Eur. Phys. J. A 4, 11–15 (1999)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

Terminating high-spin bands in ^{101}Rh

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Received: 30 October 1998
Communicated by B. Herskind

Abstract. High spin states of ^{101}Rh have been populated using the reaction ^{70}Zn+^{36}S at 130 MeV. γ-rays were detected with the EUROGAM2 array. New high-spin bands have been observed in this nucleus up to $45/2^-$, $57/2^-$ and $65/2^+$ states. They have been interpreted using the Nilsson-Strutinsky cranking formalism as terminating configurations. Two of the bands were observed up to the predicted terminating states which are built up from $g_{9/2}$ protons as well as $d_{5/2}$, $g_{7/2}$ and $h_{11/2}$ neutrons relative to a ^{90}Zr core.

PACS. 21.10.Re Collective levels – 23.20.Lv Gamma transitions and level energies – 21.60.Ev Collective models – 27.60.+j $90 \leq A \leq 149$

In a rotating nucleus Coriolis and centrifugal forces acting on the individual nucleons become more and more important with increasing spin. Due to these forces more and more nucleons outside the closed shell occupy equatorial orbits around the rotation axis inducing a gradual transition of the nuclear shape from collective deformed (for axially symmetric shape, the rotation axis is perpendicular to the symmetry axis) to non-collective deformed (the rotation axis is parallel to the symmetry axis). The nuclear states in the rotational band corresponding to this evolution become gradually less and less collective and finally non-collective. Since collective rotation around the symmetry axis is quantum-mechanically forbidden, in the non-collective deformed shape the nuclear spin is built up solely from the spin contributions of the individual nucleons and consequently it has a maximum value for a given single-particle configuration. The band terminates at this spin value. The phenomenon of band termination was extensively studied during the last few years in the nuclei around ^{158}Er, ^{109}Sb (for brief review see [1]), ^{62}Zn [2] and ^{48}Cr [3].

It was predicted recently [4] that in the $A \sim 100$ Pd, Rh, Ru nuclei the bands characterized by their (N-shell)-(intruder high-j) configurations remain yrast from the low-spin (prolate) rotational states up to the termination. In this region the terminating spins are predicted to be around $30\,\hbar$ for the valence configurations. These spin values are experimentally accessible using the recent large detector arrays.

An experiment has been carried out recently aimed at searching for terminating bands in this region. Using the data obtained from this experiment we have observed multiple band terminations in ^{102,103}Pd [5,6], in ^{102}Rh [7] and in ^{98,99,100}Ru [8]. In this paper we present the results obtained for the ^{101}Rh nucleus.

High angular momentum states in ^{101}Rh have been populated using the ^{70}Zn(^{36}S,p4n) reaction at a bombarding energy of 130 MeV. The beam was provided by the Vivitron accelerator at CRN, Strasbourg. The target was made of two stacked self-supporting foils of Zn, enriched to 70% in ^{70}Zn and 13% in ^{68}Zn, with a thickness of 440 μg/cm^2 each. γ-rays were detected with the EUROGAM2 spectrometer [9]. Events were written on tape when at least four suppressed Ge detectors in the array detected γ-rays within the coincidence time window. During the experiment a total of 6×10^8 Compton-suppressed events have been recorded, of which about 3% belong to the ^{101}Rh nucleus.

The level scheme of this nucleus has been deduced from the total and gated $E_{\gamma1}-E_{\gamma2}-E_{\gamma3}$ coincidence cubes that

