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Anomaly in spectra of ^{105}Pd and ^{103}Ru

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The anomalous change in the low-lying spectrum from ^{105}Pd to ^{103}Ru in the sequence of $N=59$ isotones is investigated. A possible attribution of this effect to the onset of a phenomenological exchange force in the interacting boson-fermion model is investigated.

The systematics of the $N=59$ nuclei exhibits an interesting anomaly: There is a pronounced difference between the low-lying positive-parity spectra of $^{103}_{44}$Ru$_{59}$ and $^{105}_{46}$Pd$_{59}$. On one hand, ^{105}Pd exhibits a simple weak-coupling pattern with a $\tilde{j}=\tilde{d}_{5/2}$, $|(\tilde{d}_{5/2},2)J\rangle$. On the other hand, ^{103}Ru exhibits a pronounced $J=j-1$ anomaly, with an anomalous low-lying doublet $3/2_1^+,5/2_1^+$.

A straightforward explanation of this onset of the $I=j-1$ anomaly in the framework of quasiparticle-core coupling is to appreciably change the pattern of neutron single particle energies, with a strong lowering of the $\nu d_{3/2}$ single-particle state in ^{103}Ru. In this case ^{103}Ru would have anomalous neutron quasiparticle energies: the low-lying doublet $\nu\tilde{d}_{3/2},\nu\tilde{d}_{5/2}$ followed by the higher-lying $\nu\tilde{g}_{7/2}$. However, this would be in clear disagreement with well-established systematics of single-particle states, which is characterized by the low-lying doublet $\nu d_{5/2},\nu g_{7/2}$ and the higher-lying $\nu d_{3/2}$.[1,2] Therefore, we have investigated the possibility of reproducing ^{103}Ru-^{105}Pd in the framework of the established pattern of neutron single-particle states $\epsilon(\nu d_{5/2})<\epsilon(\nu g_{7/2})<\epsilon(\nu d_{3/2})$.

The lowering of the $I=j-1$ state can be understood within the framework of quasiparticle-core coupling as an effect of the Pauli principle acting between an odd quasiparticle and the intrinsic structure of the core.[2] In the case of an SU(6) collective core this effect has been studied in the interacting boson-fermion model (IBFM):[3] The state $I=j-1$ is lowered with an increase of the exchange coupling strength Λ.[8] In the leading order, the parameter Λ is determined by a constant Λ_0 and occupation probabilities.[3,4] Thus, keeping the same single-particle pattern and occupation probabilities in ^{105}Pd and ^{103}Ru, a simple possibility to reproduce the experimental relative positions of the $3/2_1^+$ and $5/2_1^+$ states is to have Λ_0 larger for ^{103}Ru than for ^{105}Pd. With a further increase of Λ_0 the $1/2_1^+$ state gets lowered; such an effect is indeed observed in ^{101}Mo, which is the neighboring $N=59$ isotone towards lighter nuclei.

In the present calculations of the energy spectra of ^{105}Pd and ^{103}Ru we employ the quadrupole phonon representative for the IBM/IBFM, referred to as the TQM/PTQM.[6,7] However, given that the IBM is commonly used we adopt the IBM/IBFM parameters when discussing our results.

The core nucleus for ^{105}Pd is ^{104}Pd. This nucleus has a pronounced SU(5)-type spectrum: The first excited 2_1^+ state is followed by a closely spaced triplet $0_2^+,2_2^+,4_1^+$ at about twice the energy of the 2_1^+ state, and by the higher lying group of states $0^+,(2^+),(3^+)$. Therefore, the ^{104}Pd core is described here in the SU(5) limit of the IBM, by fitting the $2_1^+,0_2^+,2_2^+,4_1^+$ states. The corresponding IBM parameters are listed in Table I, together with the TQM counterparts.

The core nucleus for ^{103}Ru is ^{102}Ru. This nucleus exhibits a somewhat stronger splitting of the $0_2^+,2_2^+,4_1^+$ triplet than ^{104}Pd and the higher-lying group of states is closer to this triplet. ^{102}Ru has been previously fitted by Iachello and Arima[5] in the SU(5) limit of the IBM and by Bockisch *et al.*[8] away from this limiting symmetry. The corresponding IBM/TQM parameters are listed in Table I.

We note that ^{104}Pd and ^{102}Ru have been recently investigated in a two-parameter approximation of the IBM, with only one parameter for boson-boson interaction.[9] Also, these nuclei have been described in the IBM-2, with proton bosons and neutron bosons.[10] Previously, these nuclei have been investigated in the framework of the boson expansion theory of Tamura *et al.*[11] The calculated spectra of ^{104}Pd and ^{102}Ru in Ref. 11 are similar to the IBM spectra which correspond to the parametrizations in Table I.

