SHORT HALF-LIFE MEASUREMENTS OF NUCLEAR STATES

BY

DELAYED COINCIDENCE TECHNIQUE

INDRA MANI GOVIL
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ABSTRACT

The transition probability of an excited state to a lower state, through electromagnetic radiation depends on the wave functions of the two states involved as well as on the energy and the multipolarity of the electromagnetic radiation. The measurement of the transition probability, therefore, plays an important role in understanding the details of the nuclear structure. In the present work a delayed coincidence spectrometer incorporating slow and fast channels has been constructed for the measurement of half-lives of nuclear states in the nano second region. The prompt annihilation radiations from $^{22}$Ne were used to calibrate the instrument. The slope of the two sides of the prompt curve showing the inherent resolution of the detectors and the elements of coincidence circuitry was measured as $T_1 = 3.5 \times 10^{-10}$ Sec. This sets the lower limit to the half-life that can be measured with the present apparatus. The effect of various factors like phosphor decay time and photomultiplier transit-time which contribute to the time uncertainty in scintillation spectrometer has been discussed on theoretical as well as on experimental grounds.

The delayed coincidence spectrometer was used to measure the half-lives of excited states in $^{129}$I, $^{131}$Cs, $^{133}$Cs, $^{141}$Pr, $^{143}$Pr, $^{159}$Tb, $^{175}$Lu, $^{181}$Ta and $^{186}$W. The conversion coefficient of 142 KeV Level of Pr$^{141}$ was also measured. The experimental results have been compared with the existing theories. For the purpose of calculations the results have been divided in
two parts vis. (1) \( \ell \)-forbidden transitions (transitions which take place between two shell model states those differ by two units of orbital angular momenta \((\Delta \ell = 2)\) and the transitions in deformed nuclei \((\Lambda > 150)\). For \( \ell \)-forbidden transitions the experimental values of the matrix element have been compared with the single particle matrix element and the matrix element calculated by the theory of Arima et al. based on configurational mixing. The analysis of the results indicate that the experimental values of the matrix element for such transitions are much off than the single particle estimates but they are in much agreement with those calculated from Arima's theory. The experimental values of the matrix element over a wide range of nuclei have been plotted on a logarithmic scale and it was found that these transitions show some shell effect corresponding to magic numbers at \( N=28, 50, 128 \), where the value of the matrix element falls by a large factor. For the transitions between excited states of the deformed nuclei, the calculations have been made on the basis of Bohr and Mottelson unified model and it was found that the calculations succeed very well in reproducing the general trends of the experimental results.
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CHAPTER I

INTRODUCTION

The discovery of artificial radioactivity and nuclear fission revealed that most of the radioactive nuclei follow a beta decay or electron capture in which the product nuclei are left in excited states for which the particle emission is energetically impossible. The de-excitation of these quasi-stationary states proceed either by the emission of an electromagnetic quantum or by a conversion electron from one of the atomic shell or sub-shell. The transition probability for the emission of the electromagnetic radiation from an excited state to a lower state depends on the wave functions of the two states involved as well as on the energy and multipolarity of the radiation. The measurement of the transition probability or the half-life of an excited state, therefore, plays an important role in exploring the details of nuclear structure.

The "multipolarity" which is generally used to specify the kind of gamma-radiation as to both its class and multipole order depends on the spins and parities of the initial and final states involved in a particular transition. The conservation of the total angular momentum requires that the angular momentum carried away by the emitted photon must be equal to the vector difference between the angular momenta \( I_i \) and \( I_f \) of the initial and final states, i.e.

\[
I_i - I_f \leq l \leq I_i + I_f \quad (1.1)
\]
It is implied from the above selection rule that the gamma-ray transitions of different multipole order (multipole order of the $\gamma$-radiation is defined as $2^L$ so that fields corresponding to angular momenta $1, 2, 3, 4$ are referred to as being dipole, quadrupole, octopole and $2^4$ pole etc.) may take place between two states characterised by the spins $I_1$ and $I_2$. In practice, however, $L$ is confined by the relative transition probabilities, so that only the transitions of lowest possible order corresponding to $L=I_1-I_2=\Delta I$ are predominant. Sometimes a mixture $^{1-2}$ of higher order i.e., $L=\Delta I+1$ also occur along with $L=\Delta I$. Since the smallest possible spin difference carried away by the photon is unity due to the transverse nature of electromagnetic radiations, the $\gamma$-ray transitions between two states having zero angular momenta $(I_1=I_2=0)$ are strictly forbidden. The de-excitation of the nucleus in this particular case takes place only through the emission of the conversion electron or electron-positron pair $^3$ (e.g. the 6 Mev first excited state of $^{16}O$).

The classical theory of radiation combined with the quantum-mechanical aspects predicts that for each value of angular momentum $L$ of the light wave, two different waves are possible corresponding to the "electric" and the "magnetic" radiation. The electric radiation is associated with the change of charge distribution while the magnetic radiation is associated with the change of current distribution $^4$ within the nuclear field. The parity carried away by the two types
of radiations is however, different. The electric multipoles have even parity when $L$ is even and odd parity when $L$ is odd, whereas the magnetic radiations carry the opposite parities i.e. odd parity when $L$ is even and even parity when $L$ is odd. Thus, the parity of electric multipole of order $2^L = (-1)^L$ and the parity of magnetic multipole of order $2^L = -(-1)^L$. Here the resultant (+1) denotes even parity and (-1) denotes the odd parity.

Conservation of parity requires that the parity of the initial and final state should be the same for even parity radiation while it should change for odd parity radiation. Therefore, the electric dipole radiation ($L=1$) or magnetic quadrupole radiation ($L=2$) which carry the odd parities are possible only between states of different parities, while the magnetic dipole ($L=1$) or electric quadrupole ($L=2$) radiations which are of even parities may occur between states of same parity. We have therefore another selection rule, i.e.

$$\Delta \Pi = \Pi_i - \Pi_f = (-1)^L$$ for electric transitions \hspace{1cm} (1.2)

and $\Delta \Pi = \Pi_i - \Pi_f = -(-1)^L$ for magnetic transitions \hspace{1cm} (1.3)

As a result of the above selection rules only the transitions of limited multipolarities are expected between two states of specified angular momenta and parities. The results are summarised in the following table.

<table>
<thead>
<tr>
<th>Parity Change</th>
<th>Change of Angular Momentum</th>
<th>$I_i - I_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+1) No</td>
<td>$M_1$ ($E_2$)</td>
<td>$E_2$ ($M_3$)</td>
</tr>
<tr>
<td>(-1) Yes</td>
<td>$E_1$ ($M_2$)</td>
<td>$M_2$ ($E_3$)</td>
</tr>
</tbody>
</table>
In the above table only two lowest multipole orders are given. The second in parenthesis is usually less significant.

As it has been pointed out earlier that a nucleus in an excited state decays not only by the emission of an electromagnetic quantum but quite often the nuclear excitation energy is directly transferred to one of the orbital electron in K, L, or M shell, which allows the electron to overcome its binding energy and thus to escape out of the atom. The conversion electrons are monoenergetic in nature, having the energy equal to the difference between the transition energy and orbital binding energy.

The conversion coefficients defined as the ratio of the converted electrons to the unconverted $\gamma$-rays depends strongly on the energy and multipolarity of the radiation besides the atomic number and shell or subshell of the nucleus. Theoretical calculations of the conversion coefficients for the K shell and $L_1, L_2, L_3$ subshells were made originally for a point nucleus by Rose\textsuperscript{6} which were further extended by Siv and Band\textsuperscript{7} incorporating the screening and static nuclear size effect. A few of the qualitative features\textsuperscript{8} of these results are helpful in assigning the multipolarity of the transitions.

1. The K shell conversion coefficient $\alpha_K$ increases with multipole order, and for a given multipole order the electric transitions are less converted than the corresponding magnetic transitions.

2. The K/L ratio decreases with increasing multipole order for a given nucleus with fixed energy of transition.
3. $L_1$ conversion predominates over $L_2$ and $L_3$ conversions in transitions of low multipole order and becomes less important at higher multipole orders. Most of the $M_1$ transitions are characterised by this feature.

Assignment of multipole order on the basis of $\alpha$ or $K/L$ ratio alone may give ambiguous results, if there is a mixture of the two radiations, since in that case the experimental conversion coefficient may correspond to some higher multipole order. However depending on the case a combination of conversion coefficient data with half-life or angular correlation measurement may remove the ambiguity in assignment.

The theoretical knowledge about the life times of levels is of much importance in assigning the multipole order of radiations or the structure of the nuclei, if either of the two is fixed by other measurements. The calculation of the transition probability of a particular level requires the specific theory about the nuclear structure. Due to the lack of knowledge about the exact nature of nuclear forces, the theories are developed in the form of models. Early attempts were made to calculate the lifetimes using "Liquid drop model" or a radiating mechanism associated with the rotating charged particle. These models were however mostly speculative because of the insufficient experimental evidence. Around 1950 Mayer, Hexel, Jensen and Sauss independently introduced the concept of "shell model" on the basis of $\beta$-decay systematics and occurrence of island of isomerism. The model was later found to predict the spins and parities of the ground states and
first excited states for most of the nuclei with much success. This model assumes that each nucleon moves independently in the average potential produced by all of the other nucleons. The transition probability for the emission of a gamma-radiation was calculated by Weisskopf\textsuperscript{13} on the basis of single particle version of the shell model in which a single proton was assumed to make a transition between two single particle states having specified quantum numbers. The Weisskopf estimates were reduced to more realistic form by Moszkowski\textsuperscript{14-15} who pointed out that the transition probability between states of partially filled orbits is less than the corresponding single particle states by a factor $\gamma$ known as the "seniority statistical factor".

Shell model, though was found to be quite successful in explaining the remarkable uniformity of the matrix elements of $M_2$ transitions,\textsuperscript{14} falls short in explaining many $\gamma$-transitions including the $\ell$-forbidden $M_1$ transitions. According to single particle model the magnetic dipole transitions between two states differing in orbital angular momentum $\ell$ are strictly forbidden, since the magnetic dipole moment operator connects states of same orbital angular momenta and same radial quantum numbers which are degenerate in the single particle velocity independent potential. Most of the transitions distinguished as purely $M_1$ by conversion and angular correlation data do not satisfy the above selection rule and hence they are classified as $\ell$-forbidden $M_1$ transitions. Such transitions are shown to possess longer lifetimes than the ones calculated theoretically on the basis of allowed transitions from the shell model. Various attempts have been made in the past to explain these transitions on semi-empirical
as well as on theoretical basis. It has been first pointed out by Graham and Bell\textsuperscript{16} that the experimental points for such transitions may be grouped along two straight lines, given by \( \log \gamma_1 = -11.0 - 3 \log E \) (\( E \) in Mev) for odd proton nuclei and \( \log \gamma_1 = -11.7 - 3 \log E \) (\( E \) in Mev) for odd neutron nuclei. The validity of these semi-empirical curves was later verified by the experiments of de Waard and Gerholm.\textsuperscript{17}

The theoretical interpretation of these transitions came from the theory of exchange interaction\textsuperscript{18} assumed in the so-called many particle shell model. Such and others\textsuperscript{19-20} concluded that the presence of velocity dependent interactions like spin-orbit coupling and exchange forces between pair of nucleons remove the degeneracy of the levels in the nucleon configuration other than the closed shell and therefore the special selection rule which forbids \( M_1 \) transition between states of different angular momenta is relaxed. The calculation of the matrix element on the above assumptions gave a fair quantitative agreement between experimental and theoretical values, the theoretical values being somewhat too small.

An alternative approach to explain these transitions was explored by Volkov\textsuperscript{21} who realised that the departure of the actual wave functions from the shell model may give the non-vanishing matrix element for such transitions. Arima et al.\textsuperscript{2} calculated the contribution to the matrix element using wave functions consisting of all the possible admixture of zeroth order and excited configurations. The results so obtained
on the standpoint of configurational mixing in the $j$-$j$ coupling
shell model were found to be in good agreement with the
experiments.

Meanwhile the empirical data of Goldhaber and Sunyar\textsuperscript{23}
suggested that the first excited states of most of the even-even
nuclei have spin 2 and even parity. The transition from these
states often proceeds too fast to be accounted from the single
particle shell model estimates. This behaviour combined with
the anomalously large quadrupole moments for many of the nuclei
suggested that the observed quantities are not the properties
of single nucleon but contributed by the collective motion of
the nucleons. Bohr and Mottelson\textsuperscript{24} suggested that these
discrepancies can be well accounted for by the "unified nuclear
model" which involves the assumption that the nucleons move
nearly independently in a common slowly changing non-spherical
potential. In fact the unified description of the nuclear
dynamics deals with the state of the nucleus which incorporates
both the particle as well as collective degrees of freedom.
The first of these represents the motion of the nucleons in a
fixed potential under the influence of their mutual interactions
while the second is associated with the variation in shape and
orientation of nuclear field due to collective excitations.
The competition between particle forces and the surface
interactions determines the resultant coupling scheme. In the
immediate vicinity of major closed shell the particle forces
dominate over the surface interactions and thus the spherical
symmetry of the nucleus is restored. The nuclear level scheme
may be well accounted for by considering the motion of the
nucleons under the influence of residual interactions. The striking evidence for such particle excitations is afforded by the occurrence of low lying states with a spin very different from the ground state (long-lived isomeric states). The transition probability of these states were however found to be much smaller than the shell model estimates which indicates the influence of weak surface coupling. Because of the modification of the particle wave functions implied by the non-spherical potential \(^{25}\) (leading to the situation of \(\ell\) or \(j\) forbiddenness), the transition probability is in general reduced. The enhancement of \(E_2\) transition probability between the low lying levels of the even-even nuclei is explained on the basis of the polarization \(^{26}\) of the core (closed shell) by the particles in the unfilled shell.

As more nucleons are added outside the closed shell configuration, the coherent effect of polarization due to all the nucleons in unfilled shell increases the tendency of the nucleus towards deformation. The nuclear states are thus described by the vibrational spectra corresponding to the collective oscillations of the nuclei about the spherical shape. The occurrence of \(0, 2^+, 2^+\) spectra and the energy ratio of 2 between first and second \(2^+\) excited state in many of the even-even nuclei \((60 \leq A \leq 150)\) indicates such vibrational character.\(^{27}\) Further the usual de-excitation of the second \(2^+\) state to the first \(2^+\) state through \(E_2\) radiation is in accordance with the well known selection rule for harmonic oscillator. The odd-\(A\) nuclei in this region show rather a complex superposition of individual particle and collective excitations which is described in terms of the shell model states of the odd-particle and the vibrational states of even-even core.
For nuclei far away from the closed shell the spherical shape under the influence of deforming forces due to many particles, becomes unstable and the nucleus acquires an equilibrium deformation of axially symmetric shape. For such nuclei the collective motion separates into rotational, vibrational and single particle (intrinsic) modes. The first corresponds to the rotation of the nucleus with the preservation of shape, second to oscillations about the deformed shape, and the last one to the independent motion of the outer nucleons in the average deformed field which the nucleus now effectively presents to these nucleons. The rotational spectra may be well understood by considering that the coupled system of particles and surface, rotates like a symmetric top with three constant of motions $I, M$ and $K$ representing the total angular momentum and its projections on the space fixed axis, and on the symmetry axis respectively. In even-even nuclei, corresponding to pairwise filling of all the lower orbits the ground state has $I=K=0$. The rotational band starting from this state due to symmetry properties of even-even structure is limited to

$$I = 0, 2, 4, \ldots \ldots (\text{with even parity}) \quad (1.4)$$

The transition from first excited state, due to the special sequence of levels is of purely $E_2$ character which gets strongly enhanced due to collective rotational motion. The rotational spectrum in odd $A$ nuclei depends on the angular momentum $I_0$ of the ground state. For $K=I_0 \pm \frac{1}{2}$ the rotational band forms a series of states with spin

$$I = K, K+1, K+2, \ldots \ldots (\text{same parity as of ground stat} \quad (1.5)$$
The first excited state in these nuclei is expected to decay by the emission of almost pure E1 radiation on single particle basis but in this situation a considerable mixture of E2 radiation may not be ruled out in some cases since the latter being comparably enhanced due to collective excitations. The experimental results were found to tally with the above conclusion.

While the low energy excited states and the E2 transition probabilities in heavy mass region are explained by the simple rotation of the nuclei, the complete analysis of the nuclear properties requires the knowledge of intrinsic wave functions. The problem of single particle motion of the nuclei in phenomenological potential wells has been recently explored by Nilsson and others. As a result the observed experimental spectra in various nuclei are well explained by different intrinsic states and the corresponding rotational band associated with each such state. The transition between two individual particle states corresponding to different rotational bands are hindered and are governed by the asymptotic selection rules beside $L \geq K_i - K_f$. The transitions violating the later selection rule are known as K-forbidden and are highly hindered.

In view of the above discussion, it is evident that once the transition probability for the decay of an excited level has been estimated on any one of the above mentioned models, it is required to verify it experimentally using a suitable technique. Various techniques are employed for the
measurement of half-lives of isomeric states depending on the order of magnitude. Lifetimes of a few seconds and longer are measured by the usual method of plotting the decay curve, the time being measured with the help of a stop watch. The lifetimes less than few seconds and greater than $10^{-5}$ sec. ($10^{-5} \leq \tau \leq \text{few seconds}$) are usually measured by pulsed activation technique using a pulsed beam accelerator and setting the detecting equipment near to the target. The pulsed beam which induces the activity also opens an electronic gate movable in time through mechanical arrangement. A plot of the number of events in a gate recorded for different amounts of delay between the irradiation time and the opening of the gate gives the half-life of the activity. The half-lives less than $10^{-5}$ sec. are measured by the methods discussed below.

NUCLEAR RECOIL OR TIME OF FLIGHT.

The distance which an excited recoil nucleus covers in a nuclear reaction before it emits a $\gamma$-ray depends on the recoil velocity and the lifetime of the level emitting the $\gamma$-ray. Since the recoil velocity is known from the reaction kinetics, the measurement of the recoil distance gives the lifetime of the level ($t=\frac{x}{v}$). The method consists in detecting the $\gamma$-rays from the excited recoil nucleus in a direction perpendicular to the incident beam. The arrangement for the detection of $\gamma$-rays is such that only a limited region (in front of the target) is viewed by the detector. The observations are taken either by moving the target or the collimator and detector in a direction parallel to the incident beam. A curve showing
the variation of $\gamma$-ray intensity with the distance moved by
the detector or the target is plotted. The average distance
is calculated from the peak of the distribution. This method
is generally suitable for light nuclei. Thirion and Telegdi\textsuperscript{33}
measured the half-lives from this method up to $10^{-10}$ sec.

**DOPPLER SHIFT OR DOPPLER BROADENING METHOD.**

If the recoil nucleus in a nuclear reaction is moving
in the forward direction, then because of Doppler effect the
energy of the $\gamma$-ray would be different in the forward direction
than at $90^\circ$. If however, the life time of the excited state is
large than the slowing down time of the recoil nucleus, then no
doppler effect would occur and the energy of the $\gamma$-ray in
forward direction and at $90^\circ$ would be the same. On the other
hand, if the lifetime of the excited state is less than the
slowing down time, the energy of the $\gamma$-ray in the two directions
would be different and the measurement of the energy shift would
allow the estimation of the lifetime. Elliot and Bell\textsuperscript{34} used the
Doppler broadening technique and estimated the half-life of the
$0.478 \text{ Mev state}^\text{14}_7$ as $7.5 \times 10^{-14}$ Sec.

**COULOMB EXCITATION.**

It was first realised in practice by Huus and Zupancic\textsuperscript{35}
and by McClelland and Goodman\textsuperscript{36} that a charged particle passing
closely to a non-spherical nucleus may induce oscillations in the
nuclear surface and thus is capable of exciting one or two low
energy states through electric interactions. The cross-section
for such process (known as coulomb excitation) is given by:

$$\sigma = \frac{2\pi^2}{25} \cdot \frac{m_1 v_1^2}{\sqrt{\xi}} \times \eta(\xi) \times B(E_2) \times 10^{-48} \quad (1.6)$$

where \(\eta(\xi)\) is a numerically tabulated function of the adiabatic parameter

$$\xi = \frac{Z_1 Z_2 e^2}{\kappa} \left( \frac{1}{v_f} - \frac{1}{v_i} \right)$$

\(m\) is the mass of the bombarding particle and \(v_i\) and \(v_f\) its velocities before and after the interaction, and \(Z_1\) and \(Z_2\) are the charges of the bombarding and target nuclei. Since the other quantities in the above expression are constants relating to the incident charged particle and the target nucleus, the measurement of total cross section from the resulting \(\gamma\)-ray yield for \(E_2\) decay may determine the reduced upward transition probability \(B(E_2)\).

