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High-lying three-quasiparticle bands and signature splitting in ^{81}Rb

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Two new high-lying level sequences of negative parity have been identified in the odd-proton nucleus ^{81}Rb by in-beam γ-ray spectroscopy using the reactions ^{79}Br$(\alpha,2n)$ at 27 MeV and ^{68}Zn(^{19}F,$\alpha 2n$) at 72 MeV. One sequence, dominated by $M1$ transitions, is interpreted as a three-quasiparticle band predominantly containing a neutron in the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ subshell coupled to $g_{9/2}$ proton and $g_{9/2}$ neutron excitations. The other new level sequence forms the three-quasiparticle extension of the unfavored negative-parity band, but the states decay also by $E1$ transitions. The signature splitting points to a configuration where an aligned $g_{9/2}$ proton pair is involved.

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Theoretical [1] and experimental investigations of strongly deformed nuclear shapes in the mass $A = 80$ region, such as the even-even nuclei ^{82}Sr [2] and ^{84}Zr [3], have shown that collective bands at high spins can be related to the $N = 44$ neutron single-particle gap at large prolate deformation ($\beta_2 \approx 0.4$). At low or medium spins and smaller quadrupole deformation there is a competition between collective excitation modes and single-particle excitations causing a large diversity of level structures.

Recent in-beam γ-ray spectroscopic studies of transitional or medium deformed nuclei such as ^{77,79,81}Br [4–6], ^{79,83}Rb [7,8], and ^{83}Y [9–11] revealed high-lying decay sequences with dominating $\Delta I = 1$ $M1$ transitions. In most of these nuclei the lowest states of the level sequences decay to both low-lying positive- and negative-parity states. The sequences were interpreted as three-quasiparticle (qp) bands containing an unpaired neutron in the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ subshell along with a two-quasiparticle $g_{9/2}$-proton–$g_{9/2}$-neutron excitation. In the transitional nucleus $^{81}_{37}$Rb$_{44}$ such a high-lying decay sequence is not known but expected, and therefore, a new in-beam study has been performed.

The nucleus ^{81}Rb was previously studied by γ-ray spectroscopic techniques via the reactions ^{79}Br$(\alpha,2n)$ [12], ^{65}Cu(^{19}F,$p2n$) [13], and ^{55}Mn(^{29}Si,$2pn$) [14] up to states with $(\frac{37}{2}^+)$. Transition probabilities and alignment properties of both $g_{9/2}$ protons and $g_{9/2}$ neutrons were investigated [14] based on experimental data for the positive- and negative-parity level sequences with signature $\alpha = +\frac{1}{2}$, whereas experimental information about the level sequences of both parities with signature $\alpha = -\frac{1}{2}$ is limited to low-spin states, just below the onset of the first band crossing. Therefore, a second goal of this study was to extend the unfavored level sequences to higher-spin states and to explore its behavior through the band-crossing region.

Excited states in ^{81}Rb were investigated by coincidence measurements via the ^{79}Br$(\alpha,2n)$ reaction where a thick NH_4Br target of natural isotopic abundance was bombarded with 27 MeV α particles provided by the Rossendorf cyclotron and via the ^{68}Zn(^{19}F,$\alpha 2n$) reaction at 72 MeV using the FN-Tandem accelerator of the Niels Bohr Institute. In the first experiment the γ rays were recorded with two Ge(Li) detectors placed at 90° with respect to the beam axis. About 1.2×10^8 events were recorded on magnetic tape and subsequently analyzed off line. As a result a new high-lying decay sequence in ^{81}Rb was discovered [15,16] containing strong $\Delta I = 1$ transitions at 61.0, 300.5, 429.8, 565.5, and 599 keV. The presence of the 61.0 keV transition was concluded from energy differences and by the appearance of this γ-ray energy in a singles spectrum measured with a low-energy photon (LEP) detector.

