Coexistence of prolate and oblate bands with similar proton configurations in ^{121,123,125}I

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The sequence of states built on the second $\frac{7}{2}^+$ state in ^{121,123,125}I are interpreted to be associated with the low-K prolate $\pi g_{7/2}[420]\frac{1}{2}$ Nilsson orbital with admixtures from the nearby $\pi d_{5/2}[422]\frac{3}{2}$ and $\pi d_{5/2}[431]\frac{1}{2}$ orbitals on the basis of the particle-rotor model calculations. With the ground-state bands in these nuclei being already explained as arising from the oblate high-K $g_{7/2}$ and $d_{5/2}$ proton configurations, the present work indicates the coexistence of oblate and prolate deformed bands based on the same proton configuration in ^{121,123,125}I.

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I. INTRODUCTION

The odd-mass iodine nuclei with $A=117$–125 are characterized by the presence of a large number of bands, with the odd proton occupying the different Nilsson orbitals available near the Fermi level [1–6]. Both oblate and prolate deformed bands have been reported with a moderate quadrupole deformation, characteristic of transitional nuclei. With the availability of new experimental data in recent times, interpretations have been provided for several of these bands in the light of theoretical calculations. The ground-state yrast bands in the odd-A $^{121-125}$I arise from the oblate high-K $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals [3–6]. Excited $\pi g_{9/2}$ and $\pi h_{11/2}$ bands have also been observed in these as well as the lighter ^{117,119}I isotopes [1,2]. Three quasiparticle bands at an excitation energy of about 2 MeV are also reported in ^{119,121,125}I [2,3,6].

Liang *et al.* have perfromed potential-energy-surface (PES) calculations [7] in order to study the kind of nuclear shapes that are likely for the low-lying one quasiparticle configurations in the odd-A iodine nuclei. These calculations predict competing prolate and oblate shapes for the $d_{5/2}$ and $g_{7/2}$ configurations. Although the oblate states are predicted to be lower in energy for the iodine nuclei with $A\geqslant 121$ and the prolate states are favored for the lighter ^{119}I, the energy difference between the oblate and the prolate states are predicted to be small. This suggests that while the oblate high-K $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals are associated with the ground-state bands in ^{121,123,125}I [3–6], consistent with the predictions of the PES calculations, prolate deformed states based on the low-K proton $d_{5/2}$ and $g_{7/2}$ configurations are not ruled out in these nuclei. Liang *et al.* [3] have indeed pointed out subsequently that the states built on the second $\frac{7}{2}^+$ state in ^{121}I may be associated with the low-K $\pi g_{7/2}$ prolate configuration.

Interestingly, sequences of similar $\Delta I=2$ states built on the excited $\frac{7}{2}\frac{+}{2}$ state have been reported in the three odd-A iodine nuclei with $A=121$–125 [3–6]. Figure 1 shows the partial level schemes for these three nuclei, reported in Refs. [3–6]. The bandheads lie at an excitation energy of about 500 keV and decay to the $\frac{5}{2}^+$ ground state. Interband transitions to and from these states are either very weak or not observed at all. However, the literature, which confirms the ground-state bands to be associated with the oblate $d_{5/2}$ and $g_{7/2}$ orbitals, does not provide a clear interpretation of the structure of the states belonging to the above mentioned $\Delta I=2$ sequences in these nuclei. Considering the results of the PES calculations of Liang *et al.* [7] that predict competing oblate and prolate shapes associated with the $d_{5/2}$ and $g_{7/2}$ orbitals, the motivation in the present work is to study if the bands built on the second $\frac{7}{2}^+$ states in ^{121,123,125}I indeed have a prolate deformation and are associated with low-K $\pi d_{5/2}$ and $\pi g_{7/2}$ configurations.

II. THEORETICAL CALCULATIONS AND DISCUSSION

Theoretical calculations have been performed for ^{121,123,125}I within the framework of the particle-rotor model (PRM). Figure 1, as stated above, shows the experimental partial level schemes for these nuclei. Figure 2 presents the Nilsson diagram for ^{125}I. The results of the PRM calculations are summarized in Tables I and II and Fig. 3.

