High spin states of $^{204}$At: search for isomeric states and evaluation of shears band structure

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High spin states of neutron deficient Trans-Lead nucleus $^{204}$At were populated up to $E_x \sim 8$ MeV through the $^{12}$C + $^{197}$Au fusion evaporation reaction. Decay of the high spin states including prompt and delayed gamma ray emission were studied to understand the underlying nuclear structure. The level scheme, which was partly known from earlier studies, was extended further through our experiment and analysis of spin and parity of the associated levels. An isomeric $16^+$ level ($\tau = 52(5)$ ns), corresponding to $M2$ transition, was established from our measurements. Attempts were made at interpretation of the excited states based on multi quasiparticle and hole structure involving $2f_{5/2}$, $1h_{9/2}$, and $1i_{13/2}$ shell model states, along with moderate core excitation. Magnetic dipole band structure over the spin parity range: $16^+ - 23^+$, which was found in the earlier Gammasphere study, was confirmed and explored in more detail, including the missing cross-over $E2$ transitions. Band-crossing along the shears band was observed and compared with the evidence of similar phenomena in the neighboring neutron deficient $^{202}$Bi, $^{205}$Rn isotones and the neighbouring $^{203}$At isotope. Based on comparison of the measured $B(M1)/B(E2)$ values for transitions along the band with the semiclassical model based estimates, the shears band of $^{204}$At was firmly established along with the level scheme.

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I. INTRODUCTION

The nuclear structure of the neutron deficient nuclei very near the doubly magic $^{208}$Pb nucleus has been one of the major areas of experimental investigation for many reasons. Firstly, many of these nuclei were studied to look for applicability of shell model with moderate core excitation to explain the high spin states\cite{1,2,3}. These studies were possible due to the availability of cooled Hyper Pure Germanium (HPGe) based gamma ray detectors with unprecedented energy resolution to pin point the basic structural subtleties. Secondly, the yield of neutron deficient trans-Lead nuclei populated to high spin states by fusion evaporation pathway is very low due to depletion of the compound nuclei by the competing fission channels. However, large array of HPGe detectors and the Clover detectors made available over the last three decades, along with versatile techniques of channel selection, made it possible to probe these nuclei to very high spin and excitation energy. Thirdly, these nuclei with a few valence protons and neutron holes, which belong to relatively high $j$ orbitals ($f_{5/2}, h_{9/2},$ and $i_{13/2}$), are expected to manifest various co-operative phenomena as the collectivity sets in for the high spin states.

With moderate core excitations as the basis, these nuclei ($Z \sim 82, N \sim 120$) first evolve from a spherical to weak oblate shape. The valence particles and holes tend to align along the rotational symmetry axis giving rise to evolution of collective phenomena, the simplest manifestation being the observation of a series of magnetic dipole transitions between the high spin states which appear to be regularly or semi-regularly placed following some order pattern. The magnetic dipole band, interpreted...
physically by the shears mechanism, has been explained by the tilted axis cranking (TAC) model\cite{4, 5}. Shape co-existence and shape transition due to transformation from weak oblate shape to prolate shape occur as the neutron number decreases further. This was first experimentally observed in this mass region in $^{180}$Pb\cite{6}. These were also observed in the neutron deficient Polonium isotopes produced in the high spin states by Coulomb excitation of post accelerated beams of Polonium isotopes at the REX-ISOLDE facility\cite{7}. Theoretical attempts were also made using Relativistic Mean Field (RMF) and other many body techniques to explain the results. Exclusive RMF calculations were also done to predict the shape evolution in the neutron deficient At isotopes\cite{8}. Multiple minima on the potential energy surfaces (PES) predict shape coexistence for Astatine isotopes around $A \sim 200$. The shape stabilizes from weak oblate around $A \sim 204$ towards spherical shape at larger $A$ values.

Magnetic dipole bands were first observed in neutron deficient isotopes of Pb\cite{9}. Following these studies, a number of magnetic dipole bands were discovered in nuclei around Lead with onset of weak oblate deformation\cite{10, 11}. Only a few magnetic dipole bands were found in nuclei for $Z = 84$ and above. These are: $^{205}$Ru\cite{12}, $^{206}$Fr and $^{204}$At\cite{13} and recently in $^{201}$At\cite{14} and $^{203}$At\cite{15}. In almost all the cases, these shears bands are created based on the coupling of a few high spin protons involving $h_9/2$ and $i_{13/2}$ orbitals and the neutron holes in the $i_{13/2}$ sub shell. Gammasphere study of the $^{204}$At\cite{13} nucleus revealed the dipole band, however, the corresponding spin parities were not assigned due to unavailability of data on the gamma transitions of the neighbouring states, which are either feeding the states belonging to the dipole band or fed by these states. Furthermore, cross over $E2$ type intra-band transitions could not be observed or studied. Qualitative or quantitative estimates based on the TAC or other empirical models could not be done to understand or compare the band structure with theoretical predictions.

In this paper, we have attempted to establish the level scheme, which was partly known. Attempts are also made to find isomeric states which are in general, abundant in the trans-Lead nuclear region. The shears bands observed in $^{204}$At earlier, has been evaluated in more detail and established to be in reasonable agreement with its mechanism of formation on the basis of the shears mechanism with principal axis cranking (SPAC) model.

