Band terminations in ^{103}Pd

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The level scheme of ^{103}Pd has been reconstructed using high-fold γ-ray coincidence data obtained with the EUROGAM-2 spectrometer in the ^{70}Zn(^{36}S,3n) reaction at $E=130$ MeV. New spins and excitation energies are given for levels in the strongly coupled positive parity bands. Four high-spin bands are discussed in terms of terminating configurations using Nilsson-Strutinsky cranking calculations. One of them, having valence-space configuration, is observed up to its predicted terminating state of $I^{\pi}=65/2^{+}$. Another band, which is possibly observed up to its terminating state at $I>40$, is assigned to have a $2p$-$2h$ core-excited configuration. [S0556-2813(99)04707-X]

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The interplay between collective and noncollective behavior of nuclei can be studied experimentally up to very large angular momenta with the high efficiency γ-ray detector arrays. This interplay is clearly illustrated in terminating bands in which the angular momentum of a given configuration is gradually exhausted as the highest spin state is reached [1,2]. The angular momentum of the terminating noncollective state is built from the single-particle angular momenta of the particles and holes in open shells which are fully aligned along the quantization axis, the ''rotation'' axis. Evidence for band terminations has previously been reported, e.g., in the $A\approx160$ region (see, e.g., ^{158}Er [3]), in the $A\approx110$ region (see, e.g., ^{109}Sb [4]) and in the $A\approx60$ region (see, e.g., ^{62}Zn [5]). These results are reviewed in Ref. [6].

In the $A\approx100$ region the valence space configurations of several nuclei with $Z\approx44$–46 are predicted to evolve up to their termination just above $I\approx30\hbar$, see Ref. [7]. This work suggested that the observed yrast band of ^{103}Pd [8] might correspond to a terminating configuration while no reasonable interpretation was found for another ''more collective'' band in that nucleus. The first experimental evidence for terminating bands in Pd nuclei has recently been reported in Ref. [9]. Four band structures in ^{102}Pd have been observed up to termination and interpreted as valence-space and core-excited configurations. Under the same experimental conditions as in Ref. [9], several high-spin band structures have been identified in Rh [10,11] and Ru [12] isotopes, many of which have also been interpreted as terminating configurations. Motivated by the predictions of Ref. [7] and these recent experimental observations, we reinvestigated the level structure of ^{103}Pd with the aim to extend its high-spin bands. In the present paper we report on firm evidence for the existence of terminating configurations in ^{103}Pd. Particularly, the band previously assigned [8] as strongly collective is reinterpreted as a core-excited terminating band.

High spin states in the nucleus ^{103}Pd were populated in the ^{70}Zn(^{36}S,3$n\gamma$) reaction at a bombarding energy of 130 MeV, using the beams of the Vivitron tandem accelerator at IReS, Strasbourg. Two self-supporting foils of stacked Zn targets, enriched to 70% in ^{70}Zn and each having a thickness of 440 μg/cm^2 were used. Coincidence γ-rays were detected with the EUROGAM-2 spectrometer array [13]. A total of 6×10^8 fourfold and higher-fold Compton-suppressed coincidence events, 20% of which belonged to ^{103}Pd, were stored on magnetic tapes. These events were unpacked off-line into a *total* $E_{\gamma1}-E_{\gamma2}-E_{\gamma3}$ triples-coincidence cube, and, using the higher-fold events, into a *gated* (quadruples) cube by requiring coincidences with the strongest transitions in the yrast and the two positive-parity cascades of ^{103}Pd. For data reduction the RADWARE spectrum analysis package [14] was used.

The level scheme of ^{103}Pd has been constructed on the basis of the triples and quadruples γ-ray coincidence relations, and the intensity and energy balances extracted from these coincidence cubes. For achieving firm spin and parity assignments for the levels, the directional correlation (DCO) ratio and the γ-ray linear polarization, using the definitions in Ref. [15], of the more intense transitions have also been measured. The partial level scheme of ^{103}Pd as derived from this work is shown in Fig. 1. The level scheme, compared to the most recent one proposed in Ref. [8], has been substantially modified with respect to the position of the two positive-parity bands relative to the negative-parity yrast band and to each other.

The negative-parity yrast band (band 1) built on the $11/2^-$ state at 785 keV has been established up to the $I^{\pi}=51/2^-$ level at $E_x=11.638$ MeV. The data did not allow for any of the levels feeding to this one to be firmly assigned as an extension of the band.

