INVESTIGATION OF THE PROPERTIES OF THE EXCITED LEVELS OF RADIOACTIVE NUCLEI

G. NAGESWARA RAO
1963
God Thes in the
Abstract:
Page 5
ABSTRACT

The work reported in the thesis on "Investigation of the Properties of the Excited Levels of Radioactive Nuclei" has been presented in five chapters.

Chapter I. INTRODUCTION

The scope of the measurements reported in this thesis in the determination of the properties of the excited and ground levels of radioactive nuclei has been discussed. The suitability of the available nuclear models in explaining these properties and a brief account of the processes of internal conversion and angular correlation of cascade gamma rays are also given.

Chapter II. INSTRUMENTATION AND ANALYSIS OF DATA

In section A, the procedure followed in mounting the crystals and an account of the various electronic equipment that have been assembled and tested in setting up of the coincidence scintillation spectrometer are given. In section B, working of these spectrometers along with the methods followed in the analysis of the data and the various corrections applied have been described.

Chapter III. DECAY SCHEME STUDIES

The results obtained in the decay scheme studies of the various radioactive nuclei have been reported.

1) THE ENERGY LEVELS OF $\text{I}^{129}$: The energy levels of $\text{I}^{129}$ have been studied through the $\beta$-decay of $\text{Te}^{129}$ employing two NaI (Tl)
scintillation spectrometers in coincidence arrangements. In addition to confirming the presence of the previously known gamma rays of energies 27, 212, 475, 720 and 1120 keV, evidence is found for seven new gamma rays. The new gamma rays have energies of 448, 450, 625, 693, 1073, 1320 and 1520 keV. From the coincidence experiments a probable energy level scheme for $^{129}$I is proposed. Spin assignments for some of the levels are also made in the light of the existing data. The energy levels thus established experimentally are compared with the theoretical predictions based on the unified model.

B) DECAY OF $^{115}$Cd (2.3d): The decay of $^{115}$Cd (2.3d) has been studied by scintillation beta and gamma spectroscopy. The K-internal conversion coefficients of the 35, 335 keV gamma transitions in the de-excitation of $^{115}$In have been measured to be $7.6 \pm 0.8$ and $0.84 \pm 0.09$, respectively. The $\beta$-$\gamma$ coincidences showed that the 590 and 860 keV beta branchings may be of an allowed and $\Delta I=2$ unique forbidden types, respectively. From the angular correlation studies of 35-492 keV and 230-262 keV cascades, $5/2^-$, $3/2^-$ and $1/2^-$ or may be assigned to the 597, 827 and 862 keV levels respectively.

C) RADIOACTIVE DECAY OF $^{143}$Ce (33 h): The gamma rays in the decay of $^{143}$Ce (33 h) have been studied with the help of a scintillation coincidence spectrometer. The relative branchings of the various gamma rays have been estimated. By studying the $\gamma$-$\gamma$ coincidences the K - internal conversion coefficients of the 56 keV, 230 keV and 293 keV transitions were determined to be $6.4 \pm 0.6$, $0.07 \pm 0.007$ and $0.12 \pm 0.02$, respectively. The angular correlation measurements have been performed for the 293 - 56 keV cascade. From these
measurements, the spins of the ground, first and the second excited states in Pr$^{143}$ have been assigned to be 5/2 +, 7/2 + and 9/2 +, respectively. The 56 keV gamma ray was found to be a mixture of 99 ± 1% M1 and 1 ± 1% E2 and the 293 keV gamma ray a mixture of 97±1 M1 and 3 ± 1% E2.

D) THE K-CONVERSION COEFFICIENT OF THE 145 keV TRANSITION IN Pr$^{141}$: The K-internal conversion coefficient of the 145 keV transition in the decay of Ce$^{141}$ is measured with the help of scintillation spectrometers to be 0.38 ± 0.04. This value has been compared with the theoretical calculations of Sliv and Band.

E) TOTAL INTERNAL CONVERSION COEFFICIENT OF THE 840 keV TRANSITION IN Cr$^{54}$: The total internal conversion coefficient of the 840 keV transition in the decay of Mn$^{54}$ is measured to be 2.0 ± 0.5 x 10^-4. A comparison of this value with the theoretical calculations of Rose favoured the assignment of E2 multipolarity for the 840 keV gamma transition and 2 + assignment for the first excited state in Cr$^{54}$.

F) GROUND STATE SPIN OF Pr$^{144}$: The angular correlation of the 50 - 80 keV γ-γ cascade in the de-excitation of Pr$^{144}$ has been studied in a coincidence counter arrangement of half angle 90°. The analysis of these results strongly favoured a spin assignment of 1 for the ground state of Pr$^{144}$ over the previously accepted value of 0 for this state.

G) LEVEL SCHEME OF Sm$^{149}$: The gamma ray decay of Pm$^{149}$ (54 h) has been studied using scintillation spectrometers. The source was
obtained by the thermal neutron irradiation of Nd$_2$O$_3$ and the other activities were separated by an ion-exchange method. The gamma ray photopeaks were observed at 39 keV X-ray, 90, 175, 235, 530, 860 and 1100 keV energies. The halflife studies of these individual photopeaks showed that all of the 285 keV photopeak, most of the 39 keV X-ray peak and part of the 530 keV broad peak are from the decay of Pm$^{143}$ (54 h). The other peaks were attributed to various impurities. These halflife studies gave evidence for the existence of some new gamma transitions in addition to the gamma rays reported earlier.

H) DECAY OF Cu$^{62}$ (9.9 m): The source was prepared by (n,2n) reaction on pure copper target in a Cockcroft-Walton type accelerator. The gamma spectrum recorded in a 20 channel analyser gave photopeaks corresponding to 0.88, 1.15, 1.4 and 1.7 MeV energies. The peaks at 0.88 and 1.15 MeV support the earlier results. The other two high energy peaks are assumed to be from the 14m Co$^{62}$ activity which might have been produced from (n,$\alpha$) reaction.

Chapter IV. SYSTEMATICS OF E2-M1 MIXING RATIOS OF 2$^+$→2$^+$ TRANSITIONS IN EVEN NUCLEI: Systematic variation of the reduced mixing ratio ($\delta^2/E_\gamma$) of the 2$^+$$\rightarrow$ 2$^+$ mixed gamma ray transition as a function of neutron number in even nuclei is investigated. It is seen that the reduced mixing ratio approach the single particle estimate near the neutron magic numbers and near the closed neutron shells, the addition of two neutrons changes the reduced
mixing ratio quite drastically. The corresponding effect of
proton magic numbers in bringing the value of the reduced mixing
ratio nearer to the single particle estimate is observed to be
relatively small.

Chapter V. DISCUSSION: With the help of the results obtained in
the studies of the decay of some of the radioactive nuclei
presented in Chapter III, the behaviour and properties of the
ground and excited states of these nuclei have been discussed
in the light of the presently available nuclear models.
A thesis submitted to The Faculty of Science, Muslim University, Aligarh, in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Physics.
The work reported in this thesis has been done under the guidance and supervision of Dr. H.S. Hans, in the laboratories of the Department of Physics, Muslim University, Aligarh.
ACKNOWLEDGEMENTS

It is indeed a great pleasure to express my indebtedness and gratitude to Dr. H.S. Hans, Reader, Department of Physics, Muslim University, Aligarh; for his help and guidance at all stages of the present work. I am also deeply indebted to Professor P.S. Gill, M.S(S. Calif.); Ph.D.(Chicago); F.N.I; for his kind help and continued interest and encouragement throughout the course of these studies.

My thanks are also due to Dr. V.R. Potnis, Scientific Pool Officer, for many valuable discussions. I am grateful to Drs. M.L. Sehgal and C.S. Khurana for useful suggestions and Dr. W.U. Malik of the Chemistry Department for helping in the chemical separations.

Last, but not the least the award of a Research Training Scholarship by the SRCA (Scientific Research & Cultural Affairs) Ministry, Govt. of India, is gratefully acknowledged.

(G. Nageswara Rao)
Physics Department,
Muslim University, Aligarh.
# CONTENTS

<table>
<thead>
<tr>
<th>Chapter I</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1 - 21</td>
</tr>
<tr>
<td>A) NUCLEAR MODELS</td>
<td></td>
</tr>
<tr>
<td>1. Single Particle Shell Model</td>
<td>10</td>
</tr>
<tr>
<td>2. Nilsson Model</td>
<td>11</td>
</tr>
<tr>
<td>3. The Collective Model</td>
<td>11</td>
</tr>
<tr>
<td>B) INTERNAL CONVERSION PROCESS</td>
<td>12</td>
</tr>
<tr>
<td>C) ANGULAR CORRELATION OF CASCADE GAMMA RAYS</td>
<td>15</td>
</tr>
</tbody>
</table>

| Chapter II | |
| INSTRUMENTATION AND ANALYSIS OF DATA | 22 - 39 |
| A) CONSTRUCTION AND SETTING-UP OF THE SPECTROMETERS | |
| 1. Polishing and Mounting of NaI(Tl) crystals | 22 |
| 2. Linear Amplifier | 23 |
| 3. Cathode Followers | 24 |
| 4. High Voltage Power Supplies | 24 |
| 5. Coincidence Circuit | 25 |
| 6. Gate Circuit | 25 |
| B) ANALYSIS AND CORRECTIONS | |
| 1. Scintillation Spectrum | 26 |
| 2. Compton Edges and Backscattered Peaks | 27 |
| 3. Intensity Measurements | 28 |
| 4. Escape Peak Intensities | 28 |
| 5. Calculation of the Intensities of Sum Peaks | 29 |
| 6. Calculation of the Percentage Contributions in (γ-γ) Cascades | 30 |
| 7. Gamma Ray Transition Probabilities | 31 |
| 8. Angular Correlation Studies | 32 |
| 8.1 Evaluation of the \( C_4 \) Coefficients | 34 |
| 8.2 Finite Angular Resolution Correction | 35 |
Chapter III

DECAY SCHEME STUDIES

A) THE ENERGY LEVELS OF I\textsuperscript{129}

1. Introduction 40
2. Source Preparation 40
3. Gamma Ray spectrum 41
4. Gamma-gamma Coincidence Experiments 43
5. Angular Correlation Experiment 46
6. The Decay Scheme 47

B) DECAY OF Cd\textsuperscript{115}(2.3d)

1. Introduction 51
2. Coincidence Studies 51
3. The $\gamma$ Measurements 54
4. Beta-gamma Coincidences 55
5. Angular Correlation Measurements 56
6. Discussion and Results 57

C) RADIOACTIVE DECAY OF Ce\textsuperscript{143}(33h)

1. Introduction 62
2. Gamma Ray Intensity Measurements 62
3. The $\gamma$ Measurements 64
4. Angular Correlation Measurements 66
5. Discussion and Results 67

D) THE K-CONVERSION COEFFICIENT OF THE 145 keV TRANSITION IN Pr\textsuperscript{141} 71

E) TOTAL INTERNAL CONVERSION COEFFICIENT OF THE 840 keV TRANSITION IN Cr\textsuperscript{54} 74

F) GROUND STATE SPIN OF Pr\textsuperscript{144}

1. Introduction 77
2. Source Preparation 77
3. Angular Correlation Studies 78
4. Discussion and Results 78
G) LEVEL SCHEME OF Sm$^{149}$
1. Introduction 81
2. Source Preparation 82
3. Halflife Studies 82

H) DECAY OF Cu$^{62}$ (9.9m)
1. Introduction 85
2. Source Preparation 85
3. Gamma Ray Spectrum 86

Chapter IV

SYSTEMATICS OF E2 - M1 MIXING RATIOS OF 2$^+$ → 2$^+$ TRANSITIONS IN EVEN NUCLEI 88 - 101
1. Introduction 88
2. Systematics of '5' in 2$^+$ → 2$^+$ Transitions in Even Nuclei 92
3. Results 94
4. Discussion 95
5. References for '5' 96

Chapter V

DISCUSSION 102 - 107
Chapter I

Introduction

One of the main problems of low energy nuclear physics is the determination of the properties of the nuclear energy levels. They are usually characterised by the energy \( E \), total angular momentum \( J \), parity \( \pi \), magnetic moment \( \mu \), electric quadrupole moment \( Q \), partial level widths and total transition probabilities. A short account regarding the scope of the work reported in this thesis in the determination of some of these properties of the ground and excited levels of the radioactive nuclei, is given below.

A nucleus in an excited state can decay through one, or many of the various processes, namely, by the emission of a gamma ray, conversion electron, beta positive, beta negative, \( \alpha \)-particle etc. and by capturing an orbital electron. By studying the nature of these transitions, one can infer the properties of the nuclear energy levels.

The conservation of angular momentum and parity give the selection rules for the gamma ray emitted, such as 1)

\[
|J_i - J_f| \leq L \leq (J_i + J_f)
\]

\[
\Delta \pi = \pi_i / \pi_f = (-1)^L \text{ for EL transition}
\]

\[
= (-1)^{L-J} \text{ for ML transition}
\]

Where \( J_i, J_f \) are the angular momenta for the initial and final states and \( \pi_i, \pi_f \) are the corresponding parities for these
states respectively. Because of the transverse nature of the radiation, the electromagnetic monopole (EO) emission is forbidden.

Expansion of the radiation field in spherical harmonics gives a series of terms for the radiation field, which are associated with definite angular momenta. Since the wavelength ($\lambda$) of the emitted radiation is usually much larger than the nuclear size ($R$), the probability for the emission of higher multipoles become smaller by increasing powers of $(R/\lambda)^2$, which implies that for all practical purposes we have to consider only the lowest multipole fields unless they are forbidden by some special selection rules. The transition probability

$$\lambda_L = \frac{8\pi (L+1)}{L[(2L+1)!!]^2} \frac{(\omega/c)^{2L+1}}{\hbar} \beta(L, J_i \rightarrow J_f)$$

where the evaluation of the reduced matrix element

$$\beta(L, J_i \rightarrow J_f) = \sum_{m_i, m_f} f / Q_{LM}^2$$

depends upon the specific nuclear model under consideration.

Because of the poor resolution of the scintillation spectrometers, they are particularly unsuitable for precision energy measurements. However, in the case of gamma ray energy measurements, calibration of the spectrometer with various standard gamma sources and a least-squares fit of the data to a straight line (since the response of the well mounted NaI(Tl) crystals are found to be fairly linear even up to low energies) can give energies accurate to 0.5%. In the energy measurements
given in this thesis, the centroid of the photopeak was carefully located and the energies were determined from the least-squares fitted energy calibration curve. The errors in the gamma ray energies were estimated from the uncertainties in the calibration curve and in locating the centroid of the peak positions. The errors, which are introduced when the low energy photopeaks are separated from the Compton background of the high energy gamma rays were also considered.

The energy dependence of the efficiency introduces some errors even in the relative intensity measurements. While measuring the relative intensities every care has been taken to reproduce the geometry of the source and the crystal. These measurements even after applying the usual corrections may contain an error of \( \approx 2\% \) or even more. The precise gamma ray energy measurements are quite helpful in assigning the level energies, establishing the cross-over transitions and in determining the beta ray end-point energies also. These measurements have also been quite useful in studying the systematics and the suitability of the various nuclear models.

The intensity measurements besides giving valuable information about the nature of the transition involved (which may further help in assigning the spins and parities of the various excited states) may also throw some light on the branching ratios, order of the levels, cascade gamma rays and on the partial half-lives of the beta branchings.
While establishing the decay scheme of a radioactive nucleus, ($\beta^{-\gamma}$) coincidence measurements can decide the position of a gamma transition. The shape of the beta spectrum along with the log($ft$) value is useful in deciding the degree of forbiddenness of the beta transition, which helps in assigning the spins and parities of the excited states involved.

The study of the beta decay processes gives good information about the type of beta interaction also. From an estimate of the relevant matrix elements, successful attempts have been made to define the order of the interaction constants $^3, ^4$. The electron-neutrino correlations in particular should settle whether the tensor or pseudo-vector coupling is responsible for the G.T. component of radiation, or whether the scalar or vector coupling is responsible for the Fermi radiation. Experiments regarding the time reversal invariance and the lepton conservation in the beta decay are yet to be performed.

The pulse-height produced per MeV energy lost in the organic phosphors like anthracene and stilbene is much smaller than that produced in the inorganic crystals like NaI(Tl) etc., but still the organic crystals are usually preferred in scintillation beta spectrometry, since their low atomic number reduces the scattering of the primary electrons. The bad resolution of the beta scintillation spectrometers makes them unsuitable for the studies of the beta energies below 30 keV or so. They are reliable for studying the shapes of the beta spectra etc., but
the beta end-point energies obtained with the beta scintillation spectrometers are not very accurate as they may contain large errors even after applying the finite resolution corrections. The $4\pi$ geometry of the split crystal scintillation spectrometer makes it indispensable in the studies of the low specific activity sources. Because of the fast response of the scintillation spectrometers, they are particularly useful in the fast coincidence work.

The study of the conversion process has been found to give many finer details. The importance of the precision conversion coefficient measurements is tremendously increased after the now well established static nuclear size effects of Sliv and Listengarten\textsuperscript{5} and the dynamic effects of Church and Weneser\textsuperscript{6}. Besides them the nuclear model dependence of the conversion coefficients has been theoretically investigated\textsuperscript{7}. The studies of the systematics\textsuperscript{8} of the internal conversion coefficients of the pure E2 multipoles in $2^+ \rightarrow 0^+$ transitions in the deformed nuclei of the heavy elements show some similar effects. However before coming to concrete conclusions we should remeasure most of the conversion coefficients with better accuracy and precision so that these finer details may be well observed. The conversion coefficient data besides giving good information about the applicability of nuclear models, also gives valuable insight about the type of nuclear transitions involved. Comparison of the experimental results with the theoretically calculated values enable us to infer the nature
of the gamma rays emitted which may further allow us to assign
the spins and parities of the nuclear energy levels. For the
experimental determination of these conversion coefficients, the
suitability of a particular technique mainly depends upon the
case under consideration. However, when the X-ray energy is
considerable, a comparison of the intensities under the X-ray
peak and the gamma ray photopeak either in coincidences or in
single spectrum of a scintillation spectrometer can give fairly
consistent results after taking account of the usual corrections.
Yet times, the scintillation spectrometer in spite of its poor
resolution is more suitable for conversion coefficient measurements
because of its high efficiency and its less likeliness to contain
systematic errors.

The E.C/\(\beta^+\) values combined with the log (ft) values and
shapes of the beta spectra can give good information about the
spins, parities and energies of the excited levels involved.
The branching ratios (E.C/\(\beta^+\)) are quite sensitive to the
end-point energies. A comparison of the experimental and
theoretical values of these ratios can give accurate end-point
energies. In non-unique cases, these ratios may perhaps be
made use of in the evaluation of nuclear matrix elements also.
Though the finite nuclear size effects were theoretically shown
to be small\(^9\), it is quite possible that these effects may also
be observed in accurate and systematic studies of the branching
ratios. These may yield some information about the nuclear
charge distribution. It is quite expected that these studies along
with the development of the theory may give some idea about
the finite nuclear size effects, nuclear charge distribution,
second order corrections, effects of averaging the wave functions
over the nuclear volume\textsuperscript{10}) etc.. The fact that these branching
ratios are very sensitive to the Fierz interference terms allowed
Sherr and Miller\textsuperscript{11}) to calculate the value of $\frac{\gamma_\alpha}{\gamma_\gamma} \approx 1 \pm 2\%$
in the case of a pure G.T. coupling in Na\textsuperscript{22}. Recently much work
has been done in obtaining the Fierz interference terms from the
accurately determined branching ratios.

The internal bremsstrahlung is the process in which
neutrinos and inhomogeneous gamma rays are simultaneously
emitted along with the beta decay. The photons are emitted
when the electronic charge is suddenly changed from the nucleus
to a region outside. The gamma spectrum and angular correlation
was shown to depend on the beta interaction only thro ' the
beta-ray spectrum\textsuperscript{12}). The extension of this theory\textsuperscript{13}) to
forbidden transitions gave some small explicit dependence on
the type of interaction involved, the order of which is too
small to be observed with the presently available experimental
techniques. Theoretical studies\textsuperscript{14}) regarding the emission of
internal bremsstrahlung in orbital electron capture which is
also called the 'radiative electron capture' were found to be
in fair agreement with the experiments\textsuperscript{15}). Some evidence\textsuperscript{16}) was
also observed in beta decay experiments for the emission of
some new charged particles of mass of the order of an electron.
The reported existence of these particles is yet to be confirmed
with improved experimental techniques\textsuperscript{16,17})
When the transition energy is more than 1.02 Mev, the nucleus may decay by the emission of electron positron pair. A comparison of the experimental pair conversion coefficients with the theoretically calculated values\(^{18}\) along with the shape of the positron spectrum and the angular correlation studies can give the multipole nature of the transition involved\(^{19}\). The 'Uniform field pair spectrometer' proposed by W.F. Hornyak, the 'Orange pair spectrometer' of O.B. Nielsen and the 'Intermediate image statistical separation pair spectrometer' designed by Daniel and Bothe will be quite useful in accurate studies of these high energy transitions.

The angular correlation studies are quite valuable in the determination of the angular momentum carried by the \(\gamma\)-rays and in assigning the spins and parities of the various excited states. This technique was also found to be suitable for determining the nuclear 'g' factors, the matrix elements in the beta decay, the nuclear structure dependence in the conversion process\(^{20}\), the magnetic and quadrupole moments and in obtaining some information about the molecular structure and the structure of liquids and solids\(^{21}\). In the work reported herein the angular correlation of cascade gamma rays was performed mainly to assign the spins of the excited states and to obtain the sign and magnitude of the mixing parameter \('S' of the gamma rays. The mixing parameter \('S' was found to play a decisive role in the verification and improvement of the existing nuclear models. The simple angular correlation studies without polarization are not much helpful in assigning the parities of the levels, but indirect evidence could
be obtained by corroborating this with some other data like transition probabilities, internal conversion coefficients etc., if available.

In view of this discussion, it is quite imperative that we should obtain more precise and accurate data regarding the properties of the ground states and excited states of the radioactive nuclei and about the nature and the type of transitions involved. The studies described in this thesis were undertaken, mainly to investigate the properties of the nuclear levels by studying the nature of the $\beta$- and $\gamma$-transitions in some of the radioactive nuclei for which the data have been either incomplete or ambiguous. The suitability of the presently existing nuclear models in explaining the experimental data have also been studied.

A) NUCLEAR MODELS

The existing nuclear models may be classified as

a) the strong interaction models in which the nucleus is assumed to be an assemblage of closely coupled particles, the model which is well suited for explaining the high energy reactions, scattering etc., where the closely packed energy levels may be approximately defined by statistical theories;

b) the independent particle models in which the nucleons are assumed to move rather independently in an average potential due to all the remaining nucleons. This model is particularly
good for the ground state properties and for the low lying energy levels, where the independent particle motion is a good approximation. We are mainly interested in the low energy phenomena where the independent particle models are more applicable.

i) Single Particle Shell Model

The nuclear shell model\(^{22,23}\) assumes that the nucleus move nearly independently in a common static potential with a strong spin-orbit coupling obeying the Pauli's exclusion principle. The splitting between the two levels \(j = l \pm \frac{1}{2}\) is proportional to \((2l+1)\) and the radial wave function \(f(r)\).

Drell and Walecka\(^{24}\) have performed theoretical calculations to check whether the nucleons moving independently in a nucleus are identical with the free nucleons or not. Their results show that the quenching of the intrinsic moment of a nucleon is \(\approx 6\%\) when it is being immersed in a sea of identical nucleons. Since these effects are small, the interaction Hamiltonian \(H\) can be derived from the single particle potential \(U(i)\) and the residual two body interaction \(V_{ij}\), which can be treated as a perturbation,

\[
H = \sum T_i + \sum U(i) + \frac{1}{2} \sum_{i \neq j} V_{ij}
\]

Two nucleons of the same kind with the same orbital momentum are most strongly bound if their total angular momentum is zero. The difference between the binding energy of such a pair and twice the binding energy of one nucleon with the same orbital momentum is called the pairing energy which increases with \(l\). This simple model was found to explain many properties of the low lying nuclear levels.
The shell model has to be modified for configurational interaction which will partly mix the states having the same \( l \). Therefore many states will be neither pure single-particle nor pure many-particle states. Near the closed shells the configurational interaction becomes less important and therefore the states becomes purer.

ii) Nilsson Model

The size of the nuclear electric quadrupole moments can in some cases be explained by assuming an ellipsoidal nuclear shape. In this case the degeneracy of shell model orbitals \( l_j \) with respect to the projections \( K \) of their momenta \( j \) along the axis of the nucleus is removed. The total angular momentum \( J \) of the nucleus is then the combination of \( K \) with a rotation of the nuclear surface around an axis normal to the symmetry axis of the nucleus. Now, every level of the shell model yields \( \frac{1}{2}(2J + 1) \) intrinsic levels with spin \( K \leq j \). This splitting as a function of a parameter \( S \) which is approximately the fractional difference between the maximum and the minimum diameter of the nucleus has been calculated and drawn by Nilsson\(^{26}\). This model was found to be good in explaining the spins of some of the excited levels of nuclei in the region \( 150 < A < 186 \).

iii) The Collective Model

In order to explain the observed large quadrupole moments in the regions far away from the closed shells, it was first suggested by Rainwater\(^{27}\) that these nuclei may have a permanent
non-spherical essentially spheroidal shape. "Then the nuclear deformations result from the polarizing action of one or several loosely bound nucleons on the rest of the nucleus". Further evidence for these collective effects have been observed in the enhanced E2 transition probabilities, when compared to the single particle estimates in many even-even nuclei. This collective interaction between the nucleons can be due to the vibrations or rotations of the nuclear surface. For nuclei slightly away from the closed shells the spectra can be explained as due to collective vibrations about a spherical equilibrium shape. For even-even nuclei very far from the closed shells (155<A<185; A>225) the spectra may be accounted as due to rotational-vibrational excitations.