Here we adopt the following starting points:

1. The core parametrization is taken from Table I.
2. The single-particle states $d_{5/2},g_{7/2}$ are sizably lower than $s_{1/2},d_{3/2}$.
3. The occupation probabilities for $\tilde{d}_{5/2}$ and $\tilde{g}_{7/2}$ quasiparticles are the same in ^{105}Pd and ^{103}Ru.

Under these conditions the quasiparticle parameters are $E(\tilde{g}_{7/2})-E(\tilde{d}_{5/2})=0.34$ MeV in the calculation with parameters (a) for ^{103}Ru, 0.75 MeV in the calculation with parameters (b) for ^{103}Ru, and 0.5 MeV in the calculation for ^{105}Pd. The occupation probabilities in all three cases

TABLE I. IBM/TQM parameters for ^{102}Ru and ^{104}Pd. The number of bosons is $N=7$ for ^{102}Ru and $N=6$ for ^{104}Pd.

Parameters		^{102}Ru^{a}		^{102}Ru^{b}		^{104}Pd	
IBM	TQM	IBM	TQM	IBM	TQM	IBM	TQM
$\epsilon_d-\epsilon_s$	h_1	0.481	0.481	0.561	0.561	0.556	0.556
$\tilde{v}_0$	h_2	0	0	−0.122	−0.086	0	0
$\tilde{v}_2$	h_3	0	0	0.078	0.078	0	0
c_0	h_{40}	−0.018	−0.009	−0.177	−0.089	0.218	0.109
c_2	h_{42}	0.141	0.158	−0.175	−0.195	0.228	0.255
c_4	h_{44}	0.144	0.216	0.081	0.122	0.212	0.318

[a] IBM parameters are taken from Ref. 5.

[b] IBM parameters are taken from Ref. 8.

are $v^2(\tilde{d}_{5/2})=0.6$ and $v^2(\tilde{g}_{7/2})=0.1$. We note that these quasiparticle parameters, adjusted to ^{105}Pd and ^{103}Ru, approximately correspond to the Bardeen-Cooper-Schrieffer (BCS) solutions obtained for Kisslinger-Sorensen parameters[1] if one lowers the $h_{11/2}$ single particle state; this seems to be in agreement with the observed low-lying $11/2^-$ state in this region.

The boson-fermion interaction strengths used in our calculations are $\chi=-\sqrt{7}/2$, $\Gamma_0=0.14$, $A_0=0.13$, and $\Lambda_0=0.76$ for ^{103}Ru and $\chi=-\sqrt{7}/2$, $\Gamma_0=0.14$, $A_0=0.1$, and $\Lambda_0=0.07$ for ^{105}Pd. Here, the strengths are defined in accordance with Ref. 12:

$$A_j=A_0\sqrt{5}(2j+1)\ ,$$

$$\Gamma_{ij}=\Gamma_0\sqrt{5}(u_iu_j-v_iv_j)\langle i\,||\,Y_2\,||\,j\rangle\ ,$$

$$\Lambda_{ijk}=-\Lambda_0 2\sqrt{5}(2k+1)^{-1/2}\beta_{ik}\beta_{kj}\ ,$$

$$\beta_{ij}=(u_iv_j+u_jv_i)\langle i\,||\,Y_2\,||\,j\rangle\ ,$$

where i,j,k denote single-particle states and u,v are the occupation probabilities.

As seen, $\Lambda_0(^{103}\mathrm{Ru})\gg\Lambda_0(^{105}\mathrm{Pd})$, in agreement with our qualitative argument. For ^{105}Pd there is $\Lambda_0<\Gamma_0$, with a rather small effect of the exchange term, while for ^{103}Ru there is $\Lambda_0>\Gamma_0$, with a pronounced effect of the exchange term, which is especially reflected in the lowering of the $3/2_1^+$ state.

The calculated spectra of ^{103}Ru [parameters (a)] and ^{105}Pd are presented in Fig. 1 and labeled by A and B, respectively. We note that in previous phenomenological calculations in the IBFM the fitted parameter Λ_0 was also varied from nucleus to nucleus. For example, in the well-known calculations[4] for ^{149}Eu, ^{151}Eu, and ^{153}Eu the fitted values for Λ_0 were 1.91, 2.73, and 3.69, respectively, with the change from isotope to isotope $\Lambda_0(A)-\Lambda_0(A-2)\approx 1$. Thus, the absolute change of the fitted parameter Λ_0 between ^{103}Ru and ^{105}Pd is compatible with the previous work. However, the relative change is larger than previously experienced, because of a very small value of Λ_0 for ^{105}Pd. We note that the expression for the exchange coupling strength in the IBFM (Ref. 4) (PTQM) (Ref. 7) contains the leading-order variation due to the change of u_j and v_j with the number of nucleons, while the zero-order strength Λ_0 is treated phenomenologically. It would be desirable to microscopically investigate the variation of Λ_0 with the nucleon number. Particularly, the onset of Λ_0 between ^{105}Pd and ^{103}Ru might be based on the change in the proton-neutron interaction between the spin-orbit