New spin and energy values have been given for the levels in the high-spin positive-parity cascade (band 2), due to a set of newly identified electric dipole transitions connecting this band to the negative-parity yrast band. The 1097 keV and 1232 keV connecting transitions (Fig. 1) are energy dou-

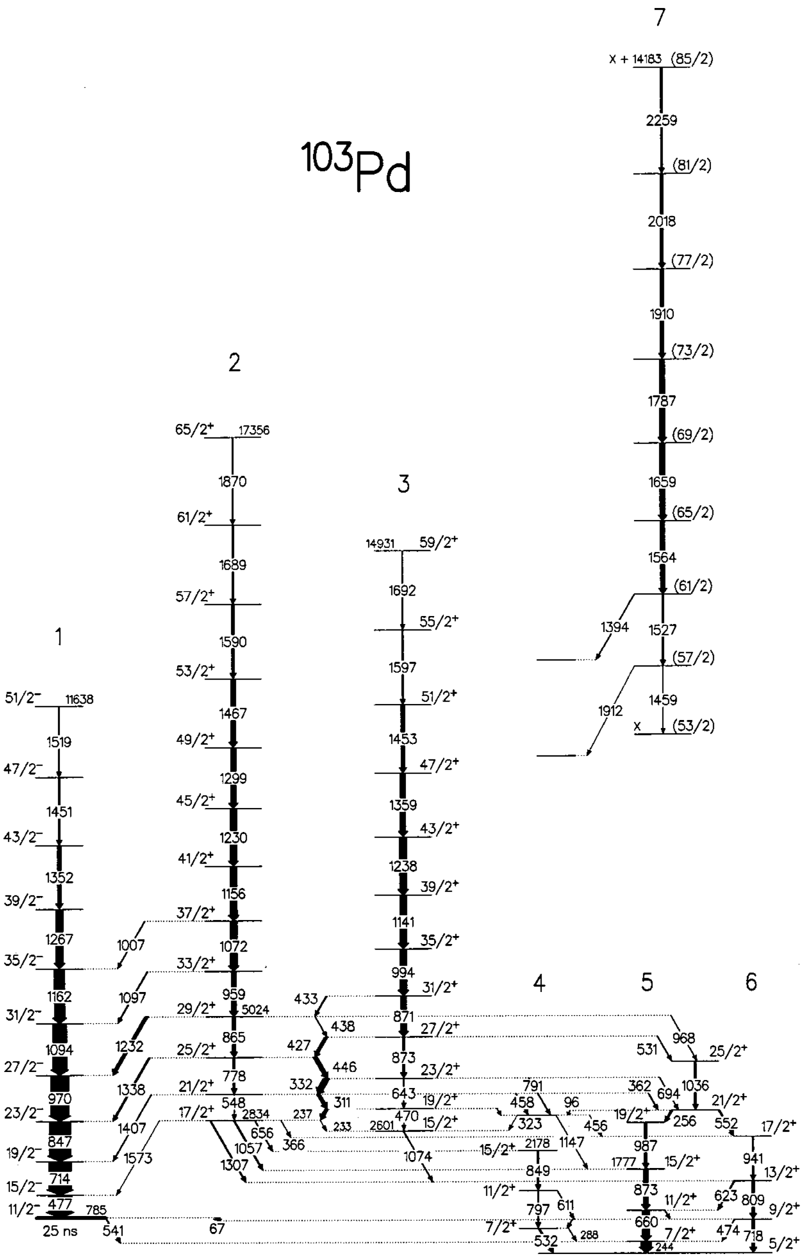

FIG. 1. The partial level scheme of ^{103}Pd obtained in the present work. Energies are given in keV and the thickness of lines representing the γ-ray transitions are proportional to their measured intensities. For the value of x, see text.

blets of the strong band-1 1094 keV and band-2 1230 keV transitions, respectively. Taking the strongest, 1232 keV, connecting transition, the energy and the spin of the state fed by the 959 keV line have been fixed at $E_x = 5024$ keV and $29/2\hbar$. A spectrum obtained by setting a double gate on the 1230/1232 keV energy doublet is shown in Fig. 2 to illustrate the correctness of the newly established relative position of these two bands, which were connected by a single $E_\gamma = 1411$ keV transition in Ref. [8]. In the present data, this γ-transition was found to be a self-coincident energy triplet and it was not possible to unambiguously place these gamma-rays in the level scheme. The observed coincidences of this triplet could not prove either that any of its members was the former connecting transition.