II. EXPERIMENT DETAILS AND DATA ANALYSIS

High spin states of proton rich Astatine nuclei ($^{204}$–$^{206}$At) were produced by bombarding a 5.0 mg cm$^{-2}$ self-supporting Gold (99.95% purity) target with $^{12}$C beam at 65 MeV and 75 MeV, provided by the TIFR-BARC Pelletron Linac facility, Mumbai. Estimation of formation cross sections of the evaporation residues (ER) and the fission yield were done using the code PACE-IV\cite{16}. Based on these calculations, $\sim 10 - 20\%$ of the fusion products at these bombarding energies are estimated to undergo fission. The recoil velocity of the compound nucleus was $\leq 1\%$ of c. The nucleus $^{204}$At was populated through the $(5n)$ channel whose yield was about $20\%$ of the total cross-section according to PACE code. The de-exciting prompt $\gamma$-rays were detected using the Compton suppressed HPGe Clover detector array (INGA)\cite{17} surrounding the target. At the time of the experiment, INGA comprised of 15 detectors, arranged in a spherical geometry of six different angles with three detectors at 157$^\circ$, four detectors at 90$^\circ$, and two clovers each at 40$^\circ$, 65$^\circ$, 115$^\circ$, and 140$^\circ$ with respect to the beam direction to enable angle dependent direction correlation of oriented states (DCO) and polarization direction correlation of oriented states (PDCO) measurements. The Clover detectors were calibrated for $\gamma$-ray energies and relative efficiencies by using $^{133}$Ba and $^{152}$Eu radioactive sources by placing them at the target position of the array. Two and higher fold Clover coincidence events with time stamps were collected by a fast digital data acquisition (DDAQ) system, based on Pixie-16 modules of XIA LLC\cite{18}. A time window of 400 ns was set for this coincidence between the fast triggers of individual channels. Time stamps from a real time clock (RTC), with dwell time of 10 ns, was used for the purpose. The time-stamped data from different Pixie modules were merged to a single data stream in off-line mode. The data sorting routine Multi pARameter time-stamped based CO incidence Search program (MARCOS) developed at the Tata Institute of Fundamental Research (TIFR)\cite{19, 20} was used to generate various symmetric and antisymmetric $\gamma-\gamma$ matrices and $\gamma-\gamma-\gamma$ cube in a RADWARE and INGASORT\cite{21, 22} compatible format for further analysis. Angle dependent asymmetric $\gamma-\gamma$ DCO matrices and crystal orientation dependent polarization matrices were constructed using MARCOS to assign the spin-parity to the excited states. To construct the level scheme of $^{204}$At, the coincidence and the intensity relationships of the $\gamma$-rays were taken into consideration. Single and double gates were set on the known $\gamma$-ray transitions in the $\gamma-\gamma$ matrices and $\gamma-\gamma-\gamma$ cube, for determining the coincidence relations. A few examples of gated $\gamma$-ray spectra from the $\gamma-\gamma$ matrix are shown in Fig. 3. The relevance of these spectra in the level scheme will be discussed in the next section (Sec. III). The multipolarities and the electromagnetic character of the observed $\gamma$-ray transitions for assigning the spin-parity of the levels, have been determined using the DCO\cite{23, 24} and the PDCO ratios\cite{25, 26}. For the DCO ratio analysis, the coincidence events were sorted into an asymmetric matrix with data from the 90$^\circ$ detectors and from the 157$^\circ$ detectors. The ratio of $\gamma$-ray intensities, obtained by setting gates on known stretched $E2$ or $M1$ transitions on the two axes of that matrix, were calculated through the following equation,
\[ R_{DCO} = \frac{I_{\gamma_2 \text{observed at } 157^\circ}}{I_{\gamma_2 \text{observed at } 90^\circ}} \text{, gated by } \gamma_1 \text{ at } 90^\circ \text{ and } \gamma_2 \text{ at } 157^\circ, \]

where, \( I_{\gamma_1(\gamma_2)} \) is the number of counts within a particular peak of the detected gamma ray. The mixing ratio \( \delta \) and the theoretical \( R_{DCO} \) were calculated using the software code ANGCOR [29] taking the spin alignment parameter \( \sigma/J = 0.3 \). Theoretically, for a stretched transition, the value of \( R_{DCO} \) would be close to unity for the same multipolarity of \( \gamma_1 \) and \( \gamma_2 \). For different multipolarities and mixed transitions, the values of \( R_{DCO} \) depend on the detector angles, mixing ratio (\( \delta \)) and the width of the substate population (\( \sigma/J \)). The validity of the \( R_{DCO} \) measurements was checked with the known strong transitions in \( ^{205}\text{At} \) [30] and with the calculated values. In the present geometry, the measured value of \( R_{DCO} \) for a known dipole transition (468 keV of \( ^{205}\text{At} \)), gated by a stretched quadrupole transition (664 keV ground state) is \( \approx 0.54 \) while for a quadrupole transition gated by a pure dipole, the calculated value is \( \approx 1.85 \). Moreover, the value of \( R_{DCO} \) for a stretched quadrupole transition (566 keV) gated by another stretched quadrupole transition (664 keV ground state) is \( \approx 1.01 \). These compare well with the theoretical values.

The linear polarisation may be experimentally measured by the use of the Clover detectors as Compton polarimeters utilising the direction of the scattered radiation to determine the electric or magnetic nature of the transition [27][28]. The asymmetry of Compton scattered polarised photons inside the detector medium, are defined as:

\[ \Delta_{DCO} = \frac{a(E_{\gamma})N_\perp - N_\parallel}{a(E_{\gamma})N_\perp + N_\parallel}, \]

where, \( N_\perp \) and \( N_\parallel \) are the number of \( \gamma \)-rays of a particular energy, Compton scattered in the planes perpendicular and parallel to the reaction plane. \( a(E_{\gamma}) \) is the correctional term due to the geometrical asymmetry of the Clover crystals in the array set up, and is defined as:

\[ a(E_{\gamma}) = \frac{N_\parallel(\text{unpolarised})}{N_\perp(\text{unpolarised})}. \]

This asymmetry correctional factor was evaluated as a function of energy using \(^{152}\text{Eu} \) and \(^{133}\text{Ba} \) sources placed at the target position inside the array and was found to be 1.05(4), over the energy range 300 – 1400 keV. The measured \( a(E_{\gamma}) \) values are shown in Fig. 1.

