CONFLICTING COUPLING OF UNPAIRED NUCLEONS AND THE STRUCTURE OF COLLECTIVE BANDS IN ODD-ODD NUCLEI

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The conflicting coupling of unpaired nucleons in odd-odd nuclei is discussed. A very simple explanation is suggested for the damping of the energy spacing of the lowest levels in the rotational bands in odd-odd nuclei with the "conflicting" coupling of an odd proton and an odd neutron comparative to those of the bands based on the state of a strongly coupled particle in the neighboring odd nucleus entering the "conflicting" configuration.

1. Introduction

There are two coupling schemes of the unpaired nucleons in odd-odd nuclei referring to two different mutual orientations of their angular momenta. If the unpaired neutron and proton are coupled to the deformed core in the same way (strongly coupled or decoupled), i.e. the angular momenta $\mathbf{j}_n$ and $\mathbf{j}_p$ are both oriented either along the symmetry axis or along the rotation axis, the situation is termed "peaceful" coupling [1] of the unpaired nucleons to the deformed core. In this case, the structure of the collective bands can adequately be described in terms of the model "axial rotor + quasiparticle" if the proton and the neutron are considered as a single "superquasiparticle" [2]. If the neutron and the proton are coupled to the core, with the angular momentum of one nucleon being oriented along the symmetry axis and the other along the rotation axis (Fig. 1), the coupling of the unpaired nucleons with the deformed even-even core is referred to as "conflicting" [3]. In the case of a prolate (oblate) deformation, the "conflicting" coupling can be realized in nuclei, in which the nucleons of one kind just start to fill the Nilsson orbits belonging to a definite single-particle lj, decoupled (strong coupled), and the orbits of the nucleons of the other kind are almost filled, strong coupled (decoupled). Such a situation can be found in the regions of nuclear masses given in Table 1.

One of the manifestations of the "conflicting" coupling was considered in our paper [4]: the reduced M1-transition probabilities between collective-band levels in the odd-odd nuclei are enhanced in comparison with those in the neighboring odd nuclei with strong coupling of the odd nucleon. The aim of the present paper is to investigate the structure of the collective bands in those odd-odd nuclei that are based on the "conflicting" states of the unpaired proton and neutron. Particularly, we consider the reduction of the energy intervals at the beginning of the "conflicting" bands relative to the bands in the neighboring odd nuclei using a quasiclassical limit of the model "axial rotor + two quasiparticles" in the analysis.

T a b l e 1. Regions of nuclear masses, where the "conflicting" coupling of unpaired nucleons in odd-odd nuclei can be realized

Mass of nuclei	Shape	Orbits of definite single-particle lj: beginning to fill	Orbits of definite single-particle lj: almost closed
~ 110	prolate	$\nu h_{11/2}$	$\pi g_{9/2}$
~ 135	prolate	$\pi h_{11/2}$	$\nu h_{11/2}$
~ 170	prolate	$\nu i_{13/2}$	$\pi h_{11/2}$
~ 200	oblate	$\pi h_{9/2}$	$\nu i_{13/2}$

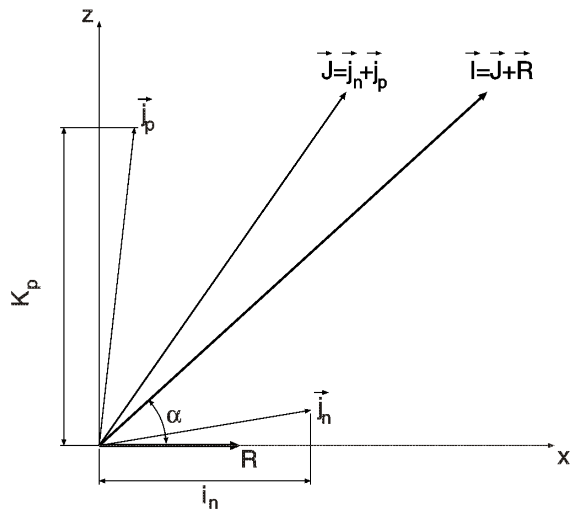

Fig. 1. Possible type of coupling of the odd nucleons to the deformed core in odd-odd nuclei: the "conflicting" coupling

