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Terminating bands in the doubly odd nucleus ^{102}Rh

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High spin states have been populated in ^{102}Rh using the reaction ^{70}Zn(^{36}S,$p3n\gamma$) at 130 MeV. The γ rays have been detected with the EUROGAM2 array. The level structure of ^{102}Rh has been investigated. Several bands have been identified and established over a wide range of spin. They are interpreted using the Nilsson-Strutinsky cranking formalism and explained in terms of band terminations. Their configurations are built from the valence particles and valence holes relative to a ^{90}Zr core: $g_{9/2}$ protons (and $N=3$ proton holes) and $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ neutrons. After ^{102}Pd, ^{102}Rh is the second heavy nucleus and the first odd-odd nucleus in which configurations in the valence space are followed from low spin up to their termination. [S0556-2813(99)50502-5]

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Transitional nuclei with $Z<50$ and mass $A\simeq100$ are characterized by a small quadrupole deformation and a very γ-soft potential at low and moderate angular momenta. The doubly odd nuclei have configurations with the odd proton in orbitals situated below the $Z=50$ gap and the odd neutron in orbitals situated above the $N=50$ gap. This induces complex level structures for which the proton and the neutron occupy high-Ω and low-Ω orbitals, respectively. In addition, the coexistence of near-spherical and deformed shapes increases the complexity of the level structures.

Both the low-spin and high-spin domains for nuclei in this mass region are poorly known. Using a powerful instrument, namely, the EUROGAM2 γ-ray spectrometer, a study of Pd($Z=46$) and Rh($Z=45$) isotopes at high angular momenta has been undertaken, mainly focusing on predicted terminating structures [1]. The terminating states have spins built solely from the angular momentum of the valence particles and valence holes. They have noncollective oblate ($\gamma=+60°$) or prolate ($\gamma=-120°$) shape and correspond to the highest spin states of configurations which have some collectivity at low spin but gradually lose it with increasing spin.

Contrary to other regions, data on terminating bands are very scarce below $Z=50$. In the $A\simeq100$ transitional region there was only an indication of band termination [2] before our results on ^{102}Pd [3]. This nucleus is the first in which terminating bands built on valence-space configurations *and* core-excited configurations, respectively, have been observed. This confirms the theoretical predictions [1] about the existence of many yrast configurations terminating at spins in the $I=30$–$40\hbar$ range for nuclei with $Z\simeq45$ and $A\simeq100$. In this Rapid Communication, we present results on band terminations observed in the odd-odd nucleus ^{102}Rh. In the first part, band structures established over a wide range of spin are described. Then an interpretation of the bands is given in terms of terminating configurations. Preliminary data have been presented elsewhere [4].

The reaction ^{70}Zn(^{36}S,$p3n$) at a bombarding energy of 130 MeV has been used to populate states in ^{102}Rh. The target consisted of two stacked self-supporting foils of Zn, enriched to 70% in ^{70}Zn and 13% in ^{68}Zn, each with a thickness of 440 μg/cm^2. The beam was provided by the Vivitron accelerator at IReS, Strasbourg. The γ rays were detected by using the EUROGAM2 spectrometer equipped with 30 tapered coaxial Ge detectors and 24 clover-type detectors, all in Compton-suppression shields [5]. Coincidence events were collected when at least four suppressed Ge detectors fired. A total of 6×10^8 Compton-suppressed events were written onto magnetic tapes. A total and several gated $E_{\gamma1}-E_{\gamma2}-E_{\gamma3}$ cubes have been analyzed using the LEVIT8R graphical spectrum analysis package [6].

Excited levels in ^{102}Rh were previously observed in-beam in the reactions ^{102}Ru($p,n\gamma$) [7,8] and ^{98}Mo(^{7}Li,3$n\gamma$) [9]. From a decay study of the $I^\pi=6^+,T_{1/2}=1057$ d isomer, the existing level schemes were modified and a new scale was fixed for the excitation energies of the levels [10]. These data together with results from other decay studies [11] have been used as a starting basis for our level scheme presented in Fig. 1.