By using the fitted parameter \( a(E_{\gamma}) \), the PDCO of the \( \gamma \)-rays in \( ^{204}\text{At} \) have been determined. A positive value of PDCO indicates an electric-type transition whereas a negative value favors a magnetic-type transition. PDCO values could not be measured for the low energy and the weak transitions. The low-energy cutoff for the PDCO measurements was about 200 keV in this work. Like DCO, the validity of the method of the PDCO measurements was also confirmed from the known transitions in \( ^{205}\text{At} \). The experimental asymmetry, for the transitions of interest, was evaluated from the two \( \gamma - \gamma \) matrices. One axis of both the matrices corresponds to the event recorded in any clover detector while the other axis contains the coincident scattered events inside the clover detectors placed at 90\(^\circ\) with respect to the beam axis, in a direction perpendicular or parallel to the emission plane.

### III. EXPERIMENTAL RESULTS

The \( \gamma \)-ray spectroscopy of \( ^{204}\text{At} \) was attempted with the aims to confirm and extend the previously reported results [13], and to investigate in detail a possible magnetic rotational (MR) band within the framework of shell model approximation in this doubly odd \( \text{At} \) isotope. The ground state of \( ^{204}\text{At} \) has spin-parity of \( 7^+ \), and is known to be of \( \pi(1h_{1/2}) \otimes \nu(2f_{5/2}) \) configuration outside the \( ^{202}\text{Po} \) core. However, the 587 keV 10\(^{-7}\) first excited state is a \( j \)-forbidden isomeric state with \( \sim 100 \) ms life time, resulting from the \( \pi(1h_{9/2}) \otimes \nu(1i_{13/2}) \) configuration as identified earlier [31]. The main sequence of transitions including 601, 491, 717 keV gamma rays and the \( \Delta I = 1 \) possible shears band-like structure of transitions involving 131, 296, 299 and 246 keV gamma rays were identified by the previous workers [13]. All the previously observed gamma transitions were observed in the present experiment. Majority of the transitions in \( ^{204}\text{At} \) are reported here for the first time.

The proposed level scheme of \( ^{204}\text{At} \) (Fig. 2), obtained from the present experiment, is established using the \( \gamma - \gamma \) coincidence information, relative intensity, and multipolarity information from the \( R_{DCO} \), and linear polarisation measurements. The width of the arrows in the figure indicates the total decay intensity (sum total of gamma ray and expected internal conversion estimated from the Ref. [32]). The existing level scheme has been modified.
FIG. 2: Proposed level scheme of $^{204}$At obtained from the present work. Transition energies are rounded off to keV.
with better statistics and a few new branches of transitions identified in this work. From the prompt $\gamma - \gamma$ matrices, constructed from the online data taken at 75 MeV beam energy and by gating on the 601 keV ground state transition, the intense 491 keV transition (Fig. 3 (b)), and also on the Astatine $X$-rays, a significant number of new low lying transitions were observed. The sequences of transitions in the level scheme are indicated by the roman numerals (I - V). A few new transitions linking the $\Delta I = 1$ $M_1$ band (sequence V) with the ground state populating branch could also be observed and fitted into the level sequence. Further investigations into the cross correlation of the transitions reveal the main yrast sequence I. Gamma ray spectra, obtained by gating on the known transitions of the $\Delta I = 1$ band (Fig. 4), reveal six new cross-over transitions (Fig. 4 (a) inset) and several other new transitions. These new $\gamma$-rays are clearly visible in this sum gated spectrum, obtained by adding the gates on 295, 299 and 285 keV transitions. However, these were not found in coincidence with any of the known $^{205}$At or $^{203}$At gamma rays. DCO ratios and polarization asymmetry results were used to estimate the multipolarity and to ascertain the electric or magnetic nature of the transitions (Figs. 5, 6, and 7).

The level scheme of $^{204}$At has been extended to an excitation energy of $\lesssim 8.0$ MeV and $\sim 25 \, h$, and is a much improved one compared to the previously known level scheme reported in Ref. 13. The relative $\gamma$-ray intensities were measured and normalised using two different coincidence gates. In the first case, the gate was set on the 600.7 keV ground state transition. In the second case, intensities of the gamma transitions from the states above the $13^+$ state (the sequence V transitions and others feeding them) are normalized to the intensity of the 285 keV transition. Because of the existence of low lying isomers with half-lives (ns to ms), and also due to the large internal conversion of some of the levels, the intensity balance across the levels could be done with some approximations. For most of the transitions, relative intensities are corrected by taking into account the estimated electron conversion coefficients. The observed $\gamma$-rays and their relative intensities match qualitatively with those obtained by the previous workers. Based on the intensity correlations obtained from the gated spectra, the DCO and the PDCO ratios, the level scheme for $^{204}$At is clearly established as shown in Fig. 2.

There are more than one sequence of transitions passing through 491 keV ($11^+ \rightarrow 9^+$), which directly feeds the 601 keV state. Out of these, sequence II passing through 786, 635, 718 keV and the sequence IV consisting of 743, 475, 192, 167, 538 keV transitions were observed. The major sequence of transitions (III) passing through 110, 694 and 704 keV, extends via the sequence of $M_1$ band transitions (V) all the way to $E_x \sim 7$ MeV. In all the sequences, ordering of the transitions were cross-checked by intensity correlations and also by reverse gating as far as possible. About 30 new transitions, over and above those observed by Hartley et al., were found. All these lines were found in coincidence with the Astatine X-rays. A few relevant gated spectra are shown in Fig. 3 and Fig. 4. The 1680 keV level decays to 1092 keV level via 588.3 keV $\gamma$-rays (reported as 589 keV in the earlier work). From the measured $R_{DCO}$ and polarization asymmetry, it is concluded that the 588.3 keV transition has a pure dipole character with no change in parity. We were unable to observe any other new transitions to extend this branch beyond the 1680 keV level.