Bohr and Mottelson\(^2\) developed the 'Unified model' assuming that the nucleons move nearly independently in a common slowly changing potential taking account of the collective excitations as variations of the shape and orientation of the nucleus as a whole. In this model, it was assumed that the nuclei are non-spherical but essentially spheroidal and that the nuclear motion separates into intrinsic and rotational motions; the assumption, which is valid when the frequencies of the collective excitations are small compared with those characterizing the intrinsic nucleonic motion.

B) INTERNAL CONVERSION PROCESS

A nucleus in an excited state with excitation energy less than the binding energy of the last nucleon usually decays
either by the emission of a gamma ray or by the ejection of one of the orbital electrons. The ratio of the transition probabilities for electrons to gamma rays is called the internal conversion coefficient. The values of the internal conversion coefficients mainly depend upon the gamma ray transition energy ($E_\gamma$), the nuclear charge ($Z$), the shell from which the electron is ejected, multipolarity and nature (EL or ML) of the gamma ray. Rose$^{29}$ has calculated the values of the internal conversion coefficients assuming the nucleus to be a point charge. Later it was shown that the finite nuclear size effects the internal conversion coefficients quite considerably. These effects can be 1) the static effect describing the influence of the finite nuclear size on the conversion coefficients through the modification of the electron wave functions to include the finite spread of the charge distribution, 2) the dynamic effect in which an electron can move inside the position of the nucleon. Sliv and Band$^{30}$ have calculated the internal conversion coefficient values by taking the static effects into consideration. The Sliv's values which are smaller than the Rose's values by as much as 50% in the case of some M1 transitions in heavy nuclei were found to be in better agreement with the experimental values.

The second effect corresponds to the part of the electron wave function falling inside the nuclear charge distribution, which results in the E0 transition. The radial integral after taking the finite nuclear size effects into consideration may be
written as\textsuperscript{6})

\[
\left( \int_0^{\infty} \beta_H F^{(b)} r^2 dr - \int_0^{\infty} f H F^{(b)} r^2 dr \right) + \int_0^{\infty} f_{\text{inside}} S F_{\text{inside}} r^2 dr \\
+ \left[ \Delta_1 \int_0^{\infty} g H F^{(b)} r^2 dr + \Delta_2 \int_0^{\infty} f H G^{(b)} r^2 dr \right]
\]

The first term corresponds to the point nuclear size assumption, the second term is the structure dependent term due to the static effects considered by Sliv and Listengarten, $S$ is the form factor, $f$ inside and $F$ inside are electron wave functions in the smeared-out potential inside the nucleus. For electric multipoles this integral contributes for the EO transitions also. The third term in the radial integral is the contribution from the irregular solutions $g$ and $G$ to the Coulomb potential which enters the picture when the inside wave functions are joined to the Coulomb potential at the nuclear surface. The quantities $\Delta_1$ and $\Delta_2$ represent the magnitude of these contributions. The first and the third terms are connected to the hyperfine structure\textsuperscript{31).} Bohr and Weisskopf\textsuperscript{32)} have calculated the structure dependent second term which may vary from nucleus to nucleus.

Church and Weneser\textsuperscript{6)} have shown that the EO contribution will be quite considerable particularly when the transitions are hindered due to some special nuclear selection rules. The forbidden selection rules may be 1) 1 selection rule for M1 transitions for which $\Delta 1 \neq 0$ 2) forbidden M1 transitions in $2^+ \rightarrow 2^+$ transitions in heavy even-even nuclei 3) forbidden M1 transitions between the rotational levels of the highly deformed heavy nuclei etc. The calculations of Church and Weneser properly
explain the many anomalous internal conversion coefficient values which were found to be greater by many orders when compared to the values of Rose, Sliv and Band.

The recent accurate determination of the internal conversion coefficients by M.C. Joshi and B.V. Thosar further support the significance of the EO transition in some of the forbidden M1 transitions. Similar calculations for the electric monopole transitions (EO) have been made by Nilsson who has also shown that the EO contribution is quite considerable in the case of the forbidden electric dipole transitions. The significance of the EO transition in the case of highly deformed heavy nuclei has been experimentally shown to be considerable by many workers.

C) ANGULAR CORRELATION OF CASCADE GAMMA RAYS

Let us consider a simple \( i^-i^- \) cascade with the initial state \( A \), intermediate state \( B \) and the final state \( C \). Let the angular momenta of those states by \( j_1 \), \( j \) and \( j_2 \) respectively. The angular distribution of the different multipole components \( L, m \) in a single transition \( A \rightarrow B \) may be written as

\[
Z_{L,m}(\theta, \phi) = \frac{1}{2} \left[ 1 - \frac{m(m+1)}{L(L+1)} \right] \left| Y_{L,m} \right|^2 \\
+ \frac{1}{2} \left[ 1 - \frac{m(m-1)}{L(L+1)} \right] \left| Y_{L,m-1} \right|^2 + \frac{m^2}{L(L+1)} \left| Y_{L,m} \right|^2 
\]

where \( Y_{L,m} \)'s are the spherical harmonics. This will give an isotropic distribution in the case of randomly oriented nuclei since various \( m \) states are equally populated, but the
transitions between specified m states will have a characteristic angular distribution given by eq(1). To observe this sort of angular distribution, either we should align the nuclei in a particular direction, or we can select a certain number of nuclei aligned in a certain direction out of the randomly oriented nuclei. The first condition may be achieved by means of an external field which interacts with the nuclear magnetic moment or the electric quadrupole moment. In the second method, we select a certain number of gamma rays from A→B emitted in a small cone of solid angle, which are obviously from the N nuclei with their spin orientation in a particular direction. The succeeding gamma rays (from B→C) coming from these N nuclei will show a characteristic distribution with respect to the direction of the first γ-ray. Let $\vec{A}_1 \vec{A}_2$ be the propagation directions of the radiation, then the correlation function $W ( \vec{A}_1 \vec{A}_2 )$ may be written in the form\(^{40}\)

$$W ( \vec{A}_1 \vec{A}_2 ) = S \sum_{m_1 m_2 m'_2} \frac{\langle j_1 m_1 | H_j | j m \rangle \times \langle j_1 m_1 | H_j | j' m' \rangle}{1 + i \frac{E \tau}{\hbar}}$$

Where $S$ denotes the summation over all the unobserved properties of the radiations 1 and 2; $H_j$ is the interaction Hamiltonian causing the emission of the radiation in the direction $\vec{A}_1$ etc. $E_{mm'}$ is the energy splitting of the substates $mm'$ due to extranuclear fields and $\tau$ is the mean life of the middle level B. The matrix elements of distinct multipole order can be split into geometry factors and reduced matrix elements and the
dependence on the magnetic quantum numbers may be expressed in terms of the 'F' coefficients. The expression (2) may be written as an expansion in Legendre Polynomials,

$$\mathcal{W}(\theta) = \sum_{\ell=0}^{\ell_{max}} \ell_p \mathcal{P}_\ell(\cos \theta)$$

(3)

after normalization

$$\mathcal{W}(\theta) = 1 + A_2 \mathcal{P}_2(\cos \theta) + A_4 \mathcal{P}_4(\cos \theta) + \cdots$$

(4)

Now the $A_2$ coefficient may be written as a product of two independent factors each depending on the particular gamma transition such that,

$$A_2 = A_2^{(\gamma)} \cdot A_2^{(\gamma')}$$

$$= F_2^{(\gamma)}(L \ell L' \ell' j j) \cdot F_2^{(\gamma')}(L \ell L' \ell' j j)$$

(5)

For pure multipole gamma rays the experimental $A_2$ values may help in unique spin assignments, the accuracy of which mainly depends on the particular case under consideration.

When both the $\gamma$-rays are mixtures,

$$A_2^{(\gamma)} = F_2^{(\gamma)}(L \ell L \ell' j j) + 2 \delta_1 F_2^{(\gamma)}(L_1 L_1+1 j j) + \delta_2^2 F_2^{(\gamma)}(L_1+1 L_1+1 j j)$$

(6)

and a similar expression for $\gamma'$

Since the 'F' coefficient has to satisfy the triangular conditions; $\gamma$ can have values such that

$$0 \leq \text{even } \gamma \leq \text{min. } (2 j_1, 2 L_1, 2 L_2)$$

(7)

where $\delta$ is the mixing parameter,

$$\delta^2 = \frac{L_2+1}{L_2}$$

(8)

The value of $\gamma_{\text{maxi}}$ in eq (3) mainly depends upon the selection rules (7).

From the properties of the 'F' coefficients for $\gamma = 0$

$$A_2 = A_2^{(\gamma)} A_2^{(\gamma')} = \left[ \left( \frac{\mathcal{L}_2^{(\gamma)}}{1 + \delta^{(\gamma)}} \right)^2 \left( \frac{\mathcal{L}_2^{(\gamma')}}{1 + \delta^{(\gamma')}} \right)^2 \right]$$

(9)
defining
\[ Q_{\gamma} = \frac{s_{\gamma}^2}{1 + s_{\gamma}^2} \]  
(10)
eq(6) may be written in a convenient form 42
\[ \alpha_{\gamma}^{(\gamma)} = F_\gamma \left( L_{\gamma_1} L_{\gamma_2} j' j \right) \left( 1 - Q_{\gamma} \right) + 2 F_\gamma \left( L_{\gamma_1} L_{\gamma_2} + 1 j' j \right) \left\{ Q_{\gamma} \left( 1 - Q_{\gamma} \right) \right\} \]
\[ + F_\gamma \left( L_{\gamma_1} + 1 L_{\gamma_2} + 1 j' j \right) Q_{\gamma} \]  
(11)
As a special case let \( \gamma_1 \) be a mixture of \( 2^1 \) and \( 2^2 \), and \( \gamma_2 \) be a pure \( 2^2 \); Now
\[ A_2 = A_2^{(\gamma_1)} A_2^{(\gamma_2)} \]  
(12)
where \( A_2^{(\gamma_1)} \) is given by eq (11) and
\[ A_2^{(\gamma_2)} = F_2 \left( L_{\gamma_2} L_{\gamma_2} j' j \right) \]
\[ A_4 = A_4^{(\gamma_1)} A_4^{(\gamma_2)} \]
\[ = \left\{ F_4 \left( L_{\gamma_1} + 1 L_{\gamma_1} + 1 j' j \right) \right\} Q_{\gamma_1} A_4^{(\gamma_2)} \]  
(13)
the other terms vanish because of the triangular conditions.
The plots of \( A_2^{(\gamma_1)} \) vs \( Q_{\gamma_1} \) in eq (12) and \( A_4^{(\gamma_1)} \) vs \( Q_{\gamma_1} \) in eq (13)
give respectively an ellipse and a straight line passing through the origin \((0,0)\). The triangular conditions (7) restricts the
\( A_4 \) values to depend only upon the quadrupole content of the gamma transitions, which make the analysis quite simple.
Assuming different values of \( Q_{\gamma_1} \) one can find out the corresponding values of \( A_2^{(\gamma_1)} \) with arbitrary values for \( j' j j'' \) for the three levels and the multipolarities \( 2^1 \) and \( 2^2 \) for the upper transition.
In order to obtain the value of \( Q_{\gamma_1} \), we have to divide the \( \alpha_{\gamma}^{(exp)} \) by \( A_2^{(\gamma_1)} \) and \( A_4^{(\gamma_1)} \) by \( A_4^{(\gamma_1)} \) of the pure transition.
The resulting values can be compared with the single transition curves which give the value of \( Q_{\gamma_1} \) consistent with the experiment.
When both the gamma transitions are mixtures of multipoles, $A_2$ will become the product of two expressions (for $\gamma_1$ and $\gamma_2$) of the type eq (11) and $A_4 = A_4^\prime A_4^\exp$. Knowing the $A_4^\prime$, the values of $A_4^\prime$ and $A_4^\exp$ could be plotted as an area between the equilateral hyperbolas. Two more graphs could be drawn 1) keeping the zero on the same horizontal line as explained above and also with the same scale as that of $A_4^\prime$ so that $A_4^\exp$ values could be correlated easily. Similarly on a straight line parallel to that of $A_2^\prime$ and on the same scale as that of $A_2^\prime$ another graph could be drawn just similar to that of the previous one, which results in two ellipses and two straight lines in total. Thus, in these graphs a range of $Q_1^\gamma$ consistent with the first transition will correspond to a range of values of $Q_2^\gamma$ for the second transition required by the experimental graph and vice versa. Therefore additional information is always necessary for making unique assignments. These limits can be placed from the internal conversion data, half-life measurements and transition probabilities. Knowing the value of $Q$ at least in one transition from other data, the multipole nature of the second gamma ray can be uniquely assigned.

References

3) G. Alaga et al., Mat. fys. Medd. 28 (1953) No 3
4) J. F. Davidson and D. C. Peaslee, Phys. Rev. 91 (1953) 1232
6) E.L. Church and J. Weneser, Phys. Rev. 104 (1956) 1382
8) For example, B.N. Subbarao, Nuovo Cimento 17 (1960) 189
   E.M. Bernstein, Phys. Rev. Letters 8 (1962) 100
9) M.E. Rose and D.K. Holmes, ORNL Report - 1022
10) H. Brysk and M.E. Rose, ORNL Report - 1330
   E. Bloch, Phys. Rev. 50 (1936) 272
13) C.S.W. Chang and D.L. Falkoff, Phys. Rev. 76 (1949) 365
   L. Madansky et al., Phys. Rev. 84 (1951) 595
14) R.J. Glauber and P.C. Martin, Phys. Rev. 95 (1954) 572
   P. Morrison and L. Schiff, Phys. Rev. 58 (1940) 24
15) T. Lindqvist and C.S. Wu, Phys. Rev. 100 (1955) 145
17) K.T. Bainbridge, Nature 160 (1947) 492
18) M.E. Rose, Phys. Rev. 76 (1949) 678
19) S.D. Bloom, Phys. Rev. 88 (1952) 312
   Dougherty, W.F. Hornyak, C.C. Lauritsen and
   V.K. Rasmussen, Phys. Rev. 74 (1948) 712
   V.K. Rasmussen, W.F. Hornyak, C.C. Lauritsen and T. Lauritsen
   Phys. Rev. 77 (1949) 617
20) T.A. Green and M.E. Rose, Phys. Rev. 110 (1958) 105
   E.L. Church, M.E. Rose and J. Weneser, Phys. Rev. 109 (1958) 1299
21) R.H. Steffen, Advances in Physics (Supplement to Philosophical
    Magazine) 4 (1955) 293
23) J.P. Elliott and A.M. Lane, The Nuclear Shell-Model in
    Handbuch der Physik 39 (1957) 242
24) Drell and Walecka, Phys. Rev. 120 (1960) 1069

S.G. Nilsson, Dan. mat.-fys. Medd. 29 (1955) No.16
S.A. Moszkowski, Phys. Rev. 99 (1955) 303
K. Gottfried, Phys. Rev. 103 (1956) 1017

27) J. Rainwater, Phys. Rev. 79 (1950) 432

28) A. Bohr and B. Mottelson, Dan. mat- fys. Medd. 27 (1953) No.16

29) M.E. Rose in Beta and Gamma-Ray Spectroscopy Ed. by K. Siegbahn (1955) and ORNL Report - 1023

30) L.A. Sliv and I.M. Band, Reports 57 ICC KL and 58 ICC LI, circulated by The Physics Dept., University of Illinois

31) A.L. Schawlow and M.F. Crawford, Phys. Rev. 76 (1949) 1310

32) A. Bohr and V. Weisskopf, Phys. Rev. 77 (1950) 94

33) for example, F.K. McGowan and P.H. Stelson, Phys. Rev. 107 (1957) 1674


36) F.E. Durham et al., Proc. of the Kingston Conf. on Nucl. Str. (1960) p. 594

37) S.G. Nilsson, UCRL Report-3803

38) for example, W.F. Edwards and F. Boehm, Proc. of the Kingston Conf. on Nucl. Str. (1960) p. 598

39) reference 1) p. 594

40) L.C. Bidenharn and M.E. Rose, Rev. Mod. Phys. 25(1953) 729


CHAPTER II

INSTRUMENTATION AND ANALYSIS OF DATA

A) CONSTRUCTION AND SETTING-UP OF THE SPECTROMETERS

1. Polishing and Mounting of NaI (Tl) Crystals

Two raw blanks of NaI (Tl) crystals purchased from The Harshaw Chemical Co. were polished and mounted in a specially constructed dry box. The free iodine and water which may be adhering the crystal blanks were removed by grinding them in the dry box until they are crystal-clear. All the sides of the crystal were left perfectly rough (by grinding with zero-zero abrasive paper) excepting one face, which was coupled to the face of the photomultiplier. This face was polished with acetone using tissue paper. The crystals were mounted in thin Al cans, keeping minimum amount of the Al$_2$O$_3$ around the crystal in order to minimize the Compton scattering in the housing of the crystal. The crystals were sealed with 'araldite' ('Ciba' adhesive) after optically coupling them with perfectly plane thin glass plates using DC-200 silicone oil. The mounted crystals were again optically joined to DuMont-6292 photomultipliers with silicone oil. The crystal-photomultiplier systems were made light tight. With these mounted crystals a resolution of 9% was obtained for the 662 keV gamma ray of Cs$^{137}$. Anthracene and plastic scintillators were also polished and coupled to the photomultipliers using thin (5mg/cm$^2$) aluminium foil as a reflector and light shield.
2. Linear Amplifier

DD2 type "Non-blocking Double-line Linear Pulse Amplifier" of gain $\approx 40,000$ was assembled and tested in the laboratory using Tektronix 513D oscilloscope. This amplifier consists of three non-blocking feedback groups of approximate gains 70, 70 and 50. The double differentiation method incorporated in the first and the second stages of this amplifier such that the positive and the negative components of the pulse are exactly symmetrical, reduces the shift in the energy axis at high counting rates, the trouble which was found to be quite serious in the conventional amplifiers. This shaping was accomplished by means of delay lines. By suitably locating these differentiators, the noise and pile-up is also minimised. The non-overloading features were obtained by maintaining the operating point of the cathode coupled pair in each of the three feedback groups such that there is no appreciable grid current. Besides these excellent features and its high gain, good stability, wide gain control range, good linearity at all gain settings and counting rates, low noise, variable bandwidth, freedom from blocking and the ability to operate under high duty cycle conditions make it a versatile instrument in scintillation and proportional counter spectrometry.

The high gain makes it easily susceptible for oscillations. The three feedback groups were carefully adjusted such that the feedback phase is always negative with respect to the applied signal. Even a slight unbalance of this condition may give a total phase-shift of $180^\circ$, which may lead to oscillations.
Every care was taken to shield the pulse cables, to minimise the length of the pulse carrying wires by properly planning the positions of the components and in reducing the cross-connections of the pulse wires. All the earth points were grounded at only one point of the chasis to reduce the chasis currents.

3. Cathode Followers

Two White Cathode Followers\(^2\) which were also constructed and tested in the laboratory were designed to match with the DD2 amplifiers. These cathode followers faithfully transmit long tail pulses (\(\approx 100 \mu \text{sec at the base}\)) of either polarity, which is the input requirement of the DD2 amplifier. The output of these cathode followers contain minimum nonlinearity, distortion and noise.

4. High Voltage Power Supplies

High voltage power supplies with good stability, low noise and ripple are essential for scintillation spectrometers. The precision regulated high voltage power supplies of Higinbotham\(^9\) fairly satisfy the above conditions. Two such power supplies have been assembled and thoroughly tested in the laboratory. They are giving excellent stability (the variation in the DC high voltage is less than 0.2\% for the input variation from 180 to 260 volts.) low noise and ripple and practically no drift for continuous operation of about six hours.
LINEARITY AND RESOLUTION OF SPECTROMETERS

LINEARITY OF THE NaI(Tl) CRYSTAL SCINTILLATION SPECTROMETER.
PULSE HEIGHT VS GAMMA RAY ENERGY.

RESOLUTION OF THE NaI (TI) CRYSTAL SCINTILLATION SPECTROMETER FOR VARIOUS MONO-ENERGETIC GAMMA SOURCES.
Fig. 8 - ESCAPE PEAK TO PHOTOPEAK AS A FUNCTION OF INCIDENT GAMMA RAY ENERGY

- Theoretical curve
- Experimental value

Fig. 3 - GAMMA RAY SPECTRA OF SOME STANDARD SOURCES (Tm$_{170}$, Cs$_{137}$, AND Mn$_{54}$).
Fig. 2

THE BLOCK DIAGRAM OF THE SCINTILLATION COINCIDENCE SPECTROMETER
trigger a 6J6 univibrator. The gate pulses for the 20 channel analyser were taken from the plate, which are of about 25 volts in amplitude and of 2 \( \mu \text{sec} \) width at the base.

The block diagram of the circuitry employed is shown in fig. 2.

B) ANALYSIS AND CORRECTIONS

1. Scintillation Spectrum

The scintillation spectra of mono-energetic gamma ray sources may contain a photopeak corresponding to its incident energy, the Compton continuum with a sharp edge, a backscattered peak, pair peaks and escape peak corresponding to the incident photon energy minus the energy of the iodine X-ray. Some of the spectra recorded in the present setup with the standard gamma sources are given in fig. 3. Though the recent experiments showed that the NaI(Tl) crystals are not perfectly linear, in all the following measurements, the calibrated energies are least-squares fitted to a straight line as given in fig. 4. The resolution of the scintillation spectrometer mainly depends upon the statistical uncertainties in the number of photons emitted by the phosphor; in the number of photoelectrons emitted at the photocathode and in the processes of multiplication of these electrons at the dynodes in the photomultiplier. Since the resolution is mainly dependent on these statistical factors, it varies inversely as the square-root of the incident gamma ray energy as obtained in fig. 5.
Fig. 6 COMPTON EDGE AND BACK-SCATTERED PEAK ENERGIES VS. INCIDENT GAMMA RAY ENERGIES.

- Theoretical curves
- Observed Compton edge positions.
- Observed backscattered peak positions

Fig. 7 THE EFFECTIVE PHOTON PEAK EFFICIENCIES FOR MONO-ENERGETIC GAMMA SOURCES WITH THE SOURCE AT 4 cm. FROM THE FACE OF THE CRYSTAL.

CURVE (A) \( \frac{\sigma_{\text{photo}}}{\sigma_{\text{photo}} + \sigma_{\text{compt}} + \sigma_{\text{pair}}} \) from the \( \sigma_{\text{compt}}/\sigma_{\text{pair}} \) graphs of white \( \frac{1}{4} \)

CURVE (B) \( \frac{\text{peak}}{\text{total}} \) FOR \( \frac{1}{12} + \frac{1}{12} \) NaI(Tl) crystal

Observed
The gamma sources were always prepared in thin perspex rods and they were mounted at the central axis of the crystal. In order to reduce scattering, all the scattering material was kept away from the source. The unknown gamma spectrum was analysed by successively subtracting the spectrum of some known mono-energetic gamma ray source of approximately the same strength and energy as that of the highest gamma ray present in the unknown spectrum.