The reduced upward transition probability \(B(E_2)\) is related to the downward decay probability by the expression

$$B(E_2)_{I\rightarrow I_0} = B(E_2)_{I_0\rightarrow I} \frac{2I_0 + 1}{2I + 1} \quad (1.7)$$

where \(I_0\) and \(I\) correspond to ground state and excited state respectively. Thus knowing the upward reduced transition probability, one can estimate the reduced downward decay probability from which the lifetime of the level may be deduced using the expression

$$\frac{1}{\gamma} = \lambda_\gamma(E_2) = 1.16 \times 10^{13} E_\gamma^5 B(E_2) \quad (1.8)$$

where \(E_\gamma\) is in MeV and \(B(E_2)\) in units of \(10^{-48} \text{ e}^2 \text{ cm}^2\).
NUCLEAR RESONANCE SCATTERING AND ABSORPTION.

According to the well-known Heisenberg uncertainty principal the level width $\gamma$ of a nuclear energy level is related with the lifetime of the level as

$$\gamma \Gamma = \hbar$$

The lifetime of the level may thus be estimated if the level width $\Gamma$ is known.

One of the methods to determine the level width depends on the measurement of the cross-section for resonant scattering and absorption of $\gamma$-rays. According to electromagnetic theory the cross-section for resonant absorption is given by

$$\sigma = \frac{2I+1}{2L+1} \cdot \frac{\lambda^2}{8\pi} \frac{\Gamma^2}{(E-E_0)^2 + \Gamma^2}$$

where $E$ is the energy and $\lambda$ the wavelength of the incident photon and $E_0$ is the energy and $\Gamma$ the level width of the level. Evidently the cross-section is maximum for $E=E_0$ and it becomes too small to be observed experimentally, if $(E-E_0)$ is large compared to the level width. Owing to the last conclusion, even though when the incident $\gamma$-ray energy is supplied from an active nuclei of the same kind as scatterer, yet the resonant scattering is difficult to observe since the energy equivalent to $E^2/Mc^2$ (which most of the time is more than the level width) is lost due to recoil of the nucleus in the process of emission and absorption of $\gamma$-ray. Various methods like heating the source or rotating it on the top of the high
speed motor, are used to compensate for the energy loss due to recoil of the nucleus so that the resonant scattering is realised in practice.

Recently Mossbauer suggested that the resonant absorption may also be observed if the energy loss due to recoil is made negligible. He pointed out that if the emitting or the absorbing nucleus is bound in a solid, the momentum conservation is satisfied by the crystal as a whole and the large mass of the recoiling entity makes the recoil energy loss negligibly small. This process of recoilless resonant absorption has found an important place in measuring short half-lives of excited states.

DELAYED COINCIDENCE TECHNIQUE.

Out of all the possible methods discussed in the foregoing paragraphs, the delayed coincidence technique is the most systematic and direct method for the measurement of the half-lives in millimicrosecond region. The technique incorporates the direct measurement of time between two electronic signals, one produced at a time when the level is formed and the other when the level decays. The first or the zerotime signal is provided by β- or γ-ray by which the level is formed. In case a pulsed beam accelerator is used to form the excited state, the zero time signal is often picked up from the pulsing oscillator.

In the beginning the fast coincidence circuits with
high resolving times were used for the measurement of time intervals. The coincidence counting rate was plotted as a function of various delays inserted in one of the Channel by mechanical delay lines or coaxial cables. At present fast coincidence circuits are replaced by time-to-pulse height converters used in conjunction with multichannel pulse height analyser. The later improves the stability and increases the efficiency on data collection.

The data on the delayed coincidences are analysed mostly by observing the logarithmic slope of the delayed coincidence curve, since it is the simplest and least ambiguous approach. However if the lifetime is shorter than the resolving time of the coincidence circuit an estimate of the half-life can still be made by the moment analysis or by the shift of the centroid of the delayed coincidence curve with respect to the prompt peak. The self-comparison method (in which the two plots, one obtained before and the other after interchanging the function of the two detectors are compared) is an alternative method for the determination of the half-lives shorter than the resolving time of the coincidence circuitry.

In the present work a delayed coincidence spectrometer incorporating slow and fast channels has been constructed and assembled for the measurement of the half-lives in the nanosecond region. Half-lives of excited states in $^{129}$I, $^{133}$Gd, $^{137}$Cs, $^{143}$Pr, $^{141}$Pr, $^{103}$Rh, $^{159}$Gd, $^{186}$W, $^{181}$Ta, $^{175}$Lu have been measured. Emphasis has also been given on the radioactivity
of the source, wherever, it is found necessary. The experimental values have been compared with the existing theories. Certain interesting features about the structure of the nuclei are revealed and are discussed in the last chapter.
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CHAPTER II

DELAYED-COINCIDENCE SPECTROMETER

SOURCE PREPARATION AND MOUNTING

The preparation of source plays an important role when one is concerned with the measurement of short half-life, since a non-uniform and extended source may give rise to a time uncertainty in millimicrosecond region. In the present work the sources were prepared in the following manner.

SOURCES FOR GAMMA-RAYS.

The sources for $\gamma - \gamma$ coincidence measurement were prepared in a perspex envelope of 0.5 cm. dia. x 1 cm length. A few drops of the active material were poured, through a pipette in a suitable cavity drilled in the container which were subsequently dried up by an infra red lamp. The sources thus prepared were invariably point sources and were fixed on the adjustable stand in the centre of the two crystals.

SOURCES FOR BETA-RAYS.

The sources for $\beta - \beta$ and $\beta - \gamma$ coincidences were prepared on the aluminium and perspex discs of 2.5 cm. dia. x 0.1 cm thickness. The source diameter was kept about 0.4 cm by drilling a hole in the centre of the disc. The backing of the source was a 3mg/cm$^2$ thin sheet of aluminium. The source was directly attached to the face of one of the photomultiplier detecting the $\beta$ -rays. The
sources emitting $\beta$-particles acquire static positive charge which causes a change in the velocity of the electron emanating from the source. This introduces a possibility of producing a time jitter. The aluminium disc carrying the source was therefore electrically connected to the ground to avoid any such uncertainty in time measurement.

**MOUNTING OF THE CRYSTALS**

**MOUNTING OF NaI CRYSTALS.**

The sodium iodide (thallium activated) crystals in particular sizes were obtained from Harshaw chemical company in the form of raw blanks. The polishing and mounting of the same was done here in a specially constructed dry box at a humidity of 3%. The crystals were made clear by zero grade grinding paper so that the layer exposed to moisture and free iodine is removed. One side of it was then polished by successively rubbing the crystal on a tissue paper wetted with acetone, till all the scratches were removed. A coating of about 10mg/cm² of aluminium oxide was uniformly dusted on the unpolished sides so as to make them perfectly reflecting surfaces. The crystal with its polished surface on the upper side was then placed in an aluminium can of 0.08 cm thickness on all the sides. The polished surface was covered with a clean glass plate which was sealed against moisture with a thin film of araldite adhesive applied at the corners. The optical coupling between glass plate and the polished surface
was made by using D.C. 200 silicon fluid and care was taken, that no bubble remained in the fluid. This mounted crystal was joined firmly to the cathode of the photomultiplier with the help of cellulose black tape and aspen Q compound. D.C. 200 (silicon fluid) was again used between the joint to ensure good resolution.

MOUNTING OF THE PLASTIC SCINTILLATORS.

Plastic scintillator in the form of a long cylinder 1.5" dia x 4" long was obtained from Department of Atomic Energy, Trombay. The acetone was not found to be a suitable reagent for polishing and shaping the same in required sizes. The crystal was therefore properly polished on one side and cut to required size by a high speed lathe. The other sides of it were covered with 6mg/cm² highly reflecting sheet of aluminium. The aluminium sheets were blackened on the back side with the help of aquadag which served the purpose of outer light shielding. The scintillator was coupled to the photocathode of the photomultiplier using D.C. 200 as an optical coupler.

The polished anthracene crystals in the required sizes were obtained from the Department of Atomic Energy, Trombay and were mounted in the same manner as plastic scintillators.

PHOTOMULTIPLIER TUBE (6810 A)

A recently developed photomultiplier tube type R.C.A. 6810A was used for the present measurements. The tube
provides a low transit-time and high gain characteristics. It consists of fourteen multiplying stages and therefore is capable of rendering the output pulse of the order of 100 volt per Mev. The main advantage of this tube lies in the fact that it eliminates the use of the distributed amplifiers to amplify the output signal and therefore increases the stability of the operation and reduces the inherent noise present in these amplifiers.

A fairly stabilised negative voltage power supply was used to provide the high voltage to the photomultiplier. The voltage to the various dynodes was distributed through a network of resistances. The bleeder current across the resistances was kept sufficiently large so that the pulse current in the photomultiplier may not produce an excessive voltage swing on the various dynodes. Few capacitances were also connected in parallel to the resistances to provide a low impedance path for the large amplitude pulses appearing on the dynodes at the later stages as shown in fig. 1. The voltage between the photocathode and the first dynode of the photomultiplier was kept to its maximum value to reduce the statistical fluctuations and to minimise the transit-time between this passage. The potentiometers used for the focusing and accelerating electrodes were mounted on the perspex insulator so as to avoid the leaking of the high voltage. The potential of the focusing-electrode was adjusted to optimise the magnitude, uniformity, and the speed of response. However
Fig. No. 1
PHOTO MULTIPLIER DYNOODE VOLTAGE DIVIDER CIRCUIT PLUS THE
OUT PUT CATHODE FOLLOWER FOR SLOW OPERATION
DIFFERENTIAL PULSE HEIGHT SPECTRUM OF GAMMA RAYS IN NaI(TL) CRYSTAL FROM THE DECAY OF:
- $\text{Co}_6^{\text{60}}$
- $\text{Na}_{22}$
- $\text{Cs}_{137}^{170}$
- $\text{Tm}_{170}^{\text{60}}$

32 KeV BaK X-RAY

510 KeV PEAK DUE TO ANNIHILATION RADIATION

820 KeV PAIR PRODUCTION WITH ESCAPE OF ONE ANNIHILATION PHOTON

1.17 MeV PHOTO PEAK

1.33 MeV PHOTO PEAK

660 KeV Cs137 PHOTO PEAK

23 KeV ESCAPE PEAK

51 KeV YbKX RAY

3X MULTIPLEX

BACK SCATTER PEAK

COMPTON EDGE

PULSE HEIGHT (VOLTS) ARBITRARY SCALE

Fig. No. 2
the accelerating electrode voltage was adjusted to obtain the minimum anode-dark current with some sacrifice in gain. The photomultiplier was covered with a cylindrical \( \mu \)-magnetic shield to avoid deflection of electron-cascade due to the stray magnetic field of the earth. Each signal from the photomultiplier was split up into a fast signal (taken from the anode) and a slow signal (taken from an intermediate dynode).

**SLOW CHANNEL**

The positive pulses for the energy discrimination were taken from the tenth dynode of the photomultiplier so as to avoid the nonlinearity due to the saturation of the high energy pulses at the later stages. The voltage pulses appearing across the 47K ohms resistance were coupled to the cathode follower through a 50pf high voltage capacitance and the millivolt pulses after the cathode follower were amplified by a linear amplifier\(^2\). The amplified pulses from the output of the amplifier having their amplitudes proportional to the energies of the various radiations from the source were fed to the single channel pulse height analyser\(^3\) for analysis. The whole assembly known as single channel spectrometer was used to select the proper energy pulses corresponding to the decay of a particular level.

**ENERGY CALIBRATION AND LINEARITY.**

The energy calibration of the spectrometer was made by observing the singles spectrum of \( \gamma \)-rays from Tm\(^{170} \), Na\(^{22} \),
CURVE SHOWING THE LINEAR ENERGY RESPONSE OF SCINTILLATION SPECTROMETER WITH NaI(TL) CRYSTAL

Fig. No. 3  
ENERGY IN KeV

CURVE SHOWING THE VARIATION OF PULSE HEIGHT RESOLUTION WITH ENERGY IN NaI(TL) CRYSTAL

Fig. No. 4  
100 / ENERGY IN KeV
Cs$^{137}$ and Co$^{60}$ in NaI (Tl) crystal of size 2.5 cm dia x 2.5 cm thick, as shown in fig. 2. The gross features of the spectrum showed a predominant photopeak corresponding to the total absorption, escape peak due to the escape of iodine K X-ray, back scattered peak and compton edge etc. The nuclei decaying through $\beta^+$ emission had an additional peak at 511 keV corresponding to annihilation radiation of positons. The pulse height corresponding to the photopeak was noted for each case, and a graph between energy vs. pulse height was plotted as shown in fig. 3. The calibration curve so obtained was a straight line passing through zero of the scale which assured the linear response of the scintillation spectrometer.

ENERGY RESOLUTION.

Due to the statistical nature of the light emission from the phosphor and the subsequent phototube variations, there results, not a unique pulse height but rather a distribution of pulse heights for an incident monoenergetic beam of particles. The spectrum of the pulses resulting from a monoenergetic source follows a Poisson distribution. The full width at half maximum of the spectrum defined as the resolution varies inversely as the square root of the incident energy.$^4$-$^5$ The photopeak resolutions with the aid of spectra shown in fig. 2 were calculated for the various energies and a graph between resolution vs. $1/E^2$ (where $E$ is the energy of the $\gamma$-ray) was plotted as shown in fig. 4. The curve was found to be linear within statistical limits in confirmation with the theory.
RESPONSE OF THE PLASTIC SCINTILLATOR FOR THE $\beta$-RAYS FROM Cs\textsuperscript{137}

660 KeV CONVERSION ELECTRON PEAK

RESPONSE OF THE SLOW COINCIDENCE FOR THE ANNihilation QUANTA FROM Na\textsuperscript{22}

$2T = 0.25 \mu$ Sec.
INTENSITY MEASUREMENT OF \( \gamma \)-RAYS.

The intensity measurement for the various \( \gamma \)-rays present in a particular source was made by using NaI (Tl) crystal and analysing the unknown spectrum with the help of known monoenergetic sources of \( \gamma \)-rays. The singles spectrum from the known sources was successively subtracted starting from the highest energy \( \gamma \)-ray. The resulting areas under photopeaks after applying the appropriate correction for photopeak efficiency and absorption due to crystal backing were compared to yield the relative intensity of \( \gamma \)-rays present in the source.

SPECTROSCOPY OF \( \beta \)-RAYS.

As NaI (Tl) crystals because of their hygroscopic nature have to be mounted in air tight containers, they can not be used for the detection of \( \beta \)-particles from the external sources, since most of the betas would get scattered or absorbed before entering the crystal. Plastic or anthracene crystals were used for the detection of \( \beta \)-particles. The response of a plastic crystal 1" dia x 1.5" thickness for 660 keV conversion electrons from Cs\( ^{137} \) has been shown in fig. 5. The resolution from this curve for the 660 keV conversion electrons comes out to be 25%. The resolution was however found to be very much dependant on the source size, shape and the distance of the source from the crystal.

SLOW-COINCIDENCE

The pulses from the two slow channels corresponding
Fig No. 6
CIRCUIT DIAGRAM OF SLOW-COINCIDENCE UNIT
to selected energies were fed to a slow coincidence unit, which was specially designed and fully worked out. The circuit diagram of the same is shown in fig. 6. The negative pulses from one spectrometer were inverted by the tube VI to trigger the negatively biased blocking oscillator comprising the tubes $V_2$ and $V_3$. The cathode of the tube $V_3$ provides the shaped pulses of constant amplitude of about 20 volt and having the width at the base of about $0.2 \, \mu\text{sec}$, which were fed to the quadrature grid of 6BN6 coincidence tube. The pulses from the other spectrometer were also shaped in the similar way and were applied to the limiter grid of the coincidence tube through a lumped delay line consisting of twelve steps, each having a delay of $0.06 \, \mu\text{sec}$. The 6BN6 tube which is initially in a nonconducting state due to the positive cathode voltage determined by the $2.6\Omega$ potentiometer, starts conducting when the pulses at its two grids overlap in time and thus a coincident negative pulse at the anode is formed. The cathode potentiometer was adjusted so as to keep the resolving time of the coincidence circuit to be $0.25 \, \mu\text{sec}$, though higher bias of the cathode may be used for better resolution. The resolution of the slow coincidence circuit was measured by the two well known methods, first by using a pulse generator and second by using two independent radioactive sources and using the expression $N_c=2N_1N_2T^2$, $N_c$ being the chance coincidences, and $N_1$, $N_2$ being the singles counting rates in the two counters. The response of the coincidence unit for the prompt annihilation quanta from $^{22}\text{Na}$ is shown in fig. 7.
Fig. No. 9
CIRCUIT DIAGRAM OF FAST DISCRIMINATOR AND PULSE LIMITER

Fig. No. 8  CIRCUIT DIAGRAM OF GATING UNIT
The output pulse from the coincidence circuit was negative having an RC tail, which was unsuitable for operating the 20-channel analyzer. This pulse was therefore shaped in amplitude and width to meet the requirements of 20-channel analyzer. The gating circuit so designed is shown in fig. 8. It consists of an inverter tube 6AK5 and the univibrator tube 6J6. The bias of the univibrator (Schmitt circuit) which determines the amplitude and duration of the output pulse, was so adjusted that an output pulse of about 30 volt in amplitude and 4 \( \mu \text{sec} \) in duration was obtained. This pulse was most suitable to provide the gate for the 20-channel pulse height analyzer (Eldorado Electronics. Co. Model PA400).

**FAST CHANNEL**

The negative pulse for the fast channel was taken from the anode of the photomultiplier tube across a 5K resistance which was carefully selected since the pulse amplitude at the anode was found to be dependant on the value of this resistance. Various resistances from 200 ohms to 10K were therefore tried and the amplitude of the pulse was noted for each value using NaI (Tl) as phosphor. The amplitude was found to vary rapidly in the beginning up to 1K, and then slowly up to 10K. The change in amplitude after 10K was negligible. The decay time or the width of the pulse was found to increase with the increase of the resistance but the rise time had been unaffected. The
resolution and the stability was better for higher resistances. A value of 5K which was found to be most suitable was used in the present measurements.

**DISCRIMINATOR AND PULSE LIMITER.**

A fast discriminator and pulse shaper was constructed for the processing of the output pulse from the anode. The discriminator bias may be varied from 0 to 100 volt and it introduces essentially no delay for the pulses having amplitudes greater than 2-volt above threshold. The detailed circuit diagram of the same is shown in fig.9. The tubes 6x8 and 6CL6 form the discriminator part while the two 404A tubes are used as limiter and cathode follower respectively. The triode portion of the 6x8 tube remains in a cut off position with a bias determined by the threshold potentiometer while the pentode section of it conducts heavily. The application of a negative input pulse causes a drop in the common cathode potential of 6x8 until the triode section of this tube is triggered, forming a negative pulse at its anode. Tube 6CL6 fastens the operation of 6x8, since in the event when the cathode potential of this tube does not fall as fast as the input pulse, a positive pulse at the anode of its pentode section is formed. This positive pulse increases the current in 6CL6 which subsequently fastens the rate at which the common cathode potential of 6x8 falls. The output pulse from the discriminator having the rise-time approximately the same as that of the input pulse, was allowed to cut-off a steady current of about 20 mA in R.C.A. 404A tube. The plate load of the 404A
Fig. No. 10
THE BLOCK DIAGRAM OF TIME TO PULSE HEIGHT CONVERTER
was a section of HH-2000 delay cable (Zo=2000 ohms, 0.12 μsec. delay/ft) which was shorted at the plate supply end with a condenser of 0.1 μF. The pulse thus formed at the anode was a square pulse of 20 volt amplitude and duration 2 t (t being the one way delay time of the shorted cable). The width of the pulse was kept approximately 300μ sec. (adjusted with the length of the delay cable) so as to provide the necessary dead time for the other pulses which may result due to long decay time of the phosphor.