In the previous work by Hartley et al., the nature of 601 keV ground state transition was not clear and tentatively assigned as dipole. In the present work, however, this assignment is modified to electric quadrupole in nature based on DCO and PDCO measurements. The DCO ratio for this $\gamma$-ray has been measured by gating on the 491 keV $\gamma$-ray, which was known to be a quadrupole ($E2$) transition on the basis of angular distribution analysis. The 718 keV transition is confirmed in the present work as $E2$ transition based on the DCO and the PDCO ratios in agreement with the earlier results. Intensity correlation also confirms the order of
FIG. 4: (a) Representative spectra with gates on several in-band transitions belonging to the M1-band manifesting mainly the M1-band transitions and transitions in coincidence. A few weak crossover E2 transitions and the ground state populating 491-601 keV lines are indicated within inset. (b) Expanded plot of the spectra shown in (a) to bring out the weak transitions noted in the experiment. Contamination lines are indicated by *.

placement along the cascade.

The 2347 keV level[13] was found to decay through the 537 and 717 keV transitions via the 491 - 601 keV sequence. In the present work, this assignment was re-examined and modified as: 537.9 ± 2.9 and 717.8 ± 3.2 keV, and henceforth designated as 538 and 718 keV γ-rays respectively. It was observed that the 538 keV transition, though passing through the 491 - 601 keV sequence, was not in coincidence with the 718 keV γ-ray (Fig. 3 (a)). Therefore, the 538 keV transition is placed in the sequence IV depopulating the 1630 keV level. The 718 keV transition was identified as E2, whereas 538 keV was found to be M1. Newly observed 743, 475, 192, 167 keV γ-rays have been placed above the 1630 keV level in the sequence IV based on the corresponding coincidence and intensity relations (see Fig. 3 (a)), and were found to be M1. Similarly, 786 keV M1 and 635 keV E1 transitions are placed in the sequence II above the 1810 keV level. A new transition with $E_γ = 235$ keV, depopulating through sequence I and parallel to the sequence II, was identified as $E1$. This was observed only in the 718, 491 and 601 keV gate, but not in coincidence with any other transition of nearby parallel sequences.

A new sequence III, including 703.5, 693.6 and 110.1 keV transitions (see Fig. 3 (b)), was observed as feeding the 1092 keV 11+ level. The first two transitions were found to be $M1$. For the 110.1 keV transition, only DCO ratio estimation could be done. Based on our measured DCO ratio of $(1.14 ± 0.06)$, gated by the 601 keV $E2$ transition, $ΔJ = 0$, $E1$ $(11− → 11+)$ character was assigned. Based on this result, $(J^π)$ of $11−$ has been assigned to the 1202 keV level. The configuration of the initial and the final states are different as highlighted in the interpretation section. Intensity mismatch for the transition belonging to the sequence III was observed, which may be attributed partly to significant internal conversion ($α ∼ 0.4$). Weisskopf estimate for half life of this $E1$ transition was $1.4 × 10^{−13}$ sec. Despite our isomer search within the limitations of the experiment, no measurable half-life was found.

Several parallel sequences of transitions were observed between the 13− and 16+ states above the sequence III. Two such sequences are indicated in the level scheme of Fig. 2. The intensities of the 976 and the 442 keV transitions were nearly equal and so were those of the 718 keV and the 700 keV transitions. While building up the tentative level scheme of $^{204}$At, a few transitions, such as the 442 keV transition, were reported to have coincidence relationship with gamma rays belonging to the $M1$ band, although these could not be placed in the level scheme[13]. Based on our data and analysis, this was placed between the states 13− and 14−, along with other transitions, all of which are in coincidence with γ-rays belonging to the $M1$ band and the At X-rays. One 601.2 keV transition was found to exist in coincidence with the 600.7 keV ground state transition. The 601.2 keV transition could not be resolved from the 600.7 keV ground state transition and therefore, its intensity remained tentative and unevaluated. However, based on the DCO, PDCO measurements and placement of related transitions in the level scheme, the transition was assigned as $M2$ (see Fig. 2). Based on this tentative multipolarity assignment, the Weisskopf estimate of half life was $∼ 11$ ns, which indicates possible mismatch in intensity with respect to a faster related transition (eg. $M1$ or $E2$). The isomer half life for the associated 11− level could not be measured because of unresolvable proximity to the 600.7 keV ground state transition.

Figure 4 shows cascade of prompt γ-rays of the $M1$ band in the 295, 299 and 285 keV summed spectrum. As the statistics in the individually gated spectrum were poor, all these gated spectra were added to create the summed spectrum. The band-head energy and spin of the band has been suggested to be of 4018 keV and $16^+$, based on energy, spin summing of γ-rays and multipolarity information. However, any change in the band-head
spin and/or missing levels in between would simply shift the level scheme along the vertical axis. The relative placement of the $\gamma$-rays in the band are based on their coincidence relations and intensity profiles, taking into account the theoretical total electron conversion coefficients [32]. This ordering is same as reported earlier by Hartley et al. The spins and parities of the states in this band are assigned from the measured DCO and the PDCO ratios, wherever possible. The $R_{DCO}$ values of these transitions are very close to the expected values for pure dipole transitions. The negative values obtained for the PDCO ratios for the 285, 298, 295 and the 246 keV transitions, together with their $R_{DCO}$ values and high X-ray yield in coincidence, give clear evidence that they are predominantly $M1$ in nature. Since the other $\gamma$-rays like 131, 177 and 196 keV are also in-band with the $M1$ transitions, and manifested $R_{DCO}$ values expected for pure dipole transitions, we have assigned $M1$ nature for these $\gamma$-rays, although the sign of the polarisation asymmetry could not be determined unambiguously due to lower Compton scattering probability for $\gamma$-rays of such low energy ($\sim$ 200 keV). Six crossover $E2$ transitions were found (see Fig. 4(a) inset) in the present work which were not observed earlier. Measured DCO and the PDCO ratios identified the $E2$ nature of these transitions. Observation of crossover $E2$ transitions lead to conclusion beyond doubt about the correct ordering of the dipole transitions along the band. Doppler lineshape analysis to determine the life times and consequent estimation of the transition rates $B(M1)$ and $B(E2)$ could not be done due to limitations in our experimental arrangements. However, the ratio of reduced transition probabilities $B(M1)/B(E2)$ could be extracted from experimental $\gamma$-ray branching ratios of competing $\Delta I = 2$ and $\Delta I = 1$ transitions [33] as:

$$\frac{B(M1)}{B(E2)} = 0.697 \frac{E_2^3}{E_1^3} \frac{1}{1 + \delta^2} I_\gamma(\Delta I = 1)$$