2. Theoretical Background

The Hamiltonian of an odd-odd nucleus in the model "axial rotor + two quasiparticles" can be written as

$$\hat{H} = \hat{H}_p + \hat{H}_n + A\hat{R}^2 + \hat{V}_{p-n}, \tag{1}$$

where $A = \hbar^2/2\mathcal{J}$ is the inertial parameter, $\hat{H}_p$ and $\hat{H}_n$ are the single-particle Hamiltonians for a proton and a neutron, $\hat{V}_{n-p}$ is the residual n-p – interaction, and $\hat{R}$ is the operator of collective rotation. Since $\mathbf{R} = \mathbf{I} - (\mathbf{j}_p + \mathbf{j}_n)$, where $\mathbf{I}$ is the total angular momentum of the nucleus, and $\mathbf{j}_p$ and $\mathbf{j}_n$ are the angular momenta of the odd proton and neutron, respectively, expression (1) can be written as

$$\hat{H} = \hat{H}_p + \hat{H}_n +$$

$$+A\left\{\hat{I}^2 - \hat{I}_z^2 - 2(\hat{I}_+\hat{J}_- + \hat{I}_-\hat{J}_+) + (\hat{J}^2 - \hat{J}_z^2)\right\} + \hat{V}_{n-p}, \tag{2}$$

where $\mathbf{J} = \mathbf{j}_p + \mathbf{j}_n$. The term $2A(\hat{I}_+\hat{J}_- + \hat{I}_-\hat{J}_+)$ represents the Coriolis interaction of the odd nucleons with the rotating core, and $\hat{I}_\pm = \hat{I}_x \pm i\hat{I}_y$ and $\hat{J}_\pm = \hat{J}_x \pm i\hat{J}_y$. The term $A(\hat{J}^2 - \hat{J}_z^2)$ represents the recoil energy of the rotor which depends only on the quantum numbers of the odd nucleons.

The contribution of the term $\hat{V}_{n-p}$ is the most difficult one to estimate. However, as the matrix elements of the operator $\hat{V}_{n-p}$ do not depend directly on I, they are much smaller for the high-spin states than the matrix elements of the Coriolis interaction. Furthermore, it is possible to write [5]

$$\langle IMK\Omega_p\Omega_n \mid \hat{V}_{n-p} \mid IMK\Omega_p\Omega_n\rangle = E_o + (-)^I B, \tag{3}$$

where K, Ω_p, and Ω_n are the projections on the symmetry axis of J, j_p, and j_n, respectively. The second term in (3) leads to the odd-spin even-spin shift of the levels of the rotational band, but it is different from zero only if $K = 0$, that is when $\Omega_p = -\Omega_n$. Since, in the case of "conflicting" coupling, the Fermi level of a decoupled nucleon is close to the orbitals with the lowest value of the angular momentum projection on the symmetry axis $\Omega = 1/2$, and the Fermi level of the strongly coupled nucleon is close to the orbitals with the highest value of the projection $\Omega = j$, the condition $\Omega_p = -\Omega_n$ is never fulfilled. Therefore, only the first term in (3) is present, by leading to equal shifts of all levels of the collective band and thus not influencing its structure. As we are interested only in the structure of the collective bands, i.e. in the energies of the band levels relative to the energy of the band head, this constant shift of all levels is ignored. It has no influence on the band structure, but it is important for the absolute values of the level energies.

Taking these arguments about $\hat{V}_{n-p}$ into account, the specific properties of the rotational bands in odd-odd nuclei are determined by the diagonalization of the Coriolis interaction of the odd nucleons with the rotating core [4]. Therefore, the rotational part of (2) can be written as

$$\hat{H}_{\mathrm{rot}} = A[\hat{I}^2 - \hat{I}_z^2 - 2(\hat{I}_+\hat{J}_- + \hat{I}_-\hat{J}_+) + (\hat{J}^2 - \hat{J}_z^2)]. \tag{4}$$

We now consider the case of extreme "conflicting" coupling, i.e. one nucleon is completely decoupled, and the other is completely coupled to the deformed even-even core. This corresponds to the classical limit where the angle between the vectors $\mathbf{j}_p$ and $\mathbf{j}_n$ is equal to 90°, and a weak "conflicting" coupling corresponds to angles less than 90°. Let us suppose that the odd neutron is a decoupled particle and the odd proton is a strongly coupled particle. Then the proton state is characterized by the maximum value of $\Omega_p = j_p$. The neutron is oriented along the rotation axis, and the neutron state is characterized by the minimum value of Ω_n.