Angular distributions of the γ rays were measured via

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the $(\alpha,2n)$ reaction at 27 MeV using a 98.6% enriched $Na^{79}Br$ target. The γ rays were detected with a high-purity (HP) Ge detector of 10% relative efficiency located 14 cm from the target at angles of 30°, 90°, 105°, 120°, 135°, 150°, and 158° to the beam axis. Radioactive sources of ^{133}Ba, ^{152}Eu, and ^{226}Ra have been employed for energy calibration. The normalization of the peak areas was performed assuming a stretched $E2$ multipolarity for the 622.8 keV γ ray in accordance with measured [12] angular distribution coefficients. Angular distributions were also measured with a LEP detector which had an energy resolution of 0.6 keV at 122 keV. This detector was placed at angles of 90°, 110°, 130°, and 150° with respect to the beam. Here the normalization factors were obtained from the 153.5 keV γ ray. Its peak areas were normalized in such a way that the resulting angular distribution coefficients matched those of the HPGe measurement. Angular distribution coefficients are given in Table I for selected transitions assigned to the new structures in ^{81}Rb. The complex line groups at 300 keV and 430 keV [contaminated by a ^{81}Kr line [17] produced via the (α,pn) reaction] could not be resolved in these singles measurements.

In the second experiment via the $^{68}Zn(^{19}F,\alpha 2n)$ reaction two coincidence measurements were performed, one with a thin and another with a backed target. In the first measurement the γ rays emitted from a thin 1 mg cm^{-2} self-supporting ^{68}Zn foil (enrichment 99%) were measured with the NORDBALL detector array consisting of 18 Compton-suppressed HPGe detectors and 10 BaF_2 detectors as a multiplicity filter. Approximately 5×10^7 events were collected on magnetic tape. In the second measurement a thin ^{68}Zn layer of 1 mg cm^{-2} evaporated onto a 7.5 mg cm^{-2} Bi backing was used as target. The γ rays were recorded with a version of NORDBALL comprising 19 Compton-suppressed HPGe detectors and one Compton-suppressed low-energy photon spectrometer. These detectors were operated in coincidence with a multiplicity filter consisting of 39 BaF_2 detectors. Here a total number of about 9×10^8 events was stored on magnetic tape.

The data from the thick target measurement were sorted into separate matrices for prompt and nanosecond-delayed events. Examples of coincidence spectra obtained by setting gates in the total prompt matrix and relevant for the new bands in ^{81}Rb are shown in Figs. 1, 2, and 3. In the 1927 keV gate (see Fig. 1) the transitions assigned to the new band from the $(\alpha,2n)$ reaction are clearly seen, including the previously inferred [15,16] 61.0 keV γ ray.

Asymmetry ratios (R_{asym}), which correspond to directional correlation of oriented nuclei ratios but summed over all different detector plane angles, were obtained from both NORDBALL measurements. Gamma rays recorded by detectors at 37° were sorted against coincident γ rays detected at 79° or 101°, and stored into a matrix. Similarly, another coincidence matrix was built for the events from the detectors at 143°. By setting gates in these matrices, limited multipolarity information could be obtained and is compiled for selected transitions

TABLE I. Energy and spin of the initial state as well as γ-ray energy, angular distribution coefficients, and asymmetry ratios for selected transitions assigned to ^{81}Rb.

E_x (keV)	$I^{\pi\,a}$	$E_\gamma{}^{b}$ (keV)	$A_2/A_0{}^{c}$	$A_4/A_0{}^{c}$	$R_{\mathrm{asym}}{}^{d}$
2636.2	$\frac{15}{2}^-$	210.5(1)	−0.33(11)	0.06(20)	-
		1926.4(5)	−0.41(7)	0.09(14)	0.43(14)
2656.4	$\frac{17}{2}^-$	917.6(2)	-	-	0.94(9)
2697.2	$\frac{17}{2}^-$	61.0(1)	−0.30(3)[e]	−0.01(6)[e]	-
		958.5(2)	0.38(24)	−0.2(4)	1.04(20)
2997.7	$\frac{19}{2}^-$	300.5(2)	-	-	0.48(8)
3427.5	$\frac{21}{2}^-$	429.8(2)	-	-	0.45(7)
3055.8	$\frac{19}{2}^-$	1471.6(3)	−0.89(12)	0.66(22)	0.40(8)
3956.5	$\frac{23}{2}^-$	900.6(2)	-	-	0.85(20)
		1348.4(3)	-	-	0.57(14)

[a]Spin of the initial state.
[b]Uncertainties in the last digit are given in parentheses.
[c]Measured with a HPGe detector via the $(\alpha,2n)$ reaction at 27 MeV.
[d]Asymmetry ratio $I_\gamma(37° \,\&\, 143°)/I_\gamma(79° \,\&\, 101°)$ measured via the $^{68}Zn(^{19}F,\alpha 2n)$ reaction at 72 MeV.
[e]Measured with the LEP detector.