An axially symmetric deformed Nilsson potential [8] was used in obtaining the proton single-paricle energies for ^{125}I, plotted as a function of the quadrupole deformation parameter $\delta(=0.95\beta)$ in Fig. 2. The Nilsson parameters $\mu=0.48(0.54)$ and $\kappa=0.070(0.056)$ for the $N=4(5)$ oscillator shell were used in the calculation of the single-particle energies. These values of μ and κ were previously suggested from a theoretical fit to the available experimental bandhead energies in odd-proton nuclei over the whole $A=120$–140 region [9]. It is to be noted that the above (μ,κ) set, referred to as the fitted parameters, lower the energy of the $d_{5/2}$ orbital relative to the $g_{7/2}$ orbit in the Nilsson diagram (Fig. 2), in contrast to the single-particle spectrum derived from the standard (μ,κ) parameters [9]. Although most of the earlier calculations for the odd-A iodine nuclei used the standard values of these parameters [2,3], the fitted (μ,κ) values have been successful in reproducing the experimental data accurately in several nuclei in this mass region [10,11].

The Fermi level λ, which appears as a parameter in the PRM calculations, was chosen near the oblate $\pi g_{7/2}[404]\frac{7}{2}$ and $\pi d_{5/2}[413]\frac{5}{2}$ orbitals (Fig. 2) that correspond to the ground state in ^{125}I. It is interesting to note from Fig. 2 that the low-K $g_{7/2}$ and the $d_{5/2}$ orbitals tend to slope down and

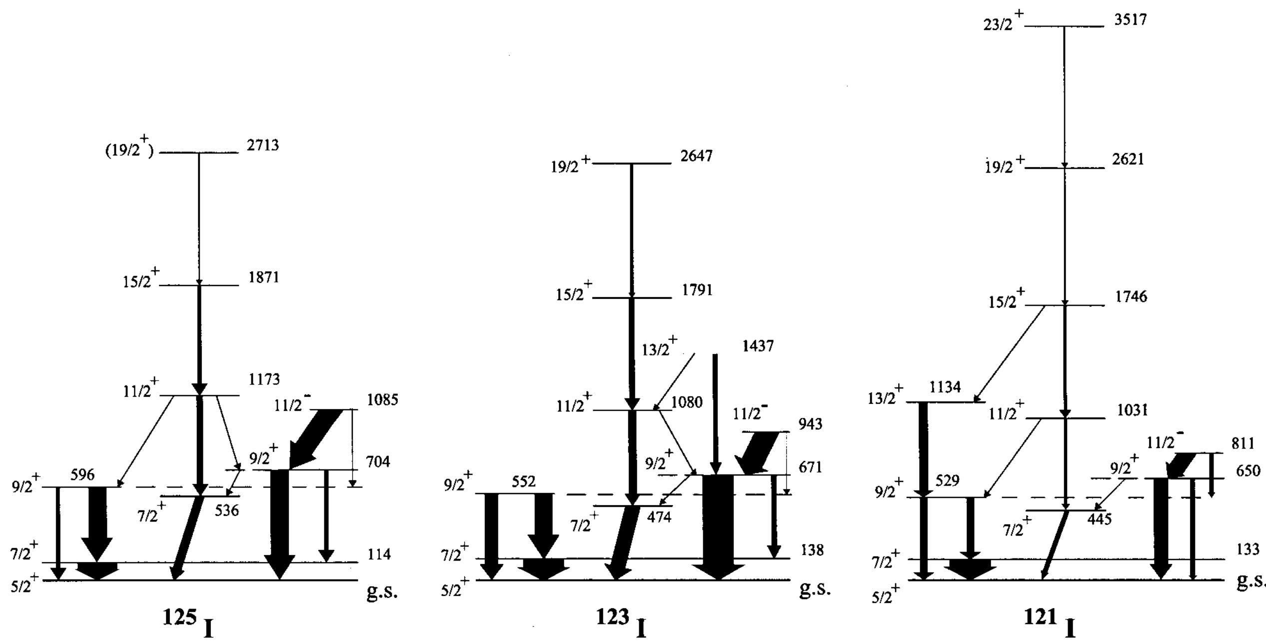

FIG. 1. Partial level schemes of ^{121,123,125}I showing the $\Delta I=2$ sequence of states built on the second $\frac{7}{2}^+$ state. Some low-energy states belonging to the ground-state band and a few other states are included to show the interband transitions to and from the $\Delta I=2$ band. The level energies are given in keV and the widths of the lines indicating the transitions are proportional to their relative intensities. Experimental data are taken from Refs. [3–6].