(1)

$E_1$ and $E_2$ are the energy of the $M1(\Delta I = 1)$ and $E2(\Delta I = 2) \gamma$-ray transitions in MeV respectively. The value of $\delta$ determines the $E2/M1$ mixing ratio of the $\Delta I = 1$, $M1$ transition. The mixing ratio $\delta$, estimated from the DCO ratios for the 285, 295 and 299 keV $M1$ transitions belonging to the band in sequence V, were found to be $\lesssim 0.02 \pm 0.08$, indicating negligible mixing of $E2$ for these transitions. The experimental $B(M1)/B(E2)$ ratios are shown in Fig. 11 where ever it was possible to identify the crossover $E2$ transitions. These ratios are found to be quite large ($\gtrsim 30$ $\mu^2$), suggesting magnetic rotational nature of the band.

A few other band-like structures with large number of new transitions are also observed in the present work through conventional $\gamma-\gamma$ and $\gamma-\gamma-\gamma$ coincidence analysis. The sequence of 363, 669, 618, 455, 659 and 500 keV transitions were found to be in coincidence with the $M1$ band transitions and the At $X$-rays. These are placed above the $19^+$ states of the $M1$ band accordingly. The intensity profile of each transition was calculated from several alternative gates at 285 keV, 299 keV and 363 keV. Similarly, another two minor sequences of transitions composed of 447-887-220 keV and 589-793-309 keV have been placed above the $20^+$ and $21^+$ states of the $M1$ band respectively. The observed $\gamma$-rays belonging to these branches, can be seen in the spectra shown in Fig. 4.

Due to limitations in the counts and contaminations in some of the gating transitions, the electromagnetic characters of most of these transitions could not be firmly established. $M1$ character of the $362.7$ keV transition ($5096 \rightarrow 4733$ keV) was clearly established. Above this $5096$ keV level, only tentative DCO ratio estimation is possible, which indicates that these are mostly dipole transitions. In the absence of polarization data, we have only tentatively assigned the spin-parity of these states. Similar arguments may be given for other minor branches of weaker transitions for which, tentative spin assignment were done.

![DCO ratios](image_url)

**FIG. 5:** Plots of DCO ratios for a few transitions with respect to the 491 keV $E2$ transitions in $^{204}$At.

Search for an isomeric state, as found from the missing intensity balance, was carried out by generating time-difference spectra, constructed by the 285, 299, and 295 keV transitions above $16^+$ state as start and the 442 or the 700 keV transitions below the $16^+$ state as the stop signal. The spectra showed delayed nature in the form of asymmetric tail of a Gaussian distribution. As statistics in the individual spectrum was limited, a few of these spectra were added and shown plotted in the Fig. 8. A half-life of $52 \pm 5$ ns was extracted through exponential fit on the decay tail of the gated $\Delta T$ spectra for the 4018 keV level (Fig 8). This method is not suitable for finding isomers with half-lives $\lesssim 30$ ns because of limitations in the dwell time and the intrinsic time resolution of the HPGe Clover detectors. Similarly, limitations on the coincidence time window had limited our search for long lived-isomers with $\tau \gtrsim 200$ ns.
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vicinity of Z = 82 and N = 126, shell model estimations
by considering an inert core excitations involving a few

FIG. 6: Plots of DCO ratios for a few transitions with respect
to the 299 keV M1 transitions in $^{204}$At.

FIG. 7: Plots of PDCO ratios for a few transitions in $^{204}$At.

IV. INTERPRETATION

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As mentioned before, the $7^+ (\pi(1h_{9/2}) \otimes \nu(2f_{5/2}^{-1}))$
ground state and the $10^- (\pi(1h_{9/2}) \otimes \nu(1i_{13/2}^{-1}))$ first ex-
cited isomeric state of $^{204}$At were reported earlier[31].
The main sequence of 601-491-718 keV gamma ray transi-
tions, reported earlier[31] was also confirmed in our mea-
surements and firm spin-parity assignments were done
based on our DCO and PDCO measurements(see Fig. 2).
In addition, a significant number of linking new transi-
tions were established and placed in the level scheme.
Most importantly, one isomeric transition and some of
the crucial $E2$ crossover transitions were established
through our experiment to confirm the shears band struc-
ture at high spin in $^{204}$At. Interpretation of these ob-
servations through the geometric model was also done,
which will be discussed later (see Sec. IV C). In the fol-
lowing sections, interpretation of different types of tran-
sitions and their sequences are discussed along with sug-
gested predominantly single particle configurations and
weak collectivity of $^{204}$At as manifested from our analysis
and results from the neighbouring nuclei.

particles (both protons and neutrons) and corresponding
holes across the shell gap, have been attempted[3]. How-
ever, shell model calculations for $^{204}$At (Z = 85, N =
119) nucleus, with 3 proton particles and 7 neutron holes,
become quite complicated. Furthermore, onset of collec-
tive behavior, specially the formation of magnetic dipole
band is expected to occur in similar nuclei (eg. $^{202}$Bi[35],
$^{204}$Bi[1]) However, possible configuration of the low ly-
ning yrast levels as well as the high spin non-yrast states
can be assigned based on our experimental data and re-
lated analysis, systematics of neighbouring nuclei and
earlier results[13].