The level scheme of ^{102}Rh was obtained using arguments based on triples and quadruples γ-ray coincidence relationships, γ-ray intensity and energy balances, multipolarities of transitions, and γ-ray linear polarizations. Examples of spectra showing transitions in the main bands are presented in Fig. 2. They were obtained by setting double gates on gated cubes which were made by requiring coincidence conditions

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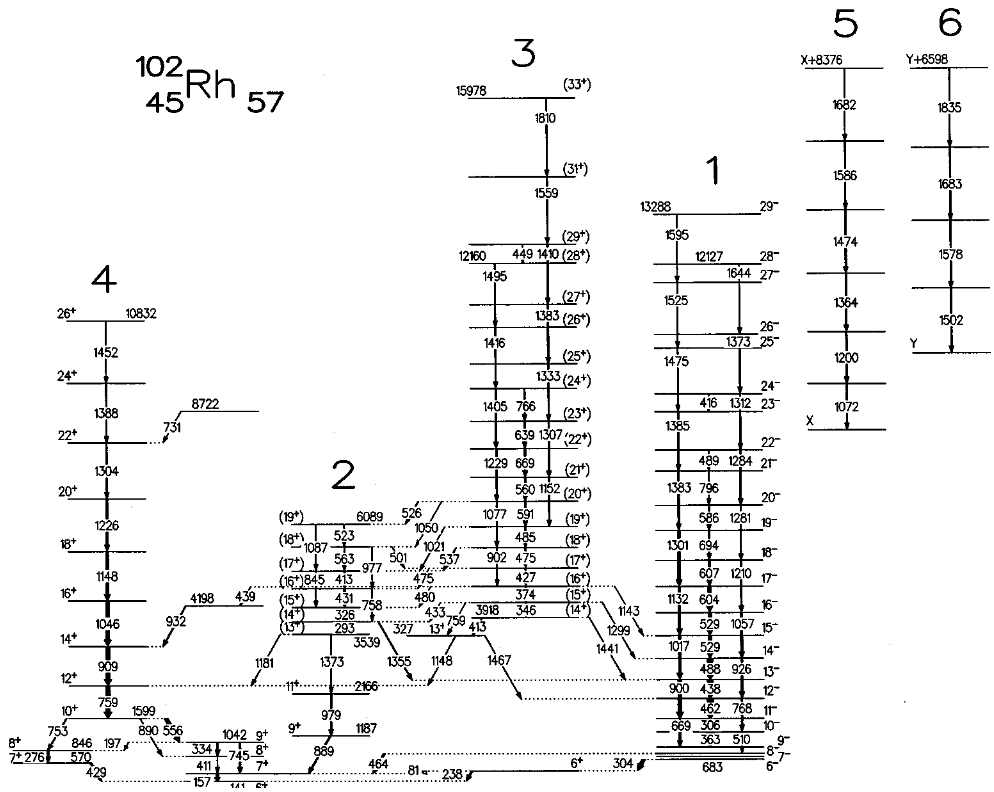

FIG. 1. Partial level scheme of ^{102}Rh above the 141 keV, 6^+ state. Level and γ-ray energies are given in keV. The width of the arrows is proportional to the γ-ray intensity.

with the strongest low-lying transitions in the level scheme. Prior to the present work, only the nine lowest levels of band 1 were known [9]. Bands 2–6 are newly identified. Due to the large number of observed excited levels and to the fact that, in this Rapid Communication, we concentrate on the properties of band structures at high spin, the full level scheme has been simplified. Only the band structures discussed in the text and the levels which are necessary to establish the positions and the connections of these bands are shown in Fig. 1. For example, the decay of band 1 which proceeds via nine $E1$ transitions to lower excitation-energy levels is represented by the strongest transition only.

Among the observed levels, a strongly populated and very well developed band structure (band 1) based on the $I^\pi = 6^-$ state at 682.7 keV excitation energy [10] has been established. It is made of levels populated and deexcited by stretched quadrupole and mixed $M1/E2$ transitions whose multipolarities are unambiguously determined by angular correlation and linear polarization measurements.

Bands 2 and 3 are also of $\Delta I = 1$ type but the bottom stretched quadrupole transitions are not observed in band 3. There are many links between them and with the rest of the level scheme. Most of the connecting γ rays are weak and/or composite which precludes precise γ-ray angular correlation measurements. The tentatively proposed spin and positive parity assignments are the most probable supposing stretched character for the transitions connecting the bands to each other and to the other bands.

Band 4 is a cascade of eight transitions placed above the $I^\pi = 10^+$ level at 1599 keV excitation energy. The decay mode of this level is totally shown in Fig. 1. The $\Delta I = 2$ character of band 4 is established by angular correlation ratios.

