1380-81 keV cascade has been measured by Frasher and Hilton\(^{9)}\), "Arkland et al.\(^{10)}\) and Bodenstedt et al.\(^{11)}\). All of them have found a severe attenuation by the internal fields. Frasher and Hilton\(^{9)}\) used a source of melted \( \text{HoCl}\textsubscript{3} \) and from their angular correlation measurements of 1380-81 keV cascade, they have assigned the spin zero to the 1460 keV level. Their integral attenuation factors \( G_{2} \) and \( G_{4} \) are 0.38±0.01 and 0.49±0.02 respectively. From their angular correlation measurements on 1573-81 keV cascade they were not able to assign a unique spin value for the 1654 keV level. "Arkland et al.\(^{10)}\) have used a liquid source of \( \text{HoCl}\textsubscript{3} \) in aqueous solution for the measurements and they have obtained the values of attenuation factors \( G_{2} \) and \( G_{4} \) as 0.63±0.03 and 0.66±0.03 respectively. The authors have pointed out that their value of \( G_{4} \) is greater than \( G_{2} \).
Fig. 3-15

Decay Scheme for \(^{166}\text{Ho}\)
and this is in accordance with the prediction of A. Abragam and H.V. Pound\textsuperscript{12}) for attenuation by time dependent electric interactions. They have assigned a value of 1\textsuperscript{2} for the spin of 1654 keV level and conclude that the 1573 keV gamma radiation is almost pure \(E_1\). Bodenstedt et al\textsuperscript{11}) have used an unsaturated solution of HoCl\(_3\) in water. Their values for the integral attenuation factors \(G_2\) and \(G_4\) come out to be 0.86\(\pm\)0.08 and 0.56\(\pm\)0.04 respectively. The authors have explained their value of \(\frac{G_4}{G_2}<\frac{1}{2}\) on the basis of predictions of A. Abragam and H.V. Pound\textsuperscript{12}) assuming that the attenuation is caused by time dependent magnetic interactions. In view of these discrepancies it was considered worthwhile to reinvestigate the angular correlation of 1380-81 keV and 1573-81 keV cascades.

b) \textbf{Experimental Technique and Source Preparation:}

The isotope Ho\textsuperscript{166} (27 h) was obtained from Bhabha Atomic Research Centre, Trombay in the form of HoCl\(_3\) solution. The source was prepared in a perspex cylindrical cell and the aqueous solution of HoCl\(_3\) was used for the measurements. Both the crystals were shielded by lead and a lead absorber was placed before the high energy detector to reduce the back-scattering. The coincidences were recorded at \(\pi\) in equispaced angles from 90\(^\circ\) to 270\(^\circ\).

c) \textbf{Measurements:}

As the low energy detector was calibrated at 81 keV peak, the unwanted admixture of K-X-rays was prevented. The
spectrum in coincidence with 81 keV gamma ray is plotted and is shown in fig. 3.16. From the spectrum it is obvious that there will be some contribution of 1573 keV gamma ray when the 1380 keV gate is channeled at any position on 1380 keV peak. In our channel position the contribution of the 1573 keV gamma-ray was found to be (15.6±1.2)% from the analysis of the coincidence spectrum shown in fig. 3.16.

The angular correlation function for the 1380-81 keV cascade after applying solid angle correction is comes out to be,

\[ W(\theta) = 1 + (0.198\pm0.010)P_2(\cos \theta) + (0.612\pm0.022)P_4(\cos \theta) \]  

and the angular correlation function for the 1573-81 keV cascade after applying the solid angle correction is

\[ W(\theta) = 1 - (0.21\pm0.014)P_2(\cos \theta) + (0.051\pm0.029)P_4(\cos \theta) \]  

This correlation function is in agreement with the values obtained by Harklund et al. \cite{10} and Bodenstedt et al. \cite{11}.