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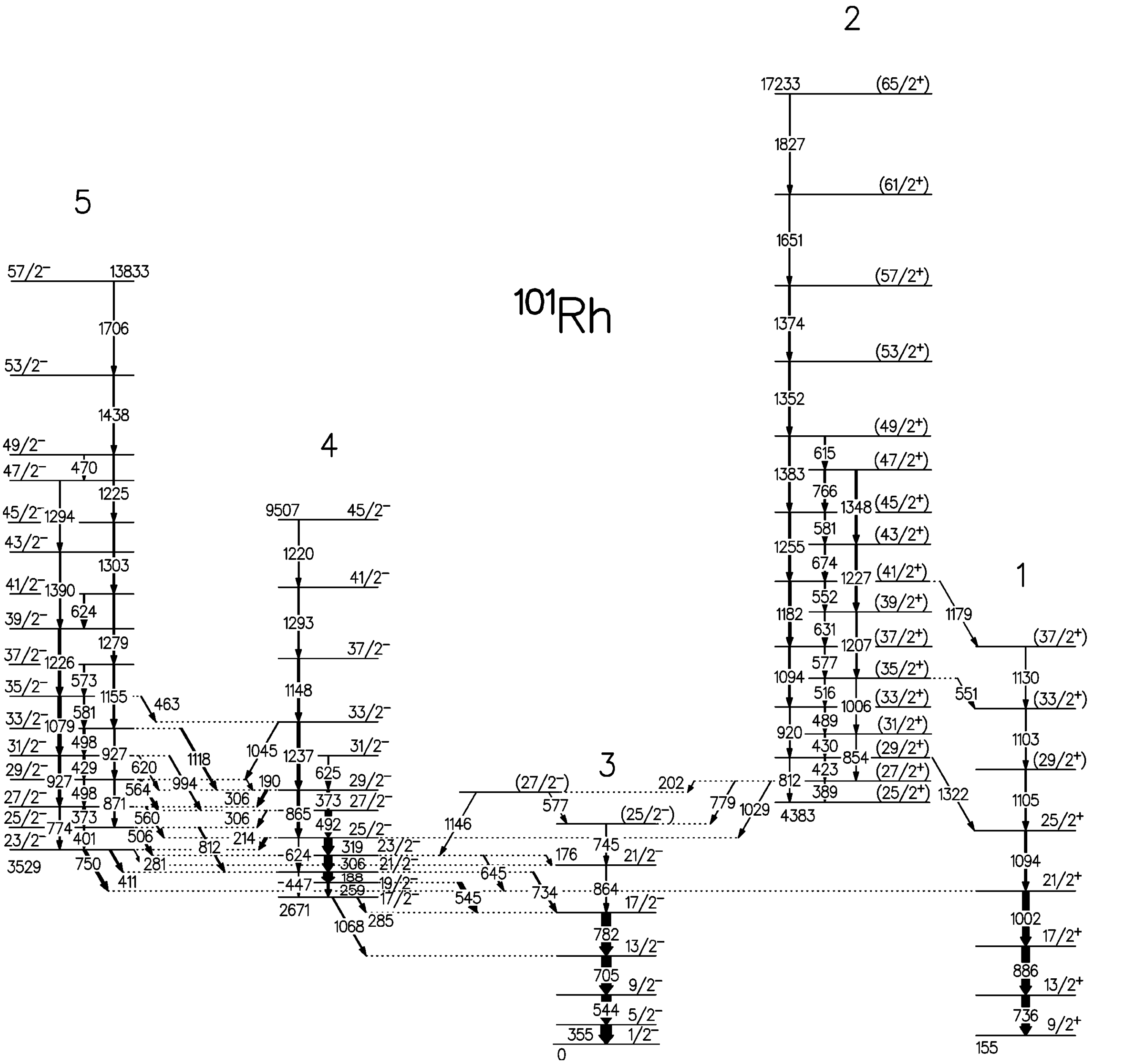

Fig. 1. Partial level scheme of ^{101}Rh obtained in the present work. Level and γ-ray energies are given in keV. The width of the arrows is proportional to the γ-ray intensity

have been sorted from the measured data and analysed using the RADWARE program package [10]. The spins and parities of levels were deduced from DCO ratios and linear polarisation values as defined in [11]. In Fig. 1 the partial level scheme of ^{101}Rh obtained from the present experiment is shown.