Two other cascades of γ rays (bands 5 and 6) which are very likely electric quadrupoles are also assigned to ^{102}Rh. They decay to the negative-parity band 1 only but, due to a likely complex decay, their links have not been observed. The fact that they feed band 1 in the spin range $I = 15 - 19\hbar$ suggests a lower limit of $I \approx 20\hbar$ for their lowest levels.

The full level scheme will not be discussed in detail in the present publication. Only the well developed bands are analyzed. Calculations have been performed for ^{102}Rh using the cranking Nilsson-Strutinsky formalism. These calculations are analogous to those performed for other nuclei in the $A = 100$ region, i.e., ^{100}Ru and Pd isotopes [1] and more recently for ^{102}Pd [3]. In our formalism [12] the configurations are determined by the number of particles in the N shells of the rotating basis. An additional feature [13,14] is that after the diagonalization, we identify the orbitals of dominant high j character and thus we can also distinguish between particles in the intruder high-j shells and in the other j shells. The different configurations are then labeled by the number of particles in the different j shells or groups of j shells relative to a ^{90}Zr core. For simplicity the shorthand notation $[(p_0)p_1p_2,n]$ is used. In this notation, (p_0) is the number of proton holes in $N=3$ orbitals, p_1 the number of protons in $g_{9/2}$ orbitals, p_2 the number of protons in $h_{11/2}$ orbitals, and n the number of neutrons in $h_{11/2}$ orbitals. (p_0) and p_2 are omitted for configurations with no proton holes in the $N = 3$ orbitals and no protons in $h_{11/2}$ orbitals, respectively.