As mentioned before, the $7^+ (\pi(1h_{9/2}) \otimes \nu(2f_{5/2}^{-1}))$
ground state and the $10^- (\pi(1h_{9/2}) \otimes \nu(1i_{13/2}^{-1}))$ first ex-
cited isomeric state of $^{204}$At were reported earlier[31].
The main sequence of 601-491-718 keV gamma ray transi-
tions, reported earlier[31] was also confirmed in our mea-
surements and firm spin-parity assignments were done
based on our DCO and PDCO measurements(see Fig. 2).
In addition, a significant number of linking new transi-
tions were established and placed in the level scheme.
Most importantly, one isomeric transition and some of
the crucial $E2$ crossover transitions were established
through our experiment to confirm the shears band struc-
ture at high spin in $^{204}$At. Interpretation of these ob-
servations through the geometric model was also done,
which will be discussed later (see Sec. IV C). In the fol-
lowing sections, interpretation of different types of tran-
sitions and their sequences are discussed along with sug-
gested predominantly single particle configurations and
weak collectivity of $^{204}$At as manifested from our analysis
and results from the neighbouring nuclei.
A. Low lying states below 16\

Configuration of the 7$^+$ ground state with one proton in 1h$_9/2$ suggests that two more 1h$_9/2$ protons may be brought to the valence shell by breaking pairs leading to the configuration: $(\pi(1h_9/2)^3 \otimes \nu(2f_5/2))$, which can account for the level sequence in the range 9$^+$ to 13$^+$ (marked as (I) in Fig. 2). The negative parity states feeding the 13$^+$ level may have a possible configuration: $(\pi(1h_9/2)^3 \otimes \nu(1i_{13/2})^2) \otimes \nu(2f_5/2))$, leading to maximum spin $I_{\text{max}} = 17^+$ and marked as (II) in Fig. 2. This would involve promoting a neutron hole from $f_5/2$ to $i_{13/2}$, without changing the relatively robust proton configuration.

However, two more sequence of transitions were found to feed the 11$^+$ state. These are marked as (III) and (IV) in the level scheme in Fig. 2, and are likely to belong to different single particle configurations. One of the sequences leads to the $\Delta I = 1$ band lying above the the 16$^+$ level. For this sequence marked by (III), a tentative assignment of configuration: $(\pi(1h_9/2)^2 \otimes \nu(1i_{13/2})^3 \otimes \nu(2f_5/2))$ would account for the level sequence till $I_{\text{max}} = 14^-$. A configuration change is expected to happen above in the same sequence leading to the possible configuration: $(\pi(1h_9/2)^2 \otimes \nu(1i_{13/2})^2 \otimes \nu(1i_{13/2}))$, populating levels up to 21$^+$. Existence of isomeric transition ($T_{1/2} = 52 \pm 5$ ns) from $E_x = 4018$ keV 16$^+$ level is expected to be of magnetic quadrupole type, as inferred from our isomer lifetime, DCO and PDCO measurements (see Sec. III). Weisskopf single particle estimate of the life time based on the transition is $\sim 1 - 6$ ns, which is one order of magnitude lower than the experimental results. The difference may be attributed to the onset of collective behaviour.

The other level sequence marked as (IV) may be built up from the configuration: $(^{202}\text{Pb}(4^+) \otimes \pi(1h_9/2)^3 \otimes \nu(2f_5/2))$, leading to $I_{\text{max}} = 17^+$. Based on our observation of coincident K X-ray intensities and theoretical estimates, the 192 keV and 167 keV $M1$ transitions are expected to be significantly converted. Our search for isomeric nature of the associated levels did not yield any conclusive result. Though the 588.3 keV $M1$ transition feeding the 1092 keV level could be observed in our experiment, no further transition feeding the 1680 keV $12^+$ level could be found. No attempt was made to assign configuration to the feeding level.

B. States above 16\

As stated in the previous section, the isomeric 16$^+$ level has been interpreted to originate from the configuration involving coupling of $i_{13/2}$ proton to aligned $h_9/2$ proton pairs, along with neutron hole in $i_{3/2}$, leading to: $(\pi(1h_9/2)^2 \otimes \nu(1i_{13/2})^2 \otimes \nu(1i_{13/2}))$ configuration. It is worth mentioning that the same proton configuration was found to be responsible for the isomeric 29/2$^+$ state in $^{203}\text{At}$ [15]. Taking clue from this observation, it may be suggested that the above mentioned high-$j$ protons and the $i_{13/2}$ neutron hole will form the two angular momenta components contributing to the shears band observed in our experiment, with 16$^+$ as band head.

Quite a few gamma transitions are observed around the shears band. These are placed in the level scheme (see Fig. 2) which is extended up to $E_x \approx 8$ MeV. Based on the feeding levels and our DCO and PDCO measurements, the spin parity assignments are partly done for these levels. Some of these transitions are found to be feeding the levels belonging to the shears band. No attempt is made to assign configuration to the high spin states due to incomplete information available.

C. Shears band in $^{204}\text{At}$

Energy levels of the shears band $(I^\pi = 16^+ - 23^+$), with band-head energy $(E_0)$ as the reference, are plotted as function of the spin in the Fig. 9 (a), which clearly shows the expected quadratic pattern of a band. In addition, the nucleus was found to be weakly oblate with the quadrupole deformation parameter $(\beta_2 = -0.084)$, as estimated from the finite range droplet model (FRDM) [30]. Another estimate based on PES calculations using relativistic mean field (RMF) theory with NL3 effective interaction[8] predicts somewhat larger value $(\beta_2 = -0.143)$, though it indicates predominantly oblate deformation as well. Furthermore, based on earlier observations[13], and our measurements of DCO and PDCO ratios of the transitions belonging to the sequences above 16$^+$, magnetic dipole nature of the band is confirmed. Weak $E2$ cross-over transitions were clearly evident as interspersed within the band. In addition, high $j$ orbitals are involved as the active orbitals, resulting in weak oblate deformation and the shears band structure involving two blades of a shear, possibly along with coupling of the core angular momentum.