2. Compton Edges and Backscattered Peaks

When a gamma ray escapes after Compton scattering, the maximum energy given to the electron gives rise the Compton edge

\[
E_{\text{Comp. edge}} = \frac{E_{\gamma (\text{incident})}}{1 + \frac{m c^2}{2 E_{\gamma}}}
\]  

(1)

If the Compton scattered gamma ray is also simultaneously absorbed in the crystal, the probability of which increases with the size of the crystal, then the pulse will fall under the photopeak. If it is scattered back by the surrounding material it will give the so called backscattered peak, corresponding to an energy \(E = E_{\gamma \text{incident}} - E_{\text{Compton edge}}\), the intensity of which could be reduced by keeping minimum amount of substance around the crystal and by selecting the surrounding material to be of low Z. While analysing the unknown spectrum, the Compton edges and backscattered peaks are identified with the help of fig. 6 plotted with mono-energetic gamma sources.
3. Intensity Measurements

Knowing the linear absorption coefficient\(^\text{14}\), one can obtain the theoretically calculated\(^\text{15}\) values of the detection efficiency \(\epsilon\). The relative values of \(\epsilon / \Omega\) where \(\Omega\) is the solid angle can be experimentally determined with the help of the standard sources with known gamma ray intensity ratios (Co\(^{60}\), Y etc.). Elimination of \(\Omega\) from these ratios will give the value of \(\epsilon\). An estimate of the probability that a gamma ray may be completely absorbed by means of multiple processes like the Compton scattering and the subsequent photoprocesses and give a pulse under the photopeak, can be obtained by plotting the theoretical and effective experimental values of \(\frac{d\sigma_{\text{photo}}}{d\sigma_{\text{photo}} + \text{Compt+pair}}\) for mono-energetic gamma sources as shown in fig. 7. The effective photo-efficiency for the detection of the counts under the photopeak is given by

\[
\left[\frac{\text{Counts under the photopeak}}{\text{Total counts}}\right] \times \text{total efficiency for the gamma ray}
\]

4. Escape Peak Intensities

If the energy \((E_{\gamma})\) of the incident gamma ray is totally lost in the crystal, then the pulse will fall under the photopeak. But when the iodine K-X-ray escapes from the crystal, we will get an 'escape peak' corresponding to an energy \((E_{\gamma} = 28.4\ \text{keV})\). It was shown by Axel\(^\text{16}\) that the ratio of the escape peak intensity to that of the photopeak intensity mainly depends upon the energy of the incident gamma ray, geometry of the experimental set up and
on the dimensions of the crystal. The escape peak intensities are negligible for incident gamma ray energies of 200 keV or above. Axel\(^{16}\) has calculated the escape peak to photopeak intensities for different energies and for various geometries. The values of the escape peak to photopeak intensity ratios obtained from the formulae of Axel\(^{16}\) for the geometry of the set-up used in the present measurements have been compared with the experimentally obtained values as shown in fig. 8 (please see the fig. facing page 26). This graph has been used for correcting the photopeak intensities.

5. Calculation of The Intensities of The Sum Peaks

While analysing the singles gamma spectrum, one should carefully separate the simulated peaks due to summing up of the coincident gamma rays. They could be identified by the fact that the photopeak counts due to a genuine mono-energetic gamma ray falls as \(1/\Omega\) the solid angle; and the counts under the coincident sum peak falls as \(\Omega^2\). An estimate of the counts under the coincident sum peak will help in checking up the genuinity of the observed peaks and in determining the exact relative intensities of the gamma rays, particularly when there is a cross-over transition between the cascade gamma rays. The intensity of the coincident sum peak (Pcs) can be obtained from the eqn.\(^{17}\)

\[
P_{\text{cs}} = \frac{P(\gamma_1)}{1 - \varepsilon_\gamma(\gamma_2) \Omega f} \cdot \varepsilon_p(\gamma_2) \Omega f + N_n
\]  \hspace{1cm} (2)
where \( P_{c.s} \) and \( P (Y_1) \) are the areas under the coincidence photopeak and the photopeak in the fixed channel which is set on the \( Y_1 \)-ray; \( \varepsilon_p \) and \( \varepsilon_T \) are the photopeak and total efficiencies, \( f \) is the fraction of the \( Y_1 \)-ray in coincidence with the \( Y_2 \)-ray and \( \Omega \) is the solid angle. \( N_r \) is the random summing of two pulses of the proper pulse height which can be obtained from the resolving time of the amplifier.\(^{13} \)

6. Calculation of The Percentage Contributions in \((Y'-Y)\) cascades

When more than one gamma transition (let one of them be denoted by \( Y' \)) leads to a certain level which further de-excites by means of another gamma transition, (here called \( Y \)); the percent contributions by each of the upper gamma rays (\( Y' \)) to the intensity of the lower gamma ray (\( Y \)) gives useful information in establishing the decay scheme, in checking-up the partial intensities of the beta ray groups and in keeping the gamma transitions at appropriate places in the decay scheme. The percentage contributions (\( x \)) of the upper gamma rays (\( Y' \)) to the intensity of the lower gamma ray (\( Y \)) can be obtained from the formula\(^{19} \)

\[
\chi = \frac{100 \frac{P(Y')}{P(Y') + \varepsilon_p(Y')} \frac{1 + \varepsilon(Y')}{\Omega} C(Y)}{t \varepsilon_p(Y') \varepsilon(Y')} \Omega C(Y) \]  

(3)

where \( \Omega \) is the solid angle, \( \varepsilon_p(Y') \) is the photopeak efficiency \( C(Y) \) is the observed counting rate in the fixed channel after
applying corrections for the Compton contribution of the high energy gamma rays, \( P (\gamma') \) is the area under the photopeak of \( \gamma' \)-ray observed in time \( t' \) and \( K \) is the correction factor for the external absorbers. The quantity \( L(\gamma') \) is the conversion coefficient of \( \gamma' \)-ray. \( \bar{W}(90^\circ) \) is the angular distribution of the two coincident gamma rays obtained from the angular correlation data. From the same formula, knowing the percentage contributions (\( x \)), the value of the conversion coefficient \( L(\gamma') \) can also be evaluated.

7. Gamma Ray Transition Probabilities

The transition probabilities for the electric and magnetic transitions for a single neutron in the single particle model after simplification are given by\(^{20}\):

\[
\lambda_{\text{sp}}^{(EL)} = \frac{4 \cdot 4(L+1)}{L} \left( \frac{3}{L+3} \right)^2 \left( \frac{\hbar \omega}{197 \text{ MeV}} \right)^{2L+1} (a \text{ in } 10^{-13} \text{ cm})^{2L} \times S(J_c, L, J_f) \times 10^{21} \text{ sec}^{-1} \tag{4}
\]

and

\[
\lambda_{\text{sp}}^{(ML)} = \frac{0.19(L+1)}{L} \left( \frac{3}{L+2} \right)^2 \left( \frac{\hbar \omega}{197 \text{ MeV}} \right)^{2L+1} \times S(J_c, L, J_f) \times 10^{21} \text{ sec}^{-1} \tag{5}
\]

The reduced matrix element in the Bohr and Mottelson model\(^{21}\) is

\[
B(E2) = \frac{15}{32 \pi} \frac{e^2 Q_e^2}{(2J+3)(2J+5)} \frac{(J+1)(J+2)}{(2J+1)(2J+3)} \tag{6}
\]
where $Q_0$ is the intrinsic nuclear quadrupole moment due to deformation. Or

$$
B(E2) = \frac{15}{16 \pi} \frac{e^2 Q_0^2 \kappa^2 (J+1-K)(J+1+K)}{J(J+1)(2J+3)(J+2)}
$$

and

$$
B(M1) = \frac{3}{4 \pi} \left( \frac{e \hbar}{2MC} \right)^2 (g_k - g_R)^2 \frac{\kappa^2 (J+1-K)(J+1+K)}{(J+1)(2J+3)}
$$

where $Q_0 = 4/5 Z R_0^2 \frac{\Delta R}{R_0}$; and $\Delta R/R_0$ can be approximately obtained from the Nilsson diagram. In very rough estimates $g_k - g_R \approx 1$; which is justified since $g_R = Z/a$ and $g_k$ correspond to the last proton. The relative transition probabilities in the same band can be obtained from the formula

$$
\frac{B(L, J_i \rightarrow J_f)}{B(L, J_i \rightarrow J_i')} = \frac{\langle J_i L \ k_i k_f' - k_i' | J_i L | J_f k_f \rangle^2}{\langle J_i L \ k_i k_f' - k_i' | J_i L | J_f k_f \rangle^2}
$$

The values of the transition probabilities for the various rotational and vibrational states in the Davydov and Filippov model are calculated from Eqs. (2) and (3) of Chapter V.

8. Angular Correlation Studies

The table carrying the detectors which was made of a thin cardboard has been kept away from all the scattering material. The source was always prepared in a thin perspex rod and it was mounted at the origin of the central axes of the detectors. This was tested by noting the single counts at different angles between the counters. The following tests were also performed.
to check the scattering from the detectors and the surrounding material. The coincidence counting rate for angles symmetric with respect to $90^\circ$ were observed to be the same within statistics. The coincidence counting rate was found to be not affected by an additional absorber between the detectors for $\theta=90^\circ$ position. The coincidences were recorded for 5 min at each angle from $90^\circ$ to $180^\circ$ between the central axes of the detectors. The strength of the source was always selected such that the true-to-chance ratio was high. The chances were subtracted by repeatedly testing the coincidence circuit by the random coincidence method. The coincidence rate was normalised by dividing with the single counting rates $N_1 N_2$ and multiplying by $N_1 (180^\circ) N_2 (180^\circ)$. This method takes account of the source decay during observation, source alignment and any slight drift in the single counting rates. The least squares fit of the data was made to the eqn.

$$W(\theta) = \sum_{\gamma=0,even}^{2m} \lambda_\gamma \tilde{P}_\gamma (\cos \theta)$$

Before taking up the actual case for angular correlation studies, the spectrometers were always tested for the anisotropy of the Co$^{60}$ source.

Low source strengths were employed, so that the counting loss corrections, $N^C = N^C_m (1 + S^C)$ are small. From the singles counting rate the background $N_0$ has been subtracted. Since the source dimensions were always maintained small and the source was always made in a thin perspex rod, the corrections
for the scattering in the source and the source holder and the
finite source size effects are also neglected. The attenuation
of the angular correlation due to extra-nuclear fields has been
assumed to be small, because the experiments were always performed
with the source in a conducting acid medium either in a liquid
or in a semi-solid state. The attenuation due to the time
dependent fields is also negligible because of the slow coincidence
circuitry (τ = 0.15 μ sec) employed.

1) Evaluation of The \( C_0 \) Coefficients: The \( C_0 \) coefficients which are
the most probable values for the given data are obtained from
\[ \sum_i W_i \left( \mu_i - \sum_\lambda \kappa_\lambda A_{i,\lambda} \right)^2 = \text{Min} \] (11)
The required normal eqns. (eqns. expressing the condition that
the first derivative of each variable should be zero) are
\[ \sum_i W_i \left( \mu_i - \sum_\lambda \kappa_\lambda A_{i,\lambda} \right) A_i = 0 \] (12)
which may be written as:
\[ \left( 1 - \frac{\kappa_0 + \kappa_2 A_{12} + \kappa_4 A_{14}}{\mu_1} \right) A_{10} + \left( 1 - \frac{\kappa_0 + \kappa_2 A_{12} + \kappa_4 A_{14}}{\mu_2} \right) A_{20} + \cdots = 0 \]
(13)
and
\[ \left( 1 - \frac{\kappa_0 + \kappa_2 A_{12} + \kappa_4 A_{14}}{\mu_1} \right) A_{12} + \left( 1 - \frac{\kappa_0 + \kappa_2 A_{12} + \kappa_4 A_{14}}{\mu_2} \right) A_{22} + \cdots = 0 \]
(14)
By solving these three equations, the three unknown
coefficients \( \kappa_0, \kappa_2, \) and \( \kappa_4 \) can be evaluated. Substitution of
these values in eq(10) gives the least-squares fitted curve.
11) Finite Angular Resolution Correction: The theoretical correlation given by eq(10) has to be modified for the finite solid angles subtended by the detectors at the source. When the source is mounted at the origin, the form of the correlation function is unchanged. The attenuation factor by which the experimental $\lambda_3$ coefficients would be attenuated can be calculated accurately. For similar detectors and for $\gamma$-rays with similar absorption coefficients, the average observed correlation

$$\bar{W}(\theta) = \lambda_0 + \lambda_2 P_2(\cos \theta) \left( \frac{J_2}{J_0} \right)^2 + \lambda_4 P_4(\cos \theta) \left( \frac{J_4}{J_0} \right)^2$$

where

$$J_\ell = \int_0^\pi P_\ell(\cos \beta) (1 - e^{-\tau x_1}) \sin \beta \, d\beta$$

following Rose's notation.

When the energies of the gamma rays $\gamma_1$ and $\gamma_2$ are close to the annihilation radiation,

$$\frac{J_\ell}{J_0} = \frac{P_{\ell-1}(\chi_0) - \lambda_0 P_\ell(\chi_0)}{(\ell+1) (1 - \chi_0)}$$

where $\chi = \cos \gamma$ and $\gamma$; the halfwidth can be obtained from the annihilation radiation of Na$^{22}$. Since this method is usually not very accurate, the coefficients have been corrected by analytically computing the value of $(J_\ell/J_0)$ from the equations of Rose$^{22}$.

The errors quoted for the $\lambda_3$ coefficients are the statistical errors. The set-up has been tested for the systematic errors also by Rose's method$^{22}$. 

9. Log (ft) Values

Experimental determination of the half-life (t½) and the end-point energy W₀ of a beta emitter with only one group together with the knowledge of Z of the daughter nucleus, one can obtain the log (ft) values taking the f(Z,W₀) values from the graphs of Feenberg and Trigg. When there are more than one group, the halflife (t½) is to be replaced by the partial halflife tᵢ = \frac{t_{½} \times 100}{x} where x is the relative percentage abundance of the ith group. These log(ft) values are useful in classifying the transition as allowed or forbidden. The Fermi-Kurie plots of the beta spectra have been drawn with the help of the standard tables.

10. End-point Correction for the β-spectrum

Assuming the linearity of the scintillators, Palmer and Laslett have given the true distribution of counts

\[ \eta_ε(E) = \frac{1}{c} \left[ N_ε(V) - \frac{R^2}{2V^2} V N_ε'(V) - \frac{1}{4} \frac{R^2}{V^2} V^2 N_ε''(V) \right] \] (16)

where N_ε(V) is the observed counting rate at the base line voltage V. N_ε'(V) and N_ε''(V) are the first and the second derivatives of N_ε(V) which are evaluated by the least-squares method, and R is the halfwidth of a mono-energetic peak at 1/e of the maximum counting rate when the centre of the line coincides with V. R can be obtained by knowing the resolution of the spectrometer for 632 keV mono-energetic conversion.
electrons of Cs\textsuperscript{137} at any voltage V. The constant C is evaluated from the integral

\[
C = \int_0^\infty \frac{1}{(R^2)^{3/2}} e^{-\frac{(V - E_0/k)^2}{R}} dE_0
\]

(17)

where \( k = E/V \) and \( E_0 \) is the beta particle energy. Even after applying these corrections the values of the end point energies obtained from \( \beta \)-scintillation spectrometers may contain an error of \( \pm 10\% \) or even more.

11. Backscattering of Beta Rays:

The ratio of the counting rate with and without backscatterer is called the backscattering factor\,\,\,(26) \( (f_b) \)

\[
f_b = \frac{I_b}{I_o} + 1 = 1 + \frac{\beta}{\mu + \lambda} \left[ 1 - e^{-\frac{(\mu + \lambda)d}{\lambda}} \right]
\]

(18)

Where

\[
\frac{\lambda}{\mu} = \frac{22.5}{106 + \lambda}; \quad \mu = \frac{35.2}{A E_m^{1.14}} \text{ cm}^2/\text{gm} (\lambda \leq 13)
\]

\[
\beta = (\mu + \lambda) (1 - e^{-2/40}); \quad \frac{\lambda}{E_m^{1.14}} = \frac{0.31}{E_m^{1.14}} \text{ cm}^2/\text{gm} (\lambda > 13)
\]

Where \( I_b \) and \( I_o \) are the backscattered and original beta intensities, \( d \) is the thickness of the backscatterer, \( \mu \) is the (apparent) mass absorption coefficient (in cm\textsuperscript{2}/gm) and \( \lambda \) is the absorption coefficient of the backscattered radiation. In all the observations discussed in this thesis, a thin cello
tape (3 mg/cm²; Z = 5.6) after removing the gum is used for preparing the beta sources. With the help of the above formulae the backscattering factor \( f_b \) was found to be \( \approx 1.025 \) in this particular case.

12. Solid Angle Subtended by an Extended Source:

The geometry of a counter \((G)\) is the percent of solid angle about the source subtended by the sensitive volume:

\[
G = 0.5 \left[ 1 - \frac{1}{(1+\beta)^{3/2}} - \frac{3}{8} \cdot \frac{\beta^2}{(1+\beta)^{9/2}} \right] 
- \gamma^2 \left( - \frac{5}{16} \cdot \frac{\beta}{(1+\beta)^{7/2}} + \frac{35}{64} \cdot \frac{\beta^2}{(1+\beta)^{9/2}} \right) 
- \gamma^3 \left( \frac{35}{128} \cdot \frac{\beta}{(1+\beta)^{11/2}} - \frac{315}{256} \cdot \frac{\beta^2}{(1+\beta)^{9/2}} + \frac{1155}{1024} \cdot \frac{\beta^3}{(1+\beta)^{13/2}} \right) \]

Where \( \beta = \frac{I}{a^2} \) and \( \gamma = \frac{c^2}{a^2} \); 'a' is the source to the crystal distance, 'b' is the radius of the detector and 'c' is the radius of the source. The value of \( G \) was obtained to be \( \approx 0.44 \) in the particular set up used for the conversion electron detection in the case of Mn\(^{54}\).

References

1) J.B. Birks, Scintillation Counters (Pergamon Press, 1953) p.52
2) P.R. Bell, Beta-and Gamma-Ray Spectroscopy Ed. by K. Siegbahn (1955) p. 133
3) S.C. Curran, Luminescence and Scintillation Counter (1953)
5) E. Fairstein, Rev. Sci. Instr. 27 (1956) 475
6) Magree, Bell and Jordan, Rev. Sci. Instr. 23 (1952) 30
R.L. Chase and W.A. Higinbotham, Rev. Sci. Instr. 23 (1952) 34
Francis; Bell and Kelley, Nucleonics 12 (1954) 55
8) Moody, Howell and Taplin, Rev. Sci. Instr. 22 (1951) 557
9) W.A. Higinbotham, Rev. Sci. Instr. 22 (1951) 429
12) D. Engelkemeir, Rev. Sci. Instr. 27 (1956) 589
13) G.A. Morton, Nucleonics 10 (1952) 3
14) G. White, National Bureau of Standards Report-1003 (1952)
15) S.H. Vegers et al., Report IDO-16370
18) N.H. Lazar and E.D. Klema, Nucleonics 5 (1949) 28
21) A. Bohr and B. Mottelson, Dan. mat.-fys. Medd. 27 (1953) No.16
22) M.E. Rose, Phys. Rev. 91 (1953) 610
23) E. Feenberg and G. Trigg, Rev. Mod. Phys. 22 (1950) 399
CHAPTER III

DECAY SCHEME STUDIES

A) THE ENERGY LEVELS OF I\(^{129}\)

1. Introduction

Early work\(^1,2\) on Te\(^{129m}\) showed that it decays by the emission of 106 keV isomeric transition to the ground state of Te\(^{129}\), which then decays by beta emission with a half-life of 74 minutes to the levels of I\(^{129}\). Graves and Mitchell\(^3\) reported that the 74 min activity of Te\(^{129}\) excites energy levels in I\(^{129}\) at 27,502,720 and 1150 keV. They also showed that the 41 day Te\(^{129m}\) decays by beta emission, in addition to the 106 keV isomeric transition, and the $\beta^{-}/\text{I.T.}$ ratio was found to be about five percent. In order to explain the five percent beta branching, it was suggested\(^3\) that a beta ray transition of end point energy 1586 keV takes place between Te\(^{129m}\) and the ground state of I\(^{129}\). However, recent measurements\(^4\) for this ratio have shown that it is about 32 percent. This leads to the possibility of Te\(^{129m}\) exciting some new levels in I\(^{129}\) by electron emission. Banerjee and Gupta\(^5\) have calculated the energy levels of I\(^{127}\) and I\(^{129}\) on the basis of the unified model. The decay of Te\(^{129m}\) is investigated with the expectation of finding new levels in I\(^{129}\) and also to compare the theoretical calculations with the experimental data.

2. Source Preparation

The Te\(^{129m}\) isotope was obtained as a fission product in

\(^{\dagger}\) To be published in Nuclear Physics 44 (1963)
Fig. 1. The energy spectrum of gamma rays.
the "Apsara" reactor at Trombay*. The chemical separation was performed to separate Te$^{129m}$ from the radioactive isotopes of other elements formed during fission. About 20 $\mu$g of Te$^{129m}$ was dissolved in dilute nitric acid and the source was prepared in a thin perspex rod with a hole 3 mm deep and 2 mm in diameter by repeatedly drying the dilute solution under a heating lamp. No evidence was found for the existence of other tellurium activities.

3. Gamma Ray Spectrum

The energy spectrum of gamma rays recorded in a 3.8 x 3.8 cm cylindrical NaI (Tl) crystal scintillation spectrometer is reproduced in fig. 1. Evidence for the existence of photopeaks at 27, 475, 720, 1100, 1320 and 1520 keV is clearly seen. By following their decay, all the photopeaks were found to have the same half life of about 40 days. While taking the singles spectrum, an aluminium disc of 1 gm/cm$^2$ thickness was placed before the crystal to absorb betas and to reduce the external bremsstrahlung contribution to the gamma ray spectrum. From the known resolution of the spectrometer it was found, that the photopeaks at 475, 720 and 1100 keV energy displayed half-widths more than the expected values for monoenergetic gamma rays of the same energies. Hence, it was inferred, that each of these photopeaks was made up of more than one gamma ray, which was confirmed in the coincidence studies. Photopeaks at 1320 and 1520 keV energy show the presence of two new gamma rays which

* Dept. of Atomic Energy, Govt. of India, Trombay, Bombay.
were not observed in earlier studies. The broad peak at 180 keV is interpreted to be due to the back scattering from the 475 and 720 keV gamma rays. The small hump around 245 keV is due to the presence of a gamma ray of 245 keV energy which was definitely established in the coincidence experiments. The small peak at 100 keV is probably due to the 106 keV isomeric transition. The photopake at 27 keV is due to iodine K X-rays and 27 keV gamma ray found in earlier studies. The low energy end of the spectrum taken with high amplification did not reveal any further details.

After applying the usual corrections for absorbers between the source and the crystal and for the effective photoefficiency of the crystal, a rough estimate of the unconverted quantum intensities can be made from the data of fig. 1. The intensities so obtained are given in table 1.

<table>
<thead>
<tr>
<th>Gamma ray energy (keV)</th>
<th>Relative intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>448</td>
<td>31</td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
<tr>
<td>475</td>
<td></td>
</tr>
<tr>
<td>625</td>
<td>49</td>
</tr>
<tr>
<td>693</td>
<td></td>
</tr>
<tr>
<td>720</td>
<td></td>
</tr>
<tr>
<td>1073</td>
<td>1.00</td>
</tr>
<tr>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>1320</td>
<td>0.55</td>
</tr>
<tr>
<td>1520</td>
<td>0.16</td>
</tr>
</tbody>
</table>
The energy spectrum of coincidence gamma rays with the gating channel fixed on the 27 keV photopeak,
(a) Coincidences around 240 keV region,
(b) Coincidences around 400 to 800 keV region
4. Gamma-gamma Coincidence Experiments

The coincidence spectra have been examined with a 20-channel scintillation coincidence spectrometer using two identical 3.8 x 3.8 cm NaI (Tl) cylindrical crystals coupled to Du Mont-6292 photomultipliers and DD2 type non-overloading amplifiers. Pulses from one of the counters are fed to a single-channel pulse-height analyser and to the coincidence circuit of resolving time of 0.15 μsec. The coincidence output is used to gate the 20-channel analyser. The counters were placed at 130° to each other to reduce backscattering. Thick perspex discs were introduced in front of the counters for absorbing betas and conversion electrons.

The spectrum of coincidence pulses observed with the gating channel set at 27 keV is shown in fig. 2. Along with the 27 keV gamma ray however, there will be some contribution from the iodine K X-rays arising out of the internal conversion of gamma-rays. Since no conversion lines were observed in the β-ray spectra for these gamma rays, it is assumed that the contribution due to iodine K X-rays is negligible. In fig. 2 clear coincidence peaks at 245, 450 and 700 keV are seen. The shift towards lower energies of the coincidence photopeaks from the 475 and 720 keV photopeaks in the singles spectrum is of the order of 27 keV. So the 475 and 720 keV gamma rays could well be the cross-over transitions of the 450-27 keV and 693-27 keV cascades. This also confirms that the photopeaks
Fig. 3. The energy spectrum of the coincidence gamma rays with coincidence channel set on the high energy end of the 475 keV photopeak.

(a) Gating channel covering the full 475 keV photopeak.