Low-energy low-spin levels of ^{101}Rh have previously been investigated from the (p,nγ) reaction [12]. Band structures (bands 1 and 3 in Fig. 1) have also been observed up to spin $25/2\,\hbar$ from the (^{6}Li,3nγ) reaction [13]. These results were used as a starting point in the construction of the present level scheme.

From the present experiment we have extended the two bands published in [13] and we have observed three new coupled band structures (bands 2, 4 and 5). In this paper we focus on the structure of these new high-spin bands. In Fig. 1 only the relevant part of the level scheme is presented. The detailed discussion of the level scheme and the structure of the low and intermediate spin states will be presented in a forthcoming paper.

The lowest energy level of band 4 has previously been observed [13] and a probable $17/2^-$ spin-parity assignment was proposed for it on the basis of the angular distributions of the depopulating γ-rays. The same value has been obtained for this state from the present analysis. Our spin-parity assignments for bands 4 and 5 were based on the DCO and linear polarisation values deduced for the strong inband and connecting transitions. Using these values we derived an E1 character for the 750 keV, and E2 character for the 734 keV transitions connecting band 5 and band 4, respectively, to the known $21/2^+$ and $17/2^-$ levels. The M1 character obtained for the strong 411, 214, 506 and 306 keV interband transitions confirms also the relative spins and parities of these two bands. On the basis of the above multipolarities assuming that the transitions are stretched and go alongside the yrast line (i.e. the spins are decreasing during the transition) we propose $17/2^-$ and $23/2^-$ spin-parity for the lowest levels of bands 4 and 5, respectively. Specific features of these bands are that they decay into each other with M1 and E2 transitions that are almost as strong as the inband transitions. The $\alpha = +1/2$ signature branch of band 4 extends in spin from $17/2\,\hbar$ to $45/2\,\hbar$ while the $\alpha = -1/2$ branch which starts at $19/2\,\hbar$ goes only up to $31/2\,\hbar$. Levels of band 5 extend up to spin $57/2\,\hbar$ and $47/2\,\hbar$ in the $\alpha = +1/2$ and $\alpha = -1/2$ signature branches, respectively.

We have observed another coupled band structure (band 2 in Fig. 1) which decays out to band 1, band 3 and band 4 through many weak paths. Only a few of these decay paths could be observed in this analysis which did not allow precise spin and parity assignment for the band. However, γ-ray spectra in coincidence with band 2 transitions show that this band decays mainly to band 1 and only to a smaller extent to the negative parity bands, which indicates a probable positive parity for the band. Tentative spin assignment for the levels in this band can be obtained assuming that the observed decay-out transitions to levels with known spin-parity are stretched dipoles or quadrupoles. Using these arguments we have tentatively assigned band 2 as having positive parity and extending in spin from $25/2\,\hbar$ to $65/2\,\hbar$ in the $\alpha = +1/2$ signature branch and from $27/2\,\hbar$ to $47/2\,\hbar$ in the $\alpha = -1/2$ signature branch.

Calculations have been performed for ^{101}Rh using the cranking Nilsson-Strutinsky formalism. They are analogous to those performed for other nuclei in the $A \sim 100$ region, i.e. ^{100}Ru and ^{103}Pd isotopes [4] and more recently for ^{102}Pd [5] and ^{102}Rh [7]. In our formalism [14] the configurations are determined by the number of particles in the N-shells of the rotating basis. An additional feature [1,15] is that after the diagonalisation, 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 configurations are then labelled by the number of particles in the different j-shells or groups of j-shells relative to a ^{90}Zr core. In the case of ^{101}Rh the number of proton holes in the $N = 3$ shell, the number of protons in the $g_{9/2}$ and $h_{11/2}$ orbitals, and the number of neutrons in the $h_{11/2}$ orbital define the configuration. However, in the lowest energy configurations that are discussed in the following, $h_{11/2}$ protons were not involved. For simplicity the shorthand notation $[(p_0)p_1, n]$ is used. In this notation, p_0 is the number of proton holes in

