Spectroscopy of $^{201}\text{At}$ including an isomeric shears band and the $29/2^+$ isomeric state

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(Received 18 December 2014; published 24 February 2015)

The excited states of $^{201}\text{At}$ were studied and an isomeric $29/2^+$ state [$T_{1/2} = 3.39(9)\, \mu$s] was identified by using a fusion-evaporation reaction, a gas-filled recoil separator, and recoil gating techniques. The $29/2^+$ state is suggested to originate from the $\pi(h_{12}) \otimes [^{209}\text{Po}; 11^-]$ configuration, and it decays through the 269- and 339-keV $E2$- and $E3$-type transitions, respectively. Moreover, a cascade of magnetic dipole transitions that is suggested to originate from a shears band was observed by using recoil-gated $\gamma - \gamma(-\gamma)$ coincidence techniques.

DOI: 10.1103/PhysRevC.91.024324 PACS number(s): 23.20.Lv, 23.20.Nx, 23.35.+g, 27.80.+w

I. INTRODUCTION

The region of neutron deficient nuclei around lead offers a large variety of interesting nuclear phenomena. These phenomena include, for example, coexisting different nuclear shapes, sudden changes in the the ground-state deformation, and changes in the ground-state spin and parity between neighboring nuclei. In neutron-deficient even-mass polonium nuclei and changes in the ground-state deformation, phenomena include, for example, coexisting different nuclear states in isotopes $^{197}$Po

II. EXPERIMENTAL DETAILS

The experiment was performed in the Accelerator Laboratory at the Department of Physics at the University of Jyväskylä. The astatine nuclei of interest were produced using the fusion-evaporation reaction $^{165}\text{Ho}(^{40}\text{Ar},4n)^{201}\text{At}$. Production yields for the nuclei produced in this experiment can be estimated from the $\alpha$-particle energy spectrum shown in Fig. 1. The self-supporting holmium target had a thickness of 350 $\mu$g/cm$^2$. The $^{40}\text{Ar}^{8+}$ beam was produced using an electron cyclotron resonance ion source and was accelerated with the K-130 cyclotron to an energy of 172 MeV. Moreover, a typical intensity of 11 pnA (particle nA) and an irradiation time of 83 h were used for the production of $^{201}\text{At}$.

The JUROGAM II array consisting of Compton-suppressed high-purity germanium detectors (HPGe) was used to detect prompt $\gamma$ rays at the target position. The array consists of 24 clover [21] and altogether 15 PhaseI- [22] and GASP- [23] type detectors. The gas-filled recoil separator RITU [24,25] was used to separate the fusion-evaporation residues (later recoils) from the primary beam and other unwanted particles. The recoils were then guided through a multiwire proportional

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gas counter (MWPC) to the focal plane of RITU, where they were studied using the GREAT spectrometer [26]. In GREAT the recoils were implanted into a 300-μm-thick double-sided silicon strip detector (DSSD) surrounded by 28 silicon PIN diodes in a box arrangement. The delayed γ rays at the focal plane were detected with three clover detectors and one planar-type HPGe detector placed in close geometry around the DSSD. An add-back procedure was introduced to the analysis of all γ-ray data observed in clover-type detectors. Data from all channels were recorded independently using the triggerless total data readout (TDR) method [27]. Absolute time stamps for each event were given by a 100-MHz clock. The data analysis was performed using GRAIN [28] software. A more detailed description of the experimental setup is presented in Ref. [29].

III. RESULTS

A. 29/2+ isomeric state

Figure 2(a) shows the recoil-gated prompt γ-ray singles energy spectrum observed in JUROGAM II. Figure 2(b) shows the delayed γ-ray energy spectrum observed in the focal-plane clover array within 14 μs from the recoil implantation. This search time corresponds roughly to 4 times the half-life of the isomeric state under interest, and it is applied to the analysis of all delayed γ-ray spectra presented in this work. The deduction of the half-life is explained at the end of this section. When comparing these two spectra, two observations can be made: First, the same γ-ray transitions can be identified in both spectra, and some of these are previously known [6]. Second, the 269- and 339-keV transitions are present only in the delayed spectrum. These two observations suggest that there is a high-lying isomeric state in 201At, which is depopulated by the 269- and 339-keV transitions.