The relative position of the two positive-parity bands (bands 2 and 3) has also been changed. The 1232 keV line has been removed from band 2 (formerly it was placed below the 959 keV transition), and new stretched $E2$ in-band transitions have been identified at the bottom of both bands. These are, in band 2, the weak 778 keV and 548 keV transitions, and, in band 3, an $E_\gamma \approx 872$ keV transition, a member of a newly resolved in-band energy doublet (see Fig. 2), and the weak 643 keV and 470 keV transitions. The $E2$ assignment of these weak transitions is based on the observation of the interlinking $\Delta I = 1$ $M1$ transitions and on the rotational character of them. The coincidence relations between the stretched $E2$ and the known $M1$ transitions, [8], establish a new ordering of the latter ones, which now represent a strong coupling between the lower parts of these bands (Fig. 1). The new ordering is further supported by the existence of several connecting transitions to the bands built on the $5/2^+$ ground state and on the first and second $7/2^+$ excited states (bands 4–6; quoted as *low-spin bands* from now on). For the sake of

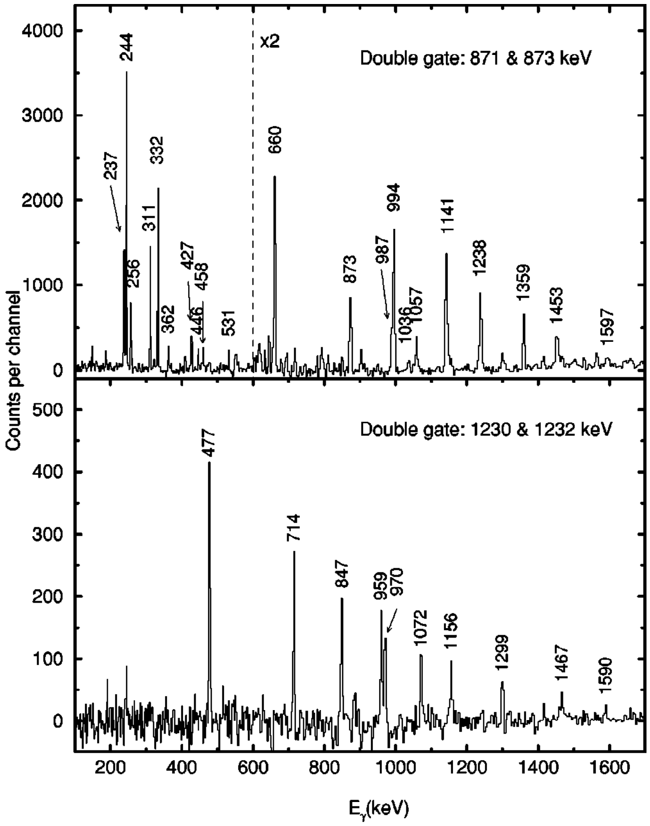

FIG. 2. Coincidence spectra obtained from the *total* cube for double gates set on (bottom) the 1230/1232 keV doublet; (top) the 871/873 keV doublet in band 3.

clarity, only the strongest of these connecting transitions are shown in Fig. 1.

Due to the strong coupling between bands 2 and 3, new spin and energy values have been established also for the levels in band 3. In addition, these bands have been extended at their highest spins. Band 2 is built on a $17/2^+$ state at $E_x = 2.834$ MeV the spin and parity of which is firmly established by the measured $M1$ character of the 656 keV and 1057 keV transitions to the $15/2^+$ states at 2.178 MeV (band 4) and 1.777 MeV (band 5) [16], respectively. Having a cascade of twelve $E2$ transitions, two of the high-lying ones being newly identified, band 2 extends up to a $65/2^+$ level at $E_x = 17.356$ MeV. Above this no continuation of the band could be found. Band 3 has been observed from the $15/2^+$ level at $E_x = 2.601$ MeV up to a $59/2^+$ state at $E_x = 14.931$ MeV.