The corrected value of the angular correlation function for 1380-81 keV cascade after subtracting the contribution of 1573-81 keV cascade is

\[ W(\theta) = 1 + (0.27\pm0.014)P_2(\cos \theta) + (0.715\pm0.029)P_4(\cos \theta) \]  

The spin and parity of the ground state, the 81 keV level and 1460 keV level are well established\cite{12,13,14,15} to be as 0\(^+\), 2\(^+\) and 0\(^+\) respectively. The theoretical value of angular correlation for a 0\(^+\)\(\rightarrow\)2\(^+\)\(\rightarrow\)0\(^+\) cascade is

\[ W(\theta) = 1 + 0.3571 \ P_2(\cos \theta) + 1.1426 \ P_4(\cos \theta) \]  

(4)
Coincidence Spectrum with the 81 keV Gamma-ray. The setting of the Channel on 1380 keV peak for the measurement of the 1580-81 keV angular correlation is shown. The double shaded area shows the contribution of 1573 keV Gamma-ray.
Comparing eq. (4) with (3), one gets the values of integral attenuation coefficients as

\[ G_2 = \frac{A_2^{\text{exp.}}}{A_2^{\text{theory}}} = 0.766 \pm 0.041 \]

\[ G_b = \frac{A_b^{\text{Exp.}}}{A_b^{\text{Theory}}} = 0.626 \pm 0.026 \]  

In our case, \( G_2 \) is greater than \( G_b \), which is in agreement with the values obtained by Bodenstedt et al.\textsuperscript{11} and in contrast with the values obtained by Narklund et al.\textsuperscript{10}.

As the intermediate level for the cascades 1573-81 keV and 1380-81 keV is the same, we can use the values of integral attenuation coefficients measured for the 1380-81 keV cascade to find the corrected correlation function for 1573-81 keV cascade, which comes out to be

\[ k(\beta) = 1 - (0.279 \pm 0.023) P_2(\cos \theta) + (0.052 \pm 0.047) P_4(\cos \theta) \]  

The above correlation function is in accordance with the spin sequence 3(1,2)2(0) and 1(1,1)2(0). As a strong crossover transition of 165\(^\text{keV}\) keV has been observed\textsuperscript{9,10} the possibility of the spin sequence 3(2,0)2(0)0 can be ruled out. The analysis of the correlation function given by equation (6) in terms of spin sequence 1(1,0)2(0)0 is shown in fig. 3,17. From the graphical analysis the value of multipole admixture in 1573 keV gamma ray is found to be 0.23\%. Therefore 1573 keV gamma ray is almost dipole in character. As the 165\(^{\text{keV}}\) keV level is having the negative
Analysis of 1573-81 keV angular correlation in terms of \(1(D,\alpha)2(Q)0\) spin sequence
parity) the 1573 keV gamma transition is 99.77% $E_1$.

d) **Discussion**

From the 1380-61 keV angular correlation the value of $G_2$ comes out to be greater than $G_4$. This value is in agreement with the values of Wodzicki et al. [11] but in disagreement with the values of Marklund et al. [10]. To find out whether the attenuation is due to the time dependent magnetic interaction or due to time dependent electric interaction we have calculated the value of $\frac{\lambda_4}{\lambda_2}$ (defined in Chapter I and ref. 12) from our $G_2$ and $G_4$ values. This value is

$$\frac{\lambda_4}{\lambda_2} = (1.98 \pm 0.43)$$

As the ratio $\frac{\lambda_4}{\lambda_2}$ for the spin of the intermediate state $I = 2$, for time dependent electric interaction and time dependent magnetic interaction, i.e., 0.59 and 3.34 respectively [11], our value of $\frac{\lambda_4}{\lambda_2}$ suggests that the attenuation of the angular correlation is mainly due to time dependent magnetic interaction.
References