Figure 3 shows some examples of the γ-γ coincidence analysis of the focal-plane clover data. In Fig. 3(a) the energy spectrum of γ rays in prompt coincidence with the 269-keV transition is shown. In Fig. 3(b) a prompt coincidence with the 476-keV or the 594-keV γ-ray transition is demanded. The

FIG. 1. Raw α-particle energy spectrum observed in the DSSD obtained with the reaction used in this study.

FIG. 2. (a) Recoil-gated γ-ray energy spectrum observed in JUROGAM II. (b) γ-Ray energy spectrum observed in the focal-plane clover array within 14 μs from the recoil implantation.

FIG. 3. Recoil-gated delayed γ-γ energy spectra observed in the focal-plane clover array: (a) Energy spectrum of γ rays in prompt coincidence with the 269-keV γ ray. (b) Energy spectrum of γ rays in prompt coincidence with the 476-keV or the 594-keV γ-ray transition.
high focal-plane clover detectors. It is worth noting the abnormally 427-keV PIN diodes: (b) conversion electrons in prompt coincidence with the 269-keV transition observed in the planar detector. Prompt coincidence with the positive-parity cascade in \(^{201}\text{At}\) \([6]\). The spectrum shown in Fig. 4(a) recoils-gated delayed low-energy \(\gamma\)-ray energy spectrum observed in the planar detector. Prompt coincidence with the 269-keV \(\gamma\)-ray observed in focal-plane clover array. (c) same as in panel (b) with 476- or 594-keV \(\gamma\)-ray energy gate used.

427-, 746-, and 749-keV transitions are known to belong to the positive-parity cascade in \(^{201}\text{At}\) \([6]\). The spectrum shown in Fig. 3(a) suggests that the 269-keV transition mainly feeds this positive-parity cascade, and, respectively, Fig. 3(b) suggests that the 339-keV transition feeds the negative-parity cascade. The 476-, 594-, and 635-keV transitions were previously assigned to the negative-parity band \([6]\) in \(^{201}\text{At}\).

In addition to the transitions visible in the presented clover spectra, there are a few low-energy transitions that are only observed in the planar detector. Figure 4(a) shows the energy spectrum of low-energy \(\gamma\) rays observed in the planar detector in coincidence with the 269-keV \(\gamma\) ray observed in any of the focal-plane clover detectors. It is worth noting the abnormally high \(K_\alpha/K_\beta\) x-ray intensity ratio. This suggests that there is a \(\gamma\)-ray transition in the positive-parity cascade with a transition energy partially overlapping with the \(K_\alpha\) x-ray peak.

Observed \(\gamma\) rays below the isomer are listed in Table I, and the internal conversion coefficients were taken from the BrIcc \([30]\). Based on the multipolarity information and the \(I_{\text{TR}}(\text{FP})\) information for each transition, the spin and parity of the isomer is suggested to be \(9/2^+\).

The isomer decays mainly through the 269-keV \(E2\)-type transition, but also an \(E3\)-type transition with a transition energy of 339 keV has been observed. These transition-type assignments were confirmed by the conversion-electron energy spectra observed in the PIN diodes. These spectra are shown in Figs. 4(b) and 4(c). The deduced internal-conversion intensity ratio \(I_{\alpha}/I_{\gamma} = 0.93(5)\) matches well with the theoretical [30] value of 0.89(2) calculated for the 269-keV \(E2\)-type transition. The 339-keV \(K\)-conversion peak overlaps with the \(L+M+\cdots\) conversion peaks from the 269- and 276-keV transitions. Therefore, the number of 269- and 276-keV \(L+M+\cdots\) conversion events in the \(\sim 250\)-keV peak in Fig. 4(c) were estimated. These estimates were based on