As a measure for the decoupling or alignment, Flaum and Cline [6] proposed to take the expectation value of the projection of the intrinsic angular momentum $\mathbf{J}$ onto the component of the total angular momentum $\mathbf{I}$ perpendicular to the symmetry axis,

$$J_\perp = \left\langle \frac{\mathbf{I}\cdot\mathbf{J} - K^2}{I_x} \right\rangle = \left\langle \frac{I_+J_- + I_-J_+}{[(I+1)I - K^2]^{1/2}} \right\rangle, \tag{5}$$

where $I_x = \sqrt{(I+1)I - K^2}$ is the projection of the total angular momentum on the rotation axis. The choice of (5) as a measure for the alignment is convenient, because $J_\perp = 0$ for the strong coupling of both odd nucleons. In this case, $\mathbf{I} \cdot \mathbf{J} = K^2$, which corresponds to the orientation of $\mathbf{J}$ along the symmetry axis. In the case of the full decoupling, $J_\perp = J$, because $I_+J_- + I_-J_+ = JI_x$ [7], which corresponds to the orientation of $\mathbf{J}$ along the rotation axis.

In view of (5), the rotational part of Hamiltonian (1) can be rewritten as

$$\langle \hat{H}_{\rm rot} \rangle = A[(I_x - J_\perp)^2 - J_\perp^2 + \langle \hat{J}^2 - \hat{J}_z^2 \rangle]. \tag{6}$$

It is possible to write

$$\mathbf{I}_{\rm odd-odd} = \mathbf{R} + \mathbf{j}_n + \mathbf{j}_p = \mathbf{I}_{\rm odd} + \mathbf{j}_n, \tag{7}$$

where $\mathbf{I}_{\rm odd} = \mathbf{R} + \mathbf{j}_p$ is the total angular momentum of the levels of a rotational band in the neighboring odd nucleus, based on the state of a strongly coupled proton.

Therefore, in the case under consideration, we have $(I_x - J_\perp)_{\rm odd-odd} = (I_x)_{\rm odd}$. Since $(I_x^2)_{\rm odd} = I_{\rm odd}(I_{\rm odd} + 1) - K_p^2$, $K_p = j_p$ for a strongly coupled proton, and $J_\perp = j_n$ for the extreme "conflicting" coupling with the neutron being decoupled, expression (6) takes the form

$$\langle \hat{H}_{\rm rot} \rangle = A[I_{\rm odd}(I_{\rm odd} + 1) - K^2], \tag{8}$$

where $K = \Omega_p + 1/2$ for the case considered in our example.

Thus, the energy spectrum of the rotational band in an odd-odd nucleus based on the "conflicting" state is determined by the rotational excitations of the neighboring odd nucleus with the strongly coupled particle being the one entering the "conflicting" state in the odd-odd nucleus, where a sequence of levels with $\Delta I = 1$ is observed. The spin value of such a band head is approximately equal to $I_{\rm head} = \sqrt{j_n^2 + j_p^2}$. In the quasiclassical limit, $\| I \| = \| \mathbf{j}_n + \mathbf{j}_p \| = \sqrt{j_n^2 + j_p^2 + 2j_pj_n \cos(\mathbf{j}_n, \mathbf{j}_p)}$ with $\cos(\mathbf{j}_n, \mathbf{j}_p) = 0$ in the case of "conflicting" coupling.

There is a correspondence between the "conflicting" bands in the odd-odd nuclei and the rotation-aligned bands in the odd nuclei. In the rotation-aligned bands, the angular momentum of the odd nucleon does not influence the structure of the rotational band which is similar to that of the neighboring even-even nucleus, and the decoupled nucleon can be considered as a spectator. In the case of "conflicting" bands in odd-odd nuclei, the decoupled particle can be considered as a spectator, but its role is somewhat more complicated, as will be explained in the following chapter.