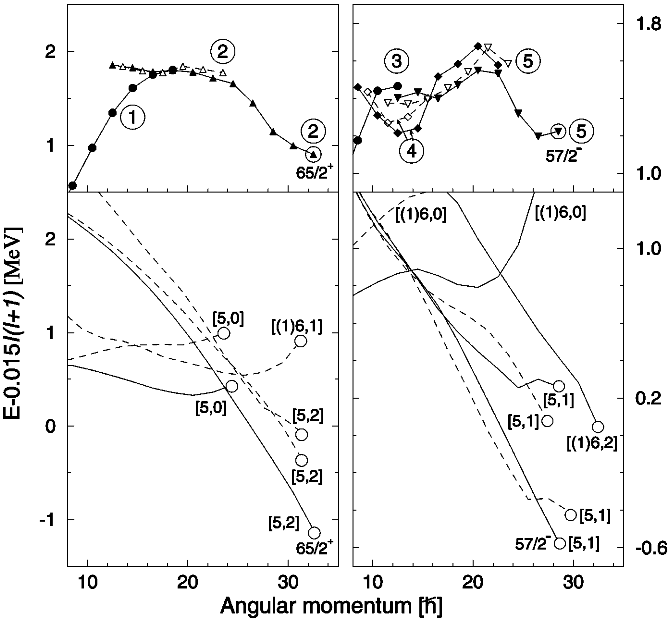

Fig. 2. Excitation energy relative to a rigid rotor reference as a function of the spin for the experimental (top) and calculated (bottom) bands. The left panel shows the positive-parity while the right one the negative-parity bands. Full and open symbols as well as solid and dashed lines correspond to $\alpha = +1/2$ and $\alpha = -1/2$ signature branches, respectively. The observed bands are labelled with the numbers used in Fig. 1 while the calculated curves are labelled with their configurations defined in the text. Open circles at the end of the curves indicate terminating states

the $N = 3$ shell (omitted when p_0=0), p_1 is the number of $g_{9/2}$ protons and n is the number of $h_{11/2}$ neutrons. 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 within specific configurations to be traced as a function of spin. The pairing correlations are neglected in the calculations which could thus be considered as realistic only at high spin, say above $\sim 15 - 20\hbar$. As the single-particle parameters are not very well known in the $A \sim 100$ region, we have used standard parameters of [14] for the Nilsson potential. In Fig. 2 the experimental energies of the observed high-spin bands are compared with the corresponding theoretical values, subtracting the same rigid rotor reference from all of them. Here the experimental level energies are given relative to the ground state energy while the reference of the calculated levels is the liquid drop energy at $I = 0$. Thus, the difference between the two scales depends essentially on the ground state shell energy. In the case of ^{101}Rh this difference is $\sim$2 MeV, as it is seen in Fig. 2. The left and right panels of this figure show the positive- and negative-parity bands, respectively.

The yrast positive parity band at high spin is calculated to have the [5,2] configuration, as it can be seen in the left panel of Fig. 2. The $\alpha = +1/2$ signature branch of this configuration is predicted to be the favoured one and terminates at spin $65/2\,\hbar$. The experimentally observed band 2 has the same characteristics. It is yrast at high spin, its favoured signature branch is the $\alpha = +1/2$ one and it is observed up to spin $65/2\,\hbar$. The slope of the energy versus spin curve for this branch of band 2 above spin $22\,\hbar$ is also reasonably similar to the slope calculated for the [5,2] configuration. On the basis of these arguments we assign the [5,2] configuration to band 2. This assignment is supported also by the fact that the energy versus spin curve of band 2 is very similar to that of the band 3 in ^{102}Rh which has been assigned as a [5,2] configuration, too [7]. According to this assignment the observed $65/2^+$ state is terminating and has the $\pi(g_{9/2})^5_{12.5}\nu(d_{5/2}g_{7/2})^4_{10}(h_{11/2})^2_{10}$ single-particle configuration. The $\alpha = -1/2$ signature of this configuration is predicted to terminate at spin $63/2\,\hbar$. However this branch of band 2 is observed only up to spin $47/2\,\hbar$ consistent with the calculated property that the signature splitting of this band is increasing with spin and the $\alpha = -1/2$ signature levels move up from the yrast line. Although the calculations are realistic only at high spins, some features of the observed bands are reproduced even for the lower spin region. According to the calculations the [5,2] configuration is crossed at around spin $22\,\hbar$ by the [5,0] configuration which is yrast in the low and intermediate spin region. Indeed, the $\alpha = +1/2$ signature branch of band 2 is crossed at spin $\sim 18\,\hbar$ by band 1 which remains yrast below this spin. However the slope of the energy versus spin curve of band 1 is rather different from the slope calculated for the [5,0] configuration. Such a difference is not unexpected due to the pairing which was not taken into account in the calculation. The [5,0] configuration assignment for the higher spin part of band 1 is also consistent with the one $g_{9/2}$ quasiproton configuration proposed previously [16] for this band.