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\(E_\gamma\) (keV) & \(I_{\gamma}\) & \(A_2\) & \(I_{\text{TR}}\) (FP) & \(I_{\alpha}\) (h) & \(I_{\gamma}\) (h) \\
\hline
46.5(2)* & 90(30)* & \(25/2^+\) & \(25/2^+\) \\
58.5(2)* & 6(2) & \(11/2^+\) & \(11/2^+\) \\
83.0(4) & 120(40)* & \(21/2^+\) & \(21/2^+\) \\
114.1(2) & 12(2) & \(11/2^+\) & \(11/2^+\) \\
130.3(2) & 3.9(4) & \(-0.36(7)\) & \(20(3)\) & \(17/2^+\) & \(17/2^+\) \\
216.3(3) & 1.3(3) & \(21/2^+\) & \(21/2^+\) \\
233.4(2) & 14.5(4) & \(-0.05(2)\) & \(24(3)\) & \(17/2^+\) & \(17/2^+\) \\
269.0(2) & 118(11) & \(29/2^+\) & \(29/2^+\) \\
275.5(2) & 6.6(2) & \(-0.47(2)\) & \(12(2)\) & \(25/2^+\) & \(25/2^+\) \\
299.5(2) & 40(2) & \(0.11(4)\) & \(60(6)\) & \(21/2^+\) & \(21/2^+\) \\
299.3(2) & 5.0(7) & \(21/2^+\) & \(21/2^+\) \\
339.2(2) & 14(2) & \(29/2^+\) & \(29/2^+\) \\
364.1(3) & 6.5(3) & \(-0.11(3)\) & \(8(2)\) & \(15/2^+\) & \(15/2^+\) \\
426.5(2) & 39(2) & \(0.14(7)\) & \(69(9)\) & \(17/2^+\) & \(17/2^+\) \\
476.2(2) & 33(1) & \(0.13(4)\) & \(21(4)\) & \(17/2^+\) & \(17/2^+\) \\
511.8(2) & \(-0.14(3)\) & \(38(7)\) & \(19/2^+\) & \(19/2^+\) \\
593.8(2) & 77(5) & \(0.08(2)\) & \(25(4)\) & \(17/2^+\) & \(17/2^+\) \\
635.1(2) & 100(3) & \(0.09(4)\) & \(42(6)\) & \(15/2^+\) & \(15/2^+\) \\
691.1(2) & 11(2) & \(11/2^+\) & \(11/2^+\) \\
745.5(2) & 74(2) & \(0.4(2)\) & \(72(8)\) & \(15/2^+\) & \(15/2^+\) \\
749.3(2) & 105(12) & \(13/2^+\) & \(13/2^+\) \\
876.1(2) & 19.4(6) & \(0.16(3)\) & \(24(3)\) & \(17/2^+\) & \(17/2^+\) \\
\hline
\end{tabular}
\caption{Observed \(\gamma\) rays following the decay of the \(^{201}\text{At}\) \(^{9/2^+}\) isomeric state. \(I_{\gamma}\) is the relative \(\gamma\)-ray intensity and \(A_2\) is the angular distribution parameter, and both are derived from JUROGAM II data. The \(\gamma\)-ray energy \(E_{\gamma}\) and the transition intensity at the focal plane \(I_{\text{TR}}(\text{FP})\) are deduced from the focal-plane clover data if not specified. Internal-conversion coefficients for the calculation of \(I_{\text{TR}}(\text{FP})\) were taken from Ref. \([30]\). \(I_{\text{TR}}(\text{FP})\) is normalized such that the 269-keV \(\gamma\)-transition has an intensity of 100.}
\end{table}
FIG. 5. Partial level scheme of $^{201}$At. Levels associated with the isomeric $\frac{1}{2}^+$ state \( T_{1/2} = 45(3) \text{ ms} \) lying at the excitation energy of 459 keV are shown in Ref. [29]. The number inside a circle indicates the number of a transition group used to categorize transitions. The mean lifetime of the $\frac{1}{2}^+$ state is taken from Ref. [6], and the rest of the information is from this work.

the intensity ratio $I_{\gamma}(260)/I_{\gamma}(276)$ [extracted from the spectrum shown in Fig. 3(b)], the number of observed 269- and 276-keV $K$-conversion events, and the theoretical $K/L + M$... ratios for the 269-keV $E2$ and 276-keV $M1$ transitions. The remaining events in the $\sim250$-keV peak belong to the 339-keV $K$ conversion. For the 339-keV transition this method yields the $K/L + M$... intensity ratio of 0.45(4), which is in agreement with the theoretical value of 0.416(8) for a 339-keV $E3$-type transition.