4. Gamma Gamma Angular Correlation in Ce$^{110}$-

a) Introduction-

The energy levels of Ce$^{110}$ following the decay of 
Ag$^{110m}(T_{1/2}=249 \text{ d})$ have been extensively studied.\cite{1-5} The decay
scheme as shown in fig. 3.18 can be considered as well established. The spins and parities of most of the energy
levels have been assigned on the basis of angular correlation
measurements\cite{6-11} and conversion coefficient measurements.\cite{12-15} The spin assignment for the level at 2220 keV is not definite
because the angular correlation measurements on the cascade
transitions coming to this level or starting from this level
are complicated due to the presence of many other interfering
cascades. We have tried to measure the angular correlation
of 1565-658 keV cascade to assign a unique spin value to the
2220 keV level. As the 1565 keV gamma ray is a weak gamma ray and is completely merged in relatively strong 1505 keV
photopeak, therefore any gate channelled to study 1565-658 keV
angular correlation will have sufficient contribution of
1505-655 keV cascade along with other interfering cascades
and needs correction. The knowledge of 1505-655 keV
correlation is necessary to study the 1565-658 keV correlation.
It has also been found that the values of quadrupole admixture
in 1505 keV gamma ray obtained from 1505-655 keV and
764-1505 keV angular correlation measurements are different.
That is why the angular correlation measurements on the
Decay Scheme of Ag$^{110m}$
1505-558 keV and 76-1505 keV cascades have been performed. The enhancement of various transitions are discussed in the light of nuclear models.

b) Experimental technique and source preparation

The isotope Ag$^{110m}$ ($T_{\frac{1}{2}}=249$ days) for these measurements was obtained from the isotope division of Sahada Atomic Research Centre, Trombay, India. All the coincidence and angular correlation measurements were carried out with the help of two identical $\frac{1}{4"}{\times}2"$ NaI(Tl) crystals and conventional slow-fast coincidence circuit of resolving time $T=0.15$ microseconds.

The source was placed in a source holder which consisted of thin perspex rod having hole of 1/8 inch in diameter and 1/4 inch in length and was used for the measurements when it was in completely dry form. The source holder was placed at a distance of 10 cms from each crystal. The coincidences were recorded at nine equispaced angles between 90° and 270°.

c) Measurements:

(i) 76-1505 keV cascade

The singles spectrum of Ag$^{110m}$ is shown in fig.3.19. For the study of the angular correlation of this cascade, the 1505 keV gate channel was set in such a way so that the contribution of 1476 keV gamma ray in 1505 keV gate is
Gamma ray Spectrum of \( ^{156}Eu \) position used for 1565-65 keV angular correlation is shown.

- 658 keV
- 764 keV
- 884 keV
- 937 keV

Counts × 10^-4

Pulse height in Volts
minimum. The single channel analyser on the 764 keV gamma ray was adjusted as shown in fig. 3.20(a). This figure shows the coincidence spectrum in coincidence with the 1505 keV gate. At these settings no contribution of other cascades except the unknown interferences due to the cascades 764-1476 keV and 1476-667 keV is expected. The correlation function after applying the solid angle correction is found to be,

\[ W(\theta) = -0.147 \pm 0.009 P_2(\cos \theta) + 0.017 \pm 0.019 P_4(\cos \theta) \]  \hspace{1cm} (1)

The 2162 keV and 2926 keV levels are having spins 2/3 and 5 respectively.\(^5\) Therefore 764-1505 keV cascade follows the spin sequence 5(0)3(0,1)2. By the graphical analysis (shown in fig. 3.21(a)) of this cascade angular correlation function in terms of 5(0)3(0,1)2 spin sequence, the value of mixing parameter was found to be,

\[ \xi = -0.23 \pm 0.05 \hspace{1cm} \text{or} \hspace{1cm} \xi = -2.2 \pm 0.2 \]

From this one gets the value of quadrupole admixture \( Q_{1505} = (0.05 \pm 0.01) \) or \( (0.63 \pm 0.03) \). Thus 1505 keV gamma ray is mostly dipole in character having \( (5_{21}) \) quadrupole admixture or mostly quadrupole in character having \( (1_{21}) \) dipole admixture. For this gamma ray neither the internal conversion coefficient measurements\(^3,5\) nor the N\(_e\) value (as it is having the error comparable with its value) can give a unique value of admixture.
(a) Gamma-ray Spectrum in coincidence with 1505 keV Gamma ray. The gate positions used for 1505-658 and 764-1505 keV angular correlation are shown.