3. The Structure of the Collective Bands in Odd-Odd Nuclei in the Case of Extreme "Conflicting" Coupling

The analysis of the energy spectra of rotational bands in odd-odd nuclei investigated experimentally by the in-beam γ-spectroscopy allowed one to identify "conflicting" bands in the following nuclei: ^{102,104,106}Ag [8], ^{106,108,110}In [9–11], ^{112,114,116,118,120}Sb [12–14], ^{116,118,120,122}I [15], and ^{120,122}Cs [16] with a decoupled $h_{11/2}$-neutron and a strongly coupled $g_{9/2}$-proton; ^{124,128}Cs [17, 18], ^{126,128,130,132}La [19–22], ^{130,132,134}Pr [23–25], ^{136}Pm [25], and ^{138}Eu [26] with a decoupled $h_{11/2}$-proton and a strongly coupled $h_{11/2}$- or $g_{7/2}$-neutron; ^{170}Ta [27] and ^{194,196,198,200}Tl [28, 29] with a decoupled $i_{13/2}$-neutron and a strongly coupled $h_{11/2}$-proton. Common to all these nuclei is a well-developed band with a $\Delta I = 1$ sequence built on states with spins approximately equal to $\sqrt{j_p^2 + j_n^2}$.

Let us compare the energy intervals between the levels of rotational bands in the odd-odd and in the neighboring odd nuclei. According to (8), the spectrum in an odd-odd nucleus for the case of "conflicting" coupling is determined by the total angular momentum of the odd nucleus. Therefore, the difference in the energy intervals has to be caused by a modification of the effective moment of inertia going from the odd to the odd-odd nucleus.

We assume that the dependence of the effective moment of inertia on the rotation frequency for a band based on the "conflicting" state can be expressed as

$$\mathcal{J}_{\rm odd-odd}(\omega) = \mathcal{J}_{\rm odd}(\omega) + \alpha/\omega, \tag{9}$$

where the first term is the moment of inertia of the rotating deformed core, the second term is the contribution of the angular momentum of the decoupled particle (α is the alignment of the decoupled particle). This expression originated from the cranking model [30], but it can also be considered as a reflection of the assumption about an additional contribution to the moment of inertia based on the known relation $I_x = \mathcal{J}\omega$. It is simply based on the additivity of the angular momentum projections of the core and the decoupled particle. Applying this relation to the moment of inertia of an odd-odd nucleus, expression (9) can be transformed to

$$\mathcal{J}_{\rm odd-odd}(\omega) = \mathcal{J}_{\rm odd}(\omega)(1 - \alpha/(I_x)_{\rm odd-odd})^{-1}. \tag{10}$$

The alignment α is defined as $\alpha = (I_x)_{\rm odd-odd} - (I_x)_{\rm odd}$, where $(I_x)_{\rm odd}$ is the projection of the total angular momentum of the odd nucleus on the rotation axis. For the moment of inertia, we find

$$\mathcal{J}_{\rm odd-odd}(\omega) = \mathcal{J}_{\rm odd}(\omega)\frac{(I_x)_{\rm odd}}{(I_x)_{\rm odd-odd}}. \quad (11)$$

Then we notice that the rotational band in an odd-odd nucleus can be represented in the usual form

$$E_{\rm odd-odd} = \frac{\hbar^2}{2\mathcal{J}_{\rm odd-odd}}[I_{\rm odd-odd}(I_{\rm odd-odd}+1) - K^2] \quad (12)$$

and, according to (8), in the form

$$E'_{\rm odd-odd} = \frac{\hbar^2}{2\mathcal{J}'_{\rm odd-odd}}[I_{\rm odd}(I_{\rm odd}+1) - K'^2]. \quad (13)$$

The relation between the two moments of inertia $\mathcal{J}_{\rm odd-odd}$ and $\mathcal{J}'_{\rm odd-odd}$ is obtained by comparing the energy intervals between the levels with spins I and $I-1$ calculated with Eqs. (12) and (13)

$$\mathcal{J}_{\rm odd-odd}(\omega) = \mathcal{J}'_{\rm odd-odd}(\omega)\frac{I_{\rm odd-odd}}{I_{\rm odd}}. \quad (14)$$

Then, using (11) and (14) with regard for the relation $I_x = I\sin\theta$, where θ is the angle between the vector of the total angular momentum and the symmetry axis so that

$$\sin\theta = [1-(K/I)^2]^{1/2} \quad (15)$$

in the quasiclassical approximation, we represent the moment of inertia in the form

$$\mathcal{J}'_{\rm odd-odd}(\omega) = \mathcal{J}_{\rm odd}\frac{\sin\theta_{\rm odd}}{\sin\theta_{\rm odd-odd}}. \quad (16)$$