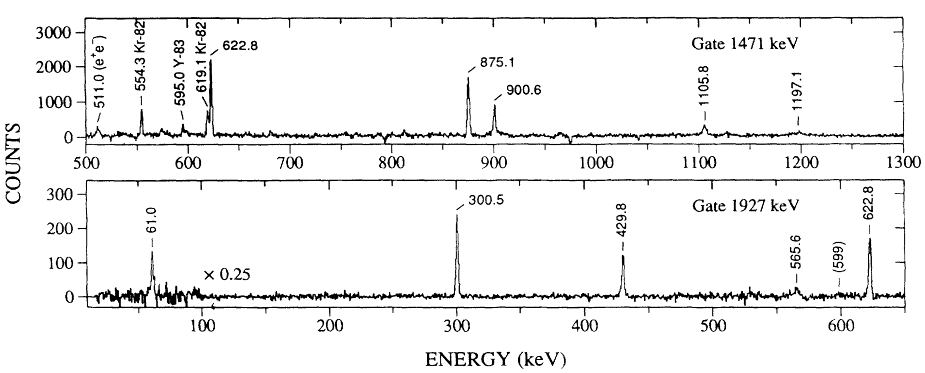

FIG. 1. Portions of background-corrected coincidence spectra generated by gating on the 1471 and 1927 keV peaks in the total prompt energy (HPGe)-energy(HPGe) matrix of the backed-target NORDBALL measurement. Note the scaling factor that has been applied to ensure a readable plot.

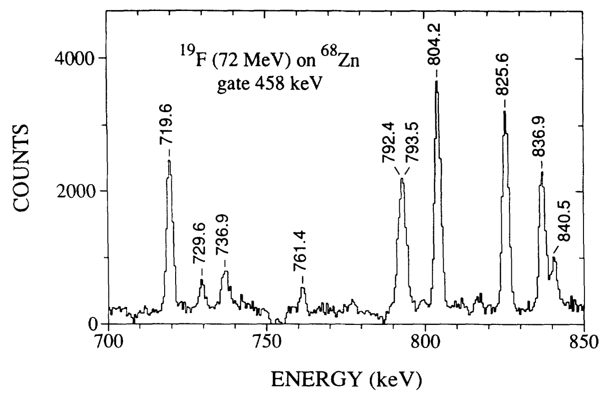

FIG. 2. Portion of a background-corrected γ-ray spectrum in coincidence with the 458 keV $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$ transition. The spectrum is generated from the same matrix as Fig. 1.

TABLE II. Lifetimes and electromagnetic transition strengths for selected states in ^{81}Rb.

E_x (keV)	I^π	E_γ (keV)	τ (ps)	$\sigma\lambda$[a]	$B(\sigma\lambda)$ (W.u.)[b]
3956.5	$\frac{23}{2}^-$	1348.4	1.6(2)	$E1$	$5(1)\times10^{-5}$
		900.6		$E2$	17(3)
		958.6		$E2$	6(1)
5062.3	$\frac{27}{2}^-$	1105.8	0.7(2)	$E2$	34^{+13}_{-8}
3427.5	$\frac{21}{2}^-$	429.8	1.5(5)	$M1$	0.27^{+13}_{-7}

[a]Multipolarity.
[b]Transition strengths in Weisskopf units, 1 W.u.$(E1) = 1.21e^2$ fm^2; 1 W.u.$(E2) = 20.82e^2$ fm^4; 1 W.u.$(M1) = 1.79\mu_N^2$.

in Table I.