TIME-TO-PULSE-HEIGHT CONVERTER.

Time-to-pulse-height converter (TPH) was similar to that described by Weber, Jhonstone and Gramberg. A few changes were, however, made in the original circuit of the time-to-pulse height converter to make it suitable for our purpose. The block diagram of the converter is shown in fig. 10. It uses essentially two coincidence tubes 6A36 and 6BN6. The control grid of the 6BN6 is held at approximately zero bias while the quadrature grid of 6BN6 and suppressor grid of 6A36 are connected together and are biased beyond cut-off. The two radiations one populating the level concerned and the other by which the level decays form the start and stop pulses. The application of stop pulse in the absence of start pulse produces no action as both the coincidence tubes remain in a cut off position. The start pulse of sufficient amplitude on the other hand turns on a saturated plate current to flow in the 6BN6 tube which causes the discharging of the capacitor C linearly with time. If during the discharge of the capacitor, i.e. in the presence of
start pulse a stop pulse also occurs, it will trigger the 6AS6 tube forming a negative pulse at its anode. This pulse is coupled to the control grid of the 6BN6 and therefore will put the same in a non-conducting state charging back the capacitor to its original potential through R. The overall effect is that a negative pulse is produced at the anode of 6BN6, having a tail determined by RC and the amplitude proportional to the delay between the start and stop pulses. The value of R was chosen to be 250 K to suit the requirement of the linear amplifier following the TPH. The negative pulse at the plate of 6AS6 is limited in amplitude by the biased diode (IN34) to 20 volt to prevent excessive stop feed through.

The output of the time-to-pulse-height converter varies from 0.02 volt to 4 volt, depending on the overlapping time between two pulses. The Los Alamos DD2 non-overloading linear amplifier which has the excellent features like low noise, large band width, wide range of gain control and high stability, was used to amplify these pulses. However an RC attenuator of the type shown in fig.10 was used before feeding the pulses to the amplifier since the first stage of the same requires the pulses in millivolt amplitude. The attenuator reduces the amplitude of all the pulses linearly by a factor of ten without affecting their shape. The width of the output pulse from the amplifier was 4 μsec. which was specially suited for operating the 20-channel pulse height analyser. The output of the amplifier was displayed on the 20-channel in coincidence with the gate provided by the side slow channels. The multichannel
THE PROMPT DECAY CURVE OF $^{22}$Na ANNihilation RADIATION OF POSITIONS

CALIBRATION: 2 CHANNELS/10^{-9} sec.

DECAY SCHEME OF $^{22}$Na

$T_{1/2} = 0.35 \times 10^{-9}$ sec.
analyser therefore records the number of events as a function of pulse height which in turn is proportional to the delay between the two selected events. The whole assembly is known as slow-fast coincidence spectrometer.

PERFORMANCE AND TIME CALIBRATION OF THE APPARATUS

The annihilation radiations from Na\textsuperscript{22} were used as a prompt source to calibrate the instrument. The insert in fig. 11 shows the decay scheme\textsuperscript{15} of Na\textsuperscript{22}. As is clear from the decay scheme, Na\textsuperscript{22} decays by positron emission. The positrons when get annihilated emit two simultaneous (prompt) $\gamma$-radiations of 511 keV each. The delayed coincidence spectrum for the prompt radiations from Na\textsuperscript{22} using two NaI (Tl) detectors at a stop delay setting of 10$\mu$sec. is shown in fig.11. The slope of the two sides in this spectrum showing the inherent resolution of the two detectors and the elements of the coincidence circuitry was measured as $T_{\gamma}=3.5\times10^{-10}$ sec. This sets the lower limit of the half-life to be measured with the present apparatus. Known delays with the help of RG/63U (Zo=1250hms, 1.25m $\mu$sec./ft) coaxial cables were inserted in the stop channel of the time-to-pulse height converter. The position of the prompt peak was recorded for different settings of delays and a calibration curve (delay Vs. channel No.) as shown in fig.12 was plotted. The curve was found to be linear over a wide range of delays from 6$\mu$sec. to 110$\mu$ sec. The nonlinearity in the beginning for about 6$\mu$ sec is attributed due to the presence of the inherent delay in the start channel which is first compensated before the effect of the stop pulse
CALIBRATION CURVE OF TIME TO PULSE HEIGHT CONVERTER
FOR DIFFERENT SETTINGS OF GAIN

2.0 CHANNEL / $10^9$ sec.
AMP. GAIN = 2.0

10 CHANNEL / $10^9$ sec.
AMP. GAIN = 1.0

0.4 CHANNEL / $10^9$ sec.
AMP. GAIN = 0.4

0.23 CHANNEL / $10^9$ sec.
AMP. GAIN = 0.2

Fig. No. 12  DELAY IN  m $\mu$ sec.
takes over.

ERRORS IN THE MEASUREMENT OF THE HALF-LIVES

The main sources of systematic errors which may contribute in the measurement of the half-life are the following.

A. Error in the time calibration
B. Error due to the variation in the system gain
C. Error due to the counting statistics
D. Error due to the random coincidences
E. Error due to the scattering of radiations from one scintillator to other.

A. ERROR IN THE TIME CALIBRATION.

Time calibration of the TPH has been made by noting the shift in the centroid of the prompt curve vs. the delay introduced in one of the channel through coaxial cables. The accuracy of the time calibration thus depends on the (a) proper fixing of the centroid and (b) delay time of the coaxial cables.

a) The centroid of the prompt curve was fixed by plotting a smooth curve between counts vs. channel no. Though the total counts in each channel were kept high, the finite channel width of the 20 channel introduces an error of about 3% in the measurement.

b) The delay time of the coaxial cables was estimated by their lengths. The electrical length of these cables had previously been measured using standard radio frequency techniques. It has
been experimentally shown by Fidecaro\textsuperscript{16} that the delay time of these cables varies with the frequency of the pulse. An error of 2\% was therefore assigned to allow for the possibility of the velocity of propagation of the pulses in the coaxial cable being different than \( c \) (the velocity of light), and as well as for the possibility of slight mismatching of the delay cable at its end.

B. ERROR DUE TO THE VARIATION IN THE SYSTEM GAIN.

The variation in the gain of the amplifier following the time-to-pulse height converter may change the time calibration constant. The time calibration was therefore obtained before and after the run on each half-life measurement. Generally running the apparatus continuously for twelve hours showed a variation of 1\% in calibration constant.

C. ERROR DUE TO THE COUNTING STATISTICS.

The counting statistics of the delay curve introduced the principal source of error. The measurements were made for more than twelve hours in each case to have a better statistics. This, however, introduced a standard deviation in the half-life measurement which varied from 3\% to 6\% depending on the intensity of the radiation feeding to the level concerned.

D. ERROR DUE TO THE RANDOM COINCIDENCES.

In many of the cases, the large background of the unwanted radiations present in the source produced a considerable number of random coincidences. These coincidences
which spread uniformly in all the channels tend to broaden the base part (where the counting rate is small) of the delayed curve. These random coincidences were obtained by shifting the bias of the multi-channel analyser to a high value (approximately 10 times the half-life of the level concerned), where no real count may be registered. This background which causes a systematic error of usually 2½% was subtracted from the final run of the half-life.

E. ERROR DUE TO THE SCATTERING OF RADIATIONS FROM ONE SCINTILLATOR TO THE OTHER.

The scattering of the radiations from one scintillator to the other will produce the prompt coincidences which may reduce the apparent lifetime. The contribution due to these prompt radiations was reduced to minimum by putting the appropriate absorbers before each counter so that the radiation detected in one of the counter may not reach the other. Secondly since the half-life was measured from the slope of the middle portion of the delayed curve, the error introduced due to this factor was less than 0.5%. 
REFERENCES

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6. A.H. Wapstra, G.J. Nijgh, and R.V. Lienhout, Nuclear Spectroscopy Table, p. 131
CHAPTER III
THE TIME RESOLUTION IN SCINTILLATION SPECTROMETER

THEORETICAL ANALYSIS

The basic processes which result in the detection of a nuclear event in a scintillation spectrometer and contribute to the timing uncertainties are mainly of the following type.

DECAY TIME OF THE PHOSPHOR.

A nuclear event entering the phosphor interacts with the scintillator and excites the optically active states. The decay of these states give rise to light photons, which are not prompt but there exists a probability distribution for the small time interval which elapses between the initial exciting event and the emission of light photons. The decay of these excited states follow an exponential law and the resulting decay constants are different for different phosphors. The light photons produced by the scintillator are subsequently collected by the cathode of the photomultiplier tube and the resulting photoelectrons are multiplied in the succeeding multiplication stages. The whole process introduces a random time delay which sets a limit to the measurement of the minimum time. Post and Schiff have shown that the variance (V) in the time of production of the qth photoelectron is given by

\[ V(q) = \frac{q^2}{R} \left[ 1 + \frac{2(q+1)}{R} \right] + \text{higher order term in } \frac{1}{\sqrt{R}} \]
If \( Q \) is designated as the average number of photoelectrons that would be produced in a time equal to the average rise time of the output pulse, then the variance in the time of response of the system to the pulse may be assumed to be equal to the arithmetic mean of the variances associated individually with the first \( Q \) electrons, which is given by

\[
V_{av} (Q) = \frac{QR^2}{2RT^2} \left\{ 1 + \frac{1}{Q} + \frac{Q}{2RT} \right\}
\]

(3.2)

where \( T \) is the mean life of the light flash from the phosphor and \( R \) is the total number of photoelectrons produced by the passage of the event through the phosphor, which is proportional to the energy of the detected particle. It is evident from the above expression that the decay time \( T \) of the phosphor should be as small as possible so as to have the minimum time jitter.

**SPREAD OF TRANSIT-TIME IN THE PHOTOMULTIPLIER.**

Statistical fluctuations in the transit-time between the various dynodes of a photomultiplier tube during the formation of the electronic cascade produce another source of timing uncertainty. This effect however has little importance in deciding the resolving time with the phosphors having long decay time constant (e.g. NaI), but it may increase the minimum possible resolving time when faster phosphors like plastic and stilbene are used. Colombo et al.\(^6\) have considered this problem in detail and have shown that the shape of the
The electronic cascade resulting from the photomultiplier due to a single photo-electron arising at the photo cathode has the form

\[ f(t) = \left( \frac{1}{\lambda} \right) e^{\left( -\frac{t}{\lambda} \right)t} - e^{\left( -\frac{t}{\lambda} \right)t} \]  

(3.3)

where \( \lambda = (n-1)^{\frac{1}{2}} t_{dd} \), \( n \) is the number of dynodes and \( t_{dd} \) the r.m.s. variation in the transit-time of electrons between successive dynodes.

On the basis of the hypothesis of constant illumination \( (R/I) \) and zero width of \( f(t)(\lambda = 0) \), the apparent total r.m.s. variance in pulse time due to statistics of photoelectron emission, fluctuations in gain and fluctuations in the average transit-time is given by

\[ V(t) = \frac{1}{3} \frac{t_{cd}^2}{R^2} (1+a^2) + \frac{t_{ph}^2}{q} \]  

(3.4)

where \( a^2 \) is the variation in photomultiplier amplification \( (1/g-1, g \) being the multiplication per stage), and \( t_{ph} \) is the total variation in photomultiplier transit-time which is the sum of the time variation from cathode to first dynode \( t_{cd}^2 \) and interdynode transit-time \( t_{dd}^2 \) so that

\[ t_{ph}^2 = t_{cd}^2 + t_{dd}^2/g-1 \]  

(3.5)

The equation (3.4) may be utilized for calculating the value of \( q \) corresponding to minimum dispersion in time.
by putting $\frac{dV(q)}{dq} = 0$. The derivation yields

$$\frac{q}{R} = \left[\frac{3t_{ph}}{T(1+a^2)}\right]^{\frac{1}{2}} \quad (3.6)$$

and thus the minimum of the apparent variance is given by

$$V_{\min}(q) = \left[\frac{4}{3} (1+a^2)\right]^{\frac{1}{2}} \times \frac{T}{R} t_{ph} \quad (3.7)$$

For a coincidence system using two photomultipliers, the variance of the time response curve will be $2V$, and the width at half-maximum of this curve will be given by

$$W_v = 2.36 \ (2V)^{\frac{1}{2}} \quad (3.8)$$

Using equation (3.7), the minimum resolution (width at the half-maximum) of the delayed coincidence curve is given by

$$W_v(\text{min}) = 2.36 \times 2^{\frac{1}{2}} \times \left[\frac{4}{3} (1+a^2)\right]^{\frac{1}{2}} \times \left[\frac{T}{R} t_{ph}\right]^{\frac{1}{2}}$$

$$= 3.6 (1+a^2)^{\frac{1}{2}} \left[\frac{T}{R} t_{ph}\right]^{\frac{1}{2}} \quad (3.9)$$

If we consider the variation in the gain of the photomultiplier to be within 10% then we have to a good approximation:

$$W_v(\text{min}) = 4 \left[\frac{T}{R} t_{ph}\right]^{\frac{1}{2}} = 4 \left[\frac{T}{R} t_{ph}\right]^{\frac{1}{2}} \cdot E^{-\frac{1}{2}} \quad (3.10)$$
where $N(E)$ is the number of photoelectrons released per MeV of electron energy absorbed in the phosphor.

The equation (3.10) indicates that the total variation in the arrival time of $Q$ photoelectrons, which are necessary to trigger the associated electronic circuitry, depends mainly on $T$ (decay time of phosphor), $a$ (fluctuations in the photomultiplier gain) and $t_{ph}$ (fluctuations in the average transient time), which should be kept minimum for better time resolution.

WALK IN THE OUTPUT PULSE.

If a minimum number of $Q$ photo-electrons are required to trigger the associated electronic circuitry, then in addition to the statistical fluctuations in the arrival time of the $Q$ photo-electrons as mentioned above, one has also to consider the uncertainty in the arrival of the centroid of the pulse due to these $Q$ photo-electrons at the anode. The arrival time $t_{av}$ of the centroid of the pulse due to $Q$ photoelectrons is given as:

$$ t_{av} = \frac{(Q+1)}{2} \frac{T}{R} $$

(3.11)

and therefore the uncertainty in the arrival of the centroid at the anode $dt_{av}$, called as the "walk" in the output pulse is given by:

$$ dt_{av} = \frac{(Q+1)}{2} \frac{T}{R} \frac{dR}{R} $$

(3.12)
From the above expression, it is evident that the walk of the output pulse \( \Delta t_{av} \) which introduces some uncertainty in the time resolution, may be controlled by limiting the value of \( dR \) which is usually done by selecting a limited amplitude band for the accepted pulses by means of a slow side channel, consisting of a single channel pulse height analyser. The so-called slow-fast coincidence circuitry is therefore used to yield the best timing resolution.

RESPONSE OF NaI AND PLASTIC PHOSPHORS.

It is evident from the above discussions that the limit on the measurement of minimum time with the scintillation technique depends strongly on the characteristics of the phosphor, particularly on its efficiency for light conversion and its decay time. The NaI (Tl) crystals are most suitable for the detection of \( \gamma \)-rays, since they have better energy resolution due to their high atomic mass and large light output per electron volt of the incident energy, but the time resolution obtained from these crystals is comparatively poorer because of their long decay time. The plastic phosphor on the other hand contribute the minimum time uncertainty because of their fast response but the probability for the selection of a particular event is impaired.

In the present work a proper choice between NaI (Tl), entrance and plastic scintillators has been made depending on the decay scheme of the source and the energies involved in the transitions pertaining to the level whose half-life is to be measured.
EXPERIMENTAL ANALYSIS

The effect of various factors on time resolution, which was noted experimentally has been discussed below.

START AND STOP BIASES.

The proper biases of the fast discriminators in the start and stop channel were of importance in determining the time jitter and therefore the overall time resolution. The prompt curve was obtained by fixing the stop and start biases to values so as to just exclude the major noise part. The repetition of the same experiment under the different settings of start bias showed that the resolution was maximum when the bias on the start side was one or two volts above the value needed to cut the major noise part. This value of the bias corresponded to the situation where nearly whole of the noise was cut-off. The resolution, however, was found to decrease considerably for higher start biases. In the other experiment the start bias was kept for best resolution while the stop bias was increased from its minimum value and it was found that increase of the stop bias decreases the resolution. The above observations suggest that a little noise in the stop channel do not effect the resolution while the same in start channel has a considerable effect. The appropriate biases in the two channels were therefore carefully selected to get the best resolution.
HIGH VOLTAGE TO THE PHOTOMULTIPLIER.

Kane et al., using Amperex type 56AVP photomultiplier tubes have pointed out that the time resolution is dependent on the voltage to the photomultipliers. We, therefore, investigated the effect of the high voltage on the time resolution in the case of 6810A photomultiplier tubes. The crystals used on both the sides were NaI (Tl) of identical sizes. The voltages to the two photomultipliers were varied from 1200 to 2500 volt in a step of 100 volt and the start and stop biases were changed for every step so as to get the best resolution as discussed in the preceding paragraph. The resolution was found to increase with the increase of the voltage upto 2200 volt. For the voltage more than 2200 volt and less than 2400 volt (2200 ≤ V ≤ 2400), there was practically no change in the resolution for 511 keV (corresponding to prompt radiation from Na$^{22}$) radiation, however, the resolution for low energies (E ≤ 100 keV) was definitely better in this region. Beyond 2400 volt the resolution gets poorer for high as well as for low energies.

ENERGY OF THE EVENT.

According to the theoretical estimates of Post and Schiff the energy of the event expended in the crystal is an important factor to decide about the minimum resolving time. The effect of the Energy parameter was therefore investigated experimentally in detail. The NaI (Tl) crystals of size 1" thick x 1" die were mounted on the two photomultipliers and
CURVE SHOWING THE LINEAR ENERGY RESPONSE OF SCINTILLATION SPECTROMETER WITH NaI(TL) CRYSTAL

Fig. No: 3  
ENERGY IN KeV

CURVE SHOWING THE VARIATION OF PULSE HEIGHT RESOLUTION WITH ENERGY IN NaI(TL) CRYSTAL

Fig. No: 4  
100/ENERGY IN KeV
A Na\(^{22}\) source was evenly placed between them. The peaks corresponding to 511 keV annihilation quanta were selected in the two side channels, and a delayed coincidence spectra on the multichannel was recorded. The experiment was repeated for various biases in the slow channels corresponding to different energies and the resolution was noted for each case. A graph showing the resolution vs. energy is shown in fig. 13, which clearly indicates that higher the energy better is the resolution.

The theoretical curves showing the minimum resolving time for various energies in the NaI(Tl) and plastic phosphors are shown for comparison. The curves were obtained by using equation (3.10). The \(\tau_{ph}\) (r.m.s. dispersion in photomultiplier transit-time) for 6810A was taken to be \(1.2 \times 10^{-9}\) m \(\mu\)Sec.\(^{11}\) and \(T\) (phosphor decay time) for NaI and plastic phosphor was put equal to 250 m \(\mu\)Sec and 3 m \(\mu\)Sec. respectively. The value of \(R(E)\), the number of photoelectrons released per MeV of electron energy absorbed in the phosphor have been calculated from the value of 56 ev per photon, which Wright\(^{12}\) has measured for the scintillation efficiency of a 1 cm\(^3\) crystal of anthracene. If we assume 50 percent efficiency for the transmittal of the emitted photons from the phosphor to the photo surface of the photomultiplier, then the 6810A photomultiplier which has the photocathode quantum efficiency of 11 percent (equivalent to photocathode sensitivity of 50 \(\mu\)amp per lumen) will release \(10^6\) photoelectrons per MeV of the energy absorbed in the anthracene.
EXPERIMENTAL CURVES SHOWING THE VARIATION OF TIME RESOLUTION WITH ENERGY FOR

- • NaI (TL)
- ○ PLASTIC

Fig. No 14 ELECTRON ENERGY EXPENDED IN PHOSPHOR (KeV)
phosphor. The value of $R'(E)$ was calculated for NaI(Tl) and plastic crystal to be equal to $2 \times 10^6$ electrons/Mev and $0.3 \times 10^6$ electrons/Mev respectively, since the relative pulse height amplitude with respect to anthracene is $\sim 2$ for NaI(Tl) and $\sim 0.3$ for plastic scintillator.