(b) Gamma-ray spectrum in coincidence with the 1565 keV Gamma ray.
(11) 1505-656 keV cascade.

For the angular correlation of this cascade the single channel analyzer was adjusted on the 656 keV gamma ray as shown in fig. 3.20(b). In this gate position the contribution of 764-1505 keV cascade was estimated to be (11.5±2.5)%. After applying the correction due to 764-1505 keV cascade by its known correlation and after applying the solid angle correction the directional correlation function comes out to be,

\[ W(\theta) = 1 - (0.032±0.012)P_2(\cos \theta) - (0.062±0.016)P_4(\cos \theta) \]  

(2)

The 1505-656 keV cascade follows the spin sequence 3(3/2)0. The analysis of the correlation function given by eq. (2) in terms of 3(3/2)2(1/2)0 spin sequence is shown in fig. 3.21(b) which gives the value of the mixing parameter \( \theta = 0.033±0.04 \) or \( \theta = 0.143±0.40 \). This corresponds to a quadrupole admixture in 1505 keV gamma ray as \( \theta_{1505} = (0.154±0.013) \) or \( (0.945±0.030) \). Thus 1505 keV gamma ray is either almost dipole in character having (15.4±1.3)% quadrupole admixture or almost quadrupole in character having (5.5±3.0)% dipole admixture. From the analysis of \( A_4 \) coefficient it is clear that the possibility of 1505 keV gamma ray being as mostly quadrupole in character is favoured.

Although the conversion coefficient measurements \(^{10,11}\) do not help at all in deciding the amount of multipole admixture in 1505 keV gamma ray but one may infer something
The analysis of the 764-1505 keV angular correlation in terms of $\gamma(0)3(0)2\gamma$ spin sequence.

Analysis of the 1505-658 keV angular correlation in terms of $\gamma(0)3(0)2(0)0$ spin sequence.
by comparing the relative intensities of the gamma rays. The gamma rays of energies 620 keV and 1505 keV originate from the same level and have the same value of $|\Delta k|$ (the change in quantum number $k$). Levels with spins $0^+$, $2^+$ and $4^+$ at energies 0 keV, 655 keV and 1542 keV represent the ground state band with $K=0$ and level with spin $3^+$ at 2162 keV is the level of the band with $K=2$. Therefore the fastness or the hindrance will be the same for both these transitions and so the ratio of the transition probabilities obtained from simple single particle calculations should be nearly equal to the ratio of their relative intensities. If we assume the 620 keV gamma ray as pure $K_1$ or pure $K_2$ then the ratios of various possible combinations of transition probabilities are

\[
\frac{T_{620}(1.505)K_1}{T_{620}(0.620)K_1} = 14.07
\]

\[
\frac{T_{620}(1.505)K_2}{T_{620}(0.620)K_1} = 0.043
\]

\[
\frac{T_{620}(1.505)K_2}{T_{620}(0.620)K_2} = 64.24
\]

\[
\frac{T_{620}(1.505)K_1}{T_{620}(0.620)K_2} = 2.773 \times 10^4
\]
where $T_{s.p}$ are the transition probabilities obtained from single particle estimates. The experimental value of the ratio of the intensities of 1.505 MeV and 0.650 MeV gamma rays is $5.0 \pm 0.5$. All these values indicate that the 1.505 MeV gamma ray cannot be pure $h_4$ or pure $h_2$ and the chance of being the 1.505 MeV gamma, as mostly quadrupole is large in comparison to the possibility of its being mostly dipole. This is consistent with our angular correlation measurements.

(iii) 1565-655 keV angular correlation.