For the negative-parity bands calculations predict the [5,1] configuration to be yrast at high spin. At the highest spins the $\alpha = +1/2$ signature branch becomes yrast and terminates at spin $57/2\,\hbar$. An interesting feature of the negative-parity bands in this nucleus is that the yrare band at high spin is predicted to have the "same" [5,1] configuration. The difference between the two bands arises only from the different distribution of the five $N = 4$ neutrons among the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$ and $s_{1/2}$ orbitals. Experimentally we see two coupled negative-parity bands, bands 4 and 5, which are connected to each other with very strong M1 and E2 linking transitions. The $\alpha = +1/2$ signature branch of band 5 is observed up to spin 57/2 $\hbar$ and is yrast at high spin. The slope of its energy versus spin curve is similar to that one predicted for the yrast [5,1] configuration. Similar slopes of the energy versus spin curves have been observed at the highest observed spins for the other signature branch of band 5 and for the same signature branch of band 4. However these branches were not observed up to the predicted terminations. These similarities between the calculated and experimental values and the fact that the states in band 5 and band 4 decay strongly into each other imply that band 5 and band 4 can be assigned as the first and second [5,1] configurations, respectively. According to this assignment the observed $57/2^-$ state is terminating and has the single-particle configuration $\pi(g_{9/2})^5_{12.5}\nu(d_{5/2}g_{7/2})^5_{10.5}(h_{11/2})^1_{5.5}$. The two [5,1] configurations are predicted to cross each other around spin $14\,\hbar$ while bands 4 and 5 cross each other around spin $16\,\hbar$ in a good agreement with the prediction. At about the same spin values they are also predicted to be crossed by the $\alpha = +1/2$ signature branch of the [(1)6,0] configuration which remains yrast at lower spins. This configuration could correspond to band 3 which crosses band 4 at spin $\sim 10\,\hbar$ and is the yrast negative-parity band below that spin. This assignment is in a good agreement with the $p_{1/2}$ quasiproton assignment which was proposed previously [17] for the ground state of ^{101}Rh.

In conclusion, three new coupled high-spin bands have been observed in ^{101}Rh. Comparing their characteristics with Nilsson-Strutinsky cranking calculations they have been assigned as terminating configurations. Two of them are observed up to the predicted terminating states. A unique feature of the two observed negative-parity bands is that they are assigned as having the same (N-shell)-(intruder high-j) configurations.

Two of us (J.T. and Gh.C-D) thank ISN, Grenoble for hospitality. This work was supported in part by the exchange programmes between CNRS and the Hungarian Academy of Sciences, and between IN2P3 and IFA(Bucharest). It was supported also in part by the Hungarian Scientific Research Fund, OTKA (contract No. 20655) and by the Swedish Natural Science Research Council. Four of us (A.J.B., D.T.J., N.J.O., C.M.P.) acknowledge UK EPSRC postgraduate studentships during this work. EUROGAM was funded jointly by the French IN2P3 and the U.K. EPSRC.

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