Figure 6 shows the time distribution between the recoil implantation and the subsequent 269-keV $\gamma$ ray observed in the planar detector. In addition, one of the 296-, 427-, 594-, 635-, 746-, or 749-keV $\gamma$ rays has been demanded to be observed in any of the focal-plane clover detectors in prompt coincidence with the 269-keV $\gamma$ ray. The logarithmic time scale method [31] yields a half-life of 3.39(9) $\mu$s for the 29/2$^+$ isomeric state. This half-life corresponds to reduced transition strengths of $1.33(4) \times 10^{-3}$ W.u. and $11(2)$ W.u. for the 269-keV $E2$- and the 339-keV $E3$-type transitions, respectively.

B. Shears band

Figure 7 shows the low-energy part of the double-gated prompt $\gamma$-ray energy spectrum. The other gate is a sum of gates 145, 198, 244, 272, 287, 317, and 335 keV, and the other is the sum of gates 427 and 746 keV. In the spectrum there are a number of low-energy $M1$ transitions. This transition-type assignment is supported by the stretched dipolelike angular distributions, and high x-ray yield in coincidence with these transitions. In Fig. 7 these $M1$ transitions are labeled with

FIG. 6. Time distribution between the recoil implantation and the subsequent 269-keV $\gamma$-ray transition observed in the planar detector. Prompt coincidence with a 296-, 427-, 594-, 635-, 746-, or 749-keV $\gamma$ ray in any of the focal-plane clovers is demanded. The logarithmic time scale method [31] yields a half-life of 3.39(9) $\mu$s. The longer living component of the distribution is a result from random $\gamma$-ray coincidences, originating, for example, from Compton scattering.
TABLE II. \( \gamma \)-ray transitions associated with the shears band. \( I_2 \) normalized such that \( I_1 \) (635keV) = 100. Intensities and energies are deduced from the sum of gates gates (746- and 427-keV transitions) \( \gamma \)-\( \gamma \) data.

| \( E_\gamma \) (keV) | \( I_1 \) | \( A_2 \) | \( I_1^* \) (\( h \)) | \( I_2^* \) (\( h \)) | \( B(M1)/B(E2) \) (\( \mu_2^2/\mu_e^2 \)) |
|-----------------|--------|-------|----------------|----------------|-----------------|
| 145.0(4)        | 3.7(3) | -0.5(2) | \( (^{25/2}Z^-) \) | \( (^{21/2}Z^-) \) | -               |
| 197.9(4)        | 1.6(2) | -0.80(12) | \( (^{33/2}Z^-) \) | \( (^{31/2}Z^-) \) | >8              |
| 244.4(4)        | 8.3(5) | -0.59(9) | \( (^{27/2}Z^-) \) | \( (^{25/2}Z^-) \) | >30             |
| 272.3(4)        | 3.5(3) | -0.45(11) | \( (^{35/2}Z^-) \) | \( (^{33/2}Z^-) \) | >35             |
| 286.9(4)        | 6.6(4) | -0.47(3) | \( (^{29/2}Z^-) \) | \( (^{27/2}Z^-) \) | >25             |
| 317.3(4)        | 6.7(4) | -0.81(9) | \( (^{33/2}Z^-) \) | \( (^{31/2}Z^-) \) | >30             |
| 335.0(4)        | 1.5(2) | -0.66(4) | \( (^{27/2}Z^-) \) | \( (^{25/2}Z^-) \) | >2              |
| 1068.9(4)       | 4.5(3) | -0.47(5) | \( (^{25/2}Z^-) \) | \( (^{23/2}Z^-) \) |                |