**EFFECT OF PHOSPHORS.**

The effect of the phosphor on the resolution was investigated by using plastic and NaI (Tl) crystals of similar sizes. Plastic crystal of 1" dia x 1/4" thickness were mounted in the manner described in Chapter II. The resolution was determined for different energies by using the various biases in the slow channel as described above. Since most of the organic phosphors unlike the NaI (Tl) show non-linearity below 100 keV, it was not possible to set up the bias in the slow channel corresponding to a particular energy below this limit. Different sources were, therefore, used to estimate the resolving time in this region. The results are plotted in fig.14 and are compared with the parallel results for NaI (Tl) crystals of similar sizes. It is evident from the curves that the phosphor plays a little role in determining the resolution for the high energy events but it has considerable importance in deciding the resolution at low energies. For energies lower than 50 KeV, the resolution (width at the half-maximum) in the case of NaI (Tl) crystals is worse than 14m $\mu$ Sec., while with the plastic crystals the same is about 6m $\mu$ sec. It is also
noted from the experimental curves that the resolution in
the two crystals decreases linearly (when plotted on logarithmic
scale) with energy till a constant value (3μ-sec.) is reached,
beyond which there is no change. The result is attributed to
the fact that at low energies, since the time jitter introduced
by the phosphors is large than the elements of electronic
circuitry, the resolution is decided mainly by the phosphors
and thus it decreases linearly consistent with the theoretical
curves. At higher energies, the jitter introduced by the
crystals is less compared to the jitter introduced by the
electronic circuitry (fast discriminator and T.P.H.), the
overall time resolution is therefore determined mainly by the
circuitry. Hence, the observed resolution at higher energies
remains unchanged, the constant value being the minimum
resolution of the circuitry.

The size of the phosphors was also found to effect
the resolution. A NaI (Tl) crystal of 1" diameter had the
resolution better by a factor of two in comparison with a
crystal of 1.5" diameter. This effect was noticed with both
NaI(Tl) and plastic phosphors and therefore, was attributed
mainly to the time jitter introduced by the cathode area of
the photomultiplier.

SLOW CHANNEL WIDTH.

The window width in the slow channel which selects
a particular energy width had some systematic effect on the
resolution. The Rh-103 (538 keV prompt level) for
\[ \beta - \gamma \text{ coincidences and Na}^{22} \text{ for } \gamma - \gamma \text{ coincidences were used to observe the effect of window width on resolution. The side channel window width was varied from 10\% to 40\% and the effective change in the resolution was noted. It was found that the resolution becomes poor by 20\% with the change in channel width from 10\% to 40\% when the two crystals used were NaI (Tl). The further decreasing of the channel width to values of 5\% or less does not improve the resolution since it affects the stability due to low counting rate. It was also noticed that in the case of } \gamma - \gamma \text{ coincidences the window width in the lower energy side and in the } \beta - \gamma \text{ coincidences the window width in the } \beta \text{-spectrum side had the predominant effect on the resolution. In the actual half-life measurements, a compromise was therefore made in the selection of the channelwidth so that maximum stability, best signal to background ratio and minimum walk in the output pulse was achieved.} \\

\text{SOURCE STRENGTH.} \\

The source strength was found to have a noticeable effect on resolution, when the total pulses in the start channel exceed 1000 counts/sec. However, in the stop channel still higher counting rate was tolerated without affecting the resolution. In this context the following two points are important to consider. Firstly the case may be such that only say 5\% of the events are of use and remaining 95\% may be superfluous (due to other } \gamma \text{-rays present in the source which are not feeding the level concerned). In that case an increase in the strength of the source mainly increases the chance to}
true coincidence ratio\textsuperscript{14} and therefore worsens the resolution. Secondly all the \textit{95\%} unwanted radiations and a good percentage of the \textit{5\%} wanted radiations do not find the cancelling pulse resulting in large output pulses from the T.P.H. These large pulses when fed to the amplifier result in its poor performance which affect the resolution.

Since the measurement of half-life with the present technique requires a source of sufficient strength to get the reasonable counts for better statistics within a specified time, a suitable source strength was therefore selected considering the intensities of the radiations involved in the decay. Further, since the counting rate in the stop channel has little effect on resolution, provision was made to exclude most of the unwanted pulses from the start channel by putting appropriate absorbers between source and the detector.
REFERENCES


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10. J.V. Kane, R.E. Pixley, R.B. Schwartz and A. Schwarzschild, Phys. Rev. 120, (1960) 162


Fig. No. 15  BLOCK DIAGRAM OF SLOW FAST COINCIDENCE CIRCUIT
CHAPTER IV

MEASUREMENTS

The block diagram of the equipment assembled for the present work has been shown in fig. 15. For the measurement of the half-life of an excited state, two radiations are selected, one which terminates on the level (whose half-life has to be measured) and the other through which the level decays. The method extensively used for the measurements has been the delayed coincidence technique. The pulses from the anode of each photomultiplier pass through a limiter and are then fed to start and stop channels of the time-to-pulse height converter. The energy selection of the two radiations is accomplished by taking the outputs from the tenth dynode of the two photomultipliers. The outputs so obtained are fed to the cathode followers, linear amplifiers and to the single channel pulse height analysers, where the energy of the particular event is selected. The output pulses of the two pulse height analysers are fed to the slow-coincidence circuit and the coincident pulse is used to gate the 20-channel pulse height analyser on which the spectrum from the time-to-pulse-height converter after amplification is displayed. The half-life is calculated from the logarithmic slope of the delayed coincidence curve. Each run of the half-life measurement is followed by a prompt spectrum with the biases in the slow channel left unchanged so as to ensure that the actual half-life curve is not merely instrumental. The error shown in each point in the half-life curve is only due to counting statistics, whereas
the errors assigned to the measured half-lives are the statistical errors plus the errors from other sources as described in Chapter II.
SINGLES SPECTRUM OF $^{129}$Te IN ANTHRACENE CRYSTAL

COUNTS

0 100 200 300 400 500

PULSE HEIGHT

0 4 8 12 16 20 24 28

4.75 KeV

7.20 KeV

SINGLES SPECTRUM OF $^{129m}$Te IN NaI CRYSTAL

COUNTS

0 10 20 30 40 50

PULSE HEIGHT (VOLTS)

0 16 32 48 64 72

Fig. No. 16

210 KeV

4.75 KeV PEAK
THE 27 keV LEVEL IN I\textsuperscript{129}

SOURCE PREPARATION.

The radio-isotope Te\textsuperscript{129m} was used to measure the half-life of the 27 keV level of I\textsuperscript{129}. The source of Te\textsuperscript{129m} was obtained as a fission product in the swimming pool reactor at Trombay. The Te\textsuperscript{129} activity was extracted out from the other competitive fission products as a result of varied chemical separations. A 0.5 \mu cur. sample of the source was dried up in a perspex envelope of size 2 m.m. x 2 m.m. in the manner described in Chapter II.

SINGLES SPECTRUM.

Fig. 16 shows the energy spectrum of \gamma-rays in NaI crystal of size 2.5cm dia x 1.3cm thickness at a higher gain, so that 27 keV \gamma-ray is well resolved. At a lower gain setting the existence of \gamma-rays at 475, 720 and 1140 was also detected. The intensities of the various \gamma-rays were found to be in rough agreement with the measurements of Graves and Mitchell.\textsuperscript{1} The insert in fig. 16 represents the pulse height distribution of the source in anthracene crystal of size 3.7cm dia x 0.5cm thickness. The 475 and 720 keV \gamma-rays show their well separated Compton edges. The increase in counting rate at lower bias is due to low energy \gamma-rays accompanied with noise.

DELAYED COINCIDENCE.

For the measurement of the half-life of 27 keV level the single channel in NaI (Tl) side was set at 6 volt bias
DELAYED COINCIDENCE SPECTRUM OF THE 27KeV LEVEL OF $^{129}\text{Tc}$

CALIBRATION: 0.23 CHANNEL/$10^5$ sec.

$T_{1/2} = 1.59 \times 10^8$ sec.

DECAY SCHEME OF $^{129}\text{Tc}$
corresponding to the photopeak of 27 keV \( \gamma \)-ray. The bias in anthracene side was adjusted at 12 volt with channel width increased to 3 volt so as to accept the Compton edge corresponding to 475 keV \( \gamma \)-rays. The anode pulses from the anthracene counter were fed to the start channel, while the anode pulses from NaI(Tl) counter were fed to the stop channel. Both the crystals were mounted in aluminium cans, the thicknesses of which were kept sufficient to avoid the detection of \( \beta \)-particles arising from the disintegration of Te\(^{129m}\) and its daughter I\(^{129}\). The anthracene crystal was further covered with 0.7 g/cm\(^2\) of lead to exclude unwanted x-rays and 27 keV \( \gamma \)-rays. The lead covering also reduced the recording of the false prompt coincidences produced due to the back scattered events from the anthracene and detected in NaI (Tl) counter. The slow coincidence rate of 7 counts/min was observed with the above adjustments. The delayed coincidence curve obtained after 12 hours of counting is shown in fig.17. The half-life of the level calculated from the logarithmic slop of the curve was found to be

\[
T_1 = 1.59 \times 10^{-3} \text{ Sec.}
\]

The prompt coincidences were recorded by replacing the actual source with Na\(^{22}\). The biases in the slow channel were left unchanged. The slop of the prompt curve was found to be rather poor (being equal to 8m \( \mu \)-sec.), which was largely due to the detection of low energy \( \gamma \)-rays in the slow-decaying NaI (Tl) crystal. The use of NaI (Tl) was unavoidable, since the pulses
produced for 27 keV $\gamma$-rays in organic phosphor (anthracene and plastic) were too low to be discriminated from the photomultiplier noise. The use of NaI however, does not effect the delayed spectrum of $^{129m}$Te, since the resolution has been still much less than the measured half-life.
THE 57 keV LEVEL IN Pr$^{143}$

SOURCE PREPARATION.

The half-life of the 57 keV level of Pr$^{143}$ was determined by using the Ce$^{143}$ source. The active Ce$^{143}$ was prepared by irradiating the spectroscopically pure cerium oxide enriched in Ce$^{142}$ to thermal neutrons in the "Apsra reactor" Trombay. The Ce$^{143}$ so obtained was found to have about 15% contamination of Ce$^{141}$. A 0.1 μCur. sample of the source in the form of cerous chloride in dilute hydrochloric acid was prepared in the perspex container having a cavity of 4mm x 4mm.

SINGLES SPECTRUM.

The pulse height spectra of Ce$^{143}$ was studied with NaI (Tl) crystal of size 2.5cm dia x 3.0cm thickness A typical spectrum of γ-rays is shown in fig. 18. The existence of γ-rays at 57, 142, 231, 294, 668, 724, 860 and 1065 keV was found to be nearly consistent with the decay scheme proposed by Martin et al. In addition to these γ-rays the presence of a new γ-ray at about 1.40 MeV was detected which was not reported in earlier work. The peak of the new γ-ray was found to decay with 33-hr half-life which shows that this γ-ray belongs to the decay of Ce$^{143}$ and not due to any impurity present in the source.

DELAYED COINCIDENCE.

For the measurement of the half-life of the 57 keV level,
DELAYED COINCIDENCE SPECTRUM OF THE 57keV LEVEL IN Pr$^{143}$
BOTH THE CRYSTALS ARE NaI(TL)

CALIBRATION: 0.4 CHANNEL/10$^{-9}$ sec.

$T_1/2 = 5.8 \times 10^{-9}$ sec.

DELAYED SPECTRUM WITH PROMT SOURCE

CALIBRATION: 0.4 CHANNEL/10$^{-9}$ sec.

$T_1/2 = 3.6 \times 10^{-9}$ sec.
the delayed coincidences were recorded between 294 keV and 57 keV $\gamma$-rays. In the first attempt two identical NaI(Tl) crystals of sizes 2.5cm x 3.0cm thick were used. Both the crystals were covered with 800mg/cm$^2$ of aluminium so that most of the $\beta$-rays were absorbed. One of the crystal feeding the start pulses had an extra shielding of 0.29 gm/cm$^2$ of lead and 1.1gm/cm$^2$ of cadmium to exclude most of the Pr$^{143}$ X-rays and $\gamma$-rays upto 60 keV. Slow channel bias on this side was fixed at 8 volt, corresponding to the photo peak of 294 keV $\gamma$-rays while the slow channel bias on the stop side was fixed at 6 volt, where the contribution due to X-rays becomes negligible as is evident from the shape of the coincidence curve, shown in the insert of fig. 18. Delayed coincidence spectrum under the above conditions is shown in fig. 19. The half-life calculated from the right hand side of the curve is $T_\gamma = 5.8 \times 10^{-9}$ sec.

The prompt spectrum taken under the same conditions is also shown in the insert of fig. 19. The slope of the right hand side of the prompt curve corresponds to 3.5m $\mu$sec, but with poor statistics which leaves a doubt on the measured half-life.

The experiment was thus repeated by replacing one of the NaI (Tl) crystal by a plastic scintillator of 2.5cm dia x 3cm thick for the detection of low energy $\gamma$-rays. Both crystals were mounted in aluminium cans of 90mg/cm$^2$ thicknesses so as to absorb $\beta$-rays upto about 300 keV. The NaI (Tl) crystal was further covered with 0.29g/cm$^2$ thick lead and 1.1g/cm$^2$
of cadmium as in the previous adjustment, to exclude X-rays and γ-rays up to about 60 keV in the start channel. The singles spectrum of γ-rays in plastic crystal is shown in fig. 20. The arrows indicating the energies were placed in accordance with Ca\(^{137}\) calibration. The single channel bias on the start side, corresponding to the photopeak of 294 keV was left unchanged while the proper bias in the plastic scintillator was selected by observing the slow-coincidences with 294 keV γ-rays. The coincidence spectrum is shown in the insert of fig. 20. The slow channel bias was fixed at 1.5 volt where the number of undesirable coincidences due to X-rays and photomultiplier noise had been reduced by an appreciable amount. The delayed coincidence curve was obtained for two different values of source strengths which were in the ratio of 1:2. The half-life was calculated from the logarithmic slope of the delayed coincidence curve and was found to be constant for the two source strengths. One of the curve is shown in fig. 21 which gives the half-life for the 57 keV level of Pr\(^{143}\) to be

\[ T_1 = 5.8 \times 10^{-9} \text{ sec.} \]

For comparison, the prompt curve with the same counter biases as the delayed coincidence curve is plotted on the same scale. The slope of the prompt curve in this case was about 0.8 n.sec. and the centroid of the delayed coincidence curve was found to be shifted from the prompt curve by just one mean life. The proper centroid shift was interpreted as a further check on the measured half-life.
DELAYED COINCIDENCE SPECTRUM OF THE 57 keV LEVEL OF Pr^{143}

CRYSTALS USED: NaI (TL) PLASTIC

CALIBRATION: 0.4 CHANNEL 10^3 SEC.

Ce^{143} (33h)

\[ T_\frac{1}{2} = 5.8 \times 10^3 \text{ sec.} \]
THE 361 keV LEVEL IN Pr\textsuperscript{143}

DELEYED COINCIDENCE.

The half-life of the 361 keV level of Pr\textsuperscript{143} was determined by observing the delayed coincidences between the $\beta$-rays from Ce\textsuperscript{143} leading to the 361 keV level in Pr\textsuperscript{143} and the 294 keV gamma-rays from the de-excitation of the level. The crystals used on the two sides were plastic and NaI (Tl) respectively. The slope of the delayed coincidence curve due to actual half-life comes to be compatible with the slope of the prompt curve and hence only as the upper limit of the half-life of the level is given as

$$T_H = 1.0 \times 10^{-9} \text{ Sec.}$$
THE 142 keV LEVEL IN Pr$^{141}$

SOURCE PREPARATION.

The Ce$^{141}$ was produced by irradiating the spectroscopically pure cerium oxide to thermal neutrons for about four months. The source thus produced was allowed to decay for more than a month so that the activities due to Ce$^{143}$ and its daughter Pr$^{143}$ subside completely. Few drops of the cerous chloride solution in dilute hydrochloric acid were evaporated uniformly in a small cavity drilled in an aluminium disc. The backing of the source had been a 3 mg/cm$^2$ thin sheet of aluminium. The source was attached to the face of the anthracene scintillator with the help of the cellulose tape.

SINGLES SPECTRUM.

The $\gamma$-ray energy spectrum of the source in the NaI (Tl) crystal of size 2.6 cm dia x 1.3 cm thick is shown in fig. 22. The spectrum clearly indicates the peaks at 7 volt and 28 volt corresponding to 36 keV (KX-ray) and 142 keV $\gamma$-ray. The insert in fig. 22 shows the $\beta$-spectrum of the source in anthracene crystal of size 3.7 cm dia x 0.4 cm thick. The anthracene crystal was covered with 3 mg/cm$^2$ of aluminium foil for lightshielding. The $\beta$-spectrum extends up to 20 volt corresponding to the maximum $\beta$-ray energy of 581 keV. A small peak at 5 volt represents the contribution due to 142 keV conversion electrons.

CONVERSION COEFFICIENT OF THE 142 keV TRANSITION.

The conversion coefficient of the 142 keV $\gamma$-ray has
been measured by various investigators.

Freedman and Engelkemeir\textsuperscript{3} reported the conversion coefficient of this level to be equal to 0.25, while S. Johansson\textsuperscript{4} predicted the same to be about 0.48. A more recent measurement by J.H. Cook\textsuperscript{5} has given a value \( k = 0.405 \pm 0.01 \). The present experiment was carried out to resolve the existing discrepancies.

The expression used for the calculations has been the following

\[
\lambda_k = \frac{A_y (1 + k_y)}{A_x} \cdot \frac{R_x}{A_y} \cdot \frac{E_x}{E_y} \cdot \frac{D_x}{D_y} \cdot \frac{1}{W_k}
\]

The numerical values of the various quantities in the above expression were derived by using the experimental curve (Fig. 22) and the theoretical tables. The values are given below.

- **Rx**, The observed ratio of area under photopeak to total area of the 141 keV scintillation spectrum = 0.923
- **Ry**, The ratio of area under the photopeak to the total area of the 36 keV scintillation spectrum = 1.0
- **Ax**, The observed area under \( \gamma \)-ray photopeak = 34
- **Ay**, The observed area under x-ray photopeak = 21
- **Ky**, The theoretical fraction of the k x-rays of iodine excited by 36 keV X-rays which escaped from the crystal expressed in terms of number which does not escape = 0.29
- **Ex**, The theoretical efficiency of the crystal to 142 keV \( \gamma \)-rays = 0.96
- **Ey**, The theoretical efficiency of the crystal to 36 keV X-rays = 1.00
- **Dx**, The calculated fractional reduction of the 142 keV r-rays in the 0.08 cm (1/8") thick Al can + 0.16 cm MgO Powder = 0.965
DELAYED COINCIDENCE SPECTRUM OF THE 142 keV LEVEL OF Pr$^{141}$

CALIBRATION: 1$^{\text{st}}$ CHANNEL/$10^3$ sec.

DECAY SCHEME OF Ce$^{141}$

Ce$^{141}$ (43 d)

7/2

30% 70%

7/2 +

5/2 +

Pr$^{141}$

$T_2^1 = 1.9 \times 10^{-9}$ sec

Fig. no. 23

CHANNEL NO.
The calculated fractional reduction of the 36 keV k x-ray in the .08cm (\(\frac{1}{32}\) in) thick Al can +0.16cm MgO Powder =0.855

Wy, The fluorescent yield of Pr\(^{141}\) atom (\(Z = 59\)) = .91

The above values, when substituted in equation \((1)\) give

\[ \lambda_k = (0.37 \pm 0.03) \]

The present value is compatible with the recent measurements\(^{5-6}\)

DELAYED COINCIDENCE

The half-life of the 142 keV level was measured by delayed \(\beta-\gamma\) coincidences. The beta particles were detected in anthracene crystal and the slow channel bias on this side was set at 10 volt corresponding to 300 keV \(\beta\)-particles, so that the pulses due to conversion electrons were completely excluded. NaI crystal was used on the other side to provide the stop pulses corresponding to the photopeak of 142 keV \(\gamma\)-rays. With 10% wide channel widths on both the sides the slow coincidence rate had been 5.2 counts/min. The delayed coincidence spectrum is shown in fig. 23 which corresponds to a half-life.

\[ T_\\gamma = 1.9 \times 10^{-9} \text{ Sec.} \]
Bd$^{131}$
SINGLES SPECTRUM IN NaI(TL) CRYSTAL

PULSE HEIGHT (VOLTS)

COUNT

Fig No 24

PULSE HEIGHT (VOLTS)
THE 122 KEV LEVEL IN $^{131}$Cs

SOURCE PREPARATION.