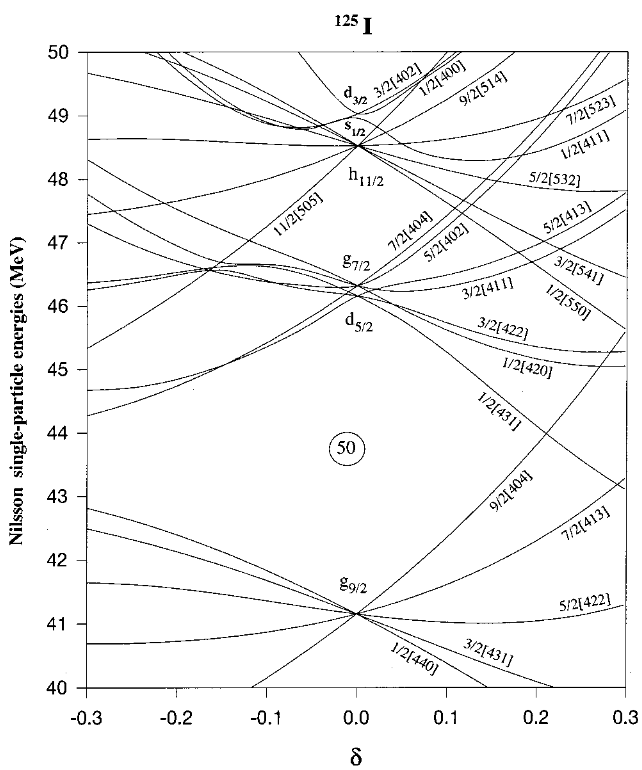

FIG. 2. Nilsson single-particle energies plotted versus quadrupole deformation parameter δ for ^{125}I. Nilsson parameters $\mu=0.48(0.54)$ and $\kappa=0.07(0.056)$ for the $N=4(5)$ oscillator shell from Ref. [9] were employed.

come near the Fermi level for a prolate deformation $\delta\sim0.2$. Hence, these $g_{7/2}$ and $d_{5/2}$ prolate orbitals are also expected to play a role in the band structure of ^{125}I. Similar arguments follow for ^{121,123}I from the Nilsson diagrams for these nuclei.

The details of the formalism for PRM are outlined in Ref. [12,13] and the references therein. The motion of the odd proton in the deformed axially symmetric Nilsson potential is coupled to the rotation of the core through the Coriolis interaction. The Hamiltonian of the odd-A nucleus is written as

$$H=H_{qp}^{o}+c\mathbf{R}\cdot\mathbf{j}+E_c(|R|), \tag{1}$$

where, H_{qp}^{o} is the Hamiltonian of the quasiparticle, given by

$$H_{qp}^{o}=\sum_k E_k\alpha_k^{\dagger}\alpha_k, \tag{2}$$

where E_k (quasiparticle energy) is $\sqrt{(\varepsilon_k-\lambda)^2+\Delta^2}$. Here, ε_k is the energy of a single particle moving in the deformed Nilsson potential and $\triangle$ is the pairing gap. The term $c\mathbf{R}\cdot\mathbf{j}$ in Eq. (1), originally introduced by Neergärd [14], describes the interaction between the core and the odd particle and the term $E_c(|R|)$ represents the collective part of the Hamiltonian. The coefficient c in the above equation can be expressed as

TABLE I. Experimental and calculated level energies for the $\pi g_{9/2}$ band in ^{121,123,125}I. Experimental data were taken from Refs. [3–6] and Nilsson parameter $\mu = 0.48$ and $\kappa = 0.07$ were taken from Ref. [9].