There are a large number of transitions in addition to those in the shears band and those below the \( 29/2^+ \) isomeric state. These transitions can be divided into three groups. Groups 1 and 2 consist of the transitions feeding the \( 21/2^- \) and the \( 29/2^+ \) states, respectively. Group 3 is formed by the transitions associated with the negative-parity ground-state cascade. Figures 8(b) and 8(a) show most of the transitions belonging to groups 1 and 2, respectively. In Fig. 8(a) the transitions in coincidence with the 716-keV transition are shown. The transitions connected with dashed lines form together, with the 716-keV transition, group 1. Figure 8(b) shows the \( \gamma \)-ray singles spectrum where the recoil has been isomer tagged with a 269-, 427-, 635-, 746-, or 749-keV delayed \( \gamma \)-ray transition observed in the focal-plane clover array within 14 \( \mu s \) from the recoil implantation. The transitions labeled with energy in Fig. 8(b) are those which feed the \( 29/2^+ \) isomeric state. The transitions belonging to groups 1–3 are listed in Table III. The level scheme of these groups were constructed based on the \( \gamma \)-\( \gamma \) coincidence information, the transition

higher than the 1069-keV transition intensity. Therefore there must be at least one additional, unobserved decay path.

FIG. 7. Recoil-gated prompt \( \gamma \)-ray transitions in coincidence with either the 427- or 746-keV transitions and any of the low-energy transitions listed in Table II. Transitions labeled with energy are suggested to belong to the shears band. Transitions marked with an asterisk are known to belong to the positive-parity cascade. The inset shows the high-energy part of the spectrum.

FIG. 8. Prompt \( \gamma \)-ray transitions observed in JUNOJAM II. In panel (a) transitions in coincidence with the 716-keV transition are shown. Transitions connected with a dashed line belong to group l together with the 716-keV transition. Panel (b) shows the singles \( \gamma \)-ray spectrum in delayed coincidence with any of the most intense \( \gamma \)-ray transitions (observed in the focal-plane clover array) below the \( 29/2^+ \) isomeric state. Note the different energy scales in panels (a) and (b).
TABLE III. Remaining observed γ-ray transitions. Information for the group 1 transitions is obtained from the sum-gated (296- and 427-keV transitions) γ-γ data. Information for group 2 is obtained from the 269-, 427-, 635-, 749-, or 749-keV delayed γ-ray tagged singles spectrum. The group 3 information is obtained from recoil-gated singles data. $I_I$ normalized such that $I_I(I_{355 \text{ keV}}) = 100$.

| Group | $E_γ$ (keV) | $I_I$ | $A_2$ | $I_π^a$ (h) | $I_π^f$ (h) |
|-------|------------|-------|-------|-------------|-------------|
| 1     | 402.6(4)   | 2.6(3) | −0.7(2) |            |            |
| 1     | 448.5(4)   | 2.8(2) | −0.4(2) |            |            |
| 1     | 540.5(5)   | 3.1(3) |         |            |            |
| 1     | 581.6(4)   | 2.1(2) | −0.44(7) |            |            |
| 1     | 607.8(4)   | 8.4(8) | 0.35(8) | $29/2^+$   | $29/2^+$   |
| 1     | 716.3(4)   | 11.9(7) | 0.46(4) | $29/2^+$   | $21/2^+$   |
| 2     | 135.0(4)   | 0.50(4) |         |            |            |
| 2     | 153.6(4)   | 0.47(4) |         |            |            |
| 2     | 206.2(4)   | 0.31(5) |         |            |            |
| 2     | 263.6(4)   | 1.2(2) | −0.26(9) |            |            |
| 2     | 297.5(4)   | 3.0(2) |         |            |            |
| 2     | 448.4(4)   | 2.9(2) | −0.3(2) |            |            |
| 2     | 538.2(4)   | 2.9(2) |         |            |            |
| 2     | 774.9(4)   | 1.7(2) | 0.29(4) |            |            |
| 2     | 870.5(4)   | 0.93(8) |         |            |            |
| 2     | 921.1(4)   | 10.1(6) | 0.20(3) | $33/2^+$   | $29/2^+$   |
| 2     | 1049.9(4)  | 2.2(2) | −0.7(3) |            |            |
| 2     | 1184.5(4)  | 1.7(2) | 0.40(8) |            |            |
| 2     | 1379.9(5)  | 1.4(2) |         |            |            |
| 3     | 371.7(4)   | 10.9(4) | 0.16(6) | $21/2^-$   | $21/2^-$   |
| 3     | 442.6(4)   | 6.0(2) | 0.35(8) | $21/2^-$   | $21/2^-$   |
| 3     | 917.8(4)   | 7.0(4) | 0.37(6) | $21/2^-$   | $17/2^-$   |

*Transition is not placed in the level scheme, as it is not in coincidence with other transitions in group 2. However, this transition is probably feeding the $29/2^+$ state.