(b) Gating channel set on the high energy end of the 475 keV photopeak.
at 475 and 720 keV in the singles spectrum of fig. 1 are composed of more than one gamma ray. To check whether the peaks at 475 and 720 keV may be solely due to the summation of 450 ($\gamma_1$)-27($\gamma_2$) and 693 ($\gamma_1$)-27($\gamma_2$) keV cascades, the coincidence peaks at 475 and 720 keV were calculated from the formula:

$$P_{cos} = \frac{P(\gamma_1)}{1 - \epsilon_p(\gamma_2) \Omega f} \frac{\epsilon_p(\gamma_2) \Omega f + N_{\gamma_2}}{\epsilon_T(\gamma_2) \Omega f + N_{\gamma_2}},$$

where $P_{cos}$ and $P(\gamma_1)$ are the areas under the coincidence photopeak and the photopeak in the fixed channel which is set on the $\gamma_1$-ray; $\epsilon_p$ and $\epsilon_T$ are the photopeak and total efficiencies; $f$ is the fraction of the $\gamma_1$-ray in coincidence with the $\gamma_2$-ray; $\Omega$ is the solid angle 0.032; and $N_{\gamma_2}$ is the random summing of two pulses which is small and is neglected here. This correction was found to be small showing that the 475 and 720 keV gamma rays mainly consist of the cross-over transitions of the above mentioned cascades. After taking into account the usual corrections, the relative intensities of the unconverted gamma rays of 245, 450 and 693 keV are 1.0, 2.6 and 2.0, respectively.

The coincidence spectrum with the gating channel covering the full 475 keV photopeak is shown in fig. 3(a). Coincidence peaks are observed at 245, 475, 625 and 720 keV energy. The presence of a coincidence peak under the 475 keV photopeak indicates another gamma ray of comparable energy and in coincidence with the 475 keV gamma ray. The coincidence
spectrum with the gating channel set only on the high energy end of the 475 keV photopeak is shown in fig. 3(b). This setting reduces the intensity of the 450 keV gamma ray being recorded in the gating channel. The coincidence peak under the 475 keV singles peak appears to be slightly shifted towards the lower energy end, the shift again being of the order of 27 keV. Moreover, the intensities of these two coincidence peaks at 475 and 720 keV are reduced relative to the intensity of the 625 keV coincidence peak. It is concluded from this measurement that a gamma ray of about 450 keV is in coincidence with the 475 and 720 keV gamma rays. The relative intensities of the 245, 450, 625 and 693 keV gamma rays estimated from fig. 3(b) after applying the usual corrections are 1.00, 0.12, 0.25 and 0.16, respectively.

The percentage contributions ($x$) of the 245, 450 and 625 keV gamma rays (here denoted $\gamma'$) to the intensity of the 475 keV gamma ray (denoted here $\gamma$) are calculated from the formula:

$$x = \frac{100 \, P(\gamma') \, \xi \, 1 + \alpha(\gamma') \, \eta}{t \, \epsilon_p(\gamma') \, W(\gamma') \, \Omega \, \alpha(\gamma) \, K}$$

where $\Omega$ is the solid angle 0.032; $\epsilon_p(\gamma)$ is the photopeak efficiency; $\alpha(\gamma)$ is the observed counting rate in the fixed channel after applying corrections for the Compton contribution of the high energy gamma rays; $P(\gamma')$ is the area under the photopeak of $\gamma'$-ray observed in time $t$; and $K$ is the correction factor for the external absorbers. The quantity $\alpha(\gamma')$ is the conversion coefficient of $\gamma'$-ray and is neglected here, since
Fig. 4. The coincidence spectrum with the gating channel set on the 720 keV photopeak.
THE ANGULAR CORRELATION DATA BETWEEN THE 245 AND 475 keV GAMMA RAYS IN THE DE-EXCITATION OF $^{129}$I.

COINCIDENCES WITH THE X-RAY PEAK IN THE FIXED CHANNEL AND THE OTHER CHANNEL SLIDING AROUND THE 525 keV PHOTO-PEAK IN THE DECAY OF $^{115}$Cd.
the conversion was found to be small.\textsuperscript{3)} \( W(90) \) is the angular
distribution of the two coincident gamma rays obtained from the
angular correlation data. Thus the estimated percent contributions
from the 245, 450 and 625 keV gamma rays to the intensity of the
475 keV gamma ray are 12.4, 1.4 and 3.6, respectively.

The coincidence spectrum with the gating channel set on
the full 720 keV photopeak is shown in fig.4. Coincidences were
observed under 475 keV photopeak, thus confirming the presence
of a gamma ray of energy \( \approx 450 \) keV in coincidence with the
720 keV gamma ray.

5. Angular Correlation Experiment

The coincidences between the 245-475 keV cascade were
recorded for 30 minutes at each angle of the sequence 90°, 135°
and 180° between the central axis of the detectors. The coinci-
dences were normalized with respect to the singles counting
rate at the 180° position. The true-to-chance ratio was very
high. The chance rate was subtracted by the random coincidence
method. The least-squares fit of the data was made to the
equation \( W(\theta) = \sum A_k P_k (\cos \theta) \). To obtain the corrected values
of the \( A_k \) coefficients, the normalised values of the \( A_k \) were
corrected for the finite angular resolution by the method due
to Rose\textsuperscript{8}). The least-squares fit curve to the observed data is
shown in fig.5. The least squares fit equation is

\[
W(\theta) = 1 - 0.52 P_2 (\cos \theta) + 0.24 P_4 (\cos \theta)
\]
Fig. 6. The energy levels of $^{129}$I. All the energies are given in keV.
The observed anisotropy $A$ is found to be 0.86 and is very high. Since the 450 keV gamma ray is found to be very weak in comparison to the 475 keV gamma ray, the observed angular correlation is thought to occur mainly between the gamma rays of the 245-475 keV cascade. The high value of the anisotropy indicates that both gamma rays are of mixed multipoles. Also the presence of the $A_4$ coefficient indicates a spin assignment of $\geq 5/2$ for the 475 keV level.

6. The Decay Scheme

Combining all the data presented in the previous sections, a probable decay scheme is constructed and is shown in fig. 6. This decay scheme differs from that of Graves and Mitchell\(^3\) in the following points: The 475 keV gamma ray which was shown to be in coincidence with the 27 keV gamma ray now appears to be the cross-over transition of the 448-27 keV cascade. Hence, the energy of the second excited level becomes 475 keV instead of 502 keV. Another gamma ray of 693 keV energy has been found to be in coincidence with the 27 keV gamma ray and thus, the 720 keV gamma ray now becomes the cross-over transition of this new cascade. Yet another cross-over transition of 1100 keV seems to occur. Evidence for this gamma ray comes from the measured half-width of the 1100 keV photopeak which is found to be more than the expected half-width from the known resolution of the spectrometer. This cross-over transition takes place across
the 27-1073 keV cascade. Graves and Mitchell\textsuperscript{3)} have established this cascade in their coincidence studies, however, the energy quoted by them for one of the cascade gamma ray is 1120 instead of 1073 keV.

The coincidence studies establish a new gamma ray of energy 625 keV, which is in coincidence with the 475 keV gamma ray. This 625 keV transition takes place between 1100 and 475 keV energy levels. From the data of figs. 3 and 4, evidence is found for a gamma ray of energy 450 keV in coincidence with the 720 keV gamma ray. This cascade establishes a new level at energy 1170 keV, which was not found earlier\textsuperscript{3)}. Because of the small energy difference between the 1100 and 1170 keV levels, the beta branching feeding these levels could not have been separated.\textsuperscript{3)} The ten percent beta branching can feed both of these levels.

The two new high energy gamma rays of energies 1320 and 1520 keV perhaps occur in 41 day Te\textsuperscript{129m} through beta decay. The 1520 keV level is evidently not fed by the beta decay of 72 min Te\textsuperscript{129}, because $Q_{\beta-}$ between the ground levels of Te\textsuperscript{129} and I\textsuperscript{129} is smaller than the gamma ray energy under consideration. The observed low intensities of the 1320 and 1520 keV gamma rays can be explained if the 32 percent beta branching\textsuperscript{4)} from Te\textsuperscript{129m} feeds both the levels at 1320 and 1520 keV also. In the $\beta-$
decay of $^{131}\text{Te}$ to $^{131}\text{I}$, levels at 1920, 2000 and 2240 keV are fed from $^{90}\text{Te}^{131m}$. From systematics, these levels appear to be similar to 1320 and 1520 keV levels in $^{129}\text{I}$. Spin assignments of $11/2^-$ and $13/2^-$ have been proposed$^9$ for 2000 and 2240 keV levels in $^{131}\text{I}$ respectively. So the 1320 and 1520 keV levels in $^{129}\text{I}$ could also have $11/2^-$ and $13/2^-$ spins, respectively.

The ground state spin of $^{129}\text{I}$ has been measured$^{10}$ to be $7/2$. Life time measurements of the 27 keV level$^{11}$ indicate that it is of the order of 15 μsec. If the 27 keV level is assumed to be a single-particle level then, the measured half-life of this level makes it possible for the 27 keV gamma ray to be a mixture of $M1$ and $E2$, but predominantly $M1$. Thus the 27 keV level could have a spin of $5/2$. From the angular correlation data a spin of $\geq 5/2$ is indicated for the 475 keV level.

In the calculations of Banerjee and Gupta$^{5}$ two levels at 466 and 471 keV with spins $5/2$ and $3/2$, respectively, are shown to occur. The level at 475 keV could be one of these theoretical levels. It could not be the 471 keV level, because the calculated spin is $3/2$, whereas the measurement shows that it has a spin of $\geq 5/2$. It could however be the 466 keV level which is predicted to have spin of $5/2$. Around the measured level at 720 keV, three levels at 713, 746 and 750 keV with spins of $11/2, 13/2$ and $11/2$, respectively, are predicted$^5$. This level could not have such a high spin because the beta branching to this level from a $d3/2$ ground state of $^{129}\text{Te}$ would then be highly forbidden$^3$. This is one source of disagreement with the
calculations of Banerjee and Gupta. Spins for higher states are not calculated and thus comparison with the experiment could not be made.

References

1) R.D. Hill, Phys. Rev. 76 (1949) 333
2) Hollander, Pearlman and Seaborg, Revs. Mod. Phys. 25 (1953) 469
4) G. Anderson and E. Hagebo, Ark. Fys. 22 (1962) 349
5) B. Banerjee and K.K. Gupta, Nuclear Physics 30 (1962) 349
8) M.E. Rose, Phys. Rev. 91 (1953) 610
9) A. Badescu et. al., Zh. eksper. teor. Fiz (USSR) 40 (1961) 91, English translation JETP 13 (1961) 61
10) Livingston, Gilliam and Gordy, Phys. Rev. 76 (1949) 149
1. Introduction

Earlier studies\textsuperscript{1-5}) in the decay of Cd\textsuperscript{115}(2.3d) have led to a tentative level scheme of In.\textsuperscript{115} Varma et al.\textsuperscript{5}) have assigned the spins and parities of the excited levels of In\textsuperscript{115} mainly from the log ft values of the various beta branchings obtained from the gamma ray transition data. The present studies were undertaken to check some of these spins and parities by studying the angular correlations of cascade gamma rays, internal conversion coefficients, and shapes of the beta spectra.

2. Coincidence studies

The Cd\textsuperscript{115} (2.3d) isotope was produced by the thermal neutron irradiation of the (spectrographically standardised) pure cadmium metal in the 'Apsara Reactor', Trombay. From time to time the 4.5 h isomer of In\textsuperscript{115} was separated from cadmium by a hydroxide precipitation using Al as carrier.

The singles pulse height distribution of gamma rays recorded in a 3.8 cm x 3.8 cm NaI (Tl) crystal scintillation spectrometer is shown in fig. 7. After the separation of indium, the singles spectrum of Cd\textsuperscript{115} gave evidence for the gamma rays

\[\text{† to be published in Nuclear Physics 44 (1963)}\]
with the following energies 230, 262, 335 and 525 keV. By following the half life of the spectrum the 335 keV peak was attributed to the isomeric decay of In\textsuperscript{115} (4.5 h). In order to confirm the decay scheme proposed by Varma et al.\textsuperscript{5} the coincidences were recorded with two identical scintillation spectrometers in coincidence (\(\gamma =0.15\ \mu\text{sec}\)). While recording all the following coincidences, the counters were placed at 60\(^\circ\) to each other and about 0.6 cms thick perspex discs were introduced in front of the counters for absorbing betas and conversion electrons, and a thick lead sheet (8 g/ cm\(^2\)) was placed in between the counters to prevent the Compton scattered high energy gamma rays escaping from one counter being detected in the other counter and to minimise the detection of the escape X-rays.

As found in earlier studies\textsuperscript{5} 230-262 keV and 35-492 keV gamma rays were found to be in cascade. A relative estimate of the coincidences from the 265-262 keV cascade in the 230-262 keV coincidence spectrum was obtained by studying the asymmetry of the coincidence peak recorded with the fixed channel at 260, 275 and 285 keV, and the other channel sliding around 230 keV. The intensity of the 265 keV gamma ray thus obtained was found to be < 0.1 relative to that of the 230 keV gamma ray. The coincidence spectrum reproduced in fig. 8 (please see the diagram facing page 46) recorded with X-rays in the fixed channel and the 525 keV gamma ray in the variable channel.
Fig. 9. Decay scheme of Cd\(^{115}\) (2.3 d) proposed by Verma et al.\(^5\). All the energies are given in keV (the spin assignments and the gamma ray energies are given from the present measurements). The level at 520 keV was observed by Coulomb excitation by Davis et al.\(^7\).
confirmed that the photopeak at 525 keV is a combined peak of 492 keV and 528 keV gamma rays in the intensity ratio 22:43. Study of the singles spectrum around the X-ray peak of Cd$^{115}$ immediately after separation of the 4.5 h. In$^{115}$ isomer gave evidence for the existence of a small peak at 34.5 keV. This however was not observed in the singles spectrum taken before the separation of In probably due to the presence of heavy Compton background. For determining its exact energy, the calibration was done with the help of 32 keV X-ray peak in Cs$^{137}$ and with the 25 keV internal conversion X-ray peak of the 335 keV gamma ray in the decay of the chemically separated In$^{115}$ isomer. From the singles spectrum and $\gamma$-$\gamma$ coincidence measurements the intensities of the various gamma rays after applying the usual corrections for various absorbers, effective photopeak efficiencies and escape of iodine X-rays are given in table 1 along with the values reported by Varma et al.$^5)$ The decay scheme proposed by Varma et al.$^5)$ is reproduced in fig. 9.

### Table 1

<table>
<thead>
<tr>
<th>Gamma ray energy (keV)</th>
<th>Intensities of the gamma ray transitions</th>
<th>Present measurements</th>
<th>Varma et al.$^5)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>528</td>
<td>46</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>492</td>
<td>18</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>265</td>
<td>$&lt;0.1$</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>262</td>
<td>3.5</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>230</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>35</td>
<td>0.93</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 11(a) SINGLES GAMMA SPECTRUM IN THE DE-EXCITATION OF THE 4.5 h ISOMER OF In$^{115}$

11(b) LOW ENERGY PART OF THE SPECTRUM TAKEN WITH HIGH AMPLIFICATION.
3. The $\kappa_K$ Measurements

The coincidence spectrum obtained with 490 keV peak in the fixed channel and the other channel sliding around the 35 keV $\gamma$-ray peak and 25 keV X-ray peak is reproduced in fig. 10. By comparing the areas under the two peaks the value of $\kappa_K$ is obtained to be $= 7.6 \pm 0.3$ after applying the usual corrections for absorption, escape peak intensities from the formula of P. Axel$^6$ and for the K-Shell fluorescence yield$^7$ of In (0.817). The detection efficiency is 100% for both X- and $\gamma$-rays. This value is quite consistent with an M1 assignment from the calculations of Rose,$^3$ who obtained $\kappa_K(M1) = 8.1$.

The In$^{115}$ (4.5 h) isomer was separated from cadmium by a hydroxide precipitation using Al as carrier and the precipitate was thoroughly washed with distilled water to remove the adhering Hexa-amino cadmium sulphate solution. A source was made in a thin perspex rod and the spectrum was measured as shown in fig. 11. After taking the various corrections into consideration a value of $0.84 \pm 0.9$ was obtained for the K-conversion coefficient. Comparison of this value with the theoretical calculations of Sliv and Band$^9$ and with the earlier reported experimental values is given in table 2. The present measurement shows that the 335 keV transition is a mixture of about 50% each of M4 and E5 which is further supported by $K/(L + M)$ value of 3.85 obtained by Varma et al.$^5$ in contradiction to the pure E5 assignment made by Estulin et al.$^{10}$
Fig. 12. (a) Singles beta spectrum, (b) F-K plot of the beta group in coincidence with the 528 keV gamma ray, (c) experimental shape factor.
Table 2

\( E^k \) Measurements of the 335 keV gamma transition in the
decay of 4.5 h In\(^{115}\)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Theoretical values of Sliv and Band.(^9)</th>
<th>Experimental values.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E5</td>
<td>M4</td>
</tr>
<tr>
<td>( E^k )</td>
<td>0.69</td>
<td>0.92</td>
</tr>
</tbody>
</table>

4. Beta - Gamma Coincidences

The singles beta spectrum, as well as the \( \beta - \gamma \) coincidences
were measured with a thin anthracene crystal scintillation
spectrometer. The resolution of the spectrometer for the internal
conversion 625 keV electron peak of Cs\(^{137}\) was 17%. In all the
following observations the beta source was prepared on a gelatin
free thin cello tape (3mg/ cm\(^2\)) fixed to a thin perspex disc.
Each time the observations were taken after the separation of
the 4.5 h. In\(^{115}\) so as to reduce the background due to the
intense internal conversion peak of 310 keV electrons. The
beta source was kept right on the face of the crystal with
only 5 mg/cm\(^2\) of Al foil which serves as a light shield and
light reflector.

The Fermi-Kurie plot of the beta group in coincidence
with the 523 keV gamma ray is reproduced in fig. 12 along with
the plot of the experimental shape factor, which is consistent
with a statistical distribution. The spectrum has been corrected
Fig. 13. Conventional and corrected F-K plots of the beta spectrum in coincidence with the 262 keV gamma ray.
for the finite resolution of the spectrometer by the method
due to Palmer and Laslett. Because of the large thickness
of the source the low energy end of the spectrum is quite distorted.
The spectral shape at the high energy end is quite in accordance
with the selection rules of $\Delta I = 0, 1$ yes suggested by Varma et al.

The conventional F-K plot of the beta spectrum in
coincidence with the 262 keV photo peak is reproduced in fig. 13
along with the spectrum corrected for the first forbidden unique
shape factor $L_1 = (w^2 - 1) + (w_0 - w)^2$. The last five points have been
corrected for the finite resolution of the spectrometer. The
spectral shape at the high energy end supports $\Delta I = 2$, yes unique
forbidden type transition. But because of the poor statistics,
one cannot rule out the possibility of the allowed shape simply
from the shape of the spectrum. However, as shown subsequently
this is consistent with the angular correlation measurements.

5. Angular Correlation Measurements

The 4.5 h isomer of In$^{115}$ was separated in the usual
manner and the source which was in the form of Hexa-amino
cadmium sulphate was concentrated and the angular correlation
measurements were performed with the source in a semi-solid
state. The chance coincidences were subtracted by repeatedly
testing the coincidence circuit by the random coincidence method.
A least-squares fit of the data was made to the eqn $W(\theta) = \sum_k A_k' P_k(\cos \theta)$. The normalized $A_k'$ coefficients were corrected for
the finite angular resolution by analytically evaluating the
Angular correlation function of the 230-262 keV cascade.

Fig. 14

Angular correlation function of the 35-492 keV cascade.
\((J_1/J_0)^2\) by the method due to Rose.\(^{13}\)

The 35 - 492 keV correlation: The coincidences were collected for thirty minutes at each angle of the sequence \(90^\circ \rightarrow 135^\circ \rightarrow 180^\circ\) repeating them in turn to make the total time of observation at each angle being equal to four hours. The singles counting rate was noted from time to time and the observed coincidences were normalized to singles counting rate at 180°. This method takes into account the slight drift in the counters and the decay of the source. The separation of indium was performed after each four hours. In the least-squares fit of the curve reproduced in fig.14, the errors are the root mean square statistical errors. The least-square fit of the data after correcting for the finite angular resolution of the spectrometers gave

\[
W(\theta) = 1 - \left(0.10 \pm 0.03\right) P_2(\cos \theta) + \left(0.03 \pm 0.03\right) P_4(\cos \theta)
\]

The 230 - 262 keV correlation: The procedure adopted in these measurements is exactly similar to that mentioned previously. The coincidence counts were normalized for singles counting rate at 180°. The least-squares fit of the curve is given in fig. 15. The least-squares fit of the data after correcting for the finite angular resolution of the spectrometers gave:

\[
W(\theta) = 1 - \left(0.38 \pm 0.03\right) P_2(\cos \theta) + \left(0.05 \pm 0.04\right) P_4(\cos \theta)
\]

6. Discussion and Results

From the shell model the ground state spin and parity of \(^{115}\text{In}\) is expected to be \(1g\ 9/2\) which is consistent with the measured
The isomeric transition is known to be a mixture of $M_4$ and $E_5$ which allows a $p^+$ assignment for the 4.5 h isomeric state. Again from the shell model the ground state spin and parity of Cd$^{115}$ (67 neutrons) is $d\ 3/2$ or $s^+$. The ground state assignments of $\Lambda 1/2$ for Cd$^{115}$ and $g\ 9/2$ for In$^{115}$ are quite consistent since no beta branching was observed between these two states which will be a $\Delta I = 4$ and $\Delta J = 4$ forbidden transition. The assignment of $d\ 3/2$ is not likely for the Cd$^{115}$ ground state since it would lead to a second forbidden transition, contrary to observations.

The log $ft$ values of the various beta branchings calculated from the intensities of the gamma ray transitions are given in table 3 together with the earlier measurements.

Table 3

Log $ft$ values obtained from the gamma ray transitions.

<table>
<thead>
<tr>
<th>Activity</th>
<th>End point energy (MeV)</th>
<th>Percentage of disintegrations</th>
<th>Log $ft$ Present measurements</th>
<th>Log $ft$ Varma et al.</th>
<th>Nature of transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd$^{115}$ (2.3d)</td>
<td>1.11</td>
<td>61.6</td>
<td>7.1</td>
<td>7.1</td>
<td>$\Delta I = 2$, yes</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>1.4</td>
<td>8.4</td>
<td>8.3</td>
<td>$\Delta I = 4$, yes</td>
</tr>
<tr>
<td></td>
<td>0.63</td>
<td>10.0</td>
<td>7.0</td>
<td>6.8</td>
<td>$\Delta I = 0$, 1 yes</td>
</tr>
<tr>
<td></td>
<td>0.59</td>
<td>27.0</td>
<td>5.9</td>
<td>6.5</td>
<td>$\Delta I = 0$, 1 yes</td>
</tr>
</tbody>
</table>
From the log ft value and observed allowed shape of the beta spectrum from Cd115 to the 862 keV level, the beta transition involved should be first forbidden with $\Delta I=0,1$ yes from which one may assign $1/2^-$ or $3/2^-$ for this level. The 630 keV beta branching also seems to be $\Delta I=0,1$ yes type from the log ft value of 7.0 which again allows $1/2^-$ or $3/2^-$ assignments to the level at 827 keV. Out of these possibilities the assignment of $1/2^-$ may be ruled out since this would lead to the angular symmetry case in the 35-493 keV angular correlation. From the log ft value of 8.4 and the shape of the beta spectrum leading to the 597 keV level, $5/2^-$ assignment is quite consistent for this state. Under these conditions the possible spins and multipolarities of the various gamma rays in the 35-492 keV and 230-262 keV cascades leading to the ground state are as given below:

35-492 keV: $3/2^-(M1(E2)) \rightarrow 3/2^-(M1(E2)) 1/2^-(M1(E2))$

$1/2^-(M1(E2)) \rightarrow 3/2^-(M1(E2)) 1/2^-(M1(E2))$

230-262 keV: $3/2^-(M1(E2)) \rightarrow 5/2^-(E2(M3)) 1/2^-(M1(E2))$

The measured values of $A_2 = -0.10 \pm 0.03$, $A_4 = 0.03 \pm 0.03$

for the 35-492 keV cascade, and $A_2 = -0.38 \pm 0.03$

$A_4 = 0.05 \pm 0.04$, for the 230-262 keV cascade are not compatible with any of the following pure transitions;

35-492 keV: $3/2^-(M1 pure) \rightarrow 3/2^-(M1 pure) 1/2^-(M1 pure)$; $A_2=0.20, A_4=0$

$1/2^-(M1 pure) \rightarrow 3/2^-(M1 pure) 1/2^-(M1 pure)$; $A_2=0.20, A_4=0$

230-262 keV: $3/2^-(E2 pure) \rightarrow 5/2^-(E2 pure) 1/2^-(E2 pure)$; $A_2=0.0535, A_4=0$
The values of the F coefficients were obtained from the tables of Ferentz and Rosenzweig.\textsuperscript{15) However, assuming 35 keV to be a pure M1, we get $Q_2 = \frac{E_2}{M_1 + E_2} = 0.14$ or $0.97$ for the 492 keV gamma ray, when we analyse the data by the graphical method due to Arns and Wiedenbeck\textsuperscript{16) for the spin assignments of 1/2-, 3/2- and 1/2- for the 862, 827 and 335 keV levels respectively.