Fig. 3.20(b) shows the coincidence spectrum when the gate channel was fixed at the sloping portion of 1505 keV peak (shown by two lines in fig. 3.19) to accept the 1565 keV gamma rays. In this gate position there will be enough contribution of 1505 keV gamma ray and a very small contribution of 1476 keV gamma ray. The contribution of 1505 keV gamma ray is evident due to the fact that a second peak at 764 keV exists (shown in fig. 3.20 b) with enough intensity, which was not expected if the gate was having only 1565 keV gamma ray. In the coincidence spectrum the 658 keV and 764 keV gamma rays in coincidence with 1505 keV gamma ray would be detected with equal intensity after allowance for the variation of intrinsic photo-peak efficiency. Therefore contribution of coincidence counts due to 1505-658 keV cascade in the gate channel set to accept the 1565 keV gamma ray will be equal to the area under the coincidence photopeak of 764 keV which has been assumed to be solely due to the coincidences with 1505 keV gamma ray in the gate channel.
Although this assumption is not completely correct because there will always be some contribution due to the unknown coincident gammas, like 1565-744 keV in 764 keV as well as 658 keV gamma ray photopeaks, and these may effect the angular correlation. On the basis of this assumption the contribution of the 1505-658 keV cascade in the gate channel, set to study the 1565-656 keV angular correlation was found to be (66.9 ± 5.6)% and the uncorrected angular correlation after applying the solid angle correction is

$$W(\theta) = 1 - (0.223 \pm 0.022) \mu_2(\cos \theta) - (0.033 \pm 0.032) \mu_4(\cos \theta) \quad (3)$$

After applying the correction for the interfering 1505-658 keV cascade by its known correlation, the true correlation coefficients for 1565-656 keV are given by

$$W(\theta) = 1 + (0.063 \pm 0.030) \mu_2(\cos \theta) + (0.020 \pm 0.04) \mu_4(\cos \theta) \quad (4)$$

The spins $3/2$ or $4$ have been suggested for the 2220 keV level because this level is connected to $2^+, 4^+$ and $5^+$ by $E2$ or $M1+E2$ transitions. Thus the correlation coefficient for the 1565-656 keV cascade can be interpreted in terms of $3(3/2)2(1/2)0$ or $4(1/2)2(1/2)0$ spin sequence. The positive value of the $A_2$ coefficient even after considering the errors favours $4(1/2)2(1/2)0$ spin sequence. Thus the spin of 2220 keV level is $4$ which is also consistent with the favourable value obtained from the conversion coefficient measurements of Horagau et al. 5)
d) Discussion

From the results of the 1565-656 keV correlations we can infer that the favourable value of the spin for the 2220 keV level is 4 as the value of spin 3 will give large negative value of $A_2$ coefficient.

The values of angular correlation coefficients for 764-1505 keV and 1505-656 keV cascades agree with the values obtained by other investigators\(^{11}\) within the limit of experimental errors. The different values of the admixture present in 1505 keV gamma ray obtained from the two angular correlation measurements may be attributed to the unknown interferences present.

The ordering and spacing of the strongly excited states in Cd\(^{110}\) are quite similar to those predicted by the non-axial rotator model of Davydov and co-workers.\(^{13,14}\) It is interesting to compare some of the measured transition probabilities\(^{15}\) with the prediction of this model.\(^{13,14}\) This can be done by first calculating the value of the non-axiality parameter $\gamma_0$ from the energies of the states and then comparing the measured transition probability with the theoretical value calculated by substituting the value of $\gamma_0$ in the expression for this model. The value of $\gamma_0$ obtained from the energies of the first $2^+$ and second $2^+$ excited states is 26.1°. If this value is substituted in the expression for $B(E2; 22 \rightarrow 21)/B(E2; 22 \rightarrow 0)$ given in ref. 13, the value
obtained is 1.07 which can be considered to be in agreement with the experimental value\textsuperscript{15) of 1.30±0.25 within the experimental errors. The higher experimental values of the transition probability ratio may be due to the interaction of rotation and vibration in the non-axial even-even nuclei which should be taken into account as the value of the non-adiabaticity parameter $\gamma$ for Cd$^{110}$ is 0.56.\textsuperscript{14)}

The enhancement of $E_2$ transitions from the 4$^+$ and 2$^+$ states are; for 664 keV transition $P(4 \rightarrow 2) = 45.2\pm5.3$ and for 658 keV transition $P(2 \rightarrow 0) = 28.9\pm3.4$. These enhancements can be compared with the other neighbouring nuclei (see Table I and Table II of Chapter IV) and they are approximately of the same order.
References