A sufficient amount of spectroscopically pure Barium in the form of barium carbonate was irradiated in the thermal neutron column of the swimming pool reactor at Trombay for a period of more than a month. The irradiated sample was processed chemically and the $^{131}$Cs activity (produced as a decay product of $^{131}$Ba) was removed. The source was obtained as barium chloride in dilute hydrochloric acid. About 0.5 µcur. of the solution was evaporated in a perspex envelope of 4 mm x 4 mm.

SINGLES SPECTRUM.

The pulse height distribution of γ-rays from $^{131}$Ba in a 2.5 cm dia x 3 cm thickness crystal is shown in fig. 24. The spectrum shows the presence of γ-rays at 122, 214, 372, 496, 618, 820, 912 and 1034 keV which is nearly consistent with the decay scheme proposed by Beggs et al. The differential pulse height spectrum of $^{131}$Ba in plastic crystal of 2.5 cm dia x 2.5 cm thick is shown in the insert of fig. 24.

DELAYED COINCIDENCE.

For the measurement of the half-life of 122 keV level, NaI (Tl) and plastic crystals were used. The pulses from the NaI (Tl) crystal corresponding to the 496 keV photopeak (slow-channel bias at 38 volt) were fed to the start channel while
DELAYED COINCIDENCE SPECTRUM OF THE 122KeV LEVEL OF Cs\textsuperscript{131}

CALIBRATION: 0.6 CHANNEL / 10\textsuperscript{-9} sec.

\textsuperscript{Ba}\textsuperscript{131}(11.5 d)

DECAY SCHEME OF \textsuperscript{Ba}\textsuperscript{131}

T\textsubscript{1/2} = 4.1 \times 10\textsuperscript{9} sec
the pulses from the plastic crystal corresponding to 122 keV γ-rays were fed to the stop channel. Lead shield of 2.0 gm/cm² and cadmium shield of 1.1 gm/cm² were used between the source and the NaI (TI) crystal to prevent the detection of γ-rays up to 214 keV in the start channel. A typical delayed coincidence spectrum obtained as a result of several runs is shown in fig. 25. The slope of the curve yields the half-life of 122 keV level of Cs¹³¹ to be

\[ T_\frac{1}{2} = 4.1 \times 10^{-9} \text{ Sec.} \]

The tail of the curve shows the presence of some longer half-life component as predicted by Bodenstadt et al., but the evidence is merely speculative because of the low counting statistics.

**THE 214 keV LEVEL OF Cs¹³¹**

**SLOW COINCIDENCE.**

For the measurement of the half-life of 214 keV level the source strength was increased to 2 μ cur. and a separate run on slow coincidences was made, using two NaI (TI) crystals of sizes 2.6 cm dia x 2.5 cm thick and 3.8 cm dia x 3.8 cm thick. The single channel on one side was fixed at the peak of 214 keV γ-ray (bias at 15 volt) while the other channel scanned the energy region between 400 to 1050 keV. The peaks were observed at 489 and 820 keV indicating the presence of 489-214 and 820-214 keV γ-ray cascades as reported by August et al.
DELA YED COINCIDENCE.

While taking the delayed coincidences, the large crystal was covered with 2.0gm/cm² of lead and 1.1gm/cm² of cadmium to prevent the detection of γ-rays up to 214 keV as in the previous case, but the single channel was used as a discriminator to accept all the pulses above 600 keV. The single channel on the stop side was set at 16 volt corresponding to the 214 keV γ-ray peak. With this adjustment the coincidence counts due to strong 499-122 γ-ray cascade were completely excluded. The average slow coincidence rate had been approximately 3 counts/min. The time spectrum taken for more than 12 hours yielded an upper limit to the half-life i.e.

\[ T_\frac{1}{2} \gtrsim 5.0 \times 10^{-10} \text{ Sec.} \]
Fig. No. 26

Ba$^{133}$
SINGLES SPECTRUM IN ANTHRACENE

Counts (arbitrary scale)

Counts

Pulse Height (volts)

K X-RAY

81 KeV

80 KeV

355 KeV

Ba$^{133}$
SINGLES SPECTRUM IN NaI(TL)

355 KeV
THE 80 keV LEVEL OF $^{133}$Cs

SOURCE PREPARATION.

For the measurement of 80 keV level of $^{133}$Cs, the source of $^{133}$Ba was procured from The Radio Chemical Centre, Amersham, Buckinghamshire. A 0.1 $\mu$Ci sample of the source was prepared in the perspex cell of size 2 mm x 2 mm. The sample thus prepared was mounted evenly in the centre of the two counters.

SINGLES SPECTRUM.

The $\gamma$-ray spectrum of the source in NaI (Tl) crystal of size 2.5cm dia x 1.3cm thick is shown in fig. 26. The photopeaks corresponding to 32 (K X-ray), 80 and 355 keV were found to be well defined. The peak at 355 keV was broader than the resolution of the spectrometer which indicated the presence of 302 keV $\gamma$-ray consistent with the earlier results. The $\gamma$-rays corresponding to 50 and 160 keV as reported by Kricki et al. were not established. The pulse height distribution of the various $\gamma$-rays from the source in anthracene crystal is shown in the insert of fig. 26.

DELAYED COINCIDENCE.

The half-life of the 80 keV level was measured by observing the delayed coincidences between 355 keV $\gamma$-ray feeding to the 80 keV level and the 80 keV $\gamma$-ray resulting from the de-excitation of the same to the ground state. The single channel on NaI (Tl) side was set at 14 volt corresponding
DELAYED COINCIDENCE SPECTRUM OF THE 81 keV LEVEL OF Cs$^{133}$

CALIBRATION: 0.4 CHANNEL/10$^9$ sec.

DECAY SCHEME OF Ba$^{133}$

Fig. No. 27  CHANNEL NO
to the photopeak of 80 keV γ-ray while the single channel on the anthracene side was used as a discriminator to accept all pulses above 80 keV. The anthracene crystal was covered with 1.0 gm/cm² of lead to minimize the detection of unwanted 32 keV X-rays and 80 keV γ-rays. The delayed coincidence spectrum obtained with the above adjustments is shown in fig. 27. The slope of the curve corresponds to a half-life of 80 keV level which is given by

\[ T_\gamma = 6.08 \times 10^{-9} \text{ Sec.} \]
Ru$^{103}$ SINGLES SPECTRUM IN NaI (TL) CRYSTAL
THE 95 keV LEVEL IN Rh\(^{103}\)

SOURCE PREPARATION.

The half-life of the 95 keV level of Rh\(^{103}\) was measured by using the Ru\(^{103}\) source. The active Ru\(^{103}\) was prepared by irradiating spectroscopically pure ruthenium metal sponge in the thermal column of "Apsara reactor". The material was purified by distillation and impurities were removed after chemical separation. Finally the source was obtained in the form of black ruthenium oxides. The 2.9-d Ru\(^{97}\) and 4.5-h Ru\(^{105}\) were allowed to decay before proceeding with the measurements. A minute piece of amorphous ruthenium oxide having an activity of approximately 2 \(\mu\) cur. was placed in a small cavity in the perspex disc. The disc was attached to the face of the NaI(Tl) crystal.

SINGLES SPECTRUM.

The \(\gamma\)-ray spectrum of Ru\(^{103}\) in the NaI(Tl) crystal of size 2.5cm dia x 2.5cm thick is shown in fig. 28. The spectrum reveals the existence of \(\gamma\)-rays at 55,495 and 610 keV. The insert in fig. 28 represents the pulse height distribution of the \(\gamma\)-rays from the source in plastic crystal of size 2.5cm dia x 2.5cm thick.

SLOW COINCIDENCE.

Saraf and Rietjens et al.\(^{11}\) have reported the existence of two weak \(\gamma\)-rays of 433 and 565 keV, which populate the 95 keV
level of $^{103}\text{Rh}$, and this level of 95 keV in turn decays to the 40 keV isomeric state (56 min) with the emission of 55 keV $\gamma$-radiation. Recently Naqui and Hogg have confirmed the presence of 555-56 keV cascade but their result for 443-56 cascade were negative. We therefore had a separate run of slow $\gamma$-$\gamma$ coincidences using two identical NaI (Tl) crystals to make sure of the presence of the above mentioned cascades. The single channel on one side was fixed to accept 55 keV $\gamma$-ray peak and the other channel was used to scan the high energy spectrum. The coincidence spectrum showed the existence of two peaks at 443 and 555 keV. To determine, whether the peaks are of genuine nature or are simply due to the Compton scattering of the 498 and 610 keV $\gamma$-rays coincident with the back scattered quanta of 55 keV, a 0.7g/cm$^2$ thick lead sheet (sufficient to absorb 55 keV $\gamma$-rays) was placed before the high energy counter. The peak at 443 keV nearly vanished while the peak at 555 keV still prevailed. The present result is therefore consistent with the results of Naqui and Hogg.

DELAYED COINCIDENCE.

For the measurement of the half-life of 50 keV level NaI (Tl) and plastic crystals were used. The thicknesses of cans containing the crystals were sufficient to absorb $\beta$ rays and conversion electrons. NaI (Tl) crystal was covered with an extra shielding of 0.7gm/cm$^2$ to exclude 55 keV $\gamma$-rays. The single channel on the NaI (Tl) side was set to accept the
DELAYED COINCIDENCE SPECTRUM OF THE
55keV LEVEL OF RH\textsuperscript{103}

CALIBRATION: 10 CHANNEL/10\textsuperscript{3} sec.

Fig. No. 29

T_{1/2} = 10 \times 10\textsuperscript{-9} sec.
pulses between 520 to 580 keV, while the single channel on the plastic side was set so as to accept the pulses due to 50 keV $\gamma$-rays. The slow coincidence rate had been about 3.5 counts/min. The delayed coincidence spectrum is shown in fig. 29, which yields for the 58 keV level a half-life of

$$T_\frac{1}{2} = 1.0 \times 10^{-9} \text{ Sec.}$$
SINGLES SPECTRUM OF Gd$^{159}$ IN NaI(TL) CRYSTAL

SINGLES SPECTRUM OF Gd$^{159}$ WITH 0.12 cm THICK LEAD ABSORBER.

PULSE HEIGHT (VOLTS)

COUNT ARBITRARY SCALE

COINCIDENCE COUNT

COINCIDENCE SPECTRUM WITH 220KeV $\gamma$-RAY

44KeV KX-RAY

56KeV $\gamma$-RAY

307KeV

364KeV

79KeV

57KeV

79KeV

Fig.No.30 BASE LINE (VOLTS)
THE 136 KeV LEVEL IN Tb\textsuperscript{159}

SOURCE PREPARATION.

The Tb\textsuperscript{159} nucleus is a daughter of Gd\textsuperscript{159} which decays entirely by $\beta$-emission. The Gd\textsuperscript{159} source was produced by thermal neutron irradiation of spectroscopically pure gadolinium oxide enriched to 92.9\% in Gd\textsuperscript{158}. A 0.5 $\mu$ cur. of the sample in the form of gadolinium chloride solution in dilute hydrochloric acid was prepared in the perspex envelope of 0.5 cm x 0.5 cm. Due to the short-lived activity (18h) of the source, the measurements were carried in the semi-liquid form.

SINGLES SPECTRUM.

The $\gamma$-ray energy spectrum of the Gd\textsuperscript{159} in NaI (TI) crystal of size 2.5 cm dia x 2.5 cm thick is shown in fig. 30. The spectrum when split into its components after subtracting the compton back grounds of various $\gamma$-rays shows the peaks at 44, 57, 79, 100, 228, 306 and 364 keV. The peak at 100 keV was interpreted to be due to the back scattering of 364 keV $\gamma$-rays by studying the intensities of the singles spectrum at different source to crystal distances and also by noticing the relative attenuation of various $\gamma$-rays with the lead absorbers of different thicknesses between source and the counter. The dotted curve in fig. 30 shows a typical spectrum with the crystal covered by 1 gm/cm\textsuperscript{2} thick lead.
SLOW COINCIDENCE.

The decay scheme of $^{159}$Gd proposed by various investigators has essentially the same features except the intensity ratio of various $\gamma$-rays. The intensity of 79 keV $\gamma$-ray reported by these authors differs considerably, we therefore, confirmed the presence of 79 keV $\gamma$-ray by making a separate run on slow coincidences using NaI (Tl) crystals on both sides. Slow channel on one side was fixed to accept the $\gamma$-rays corresponding to 228 keV while the other channel was scanned from 30 keV to 136 keV. The coincidence spectrum is shown in the insert of fig. 30. The existence of the 79 keV $\gamma$-ray was thus established.

DELAYED COINCIDENCE.

To measure the half-life of the 136 keV level in $^{159}$Tb, NaI (Tl) and plastic phosphors were used. The higher energy $\gamma$-ray of 220 keV was selected in NaI (Tl) crystal by putting the bias of the slow channel at 25 volt with 3 volt channel width. Since the intensity of 364 keV $\gamma$-ray is quite large compared to 228 keV $\gamma$-ray, a considerable number of Compton scattered events of 364 keV get detected in this channel within the specified channel width. Some of the events escaped from the crystal in the back direction may give rise to prompt coincidences. The NaI (Tl) crystal was therefore covered with 0.9 gm/cm$^2$ of lead and 1.1 gm/cm$^2$ of cadmium so that the back scattered quanta of 140 keV may...
DELAYED COINCIDENCE SPECTRUM OF
THE 135 keV LEVEL IN Tb^{159}

CALIBRATION: 10 CHANNEL/10^9 sec

\[ T_1/2 = 9 \times 10^9 \text{ sec} \]

DECAY SCHEME OF Gd^{159}
not reach the other crystal. The absorber also helped in reducing the low energy $\gamma$-rays to be detected in the start channel. The plastic crystal on the other side was used to supply stop pulses corresponding to 79 keV. The slow coincidence rate in this case was found to be quite low, being equal to an average of 1.5 counts/min. The delayed coincidence curve is shown in fig.31, which corresponds to a half-life

$$T_\frac{1}{2} = 9 \times 10^{-10} \text{ Sec.}$$

Due to low counting rate and poorer resolution at low energies the stated half-life should be taken as an upper limit.
$^{181}\text{Hf} / ^{175}\text{Hf} = 2:1$

SINGLES SPECTRUM IN NaI(TL) WITH 1.2 Gm/Cm$^2$ OF LEAD ABSORBER
IHE 4S2  
LEVEL OF SOURCE PREPARATION.

The half-life of 482 keV level was measured by using the source of Hf$^{181}$. The source was prepared from the spectroscopically pure HfO$_2$ powder irradiated in the swimming pool reactor at Trombay. The active substance was allowed to decay for a couple of days so that short time activities like 4.8 sec- Hf$^{180m}$ and 5.5 hr- Hf$^{178m}$ may subside. A 0.2 $\mu$cur. of the activated powder (Hf$^{181}$/Hf$^{175}$ = 2:1) was put in a perspex container.

SINGLES SPECTRUM.

The $\gamma$-ray spectrum of the source which was obtained after inserting a 0.8g/cm$^2$ thick lead absorber between the source and the detector is shown in fig. 32. The spectrum clearly indicates the presence of 54 (X-ray), 89, 133, 345 and 482 keV $\gamma$-rays. 54 keV X-ray peak is mostly attenuated due to the absorber. The peaks at 89 and 345 keV are attributed to be due to the contamination of Hf$^{175}$. The region between the peaks at 133 and 345 keV indicates the superposition of many $\gamma$-rays arising from the disintegration of both Hf$^{175}$ and Hf$^{181}$.

DELAYED COINCIDENCE.

Half-life of the 482 keV level in Ta$^{181}$ was measured by using a 0.5 $\mu$Cur. source of Hf$^{181}$. The crystals used were both NaI (Tl) of size 2.5cm dia x 2.5cm thick. The bias on
DELAYED COINCIDENCE SPECTRUM OF THE 482 KeV LEVEL OF Ta^{181}

CALIBRATION: 0.32 CHANNEL / 10^{-9} sec.

$T_{1/2} = 10.5 \times 10^{-9}$ sec

COUNTS

Hf^{181} (45 d)

1/2^{-} \beta

5/2^{+} 0.619 0.615
8/2^{+} 0.482
7/2^{+} 0.301
0.136
0

DECAY SCHEME OF Hf^{181}

Fig. No. 33

CHANNEL NO.
one side was fixed corresponding to 482 keV $\gamma$-ray while the bias on the other side was kept corresponding to the peak at 136 keV $\gamma$-ray. Since the counting rate in the start channel has to be kept low the high energy 482 keV $\gamma$-ray was fed to the start channel and its crystal was covered with 1.2g/cm$^2$ of lead and 1.1g/cm$^2$ of cadmium to cut off the $\gamma$-rays up to 136 keV. The delayed coincidence spectrum is shown in fig. 33. The half-life measured from the slope of the curve was found to be

$$T \frac{1}{2} = 10.5 \times 10^{-9} \text{ Sec.}$$

THE 343 keV LEVEL OF Lu$^{175}$

DELAYED COINCIDENCE.

The source used to measure the half-life of the 343 keV level of Lu$^{175}$ was the same as that for Ta$^{181}$, but one of the NaI (Tl) crystal was replaced by plastic phosphor to detect the low energy X-rays. The delayed coincidences were obtained between X-rays (resulting from the electron capture in Hf$^{175}$) feeding to the 348 keV level of Lu$^{175}$ and 343 keV $\gamma$-rays resulting from the de-excitation of the same level to the ground state. The NaI crystal was used on the start side to select the peak corresponding to 343 keV $\gamma$-rays while on the stop side the plastic crystal was set to accept the pulses corresponding to 55 keV X-rays. The time spectrum (fig.34) so obtained was found to be complex, consisting of two
DELAYED COINCIDENCE SPECTRUM OF THE 345keV LEVEL OF Lu$^{175}$

CALIBRATION: 0.4 CHANNEL/10$^9$ sec.

DECAY SCHEME OF Hf$^{175}$

$T_{1/2} = 0.7 \times 10^9$ sec

$T_{1/2} = 10.5 \times 10^{-9}$ sec
exponential decays. The longer component decaying with the half-life of 10.5m μ-sec., was interpreted to be due to the coincidences produced by the Compton pulses of 432 keV γ-ray which fall within the peak of 343 keV γ-ray. The fast component represents the coincidences due to the actual decay of the 343 keV level which corresponds to a half-life

\[ T_\frac{1}{2} = 0.7 \times 10^{-9} \text{ sec.} \]
Singles Spectrum of $\text{Re}^{186}$ in Plastic Crystal

- 123 KeV + 137 KeV
- 631 KeV

Low Energy $\gamma$-Spectrum of $\text{Re}^{186}$ in Cooled NaI Crystal

Cooling Arrangement

- Perforated Aluminium Partition
- Base 6810A
- Source
- Freezing Mixture

Fig. No. 35

Pulse Height (Volts)
123 keV LEVEL OF W$^{188}$

SOURCE PREPARATION.

The $^{186}$ nucleus decays partly by electron capture, populating the 123 keV level of W$^{186}$. The $^{186}$ source was produced by thermal neutron irradiation of enriched Re$^{186}$. The source thus produced was allowed to decay for five days so that the small 17-h activity due to Re$^{188}$ produced along with Re$^{186}$ may completely subside. Evidence was found for no other contamination. Few drops of nitric acid solution of active per-rhenic acid were allowed to evaporate in a small cavity 3mm x 2mm drilled in the perspex container. The sample thus produced was mounted evenly between two counters.

SINGLES SPECTRUM.