The deduced level scheme of ^{81}Rb is shown in Fig. 4. The observed levels have been grouped in bands and labeled above it with serial letters (A)–(I) to facilitate the discussion. The previously known bands (B), (C), (E), (G), and (H) could be confirmed and on the bands (B), (C), and (E) one transition on top of each could be added. New level sequences have been found on top of the $(\frac{3}{2}^-)$ level at 301.3 keV level [band (A)] and on the new $\frac{13}{2}^-$ level at 2425.7 keV [band (F)]. The low-lying part of band (D) could be extended by four new levels connected by $\Delta I = 2$ transitions, and strong $E1$ decay of the new states to the positive-parity yrast band [band (H)] has been observed. Most of the new states are connected by several linking transitions to known low-lying levels. Wherever possible, spin assignments are based on the measured angular distribution coefficients and/or asymmetry ratios; e.g., a firm spin and parity assignment of $\frac{17}{2}^-$ could be made to the 2656.4 keV level in band (B) as discussed in Ref. [14].

Doppler-shifted line shapes have been obtained from the two matrices of the backed-target experiment and have been analyzed for some of the new transitions in ^{81}Rb. Lifetimes have been derived by comparing the observed line shapes with calculated line shapes based on a Monte Carlo calculation of the velocity distribution of the recoil nuclei. In this calculation reactions in different depths of the target, the kinematics of an evaporation reaction as well as slowing down and deflection of the recoiling nuclei were taken into account. For the slowing down process Lindhard's cross sections have been used with correction factors $f_e = 0.9$ and $f_n = 0.7$ for the electronic and nuclear stopping powers, respectively. Cascade feeding from higher-lying levels and continuum side feeding have also been taken into account; e.g., for the levels at excitation energies between 3.5 and 5 MeV side-feeding times between 0.2 and 0.1 ps, respectively, have been assumed. The assumption of fast feeding has only a small influence on the relatively long deduced lifetimes. As an example, measured and calculated line shapes obtained for the 1105.8 keV γ ray at the two observation angles are shown in Fig. 5. This transition is assigned to the new part of band (D). Lifetimes and transition probabilities belonging to the new band structures are compiled in Table II.

Several states of the new sequence of $M1$ transitions [band (F)] decay to both positive- and negative-parity states. Spin and parity assignments are firm due to the observed asymmetry ratios and angular distributions of the linking transitions; e.g., for the 958.5 keV γ ray a $\Delta I = 2$ multipolarity has been deduced unambiguously (see Table I) leading to a firm $I^\pi = \frac{17}{2}^-$ assignment to the 2697.2 keV level. The measured lifetime of 1.5(5) ps for the 3427.5 keV level leads to a quite high $M1$ strength of 0.27 Weisskopf units (W.u.) for the 429.8 keV transition.

A comparison of level energies and spins for the 3qp bands observed in the $N = 44$ isotones ^{79}Br, ^{81}Rb, and ^{83}Y is shown in Fig. 6. General features are the similarity in excitation energy for the $\frac{17}{2}^-$, $\frac{19}{2}^-$, and $\frac{21}{2}^-$ states, the nonobservation of the $\frac{21}{2}^- \rightarrow \frac{17}{2}^-$ $E2$ transition, and the decay of the lowest states in ^{79}Br and ^{81}Rb to both low-lying positive- and negative-parity states. Bands with

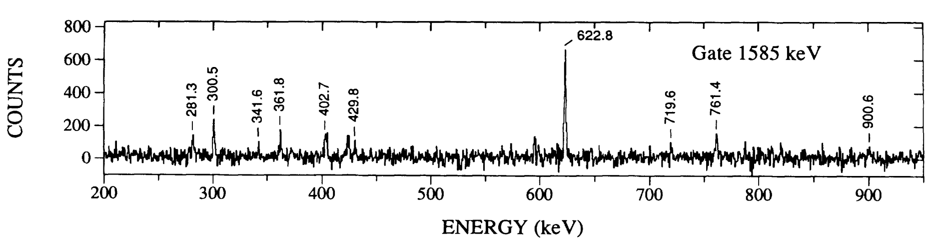

FIG. 3. Portion of a background-corrected γ-ray spectrum in coincidence with the 1585 keV $\frac{15}{2}^- \rightarrow \frac{13}{2}^+$ transition. The spectrum is generated from the same matrix as Fig. 1.