I^π	E_{level} (keV) Expt.	PRM	PRM
	A. ^{125}I ($\lambda = 44.846$ MeV, $\beta = 0.215$, $\alpha = 1.0$)	($\triangle = 0.58$ MeV)	($\triangle = 1.07$ MeV)
$\frac{9}{2}^+$	935.6	937	759
$\frac{11}{2}^+$	1269.8	1333	1153
$\frac{13}{2}^+$	1616.7	1723	1541
$\frac{15}{2}^+$	1997.3	2130	1944
$\frac{17}{2}^+$	2396.9	2557	2367
$\frac{19}{2}^+$	2814.9	2999	2808
$\frac{21}{2}^+$	3250.9	3453	3264
	B. ^{123}I ($\lambda = 45.00$ MeV, $\beta = 0.229$, $\alpha = .97$)	($\triangle = 0.65$ MeV)	($\triangle = 1.08$ MeV)
$\frac{9}{2}^+$	641.2	638	544
$\frac{11}{2}^+$	972.3	1017	921
$\frac{13}{2}^+$	1315.4	1395	1295
$\frac{15}{2}^+$	1690.2	1787	1686
$\frac{17}{2}^+$	2081.8	2184	2075
$\frac{19}{2}^+$	2500.8	2600	2494
	C. ^{121}I ($\lambda = 45.25$ MeV, $\beta = 0.242$, $\alpha = .94$)	($\triangle = 0.73$ MeV)	($\triangle = 1.09$ MeV)
$\frac{9}{2}^+$	434.9	438	402
$\frac{11}{2}^+$	798.0	804	766
$\frac{13}{2}^+$	1164.1	1174	1132
$\frac{15}{2}^+$	1551.9	1564	1522
$\frac{17}{2}^+$	1957.1	1973	1927
$\frac{19}{2}^+$	2381.7	2400	2352
$\frac{21}{2}^+$	2818.8	2840	2791

$$c \equiv \frac{(1-\alpha)}{\Im_2} = \frac{E_c(|R|=2)}{3\hbar^2}, \tag{3}$$

where $\Im_2$ is the moment of inertia for the 2^+ state belonging to the ground-state rotational band of the core and α is a free parameter obtained from a least-squares fit of the calculated energies with the observed level energies in a given band. When the moment of inertia of the core states is taken to be constant, α is identical to the usual Coriolis attenuation factor. In the present calculations where the experimental core energies have been used, the moment of inertia of the core states changes with the spin and the effective Coriolis attenuation factor becomes

$$\alpha_{eff} = 1 - \frac{\Im_R}{\Im_2}(1-\alpha). \tag{4}$$

For this, a version of the PRM reported by Müller and Mosel [15], has been used in which the level energies of the ground-state band of ^{126}Xe (core) [16], reported up to spin 10^+, were fed directly as input parameters.

TABLE II. Experimental and calculated level energies and the corresponding wave functions for the positive parity band based on the second $\frac{7}{2}^+$ state in ^{121,123,125}I. Experiemtal data were taken from Refs. [3–6].

I^π	E_{level} (keV) Expt.	PRM	Wave functions $[411]\frac{3}{2}$	$[420]\frac{1}{2}$	$[413]\frac{5}{2}$	$[422]\frac{3}{2}$	$[431]\frac{1}{2}$
A. ^{125}I	($\beta = 0.21$, $\alpha = 0.75$)						
$\frac{7}{2}^+$	536.0	534	0.099	0.642	0.112	0.607	0.442
$\frac{9}{2}^+$		979	0.155	0.913	0.005	0.094	0.347
$\frac{11}{2}^+$	1173.0	1110	0.107	0.650	0.107	0.586	0.457
$\frac{13}{2}^+$		1664	0.158	0.934	0.015	0.023	0.313
$\frac{15}{2}^+$	1870.7	1865	0.104	0.667	0.098	0.573	0.451
$\frac{17}{2}^+$		2391	0.072	0.869	0.017	0.452	0.184
$\frac{19}{2}^+$	2713.1	2673	0.058	0.730	0.055	0.613	0.289
$\frac{21}{2}^+$		3132	0.005	0.855	0.002	0.486	0.176
B. ^{123}I	($\beta = 0.21$, $\alpha = 0.67$)						
$\frac{7}{2}^+$	474.0	476	0.083	0.635	0.084	0.555	0.523
$\frac{9}{2}^+$		890	0.099	0.878	0.020	0.270	0.375
$\frac{11}{2}^+$	1079.9	1045	0.079	0.663	0.072	0.545	0.502
$\frac{13}{2}^+$		1565	0.095	0.905	0.002	0.258	0.274
$\frac{15}{2}^+$	1790.9	1806	0.074	0.701	0.057	0.498	0.500
$\frac{17}{2}^+$		2281	0.021	0.930	0.008	0.365	0.014
$\frac{19}{2}^+$	2647.2	2634	0.024	0.782	0.019	0.485	0.294
$\frac{21}{2}^+$		3195	0.049	0.813	0.006	0.490	0.055
C. ^{121}I	($\beta = 0.22$, $\alpha = 0.65$)						
$\frac{7}{2}^+$	445.4	446	0.078	0.665	0.077	0.587	0.448
$\frac{9}{2}^+$		838	0.103	0.951	0.012	0.086	0.276
$\frac{11}{2}^+$	1031.0	1003	0.076	0.675	0.068	0.558	0.442
$\frac{13}{2}^+$		1477	0.087	0.971	0.003	0.074	0.206
$\frac{15}{2}^+$	1746.2	1729	0.068	0.723	0.054	0.551	0.407
$\frac{17}{2}^+$		2227	0.052	0.930	0.007	0.065	0.197
$\frac{19}{2}^+$	2621.2	2573	0.045	0.805	0.033	0.507	0.302
$\frac{21}{2}^+$		3050	0.010	0.901	0.002	0.240	0.184
$\frac{23}{2}^+$	3517.4	3489	0.002	0.949	0.010	0.295	0.111