Existence of dipole bands are found in many of the neighbouring isotones of $^{204}\text{At}$ ($N = 119$). First observation of low energy magnetic dipole transitions between levels at high spin were first observed in the isotope $^{202}\text{Bi}$[25], followed by observation in $^{205}\text{Rn}$[12]. While the spacings of levels are regular in $^{202}\text{Bi}$, those of $^{205}\text{Rn}$ were found to be irregular. These are shown in the experimental routhian (ER) plots of Fig. 2. Recently, observation of similar M1 band with somewhat irregular spacings was reported in $^{203}\text{At}$[15]. ER plot of $^{203}\text{At}$ is also shown in the Fig. 9 which indicates similarity with that of $^{204}\text{At}$.

The MR bands identified in $^{202}\text{Bi}$ were suggested as arising from $2p - 1h$ proton configuration, with at least one of the protons in high-$j$ $h_{9/2}$ or $i_{13/2}$ orbital, coupled to one or more high-$j$ $i_{13/2}$ neutron holes. Estimated band head spins due to the coupling is expected to cover the range: $I = 10 - 16 \hbar$ of the band indicating that one configuration can build up the dipole band. No evidence of back-bending or band-crossing resulting from change of particle hole configuration is seen in $^{202}\text{Bi}$. 
On the other hand, evidence of band crossing was reported in $^{205}$Rn$^{12}$, which is included in the Fig. 9. Based on TRS calculations, two likely candidates for configuration of the dipole band of positive and negative parity were suggested. Band crossing due to alignment of $i_{13/2}$ neutron hole pairs around $\hbar\omega \sim 0.3$ MeV was evident. Though it is not supported by the large $B(M1)/B(E2)$ ratios for the lower rotational frequencies ($\hbar\omega < 0.2$ MeV) of the dipole band, another band crossing at $\hbar\omega \sim 0.15$ MeV might have occurred indicating another change of configuration or alignment of particle-hole pairs.

Back bending is clearly evident in Fig. 9 along the dipole bands for both $^{203}$At and $^{204}$At at $\hbar\omega \sim 0.25 - 0.3$ MeV. In $^{204}$At, this can be attributed to band-crossing resulting from change of particle-hole configuration. As mentioned in Sec. [V.B], the lower spin part of the band is accounted for by the $\pi(1h9/2)^2 \pi(i_{13/2}) \otimes \nu(1i_{13/2})$ configuration, while post band crossing configuration would arise from breaking of two more particle-hole pairs leading to $\pi(1h9/2)^4 \pi(i_{13/2}) \otimes \nu(i_{13/2})$. Core rotation is expected to play an important role here. Agreement or disagreement with the above mechanism at play can be made through theoretical calculations of observables such as: $B(M1)$ and $B(M1)/B(E2)$ for the shear bands using the semiclassical or geometric model$^{[10]}$ called shears mechanism with principal axis cranking (SPAC) model and compare with the experimentally extracted quantities. Details of the SPAC calculations and corresponding experimental results are discussed in the following section.

D. SPAC calculations for dipole band and interpretation of results

Details of the formalism of SPAC model with core rotation is given in Ref. $^{[31]}$. According to the energy systematics of the model, the total energy $E(I)$ for a given angular momentum $I$: $(I = j_{sh} + \hat{R})$, where $j_{sh}$ is the shears angular momentum and $\hat{R}$ is the core angular momentum contributing to the shears mechanism, is expressed as:

$$E(I) = E(\text{shears}) + E(\text{core}) + E_0,$$

where $E_0$ accounts for the potential energy, $E(\text{shears})$ and $E(\text{core})$ are the excitation energies imparted to the system through shears mechanism involving quasiparticle interaction and collective core rotation respectively. In case of nuclei around Lead region ($Z \sim 82$), the two blades of the shears can be separated into proton particles constituting one blade and neutron holes ($N < 126$) forming the other blade. The shears mechanism involves orientation of the two blades of shear carrying quasiparticle angular momenta $\vec{j}_\pi$ and $\vec{j}_\nu$, such that $j_{sh} = j_{\pi} + j_{\nu}$. Considering the rotation axis along $\hat{x}$, the core rotation angular momentum vector $\hat{R}$ must be oriented along $x$-axis. If $\theta_1, \theta_2$ are the tilt angle of $\vec{j}_\pi$, $\vec{j}_\nu$ respectively with the rotation axis $\hat{x}$, the magnitude of the core angular momentum can be written as:

$$R(I, \theta_1, \theta_2) = \sqrt{I^2 - (j_{\pi} \sin \theta_1 + j_{\nu} \sin \theta_2)^2} - j_{\pi} \cos \theta_1 - j_{\nu} \cos \theta_2.$$

The core angular momentum $\hat{R}$ is expected to make a small but non-zero correction to the component of the contribution from the shears mechanism.

![Diagram](image-url)
Based on the systematics of the effective interaction in the band-crossing may be accounted for by the \( \pi(1h_{9/2})^2 \pi(1i_{13/2}) \otimes \nu(1i_{13/2}) \) configuration, while post band-crossing configuration would arise from breaking of two more particle-hole pairs leading to \( \pi(1h_{9/2})^4 \pi(1i_{13/2}) \otimes \nu(1i_{13/2})^4 \). \( j_\pi = 12.5 \text{ h} \) for the proton quasiparticle blade of unstretched configuration and \( j_\nu = 5.5 \text{ h} \) for the neutron hole are considered. Post band-crossing, proton configuration changes but unstretched value of \( j_\pi = 16.5 \text{ h} \) is used, keeping the \( j_\nu \) unchanged.