A similar analysis of the angular correlation data of the 230-262 keV cascade with the spin assignments of 3/2-, 5/2- and 1/2- gave the following results.

If 262 keV gamma ray is assumed to be pure E2, then the $A_4$ coefficient turn out to be negative, which is inconsistent with the measured value. On the other hand a small admixture of M3 (say $\frac{M3}{E2 + M3} \approx 8\%$ obtained by the analytical method) is sufficient to account for the small positive value of the observed $A_4$ along with the observed value of $A_2$. The present studies seem to give almost unique spin assignments for the 335, 597 and 827 keV levels as 1/2-, 5/2- and 3/2- respectively. The level at 862 keV, may however have either 1/2- or 3/2-. The 520 keV level observed by Davis et al.\textsuperscript{17) in the Coulomb excitation of In\textsuperscript{115} does not seem to have been excited from the decay of Cd\textsuperscript{115}.

References

1) A.C. Wahl and N.A. Bonner, Phys. Rev. 85 (1952) 570
2) L.M. Langer and R.D. Moffat, Phys. Rev. 86 (1952) 632
3) R.W. Hayward, Phys. Rev. 87 (1952) 202 A
4) J.M. Cork et al., Phys. Rev. 79 (1950) 938
5) J. Vurma and C.E. Mandeville, Phys. Rev. 97 (1955) 977
6) P. Axel, Rev. Sci. Instr. 25 (1953) 392
9) L.A. Sliv and I.M. Band (Translation: Reports 57 ICCK 1 and 58 ICGBI circulated by the Physics Department, University of Illinois, Urbana, Illinois, 1957, 1958)
10) I.V. Estulin and E.M. Moiseeva, JETP (Soviet Physics) 1 (1955) 463
13) M.E. Rose, Phys. Rev. 91 (1953) 610
14) J.E. Mack, Revs. Mod. Phys. 22 (1950) 64
17) Davis, Divatia, Lind and Moffat, Phys. Rev. 103 (1956) 1801
PULSE HEIGHT DISTRIBUTION OF GAMMA RAYS FROM THE DECAY OF $^{143}_{{\text{Ce}}}$ (33h)

35 keV X-RAY

Escape peak of 140 keV
56 keV

230 keV (X4)

341 keV

$^{137}_{{\text{Cs}}}$ 662 keV $\gamma$-RAY

(X400)

425 keV (X20)

488 keV

665 keV

718 keV

1087 keV

THE LOW ENERGY PART OF THE SPECTRUM TAKEN WITH HIGH GAIN

35 keV X-RAY PEAK

56 keV $\gamma$-RAY

870 keV

BASE LINE (VOLTS)
C) RADIOACTIVE DECAY OF Ce\textsuperscript{143} (33 h)\textdagger

1. Introduction

The decay of Ce\textsuperscript{143} (33 h) has been studied by various authors\textsuperscript{1-6}. Recently Martin et al.\textsuperscript{6} have reported the existence of ten gamma rays and they have also suggested a tentative level scheme of Pr\textsuperscript{143}, with some doubts about the assignment of spins and parities to the various excited states. The present study was undertaken in order to obtain more information about the levels from the angular correlation data and internal conversion coefficient measurements.

2. Gamma Ray Intensity Measurements

Ce\textsuperscript{143} was prepared by the thermal neutron irradiation of spectrographically standardised 99.9\% pure cerium oxide in the swimming pool reactor, Trombay. Fig. 16. shows the pulse-height distribution of gamma rays detected by a NaI (Tl) crystal (3.8 cm x 3.8 cm) coupled to a Du Mont-6292 photomultiplier. From the graph, evidence is seen for the existence of gamma rays of energies 56, 140, 230, 293, 341, 425, 488, 665, 718, 870 and 1087 keV. By following its decay, the peak at 140 keV was attributed to the decay of Ce\textsuperscript{141} (33 d). The peak at 425 keV was interpreted to be due to the Compton edge of 665 keV and 718 keV gamma rays by studying its relative attenuation with several absorbers of varying thickness before the counter, and

\textdagger Published in Nuclear Physics 41 (1963) 511
also by studying the intensities of the singles spectrum at different source positions from the crystal. All the peaks are separated from the Compton background as shown in fig. 16. and their relative intensities are calculated by taking their corresponding effective photo peak efficiencies. The values of the intensities thus obtained were corrected for the following factors; 1) the relative absorption in the Al and Al₂O₃ housing around the crystal and in the 0.6 cm thick perspex disc introduced in front of the crystal for absorbing beta rays and internal conversion electrons, 2) the relative escape peak intensities for the medium geometry case, 3) the total internal conversion coefficients obtained with the help of the present data of K-internal conversion coefficients, 4) the source decay during observation. The separation of the 56 keV peak from the heavy Compton background may introduce an error of ±20% at most in the case of the 56 keV gamma ray intensity. The relative unconverted gamma ray intensities together with the values of the relative intensities of the various gamma ray transitions after applying the above mentioned corrections are given in table 1.

Table 1
Unconverted gamma ray intensities and relative intensities of some gamma ray transitions.

<table>
<thead>
<tr>
<th>Gamma-ray energy (keV)</th>
<th>Unconverted gamma ray intensities</th>
<th>Intensities of the gamma ray transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>0.22</td>
<td>1.80</td>
</tr>
<tr>
<td>230</td>
<td>0.067</td>
<td>0.069</td>
</tr>
<tr>
<td>293</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>341</td>
<td>0.069</td>
<td>0.065</td>
</tr>
<tr>
<td>488</td>
<td>0.063</td>
<td>0.068</td>
</tr>
<tr>
<td>565 (very weak)</td>
<td></td>
<td>(very weak)</td>
</tr>
<tr>
<td>665</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>718</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>870</td>
<td>0.018</td>
<td>0.017</td>
</tr>
<tr>
<td>1087</td>
<td>0.013</td>
<td>0.013</td>
</tr>
</tbody>
</table>
DECAY SCHEME OF \( ^{143} \text{Ce} \) (33 h) PROPOSED BY MARTIN et al.\(^6\) AND CONFIRMED BY THE PRESENT \( \gamma-\gamma \) COINCIDENCES MEASUREMENTS. (ALL THE ENERGIES ARE GIVEN IN keV.)
3. The $\gamma_X$ Measurements

The $\gamma-\gamma$ coincidences were recorded with the help of two identical (3.8 cm x 3.8 cm NaI (Tl) crystal) scintillation spectrometers in coincidence (resolving time=0.15 $\mu$sec). Various $\gamma-\gamma$ coincidence measurements have confirmed the decay scheme proposed by Martin et al.\textsuperscript{6}) reproduced in fig. 17. The $\gamma$-ray of 56 keV was found to be in coincidence with 35 keV X-rays and gamma rays of 293, 665, 870 and 1087 keV. The $\gamma-\gamma$ coincidences gave evidence also for the existence of a very weak gamma ray of about 565 keV energy. For the determination of the $K$-conversion coefficient of the 56 keV gamma ray the coincidences were recorded between 293 keV in the fixed channel and the X-ray peak and the 56 keV peak in the variable channel which are shown in fig. 18. The number of coincidence counts between the X-rays and the Compton scattered gamma rays of 488 and 341 keV detected along with the 293 keV gamma ray is negligible since both gamma rays are very weak, and neither of them are highly converted. The counters were placed at 60° with respect to each other and $\approx 0.6$ cm thick perspex discs were introduced in front of the counters to absorb betas and conversion electrons, and a lead sheet (10 gm/cm$^2$) was placed between the counters to reduce the spurious coincidences due to scattering and to prevent the detection of escape X-rays in the variable channel after escaping from the counter in the fixed channel. A comparison of the areas under the 35 keV X-ray peak and 56 keV
photo peak in the coincidence spectrum directly gives the K-conversion coefficient after taking the following factors into account: 1) the relative absorption due to the Al and Al₂O₃ housing around the crystal and the external perspex disc, 2) the fluorescence yield \(^8\) of Pr (0.398) in the K-shell and 3) the escape peak corrections. The detection efficiency is 100% for both X-rays and \(\gamma\)-rays. The escape peak intensity was calculated from the formula of P. Axel \(^9\) taking the geometry of our experimental set up into consideration. The final value of \(\lambda_K\) obtained is 6.4 ± 0.6 which is consistent with the assignments of either M₁ (\(\lambda_K = 5.7\)) or E₂ (\(\lambda_K = 6.0\)) or a mixture of them, from the calculations of Rose \(^10\).

For obtaining the K-conversion coefficient of the 293 keV \(\gamma\)-ray, the coincidences were recorded as shown in fig. 19 with the fixed channel kept at the peak of 56 keV so that practically there will not be any contribution from X-rays. Thick perspex discs 0.6 cm in thickness were put in front of both the counters for absorbing betas. Besides the corrections mentioned in the previous case the variation in effective photo peak efficiency of the crystal for the gamma rays under consideration is also taken into account. The X-ray and 665, 870, and 1087 keV Compton coincidences may introduce a maximum error of +5% in the value of \(\lambda_K\). The final value of \(\lambda_K\) obtained is 0.07 ± 0.007 which shows that the 293 keV gamma ray is predominantly M₁ in character with a small admixture of E₂.
In a similar way, the coincidence spectrum was obtained by keeping the 488 keV gamma ray in the fixed channel and the sliding channel around the X-ray peak and 230 keV photopeak as shown in fig. 20. Along with 488 keV, however, there will be some counts due to Compton scattering of 665, 870 and 1087 keV gamma rays which in turn are in coincidence with the highly converted 56 keV gamma ray as well as with its X-rays arising from its conversion. Knowing the coincidences with the 56 keV γ-ray and the $\langle T \rangle$ of the 56 keV $\gamma$-ray, the above contribution is determined and subtracted. The value of $\langle T \rangle$ thus obtained for the 230 keV gamma ray after applying the various corrections previously mentioned is $0.12 \pm 0.02$ which is compatible with an assignment of M1 ($\langle T \rangle = 0.1$) or E2 ($\langle T \rangle = 0.1$) or an M1-E2 mixture from the calculations of Sliv and Band.

4. Angular Correlation Measurements

The source which was in the form of cerous chloride in dilute hydrochloric acid is further diluted and taken in the source holder which was a thin perspex rod with a hole of 0.2 cm diameter and about 0.4 cm in length and allowed to dry under a heating lamp. This process was repeated many times and the experiment was performed when the source was in a semi-liquid form. The source was mounted at 7 cm from the central axes of the two crystals. The coincidences between 293 and 56 keV gamma rays were recorded for 5 minutes at each angle in the sequence $90^\circ, 135^\circ$ and $180^\circ$ between the central axes of the
ANGULAR CORRELATION FUNCTION OF THE 293-56keV CASCADE IN THE DECAY OF Ce$^{143}$ (33h).

Fig. 21
detectors. The true-to-chance ratio was very high. The chance coincidences were subtracted by repeatedly testing the coincidence circuit by the random coincidence method. The least-squares fit of the data was made to the equation

\[ W(\theta) = \sum_k A_k P_k(\cos \theta). \]

To obtain the corrected values of the \( A_k \) coefficients, the normalized values of \( A_k \) were corrected for the finite angular resolution of the counters by analytically computing the ratio \( (J_e/J_o)^2 \) by the method due to Rose. The correlation was probably not attenuated due to extranuclear fields since the experiment was performed when the source was in the form of solution in an acid medium. In the least-squares fit of the curve shown in fig. 21, the root mean square errors are shown. The least-squares fit of the data gave

\[ W(\theta) = 1 + (0.132 \pm 0.019) P_2(\cos \theta) + (0.008 \pm 0.02) P_4(\cos \theta) \]

5. Discussion and Results

From the single particle model the ground state of \( ^{143}\text{Nd} \) should be either \( \frac{9}{2} \) or \( \frac{7}{2} \). The fact that \( \frac{7}{2} \) was observed both from paramagnetic resonance methods and also from atomic spectroscopy allows us to accept \( \frac{7}{2} \) for the ground state of \( ^{143}\text{Nd} \). From the shape and log ft value of the observed beta spectra from \( ^{143}\text{Pr} \) to \( ^{143}\text{Nd} \), \( \frac{5}{2} + \) may be assigned for the ground state of \( ^{143}\text{Pr} \) which is quite consistent with the shell model predictions of \( \frac{7}{2} \) or \( \frac{5}{2} \). Again from the shell model the ground state of \( ^{143}\text{Ce} \) should be \( \frac{7}{2} \) or \( \frac{9}{2} \). The possibility of \( \frac{7}{2} \) is not likely since no beta
branching was observed from Ce$^{143}$ to the ground state of Pr$^{143}$. On the other hand, 9/2 could be accepted because of the non-observance of the beta branching which will be $\Delta \ell = 3$, forbidden in this case.

Both M1 or E2 assignments are quite consistent with the observed $\lambda_K = 6.4 \pm 0.6$ for the 56 keV gamma ray. But Martin et al. have assigned a predominantly M1 character because of the predominance of the Li subshell line, and the lack of an observable LII conversion line. The first excited state in Pr should therefore be either 5/2$^+$ or 7/2$^+$. Spin 7/2$^+$ is consistent with the observed shape of the beta spectrum from Ce$^{143}$ to the 56 keV level of Pr$^{143}$. 5/2$^+$ may be ruled out because, it will lead to no beta branching to this state due to its $\ell$ forbidden nature.

The predominantly M1 character of 293 keV transition allows us to assign 9/2$^+$ or 7/2$^+$ to the second excited state of Pr$^{143}$. The K/L ratio (6.1±0.6) measured by Martin et al. also support this contention, if their value is interpreted with the calculations of Sliv and Band. Under these conditions only the following alternative spins and multipolarities are acceptable for the second, first and ground states in Pr$^{143}$:

$$9/2(+) \rightarrow 7/2(+) \rightarrow 5/2(+)$$

The observed values of the $A_2$ and $A_4$ coefficients
ANALYSIS OF THE ANGULAR CORRELATION DATA BY THE GRAPHICAL METHOD OF ARNS AND WIEDENBECK 15)
\[ A_2 = +0.132 \pm 0.019 \text{ and } A_4 = +0.008 \pm 0.02 \] are not compatible with any of the following sequences:

1) \( \frac{11}{2} E_2 \text{ pure} \), \( \frac{7}{2} M_1 \text{ pure} \), \( \frac{5}{2} \); \( A_2 = -0.0726 \), \( A_4 = 0.0 \)

2) \( \frac{9}{2} E_2 \text{ pure} \), \( \frac{7}{2} M_1 \text{ pure} \), \( \frac{5}{2} \); \( A_2 = +0.0980 \), \( A_4 = 0.0 \)

3) \( \frac{9}{2} M_1 \text{ pure} \), \( \frac{7}{2} M_1 \text{ pure} \), \( \frac{5}{2} \); \( A_2 = +0.0500 \), \( A_4 = 0.0 \)

4) \( \frac{7}{2} M_1 \text{ pure} \), \( \frac{7}{2} M_1 \text{ pure} \), \( \frac{5}{2} \); \( A_2 = -0.1439 \), \( A_4 = 0.0 \)

The values of the \( F \) coefficients were obtained from the tables of Ferentz and Rosenzweig\(^\text{14}\). The small or non-existent \( A_4 \) coefficient shows that at least one of the gamma rays should be either a pure dipole in character or predominantly dipole with a very small admixture of quadrupole transition.

For obtaining the mixing ratios of the gamma rays, the angular correlation data were analysed by the graphical method due to Arns and Wiedenbeck\(^\text{15}\), as shown in fig. 22.

Accepting the 56 keV \( \gamma \)-ray to be a pure M1 transition we have three choices for the spins sequence

a) \( \frac{7}{2} + 26\% M_1 \text{ + } 74\% E_2 \rightarrow \frac{5}{2} + M_1 \text{ pure} \)

b) \( \frac{9}{2} + 97\% M_1 \text{ + } 3\% E_2 \rightarrow \frac{5}{2} + M_1 \text{ pure} \)

c) \( \frac{11}{2} + 25\% M_3 \text{ + } 75\% E_2 \rightarrow \frac{5}{2} + M_1 \text{ pure} \)

The possibility (c) may be ruled out because it will give a K-conversion coefficient\(^\text{10}\) \( \lambda_K = 0.570 \), which is incompatible with the measured value of \( \lambda_K = 0.07 \pm 0.007 \) for the 293 keV gamma ray. The choice (a) also seem to contradict the K/L measurements of Martin et al. and the present \( \lambda_K \) measurements for the 293 keV gamma ray leaving us choice(b).
Even if a small percentage (upto 5%) of E2 is accepted for the 56 keV transition the above arguments still hold good leaving us with only one possible sequence $9/2^+ \rightarrow 7/2^+ \rightarrow 5/2^+$. The value of the amplitude mixing ratio $\delta$ is $-0.031$.

References

1) M.L. Pool and J.D. Kurbatov, Phys. Rev. 63 (1943) 463.
4) E. Kondaiah, Phys. Rev. 83 (1951) 471.
Fig. 23
SINGLES GAMMA SPECTRUM IN THE DECAY OF $^{141}\text{Ce}$. SOURCE TO THE CRYSTAL DISTANCE IS 7 cm.
D) THE K-CONVERSION COEFFICIENT OF THE 145 keV TRANSITION IN Pr$^{141}$

$^{141}\text{Ce}$ (33d) decays by beta emission exciting the 145 keV level in Pr$^{141}$ which further decays through 145 keV gamma ray transition to the ground state. The K-internal conversion coefficient of the 145 keV transition has been reported by various authors$^{1-7}$). These values, which were obtained with different techniques are differing much more in value than those expected from their experimental errors. The present experiment was undertaken with the view of improving on the earlier measurements and to compare with the theoretical calculations of Sliv and Band, who have taken the finite nuclear size effects also into consideration.

The $^{141}\text{Ce}$ (33d) isotope was obtained by the thermal neutron irradiation of the «spec pure» cerium oxide in the "Apsara Reactor", Trombay. The source was allowed to decay for about 30 halflives of $^{143}\text{Ce}$ (33h) so that it is almost free from $^{143}\text{Ce}$ activity. The full spectrum was measured by making a point source in a thin perspex rod and keeping it at the central axis of the 3.8cm x3,8cm NaI (Tl) crystal coupled to a DuMont-6292 photomultiplier and is shown in fig. 23. The ratio of the areas under the $X$-ray peak and the photopeak of the 145 keV gamma ray directly gives the $\lambda_K$ value, after taking account of the following corrections: 1) the ratio of the $X$-ray escape peak intensity to that of the $\gamma$-ray escape peak intensity$^8)$, 2) the variation in effective photo-efficiency of the crystal for both $X$-and $\gamma$-rays, 3) the fluorescence yield$^9)$ of the K-X-ray of Pr(0.888), 4) their relative attenuation in the external
absorbers placed for absorbing betas and conversion electrons and in the Al housing around the crystal. The small peak around 100 keV was found to decay with the same half-life as that of Ce$^{141}$. From the known resolution of the spectrometer at 100 keV, this peak looks broad to be assigned as due to the presence of a mono-energetic gamma ray. By studying its relative attenuation with several absorbers between the source and the crystal, it is interpreted to be due to the Compton edge and escape peak of the 145 keV gamma ray. The value of $\lambda_K$ obtained after applying the various corrections is $0.38 \pm 0.04$. This is in better agreement with the theoretical calculations of Sliv and Band\(^{(10)}\) who obtains $\lambda_K(M1) = 0.39$ and $\lambda_K(E2) = 0.37$, than the earlier reported values. From these calculations, the present measurement is compatible with either pure M1 or pure E2 assignments. In order to decide between the two, the following data were considered.

Comparison of the observed K/L ratio = $6.6^{5,7}$ with the theoretical calculations of Sliv and Band\(^{(10)}\) show that this is a pure M1 transition within the experimental errors. The non-excitation of the 145 keV level by the Coulomb excitation\(^{(11)}\) and the conclusions of Ambler et al.\(^{(12)}\) and Cacho et al.\(^{(13)}\) from their experiments with aligned nuclei along with the halflife measurement of the 145 keV level by De Waard et al.\(^{(14)}\) further support the above assignment.
References

1) M.S. Freedman and D.W. Engelkemeir, Phys. Rev. **79** (1950) 897
2) S.A.E. Johansson, Ark. f. Fys. **3** (1952) 536
3) E. Kondaiah, Arkiv f. Fys. **4** (1952) 122
5) P.P. Zarzoli, Nuovo Cimento **5** (1957) 289
6) M.C. Joshi, B.N. Subbarao and B.V. Thosar, Nuovo Cimento **9** (1958) 600
10) L.A. Sliv and I.M. Band, Reports 57 ICCK1 and 58ICCK1 (The Physics Department, University of Illinois, Urbana, Illinois, 1957,1958)
13) C.F.M. Cacho et al., Phil. Mag. **46** (1955) 1287
14) H. De Waard and T.R. Gerholm, Nuclear Physics **1** (1956) 281
Fig. 24. Gamma spectrum in the decay of Mn$^{54}$.  

Fig. 25. Conversion electron peak of the 640 keV gamma transition in the de-excitation of Cr$^{54}$.  

- Internal Conversion Electron Peak
- Back scattering peak
- 830 keV

BASE LINE (VOLTS)

SINGLE COUNTING RATE IN THOUSAND/Min

BASE LINE (VOLTS)
E) TOTAL INTERNAL CONVERSION COEFFICIENT OF THE 840 keV TRANSITION IN Cr$^{54}$.  

The Mn$^{54}$ (290d) isotope decays by electron capture exciting the 840 keV level in Cr$^{54}$, which further decays by 840 keV gamma transition to its ground state. The energy of this gamma ray was very accurately measured by many investigators,$^{1-4}$ but the internal conversion coefficient or the K/L ratio have not been reported so far. An attempt has been made to determine the total internal conversion coefficient with the help of scintillation spectrometers. A thin strong source of Mn$^{54}$ (procured from the U.K. Atomic Energy Establishment, Harwell) was prepared on a gelatin free thin cello tape (3 mg/cm$^2$). The source which was in the form of MnCl$_2$ in dilute hydrochloric acid was diluted further and allowed to dry on the cello tape fixed to a thin perspex disc (2cm diameter). The complete gamma ray spectrum was measured for the various source to the crystal distances one of which is reproduced in fig. 24. The absolute intensity of the gamma ray was calculated with the help of the solid angle formula for an extended source given by Burtt,$^5$ and from the effective photopeak efficiencies obtained with the help of monoenergetic gamma sources. The mean absolute value of the gamma ray intensity for all the source to the crystal distances was determined. Since an extended gamma source was used the average distance $\langle d \rangle$ was obtained by actually measuring the length of a steel wire, through a wax cylinder of the size of the crystal in three dimensions.
The beta spectrum was studied with a thin anthracene crystal (3mm thickness) coupled to a DuMont-6292 photomultiplier. The resolution of the spectrometer for 625 keV conversion electron peak of Cs$^{137}$ was $\approx 17\%$. The crystal was just thick enough to stop all the 834 keV conversion electrons of Cr$^{54}$. In order to get the conversion electron peak, the source was placed just in front of the crystal and the combined peak due to electrons along with gamma background was recorded. Under the same conditions a thick perspex disc ($\approx 3$mm in thickness) was introduced between the source and the crystal for absorbing all the electrons, and the full spectrum was recorded again. The difference between these two sets directly gave the peak due to conversion electrons which is shown in fig. 25. Knowing the solid angle for an extended source from Burtt's formula and taking the efficiency of the crystal for the electrons to be unity, the absolute intensity of the conversion electrons was calculated, which was corrected for the backscattering in the source and the source holder. Because of the high energy mono-energetic electrons involved in this measurement, the error due to the escape of the scattered electrons from the surface of the crystal is too small. The value of $\mathcal{L}_{\text{total}}$ thus obtained is $2.0 \pm 0.5 \times 10^{-4}$. This is quite in favour of assigning an E2 multipolarity to the 840 keV gamma transition and 2+ assignment for the first excited state in Cr$^{54}$ from the theoretical calculations of Rose who obtained $\mathcal{L}_{\text{total}}(E2) = 2.96 \times 10^{-4}$.
References

1) M. Deutsch and L.G. Elliott, Phys. Rev. 65 (1954) 211
2) G.H. Stafford and L.H. Stein, Nature 172 (1954) 1103
3) Maeder, Wapstra, Nijgh and Ornstein, Physica 20 (1954) 521
5) Benjamin P. Burtt, Nucleonics 5 (1949) 23
7) Mateosian and Smith, Phys. Rev. 88 (1952) 1186
1. Introduction

The decay of $\text{Ce}^{144}_{\gamma} \rightarrow \text{Pr}^{144}$ has been recently investigated by various authors $^{1-6}$. So far, no direct measurements have been performed on the spin of the ground state of $\text{Pr}^{144}$. But the indirect evidence from ($\beta-\gamma$) angular correlation studies, the beta decay selection rules $^{7,8}$ from $\text{Pr}^{144}_{\gamma} \rightarrow \text{Nd}^{144}$ and the nuclear alignment studies $^{9}$ favoured the assignments of zero spin and negative parity for its ground state. The spin assignment of 1, which could be accounted from the single particle shell model has been discussed by Geiger et al $^{7}$ as an alternate possibility for its ground state. But the gamma transition probabilities and beta ray selection rules in the decay of $\text{Ce}^{144}$ to $\text{Pr}^{144}$ studied by Geiger et al $^{5}$ seem to favour the 0-assignment. Recently Lobashov et al $^{10}$ from their correlation studies of the $\beta$-electron and circular polarization of the gamma quantum have preferred 1- assignment over the 0- for its ground state. The present ($\gamma-\gamma$) angular correlation study was undertaken with the view of obtaining further information about the ground state spin of $\text{Pr}^{144}$.