The pairing gap parameter $\triangle = 1.07$ MeV for ^{125}I was estimated from the experimental odd-even mass difference, which is similar to the value obtained from the expression $\triangle = 12/A^{1/2}$. However, it was noted that the agreement between the experimental and the predicted bandhead energies improves remarkably for values of $\triangle$ that are less by a factor of about 2. Similar reduction in the value of $\triangle$ has been found to be necessary in several PRM calculations, reported earlier for nuclei in the rare earth region [19]. Although the actual basis for this is not clearly understood, it has been suggested that the use of $\triangle$ value obtained from the experimental odd-even mass difference results in an overestimation of the Coriolis interaction, requiring unduly large Coriolis

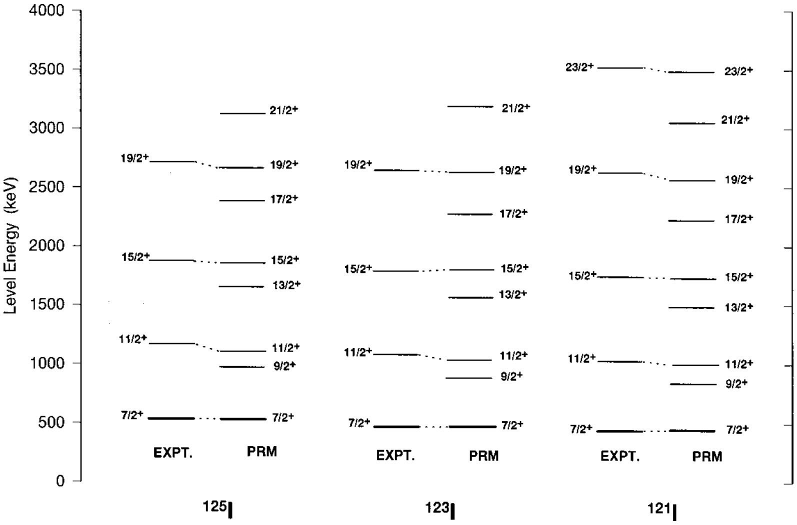

FIG. 3. Comparison of the experimental level energies with the predictions of the PRM calculations for the band built on the second $\frac{7}{2}^+$ state in ^{121,123,125}I. The ground-state bands of the respective even-even Xe nuclei were used as the cores.

attenuation coefficients. In the present work, a detailed study of the previously established $\pi g_{9/2}$ bands in ^{121,123,125}I revealed that $\triangle = 0.73$, 0.65, and 0.58 MeV, respectively, helped to reproduce the observed bands and the bandhead energies exceptionally well. The bandhead energies are all predicted within 5 keV of the experimental results. In addition, the calculations required either no or an insignificant Coriolis attenuation coefficient. These results, summarized in Table I, therefore provide the parameters μ, κ, $\triangle$, and λ for ^{121,123,125}I. Only the quadrupole deformation β and Coriolis attenuation coefficient α were used as the free parameters in the calculations for the band built on the excited $\frac{7}{2}^+$ state in these nuclei. The deformation parameter was chosen to vary around 0.20. This is based on the systematics of the suggested β values for several nuclei in this mass region, including the odd-*A* iodine nuclei [3,17,18].