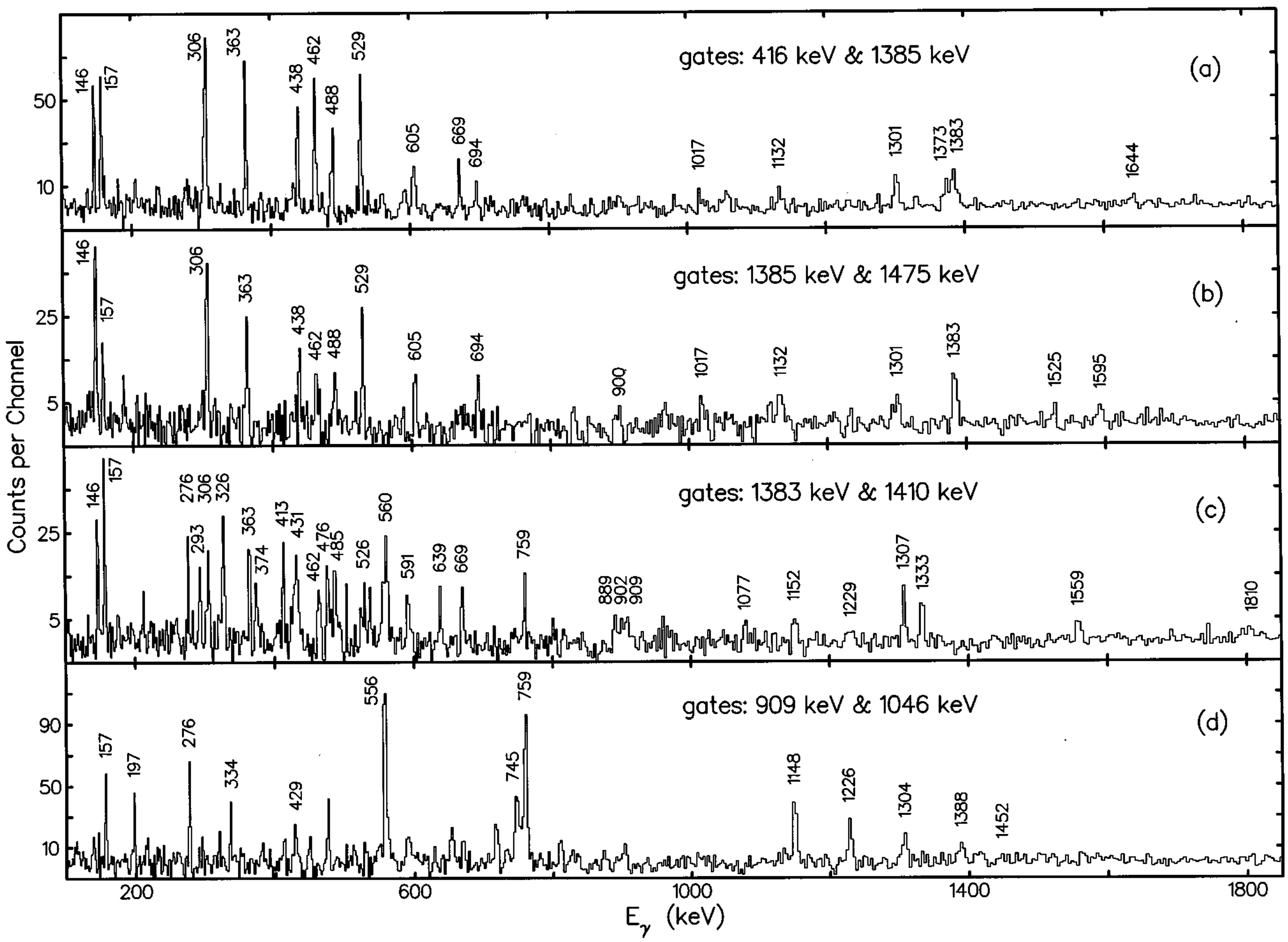

FIG. 2. Examples of double-gated γ-ray spectra from gated cubes showing transitions in band 1 (a), (b), band 3 (c), and band 4 (d). The transition energies are given in keV.

Note that our labeling of the configurations in terms of a core and particles in the valence shells is approximate. In the numerical calculations, no core is introduced and all orbitals (up to $N=8$) are treated on the same footing. The energy of each configuration at each spin is minimized in the deformation space $(\varepsilon_2,\varepsilon_4,\gamma)$ which allows the development of collectivity to be traced within specific configurations as a function of spin. For each configuration, the lowest energy solution is searched and followed with spin. Thus, a large number of configurations are found; however, only a limited number in the yrast region. These low-energy configurations are compared with the experimental bands in Fig. 3. Pairing correlations are neglected in the calculations which could thus be considered as realistic only at high spin, say, above $I\approx 20\hbar$. As the single-particle parameters are not very well known in the $A=100$ region, we have used standard parameters of Ref. [12] for the Nilsson potential.

In the comparison between experiment and calculations in Fig. 3, an $I(I+1)$ rigid rotor reference has been subtracted. Band 1 is the only observed negative-parity band and it is strongly fed because of its yrast character. Its bandhead has the $\pi g_{9/2}\nu h_{11/2}$ configuration [9]. In the calculations, the negative-parity configuration [5,1] is yrast above spin $16\hbar$ and terminates at $I^\pi=30^-$ and $I^\pi=29^-$ for the $\alpha=0$ and $\alpha=1$ signatures, respectively. We propose that band 1 at high spin can be identified with this configuration. The measured and calculated signature-splittings at high spin $(I>25\hbar)$, where the pairing correlations are of small importance, are very similar (≈ 0.5 MeV). The $\alpha=1$ signature branch of band 1 reaches termination at the $I^\pi=29^-$ level which has the configuration $\pi(g_{9/2})^5_{12.5}\nu(d_{5/2}g_{7/2})^6_{11}(h_{11/2})^1_{5.5}$. The $\alpha=0$ signature branch however could be established only up to $I^\pi=28^-$, i.e., one step before the predicted terminating state of the [5,1] configuration. This is due to contaminations even in the gated cube, although the γ-ray intensities at the top of this branch are larger than at the top of the other branch in accordance with the favored character of $\alpha=0$ signature.

The fact that the $I^\pi=28^-$ state deviates from the smooth trend, see Fig. 3, makes its interpretation more difficult. One possibility is that an aligned $I=26\hbar$ state is formed in an analogous way as the aligned $I=40\hbar$ state is formed in ^{158}Er [15,16] in the configuration which has a maximum spin of $I=46\hbar$. In the calculated [5,1] negative-parity band of ^{102}Rh, the six $d_{5/2},g_{7/2}$ neutrons couple to their maximum spin value, i.e., $I=12\hbar$, in the terminating $I=30\hbar$ state. This state is then understood as having three $g_{7/2}$ neutrons with aligned spins $m=7/2$, 5/2, and 3/2 and three $d_{5/2}$ neutrons with $m=5/2$, 3/2, and 1/2 (where in reality, $d_{5/2}$ and $g_{7/2}$ subshells are strongly mixed). If then one neutron is shifted from $g_{7/2},m=3/2$ to $d_{5/2},m=-5/2$, these six neutrons contribute with eight spin units and the total maximum spin becomes $I=26\hbar$. Such a state would be favored if the split-