The geometric factor $\sin\theta_{\rm odd-odd}/\sin\theta_{\rm odd}$ which is determined by the orientation of the total angular momenta in the odd-odd and odd nuclei leads to the relation $\mathcal{J}'_{\rm odd-odd} > \mathcal{J}_{\rm odd}$ for the low-lying states of the rotational bands. As is evident from (13), this leads to a reduction of the lowest energy intervals in the rotational band of the odd-odd nucleus compared to the corresponding intervals of the reference band in the odd nucleus. The geometric factor approaches 1 for the high-lying states, and the corresponding energy intervals turn out to be almost equal.

The same result can be obtained by comparing the energy intervals $\Delta E(I, I-1)$ in the odd-odd and odd nuclei:

$$\Delta E_{\rm odd-odd} = \frac{\hbar^2}{2\mathcal{J}_{\rm odd-odd}}2I_{\rm odd-odd}, \quad (17)$$

$$\Delta E_{\rm odd} = \frac{\hbar^2}{2\mathcal{J}_{\rm odd}}2I_{\rm odd}. \quad (18)$$

Again using Eq. (11) (i.e., the assumption about the contribution of the decoupled particle to the moment of inertia of the odd-odd nucleus), the energy intervals in the odd-odd nucleus can be expressed through the energy intervals in the odd nucleus and the geometric factor:

$$\Delta E_{\rm odd-odd} = \frac{\sin\theta_{\rm odd-odd}}{\sin\theta_{\rm odd}}\Delta E_{\rm odd} =$$

$$= \frac{\hbar^2}{2\mathcal{J}_{\rm odd}}\frac{\sin\theta_{\rm odd-odd}}{\sin\theta_{\rm odd}}2I_{\rm odd}. \quad (19)$$

Thus, the energy intervals of the "conflicting" rotational bands in the odd-odd nuclei are close to those of the bands in the neighboring odd nuclei based on the state of a strongly coupled nucleon entering the "conflicting" configuration with the exception of the low-lying intervals. The reduction of the low-lying intervals in the odd-odd nuclei is explained by the different orientations of the total angular momenta in the odd-odd and odd nuclei and is a manifestation of the characteristic action of the decoupled nucleon as a spectator. It is worth noting that a somewhat different situation is obtained if one compares the energy intervals of the rotational band in the odd nucleus based on the state of a decoupled nucleon with the energy intervals of the ground-state band in the neighboring even-even nucleus. They are very close also for low-lying states, because the total angular momentum of the odd nucleus is parallel, in this case, to the rotational angular momentum of the core (the geometric factor in (16) is equal to 1).

As an example, the spectra of the rotational bands in the odd-odd isotopes ^{118,120}Sb based on the "conflicting" state $(\nu h_{11/2} \otimes \pi g_{9/2})8^-$ and those in the odd isotopes ^{117,119}Sb [31] based on the state of the strongly coupled proton $g_{9/2}$ are compared in Fig. 2. For convenience of comparison, the positions of the band heads in the odd-odd and odd nuclei have been shifted in this and other figures. We find that the the energy intervals are indeed very close with the exception of the low-lying intervals: those in the odd-odd isotopes are smaller. The same is observed for the pairs of isotopes ^{114}Sb, ^{113}Sb and ^{116}Sb, ^{115}Sb [31].

Figure 3 presents the comparison of the rotational band in ^{130}La based on the state $(\nu g_{7/2} \otimes \pi h_{11/2})8^-$ with the strongly coupled neutron and the decoupled proton and the band in the odd ^{129}Ba [32] based on the neutron state $(g_{7/2})7/2^+$. The same behavior of the energy intervals is observed also in this case. The spectrum of the