$\gamma$-ray spectrum of Re$^{186}$ was observed in a cooled 2.5cm dia x 2.5cm thick NaI (Tl) crystal. Cooling had been done by putting the photomultiplier and the crystal in a small box containing freezing ice mixture as shown in fig.35. Walls of the box were made of perspex covered with thin sheet of cork so that the scattering of $\gamma$-rays due to enclosure may be minimised. Cooled NaI (Tl) crystal had the advantage of better time resolution due to shorter light decay time. The spectrum shown in fig. 35 indicates the presence of two prominent photopeaks corresponding to 60 keV(X-ray) and 131 keV. The half-width of the peak at 131 keV was found to be more than
DELAYED COINCIDENCE SPECTRUM OF THE 123KeV LEVEL OF W^{186}

CALIBRATION: 1.0 CHANNEL / 10^{-9} sec.

\[ T_{1/2} = 1.15 \times 10^{-9} \text{ sec} \]

DECAY SCHEME OF Re^{186}
the expected half-width from the resolution of the spectrum at this energy (estimated by 140 keV level of Ce$^{141}$), which confirmed the presence of 122 keV $\gamma$-ray as reported by Porter et al.

The insert of fig. 36 shows the $\gamma$-spectrum in plastic scintillator of size 2.5cm dia x 3cm thick. The arrows indicating the energies are placed according to Cs$^{137}$ calibration. Both the crystals were covered with 450mg/cm$^2$ of a aluminium so that the $\beta$-rays are completely absorbed.

DELYED COINCIDENCE.

The measurement of the half-life of 123 keV level of W$^{186}$ was accomplished by observing the delayed coincidences between X-rays and 122 keV $\gamma$-rays. The pulses corresponding to 60 keV X-ray photopeak were selected in NaI crystal and were fed to the start channel. The slow channel bias on the plastic side was kept at 2 volt which allowed the detection of 122 keV $\gamma$-ray and also an appreciable number of 137 keV $\gamma$-rays. With the above adjustments the coincidences between 137 keV $\gamma$-rays and X-rays due to the conversion of 630 keV $\gamma$-ray also get registered along with the real coincidences. However, since the 630 keV $\gamma$-ray is quite weak and further it has a small conversion coefficient, it does not introduce a serious error. A typical delayed coincidence spectrum is shown in fig. 36. The half-life measured from the slope of the right hand side of the curve comes to be

$$T_\gamma = (1.15 \pm 0.2) \times 10^{-9} \text{ Sec.}$$
The left hand side of the curve was found to be little slow due to the detection of low energy $\gamma$-rays in NaI crystal, but since, we are concerned with the right hand side only it does not affect our measurement. We, however, tried to repeat the experiment by changing the role of the two crystals i.e. the bias in plastic side was reduced to 1 volt to accommodate 60 keV X-ray and the single channel on NaI side was set at 4 volt corresponding to the combined peak of 122 and 137 keV $\gamma$-rays. The coincidence counting rate in this condition was found to be practically nil.
<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Level (KeV)</th>
<th>Observed Half-life Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{53}$I$^{129}$</td>
<td>27</td>
<td>$(1.59 \pm 0.13) \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{59}$Pr$^{143}$</td>
<td>57</td>
<td>$(5.80 \pm 0.13) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{59}$Pr$^{141}$</td>
<td>351</td>
<td>$(1.90 \pm 0.35) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{55}$Ca$^{131}$</td>
<td>122</td>
<td>$(4.1 \pm 0.7) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{55}$Ca$^{133}$</td>
<td>214</td>
<td>$(6.08 \pm 0.40) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{45}$Rh$^{103}$</td>
<td>80</td>
<td>$(1.0 \pm 0.5) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{65}$Tb$^{159}$</td>
<td>136</td>
<td>$\leq 9.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$^{73}$Ta$^{181}$</td>
<td>482</td>
<td>$(1.05 \pm 0.15) \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{71}$Lu$^{175}$</td>
<td>343</td>
<td>$(0.7 \pm 0.3) \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{74}$W$^{186}$</td>
<td>123</td>
<td>$(1.15 \pm 0.2) \times 10^{-9}$</td>
</tr>
</tbody>
</table>
REFERENCES

4. S. Johansson, Arkiv, Fysik 3, (1952) 533
CHAPTER V
RESULTS AND DISCUSSION

It is interesting to compare the experimental \( \gamma \)-decay transition probabilities with the theoretical values calculated on the basis of specific models of the nucleus, since the same may reveal a significant information about the nuclear structure. As a starting point the model generally used is the extreme single particle model, which in its simplest form assumes that

1. A single particle is responsible for the transition which is moving in a velocity independent central potential.
2. The wave functions are constant throughout the nucleus.
3. The radius of the nucleus is small compared to the wavelength of the radiation emitted.

The expressions for the transition probabilities, on the basis of the above mentioned assumptions, have been calculated by Weisskopf\textsuperscript{1} and are written as:

For electric transition of multipole order \( L \),

\[
\lambda_\gamma (EL) = \frac{4 \cdot 4 (L+1) \left( \frac{3}{L+3} \right)^2 \left( \frac{E \gamma}{197} \right)^{2L+1} R \times S(k, L, I)}{(2L+1)!} \times 10^3 \times \sec^{-1}
\]

(5.1)

where \( E \gamma \) is expressed in MeV and \( R \) is in fermis \( (10^{-13} \text{cm}) \)

\( (2L+1)! \) denotes \( 1, 3, 5, \ldots, 2L+1 \).
For magnetic transition, the calculation of transition probability is somewhat complicated due to the intrinsic moments of the nucleus. Weisskopf has however concluded that the magnetic matrix elements are smaller than the corresponding electric matrix elements by a factor of $10 \left( \frac{\mu}{\mu_{\text{ele}}^f} \right)^2$ and hence the transition probability for the magnetic transition of order $L$ is given by

$$\lambda_T(ML) = \frac{4 \cdot 9 (L+1)}{L(2L+1)} \left( \frac{3}{L+3} \right)^2 \left( \frac{E_{1f}}{197} \right)^{2L+1} \left( \frac{E_{1f}}{197} \right)^{2L-2} R^2 S(L, L, L_I) \times 10 \times \text{sec}^{-1}$$

The Weisskopf's estimate for the magnetic transition probability was modified by Moszkowski to take into account the dependence of orbital magnetic moment of the radiating particle on its multipole order $L$. He thus, replaced the factor $10 \left( \frac{\mu}{\mu_{\text{ele}}^f} \right)^2$ by:

$$\left[ \frac{L+3}{L+2} \left( \frac{\mu_p - L}{L+1} \right) \right]^2$$

$\mu_p$ being the proton intrinsic magnetic moment in nuclear magneton (=2.79). The magnetic transition probability after the above modification is given by:

$$\lambda_T(ML) = \frac{0.19 (L+1)}{L(2L+1)} \left( \frac{3}{L+2} \right)^2 \left( \frac{\mu_p - L}{L+1} \right)^2 \left( \frac{E_{1f}}{197} \right)^{2L+1} \left( \frac{E_{1f}}{197} \right)^{2L-2} R^2 S(L, L, L_I) \times 10^{21} \times \text{sec}^{-1}$$

(5.3)
where \( E_x \) is expressed in MeV, and \( B=1.46 \text{ A}^2 \) fermis.

The statistical factor \( S \) has been taken as unity in the Weisskopf's estimates. This however is true only for the case when final state of the transition is an s-state \((l=0)\). In general for an electric transition from an initial state having the orbital angular momentum \( l_i \) and the total angular momentum \( I_i \) to a final state with orbital angular momentum \( l_f \) and total angular momentum \( I_f \), the statistical factor is given by

\[
S(I_i, l_i, l_f, I_f) = \frac{(2l_i+1)(2l_f+1)(2I_i+1)(2I_f+1) \times |V(l_i, l_f, I_i, I_f, 0, 0)|^2}{|W(l_i, I_i, l_f, I_f, \frac{1}{2}, I_f)|^2}
\]

where the quantity \( V \) is closely related to Clebsch-Gordan coefficients and \( W \) are the coefficients introduced by Racah.

For the special case when \( L = |I_i - I_f| \) the expression takes comparatively simple form. For \( I_f = I_i - L \) i.e. when the spin of the final state is less than the spin of the initial state by the multipole order \( L \), the statistical factor is given by

\[
S(I_i, l_i, l_f, I_f) = \frac{(I_i - \frac{1}{2})! \times (2l_i+1)! \times (2I_f)!!}{(2l_i)!! \times (L)! \times (I_f - \frac{1}{2})!}
\]

In the reverse case i.e. when \( I_f = I_i + L \), the statistical factor is given as follows, in accordance with the principle of
detailed balance:

\[ S(\mathbf{I}_i, \mathbf{I}_L, \mathbf{I}_f) = S(\mathbf{I}_i + \mathbf{L}, \mathbf{L}, \mathbf{I}_f) \times \frac{2\mathbf{I}_i + 2\mathbf{L} + 1}{2\mathbf{I}_i + 1} \]  \hfill (5.6)

It is worthwhile to note that \( S \) equals to 1 for any transition for which \( I_f=\frac{1}{2} \) (\( I_f=0 \)) and \( I_f=L+\frac{1}{2} \).

In actual practice, all the nuclear states except those of the single nucleon, are states containing several particles. In the case of normal coupling, the ground state spin of odd-\( A \) nuclei equals to the angular momentum of the unfilled orbit which contains odd number of nucleons. However, there are few exceptions which fall under abnormal coupling. For normal coupling states, the wave function may be written as products of wave functions of pairs of identical particles coupling to a spin zero, and that of the wave function of the last odd particle. The transition probability calculated, between states of partially filled orbits using the above wave functions was found to be less than the corresponding single particle states by a factor \( \rho \) known as seniority statistical factor.

For an odd particle transition i.e. when the transition is represented by:

\[ \left[ (\mathbf{I}_i)^{P+1} (\mathbf{I}_f)^{Q} \right]_{\mathbf{I}_i} \rightarrow \left[ (\mathbf{I}_i)^{P} (\mathbf{I}_f)^{Q+1} \right]_{\mathbf{I}_f} \]

\[ \rho = \frac{2\mathbf{I}_i + 1 - P}{2\mathbf{I}_i + 1} \times \frac{2\mathbf{I}_f + 1 - Q}{2\mathbf{I}_f + 1} \]  \hfill (5.7)

For an even particle transition i.e. when the transition is represented by:
The single particle model because of the over simplified picture of the nucleus lends itself to easy calculations but since it represents the actual situation crudely the experimental values in most of the cases are found to be much off than the single particle estimates. Nevertheless, these calculations provide an important tool for the interpretation of known results.

\( \ell \)-FORBIDDEN M\(_1\) TRANSITIONS:

According to strict single particle model, the M\(_1\) transitions between states of different orbital angular momenta \( \ell \) are forbidden. The calculation of the transition probability for such \( \ell \)-forbidden M\(_1\) transitions requires modified assumptions about nuclear wave functions. The radiative transition probability for a magnetic dipole radiation \( \lambda_\gamma (M_1) \) may be expressed in terms of nuclear matrix element by the relation

\[
\lambda_\gamma (M_1) = \frac{1}{E_\gamma} \left( \frac{E_\gamma}{m_c^2} \right)^3 \left( \frac{m_e}{m} \right)^2 \frac{E_y^3}{\hbar c} \times \frac{1}{2I_i + 1} \times \frac{m^2}{2I_i + 1}
\]

\[
= 0.419 \times 10^{15} \quad E_y^3 \quad m^2/2I_i + 1 \quad \text{sec}^{-1}
\]

where \( E_\gamma \) is measured in MeV, and \( I_i \) is the angular momentum of the initial state. The square of matrix element \( m^2 \) is
where $\sum \mu$ is the summation of the magnetic moment operators of each nucleon in the nucleus.

Arima et al. have derived the simple expressions for the calculations of the matrix element of $M_1$ transitions on the basis of configurational mixing, and are written as:

A. For Like Core (L) transitions i.e. when odd particle changes its state, $I_1^{P^+} I_2^q(0) \rightarrow I_1^P(0) I_2^{q+1}(I_f)$. The matrix element is given by

$$m = \left[ \frac{(2I_i+1)^{1/2}}{(2I_i+1)(2I_f+1)} \right] \times \frac{(g_s-g_l)}{F_L}$$

where $(g_s-g_l) = 4.585(n.m)$ for an odd proton nucleus and $-3.326(m.m)$ for an odd neutron nucleus. The $F_L$ which has the meaning of the unfavoured factor, takes into account the contribution due to all the possible modes of excitation as given below.

1. $F_{LI}$ (when $I_1$, $I_2$ are two different mixing states but having
same orbital angular momenta \( \ell_1 \)

\[
F_{LI} = F_{LI\ell} = \frac{n_1(2I_1+1-n_2)}{(2I_1\ell_1+1)(2I_2\ell_2+1)} \frac{\ell_1(\ell_1+1)}{2\ell_1+1} \left\{ \frac{V_l I (I_1;I_2,I_1;I_1)}{(-\Delta E)} \right\}
\]

\[\left(\frac{g(v_e-v_\nu)}{2}\right) I (I_1;I_2,I_1;I_1)/(-\Delta E)\]

(5.12)

\( n_1, n_2 \) denote the even number of particles in \( I_1 \) and \( I_2 \) mixing states respectively.

The values in the curly bracket in (4.12) must be chosen in such a way that the even numbers of nucleons in the orbits \( I_1 \) and \( I_2 \) are like or unlike nucleons with those in the outermost orbit \( I_1 \). The value of \( g \) is 0.334 for the effect of neutron excitation on odd proton transition and 1.199 for the effect of proton excitation on the odd neutron transition. The interactions between nucleons are assumed as attractive and the attractive force in the triplet state is assumed to be stronger than the singlet state of the two nucleons in the ratio: \( V_t = 1.5 |V_s| \). \( I \) is a Slater integral for a delta-function interaction:

\[
I (I_1;I_2,I_1;I_1) = \frac{1}{2} \int_0^\infty R(I_1) R(I_2) R(I_1) Y^2 d\gamma
\]

(5.

The product of the singlet strength and the integral \( I \) has
A is the mass of the nucleus and $C_2$ is a constant taken to be equal to 250 MeV for harmonic oscillator wave function. $F$ is a non-dimensional constant which does not depend on $A$ but depends on the shape of the wave function. 

2. $F_{\text{LI}}$ (when the mixing state $I_1$ coincides with $I_f$)

$$F_{\text{LI}} = F_{\text{LI}} = \frac{\gamma}{2I_1 + 1} \frac{\ell_i (\ell_i + 1)}{2I_1 + 1} V_S I (I_1^2; I_i I_f) \langle I_1^2 \rangle \langle I_f \rangle \langle -\frac{1}{\Delta E} \rangle$$  \hspace{1cm} (5.15)

3. $F_{\text{III}}$ (when the mixing state $I_2$ coincides with $I_1$)

$$F_{\text{III}} = F_{\text{III}} = \frac{2I_i - 1 + \frac{1}{2}}{2I_i - 1} \frac{\ell_i (\ell_i + 1)}{2I_i + 1} V_S C (I_1^2; I_i I_f) \langle I_1^2 \rangle \langle I_f \rangle \langle -\frac{1}{\Delta E} \rangle$$  \hspace{1cm} (5.16)

B. For unlike core (U) transitions i.e. when the even particle changes its state, $I_i^P (T_1^1) I_f^q (0) \rightarrow I_f^P (I_1^2) I_f^q (I_1^2)$. The matrix element is given by:

$$m_U = \left[ \frac{\gamma}{2I_i + 1} \right]^{1/2} \left[ \frac{\ell_i (\ell_i + 1)}{2I_i + 1} \right] \frac{\chi}{2} (\theta - \theta) F_U$$

The contribution due to the first mode of excitation i.e. $F_{\text{LI}}$ is given by the same formula as the corresponding $F_{\text{LI}}$, while the contribution due to other two modes are calculated by the
The above expressions hold good only for the case when the angular momenta of the initial and final configuration are $I_i = l_i + q$ and $I_f = l_f + q$. However, for the other case in which $I_i = l_i + q$ and $I_f = l_f + q$, we need only exchange the role of initial and final states i.e. $I_f$, $l_f$, $q$ should be replaced by $I_i$, $l_i$, $p$ and vice versa in the above formulas.

TRANSITIONS IN THE DEFORMED NUCLEI.

The excited states of nuclei in the intermediate and heavy mass region ($A > 150$) show the existence of collective excitations characteristic of the deformed nuclear shape. The transition probability for $\gamma$-radiation of multipole order $L$ and of frequency $\omega$ is given by

$$\lambda_{\gamma}(\sigma' L) = \frac{3\pi(L+1)}{4(L(2L+1))} \cdot \frac{1}{\hbar} \left( \frac{\omega}{c} \right)^{2L+1} B(\sigma' L)$$  \hspace{1cm} (5.20)

* These expressions, which were left in the original paper, have been cleared in private communication with Dr. A. Arima.
where the reduced transition probability $B(\sigma L)$ which depends on the detailed nuclear structure can be expressed in terms of the matrix element of the multipole operator $m(L, \mu)$ between initial state $(i)$ and final state $(f)$ with magnetic quantum number $M_f$.

$$B(L) = \sum_{\mu, M_f} |<i | m | f>|^2$$ (5.21)

In the unified description of nuclear dynamics, the state of the nucleus is described in terms of particle and collective degrees of freedom and thus the electric and magnetic operators in the space fixed system are given by:

$$m_e(L, \mu) = \sum_p \left( e_p + (\gamma_L \frac{Z e}{A L}) \gamma_p^L \gamma_{LM} (\gamma_p \varphi_p) + \frac{3}{4\pi} \frac{Z e R_o^L \gamma_{LM}}{\hbar} \right)$$

$$m_m(L, \mu) = \frac{e \hbar}{2mc} \sum \left( \gamma^L_s \gamma^L_{LM} \right) \gamma_p \left\{ \gamma_p^L \gamma_{LM} (\gamma_p \varphi_p) \right\}$$

$$+ \frac{e \hbar}{mc} \int \overrightarrow{q} \right\{ \gamma^L \gamma_{LM} (\gamma_p \varphi_p) \} d\tau$$ (5.22)

The first term (particle part) in the two expressions represent the transition moments of the most loosely bound particles which can be
individually excited while the last term represents the multipole moments generated by the collective motion of the nucleons. In the strong coupling representation one may distinguish between particle transitions which are associated with a change in the intrinsic wave function, and collective transitions which leave the internal particle structure unaltered.

**COLLECTIVE TRANSITIONS.**

The enhancement of $E_2$ transition probability is accounted for in terms of the collective quadrupole oscillation of the nucleus, and the dominating contribution to the reduced transition probability comes from the last term of equation (5.22).

In the case of $\Delta K=0$ diagonal transitions, i.e. for transition from a rotational state ($I_1K$) to a final state ($I_2K$), the reduced transition probabilities for electric quadrupole and magnetic dipole transitions are given by

$$B(E_2, I_1 \rightarrow I_2) = \frac{5}{16\pi} e^2 Q^2 \left| \langle I_1 2K 0 | I_2 2I_2 K \rangle \right|^2$$

and

$$B(M1, I_1 \rightarrow I_2) = \frac{3}{4\pi} \left( \frac{e\hbar}{2mc} \right)^2 \left( g_e - g_\mu \right)^2 \left| \langle I_1 I_2 K \rangle \right|^2$$

where the quantities in bracket are Clebsh-Gordan coefficients.

As a special case in even-even nuclei the rotational band associated with the ground state ($I=K=0$) has consecutive states with $\Delta I=2$. The decay therefore proceeds in cascade of pure $E_2$ transitions. The reduced transition probability from the
first excited state of even-even nuclei is given by equation (5.23)

\[ B(E_2) = \frac{e^2 Q_0^2}{16\pi} \] (5.25)

and

\[ Q_0 = \left\{ \frac{50.286 \times B(E_{2\to0})}{10^{-24}} \right\} \times 10^{-10} \text{ cm}^2 \] (5.26)

where the quantity \( B(E_2) \) (expressed in \( e^2 \times 10^{-48} \text{ cm}^4 \)) may be determined from the measured transition probability \( (E_2) \) using the following relation which follows from (5.20) i.e.

\[ \lambda_\gamma(E_2) = 1.236 \times 10^{13} \times E_\gamma^5 \times B(E_2) \text{ Sec}^{-1} \] (5.27)

where \( E_\gamma \) is expressed in MeV.