2. Source Preparation

The source which was in the form of $\text{CeCl}_3$ in Hcl acid (concentration $12.38\pm10\%$ mc/ml) was obtained from the Oak Ridge National Laboratory. The $\text{Ce}^{141}$ content was $<< 1\%$ of $\text{Ce}^{144}$.
Fig. 26 - The coincidence spectrum recorded with the fixed channel on the 80 keV photopeak and the other channel around Pr K-X-ray and the 53 keV Y-ray in the decay of Ce$^{144}$:

- 35 keV X-ray
- 53 keV
- 53.53 (M1)
- 80.12 (E2)
- 59.03 (M3)

Fig. 27 - The level scheme of Pr$^{144}$ proposed by Geiger et al. All the energies are given in keV:

- 17.2% 1.1% 1.2% 33.57 (M1)
- 53.41 (M1), 40.93 (M1)
- 1.3%
- 99.95 2 -
- 80.12 1 -
- 59.03 3 -

Fig. 28 - Analysis of the angular correlation data for the 80 keV gamma ray 1 (D,Q) 1 spins. The A2 coefficient is zero if the 80 keV gamma ray is = 96% M1 and 4% E2.
The source was further diluted and the source was made in a thick perspex rod, the thickness of which was sufficient to absorb all betas and conversion electrons of Ce\textsuperscript{144} and Pr\textsuperscript{144}

3. Angular Correlation Studies

The coincidence spectrum recorded with the fixed channel on the 80 keV photopeak and the other channel around the Pr K-X-ray and the 53 keV gamma ray is shown in fig. 26. The two coincidence peaks were separated as shown. For the angular correlation studies one of the channels was fixed at 14 V base line with a channel width of 2 volts so that there is practically no contribution from the Pr K-X-ray and the 80 keV gamma ray coincidences. The source was mounted at 10 cm from the central axes of the detectors and the spatial correlation study was performed in a coincidence counter arrangement of half-angle 90°. The coincidences were recorded for five minutes at each angle of the sequence 90°, 130° and 180° between the central axes of the detectors. The least-squares fit of the data was made to the eqn.

\[
W(\theta) = \sum_k A_k P_k(\cos\theta),
\]

which gave*

\[
W(\theta) = 1 + (0.01 \pm 0.06)P_2(\cos\theta) + (0.02 \pm 0.06)P_4(\cos\theta)
\]

4. Discussion and Results

The level scheme of Pr\textsuperscript{144} proposed by Geiger et al.\textsuperscript{5)} is shown in fig. 27. The present angular correlation studies

* The correlation would not have been much attenuated due to extra-nuclear fields, since the measured halflife of the 80 keV level is quite small (1.8 ± 0.2 x 10\textsuperscript{-10} sec, Burde et al., Phys. Rev. 123 (1962) 325)
gave the following results:

i) The $A_4$ coefficient will be zero only when either both the gamma rays are pure dipoles (or predominantly dipole with almost negligible mixtures of quadrupoles) or when the spin of the middle level is < 2. These two results are obtained from the triangular conditions of the 'F' coefficients. Both these assignments support the results of Geiger et al.\(^1\)

ii) The $A_2$ coefficient can be zero when the middle level has a spin \(< 1\). But this assignment is not allowed from considerations of the other data\(^5\). Accepting the assignments\(^5\) of \(1^-\) for both the 133.53 and 80.12 keV levels, we are left with two alternate possibilities of \(0^-\) or \(1^-\) for the ground state of Pr\(^{144}\). Since the 53 keV gamma ray is pure M1\(^5\) (E2 admixture <0.2%) the $F_2(jj' LL' K')$ coefficient for this gamma ray is \(-0.354\). The assignment of \(0^-\) for the ground state is not acceptable since the $F_2$ coefficient for the 80 keV gamma ray $F_2 (10112) = +0.707$, which will give a value of \(-0.25\) for the $A_2$ coefficient contradicting the experimental value of \(\approx\) zero. The E2 transition between \(1^-\) and \(0^-\) levels is forbidden because of the gamma selection rules. This discussion seems to ruleout the possibility of \(0\) spin assignment for its ground state.

On the other hand, if we analyse the data by the graphical method due to Arns and Wiedenbeck\(^11\) it is possible to account the zero $A_2$ coefficient if the 80 keV gamma ray contains
an E2 admixture of $\approx 4\%$ as shown in fig. 28 for the spin assignment of 1 for the ground state of Pr$^{144}$.

The present angular correlation study seem to support the spin assignment of 1 for the ground state of Pr$^{144}$ over the previously accepted value of zero.

References

1) J.S. Geiger, R.L. Graham and G.T. Ewan, Nuclear Physics 16 (1960) 1
2) R.V. Gnedich, L.N. Kryukova and V.V. Murav'era JETP (U.S.S.R) 36 (1959) 329
4) A.K. Sengupta et al., Ind. J. Phys. 33 (1959) 388
6) Forafontov et al., Nuclear Physics 35 (1962) 260
9) D. Strominger, J.M. Hollander and G.T. Seaborg, Revs. Mod. Phys. 30 (1958) 585
10) V.M. Lobashov et al., ZETF (U.S.S.R) 41 (1962) 1433
G) LEVEL SCHEME OF $^{149}$Sm

1. Introduction

Early work\textsuperscript{1-8} on the decay of $^{149}$Pm showed that it decays by beta emission with a half-life of about 54h exciting the levels at 0.285 and 1.3MeV in $^{149}$Sm. The latest value of its half-life is 53h obtained by Bunney et al.\textsuperscript{9} Schmid and Burson\textsuperscript{10} have studied the beta decay of $^{149}$Pm and obtained the beta decay branchings. They reported the $^{149}$Sm levels at 285, 582, 833 and 850 keV; and the gamma ray transitions with 285, 582, 548, and 850 keV energies. Recent studies by Harmatz et al.\textsuperscript{11} in the electron capture decay of $^{149}$Eu to $^{149}$Sm gave evidence that the de-excitation of $^{149}$Sm takes place by as many as twelve gamma transitions. They have reported the excited levels of $^{149}$Sm at 22.5, 277.2, 350.2, 528.6 and 558.3 keV. Later studies of $^{149}$Eu\textsuperscript{EC} $^{149}$Sm decay by Harling\textsuperscript{12} essentially confirmed the earlier results of Harmatz et al.\textsuperscript{11} and gave evidence for a new gamma transition of 281 keV from the 558keV level to the 277 keV level. The magnetic spectrographic studies by Antoneva et al.\textsuperscript{14} and Dzhelepov et al.\textsuperscript{15} gave similar results with the exception that these authors have not observed the 558 keV level.

Though both $^{149}$Pm and $^{149}$Eu decay to the levels in $^{149}$Sm, it is quite interesting that not even a single level of $^{149}$Sm is commonly excited. The probable spin assignments made by Schmid and Burson\textsuperscript{10} along with the results of Chapman et al.\textsuperscript{13}
and Harmatz et al.\textsuperscript{11}) suggest that there exist some probability for some mixed gamma transitions. This case was taken up for a careful study of the gamma ray spectra and the (\(\gamma\)-\(\gamma\)) coincidences in view of establishing the levels of Sm\textsuperscript{149} excited through the beta decay of Pm\textsuperscript{149}.

2. Source Preparation

Pure neodymium metal target was bombarded with thermal neutrons in the 'Apsara' reactor, Trombay. Along with Nd\textsuperscript{149} (2h) activity; Nd\textsuperscript{147} (1ld) and Nd\textsuperscript{151} (15m) will be formed which respectively decay by beta emission to Pm\textsuperscript{149} (54h), Pm\textsuperscript{147} (2.6Y) and Pm\textsuperscript{151} (27.5h). After the bombardment, the chemical separations were performed for separating the impurities and the other spurious activities produced in the irradiation process. The Pm\textsuperscript{149} was separated from neodymium and the source was carrier free.

3. Halflife Studies

For following the halflives of the individual photopeaks, the source was mounted in a precision perspex source holder, with the help of which the exact reproduction of the source position was found possible. The energy distribution of gamma rays recorded in a NaI(Tl) crystal scintillation spectrometer is shown in fig. 29. From the singles spectrum, the photopeaks corresponding to the following energies are
Fig. 30 THE HALF LIFE STUDIES OF THE INDIVIDUAL PHOTOPEAKS IN THE DECAY OF $\text{Pm}^{149}$

(a) The decay curve of the 39 keV X-RAY
(b) The decay curve of the 285 keV $\gamma$-RAY

$T_{1/2} = 58 \text{ h}$
$T_{1/2} = 57 \text{ h}$
Fig. 31 - THE COINCIDENCE SPECTRUM WITH THE GATE ON THE 285 keV PHOTOPEAK

(a) 150 TO 600 keV REGION
(b) 650 TO 1 MeV REGION

- Singles
++ Coincidences

Singles

COINCIDENCES / 10 min.

CHANNEL NUMBER

SINGLES x 12

310 keV

530 keV

860 keV
seen: 39 keV X-ray, 90, 175, 285, 530, 860 and 1100 keV. By reproducing the exact geometry of the source and the crystal, the differential spectra have been plotted over a period of more than 20 days and the halflives of the individual photopeaks were carefully followed. These studies showed the existence of long halflife impurity (probably 11 day: Nd$^{147}$) in addition to the 27h Pm$^{151}$. The 285 keV photopeak was found to be pure decaying with a halflife of 57h as obtained in fig.30. Most of the 39 keV X-ray peak also decayed with 58h halflife as shown in fig.30. Probably this is mainly from the Pm$^{149}$ decay. The decay curve of the 530 keV broad-peak gave that it is partly from the 56h Pm$^{149}$ and the rest from the 11 day Nd$^{147}$. The 175 and 90 keV photopeaks are due to the 27h Pm$^{151}$ and 11 d Nd$^{147}$. The 860 keV gamma ray also seem to decay with a halflife(60h) very close to that of Pm$^{149}$ But because of its low intensity its decay was followed for only two halflives of Pm$^{149}$. The 1.1 MeV gamma ray may be due to some longer halflife activity.

The coincidence spectrum recorded in the 20 channel analyser with the gate on the 285 keV photopeak is shown in fig.31. Coincidence peaks were observed at 310 keV and under the 860 keV photopeak.

These preliminary studies show some evidence that the Pm$^{149}$ decay might be exciting some more levels in addition to those reported by Schmid and Burson$^{10}$.
References

1) H.B. Law et al., Phys. Rev. 59 (1941) 936
2) W. Bothe, Z. Naturforsch 1 (1946) 179
3) J.A. Marinsky et al., J. Am. Chem. Soc. 69.2 (1947) 2781
4) B. Ketelle, ORNL Report - 299
5) C. Mandeville and M. Scherb, Phys. Rev. 76 (1949) 186
6) E. Kondaiah, Phys. Rev. 81 (1951) 1056
8) W.C. Rutledge et al., Phys. Rev. 86 (1952) 775
9) L.R. Bunney et al., U.S. Naval Research and Development Laboratory Report - TR-305 (1959)
15) B.S. Dzhelepev et al., Nuclear Physics 30 (1962) 110
1. Introduction

Recently Gardner and Meinke\(^1\) have studied the \(\beta\) -decay of \(\text{Co}^{62}\) and reported the gamma transitions corresponding to the energies of 1.17, 1.47, 1.74, 2.03 and 2.5 MeV in the de-excitation of \(\text{Ni}^{62}\). In the reaction work\(^2-4\) \(\text{Ni}^{62}\) levels were observed at 1.172, 2.047, 2.304, 2.336 and 2.88 MeV. Brun et al.\(^5\) have studied the decay of \(\text{Cu}^{62}\) in secular equilibrium with \(\text{Zn}^{62}\) and they obtained the gamma rays with 0.66, 0.85, 1.13, 1.35, 1.46, 1.98 and 2.24 MeV. Butler and Gossett\(^6\) have carefully worked out the decay of \(\text{Cu}^{62}\). They have produced the \(\text{Cu}^{62}\) source from the radiative capture of protons from a 2 MV Vande Graaff accelerator on an enriched \(\text{Ni}^{61}\) target. They observed the gamma rays of 0.88, 1.13 and 1.17 MeV energies contradicting the earlier results. The present study was undertaken to obtain more information about the decay of \(\text{Cu}^{62}\), which is used as a standard in \((\text{n},2\text{n})\) cross-section work and in monitoring the betatron bremsstrahlung beams.

2. Source Preparation

About 300 mg of \(<\text{spec pure}>\) copper powder was taken in between two thin cello tapes and this was bombarded with 14.3 MeV neutrons in a Cockcroft-Walton type accelerator. \(\text{Cu}^{62}\) will be formed from \(\text{Cu}^{63}\) (70\%) \((\text{n},2\text{n})\) \(\text{Cu}^{62}\) reaction. The other activities that are likely to be produced are \(\text{Cu}^{64}\) (12h).
Fig. 32 SINGLES GAMMA SPECTRUM RECORDED IN THE 20 CHANNEL ANALYSER IN THE DECAY OF Cu$^{62}$ (9.9 m)
having a weak mono-energetic gamma ray of 1.35 MeV and Ni$^{62}(2.5h)$
decaying with gamma ray energies of 0.37, 1.12 and 1.49 MeV from
(n,p) reactions and Co$^{60}(5.24y)$ and Co$^{62}(14m)$ from (n,$\gamma$) reactions

3. Gamma Ray Spectrum

The singles gamma spectrum was studied with the help of the 20 channel NaI (Tl) crystal scintillation spectrometer. While recording the singles spectrum $\approx 0.6$cm thick perspex disc was introduced infront of the crystal to reduce the bremsstrahlung contribution to the gamma spectrum. The singles gamma spectrum reproduced in fig. 32 gave evidence for gamma ray photopeaks at 0.88, 1.15, 1.4 and 1.7 MeV. This spectrum has been corrected for the decay of the source during observation. All the peaks were found to decay with a halflife of about 11min. The spectrum upto 1.15 MeV energy is exactly similar to that obtained by Butler and Gossett$^6)$. The broad peak at 1.15 MeV supports the conclusions of these authors that it may be due to two gamma rays of energies 1.13 and 1.17 MeV.

About the other two high energy photopeaks, one cannot say definitely whether they arise from the decay of Cu$^{62}(9.9m)$ or from the decay of the 14m Co$^{62}$ activity, which may be formed from the (n,$\gamma$) reactions. Though the cross-section for (n,$\gamma$) is quite small compared to (n, 2n) reaction, the relative intensities of the gamma rays in the decay of Co$^{62}$ may not be negligible compared to Cu$^{62}$, since 100% of Co$^{62}$ decays by beta
emission to the excited levels in $\text{Ni}^{62}$ whereas only 2.5\% goes to the excited levels\textsuperscript{6)} of $\text{Ni}^{62}$ from the decay of $\text{Cu}^{62}$.

References

6) Butler and Gossett, Phys. Rev. \textbf{112} (1958) 1257
Chapter IV
SYSTEMATICS OF E2-M1 MIXING RATIOS OF 2^+\rightarrow 2^+ TRANSITIONS IN EVEN NUCLEI

1. Introduction

In analogy to the electron shell theory\textsuperscript{1)} in an atom, the nuclear shell model\textsuperscript{2)} assumes that every nucleon moves in a spherically symmetric average nuclear potential field. The number of neutrons or protons to be filled separately in a particular level will be decided by the Pauli's exclusion principle and the order of the levels will be governed mainly by the strong spin-orbit coupling. This simple model qualitatively explains the existence of the magic numbers, relative abundances, relative stability of the nuclei, asymmetric fission, delayed neutron emission and nuclear isomerism. This was found to be quite reliable in predicting the ground state properties of the nuclei.

In spite of the above achievements of this model, it proved to be too inadequate to explain the observed systematics of the gamma transitions in the case of the excited levels in many even-even and odd-odd nuclei. In some cases, the gamma transition probabilities, magnetic and quadrupole moments calculated from the shell model were observed to be smaller by many orders of magnitude when compared with the experimental values. In order to explain these systematics Bohr and Mottelson\textsuperscript{3)}(BM) were the first to consider that these levels

\textsuperscript{†} Published in Nuclear Physics 42 (1963)
may be due to the vibrations and rotations of the nuclear surface exhibiting a sort of collective interactions between the nucleons. Though the nuclear surfaces are supposed to be quite rigid nearer the closed shells, they may be easily deformable in nuclei which are far from the closed shells. This sort of collective mode of motion very satisfactorily explains the observed systematic level spacings of the spectra, the spins of the excited levels and the observed enhancement of the E2 transitions from the expected values of the single particle model in many nuclei which are far from the closed shells. Bohr and Mottelson have characterised the nuclear orbitals on the basis of the independent particle motion in an axially symmetric potential. The energy $E_I$ of a level in the rotational-vibrational spectrum in this model is dependent on the frequency of nuclear surface vibrations, and of the ratio of the equilibrium deformation to the zero vibration amplitude.

Recently the BM model has been extended by Marty$^4$ and by Davydov and Filippov$^5$ (DF) to include the rotations of the non-axially symmetric nuclei also. In the DF model, the rotational states satisfying the required symmetry conditions will not exist for $J=1$, but two such states will exist for $J=2$ etc. The energy of two such levels satisfying the required symmetry conditions are: for $J=2$

\[
E(2) = \frac{\kappa^2}{4B\beta^2} \cdot \frac{9(1 - \sqrt{1 - \frac{8}{9} \sin^2(3\gamma)})}{\sin^2(3\gamma)}
\]

\[
E(2') = \frac{\kappa^2}{4B\beta^2} \cdot \frac{9(1 + \sqrt{1 - \frac{8}{9} \sin^2(3\gamma)})}{\sin^2(3\gamma)}
\]
The reduced E2 transition probability in the DF model is
\[
B(E2; J_c \rightarrow J'_c) = \frac{5}{16\pi (2J+1)} \sum |J'_c, m| \langle 2_{\mu} | J_c \rangle^2
\]
\[
B(E2; 2' \rightarrow 2) = \frac{10}{7} \frac{\sin^2(3\gamma)}{9 - 8 \sin^2(3\gamma)} \tag{2}
\]
The reduced magnetic dipole radiation probability from the state 2+* to the 2+ state is
\[
B(M1, 2' \rightarrow 2) = \frac{4}{5} \sum_{m', \mu, m} \left| (21 m' | \mu(1 \mu) 22 m) \right|^2
\]
or
\[
B(M1, 2' \rightarrow 2) = \frac{90}{49 \pi^2} \frac{\mu^2}{g_R^2} \beta^2 \frac{\sin^2(3\gamma)}{9 - 8 \sin^2(3\gamma)} \tag{3}
\]
The ratio of the reduced probabilities
\[
\frac{B(M1, 2' \rightarrow 2)}{B(E2, 2' \rightarrow 2)} = \frac{80}{7} \left[ \frac{\mu^2}{e z R_o^2} \right]^2 \tag{4}
\]
or the ratio of the intensities of E2 and M1
\[
\delta^2 = \frac{T(E2)}{T(M1)} = \frac{0.21 (E_{2'} - E_2)^2}{80 (hc)^2} \left[ \frac{e z R_o^2}{\mu^2 g_R} \right]^2 \tag{5}
\]
where \( \mu = 5.05 \times 10^{-24} \) erg/gauss, \( g_R = 0.4 \)
\( R_o = 1.2 A^{1/2} \times 10^{-13} \) cm, so that
\[
\frac{\delta^2}{(E_{2'} - E_2)^2} = 6.6 \times 10^{-5} A^{4/3}
\]
which is independent of the deviation of the shape of the nucleus from the axial symmetry (\( \gamma \)).

Van Patter\(^6\) has collected all the data available in 2'+ \rightarrow 2+ \rightarrow 0+ levels in even nuclei, and has shown that the DF model is more successful in providing qualitative predictions, which are approximately in agreement with the experimental results. Though some setbacks were also experienced by the DF model because
of its failure to explain the properties of even nuclei with the values $\frac{E(2^+)}{E(2^+)} < 2$, in general ample experimental data are available to accept its validity especially in the strongly deformed regions.

The striking success of these very restricted non-axial symmetric models indicates that a more general asymmetric rotor model may give better agreement with the experimental data. With this hope Davyдов, Rabotnov and Chaban\textsuperscript{7)} have studied the most general adiabatic asymmetric model and concluded that the agreement is not much better than the hydrodynamical model of Davyдов and Filippов. However, they have suggested that the inclusion of the rotation-vibration interaction may improve the agreement. This interaction has been taken into account by Mallmann and Kerman\textsuperscript{8)} in the case of the hydrodynamical model and by Mallmann\textsuperscript{9)} in the case of the general asymmetric rotor model and found that these general models are much better in explaining the observed energies and $\gamma$-ray transition probabilities especially in the low lying even parity states for $40 \leq A \leq 250$ than the DF model.

Belisayev\textsuperscript{10)} showed the existence of collective quadrupole excitation of the vibrational type (VQE) with allowances for pairing and quadrupole interaction of nucleons. He has also shown that the energies derived from this theory are approximately equal to the experimental values. In contradiction to the DF model, VQE model has a good theoretical backing. The apparent success of the DF model, however, cannot claim any superiority
over the VQE model since the available experimental data collected by Van Patter\(^6\) in support of the DF model also purport the applicability of the VQE model. Recently Grechukhin\(^11\) has suggested some experiments to verify the success of these models. Though these experiments uniquely establishes the applicability of the DF model, the suggested experiments are yet to be performed.

Systematics of the mixing parameter '\(\delta\)' in the \(2^+ \rightarrow 2^+\) transitions in even nuclei have been studied by many workers. It has been pointed out by Malik et al\(^12\) that the DF model qualitatively accounts for the variation of '\(\delta\)' with the neutron number. Since then much data have been accumulated and an attempt has been made to study the systematics of '\(\delta\)' with the addition of the new data.

2. Systematics of \(S\) in \(2^{1+} \rightarrow 2^+\) Transitions in Even Nuclei

Low-lying states of many even nuclei have been found to possess energy levels with spin sequence \(2^{1+} \rightarrow 2^+ \rightarrow 0^+\), where, \(0^+\) is the ground state and \(2^+\) and \(2^{1+}\) are, respectively, the first and the second excited states having a spin of two. The gamma ray emitted between \(2^+\) and \(0^+\) levels is a pure \(E2\) transition. The other gamma ray emitted between \(2^{1+}\) and \(2^+\) levels is often a mixture of \(E2\) and \(M1\) transitions with \(E2\) content generally more than ninety per cent. This enhancement of the \(E2\) transition probability is indicative of the collective nature of this transition because, the \(M1\) transition will
usually be much stronger than E2 transition according to the single particle shell model. Thus the investigation of the mixing ratio $\delta$ of M1 and E2 transitions is important in revealing the type of excitation involved.

In the case of mixed transition, the relative intensities $I(E2)$ and $I(M1)$ are, respectively, proportional to the squares of the matrix elements which describe the two types of transitions. The quantity $\delta$, the mixing ratio is defined as

$$\delta = \pm \sqrt{\frac{I(E2)}{I(M1)}}$$

Thus, for a given intensity ratio, $\delta$ can have either a positive or a negative sign depending on the relative phase of the reduced matrix elements. The mixing ratio $\delta$ can be accurately determined by means of directional correlation measurements between the two gamma ray transitions of the $2^+ \rightarrow 2^+ \rightarrow 0^+$ cascade. Since the $2^+ \rightarrow 0^+$ transition is pure E2, the measurement of $\delta$ is unique. Recently there have been several surveys $^6,^{12-15}$ of the mixing ratio $\delta$. Since then new measurements on $\delta$ have become available.

The systematics of $\delta$ with neutron number was first investigated by M. Sakai$^{14}$. He proposed a regular variation of the sign and the magnitude of $\delta$ in regions preceding the closing of the g 9/2, h 11/2, and i 13/2 neutron sub-shells. These "islands" of nuclei occur for $38 \leq N \leq 48$, $64 \leq N \leq 74$, and $110 \leq N \leq 124$. From his considerations of published data, Sakai$^{14}$ concluded that the sign of $\delta$ is negative in the first and third islands and positive in the second. However, it was pointed out
later\textsuperscript{16}) that the alternate change of the sign of $\delta$ in the above neutron islands was not conclusive. Further accumulation of data\textsuperscript{17}) on the sign of $\delta$ also does not support the above proposal. As regards the magnitude of $\delta$, Sakai\textsuperscript{14}) has shown that the numerical value of $\delta$ diminishes as the neutron number approaches the magic number. In his plot of $\delta$ as a function of neutron number $N$, the effect on $\delta$ of the energy of the gamma ray transition involved was not taken into consideration. Hence the values of $\delta$ for isotopes of two elements having the same neutron number cannot be directly compared, as the energies of the mixed gamma ray transitions will be different.