The band called ''SD'' in Ref. [8] has also been observed (band 7 in Fig. 1). Three new discrete transitions have been identified: the $E_\gamma = 1394$ keV line and the $E_\gamma = 1912$ keV line, an energy doublet of the $E_\gamma = 1910$ keV in-band transition, are probably involved in the decay-out process, while the $E_\gamma = 1459$ keV line is probably the lowest detected member of the band. The measured intensity distribution along the band indicates that the lowest two or three levels take part in its decay-out. The coincidence analysis did not allow, however, within the observation limit, to establish any direct links to bands 1–3. This leaves the spin and excitation energy of the levels in band 7 undetermined, and indicates that the decay-out probably follows some multistep paths, similarly to that of band 3 in ^{102}Pd [9]. To find a ''most probable'' spin assignment and excitation energy for the levels in band 7 the entry spins where the high-spin bands are fed have been determined by comparing the 1564–1659 keV double-gate spectrum in band 7 with double-gate spectra in bands 1–3. The feedings take place, on average, at $43/2^-$ (band 1), and at $49/2^+$ and $47/2^+$ (bands 2 and 3), respectively. However, feeding to the levels just above these cannot be excluded as the relevant transitions are overlapping, within the experimental resolution, with the 1459 keV band-7 line. The increased in-band intensities of the 1467 keV and 1453 keV lines also indicate some extra feeding to them. Supposing, that the feeding to bands 2 and 3 most probably take place through 2 or 3 de-exciting γ-rays with $4–5\hbar$ angular momentum taken away, we propose, that the spin for the level fed by the $E_\gamma = 1564$ keV line is at $\approx 61/2\hbar$. With this tentative assignment band 7 would span from $53/2\hbar$ to $85/2\hbar$, with at least $3\hbar$ uncertainty. A reasonable band-head energy with these spins for the band would be around $E_x = 14–14.5$ MeV, however, in order to reduce the height of the figure, the position of the band in Fig. 1 was arbitrarily set at an excitation energy of $E_x = 11$ MeV. Experimentally, the energies of the connecting γ-rays and the parity of the band remain undetermined, however, as the feeding happens mainly to positive parity bands (bands 2 and 3), the parity of band 7 is most probably also positive.

The interpretation of the experimental data presented here for the high-spin bands of ^{103}Pd will be discussed below. The structure of the *low-spin bands* and the low-energy part of the strongly coupled bands will be discussed elsewhere [17].

The interpretation of the experimental bands is based on the calculated high-spin bands published in Ref. [7]. These calculations are carried out in the configuration-dependent cranked Nilsson-Strutinsky formalism [18,19] with pairing correlations neglected. They indicate the presence of many terminating bands for $A \simeq 100$ nuclei in the Ru-Pd region. For ^{103}Pd, the excitation energies of the experimental bands are plotted relative to a rigid-rotor reference in the upper panel of Fig. 3. The energies are shown versus angular momentum and compared with the calculated yrast valence-space and core-excited configurations [7] which are plotted in the lower panel of the figure. The short-hand notations $[(p_1)p_2p_3,n]$ identifying the configurations in Fig. 3 (Calc.) refer to the number of valence particles relative to the ^{90}Zr spherical core, where p_i and n are used as follows: (p_1) indicates the number of protons promoted from the $N=3$ shell to higher lying orbitals, p_2 and p_3 indicate the number of $g_{9/2}$ and $h_{11/2}$ protons, respectively, while n indicates the number of $h_{11/2}$ neutrons. For the sake of simplicity, the number of neutrons in the $(g_{7/2},d_{5/2})$ orbitals are not indicated in the labels, and (p_1) and p_3 are also omitted when their values are zero. The valence-space configurations shown in Fig. 3 (Calc.) are characterized by 6 $g_{9/2}$ protons and 7 neutrons in the $(g_{7/2},d_{5/2})$ and the $h_{11/2}$ subshells,