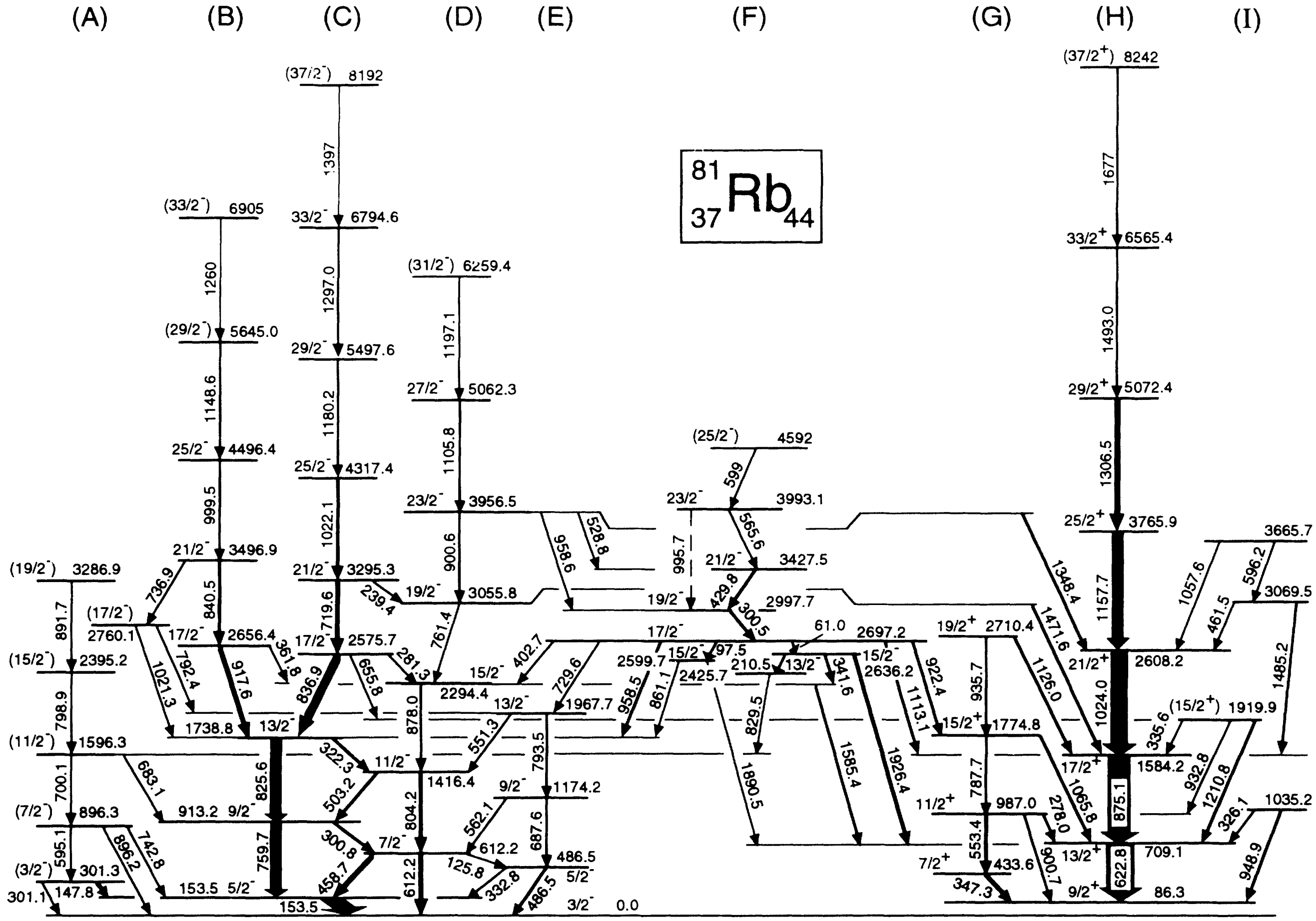

FIG. 4. Level scheme of ^{81}Rb as inferred from the present data.