Before any definite conclusion regarding the variation of the magnitude of $\delta$ can be drawn, it is essential to normalise the value of $\delta$ with respect to the energy of the gamma ray transition involved. Keeping this normalisation in mind the available data were collected in looking for a systematic variation of the magnitude of $\delta$ with neutron number.

3. Results

In this work no attempt has been made to study the variation of the sign of $\delta$ and hence the systematic variation of $\delta^2$ with the neutron number is investigated. To normalise the value of $\delta$ for the energy of the gamma ray transition, $\delta$ was divided by $E_\gamma$ where, $E_\gamma$ is the transition energy in MeV between $2^+$ to $2^+$ levels. Then \((\delta/E_\gamma)^2\) is the reduced mixing ratio independent of the transition energy. The quantity \(\log(\delta/E_\gamma)^2\)
1. Reduced mixing ratio as a function of neutron number. Filled circles represent data from the angular correlation experiment. Open circles represent data obtained from the reported percentage of E2. Crossed circles represent the latest data.
is now calculated and plotted as a function of neutron number in fig. 1. References for the data used in fig. 1 are given in section 5. In fig. 1 the single particle estimate\(^\text{18}\) and Davydov Filippov estimate\(^\text{5}\) of the quantity \(\log(S/E_\gamma)^2\) as a function of neutron number are also plotted.

4. Discussion

Fig. 1 shows that there is a large variation of reduced mixing ratio as a function of neutron number \(N\), and its value increases gradually from neutron number 30 to 130. As was pointed out earlier\(^\text{12}\), the values of reduced mixing ratio in general cluster around the Davydov-Filippov (DF) estimate which also increases gradually with neutron number. There are however several values which are drastically different from the DF estimate and it was noted\(^\text{12}\) that these deviations are perhaps related to shell effects. It is clearly seen from fig. 1 that these deviations occur near the neutron magic numbers 28, 50, 82 and 126. At these magic numbers the reduced mixing ratio falls by more than two to three orders of magnitude from the DF estimate. The heavy lines near the magic numbers are arbitrarily drawn only to focus the attention to this fact. In all these cases the percentage of M1 transition in the mixed gamma ray is more than ninety percent. This is to be expected near the magic numbers where the single particle shell model is valid, and where, the M1 transition is expected to be much stronger than the E2 transition. Single particle estimate of the reduced mixing ratio is also shown in fig. 1.
The values of reduced mixing ratio near the neutron magic numbers approach the single particle limit. It is also evident from the figure that near the closed neutron shells the addition of two neutrons changes the reduced mixing ratio quite drastically. Examples of this effect are Fe\(^{56}\)-Fe\(^{58}\), Ba\(^{134}\)-Ba\(^{136}\) and Po\(^{212}\)-Po\(^{214}\). In the regions lying between the closed shells the change due to the addition of two neutrons is small. Examples are Zn\(^{66}\)-Zn\(^{68}\), Ru\(^{100}\)-Ru\(^{102}\) and Os\(^{186}\)-Os\(^{188}\)-Os\(^{190}\). The effect of proton magic numbers in bringing the value of the reduced mixing ratio nearer to the S.P. estimate appears to be quite small, in comparison to the corresponding effect near the neutron magic numbers.

5. References for $\delta$ used in fig. 1

All the values of $\delta$ compiled by Van Patter \(^6\) are used. Original references to the measurements can be found in the above compilation. In the following, recent data on $\delta$ which have also been used in preparing fig. 1 are given.

Zn\(^{66}\):

$\delta = -4_{-2}^{+3}$, Soji Kono, Journ. Phys. Soc. Japan 17(1962)907

Zn\(^{68}\):

$\delta = -4_{-2}^{+3}$, Soji Kono, Journ. Phys. Soc. Japan 17(1962)907

Ge\(^{74}\):

$\delta = -1_{-0.5}^{+0.5}$, T. Yamazaki, H. Ikegami and M. Sakai, Journ. Phys. Soc. Japan 15 (1960) 957. The reported value of $\delta$ is not very precise because of the large positive error.

Se\(^{76}\):

$\delta = -7.2_{-1.5}^{+1.5}$, general reference 13).
Kr$^{84}$: $\delta = -1.8$ and $-0.9$, N.R. Johnson and G.D. Kelly, Phys. Rev. 108 (1957) 82, $\delta$ is calculated from the reported anisotropy in the angular correlation experiment. Both values of $\delta$ are plotted since there is no other data available to choose one of them.

Mo$^{94}$: $\delta = -0.20$, H. Bernstein and H.H. Forster, Nuclear Physics 24 (1961) 601, the directional correlation experiment is compatible with the assignment of either $2^+$ or $4^+$ for the 1.570 MeV level. The value of $\delta$ has been calculated and plotted in fig.1 assuming this level to be $2^+$.

Ru$^{100}$: $\delta = -3.1^{+1.6}_{-2.2}$, M. Koike, N. Ono, K. Takahashi and K. Hisatake, The autumn meeting of the Physical Society of Japan, 1960.

Ru$^{102}$: $\delta = +5.5^{+0.7}_{-0.5}$, K. Hisatake, Journ. Phys. Soc. Japan 16 (1961) 1280

Pd$^{106}$: $\delta = +30^{+\infty}_{-15}$, R.L. Robinson and F.K. McGowan, Phys. Rev. 119 (1960) 1692. The reported value of $\delta$ is not very precise because of the large positive error.

Te$^{122}$: $\delta = +3.7 \pm 0.3$, general ref. 15) $\delta = +3.4 \pm 0.5$ general ref. 13

Te$^{124}$: $\delta = +1.00 \pm 0.08$, general ref. 13). This measurement of the spin of the 1.326 MeV level and the calculation of $\delta$ of the 0.723 MeV gamma ray is of limited accuracy because the contributions to the coincidence rate from other cascades interfered in the angular correlation.
Moreover, the percentage of E2 reported by E.S. Dzhelepov and N.N. Zhukovsky, Nuclear Physics 6(1958) 655 is $50 \pm 40$. If the upper limit is taken then $5$ will be comparable to that of Te$^{122}$.

Te$^{126}$: $5 = +8.8 \pm 4.2 \pm .6$, Xe$^{126}$: $|5| > 5$ and Xe$^{128}$: $5 = -6.4 \pm 1.5$

Ba$^{134}$: $5^2 = 15.7$, R.K. Girgis and R. Van Lishout, Nuclear Physics, 12 (1959) 672, $5^2$ is calculated from percentage of E2.

Ba$^{136}$: $-0.25 \leq 5 \leq -0.19$, Z. Grabowski, S. Gustafsson, I. Marklund and I.B. Haller, Nuclear Physics 20(1960) 159, $5 = -0.18$, H. Bernstein and H.H. Forster, Nuclear Physics 24 (1961) 601. The above directional correlation experiments are compatible with the assignments of either $2^+$ or $4^+$ for the 1.900 MeV level. The value of $5$ has been plotted in fig. 1 assuming this level to be $2^+$.


Os$^{186}$: $5 = -10.5$, E. Bodenstedt et al., Z.f. Physik 163 (1961) 1 calculated from $A_2$ and $A_4$.

Os$^{190}$: $5^2 = 49$, F. Cappellani et al., Physica 24 (1958) 765 W.R. Kane et al., Phys. Rev. 119 (1960) 1953, $5^2$ has been calculated from percentage of E2.

Hg$^{200}$: $5^2 = 0.05$, T. Lindquist, Arkiv. for Fysik, General ref. 13
Appendix

Evaluation of \( \delta' \): In \( 2^+ \rightarrow 2^+ \rightarrow 0^+ \) transitions, the anisotropy

\[
A = \frac{W(180^\circ) - W(90^\circ)}{W(90^\circ)}
\]

\[
= \frac{3 + 8.782 + 0.715 \delta^2}{7 - 2.927 + 9.286 \delta^2}
\]

(A.1)

also \( A = \frac{1^+ A_2 + A_4}{1 - \frac{1}{2} A_2 + \frac{3}{8} A_4} - 1 \)

with the help of the reported \( A_2 \) and \( A_4 \) coefficients we get two values for \( \delta' \) when we solve eq. (A.1). Out of these two values the correct value of the mixing parameter \( \delta' \) was obtained from the graph of Malik et al., who have plotted \( A_2 \) and \( A_4 \) coefficients \( v_{12} \).

Note: After this work has been completed some more data were available on the mixing parameter \( \delta' \). R.L. Robinson, N.R. Johnson and E. Eichler (Phys. Rev. 128 (1962) 252) reported that the ratio of \( I(E2)/I(M1) \) for the 631 keV transition in \( \text{Xe}^{132} \) and for the 569 keV transition in \( \text{Ba}^{132} \)
to be 10 and $\geq 200$, respectively. M. Sakai et al., (J. Phys. Soc. Japan 17 (1962) 1087) obtained $\delta = -5.8^{+5.5}_{-22}$ for the 0.690 MeV transition in Kr$^{82}$. The angular correlation studies of M. E. Bunker et al., (Phys. Rev. 127 (1962) 844) showed that the 904 keV transition in Kr$^{82}$ has a dipole content of $99.8^{+0.1}_{-0.2}$% and D. Mac Arthur et al., (Nuclear Physics 38 (1962) 106) observed that the 865 keV transition in the de-excitation of Fe$^{58}$ is a mixture of M1 and E2 with $\delta = (1.5 \pm 0.4)$. These values plotted in fig. 1 further support the earlier conclusions.

The addition of two neutrons near the closed neutron shells changes the reduced mixing ratio quite drastically" can also be seen from Kr$^{82}$-Kr$^{84}$ and Ba$^{132}$-Ba$^{134}$ - Ba$^{136}$.

References


S.A. Moszkowski, Models of Nuclear Structure in Handbuck der Physik 29 (1958) 411

3) A. Bohr and B.R. Mottelson, Dan. Mat- Fys. Medd 27 (1953) No. 16

4) C. Marty, Nuclear Physics 1 (1956) 58; 3 (1957) 193

5) A.S. Davydov and G.P. Filippov, Nuclear Physics 8 (1958) 237

6) D.M. Van Patter, Nuclear Physics 14 (1959) 42

7) A.S. Davydov, N.S. Raboţnov and A.A. Chaban, Nuclear Physics 17 (1960) 169

8) C.A. Mallmann and A.K. Kerman, Nuclear Physics 16 (1960) 105
9) C. A. Mallmann, Nuclear Physics 24 (1961) 535
11) D. P. Grechukhin, Nuclear Physics 24 (1961) 576
12) S. S. Malik, V. R. Potnis and C. E. Mandeville, Nuclear Physics 11 (1959) 691
13) T. Lindquist and I. Marklund, Nuclear Physics 4 (1957) 189
14) M. Sakai, Institute for Nuclear Study, University of Tokyo, Japan. INS J-6 (February 24, 1958)
15) I. Asplund, L. G. Strömberg and T. Wiedling, Ark. Fys. 18 (1960) 65
16) V. R. Potnis and C. E. Mandeville, J. Franklin Inst. 266 (1958) 226
17) T. Tamura and H. Yoshida, Nuclear Physics 30 (1962) 579
   Fig. 1 appearing in this paper was prepared by M. Sakai and privately communicated to these authors.
The $^{129}$I nucleus with 53 protons and 76 neutrons falls in the odd-even class. With only three protons above the closed shell at 50, one expects this nucleus to be fairly spherical so that the single particle shell model may explain the properties of the ground state and the low lying excited levels. The shell model predicts $1g\,7/2$ or $2d\,5/2$ for the last three protons. The measured spin value of $7/2$ for its ground state shows that the ground state configuration is \((g7/2)^3\)\textsubscript{$\gamma/2$}. Again from the shell model the excited levels can have \((g7/2)^2 \, d5/2\), \((g7/2) \, (d5/2)^2\) and \((d5/2)^3\) configurations. The first excited level may be a \((g7/2)^3\)\textsubscript{$\gamma/2$} configuration consistent with the observations (Chapter III. A). For explaining the properties of the higher excited levels of $^{129}$I with 3 protons above the closed shell at 50, there can be some contribution from the collective nature of the nuclei also, so that one may try the so called 'intermediate coupling model'. This model assumes a sort of intermediate coupling between the closed shell core of the nucleus and the outer single particle nucleons. Banerjee and Gupta\textsuperscript{1}) have calculated the energy levels of iodine isotopes assuming this type of intermediate coupling. A comparison of the present experimental results with their calculations shows that the spins and parities of the ground and the first excited states assigned from the indirect experimental evidence, are properly
explained by their calculations. The observed level at 475 keV may correspond to the 466 keV level predicted by them. Around the experimental level at 720 keV, they predict three levels at 713, 746 and 750 keV with spins \( \frac{11}{2}, \frac{13}{2} \) and \( \frac{11}{2} \), respectively. The experimental evidence shows that this level cannot have such a high spin. However, calculations with different adjustable parameters may yield better agreement with the experimental results.

The gamma ray energies and their transition probabilities in \( ^{129}_n \) may be compared with the adjoining odd proton nucleus \( ^{131}_n \) which is also having similar configuration. A comparison of the beta decay branchings and the energy levels of these nuclei show a systematic trend as discussed in Chapter III.A.

From the shell model the ground state spin and parity of \( \text{Cd}^{115} \) is \( \frac{3}{2} \) or \( s^+ \). From the systematics of the measured values of \( \delta \) for \( \text{Cd}^{111} \) and \( \text{Cd}^{113} \), the ground state of cadmium may have an \( s\frac{1}{2} \) configuration. From the measured spin value of \( \frac{9}{2} \), the shell model prediction of \( g\frac{9}{2} \) configuration may be accepted for the ground state of \( \text{In}^{115} \). The isomeric transition was found to be a mixture of M4 and E5 so that \( p\frac{1}{2} \) assignment may be made for the 335 keV level. From the assigned spins and parities of the various excited states of \( \text{In}^{115} \); we expect many un-observed gamma transitions from the single particle shell model estimates (ex. M1 transition from the 1.42 MeV (9/2+) level to the ground state (9/2+) etc.). The Coulomb excitation studies by Davis et al. show that this decays through Compound Nucleus formation. Therefore
comparison of the proposed levels with any of the existing low excitation nuclear models may not be fruitful.

The shell model predictions of \( d_5/2 \) and \( h_9/2 \) for the ground states of \( \text{Pr}^{143} \) and \( \text{Ce}^{143} \) are consistent with the indirect evidence obtained from the log ft values etc. (Chapter III.C). The predominantly M1 character of the 56 keV gamma ray and other considerations show that the first excited level may be \( 7/2^+ \). It is possible to assign \( 5/2^+ \) and \( 7/2^+ \) for the ground and first excited levels from Nilsson's model with the deformation parameter \( \delta \approx -0.05 \).

Assuming the second excited state at 349 keV to be a single particle level, an estimate of the transition probabilities of the 293 keV and 349 keV gamma transitions (from eqns (4) & (5) of Chapter II) gave the corresponding values to be 293 keV (M1): 349 keV (E2) \( = 9.9 \times 10^{12} \), \( 9.0 \times 10^8 \) whereas the observed intensities are in the ratio 1:0.08. This shows that the second excited level cannot be explained by the single particle shell model \( \text{Pr}^{143}_{84} \); with 9 protons above the closed shell at 50; excited states corresponding to the collective nature of the nuclei may also be expected. The ratio of the transition probabilities calculated with the help of eqns. (6) and (8) of Chapter III for 293 keV gamma ray (M1): 349 keV gamma ray (E2) \( \approx 1:0.06 \), is very close to the observed intensity ratio of 1:0.08. In these calculations, \( \Delta R/\delta \) was obtained from the
Nilsson diagram\textsuperscript{4) to be} $\approx 0.05$; and $(g_K-g_R)\approx 1$. But the energies of the levels calculated from the Bohr Mottelson model show that the second excited level cannot have as high an energy as 351 keV. The non-observance of gamma rays in the Coulomb excitation\textsuperscript{5) in Pr\textsuperscript{141} along with the above arguments give strong evidence against the collective behaviour of the Pr\textsuperscript{143} nucleus. For the present, one can conclude that the 349 keV level is quite complex.

Pr\textsuperscript{144} with 59 protons and 85 neutrons falls under the odd-odd nuclei. The shell model predicts $d_5/2$ or $g_7/2$ for the 59th proton. From the systematics of the adjoining odd-proton nuclei the last proton may be assigned $d_5/2$. With only three neutrons above the closed shell at 82, Pr\textsuperscript{144} may be fairly spherical so that the low lying and the ground state properties may be explained by the single particle shell model. The 85th neutron may be in an $f_7/2$ orbit from the available data of the adjoining odd neutron nuclei. Therefore, from the considerations of the single particle shell model, the ground state of Pr\textsuperscript{144} can have a minimum spin of $1^-$. Though the previously accepted spin of $0^-$ for the ground state of Pr\textsuperscript{144} could be accounted if we assign a $g_7/2$ orbit for the 59th proton,\textsuperscript{6) this spin assignment is not suitable from the systematics of the adjoining odd proton nuclei like Pr\textsuperscript{139}, Pr\textsuperscript{141} and Pr\textsuperscript{143}. The presently proposed spin value of $1^-$ may be very well accounted from the systematics and also from the single particle shell model. The behaviour of the excited levels in Pr\textsuperscript{144} may perhaps help
us in predicting whether the Pr$^{144}$ nucleus is spheroidal or not.

The recent absolute transition probabilities and the halflives of the excited levels of Pr$^{144}$ reported by Burde et al. are of much interest. They concluded that almost all the excited levels are essentially of single particle nature with slightly differing configurations. Their results strongly support that the Pr$^{144}$ nucleus is essentially spheroidal. To account for the previously accepted ground state spin of 0- for Pr$^{144}$, they assumed a g7/2 orbit for the 59th proton. As discussed above, this assumption contradicts the systematics of the adjacent odd proton nuclei like the measured spin value of 5/2 for the Pr$^{141}$ nucleus and the derived spin assignments of 5/2 for the ground states of Pr$^{139}$ and Pr$^{143}$. The results of Burde et al. which essentially show that the excited levels of Pr$^{144}$ are explained by the shell model further support indirectly the present assignment of 1- instead of 0- for the ground state of Pr$^{144}$. On the other hand, Geiger et al. have explained the ground and excited levels of Pr$^{144}$ from the unified model with a prolate deformation of $\delta \approx 0.07$.

References

1) B. Banerjee and K.K. Gupta, Nuclear Physics 30 (1962) 349
2) A. Badescu et al., Zh. ekspr. teor Fiz. (U.S.S.R) 40 (1961) 91
3) Davis, Divatia, Lind and Moffat, Phys. Rev. 103 (1956) 1801
5) N.P. Heydenburg and G.M. Temmer, Phys. Rev. 100 (1955) 150
6) L.W. Nordheim, Phys. Rev. 78 (1950) 294
8) J.S. Geiger, R.L. Graham and G.T. Ewan, Nuclear Physics 16 (1960) 1
THE ENERGY LEVELS OF $^{129}$

G. N. RAO, V. R. POTNIS$^*$ and H. S. HANS$^{**}$

Physics Department, Muslim University, Aligarh, U.P., India

Received 15 February 1963

Abstract: The energy levels of $^{129}$ have been studied through the $\beta^-$ decay of $^{129m}$Te and $^{129}$Te employing two NaI (Tl) scintillation spectrometers in coincidence arrangement. In addition to confirming the presence of the previously known gamma rays of energies 27, 212, 475, 720 and 1120 keV, evidence is found for seven new gamma rays. The new gamma rays have energies of 448, 450, 625, 693, 1073, 1320 and 1520 keV. From the coincidence experiments a probable energy level scheme for $^{129}$ is proposed.

1. Introduction

Earlier work $^1$, $^2$) on $^{129m}$Te showed that it decays by the emission of 106 keV isomeric transition to the ground state of $^{129}$Te, which then decays by beta emission with a half life of 74 min to the levels of $^{129}$. Graves and Mitchell $^3$) reported that 74 min activity of $^{129}$Te excites energy levels in $^{129}$ at 27, 502, 720 and 1150 keV. They also showed that the 41 d $^{129m}$Te decays by beta emission, in addition to the 106 keV isomeric transition, and the $\beta^+$/I.T. ratio was found to be about five percent.$^4$ In order to explain the five percent beta branching, it was suggested $^5$) that a beta ray transition of end point energy 1586 keV takes place between $^{129m}$Te and the ground state of $^{129}$. However, recent measurements $^6$) for this ratio have shown that it is about 32 percent. This leads to the possibility of $^{129m}$Te exciting some new levels in $^{129}$ by electron emission. Banerjee and Gupta $^7$) have calculated the energy levels of $^{127}$ and $^{129}$ on the basis of the unified model. We have investigated the decay of $^{129m}$Te with expectation of finding new levels in $^{129}$ and also to compare the theoretical calculations with the experimental data.

2. Source Preparation

The $^{129m}$Te isotope was obtained as a fission product in the "Apsara" reactor at Trombay $^8$. The chemical separation was performed to separate $^{129m}$Te from the radioactive isotopes of other elements formed during fission. About 20 $\mu$g of $^{129m}$Te was dissolved in dilute nitric acid and the source was prepared in a thin perspex rod with a hole 3 mm deep and 2 mm in diameter by repeatedly drying the dilute solution under a heating lamp. No evidence was found for the existence of other tellurium activities.

$^*$ Present Address: Scientific Post Officer, C.S.I.R., New Delhi, India.
$^**$ Present Address: Physics Department, A&M College of Texas, College Station, Texas.
$^*$ Dept. of Atomic Energy, Govt. of India, Trombay, Bombay.
3. Gamma Ray Spectrum

The energy spectrum of gamma rays recorded in a 3.8 x 3.8 cm cylindrical NaI(Tl) crystal scintillation spectrometer is reproduced in fig. 1. Evidence for the existence of photopeaks at 27, 475, 720, 1100, 1310, and 1520 keV is clearly seen. By following their decay, all the photopeaks were found to have the same half life of about 40 d.

![Gamma Ray Spectrum Diagram](image)

Fig. 1. The energy spectrum of gamma rays.

While taking the singles spectrum, an aluminium disc of 1 g/cm² thickness was placed before the crystal to absorb betas and to reduce the external bremsstrahlung contribution to the gamma ray spectrum. From the known resolution of the spectrometer it was found, that the photopeaks at 475, 720 and 1100 keV are made up of more than one gamma ray, as confirmed in the coincidence study. Photopeaks at
1320 and 1520 keV energy show the presence of two new gamma rays which were not observed in earlier studies. The broad peak at 180 keV is interpreted to be due to the back scattering from the 475 and 720 keV gamma rays. The small hump around 245 keV is due to the presence of a gamma ray of 245 keV energy which is definitely established in the coincidence experiments. The small peak at 100 keV is probably due to the 106 keV isomeric transition. The photopeak at 27 keV is due to Iodine KX-rays and 27 keV gamma ray found in earlier studies \(^{(2)}\). The low energy end of the spectrum taken with high amplification did not reveal any further details.

After applying the usual corrections for absorbers between the source and the crystal and for the effective photo-efficiency of the crystal, a rough estimate of the unconverted quantum intensities can be made from the data of fig. 1. The intensities so obtained are given in table 1.

<table>
<thead>
<tr>
<th>Gamma ray energy (keV)</th>
<th>Relative intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1320</td>
<td>0.55</td>
</tr>
<tr>
<td>1520</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Gamma rays bracketed together were resolved in the coincidence experiments.

4. Gamma-gamma Coincidence Experiments

The coincidence spectra have been examined with a 20-channel scintillation coincidence spectrometer using two identical 3.8 x 3.8 cm\(^3\) NaI(Tl) cylindrical crystals coupled to Du Mont-6292 photomultipliers and DD2 type non-overloading amplifiers. Pulses from one of the counters are fed to a single-channel pulse-height analyser and to the coincidence circuit of resolving time of 0.15 \(\mu\)sec. The coincidence output is used to gate the 20-channel analyser. The counters were placed at 130° to each other to reduce backscattering. Thick perspex discs were introduced in front of the counters for absorbing betas and conversion electrons.