IV. DISCUSSION

A. The $29/2^+$ isomeric state and related levels

Figure 9(a) shows the systematics of several negative-parity states observed in At nuclei compared to the lowest yrast states of their isotonic polonium partners. It is evident that the energy of the observed negative-parity states up to the $21/2^-$ state follow the energies of the yrast states in their even-even Po isotones. These findings support the earlier [6] interpretation that these negative-parity states in $^{201}$At originate from the weak coupling of an $h_{11/2}$ proton to the polonium core. This interpretation is also suggested for the neighboring isotopes $^{199}$At [7], $^{203}$At [6], and $^{205}$At [39]. In $^{197}$At the deviation of the level spacing is interpreted to originate from the strengthening of the odd proton coupling to the core [7]. In $^{195}$At and lighter isotopes [11,12] the $1/2^+$ intruder state originating from the $2(s_{1/2})^{-1}$ configuration becomes the ground state. Hence the scheme of observed excited states changes drastically. Also in the nearby francium nuclei $^{203}$Fr (isotope of $^{201}$At) and $^{205}$Fr ($^{201}$At + $\alpha$) the negative-parity states have been suggested to originate from the coupling of an $h_{11/2}$ proton to the radon core, see Refs. [40,41].

In addition to the isomeric $^{11-}$ [2596 keV, $\pi(h_{11/2}f_{5/2})$] state, also the $^{9-}$ [2261 keV, $\nu(f_{5/2}h_{11/2})$], $^{8-}$ [2237 keV], $^{7-}$ [2136 keV, $\nu(f_{5/2}h_{11/2})$, $^{5-}$ [1811 keV, $\nu(f_{7/2}h_{11/2})$, and $^{8+}$ [1774 keV, $\pi(h_{13/2})$] states have been observed in $^{200}$Po, which is the isomeric partner of $^{201}$At. Also second [2200 keV, $\pi(h_{13/2}f_{7/2})$, and third [2716 keV, $\nu(f_{7/2}h_{13/2})$] $^{8+}$ states can be expected to exist [42,43]. The $11^-$ isomeric state decays to the $9^-$ and $8^+$ states via $E2$- and $E3$-type transitions, respectively. In Fig. 9(b) the energy of selected polonium states in corresponding polonium isotonic partners. The data points with the error bars are floating in the level scheme. The error bars correspond to the maximum of estimated floating. In panel (c) the measured $B(M1)/B(E2)$ ratios for the decay of the lowest $17/2^-$ state in the odd mass atstatine isotopes $^{205+\text{At}}$ are shown. Data for all panels are taken from Refs. [4,6,10,32–38] and the present work. Neutron number of $^{201}$At is 116.
The observed isomeric $^{29}2^+$ state decays through the 269-keV $E2$- and 339-keV $E3$-type transitions. These two transitions have reduced transition strengths of 1.35(4) × 10^{-3} W.u. and 11(2) W.u., respectively. Suppression of the $E2$-type transition is understandable, as it requires a significant change of $\pi(h_{9/2}^2 \otimes 200\text{Po})$ in the single-particle configuration. Structural changes in the $\pi(h_{9/2}^2 \otimes 200\text{Po})$ for the $E3$-type transition are much simpler and it involves octupole correlations [44]. Hence it is favored. The same isomeric state has been observed in 199At [7], 205At [8], 209At [9], and 211At [10]. In 199At only the $E2$ transition (0.044 W.u.) has been observed to depopulate the isomeric state. In 205At both transitions have been observed with reduced transition strengths of 1.8(5) × 10^{-3} W.u. and 19(1) W.u. for the $E2$- and $E3$-type transitions, respectively. In 209At and 211At only the $E3$ transition has been observed with transition strengths of 24(2) W.u. and 16 W.u., respectively [8]. Hence the measured reduced transition strengths in 201At are comparable with the corresponding values in neighboring nuclei. The measured transition strength in the 201At for the $E3$-type transition is comparable with the value of ~12 W.u. [42] for the $E3$-type transition (11− → 8+) in 200Po. Also the 11− → 9− $E2$-type transition is strongly hindered (10^{-2} W.u., Ref. [42]) in 200Po.