As shown in Fig. 3, the experimental $\frac{7}{2}^+{}_2$, $\frac{11}{2}^+{}_2$, $\frac{15}{2}^+{}_2$, and $\frac{19}{2}^+{}_2$ states in ^{125}I with $\alpha = -\frac{1}{2}$ (Fig. 1) are found to be reproduced remarkably well for $\beta = 0.20$, $\triangle = 0.58$, and a Coriolis attenuation coefficient of 0.75. The average energy deviation between the experimental and the calculated levels is 28.5 keV. It is evident from these calculations (see Table II) that the $\alpha = -\frac{1}{2}$ band may be associated with the prolate $\pi g_{7/2}[420]\frac{1}{2}$ orbital with admixtures from the nearby $\pi d_{5/2}[422]\frac{3}{2}$ and $\pi d_{5/2}[431]\frac{1}{2}$ orbitals. The contribution of the $\pi g_{7/2}[420]\frac{1}{2}$ orbital to the wave function of these states appears to increase with spin.

The model also predicts the $\frac{9}{2}^+$, $\frac{13}{2}^+$, $\frac{17}{2}^+$, and the $\frac{21}{2}^+$ states, associated with a configuration similar to those for the states of the $\alpha = -\frac{1}{2}$ signature band. These $\frac{9}{2}^+$, $\frac{13}{2}^+$, etc., states presumably constitute the $\alpha = +\frac{1}{2}$ signature partner of the same band. However, for the $\alpha = +\frac{1}{2}$ band, the contributions of the $\pi g_{7/2}[420]\frac{1}{2}$ orbital to the respective wave functions are larger relative to those for the states of the $\alpha = -\frac{1}{2}$ band. Experimentally, the states of the $\alpha = +\frac{1}{2}$ signature band are not observed. A $\frac{9}{2}^+$ state at 704.3 keV (Fig. 1) has been reported but it appears unlikely that this state can be identified with the predicted $\frac{9}{2}^+$ state at 979 keV. For a single-quasiparticle configuration, the signature with $(-1)^{j+\alpha} = -1$ is favored by rotation, where j is the angular momentum of the quasiparticle. The calculations suggest that the observed sequence of states with spin $\frac{7}{2}^+$, $\frac{11}{2}^+$, $\frac{15}{2}^+$, and $\frac{19}{2}^+$ and $\alpha = -\frac{1}{2}$ form the favored signature band, while the unfavored $\alpha = +\frac{1}{2}$ band has been pushed up in energy as a result of a fairly large signature splitting. This possibly explains why the states of the $\alpha = +\frac{1}{2}$ band are not observed experimentally.

Kostova *et al.* have reported theoretical calculations based on the core-quasiparticle model [20] and identified the $\frac{7}{2}^+{}_2$, $\frac{11}{2}^+{}_2$, $\frac{15}{2}^+{}_2$, and $\frac{19}{2}^+{}_2$ states in ^{125}I with the $\pi d_{5/2}$ configuration, with the $\frac{5}{2}^+$ ground state as the bandhead. However, this implies that the states with spin $\frac{5}{2}^+$, $\frac{9}{2}^+$, $\frac{13}{2}^+$, etc., should form the favored band. Experimentally, only the $\frac{7}{2}^+$, $\frac{11}{2}^+$, $\frac{15}{2}^+$, and $\frac{19}{2}^+$ states are observed while the states belonging to the expected favored sequence, excepting the $\frac{9}{2}^+$ state at 704 keV, are not observed. It is also to be noted that although the observed $\frac{9}{2}^+$ state is strongly populated, consistent with the interpretation of Kostova *et al.*, it is fed mostly (97% [5]) from the bandhead of the $\pi h_{11/2}$ band and very weakly from the $\frac{11}{2}^+$ state within the band (Fig. 1). It appears that the interpretation of the sequence of states with spin $\frac{7}{2}^+{}_2$, $\frac{11}{2}^+{}_2$, $\frac{15}{2}^+{}_2$, and $\frac{19}{2}^+{}_2$ as arising from the $\pi d_{5/2}$ configuration is inconsistent with experimental results.