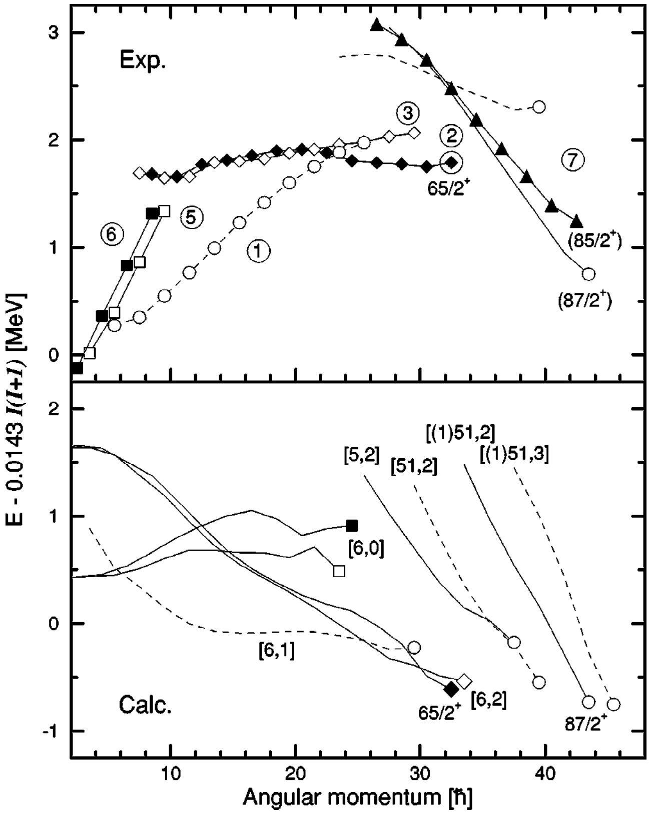

FIG. 3. (Exp) Excitation energy relative to an $0.0143 \cdot I(I+1)$ rigid rotor reference as a function of spin I for the experimental band structures 1–3 and 5–7 observed in ^{103}Pd. (Calc) The energies of low-lying calculated configurations of ^{103}Pd (from Ref. [7]) relative to the same rigid rotor reference. In both panels, solid and dashed lines are used for positive and negative parities, respectively, while full and open symbols indicate $\alpha=+1/2$ and $\alpha=-1/2$ signatures. For the calculated configurations, these symbols are shown only for the terminating states. The labels identifying these configurations are explained in the text. The observed bands are identified by their numbers in Fig. 1, and the terminating $I=65/2^{+}$ state is encircled. Band 7 is drawn assuming different higest spin values, 79/2, 85/2, and 87/2, with arbitrary absolute excitation energies. Possible configuration assignments for this band are discussed in the text.

while the core-excited configurations represent one or more protons promoted from the $N=3$ and/or $g_{9/2}$ shells to the $(g_{7/2}d_{5/2})$ and $h_{11/2}$ subshells.

The yrast positive-parity configuration below $I\approx 12\hbar$ is calculated to be the [6,0] configuration, with an increasing signature splitting up to $I\approx 16\hbar$. In this spin region the observed yrast positive-parity *low-spin bands*, bands 5 and 6, also show a slightly increasing signature splitting of the same sign as the calculated one. Even though pairing is expected to mix the different configurations at these low spin values, it seems reasonable to suggest that these observed bands are dominated by the two signature branches of this $\pi(g_{9/2})^{6}\nu(g_{7/2}d_{5/2})^{7}$ configuration.

The yrast negative-parity configuration is predicted to be the $\alpha=-1/2$ signature branch of the $\pi(g_{9/2})^{6}\otimes\nu(g_{7/2}d_{5/2})^{6}(h_{11/2})$ configuration. It has one aligned $h_{11/2}$ neutron relative to the [6,0] configuration, and it becomes yrast above spin $\sim 6\hbar$. This [6,1] configuration is therefore considered as the counterpart of the observed yrast band (band 1). By aligning the intrinsic angular momenta of all the valence particles, it is calculated to terminate at $I^{\pi}=59/2^{-}$, the protons contributing by $12\hbar$ and the neutrons by $35/2\hbar$ to the spin. Experimentally, due probably to the rapid depart of the band from being yrast above $I\sim 23\hbar$, two more transitions await identification to reach the terminating state.

The calculated yrast positive-parity configuration at higher spin values, $\pi(g_{9/2})^{6}\nu(g_{7/2}d_{5/2})^{5}(h_{11/2})^{2}$, is obtained by occupying one more $h_{11/2}$ neutron. Depending on the signature of the fifth positive-parity neutron, the corresponding bands terminate at $65/2^{+}$ and $67/2^{+}$ as shown in Fig. 3. The $\alpha=+1/2$ and $\alpha=-1/2$ signature branches of this [6,2] configuration are proposed to correspond to band 2 and band 3, respectively. Band 2, in agreement with the predictions, is observed up to the $65/2^{+}$ terminating state, where the band is yrast. Band 3, however, becomes non-yrast at spin $\sim 22\hbar$, due to the signature inversion taking place experimentally earlier than predicted. This could explain why the terminating state in this band has not been observed.