Weak oblate deformation is observed in Astatine isotopes (e.g. \( ^{208}\text{At} \) \( (J^\pi = 10^-) \), with \( Q \sim -1.67 \text{ eb} \)). \( Q_{\text{coll}} = 1.8 \text{ eb} \) before band-crossing is used in our SPAC estimates to account for the collective core rotation. The effective quadrupole moment due to quasiparticle configuration is given by \( Q_{\pi} = E^\text{eff}_\pi \times (\frac{\pi}{e}) \) \( Q_\nu \). where \( Q_\pi, Q_\nu \) are the quadrupole moments of the valence protons and neutrons bound within the nucleus and \( e_\pi, e_\nu \) are the \( E2 \) polarization charges of the valence protons and neutrons. The polarization charge is given by \( e_\nu = (T_z + 1/2) e + e_{\text{pol}}(E2) \), where \( T_z \) is the third component of isospin with \( T_z = \pm 1/2 \) for protons and neutrons respectively, and \( e_{\text{pol}}(E2) \) is the \( E2 \) polarization charge. For the Lead region, \( e_{\text{pol}}(E2) \sim 3e \) is needed to match the experimental value. The extracted value of \( Q_{\text{eff}} \) from the experimental \( B(E2) \) results for the dipole band in \( ^{198,199}\text{Pb} \), found to be \( \sim 6.5 \text{ eb} \).

Collective contribution due to core rotation is neglected in arriving at the above result and therefore, somewhat smaller value \( Q_{\text{eff}} \sim 4 \text{ eb} \) is chosen as trial value in our case for \( ^{204}\text{At} \) to match with the experimental results.
This value also agrees with the estimate of $Q_{\text{eff}}$ based on the multiparticle configuration of the band.

In the SPAC calculation, adjustment of the parameters, such as $V_2$ and the core moment of inertia $J(I)$ are done to reproduce the energy levels through minimization. Extracted parameter values are: $V_2 = 0.8 \text{ MeV}$ up to the band crossing spin $I = 20 \hbar$. This is consistent with the experimentally extracted value of $\sim 0.3 \text{ MeV}$ per particle/ hole pair contributing to the shears mechanism [10]. Since the number of particle / hole pair increases above the band crossing, $V_2 = 1.8 \text{ MeV}$ is found to be reasonably consistent. Core moment of inertia $J(I)$ need to be increased at higher spin over the range 7.8–16.5 $h^2$/MeV. Core contribution to the total angular momenta is found to be $\lesssim 20\%$, highest contribution being $\sim 17\%$ at $I = 23 \hbar$. These results are in reasonable agreement with the systematics in $^{198,199}\text{Pb}$ [37], where $5–15\%$ core contribution to the total spin was reported. The spin ($I$), as function of the rotational energy for the shears band is plotted in the Fig. 11 (a). The results of SPAC minimization at each spin is adjusted to be in reasonable agreement with the experimental results. These are also plotted in the same figure.

The $g$-factors are used as input to calculate the magnetic dipole transition rates. These results are tabulated in Ref. [40]. The factors are obtained from time dependent perturbed angular distribution (TDPAD) experiments and found to be in good agreement with the shell model estimates. From the equivalent quasiparticle configuration, the adopted values used as input to SPAC estimates are: $g_\pi = 1.060(14)$ (from $^{209}\text{At}$) and $g_\nu = -0.150(6)$ (from $^{200}\text{Pb}$).

The $B(M1)/B(E2)$ ratios, obtained from the SPAC model based estimates are compared with those results obtained from our experiment using the measured intensities of the $M1$ and corresponding cross-over $E2$ transitions (see Eq. [1]). The mixing parameter $\delta$ is considered as negligible since the corresponding DCO ratios indicate negligible admixtures to the $M1$ transitions (see Fig. [9]). The results are shown in the Fig. 11 (b). The uncertainties in the experimental data are estimated from the intensity fitting errors, which are normally large because of weak cross-over $E2$ transitions. The SPAC model estimates along the shears band agree reasonably well, supporting the band crossing and the associated quasiparticle configurations constituting the shears band.

V. SUMMARY

The excited states of doubly odd $^{204}\text{At}$, leading to high spin states up to $\sim 8 \text{ MeV}$ and $\sim 25 \hbar$ have been observed from our experiment involving decay of the evaporation residue formed in $^{12}\text{C} + ^{197}\text{Au}$ fusion reaction with $^{12}\text{C}$ as projectile at 65 and 75 MeV beam energies. The level scheme, which was partially known from earlier studies, was extended through results of DCO and PDCO measurements using the Clover Detector array INGA with 15 detectors. Quasiparticle configurations involving valence proton particles and neutron holes in respective high $j$ orbitals are found to be able to account for the level scheme. One isomeric transition of magnetic quadrupole type is found through our isomer search over a limited range of time delay available and time resolution due to time stamping of on-line data with 10 ns tick of the real time clock in our experimental arrangement. Isomers with half life: $30 \text{ ns} \lesssim \tau \lesssim 200 \text{ ns}$ would be difficult to explore with limited statistics. Mismatch of intensity was found in a few cases, but the isomer search remained inconclusive. The life time of the $M2$ transition was found to be in agreement within the approximations for the single particle Weisskopf estimates.

Existence of shears band structure at high spin was observed earlier in Gammasphere experiment [13], but it is confirmed in our experiment with observations of the cross over $E2$ transitions and the spin parity assignments based on the DCO and PDCO ratio measurements. The
experimental $B(M1)/B(E2)$ ratios for the dipole band are shown to be in good agreement within the uncertainty limit with theoretical estimates based on the SPAC model, which takes care of the shears mechanism involving participating valence nucleons (particles and/or holes) at high-$j$ orbitals. The shears band structure is found to be due to participation of proton particles in the $1h_{9/2}$ and/or $1i_{13/2}$ and neutron hole in $1i_{13/2}$. Multiple protons are expected to contribute to the structure formation. Band crossing along the shears band have also been observed and accounted for on the basis of SPAC estimates.

Although the magnetic dipole bands were first found in the neutron deficient Lead isotopes with involvement of multiple $1i_{13/2}$ neutron holes, a significant number of other nuclei around $Z = 82$, such as $^{202}$Bi, $^{203}$Rn and $^{203,204}$At are observed. Similarities and differences in the nature of these dipole bands were illustrated and the results were found to be in reasonable agreement with the model based on shears mechanism, as proposed by Machiavelli et al.\[38\].

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