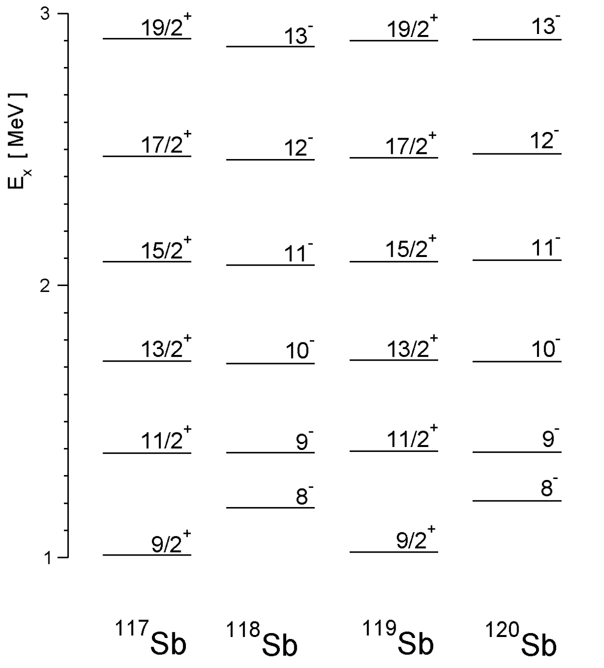

Fig. 2. Comparison of the level energies of the rotational bands in the pairs of the odd-odd and odd isotopes of Sb. For convenience of comparison, the positions of the bands are shifted to the same energy for $11/2^+$ and 9^- levels

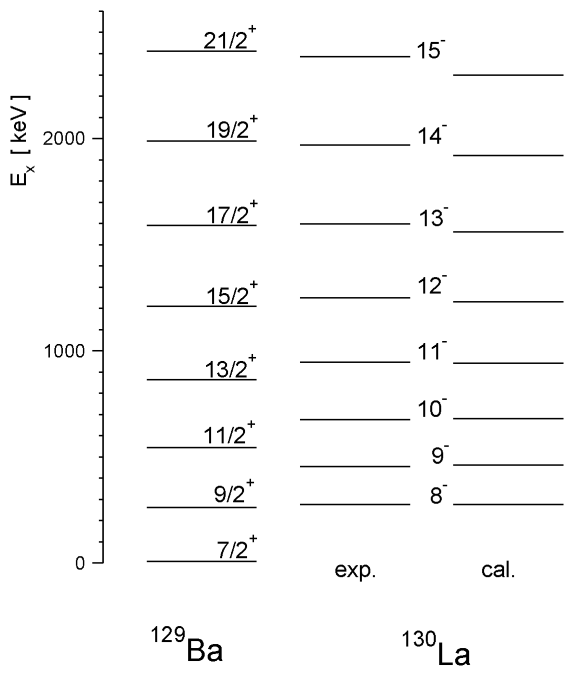

Fig. 3. Energy spectra of the "conflicting" band in ^{130}La based on the state $(\nu g_{7/2} \otimes \pi h_{11/2})8^-$ and the band in ^{129}Ba based on the neutron state $g_{7/2}$ strongly coupled to the core. The positions of the bands are shifted to the same energy for $9/2^+$ and 8^- levels

band in ^{130}La calculated by expression (13) with regard for (16) is also shown in Fig. 3. The spin dependence of the moment of inertia of the odd nucleus in expression (16) is taken in the form

$$\frac{\hbar^2}{2\mathcal{J}_{\rm odd}} = \frac{\hbar^2}{2\mathcal{J}_0} + B[I(I+1) - K^2], \tag{20}$$

where the parameters $\mathcal{J}_0$ and B were determined from the analysis of the reference band in ^{129}Ba. As is seen, the calculated values fit the experimental data very well including the characteristic reduction of the low-lying intervals.

The same picture is observed for the rotational bands based on the "conflicting" state $(\nu h_{11/2} \otimes \pi g_{9/2})8^-$ in ^{120}Cs and the state $(\pi g_{9/2})9/2^+$ in ^{119}Cs [33], for which both the experimental and calculated spectra are shown in Fig. 4.

Some comments are in place about the choice of $\langle K \rangle$ used in the calculations of the level energies in the odd-odd isotopes of Cs and La. According to the Gallagher–Moszkowski rule [34], the odd proton and neutron are coupled to the core in such a way that the projections of the intrinsic spins on the symmetry axis are parallel. The "conflicting" state $(\nu h_{11/2} \otimes \pi g_{9/2})$ in the odd-odd isotopes of Cs is formed by the neutron $[550]1/2^-$ and the proton $[404]9/2^+$. Therefore, the value $\langle K \rangle = 5$ was used in the calculations. The "conflicting" state $(\nu g_{7/2} \otimes \pi h_{11/2})$ in the odd-odd isotopes of La is formed by the neutron $[404]7/2^+$ and the proton $[550]1/2^-$. Therefore, $\langle K \rangle = 3$ was used.