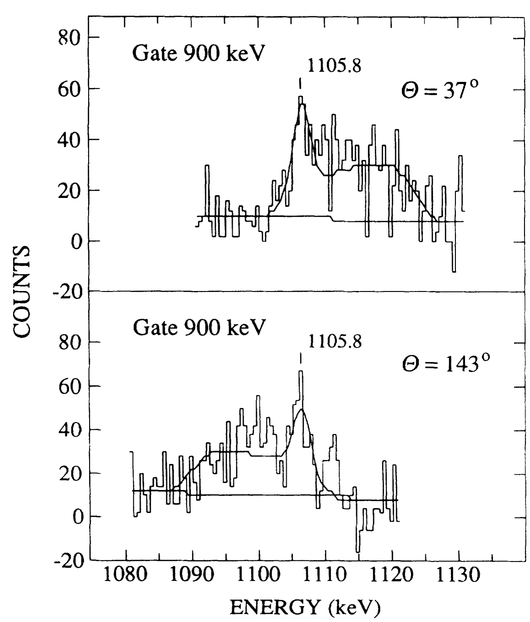

FIG. 5. Experimental and best simulated Doppler-shifted line shapes for the 1105.8 keV transition as observed at forward (37°) and backward (143°) angles in the 900 keV gate. The simultaneous analysis of the line shapes for both observation angles resulted in a lifetime of $\tau = 0.7(2)$ ps.

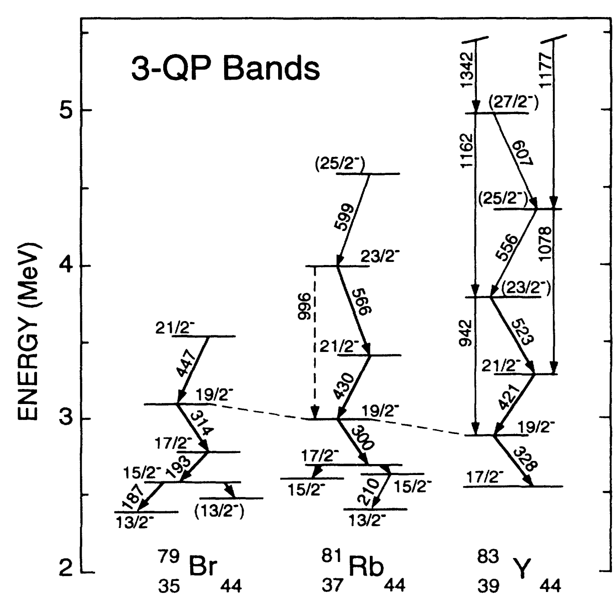

FIG. 6. Comparison of 3qp bands in $N = 44$ isotones. The experimental data has been taken for ^{79}Br from Ref. [5] and for ^{83}Y from Ref. [10].

similar properties have also been observed in other odd-A Br [4] and Rb [7] isotopes. In most cases there is a dominance of $\Delta I = 1$ transitions between the lowest levels indicating that they may be formed predominantly by quasiparticle components. In addition, the $M1$ strength observed for the 429.8 keV γ ray in ^{81}Rb is comparable with the large $B(M1)$ transition probabilities of about 0.5 W.u. found for the $M1$ transitions in the 3qp band of ^{79}Br [5].

A cranked-shell-model analysis according to the prescription outlined in Ref. [18] of level energies and spins of the 3qp bands reveals large aligned angular momenta of $I_x = \sqrt{(I+\frac{1}{2})^2 - K^2} \approx 6\hbar$ at $\hbar\omega = 0.2$ MeV for all three isotones, as displayed in Fig. 7. This indicates that at least one unique-parity $g_{9/2}$ quasiparticle must be involved. In the analysis $K = \frac{13}{2}$ has been used which can be inferred from the different Nilsson orbitals close to the Fermi levels for protons and neutron given in the single-particle diagram of Ref. [1] at moderate ($|\beta_2| \approx 0.2$) quadrupole deformation. A slightly lower value of K, like $K = \frac{11}{2}$ or $\frac{9}{2}$, would also be reasonable for the 3qp structure since the negative-parity (p, f) orbitals are so close in energy and the states of interest may contain strongly mixed configurations, including $K = \frac{1}{2}$ single-particle orbitals. However, there will be no dramatic change of the deduced properties.