From Fig. 9(b) one can also observe that the transition energy for the $E3$-type transition decreases as the neutron number decreases. The $E2$-type transition energy stays rather constant. As a result, the deexcitation of the $^{29}2^+$ isomeric state favors the $E2$-type transition in lighter and $E3$-type transition in the heavier astatine isotopes. The favoring of $E2$-type transition can also be seen as an enhancement of the reduced transition strength of the $E2$-type transition when the neutron number decreases, as mentioned above.

The $^{25}2^+$ states have been reported to have a mean lifetime of 156(3), 98(2), and 17(2) ns in the isotopes 207,205,209At, respectively [6,8,32]. If the lifetime of the $^{25}2^+$ state develops as might be expected as the neutron number decreases, it should be much shorter than ~20 ns in 201At. However, the experimental setup (10-ns time resolution) used in this study is not sensitive for lifetimes this short. An effort was made to extract the lifetime of the $^{13}2^+$ state (23(2) ns, [6]), resulting in a time distribution yielding a lifetime of ~20 ns. Similar analysis was made to extract the lifetime of the $^{25}2^+$ state; however, the result was a promptlike time distribution. Hence, based on the data obtained in this study, it can be only deduced that the lifetime of the $^{25}2^+$ state is much shorter than ~20 ns.

The $^{13}2^+$ state in astatine nuclei 197–205At is suggested to originate from the $\pi(i_{13/2})$ configuration [6–8]. In isotopes 197,199,201At at the $^{13}2^+$ level is fed by a strongly coupled rotational band, and the $^{13}2^+$ state is suggested to have an oblate deformation [7,35]. However, in 201At only the levels up to the lowest $^{13}2^+$ state show this rotational-like behavior. In the excited states higher than this, the rotational structure vanishes. Figure 9(c) shows the $B(M1)/B(E2)$ ratios for the decay of the lowest $^{17}2^+$ state in 197–205At. In isotopes lighter than 201At the ratio is small and rather constant. Starting from 201At the ratio grows rapidly as the neutron number increases. This together with the disappearance of the rotational band might indicate a decrease of deformation when moving towards heavier astatine isotopes. Hence the $^{13}2^+$ state in 201At is suggested to be weakly oblate.

The lowest $2^+$ state in 198Pb is known to lie at an excitation energy of 1064 keV [45]. This energy is comparable to the transition energies that feed the $^{29}2^+$ isomeric state (group 2). Hence the states feeding the $^{29}2^+$ might have a $\pi(h_{9/2}^2 \otimes |^{198}\text{Pb}; 2^+\rangle$-like configuration.

### B. Shears band

In shears bands a (high-$j$) proton and neutron are coupled. The coupling creates a total angular momentum vector that does not lie on any of the principal axes. The angle between proton and neutron spins ($j_p$, $j_n$) is called the shears angle, and it is often denoted with the symbol $\theta$. Once the proton and neutron states are known, the shears angle can be given using a semiclassical expression,

$$\cos \theta = \frac{\vec{j}_p \cdot \vec{j}_n}{|\vec{j}_p||\vec{j}_n|} = \frac{I(I+1) - j_p(j_p + 1) - j_n(j_n + 1)}{2\sqrt{j_p(j_p + 1)j_n(j_n + 1)}}. \quad (1)$$

When the excitation energy is increased, the shears angle decreases (like closing shears), increasing the spin of the system. Hence the name shears band. These shears bands have a few general properties that may be summarized as follows:

- (i) The states in the band (away from band crossings) follow the pattern of $E(I) - E_0 \propto (I - I_0)^2$, where $0$ refers to the band-head state.
- (ii) The band is formed from strong $M1$ transitions with weak $E2$ crossovers, typically $B(M1)/B(E2) > 20 \mu^2$ and $B(M1) \sim 2–10 \mu^2$.
- (iii) The structures have small quadrupole deformation.
- (iv) The active orbitals must involve high $j$ values.
- (v) The ratio of the dynamic moment of inertia over $B(E2)$ is large, >100 MeV^{-1}(eb)^{-2}, when compared to well-deformed [~10 MeV^{-1}(eb)^{-2}] or superdeformed [~5 MeV^{-1}(eb)^{-2}] bands.
The lack of band were identified to form a rotational-like cascade of rays and x-ray yield, the transitions in the suggested shears at lower energy. The shears “blades” may differ before and after the crossing. In as a “backbending” in the inset of the Fig. 10. The lengths of remain tentative with the information obtained in this study, but any level spin. The spin and excitation energy of the band-head state (i) listed above). The bump around spin and excitation energy labeling of the band-head state are to the band-head dominates over the shears mechanism. Text values in order to allow excitations from the or/ν132, 29/2+ orbital. Such excitations may require a breaking of a neutron pair, but excitation energies of ~3–5 MeV are enough to make this energetically possible. All of these single-particle states have a high-j value, such as is required to form a shears band (property (iv)). In the inset of Fig. 10, the 204At and 206Fr backbending is astonishingly similar when compared to 201At. This might suggest that the proton and neutron configurations in the shears bands of all these nuclei are similar. In the study by Hartley et al. [15] the proton and neutron configuration for 204At and 206Fr shears bands remained unknown. In these nuclei most likely the h9/2 and/or ν132, 5/2+ neutrons are involved in the configuration of the shears bands [15].

For the band-head states in shears bands, the shears angle is ~90°. Therefore, equation (1) can be used to calculate the band-head state spin in shears bands for different proton and neutron configurations. Similarly, by setting the shears angle to ~0°, the maximum spin can be calculated. A selection of the results of such calculations is presented in Table V, together with the sum of proton- and neutron-state level energies. Corresponding experimental values are 21/2 h and 2990 keV for the band-head state, and ~16 h and ~4200 keV for the observed band crossing. These experimental values match well with the calculated values shown in Table V, hence the proposed proton- and neutron-state configurations are \( \pi(1h9/2)^2 \otimes (f9/2, 19/2^+, 9^-) \) for the lower cascade and \( \pi((h9/2)^2 \otimes (f9/2, 19/2^+, 9^-)) \) above the band crossing. These configurations suggest a negative parity for the observed shears band. In several odd-mass lead isotopes.
lighter than $A = 197$ a similar alignment have been observed (Ref. [46] and references therein). In these nuclei the band crossing is caused by the alignment of $i_{13/2}$ neutrons.

V. SUMMARY

In the present study of $^{201}$At an isomeric $29/2^+$ state [$T_{1/2} = 3.39(9)$ ms] has been observed that is suggested to originate from the $\pi (h_{11/2}) \otimes ^{200}$Po$_{11}^-$ configuration. The isomer decays through the 269-keV $E2$ and 339-keV $E3$ transitions with reduced transition strengths of $10^3 \mu$W.u. and $11(2)$ W.u., respectively. Some other observed excited states with their spins and single particle configurations are summarized in Table IV. We have also observed a cascade of magnetic dipole transitions that is suggested to form a shears band. The results of this study agree well with the previous results in the neighboring nuclei and the overall systematics in this region of the nuclide chart.

ACKNOWLEDGMENTS

This work has been supported by the Academy of Finland under the Finnish Center of Excellence Programme (2012-2017). The authors also thank the GAMMAPOOL European Spectroscopy Resource for the loan of the detectors for the JUROGAM II array. Support has also been provided by the EU 7th framework programme, Project No. 262010 (ENSAR). U.J. acknowledges support from the Finnish Academy of Science and Letters and the Vilho, Yrjö, and Kalle Väisälä Foundation.