As nucleons are filling the shell, the odd nucleon initially aligned along the rotational axis can change its orientation, because the proportion between the interactions with the deformation and the rotation changes (the Fermi level is shifted to the orbitals with larger values of Ω). A decrease in the alignment of the nucleon leads simultaneously to an increase of Ω, which results in a change of the geometric factor in Eq. (16). Therefore, the intervals between the low-lying levels of the "conflicting" band are firstly reduced as compared with those of the reference band, and then the ratios of these intervals get closer to 1 with increase in the mass number.

As an example, we consider the ratio of the energy intervals of the rotational bands based on the "conflicting" state $(\nu h_{11/2} \otimes \pi g_{9/2})8^-$ in the odd-odd isotopes ^{116,118,120}I and those based on the state of a strongly coupled proton $g_{9/2}$ in the odd isotopes ^{117,119,121,123}I. Such a comparison is given in Table 2.

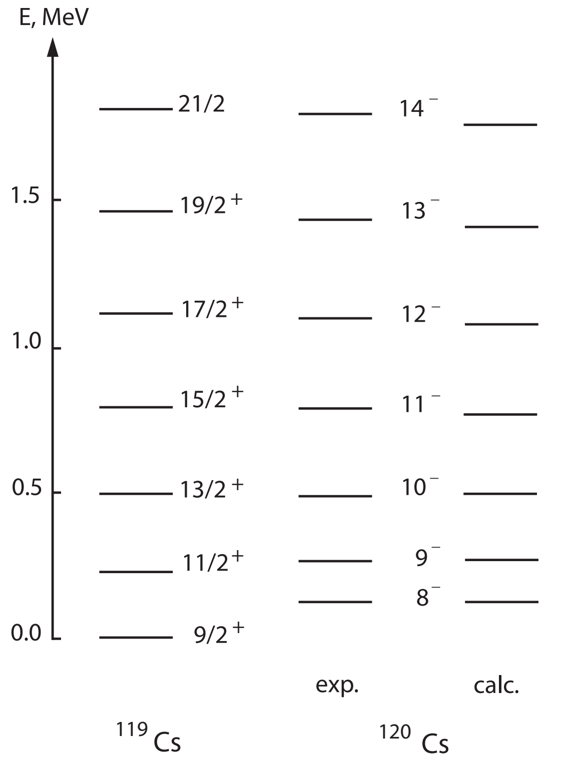

Fig. 4. Comparison of the energy spectra of the "conflicting" band in ^{120}Cs based on the state $(\nu h_{11/2} \otimes \pi g_{9/2})8^-$ and the band in ^{119}Cs based on the proton state $g_{9/2}$ strongly coupled to the core. The positions of the bands are shifted to the same energy for $13/2^+$ and 10^- levels

As can be seen, the ratio of energy intervals between the low-lying levels that are the most sensitive to the orientation of the total angular momenta approaches 1 with increase in the mass number in accordance with our assumption. It approaches also 1, as the spin increases. The calculated ratios of the energy intervals are given in Table 3. The following values of $\langle K \rangle$ were used in the calculations: 5 for ^{116}I ($\langle \Omega_n \rangle = 1/2$, $\Omega_p = 9/2$), 6 for ^{118}I ($\langle \Omega_n \rangle = 3/2$, $\Omega_p = 9/2$), and 7 for ^{120}I ($\langle \Omega_n \rangle = 5/2$, $\Omega_p = 9/2$). The variation of the alignment from the maximum value of 5.5 to the value of 4.9 corresponds to this variation in $\langle K \rangle$.