For the $\frac{17}{2}^-$ level at 2560 keV in ^{83}Y a lifetime of $\tau = 66(6)$ ps [19] and a g factor of $g = +0.29(6)$ [11] have recently been measured. The relatively long lifetime suggests that this state is a bandhead of a 3qp yrare band. The small value of the g factor has been discussed in terms of active quasiparticles of both $g_{9/2}$ protons and $g_{9/2}$ neutrons. The experimental similarities of the 3qp bands in the $N = 44$ isotones imply a resemblance of their internal structure. Therefore, we propose for the 3qp band in ^{81}Rb the same underlying configuration of $\pi g_{9/2} \otimes \nu g_{9/2} \otimes \nu(p, f)$.

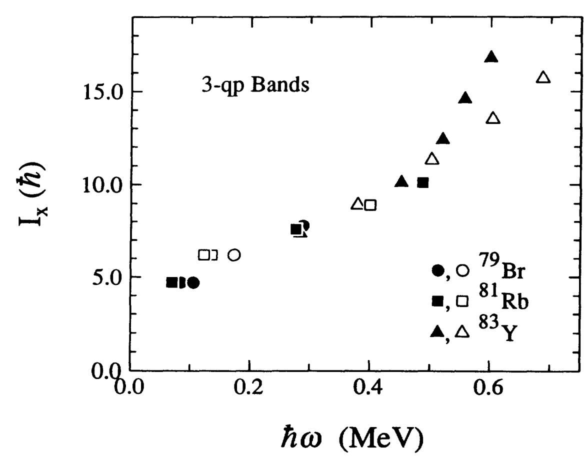

FIG. 7. Aligned angular momentum I_x of the 3qp bands shown in Fig. 6 as a function of the rotational frequency. For all bands a value of $K = \frac{13}{2}$ has been used. Solid and open symbols correspond to signatures $\alpha = +\frac{1}{2}$ and $\alpha = -\frac{1}{2}$, respectively. In cases where two levels of the same spin have been identified both I_x values are given.

The other new sequence of four γ rays was found to feed the $\frac{15}{2}^-$ level at 2294.4 keV. The transitions involved can be seen in the spectrum gated by the 1471 keV transition (see Fig. 1) which depopulates the $\frac{19}{2}^-$ level at 3055.8 keV to the $\frac{17}{2}^+$ state. From the coincidence data a weak decay branch of the 3055.8 keV state via a 761.4 keV transition to the level at 2294.4 keV was found (see Figs. 2 and 3) raising doubts on the positive-parity assignment tentatively given in Ref. [14]. Since spin and parity of $\frac{15}{2}^-$ of the level at 2294.4 keV are well established, the 761.4 keV transition would be of $M2$ multipolarity which is, however, very unlikely. Therefore, an $E2$ multipolarity is assigned to the 761.4 keV γ ray. The transitions at 1348.4 and 1471.6 keV are most likely $E1$ transitions and negative parity is assigned to this sequence. This new decay sequence is obviously the so far missing high-spin extension of the unfavored negative-parity sequence, although the weak intensity of the 761.4 keV indicates some change in the internal structure. The lifetime of 1.6(2) ps of the 3956.5 keV state and the observed branching ratio leads to an $E2$ strength of 17 W.u. for the 900.6 keV and an $E1$ strength of about 0.05 mW.u. for the 1348.4 keV transition. The observation of such $E1$ transitions is somewhat unexpected, but a similar decay pattern with $E1$ transition strengths of about 0.06 mW.u. has recently been reported for ^{83}Y [10] and related to possible octupole excitations.

As already pointed out the previously proposed $\frac{17}{2}^-$ assignment to the level at 2656.4 keV [band (B)] has been confirmed. This second $\frac{17}{2}^-$ state lies just 81 keV above the first one in band (C). Both states are members of collective bands with apparently very small mutual mixing. This observation has been interpreted as due to different aligned quasiparticles ($g_{9/2}$ protons and $g_{9/2}$ neutrons) associated with different shapes [14] caused by the deformation driving properties of the quasiparticle orbitals occupied.