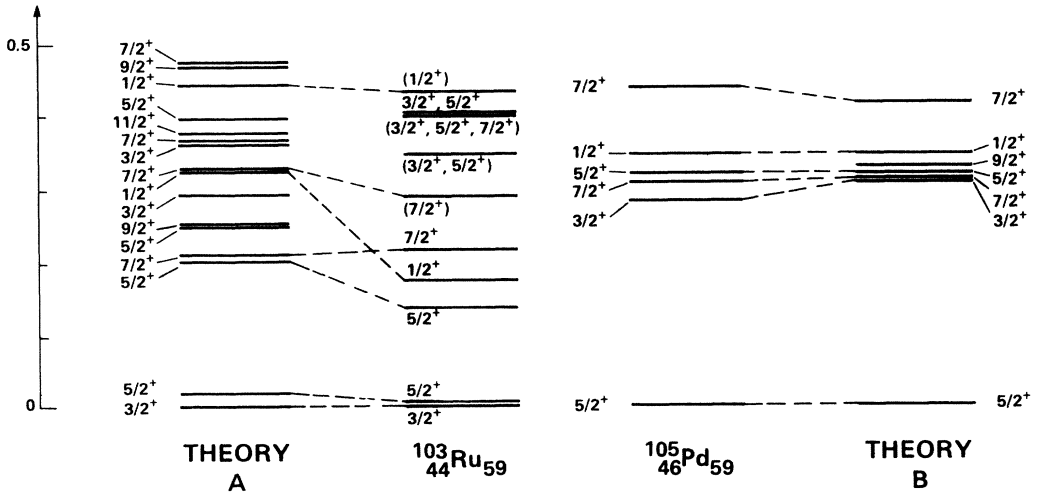

FIG. 1. Calculated spectra of ^{105}Pd and ^{103}Ru compared to experiment (Refs. 14 and 15). Tentative assignment between some calculated and experimental states is indicated. For description see the text.

TABLE II. Main components (percents) in the wave functions of ^{103}Ru. Here $|\tilde{j},nI;J\rangle$ denote quasiparticle—d-boson basis states: The quasiparticle state $\tilde{j}$ and n d bosons with angular momentum I are coupled to the total angular momentum J. (For components appearing in the table no additional quantum numbers are needed to specify the boson state and therefore are omitted.) Only components larger than 10% are listed.

$3/2_1^+$	$5/2_1^+$	$1/2_1^+$
$|\tilde{d}_{5/2},12;3/2\rangle 12$	$|\tilde{d}_{5/2},00;5/2\rangle 12$	$|\tilde{d}_{5/2},22;1/2\rangle 11$
$|\tilde{d}_{5/2},32;3/2\rangle 27$	$|\tilde{d}_{5/2},20;5/2\rangle 25$	$|\tilde{d}_{5/2},32;1/2\rangle 15$
$|\tilde{d}_{5/2},52;3/2\rangle 20$	$|\tilde{d}_{5/2},40;5/2\rangle 21$	$|\tilde{d}_{5/2},42;1/2\rangle 17$
	$|\tilde{d}_{5/2},50;5/2\rangle 10$	$|\tilde{d}_{5/2},52;1/2\rangle 11$
$7/2_1^+$	$5/2_2^+$	
$|\tilde{d}_{5/2},22;7/2\rangle 12$	$|\tilde{d}_{5/2},12;5/2\rangle 10$	
$|\tilde{d}_{5/2},32;7/2\rangle 15$	$|\tilde{d}_{5/2},32;5/2\rangle 17$	
$|\tilde{d}_{5/2},42;7/2\rangle 20$	$|\tilde{d}_{5/2},52;5/2\rangle 10$	
$|\tilde{d}_{5/2},52;7/2\rangle 11$		

partners ($\pi g_{9/2}-\nu g_{7/2}$) below the $Z=50$ shell: In the zero-order, ^{105}Pd and ^{103}Ru have more and less than a half filled $\pi g_{9/2}$ configuration, respectively. Previously, the role of the spin-orbit partners on the onset of deformation was investigated.[13] It is an interesting question whether a microscopic approach can give physical justification for the difference in Λ_0 from isotope to isotope, which is required for the phenomenological fit.

We note that the quasiparticle energy splitting $E(\tilde{g}_{7/2})-E(\tilde{d}_{5/2})$ is different in the calculations with parameters (a) and (b) for ^{103}Ru. The effect of smaller anharmonicities in the calculation with parameters (a) is partly accounted for by diminishing the energy splitting between the two quasiparticle states.