The present PRM calculations for ^{121,123}I led to a similar interpretation for the band built on the second $\frac{7}{2}^+$ state, as for ^{125}I. The pairing gap $\triangle = 0.73$ and 0.65 were used for ^{121,123}I, respectively. The results are listed in Table II. While the bandhead energies are reproduced to within a few keV, the overall agreement for the observed higher-lying states with $\alpha = -\frac{1}{2}$ is also remarkably good (Fig. 3). It appears from Table II that the $\Delta I = 2$ sequences of states built on the second $\frac{7}{2}^+$ state with spins up to $\frac{19}{2}^+$ in ^{123}I and $\frac{23}{2}^+$ in ^{121}I may be interpreted to be built on the same Nilsson orbitals as those for the analogous band in ^{125}I. Experimentally, two states with spins $\frac{9}{2}^+$ and $\frac{13}{2}^+$ with energies 671 and 1437 keV, respectively, have been reported [4] in ^{123}I, connected by weak transitions to the states of the $\alpha = -\frac{1}{2}$ band, as shown in Fig. 1. However, it is unlikely that the observed states correspond to the predicted $\frac{9}{2}^+$ and $\frac{13}{2}^+$ states, as the energy differences between the experimental and calculated states are too large compared to those for the states of the $\alpha=-\frac{1}{2}$ band (cf. Table I). The observed $\frac{9}{2}^+$ and $\frac{13}{2}^+$ states have energies that are significantly lower than expected for the unfavored $\alpha=+\frac{1}{2}$ signature band. In ^{121}I, the $\frac{9}{2}^+$, $\frac{13}{2}^+$, . . . states, identifiable with the predicted states of same spin, were not observed although a somewhat more efficient detector system was used in the experiment compared to the ones used for the study of ^{123,125}I. Liang *et al.* [3] have reported a $\frac{9}{2}^+$ level in ^{121}I at an excitation energy of 650 keV, similar to those for the $\frac{9}{2}^+$ states in ^{123,125}I. The same authors proposed that the $\Delta I=2$ band with $\alpha=-\frac{1}{2}$, built on the $\frac{7}{2}^+$, 445.4-keV state (Fig. 1), may be associated with the low-K prolate $\pi g_{7/2}$ orbital. The observed $\frac{9}{2}^+$ level at 650 keV was not considered to be a member of this band.

It is also interesting to note that there are other examples of coexistence of prolate and oblate deformed bands associated with the same single quasiproton orbital in iodine nuclei. The nuclei ^{119,121}I are reported to have two negative-parity bands, one of which is based on the low-K and the other on the high-K $h_{11/2}$ proton configuration [3,10]. The analogous strongly coupled high-K $\pi h_{11/2}$ band has not been reported in the odd-A iodine nuclei with $A>121$.

III. CONCLUSION

The particle-rotor model calculations suggest that the sequence of states built on the second $\frac{7}{2}^+$ state in the odd-A $^{121-125}$I may be associated with prolate low-K $\pi g_{7/2}[420]\frac{1}{2}$ Nilsson orbital with admixtures from the $\pi d_{5/2}[422]\frac{3}{2}$ and $\pi d_{5/2}[431]\frac{1}{2}$ orbitals. These bands are expected to be moderately deformed with $\beta\sim0.2$, characteristic of collective bands in this mass region. With the yrast bands in these nuclei already established to have an oblate deformation, arising from the high-K orbitals with the same $\pi g_{7/2}$ and $\pi d_{5/2}$ configuration, it is evident that both prolate and oblate shapes associated with the same single-proton orbital are strongly competing. This is consistent with the earlier potential-energy-surface calculations that predict energy minima for both an oblate and a prolate shape for the $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals. Similar shape coexistence phenomenon associated with the $\pi h_{11/2}$ orbital has also been reported in ^{119,121}I. However, more experimental information, including extension of the bands up to higher spins and a study of the level lifetimes, are needed for the odd-A iodine nuclei with $A\geqslant121$, to provide a better understanding of the structures of these and other bands.

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