The experimental Routhian e' of the new level sequence in comparison with known bands in ^{81}Rb is shown in Fig. 8. Throughout the observed spin region its behavior resembles that of the favored sequence, even in the band-crossing region at $\hbar\omega \approx 0.42$ MeV. The average signature splitting $\Delta e' = e'(\alpha = -\frac{1}{2}) - e'(\alpha = +\frac{1}{2})$ is quite constant at about 145 keV. Apparently, there is no change in signature splitting in the negative-parity sequences before and after the first band crossing, as can be inferred from the Routhians in Fig. 8 and the kinematic moments of inertia in Fig. 9. In the negative-parity sequences of the adjacent nucleus ^{79}Rb an average signature splitting of about 150 keV at $\hbar\omega \approx 0.4$ MeV was found [7]. The observed peak in the dynamical moment of inertia at 0.43 MeV rotational frequency in ^{79}Rb was interpreted as due to a gradual increase of alignment of a $g_{9/2}$ proton pair. This holds also for the nearby nucleus ^{83}Y [10] where a $g_{9/2}$ proton pair causes the observed crossings at $\hbar\omega = 0.43$ and 0.39 MeV in the favored and unfavored sequences, respectively, of negative parity. Therefore, a similar behavior may be present in ^{81}Rb.

In summary, three new decay sequences of negative

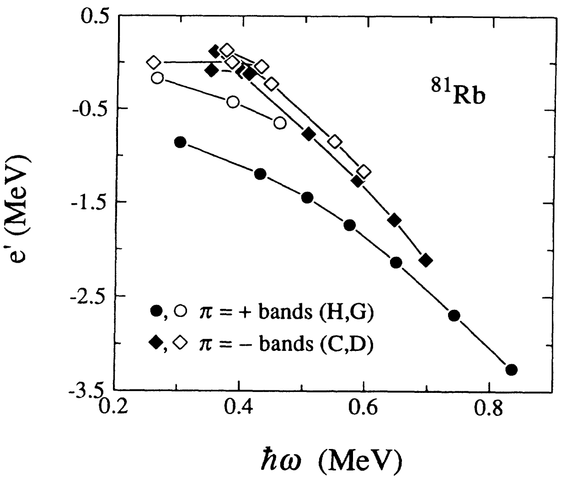

FIG. 8. Experimental Routhian e' as a function of the rotational frequency for bands in ^{81}Rb. The bands are labeled with the letters given in Fig. 4. The reference rotor parameters are $J_0 = 11\hbar^2$ MeV^{-1} and $J_1 = 4\hbar^4$ MeV^{-3}. A value of $K = \frac{3}{2}$ was used for all bands.

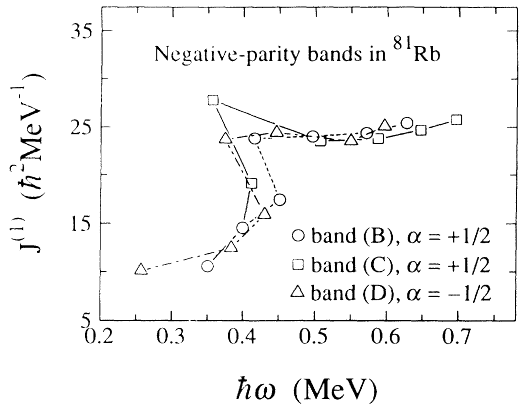

FIG. 9. Kinematic moments of inertia $J^{(1)}$ as a function of the rotational frequency for negative-parity bands in ^{81}Rb. The K values used are the same as for Fig. 8.

parity have been identified in ^{81}Rb via the ^{79}Br$(\alpha, 2n)$ and ^{68}Zn(^{19}F,$\alpha 2n$) reactions. Both high-spin level sequences are interpreted as built on 3qp excitations, one sequence as a mixed $g_{9/2}$ proton, $g_{9/2}$ neutron, and (p, f) neutron configuration and the other as containing very probably an aligned $g_{9/2}$ proton pair with possible octupole deformations.

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