Due to the effect of neglected pairing, the calculations are not expected to reproduce the experimental data at low spins. This is manifested, e.g., in the different slopes of the experimental and calculated configurations in Fig. 3, especially at the lowest spin values. In spite of these deficiences, it is interesting to note, that the relative energies and crossings of the calculated [6,0], [6,1] and [6,2] valence-space configurations in Fig. 3 show a remarkable qualitative agreement with those of the corresponding observed bands.

In ^{102}Pd [9] the highest-spin states populated were interpreted as terminating bands having core-excited configurations. The ^{103}Pd nuclei have been produced in the same heavy-ion experiment, so one can expect the feeding of even higher spin states, and consequently, the excitation of core-excited terminating bands, if they exist. The high spins which are proposed for the highest observed levels in band 7 cannot be generated in valence-space configurations. From the fact that no other transitions could be observed above the $E_{\gamma}=2259$ keV line, although it would not be contradicted by the measured intensities, the corresponding level might be considered as the terminating state of the band. A further observation is that with the spin values drawn in Fig. 1, the E_{γ} vs I curve of this band comes close to that of the band assigned as terminating at $I=38^{+}$ in ^{102}Pd [9].

The facts listed above makes it plausible to compare band 7 with core-excited terminating configurations. In spite of having tentative spin and parity assignments for the levels in band 7, some possible choices for its configuration can still be suggested. As the uncertainty of the proposed spins is large, we can allow the spins to take different values and compare the corresponding cases with different core-excited configurations, considering the yrast $1p$-$1h$ and $2p$-$2h$ configurations plotted in Fig. 3 (Calc).

The only $1p$-$1h$ configuration which goes to high spin enough to be considered as a candidate for the observed band 7 is [51,2] with one proton excited from $g_{9/2}$ to $h_{11/2}$. This configuration terminates at $I=79/2$. The corresponding generated ''experimental band'' obtained by using the measured γ-energies of band 7 and assuming $I=79/2$ as its highest observed spin value is drawn in Fig. 3 (dashed line), with its highest spin state indicated by an open circle. In general, with excitation energies drawn as in Fig. 3, calculations with pairing correlations neglected appear to describe the slope of experimental bands based on core-excited configurations better than the ones based on valence-space configurations, see Ref. [9]. Thus, because the slope of this generated ''experimental band'' differs considerably from that of the calculated [51,2] configuration, we consider it unlikely that this configuration should be assigned to the observed band.

The observed band 7 is drawn in Fig. 3 with the spin values suggested in Fig. 1 (full triangles). A generated ''experimental band'' corresponding to states with its spin values one unit higher than those of the observed band is also shown (solid line), with its highest spin state indicated also by an open circle. The slope of the calculated [(1)51,2] configuration with $I_{\mathrm{max}}=87/2$ or its signature partner with $I_{\mathrm{max}}=85/2$ (not drawn in Fig. 3) is then close to that for the observed band. Thus, within the uncertainty of the spin values, this comparison suggests that band 7 could correspond to either signature of this configuration, having two protons excited across the $N=50$ gap to $(g_{7/2},d_{5/2})$ and $h_{11/2}$ orbitals, respectively. With these assumptions band 7 is seen experimentally up to termination although one could also imagine other assignments with one or two transitions lacking before the terminating state is reached.

Some shape trajectories for the bands of ^{103}Pd are drawn in Fig. 3 of Ref. [7]. The valence space configurations are calculated at $\varepsilon_2 \leqslant 0.20$ and terminate at oblate shape $(\gamma=60°)$ with $\varepsilon_2=0.05-0.10$. The [(1)51,2] configurations are calculated at $\varepsilon_2>0.20$ for spin values up to $I\approx 30$ and terminate at $\varepsilon_2 \approx 0.17$ $(\gamma=60°)$.

In conclusion, the reinvestigation of the level structure of ^{103}Pd using high-statistics triples and higher-fold coincidence data has resulted in new spin and excitation energies for the positive-parity high-spin band structures. The observed bands have been compared with the Nilsson-Strutinsky cranking calculations of Ref. [7] and explained in terms of terminating configurations. One of the three terminating bands built in the valence space has been observed up to termination at $I^{\pi}=65/2^{+}$. A fourth band with tentative spin assignment and excitation energy is proposed to have a $2p$-$2h$ core-excited configuration and is possibly also seen up to its terminating state.

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