In odd mass nuclei the consecutive states have \( \Delta I=1 \) and therefore transition in general proceed as a mixture of \( M_1 \) and \( E_2 \). The probability for a transition \( I+1 \rightarrow I \) is given by equations (5.23) and (5.24) and may be written as

\[ B(M_1) = \frac{3}{4\pi} \frac{e^2 \hbar}{2Mc} \frac{(g_k-g_R)^2}{(I+1)(2I+1)} \frac{k^2(I+1-k)(I+1+k)}{I(I+1)(2I+3)(I+2)} \] (5.28)

\[ B(E_2) = \frac{15}{16\pi} \frac{e^2 Q_0^2}{16\pi} \frac{k^2(I+1-k)(I+1+k)}{I(I+1)(2I+3)} \] (5.29)

where \( g_k \) and \( g_R \) are the gyromagnetic ratios due to intrinsic and collective motion of the nucleons. The value \( g_k-g_R \) may be calculated from the measured half-life by using the following
relation which follows from equations 5.20 and 5.28

\[ \Lambda_y(M) = 0.419 \times 10^{13} E_\gamma \left( \frac{(g_k - q_R)^2 k^2 (I+1-k)(I+1+k)}{(I+1)(2I+3)} \right) \sec^{-1} \]  

where \( E_\gamma \) is expressed in MeV and \( g_k - g_R \) in nuclear magneton.

If the nuclear shape is spheroidal the deformation parameter \( \beta \) given by,

\[ \beta = 4 \left( \frac{\pi}{6} \right)^{1/2} \frac{\Delta R}{R_0} = 1.06 \frac{\Delta R}{R_0} \]  

(5.31)

Where \( R_0 \) is the mean radius and \( \Delta \) the difference between major and minor semi axes. For a uniformly charged nucleus of spheroidal shape the value of \( \beta \) may be calculated from \( Q_0 \) by the use of

\[ Q_0 = 3 \times (5/\pi)^{1/2} \frac{\eta}{2} R_0^2 \beta (1 + 0.16 \beta + \cdots) \]  

(5.32)

and

\[ \beta = 3.12 \left[ (1 + \frac{5.9 Q_0}{2 A^{1/3}})^{1/2} - 1 \right] \]  

(5.33)

where \( Q_0 \) is in the same units as expressed earlier \( (10^{-24} \text{cm}^2) \) and \( R_0 \) has been assumed to be equal to 1.2 fermis.

The nuclear moment of inertia depends on the structure of the intrinsic nucleonic motion. For independent particle motion of the nucleons in the rotating nuclear field, the effective moment of inertia would be approximately that corresponding to the rigid rotation and is given by

\[ \mathcal{I}_{\text{rig}} = \frac{2}{5} A M R_0^2 (1 + 0.31 \beta + \cdots) \]  

(5.34)

In the other extreme when the residual interaction becomes so strong as to break down the shell structure, the effective
moment of inertia would approach the hydrodynamics value equivalent to a wave travelling irrotationally on the surface of a liquid drop in that case

\[ J_{\text{irrot}} = \frac{2}{5} \alpha M R_0^2 \beta^2 \left\{ 0.89 + O(\beta^2) \right\} \quad (5.35) \]

In practice the moment of inertia are found to lie between these two extremes and thus the comparison between \( J / J_{\text{rig}} \) furnishes a valuable information about the strength of the residual interactions. The \( J \) is calculated from the observed energy of the excited state since

\[ E_x = \frac{k^2}{2J} I (I+1) \quad (5.36a) \]

for even-even nuclei

and

\[ E_x = \frac{k^2}{2J} \left[ I (I+1) - I_o (I_0+1) \right] \quad (5.36) \]

for odd-A nuclei

where \( I \) and \( I_0 \) being the angular momenta of excited and ground state respectively. The combination of equations 5.34 and 5.36 results in a simplified formula

\[ \frac{J}{J_{\text{rig}}} = 0.36 \times I_{\text{rig}} (I+1) \left[ E_1 A^{5/3} (1+0.31 \beta) \right]^{-1} \]

for even-even nuclei \( (5.37a) \)

and

\[ \frac{J}{J_{\text{rig}}} = 0.36 \left[ I (I+1) - I_0 (I_0+1) \right] \left[ E_1 A^{5/3} (1+0.31 \beta) \right]^{-1} \]

\( (5.37 b) \)

where \( E_1 \) is expressed in MeV.
PARTICLE TRANSITIONS.

The transition probability between two individual particle states depend on the intrinsic structure (amplitude and phases) of the partial wave functions of the two states and are independent of the collective motion. Thus in deriving the expression for the transition probability between two individual particle states, contribution due to last term in equation (5.22) may be ignored and multipole operator may be written in the form.

\[ m(L, \mu) = \sum_{\nu} m'(L, \mu) D_{\mu \nu}^{L}(\theta) \]  

(5.38)

where \( \theta \) is the Euler angle giving the orientation of the nucleus and \( m'(L, \mu) \) is the multipole operator expressed in nuclear co-ordinate system (instead of space fixed system). The transition probabilities for electric quadrupole and magnetic dipole transitions between two individual particle states \( I_k \Pi [N \eta_y, \Lambda] \) and \( I'_k \Pi' [N' \eta_y', \Lambda'] \) are given by the following expressions which are obtained from the general formula's (29), (35) and (36) in the Nilsson's paper.

\[ \lambda_y(E_1, I \rightarrow I') = 0.49 \times 10^3 \frac{E_1^S}{E_1^S + \frac{2}{A}} \left( \frac{k}{\omega_0} \right)^2 \left[ \langle I \Pi_k \Pi' \mid I \Pi'_k \rangle \right] \]

\[ \lambda_y(E_1, I \rightarrow I') = 0.105 \times 10^3 \left( \frac{k}{\omega_0} \right)^2 \left[ \langle I \Pi_k \Pi' \mid I \Pi'_k \rangle \right] \]

(5.39)

where \( E \) is the energy of transition (MeV) and \( \frac{k}{\omega_0} \) is the oscillator level spacing. The squares of the matrix element \( G^2 E_2, G^2 M_1 \) and the quantities \( E_2, M_1 \) may be calculated by
using (36), (36), and (41) in Nilsson's paper.\textsuperscript{13}

**PARTIAL RADIATIVE (γ-Ray) TRANSITION PROBABILITY.**

Since internal conversion is an inevitable parallel process which often competes with the γ-ray transition, the observed half-life of an excited state is always less than the partial half-life for the γ-transition alone. The experimental transition probabilities therefore, have to be corrected for the internal conversion before making a comparison with theory. The experimental half-life $T_\gamma$ is related to the partial radiative mean life time $\tau_\gamma$ by the following relation

$$\frac{1}{\lambda_\gamma} = \tau_\gamma = 1.44 T_{kL}^{\text{obs}} (1 + \alpha I) \quad (5.41)$$

where $\lambda_\kappa$ is the total conversion coefficient ($\lambda_\kappa = \lambda_\kappa^+ + \lambda_\kappa^- + \lambda_\kappa^n + \cdots$).

In the case of mixed $M_1 + E_2$ transition, the partial radiative life time for $M_1$ transition may be given by the following relation

$$\tau_\gamma(M_1) = 1.44 T_{kL}^{\text{obs}} \left\{ 1 + \delta_2^2 + \delta_2^2 \lambda_L + \beta_1 \right\} \quad (5.42)$$

where $\delta_2$ is the $E_2/M_1$ amplitude mixing ratio and $\lambda_L$, $\beta_1$ are the total conversion coefficients which may be obtained by the extrapolation of Rose's Table.
Table 2 summarizes the results of all the measurements along with the calculations made on the basis of single particle model. Column Ist, 2nd and 3rd in the table list the nuclides, the $\gamma$-ray transition energy and the observed half-life respectively. The $\beta$ and $\alpha_2$ given in column 4th are the total conversion coefficients for magnetic dipole and electric quadrupole transitions which have been obtained from the extrapolation of Rose's table. The values of mixing amplitude $S^2$ in column 5th are those which have been reported in literature as a result of angular correlation or polarization measurements. For the case of $^{103}$Rh for which no such data is available the value of $S^2$ has been estimated with the help of experimental $K$ conversion coefficient $\alpha_K$ and the extrapolated values of $\beta_1$ and $\alpha_2$. The last two columns in the table list the $M_1$ retardation factor and $E_2$ enhancement factor respectively. The experimental partial $\gamma$-ray transition probabilities $\lambda_\gamma(M_1)_{exp}$ have been obtained from the observed half-life $T_\gamma$ by using the values of $\beta_1, \alpha_2$ and $S^2$ along with the equation (5.42) while the single particle transition probabilities $\lambda_\gamma(M_1)_{s.p}$ and $\lambda_\gamma(E_2)_{s.p}$ are those which have been calculated with the help of equations (5.1) and (5.3).

It is evident from the table that the magnetic dipole transitions from the first excited state $(^2)$ of $^{129}\text{I}$, $^{131}\text{Cs}$, $^{133}\text{Cs}$, $^{141}\text{Pr}$ and $^{143}\text{Pr}$ which occur between $g_{7/2} \rightarrow d_{5/2}$ states are in general retarded by a large factor in accordance with the $l$-forbidden transitions. The low value of retardation factor in $^{129}\text{I}$ is probably due to the admixture of $E_2$ radiation (The
## Table 2

Comparison of the Observed Half-Life with Single Particle Estimates

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>E_\gamma (keV)</th>
<th>T_{1/2} (sec)</th>
<th>Conversion Coefficient</th>
<th>S^*(E/M_1)</th>
<th>M_1 Retardation Factor</th>
<th>E_2 Enhancement Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>{}^{45}\text{Rh} \text{103}</td>
<td>55</td>
<td>1.0\times 10^{-9}</td>
<td>1.90</td>
<td>11.6</td>
<td>0.972</td>
<td>25.0</td>
</tr>
<tr>
<td>{}^{53}\text{I} \text{129}</td>
<td>27#</td>
<td>1.59\times 10^{-8}</td>
<td>5.30</td>
<td>300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>{}^{121}\text{Cs} \text{131}</td>
<td>42#</td>
<td>4.1\times 10^{-9}</td>
<td>0.53</td>
<td>0.90</td>
<td>0.03</td>
<td>610</td>
</tr>
<tr>
<td>{}^{55}\text{Cs} \text{133}</td>
<td>80#</td>
<td>6.08\times 10^{-9}</td>
<td>1.65</td>
<td>4.0</td>
<td>0.006</td>
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</tr>
<tr>
<td>{}^{59}\text{Pr} \text{141}</td>
<td>142#</td>
<td>1.9\times 10^{-9}</td>
<td>0.52</td>
<td>0.65</td>
<td>0.006</td>
<td>450</td>
</tr>
<tr>
<td>{}^{59}\text{Pr} \text{143}</td>
<td>57#</td>
<td>5.8\times 10^{-9}</td>
<td>6.7</td>
<td>25</td>
<td>0.01</td>
<td>430</td>
</tr>
<tr>
<td>{}^{65}\text{Tb} \text{159}</td>
<td>79</td>
<td>9\times 10^{-10}</td>
<td>4.1</td>
<td>6.3</td>
<td>0.13</td>
<td>\leq 180</td>
</tr>
<tr>
<td>{}^{71}\text{Lu} \text{175}</td>
<td>343</td>
<td>7\times 10^{-10}</td>
<td>0.13</td>
<td>0.05</td>
<td>0.25</td>
<td>2.0\times 10^3</td>
</tr>
<tr>
<td>{}^{73}\text{Ta} \text{181}</td>
<td>482</td>
<td>10.5\times 10^{-9}</td>
<td>0.03</td>
<td>0.02</td>
<td>25.0</td>
<td>2.5\times 10^6</td>
</tr>
<tr>
<td>{}^{74}\text{W} \text{186}</td>
<td>123</td>
<td>1.2 \times 10^{-9}</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
effect of which has been neglected in calculations) in this transition since a slight admixture (\(S^2 = 0.05\)) will bring the observed retardation factor quite close to the other analogue transitions. The \(E_2\) transitions on the other hand are also enhanced but comparatively by a small factor (\(F \approx 15\)). This order of enhancement in the \(E_2\) transition probability may be accounted for in terms of weak surface coupling\(^{17}\) in which the last odd nucleon induces a quadrupole moment in the rest of the nucleus, which is responsible for the enhanced \(E_2\) transition. The effect may be expressed in terms of an increase in the effective proton charge. An interesting feature which emerges out of the results is that the retardation factor for \(M_1\) transition decreases as one moves away from the closed shell of protons (\(Z = 50\)), while the \(E_2\) enhancement factor increases e.g. the enhancement factor in the case of Cs isotopes (\(Z = 53\)) is \(\sim 7\) while for Pr isotopes (\(Z = 59\)) is \(\sim 15\). This behaviour clearly indicates the contribution of the collective motion to the single particle wave functions which as a consequence weakens the \(L\)-forbiddenness and increases the \(E_2\) transition probability. A similar behaviour has been found by Berlovich et al.\(^{18}\) to exist in the europium isotopes.

The 55 keV transition in \(^{103}\text{Rh}\) which proceeds from the 95 keV excited state \((59/2^+)\) has the observed transition probability much in agreement with the calculated transition probability for \(M_1\) radiation than \(E_2\) radiation and thus it may be assumed to be predominantly of \(M_1\) character. The result is supported from the conversion coefficient\(^{18}\) and angular
correlation measurements. On the same basis we may argue that the 294 keV transition from the second excited state of Pr$^{143}$ proceed primarily as E$_2$ radiation and the 214 keV transition from the second excited state of Cs$^{131}$ proceed with comparable admixture of the M$_1$ and E$_2$ radiations. The nuclei Tb$^{159}$, Lu$^{175}$, Ta$^{181}$ and W$^{186}$ fall under the region of large spheriodal deformation. The E$_2$ transition probability in the two nuclei Tb$^{159}$ and W$^{186}$ is enhanced by a factor $\geq 100$ indicating the effect of collective motion of the nucleons. The M$_1$ and E$_2$ transitions in the other two nuclei Lu$^{175}$ and Ta$^{181}$ are retarded. This rather unexpected behaviour in the collective region is explained on the basis that the concerned transitions in these nuclei take place within the states of different rotational band and are forbidden by the asymptotic selection rules.$^{19}$

$\ell$-FORBIDDEN M$_1$ TRANSITIONS.

The experimental matrix element for $\ell$-forbidden M$_1$ transitions have been compared with the single particle matrix element and the matrix element calculated by the theory of Arima et al.$^7$ based on the configurational mixing. In the single particle matrix element calculations account has also been taken of the seniority statistical factor beside the statistical factor. The results of these calculations have been made for a large number of configurations, but only those values have been listed which lie within a few factors of the experimental value. In the table, columns 2 and 3 give the proton and neutron
### TABLE 3

**EXPERIMENTAL AND ARIMA'S et al. MATRIX ELEMENTS**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Proton Configuration</th>
<th>Neutron Configuration</th>
<th>Type</th>
<th>m²</th>
<th>F</th>
<th>m²</th>
<th>F</th>
<th>m²</th>
<th>F</th>
<th>m²</th>
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<td></td>
<td></td>
<td>L</td>
<td>52</td>
<td>1030.529</td>
<td>2.42</td>
<td>0.50</td>
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<td></td>
<td>(1g$_7$/2)$^3$</td>
<td>(1h$_{11}$/2)$^{12}$(2d$_5$/2)$^6$</td>
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<td>131Cs</td>
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<td>23</td>
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<td>133Cs</td>
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c) E. Ye Berlovich, G.M. Bukat, Y. K. Gusev, V.V. ILIN, V.V. NIKITIN and M.K. NIKITIN
   Phys. Letters 2, (1962) 344
configurations respectively of the ground state and columns 4th, 5th, 6th, 7th and 8th represent respectively, the type of transitions, Like (L) or unlike (U), the single particle model matrix element for allowed M₁ transition, the retardation factor F, the matrix element from the theory of Arima et al., and the experimental matrix element. The last two columns represent the calculated and experimental values of magnetic moment ²⁰

The analysis of the results indicate that, though the seniority statistical factor is effective in bringing the theoretical values nearer to the experimental ones, yet the experimental values of the matrix element for ℓ-forbidden transitions are much off from the single particle estimates and that this results in a large retardation factor for such transitions. The large retardation factor is evidence for the fact that these ℓ-forbidden M₁ transitions cannot be explained by the simple single particle picture in which the transition takes place from one pure state to another pure state. But the comparison of the experimental matrix elements with those calculated from Arima's theory, in which the transition takes between states whose zeroth order wave functions have been mixed with the excited configurations, show that such a picture yield theoretical values quite near to the experimental values. The configurations which give the best agreement with the experimental values are invariably the same as those suggested by the comparison of the experimental and theoretical values of the
magnetic moments. For example, in the case of I$^{129}$, the experimental value of the matrix element lies between the theoretical values of the matrix element for the configuration $(1g_{7/2})^3L$ and $(2d_{5/2})^2(1g_{7/2})^1L$, and the magnetic moment data also support the same configurations. The same situation holds in the case of Cs$^{131}$, the experimental value of 0.112 for $m^2$ lies between the theoretical values 0.102 and 0.125 corresponding to the configurations $(1g_{7/2})^4(2d_{5/2})^1L$ and $(1g_{7/2})^2(2d_{5/2})^3L$. The magnetic moment data also support the same configurations.

For Cs$^{133}$ there is only one configuration $(2d_{5/2})^4(1g_{7/2})^1$ which is supported both by matrix element comparison and the magnetic moment comparison of the experimental and theoretical values. For Pr$^{141}$ however, a small negative value of quadrupole moment and the comparison of the experimental and theoretical values of magnetic moment support the configuration $(1g_{7/2})^6(2d_{5/2})^2$ whereas the matrix element support the configuration $(1g_{7/2})^4(2d_{5/2})^4$ more than $(1g_{7/2})^6(2d_{5/2})^3$. For Pr$^{143}$, it is difficult to make such a comparison due to lack of experimental value of the magnetic moment.

The analysis also reveals that the nucleons in this region show a systematic trend in occupying the $1g_{7/2}$ and $2d_{5/2}$ subshells. To start with, the nucleons prefer the $1g_{7/2}$ subshell unless it is half-filled as is evident from the configuration of I$^{129}$ and Cs$^{131}$. The experimental matrix element for I$^{129}$ is close to $(1g_{7/2})^3$ configuration while in the case of Cs$^{131}$, the matrix element is close to $(1g_{7/2})^4(2d_{5/2})^1$. 
### TABLE 4

**RATIO BETWEEN EXPERIMENTAL AND THEORETICAL VALUES OF MATRIX ELEMENTS**

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<th>$I_f$</th>
<th>$I_f$ (Sec.)</th>
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<th>$m_{s.p.}$</th>
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<td>191</td>
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<td>0.09</td>
<td>48.5</td>
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<td>$s_{1/2}$</td>
<td>$3.5\times10^{-10}$</td>
<td>.062</td>
<td>26.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{205}_{122}$Te</td>
<td>205</td>
<td>$d_{3/2}$</td>
<td>$s_{1/2}$</td>
<td>$1.7\times10^{-9}$</td>
<td>.042</td>
<td>26.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{207}_{124}$Te</td>
<td>353</td>
<td>$d_{3/2}$</td>
<td>$s_{1/2}$</td>
<td>$1.2\times10^{-9}$</td>
<td>.014</td>
<td>26.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
corresponding to the maximum number of nucleons in the \( 1g_{7/2} \) subshell, though the ground state in the two cases is different. But once the total number of the nucleons (outside the closed shell at 50) exceeds more than half the number required to fill the \( 1g_{7/2} \) subshell, nucleons start preferring the \( 2d_{5/2} \) subshell leaving \( (1g_{7/2}) \) subshell unfilled. This preference for \( (2d_{5/2}) \) subshell goes on until it is completely filled. The later trend is evident from the configurations of \( \text{Ca}^{133}, \text{Ca}^{135}, \text{La}^{137}, \text{La}^{139}, \text{Pr}^{141}, \) and \( \text{Pr}^{143} \).