We have investigated the role of different parameters in the calculations performed under assumptions 1—3. The conclusion is that Λ_0 is in this case the only parameter which significantly affects the presence or absence of the $3/2_1^+,5/2_1^+$ doublet.

The present calculations qualitatively reproduce the ground-state region. However, for the other states there are problems with the locations of some states. The calculated $1/2_1^+$ state is located too high; this is due to the absence of the $s_{1/2}$ configuration from the calculation. In ^{105}Pd the $9/2^+$ state is predicted in the low-lying multiplet above the ground state; however, no $9/2^+$ state is observed in this energy region. The level $(3/2,5/2)^+$ at 447 keV,[14] which is presented in the experimental spectrum, seems to be absent due to preliminary results.[15] The level at 673 keV, previously assigned as $5/2^+$,[14] is assigned as $3/2^+$ in a recent preliminary work.[15] In the latter case this state would arise theoretically from the additional $\tilde{d}_{3/2}$ configuration coupled to the core. We have performed such a calculation in a simplified way, by including $\tilde{d}_{5/2}$ and $\tilde{d}_{3/2}$ quasiparticles only. We note that such a $\tilde{d}_{3/2}$ quasiparticle energy seems to be too low and it may correspond to a more correlated state. However, the inclusion of a $\tilde{d}_{3/2}$ configuration above $\tilde{d}_{5/2},\tilde{g}_{7/2}$ does not have stronger influences on the lower-lying states arising from the $\tilde{d}_{5/2}$ configuration.

In Table II we present the largest components ($\geq 10\%$) in the wave functions of low-lying states in ^{103}Ru (b), expressed in the quasiparticle—d-boson basis. For ^{105}Pd, with small Λ_0, the $5/2_1^+$ state is a rather pure $\tilde{d}_{5/2}$ quasiparticle state and $1/2_1^+,3/2_1^+,5/2_2^+,7/2_1^+,9/2_1^+$ are the $n=1$ multiplet states based on $\tilde{d}_{5/2}$. For ^{103}Ru, with rather strong Λ_0, several multiplets are strongly mixed in the wave functions, with the maximum amplitude being shifted toward a higher boson number. For example, the largest component (27%) in the wave function of the $3/2_1^+$ state is the $n=3$ multiplet state $|\tilde{d}_{5/2},32;3/2\rangle$. Furthermore, it is interesting to note that the boson compositions of the $3/2_1^+$ and $5/2_1^+$ states are dominated by odd- and even-number d bosons, respectively. (In interpreting wave functions of IBFM/PTQM one should keep in mind that for particular nuclear properties, the effects of mixing are partly effectively shifted into operators, which are more complete than in the standard particle-core model.)

In conclusion, we have phenomenologically investigated in the IBFM the problem of a sudden change of energy spectrum between ^{105}Pd and ^{103}Ru as a possible consequence of the onset of the exchange effect. In this connection, the microscopic investigation of the exchange coupling strength Λ_0 would be desirable.

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[1] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

[2] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. 2.

[3] F. Iachello and O. Scholten, Phys. Rev. Lett. 43, 679 (1979).

[4] O. Scholten, thesis, University of Groningen, 1980.

[5] A. Arima and F. Iachello, Phys. Rev. Lett. 35, 1069 (1975); Ann. Phys. (N.Y.) 99, 253 (1976).

[6] D. Janssen, R. V. Jolos, and F. Dönau, Nucl. Phys. **A224**, 93 (1974).

[7] V. Paar, S. Brant, L. F. Canto, G. Leander, and M. Vouk, Nucl. Phys. **A378**, 41 (1982).

[8] A. Bockisch, M. Miller, A. M. Kleinfeld, A. Gelberg, and U. Kaup, Z. Phys. A **292**, 265 (1979).

[9] J. Stachel, P. Van Isacker, and K. Heyde, Phys. Rev. C **25**, 650 (1982).

[10] P. Van Isacker and G. Puddu, Nucl. Phys. **A348**, 125 (1980).

[11] T. Tamura, K. J. Weeks, and T. Kishimoto, Nucl. Phys. **A347**, 359 (1980).

[12] M. A. Cunningham, Nucl. Phys. **A385**, 204 (1982).

[13] P. Federman and S. Pittel, Phys. Lett. **69B**, 385 (1977).

[14] Y. A. Ellis, Nucl. Data **27**, 1 (1979).

[15] R. A. Meyer, N. Kusnezov, S. Brant, and V. Paar (unpublished); H. Seyfarth, K. Schneckenbach, R. A. Meyer, S. Brant, and V. Paar (unpublished).