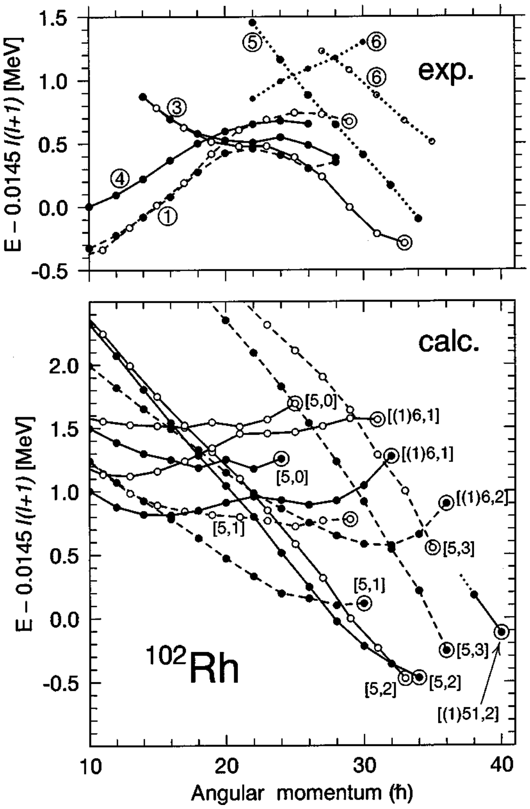

FIG. 3. Excitation energy relative to an $I(I+1)$ reference as a function of I for the experimental (top) and calculated (bottom) bands. The orbitals are labeled as described in the text, full and dashed lines are used for positive and negative parities; closed and open symbols for signatures $\alpha=0$ and $\alpha=1$, respectively. Calculated terminating states and observed states assigned to them are encircled. In the upper panel, bands 5 and 6 (dotted lines) are drawn with arbitrary excitation energies and spins as these quantities could not be determined in the present experiment. To indicate the sensitivity on the spin assignments, band 6 is drawn with two assumptions assuming $I=22\hbar$ and $I=27\hbar$, respectively, for its lowest states. The drastically different slopes in these two cases shows that the configuration assignment is highly sensitive on the spin assignment.

ting between the $d_{5/2}$ and $g_{7/2}$ subshells was larger than obtained with the present single-particle parameters. However, there are also problems associated with this increased spacing. Thus, also the other signature which appears to terminate at $I=29\hbar$ might become disturbed so that, when plotted as in Fig. 3, the 29^- state comes at a considerably higher energy than the 25^- state.

One could also note that negative-parity bands are calculated in the [(1)6,2] configuration which are not too high above those in the [5,1] configuration. The lowest state of this kind is drawn in Fig. 3. Considering general uncertainties, it cannot be excluded that it is that configuration which should be assigned to the negative-parity bands. If so, the 29^- state does not correspond to a termination. However, also with such a scenario, it is as difficult to explain the kink in the observed band when going from $I=26^-$ to $I=28^-$. It is thus clear that at present, there are some difficulties in understanding the details of the negative-parity bands which is probably at least partly associated with uncertainties of the single-particle parameters.

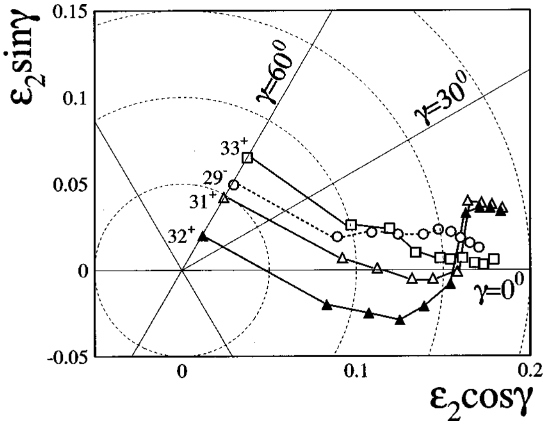

FIG. 4. Calculated shape trajectories for the two signatures of configuration [4(1),1] (open and closed triangles) and for the $\alpha=1$ signatures of configurations [5,1] (circles) and [5,2] (squares) discussed in the text. The data points (each separated by $2\hbar$) are shown for the ten highest levels in the bands, i.e., for the spin range $[I_{\max}-18, I_{\max}]$.