In Table 4 (column 5) the results of the half-life measurements for \( l \)-forbidden \( M_1 \) transitions are presented over a wide range of nuclei. In those cases where we have repeated the measurements we have taken our own values in preference to the values given in literature.\(^{21-24}\) The half-lives are converted into radiative half-lives by taking into account the total conversion coefficients obtained from the Rose's table. In a few cases of low energy transition the conversion correction could be made by utilizing measured values of \( \lambda_K \) and \( K/L \) ratios, where reliable data were available. The theoretical values for matrix element \( m_{s.p.} \) in column 7 are the ones calculated from the single particle picture. The calculated values of the matrix element from the theory of Arima et al. (column 8) are given only for one configuration for which the best agreement with the experimental value is noted. In the last two columns of the table the ratios of the experimental matrix elements with the single particle model matrix elements and the matrix elements calculated by the theory of Arima et al. are given.
The experimental values of the matrix elements are plotted on a logarithmic scale which are shown in fig. 37. The points for the same N (Neutron number) are joined by a straight line. The solid line drawn through the points is an arbitrary line. It is drawn to see, if there is any special trend. Though it is not very conclusive, fig. 37 shows some shell effect, corresponding to the magic numbers at 28, 50, 82 and 126. At these magic numbers the observed matrix element decreases by a large factor. In the region of 28 ≤ N ≤ 50 the l-forbidden M1-transition takes place between $p_{3/2} \rightarrow f_{5/2}$ states and the matrix element increases as we go away from the magic number 28 of neutrons till it attains a maximum value around $N = 44$ (Br$^{79}$) after that the value starts falling down. A similar trend is reproduced more clearly in the region 50 ≤ N ≤ 126, where the transition takes place between $\frac{3}{2} \rightarrow \frac{1}{2}$ (odd neutron nuclei) and $\frac{5}{2} \rightarrow \frac{7}{2}$ (odd proton nuclei). The value of matrix element at N=69 corresponding to Te$^{121}$ is ~1 while it drops by a factor of ten at the magic number N=82 corresponding to La$^{139}$. The same situation arises again at N=126 in the case of Thallium isotopes. The trend is also supported if we observe the change in matrix element for a given Z and increase the neutron number. If, with the addition of a pair of neutrons the nucleus approaches towards magic number (N=82), the value of the matrix element shows a downward trend. Examples of this effect are Te$^{121}$ - Te$^{123}$ - Te$^{125}$, Xe$^{129}$ - Xe$^{131}$, I$^{129}$ - I$^{131}$ whereas if the addition of a pair of neutrons takes the nucleus away from the magic number the behaviour is reversed i.e. the increase in neutron number increases the matrix
element which is evident from the pairs Pr$^{141}$-Pr$^{143}$, Eu$^{149}$-Eu$^{151}$. The pairs Cs$^{131}$-Cs$^{133}$-Cs$^{135}$ and Pm$^{145}$-Pm$^{147}$ shows however, low exceptions to this general trend.

Similarly if we look for the variation of $m^2$ with proton number for a fixed value of N, the same regularity as mentioned above is observed e.g. the pairs $^{53}$I$^{129}$-$^{55}$Cs$^{131}$, $^{131}$I$^{129}$-$^{55}$Cs$^{133}$ and $^{55}$Cs$^{135}$-$^{57}$La$^{137}$ show a general downward trend of matrix element with the increase in Z, while the pairs $^{57}$La$^{139}$-$^{59}$Pr$^{141}$, $^{59}$Pr$^{143}$-$^{61}$Pm$^{145}$-$^{63}$Eu$^{147}$ show a rise in the value of the matrix element. The exception is met with the pair $^{50}$Sn$^{119}$-$^{52}$Tl$^{121}$ which is probably due to the reason that closed shell at Z=50 plays some role in reducing the matrix element. The low value of matrix element in the case of Sn$^{117}$ may also be explained on the same basis.

To see if this effect is really the shell effect we have plotted in fig. 38a the ratio of $\frac{m^2_{\text{exp}}}{m^2_{\text{P.O.}}}$ (or retardation factor) for these $\ell$-forbidden M1-transitions in the region $50 \leq N \leq 126$ where an ample data is available. It is evident that the retardation is much above unity and lies between the values of 40 and 800. The minimum value of 40 is for nuclei away from the magic number and maximum value is for nuclei at the magic number N=82. This discrepancy is explained on the basis that, since at magic number the states are truely represented by the shell model wave functions, the magnetic dipole transition between two such states which differ in orbital angular momenta.
is strictly forbidden, and hence a large deviation of the matrix element is expected.

Fig. 38b shows the plot of \( \frac{m^2_{\text{cal.}}}{m^2_{\text{exp.}}} \) where the \( m^2_{\text{cal.}} \) are the calculated values from the Arima's theory based on configurational mixing. It is striking to note that the ratio has been brought down to a value around unity for a large number of nuclei. For nuclei with magic number of neutron or near to them there always exist a configuration which yields a value very near to the experimental value. This indicates that the picture of configurational mixing is very satisfactory at magic numbers, which further supports the shell effect. Since the zeroth order wave functions have been assumed in the calculation of Arima's et al. to be the shell model wave functions which are less perturbed by the other effects of nuclear dynamics only at the magic numbers. The smooth decrease of the ratio \( \frac{m^2_{\text{cal.}}}{m^2_{\text{exp.}}} \) for \( N > 82 \) clearly indicates that the effect of collective motion of the nucleons starts playing part in perturbing the zeroth order wave functions and thus the observed matrix element can no longer be explained by the configurational mixing.

TRANSITIONS IN DEFORMED NUCLEI.

It has been shown in the discussion of Table 2 that out of the four nuclei which fall under the region of large spheroidal deformation, two nuclei \(^{159}\text{Tb}\) and \(^{186}\text{W}\) show considerable enhancement of \( E_2 \) transition probability (F 100). The spin sequence (shown in fig. 31) \( 3/2, 5/2, 7/2 \) in \(^{159}\text{Tb}\)
<table>
<thead>
<tr>
<th>Nucleus</th>
<th>E (keV)</th>
<th>T(_1) (obs)</th>
<th>B(E_2) (exp)</th>
<th>B(E_2) (coul)</th>
<th>Q(_0)</th>
<th>E(_k-E_R) (n.m.)</th>
<th>(\beta)</th>
<th>(\frac{J}{I})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{159}_b) T(_b)</td>
<td>79 (\leq 9 \times 10^{-10})</td>
<td>0.13 (\geq 0.43)</td>
<td>1.23</td>
<td>(\geq 4.47)</td>
<td>0.27</td>
<td>(\geq 0.22 &lt; 0.41)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{186}_b) T(_b)</td>
<td>1.15 (\times 10^{-9})</td>
<td>E(_2)</td>
<td>0.71</td>
<td>0.75</td>
<td>5.97</td>
<td>-</td>
<td>0.213 0.372</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 6**

OBSERVED HALF-LIFE AND VARIOUS DEFORMATION PARAMETERS IN \(^{159}_b\) and \(^{186}_b\) NUCLIDES
(odd mass) nucleus characterises the typical deformed rotational spectrum of an axially symmetric structure. Further the energy ratio between the first two excited states at I=7/2 and I=5/2 is equal to \( \approx 2.38 \) which is in excellent agreement with the ratio 2.4 (Eq.5.36) predicted by the unified model. Thus, the levels at 136 keV (I=7/2) and at 57 keV (I=5/2) belong to the same rotational band associated with the ground state I=K=3/2. Similarly the excited state at 123 keV in \(^{136}\text{Xe}\) (even-even) nucleus correspond to the first (2+) rotational state.

It is interesting to compare the values of B(E2) from life time measurements with those obtained from Coulomb excitation measurement, and to calculate various other parameters like quadrupole moment, gyromagnetic ratios and moment of inertia etc so as to know about the mechanism responsible for the collective effects. The result of these calculations are presented in table 5. The various columns in the table represent respectively, the nuclides, energy of \( \gamma \)-transition, measured half-life, the \((E2/M1)\) mixing amplitude, the downward \(E2\) reduced transition probability from half-life measurement, the downward reduced transition probability from Coulomb excitation measurement, the Quadrupole moment \((Q_0)\), the difference between gyromagnetic ratios due to intrinsic motion and collective motion \((g_k - \bar{g}_R)\), the nuclear quadrupole deformation parameter \((\beta)\), and the ratio between actual moment of inertia and the moment of inertia due to rigid rotator. The upward transition probability from Coulomb excitation was obtained from the literature after applying the correction for the branching ratio and the conversion coefficient of the \( \gamma \)-radiation. The
upward transition probability so obtained was reduced to
downward transition probability by taking into account the
statistical factor as given by (1.7).

The result of the present half-life measurement
in the case of W has an excellent agreement with the result
of Coulomb excitation, while the lower limit to the value of
$B(E2)$ in the case of Tb is about $\frac{1}{2}$ of the value derived from
Coulomb excitation experiment. The value from Coulomb excitation
is however subject to correction due to insufficient data of the
conversion coefficient and the branching ratio for 136 keV,
but probably it may not bring the value near to the measured
lower limit. The large value of the quadrupole moment clearly
indicate the considerable deviation of both the nuclei from
their spherical shape. The low value of $J_{1/2}$ in the case of
W indicates a major contribution due to residual interactions
which decreases the actual moment of inertia. A smaller value
for the deformation parameter $\beta$ in the case of W than in Tb
(The lower limit in this case) evidently reflects the growing
contribution of the residual interactions, which as a consequence
tend to collapse the nuclear deformation.

The nuclear level scheme in $L_{\alpha}^{175}$ is well explained by
Nilsson on the basis of single particle motion in an axially
symmetric spheroidal shell. According to Nilsson the ground
state in $L_{\alpha}^{175}$ is assigned to be as $7/2^- 7/2^+ [404]$ and the 343
keV level as the first excited intrinsic state $5/2 5/2^+ [402]$. A
similar pattern is observed in $T_{\alpha}^{181}$ in which the later occurs
at 482 keV. The $M_1$ or $E_2$ transition between these two intrinsic
<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Initial State $I K\pi [NN^\pi \Lambda]$</th>
<th>Final State $I' K' \pi' [N' N'^\pi' \Lambda']$</th>
<th>Amplitudes of configuration</th>
<th>Mixing $\epsilon = 0.3$</th>
<th>$\lambda_\gamma$ (cal)</th>
<th>$\lambda_\gamma$ (obs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>343</td>
<td>5/2, 5/2+ [402]</td>
<td>7/2, 7/2+ [404]</td>
<td>$lg [443^-] \hspace{1cm} 9/2$</td>
<td>$-0.257$ $lg [443^+] \hspace{1cm} 9/2$</td>
<td>$-0.204 M_1 \hspace{1cm} 9 \times 10$</td>
<td>$7 \times 10$</td>
</tr>
<tr>
<td></td>
<td>(No 31)</td>
<td>(No 25)</td>
<td>$lg [443^-] \hspace{1cm} 7/2$</td>
<td>$+0.119$ $lg [444^+] \hspace{1cm} 7/2$</td>
<td>$+0.979$ $E_2 \hspace{1cm} 3.5 \times 10$</td>
<td>$1.8 \times 10$</td>
</tr>
<tr>
<td>482</td>
<td>5/2, 5/2+ [402]</td>
<td>7/2, 7/2+ [404]</td>
<td>$lg [442^+] \hspace{1cm} 9/2$</td>
<td>$-0.257$ $lg [443^+] \hspace{1cm} 9/2$</td>
<td>$-0.204 M_1 \hspace{1cm} 31 \times 10$</td>
<td>$2.3 \times 10$</td>
</tr>
<tr>
<td></td>
<td>(No 31)</td>
<td>(No 25)</td>
<td>$lg [443^-] \hspace{1cm} 7/2$</td>
<td>$+0.119$ $lg [444^+] \hspace{1cm} 7/2$</td>
<td>$+0.979$ $E_2 \hspace{1cm} 6 \times 10$</td>
<td>$5.8 \times 10$</td>
</tr>
</tbody>
</table>
states is $K$ allowed ($K_1 - K = 1 \leq \lambda$) but it violates the selection rule associated with the asymptotic quantum number ($\Delta K = 1, \Delta \Lambda = 1$). As a consequence of the later selection rule the observed transition probability is retarded by a large factor relative to the single particle estimates (Table 2). We have calculated these transition probabilities using Nilsson’s wave functions so as to observe, whether these longlife transitions can find proper accounts in the unified theory. The results of these calculations alongwith the various parameters assumed in the calculations are presented in table 6. The columns 1st and 2nd in the table list the nuclide and the energy of the $\gamma$-transition respectively. Quantum numbers associated with the initial and final states are given in column 3rd and 4th. Column 5th in the table lists the amplitudes of the partial wave functions which comprises the initial and final individual particle states according to Nilsson (normalized to $a_{2L_\Lambda}^2 = 1$) for a fixed value of deformation parameter ($\varepsilon = 0.3$). The last two columns of the table give the calculated and observed values of the transition probabilities.

It is evident from the table that the calculated value of $M_1$ transition in Lu$^{175}$ is close to the observed value while the similar transition in Ta$^{181}$ shows a large degree of retardation ($\sim 10^3$). The $E_2$ transitions on the other hand are enhanced in both of the nuclei, the degree of enhancement being larger in the case of Lu$^{175}(2 \times 10^2)$ than Ta$^{181}(10)$. The inhibition of the $M_1$ transition may be explained on the fact that the dominant component of the initial state is the partial wave
function $2d_{5/2}(422, \frac{1}{2})$ while for the final state the same is $1g_{7/2}(442, \frac{1}{2})$ these two wave functions have opposite sign of $\Sigma$ and have $l$ values (orbital angular momenta) that differ by two units and thus the magnetic dipole transitions between these two states are $l$-forbidden. But this does not explain the enhancement of $E_2$ transition probability since one should expect the $E_2$ transitions even more retarded as the collective $E_2$ transitions between two states having $\Delta K=1$ are completely forbidden. A plausible explanation for the enhancement of $E_2$ transition probability may however be given if one considers the mixing of the first rotational state ($I=7/2$, $K=5/2$) associated with the rotational band of $I=K=5/2$, in the ground state $I=K=7/2$ by rotational particle interaction (coriolis interaction), since the effect of even a small mixing may be effective to enhance the transition between two rotational band. The different order of enhancement of $E_2$ transition probability and retardation of the $M_1$ transition probability in the two nuclei may be understood due to the variation in the amplitude of mixing in the two cases.
REFERENCES


HALF-LIFE OF THE FIRST EXCITED STATE OF $^1^{129}$

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Abstract: The half-life of the first excited state of $^1^{129}$ has been measured from the slope of the delayed coincidence curve using time-to-pulse-height converter. The half-life was found to be $T_\frac{1}{2} = (1.59 \pm 0.13) \times 10^{-8}$ sec.

1. Introduction

Jha et al. \(^1\) have estimated the lower limit to the mean life of the first excited state of $^1^{129}$ from the nuclear resonant absorption in $^1^{129}$. We have measured the half-life of the same level by the delayed coincidence technique using a time-to-pulse-height converter.

2. Experimental Arrangement

The block diagram of the equipment employed for the measurement of the half-lives is shown in fig. 1. The time-to-pulse-height converter (TPH) was similar to that described by Weber, Johnstone and Cranberg \(^2\). A few changes were, however,

Fig. 1. Block diagram of the slow-fast coincidence circuit.

\(^1\) Present address: Department of Physics, A & M College, Texas, U.S.A.
made in the original circuit of the time-to-pulse-height converter to make it suitable for our purpose. For measuring the half-life of an excited state the radiation which terminates on the level whose half-life was to be measured was fed to the start channel and the radiation through which the level decays was fed to the stop channel of the TPH converter. The radiation feeding to the stop channel was properly shaped in amplitude and width by a pulse shaper so as to ensure good resolution.

The source was placed symmetrically between two scintillation counters each consisting of 6810A photomultiplier tubes. A NaI(Tl) crystal of size 2.5 cm diam. x 1.3 cm thickness was mounted on one of the photomultiplier tube to detect low energy $\gamma$-rays, while on the other an anthracene crystal was coupled to detect $\gamma$-rays of higher energies. Both crystals were mounted in aluminium cans, the thickness of which was kept sufficient to avoid the detection of beta particles arising from the disintegration of Te$^{129m}$ and its daughter I$^{129}$. This reduces the unwanted counting rate and thus increases the stability and performance of the TPH converter.

In the present experiment, the anode pulses from the anthracene counter were fed to the start channel while the pulses from the anode of NaI counter were fed to the stop channel. The energy selection of the two radiations was accomplished by taking the output from the tenth dynode so as to avoid the saturation of high energy pulses at the later stages. The outputs were fed to the cathode follower, linear amplifier and to the single-channel pulse-height analyser, where the energy of the particular event was selected. The outputs of the two pulse-height analysers were fed to the slow coincidence. The coincident pulse was used to gate the 20-channel pulse-height analyser on which the spectrum from the time-to-pulse-height converter was displayed. The 20-channel analyser therefore records the number of events as a function of pulse-height which in turn is proportional to the delay between the two selected events.

3. Calibration and Performance

The annihilation radiation from Na$^{22}$ positrons was used as a prompt source to calibrate the instrument. Known delays with the help of 125 ohm, RG63/U coaxial cables were inserted in the stop channel of the TPH converter. The position of the prompt peak was recorded for the different settings of delays and a calibration curve (delay/channel) as shown in fig. 2 was plotted. The curve was found to be linear over the range of delays involved in the measurements of half-lives in the present cases. The slopes of the two sides of the prompt curve (shown in fig. 3) were measured as $T_1 = 0.36 \times 10^{-9}$ sec and $T_2 = 0.42 \times 10^{-9}$ sec. The slight asymmetry of the curves is not due to any instrumental fault but is attributed to the fact that the pulses from anthracene were more sharp in rise time than pulses from the NaI(Tl) crystal.

4. Measurements

4.1. THE 80 keV LEVEL IN Cs$^{133}$

The half-life of the first excited state in Cs$^{133}$ was measured to test the working of
Fig. 2. Calibration curve of time-to-pulse-height converter for two different settings of gain.

Fig. 3. Prompt decay curve of Na$^{22}$ annihilation radiation of positons.

The apparatus. A 0.1 $\mu$Cur sample of Ba$^{133}$ was evenly placed between the two counters. The singles spectrum of Ba$^{133}$ in NaI(Tl) showed three prominent peaks
corresponding to 32 (X-rays), 80 and 355 keV. The single channel on the NaI side was set to accept the 80 keV γ-ray while on the anthracene side we used the single channel as a discriminator to accept all the pulses above 80 keV. The anthracene crystal was covered with a circular lead sheet of 0.12 cm thickness to minimize the detection of unwanted 32 keV X-rays. It also reduces the recording of the false prompt coincidences produced due to the Compton scattered events from the anthracene and detected in the NaI counter. With all these precautions the delayed curve for Cs$^{133}$ was obtained as shown in fig. 4. The half-life of the level was calculated from the slope of the curve and was found to be $T_\frac{1}{2} = (6.08 \pm 0.4) \times 10^{-9}$ sec, which confirmed the measurements of Graham and Bell $^3$.

4.2. THE 27 keV LEVEL IN I$^{131}$

Graves and Mitchell $^4$ suggested that the 41 d activity of Te$^{129m}$ decays primarily to the 74 min state of Te$^{129}$ which in turn disintegrates through β-emission. About 72% of beta goes to the 27 keV level and about 15% goes to a level at 502 keV which populates the first excited state of I$^{129}$ through the emission of the 475 keV γ-ray. Coincidences were recorded between the 470 keV γ-ray and 27 keV γ-ray for the measurement of the half-life of the 27 keV state. The single channel on the NaI side was adjusted to accept the peak of 27 keV while the single channel on the anthracene side was set on the high energy end of 470 keV γ-rays. The anthracene crystal was covered with 1 mm of lead to stop X-rays and 27 keV γ-rays to be detected.
in the start channel. The delayed coincidence curve obtained with the above adjustment is shown in fig. 5. The half-life of the level calculated from the logarithmic slope of the curve was found to be $T_\frac{1}{2} = (1.59 \pm 0.13) \times 10^{-8}$ sec, as compared to the estimated mean life $\tau = 1.5 \times 10^{-8}$ sec reported by Jha et al. \(^1\) as a result of nuclear resonant absorption measurements.

Fig. 5. Delayed coincidence curve of the 27 keV level in $^{118}$I.

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References

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