The spectrum of coincidence pulses observed with the gating channel set at 27 keV is shown in fig. 2. Along with the 27 keV gamma ray however, there will be some contribution from the iodine KX-rays arising out of the internal conversion of gamma rays. Since no conversion lines were observed in the \(\beta\)-ray spectra \(^{(3)}\) for these gamma rays.
rays, it is assumed that the contribution due to iodine KX-rays is negligible. In fig. 2 clear coincidence peaks at 245, 450 and 700 keV are seen. The shift towards lower energies of the coincidence photopeaks from the 475 and 720 keV photopeaks in the singles spectrum is of the order of 27 keV. Thus the 475 and 720 keV gamma rays could well be the cross-over transitions of the 450-27 keV and 693-27 keV cascades. This also confirms that the photopeaks at 475 and 720 keV in the singles spectrum of fig. 1 are composed of more than one gamma ray. To check whether the peaks at 475 and 720 keV may be solely due to the summation of 450($\nu_1$) - 27($\nu_2$) and 693 ($\nu_1$) - 27($\nu_2$) keV cascades, the coincidence peaks at 475 and 720 keV were calculated from the formula 6)

\[ P_{\text{coinc}} = \frac{P(\nu_2)}{1 - \varepsilon(\nu_2)\Omega f + N_i}, \]

Fig. 2. The energy spectrum of coincidence gamma rays with the gating channel fixed on the 27 keV photopeak, coincidences around 240 keV region, b) Coincidences around 400 to 800 keV region, —— singles, —— coincidences.
where $P_{cs}$ and $P(v_1)$ are the areas under the coincidence photopeak and the photopeak in the fixed channel which is set on the $v_1$-ray; $\epsilon_p$ and $\epsilon_f$ are the photopeak and total efficiencies; $f$ is the fraction of the $v_1$-ray in coincidence with the $v_2$-ray; $\Omega$ is the solid angle 0.032; and $N_r$ is the random summing of two pulses which is small and is neglected here. This correction was found to be small showing that the 475 and 720 keV gamma rays mainly consist of the cross-over transitions of the above mentioned cascades. After taking into account the usual corrections, the relative intensities of the unconverted gamma rays of 245, 450 and 693 keV are 1.0, 2.6 and 2.0, respectively.

The coincidence spectrum with the gating channel covering the full 475 keV photopeak is shown in fig. 3(a). Coincidence peaks are observed at 245, 475, 625 and 720 keV energy. The presence of a coincidence peak under the 475 keV photopeak indicates another gamma ray of comparable energy and in coincidence with the 475 keV gamma ray. The coincidence spectrum with the gating channel set only on the high energy end of the 475 keV photopeak is shown in fig. 3(b). This setting reduces the intensity

![Fig. 3. The energy spectrum of the coincidence gamma rays with the gating channel fixed on the 475 keV gamma ray. a) Gating channel covering the full 475 keV photopeak, b) Gating channel set on the high energy end of the 475 keV photopeak. —— singles, —— coincidences.](image-url)
of the 450 keV gamma ray being recorded in the gating channel. The coincidence peak under the 475 keV singles peak appears to be slightly shifted towards the lower energy end, the shift again being of the order of 27 keV. Moreover, the intensities of these two coincidence peaks at 475 and 720 keV are reduced relative to the intensity of the 625 keV coincidence peak. It is concluded from this measurement that a gamma ray of about 450 keV is in coincidence with the 475 and 720 keV gamma rays.

The relative intensities of the 245, 450, 625 and 693 keV gamma rays estimated from fig. 3(b) after applying the usual corrections are 1.00, 0.12, 0.25 and 0.16, respectively.

The percentage contributions (x) of the 245, 450 and 625 keV gamma rays (here denoted v') to the intensity of the 475 keV gamma ray (denoted here v) are calculated from the formula

$$x = \frac{100P(v')[1 + z(v')]c(v)k}{e_p(v')W(90)\Omega e(v)k},$$

where $\Omega$ is the solid angle 0.032; $e_p(v')$ is the photopeak efficiency; $c(v)$ is the observed counting rate in the fixed channel after applying corrections for the Compton

---

Fig. 4. The coincidence spectrum with the gating channel set on the 720 keV photopeak.
contribution of the high energy gamma rays; $P(v')$ is the area under the photopeak of $v'$-ray observed in time $t$; and $K$ is the correction factor for the external absorbers. The quantity $a(v')$ is the conversion coefficient of $v'$-ray and is neglected here, since the conversion was found to be small.$^{3}$ $\mathcal{W}(90)$ is the angular distribution of the two coincident gamma rays obtained from the angular correlation data. Thus the estimated percent contributions from the 245, 450 and 625 keV gamma rays to the intensity of the 475 keV gamma ray are 12.4, 1.4 and 3.6, respectively.

The coincidence spectrum with the gating channel set on the full 720 keV photo-peak is shown in fig. 4. Coincidences were observed under 475 keV photopeak, thus confirming the presence of a gamma ray of energy $\approx 450$ keV in coincidence with the 720 keV gamma ray.

5. Angular Correlation Experiment
The coincidences between the 245-475 keV cascade were recorded for 30 minutes at each angle of the sequence $90^\circ$, $135^\circ$ and $180^\circ$ between the central axis of the detectors. The coincidences were normalized with respect to the singles counting rate at the $180^\circ$ position. The true-to-enhance ratio was very high. The chance rate was subtracted by the random coincidence method. The least-squares fit of the data was made to the equation $W(\theta) = \sum A_k P_k (\cos \theta)$. To obtain the corrected values of the $A_k$ coefficients, the normalised values of the $A_k$ were corrected for the finite angular resolution by the method due to Rose.$^{6}$ The least-squares fit curve to the observed data is shown in fig. 5. The least-squares fit equation is

$$W(\theta) = 1 - 0.52 P_2 (\cos \theta) + 0.24 P_2 (\cos \theta).$$

![Fig. 5. The angular correlation data between the 245 and 475 keV gamma rays.](image-url)
The observed anisotropy $A$ is found to be 0.86 and is very high. Since the 450 keV gamma ray is found to be very weak in comparison to the 475 keV gamma ray, the observed angular correlation is thought to occur mainly between the gamma rays of the 245-475 keV cascade. The high value of the anisotropy indicates that both gamma rays are of mixed multipoles. Also the presence of the $A_\delta$ coefficient indicates a spin assignment of $\frac{1}{2}$ for the 475 keV level.

6. The Decay Scheme

A probable decay scheme which combines all the data presented is shown in fig. 6. This decay scheme differs from that of Graves and Mitchell (3) in the following points: The 475 keV gamma ray which was shown to be in coincidence with the 27 keV gamma ray now appears to be the cross-over transition of the 448-27 keV cascade. Hence, the energy of the second excited level becomes 475 keV instead of 502 keV. Another gamma ray of 693 keV energy has been found to be in coincidence with the 27 keV gamma ray and thus, the 720 keV gamma ray now becomes the cross-over transition of this new cascade. Yet another cross-over transition of 1100 keV seems to occur. Evidence for this gamma ray comes from the measured half-width of the 27 keV gamma ray.
1100 keV photopeak which is found to be more than the expected half-width from the known resolution of the spectrometer. This cross-over transition takes place across the 27-1073 cascade. Graves and Mitchell\(^1\) have established this cascade in their coincidence studies, however, the energy quoted by them for one of the cascade gamma ray is 1120 instead of 1073 keV.

From our coincidence studies we have found a new gamma ray of energy 625 keV which is found to be in coincidence with the 475 keV gamma ray. This 625 keV transition takes place between 1100 and 475 keV energy levels. From the data of figs. 3 and 4, evidence is found for a gamma ray of energy 450 keV in coincidence with the 720 keV gamma ray. This cascade establishes a new level at energy 1170 keV, which was not found earlier\(^2\). Because of the small energy difference between the 1100 and 1170 keV levels, the beta branching feeding these levels could not have been separated\(^3\). The ten percent beta branching can feed both of these levels.

The two new high energy gamma rays of energies 1320 and 1520 keV perhaps occur in \(^{41}\)d \(^{129}\)Te through beta decay. The 1520 keV level is evidently not fed by the beta decay of 72 min \(^{129}\)Te, because \(Q_{\beta-}\) between the ground levels of \(^{129}\)Te and \(^{129}\)I is smaller than the gamma ray energy under consideration. The observed low intensities of the 1320 and 1520 keV gamma rays can be explained if the 32 percent beta branching\(^4\) from \(^{129}\)Te feeds both levels at 1320 and 1520 keV also.

The ground state spin of \(^{129}\)I has been measured\(^5\) to be \(\frac{3}{2}\). Life time measurements\(^6\) of the 27 keV level\(^7\) indicate that it is of the order of 15 \(\mu\text{s}\). If the 27 keV level is assumed to be a single-particle level then, the measured half-life of this level makes it possible for the 27 keV gamma ray to be a mixture of M1 and E2, but predominantly M1. Thus the 27 keV level could have a spin of \(\frac{3}{2}\).

In the calculations of Banerjee and Gupta\(^8\) two levels at 466 and 471 keV with spins \(\frac{1}{2}\) and \(\frac{3}{2}\), respectively, are shown to occur. Our measured level at 475 keV could be one of these theoretical levels. Around our measured level at 720 keV, three levels at 713, 746 and 750 keV with spins of \(\frac{7}{2}\), \(\frac{5}{2}\) and \(\frac{3}{2}\), respectively, are predicted\(^9\). The observed 720 keV level could not have such a high spin because the beta branching from a \(d_3\) ground state of \(^{129}\)Te would then be highly forbidden\(^5\). This is one source of disagreement with the calculations of Banerjee and Gupta\(^8\). Spins for higher states are not calculated\(^9\) and thus comparison with the experiment could not be made.

It is a pleasure to express our gratitude to Professor P. S. Gill for his stimulating interest in this work. One of us (V.R.P.) is thankful to the Secretary C.S.I.R. Delhi, India, for providing the Scientific Pool Officership tenable at the Physics Department of Muslim University, Aligarh, U.P., India.

References

1) R. D. Hill, Phys. Rev. 76 (1949) 333
2) Hollander, Pearlman and Seaborg, Revs. Mod. Phys. 25 (1953) 469
4) G. Anderson and E. Hagebo, Ark. Fys. 22 (1962) 349
5) B. Banerjee and K. K. Gupta, Nuclear Physics 30 (1962) 349
8) M. E. Rose, Phys. Rev. 91 (1953) 610
9) Livingston, Gilliam and Gordy, Phys. Rev. 76 (1949) 149

G. N. Rao et al.

G. N. Rao et al.

G. N. Rao et al.

G. N. Rao et al.

THE ENERGY LEVELS OF $^{123}$

THE ENERGY LEVELS OF $^{129}$

THE ENERGY LEVELS OF $^{123}$

THE ENERGY LEVELS OF $^{129}$
RADIOACTIVE DECAY OF Ce\(^{142}\) (33h)

G. N. RAO and H. S. HANS

Physics Department, Muslim University, Aligarh, India

Received 4 October 1962

Abstract: The gamma rays in the decay of Ce\(^{142}\) (33 h) have been studied with the help of a scintillation coincidence spectrometer. The relative branchings of the various gamma rays have been estimated. By studying the \(\gamma-\gamma\) coincidences the \(K\)-internal conversion coefficients of the 56 keV, 230 keV and 293 keV transitions were determined to be \(6.4 \pm 0.6\), \(0.07 \pm 0.03\) and \(0.12 \pm 0.02\), respectively. The angular correlation measurements have been performed for the 293-56 keV cascade. From these measurements, the spins of the ground, first and the second excited states in Pr\(^{143}\) have been assigned to be \(|+, -+\) and \(|+, +\) respectively. The 56 keV gamma ray was found to be a mixture of \(99 \pm 1\%\) M1 and \(1 \pm 1\%\) E2 and the 293 keV gamma ray a mixture of \(97 \pm 1\%\) M1 and \(3 \pm 1\%\) E2.

1. Introduction

The decay of Ce\(^{142}\) (33 h) has been studied by various authors\(^1\)–\(^6\). Recently Martin et al.\(^6\) have reported the existence of ten gamma rays and they have also suggested a tentative level scheme of Pr\(^{143}\), with some doubts about the assignment of spins and parities to the various excited states. The present study was undertaken in order to obtain more information about the levels from the angular correlation data and internal conversion coefficient measurements.

2. Gamma Ray Intensity Measurements

Ce\(^{143}\) was prepared by the thermal neutron irradiation of spectrographically standardised 99.9\% pure cerium oxide in the swimming pool reactor, Trombay. Fig. 1 shows the pulse-height distribution of gamma rays detected by a NaI(Tl) crystal (3.8 cm x 3.8 cm) coupled to a Du Mont-6292 photomultiplier. From the graph, evidence is seen for the existence of gamma rays of energies 56, 140, 230, 293, 341, 425, 488, 665, 718, 870 and 1087 keV. By following its decay, the peak at 140 keV was attributed to the decay of Ce\(^{141}\) (33 d). The peak at 425 keV was interpreted to be due to the Compton edge of 665 keV and 718 keV gamma rays by studying its relative attenuation with several absorbers of varying thickness before the counter, and also by studying the intensities of the singles spectrum at different source to the crystal distances. All the peaks are separated from the Compton background as shown in fig. 1 and their relative intensities are calculated by taking their corresponding effective peak efficiencies. The values of the intensities thus obtained were corrected for the following factors: 1) the relative absorption in the Al and Al\(_2\)O\(_3\).
housing around the crystal and in the 0.6 cm thick perspex disc introduced in front of the crystal for absorbing beta rays and internal conversion electrons, 2) the relative escape peak intensities for the medium geometry case, 3) the total internal

Fig. 1. Pulse-height distribution of gamma rays from the decay of $\text{Ce}^{144}(33 \text{ h})$.

TABLE 1

Unconverted gamma ray intensities and relative intensities of some gamma ray transitions

<table>
<thead>
<tr>
<th>Gamma-ray energy (keV)</th>
<th>Unconverted gamma ray intensities</th>
<th>Intensities of the gamma ray transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>0.22</td>
<td>1.80</td>
</tr>
<tr>
<td>230</td>
<td>0.067</td>
<td>0.069</td>
</tr>
<tr>
<td>293</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>341</td>
<td>0.069</td>
<td>0.065</td>
</tr>
<tr>
<td>488</td>
<td>0.062</td>
<td>0.058</td>
</tr>
<tr>
<td>565 (very weak)</td>
<td></td>
<td>(very weak)</td>
</tr>
<tr>
<td>665</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>718</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>870</td>
<td>0.013</td>
<td>0.017</td>
</tr>
<tr>
<td>1087</td>
<td></td>
<td>0.013</td>
</tr>
</tbody>
</table>
conversion coefficients 7) obtained with the help of the present data of K-internal conversion coefficients, 4) the source decay during observation. The separation of the 56 keV peak from the Compton background may introduce an error of ±20% at most in the case of the 56 keV gamma ray intensity. The relative unconverted gamma ray intensities together with the values of the relative intensities of the various gamma ray transitions after applying the above mentioned corrections are given in table 1.

3. The $\alpha_K$ Measurements

The $\gamma-\gamma$ coincidences were recorded with the help of two identical (3.8 cm x 3.8 cm NaI(Tl) crystal) scintillation spectrometers in coincidence (resolving time 0.15 μsec). Various $\gamma-\gamma$ coincidence measurements have confirmed the decay scheme proposed by Martin et al. 6) reproduced in fig. 2. The 56 keV gamma ray was found to be in coincidence with 35 keV X-rays and gamma rays of 293, 665, 870 and 1087 keV. The $\gamma-\gamma$ coincidences gave evidence also for the existence of a very weak 565 keV.

Fig. 2. Decay scheme of Ce$^{143}$ (33 h) proposed by Martin et al. 4) and confirmed by the present $\gamma-\gamma$ coincidence measurements. (All energies are given in keV).
gamma ray. For the determination of the K-conversion coefficient of the 56 keV gamma ray the coincidences were recorded between 293 keV in the fixed channel and the X-ray peak and the 56 keV peak in the variable channel which are shown in fig. 3. The number of coincidence counts between the X-rays and the Compton scattered gamma rays of 488 and 341 keV detected along with the 293 keV gamma ray is negligible since both gamma rays are very weak, and neither of them are highly converted. The counters were placed at 60° with respect to each other and ≈ 0.6 cm

![Image](https://example.com/image.png)

Fig. 3. Gamma-gamma coincidence spectrum with the fixed channel at the 293 keV photo peak and the sliding channel moved around the X-ray peak and the 56 keV photopeak.

thick Pb x disc were introduced in front of the counters to absorb betas and conversion electrons, and a lead sheet (10 gm/cm²) was placed between the counters to reduce the spurious coincidences due to scattering and to prevent the detection of escaping X-rays in the variable channel after escaping from the counter in the fixed channel. A comparison of the areas under the 35 keV X-ray peak and 56 keV photo peak in the coincidence spectrum directly gives the K-conversion coefficient after taking the following factors into account: 1) the relative absorption due to the Al and Al₂O₃ housing around the crystal and the external Pb disc, 2) the fluores-
cence yield \(^8\) of Pr(0.898) in the K-shell and 3) the escape peak corrections. The detection efficiency is 100% for both X-rays and γ-rays. The escape peak intensity was calculated from the formula of P. Axel \(^9\) taking the geometry of our experimental set up into consideration. The final value of \(\alpha_K\) obtained is 6.4 ± 0.6 which is consistent with the assignments of either M1 (\(\alpha_K = 5.7\)) or E2 (\(\alpha_K = 6.0\)) or a mixture of them, from the calculations of Rose \(^10\).

For obtaining the K-conversion coefficient of the 293 keV γ-ray, the coincidences were recorded as shown in fig. 4 with the fixed channel kept at the peak of 56 keV so that practically there will not be any contribution from X-rays. Thick perspex discs 0.6 cm in thickness were put in front of both the counters for absorbing betas. Besides the corrections mentioned in the previous case the variation in effective photo peak efficiency of the crystal for the gamma rays under consideration is also taken into account. The X-ray and 665, 870 and 1080 keV Compton coincidences may introduce a maximum error of +5% in the value of \(\alpha_K\). The final value of \(\alpha_K\) obtained is 0.07 ± 0.007 which shows that the 293 keV gamma ray is predominantly M1 in character with a small admixture of E2.

In a similar way, the coincidence spectrum was obtained by keeping the 488 keV gamma ray in the fixed channel and the sliding channel around the X-ray peak and 230 keV photo peak as shown in fig. 5. Along with 488 keV, however, there will be some counts due to Compton scattering of 665, 870 and 1080 keV gamma rays which...
in turn are in coincidence with the highly converted 56 keV gamma ray as well as with its X-rays arising from its conversion. Knowing the coincidences with the 56 keV γ-ray and the $a_K$ of the 56 keV γ-ray, the above contribution is determined and subtracted. The value of $a_K$ thus obtained for the 230 keV gamma ray after applying the various corrections previously mentioned is $0.12 \pm 0.02$ which is compatible with an assignment of M1 ($a_K = 0.1$) or E2 ($a_K = 0.1$) or an M1-E2 mixture from the calculations of Sliv and Band 7).

4. Angular Correlation Measurements

The source which was in the form of cerous chloride/dilute hydrochloric acid is further diluted and taken in the source holder which was a thin perspex rod with a hole of 0.2 cm diameter and about 0.4 cm in length and allowed to dry under a heating lamp. This process was repeated many times and the experiment was performed when the source was in a semi-liquid form. The source was mounted 7 cm from the central axes of the two crystals. The coincidences between 293 and 56 keV gamma

![Gamma-gamma coincidence spectrum with 488 keV in the fixed channel and the sliding channel moved around the X-ray peak and the 230 keV photopeak.](image)

Fig. 5. Gamma-gamma coincidence spectrum with 488 keV in the fixed channel and the sliding channel moved around the X-ray peak and the 230 keV photopeak.
rays were recorded for 5 minutes at each angle in the sequence 90°, 135° and 180° between the central axes of the detectors. The true-to-chance ratio was very high. The chance coincidences were subtracted by repeatedly testing the coincidence circuit by the random coincidence method. The least-squares fit of the data was made to the equation \( W(\theta) = \sum A_i P_i(\cos \theta) \). To obtain the corrected values of the \( A_i \) coefficients, the normalized values of \( A_i \) were corrected for the finite angular resolution of the counters by analytically computing the ratio \((J_i/J_0)^2\) by the method due to Rose \(^{11}\). The correlation was probably not attenuated due to extranuclear fields, since the experiment was performed when the source was in the form of solution in an acid medium. In the least-squares fit of the curve shown in fig. 6, the root mean square errors are shown. The least squares fit of the data gave

\[
W(\theta) = 1 + 0.132 \pm 0.019 P_2(\cos \theta) + 0.008 \pm 0.02 P_4(\cos \theta).
\]

5. Discussion and Results

From the single particle model the ground state of \( ^{60}\text{Nd}^{143} \) should be either \( h_\uparrow \) or \( f_\uparrow \). The fact that \( f_\downarrow \) was observed both from paramagnetic resonance methods \(^{12}\) and also from atomic spectroscopy \(^{13}\) allows us to accept \( f_\uparrow \) for the ground state of \( \text{Nd}^{143} \). From the shape and log fit value of the observed beta spectra from \( \text{Pr}^{143} \) to \( \text{Nd}^{143} \) \( \frac{3}{2}^+ \) may be assigned for the ground state of \( \text{Pr}^{143} \) which is quite consistent with the shell model predictions of \( g_\downarrow \) or \( d_\downarrow \). Again from the shell model the ground...
state of Ce$^{143}$ should be $f_1$ or $h_1$. The possibility of $f_2$ is not likely since no beta branching was observed from Ce$^{143}$ to the ground state of Pr$^{143}$. On the other hand $h_2$ could be accepted because of the non-observance of the beta branching which will be $\Delta l = 3$, forbidden in this case.

Both M1 or E2 assignments are quite consistent with the observed $\sigma_K = 6.4 \pm 0.6$ for the 56 keV gamma ray. But Martin et al. 6) have assigned a predominantly M1 character because of the predominance of the L subshell line, and the lack of an observable L conversion line. The first excited state in Pr should therefore be either $\frac{3}{2}^+$ or $\frac{5}{2}^+$. Spin $\frac{3}{2}^+$ is consistent with the observed 6) shape of the beta spectrum from Ce$^{143}$ to the 56 keV level of Pr$^{143}$. The possibility $\frac{5}{2}^+$ is less likely considering our assignment of the Ce$^{143}$ ground state.

The predominantly M1 character of 293 keV transition allows us to assign $\frac{7}{2}^+$ or $\frac{9}{2}^+$ to the second excited state of Pr$^{143}$. The K/L ratio (6.1 $\pm$ 0.6) measured by Martin et al. 6) also supports this contention, if their value is interpreted with the calculations of Sliv and Band 7). Under these conditions only the following alternative
spins and multiplicities are acceptable for the second, first, and ground states in $^{143}\text{Pr}$.

\[ \frac{5}{2}^+ \rightarrow \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ , \quad \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ \rightarrow \frac{1}{2}^+. \]

The angular correlation data were analysed by the graphical method due to Arns and Wiedenbeck \(^{14}\)), as shown in fig. 7.

Accepting the 56 keV $\gamma$-ray to be a pure M1 transition we have three choices for the spin sequence

\[ \frac{7}{2}^+ \rightarrow \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ , \quad \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ \rightarrow \frac{1}{2}^+ , \quad \frac{1}{2}^+ \rightarrow \frac{1}{2}^+ \rightarrow \frac{1}{2}^+ . \]

The possibility (c) may be ruled out because it will give a K-conversion coefficient \(^{10}\) $\alpha_K = 0.570$, which is incompatible with the measured value of $\alpha_K = 0.07^{+0.007}_{-0.012}$ for the 293 keV gamma ray. The choice (a) also seems to contradict the K/L measurements of Martin \textit{et al.} and the present $\alpha_K$ measurements for the 293 keV gamma ray leaving us choice (b). Even if a small percentage (up to 5%) of E2 is accepted for the 56 keV transition the above arguments still hold good leaving us with only one possible sequence $\frac{7}{2}^+ \rightarrow \frac{3}{2}^+ \rightarrow \frac{1}{2}^+$. 

It is a pleasure to express our sincere gratitude to Professor P. S. Gill for his kind interest throughout the course of the work.

References

1) M. L. Pool and J. D. Kurbatav, Phys. Rev. 63 (1943) 463
2) M. L. Pool and N. L. Krisberg, Phys. Rev. 73 (1948) 1035
3) H. B. Keller and J. M. Cork, Phys. Rev. 84 (1951) 1079
4) E. Kondiah, Phys. Rev. 83 (1951) 471, reported in M. Siegbahn commemorative volume (Uppsala, 1951) p. 411, Ark. Fys. 4 (1952) 81
5) W. H. Burgus, Phys. Rev. 88 (1952) 1129
7) L. A. Sliv and I. M. Band, Translation reports 58 ICCKI and 58IC CCL1 (the Physics Dept., University of Illinois, Urbana, Illinois)
9) P. Axel, Rev. Sci. Instr. 25 (1953) 392 (L)
11) M. E. Rose, Phys. Rev. 91 (1953) 610
13) K. Murakawa and J. S. Rose, Phys. Rev. 82 (1951) 967