As band 2 is not well developed, no conclusion can be drawn concerning its configuration. On the contrary, band 3 extends over a wide range of spin and can be compared to calculations. It becomes yrast at $I=27\hbar$ as shown in Fig. 1. This is the situation for the [5,2] configuration relative to the [5,1] configuration as indicated by the calculations. We propose that band 3 at high spin corresponds to the [5,2] configuration which is built from five $g_{9/2}$ protons and two $h_{11/2}$ neutrons. The [5,2] configuration is calculated to terminate at $I^\pi=34^+$ and $I^\pi=33^+$. The structure of the terminating states is $\pi(g_{9/2})^5_{12.5}\nu(d_{5/2}g_{7/2})^5_{10.5,11.5}(h_{11/2})^2_{10}$. The experimental $\alpha=1$ branch of band 3 is observed up to the terminating state while two levels are missing in the $\alpha=0$ signature branch. This is consistent with the fact that the terminating state of the $\alpha=1$ signature is favored in energy in the calculations. However, contrary to experiment, the calculations suggest that the $\alpha=0$ branch should be favored in energy at lower spin. A possible origin of this discrepancy is that the parameters of the Nilsson potential for the neutron $N=4$ shell related to the relative positions of the $g_{7/2}$ and $d_{5/2}$ spherical subshells are not optimal. Another possible reason could be the residual proton-neutron interaction which is known to be important at low spin in odd-odd nuclei in general and which is not accounted for in the present calculations.

Band 4 is of $\Delta I=2$ type and its parity is positive. It could correspond to the $\alpha=0$ favored signature of a configuration lying close to yrast, the other signature being much higher in energy. This is the case of the calculated [(1)6,1] configuration for which the $\alpha=1$ unfavored signature lies about 0.5 MeV above the favored one, see Fig. 3. Based on this argument, band 4 might correspond to the [(1)6,1] configuration which terminates in the $I^\pi=32^+$ state having the structure $\pi(N=3)^{-1}_{2.5}(g_{9/2})^6_{12}\nu(d_{5/2}g_{7/2})^6_{12}(h_{11/2})^1_{5.5}$.

Because the absolute spin values and the excitation energies of bands 5 and 6 are unknown, any configuration assignment will be associated with large uncertainties. Even so these bands are drawn in Fig. 3 with some reasonable assumptions. If both bands are assumed to have lowest spin values of $I=22\hbar$, the slope suggests that band 6 might be assigned to some configuration with a proton hole in the $N=3$ shell and band 5 to the [5,3] configuration. As an alternative band 6 is then also drawn in Fig. 3 with the somewhat unlikely assumption that its spin values are increased by $5\hbar$, in which case it might be associated with the unfavored signature of the [5,3] configuration. Note that the assignment of bands 5 and 6 as having three neutrons in $h_{11/2}$ is consistent with their deexcitation modes only towards band 1, interpreted as having one $h_{11/2}$ neutron. To get some idea about the possibility that bands 5 and/or 6 are associated with a proton-core excited, the lowest calculated configuration of this kind, [(1)51,2] having one $h_{11/2}$ proton, is also shown in Fig. 3.

The shapes associated with the terminating configurations evolve drastically with the angular momentum. The terminating states are calculated to be oblate. Calculated shape trajectories in the (ε_2,γ) plane are shown in Fig. 4 for configurations discussed above. Note that all configurations are associated with rather small deformations and that the different bands terminate at maximal spin values close to spherical shape. Furthermore, increasing the number of $h_{11/2}$ neutrons drives the termination to larger oblate $\gamma=+60°$ deformation in agreement with our general understanding of these high-j particles as mainly rotating around the equator of the nucleus.

In conclusion, six band structures extending up to high spin have been established in the doubly odd nucleus ^{102}Rh. From a comparison with theory, three of these bands are assigned as terminating configurations. Two of them appear to terminate at $I^{\pi}=29^{-}$ and $I^{\pi}=(33^{+})$. The terminating states are built from $g_{9/2}$ protons (and $N=3$ proton holes) and $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ neutrons. After ^{102}Pd, ^{102}Rh is the second heavy nucleus and the first odd-odd nucleus in which configurations in the valence space are traced up from low spin up to their termination.

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