The small deviations from experiment of the calculated first four intervals in ^{116,118,120}I, the accuracy of the calculations for the energy spectra in the odd-odd nuclei ^{130}La, ^{120}Cs, ^{170}Ta, and the analysis of the energy spectra of the isotones with N=75 show that the phenomenological approximation used here describes the rotational bands in the odd-odd nuclei based on the "conflicting" states in a satisfactory way. The actual quantum state of an odd-odd nucleus on a microscopic level can be a rather complicated superposition of simple states, and the substitution of the quantum-mechanical angular-momentum operator by its classical expectation value does not take this circumstance into account. But the observed similarity of the bands in the odd and odd-odd nuclei indicates that this superposition is not changed much in going from the odd nucleus to the 'conflicting' state in the odd-odd nucleus, thus justifying the simple interpretation.

Let us return to the effects of the residual interaction. The configurations of the odd proton and neutron must change under rotation. The nucleon firstly oriented along the symmetry axis changes its orientation under the influence of the Coriolis interaction [29], and the term B in eq. (3) can differ from zero for high-spin states. Moreover, the nondiagonal matrix elements between different configurations can become important [35]. To accurately calculate these effects, one needs to know the wave functions of the model used, by sacrificing the clearity and the simplicity. But the good agreement with experiment of the simple calculations presented for the whole band and the similarity of the bands in the odd-odd and in the corresponding odd nuclei (apart from the lowest levels) indicates that the residual interaction of the odd nucleons has only a small effect on the structure of the rotational band in the case of the "conflicting" coupling. All effects of the Coriolis interaction are the same in the "conflicting" band and in the reference band of the neighboring odd nucleus. The problem of the residual interaction has been previously discussed in connection with the structure of the rotational bands in odd-odd nuclei in the Tl-region [3, 36]. It was found that

T a b l e 2. Experimental ratios of the energy intervals between the levels $(\nu h_{11/2} \otimes \pi g_{9/2})8^-$ in the odd-odd isotopes of iodine and the band based on the state of a strongly coupled proton $g_{9/2}$ in the odd isotopes of iodine

$(I_i - I_f)_{\text{odd-odd}}/(I_i - I_f)_{\text{odd}}$	^{116}I	^{118}I	^{120}I
$(9^- - 8^-)/(11/2^+ - 9/2^+)$	0.732	0.802	0.905
$(10^- - 9^-)/(13/2^+ - 11/2^+)$	0.887	0.932	1.040
$(11^- - 10^-)/(15/2^+ - 13/2^+)$	0.938	0.971	1.051
$(12^- - 11^-)/(17/2^+ - 15/2^+)$	0.971	0.995	1.060

T a b l e 3. Calculated ratios between the corresponding energy intervals in odd-odd and odd iodine isotopes

$(I_i - I_f)_{\text{odd-odd}}/(I_i - I_f)_{\text{odd}}$	^{116}I	^{118}I	^{120}I
$(9^- - 8^-)/(11/2^+ - 9/2^+)$	0.691	0.772	0.914
$(10^- - 9^-)/(13/2^+ - 11/2^+)$	0.833	0.902	1.010
$(11^- - 10^-)/(15/2^+ - 13/2^+)$	0.898	0.954	1.040
$(12^- - 11^-)/(17/2^+ - 15/2^+)$	0.933	0.979	1.044

the main features of these bands can be explained by the Coriolis interaction without taking into account effects of the residual interaction [3, 38]. Moreover if taken into account the residual interaction gives a signature-dependent contribution which has the opposite phase as needed to explain the staggering. This also supports our confidence that the residual interaction does not influence the structure of the collective bands in the case of ‘conflicting‘ coupling.

4. Structure of the Collective Bands in Odd-Odd Nuclei for "Weakly Conflicting" Coupling

In the "conflicting" coupling considered, the Fermi level for a strongly coupled nucleon is close to the orbital with the largest value of the angular momentum projection on the symmetry axis, $\Omega = j$. The Coriolis interaction is weak in this case and can be neglected. If, however, the Fermi level for a strongly coupled nucleon is situated among the intermediate values of Ω, then the Coriolis interaction can be large enough to perturb the rotational spectrum. This situation may be termed as "weakly conflicting" coupling. For odd nuclei, particularly large perturbations are observed in the case of an admixture of orbitals with $\Omega = 1/2$. The sign-changing diagonal matrix elements of the Coriolis interaction must be taken into account. This leads to the following shift of the level with spin I [5]:

$$\Delta E = -A(-)^{I+1/2}(I + 1/2)a. \tag{21}$$

Here, a is the decoupling parameter determined by the coefficients of the expansion of the intrinsic wave function in terms of the eigenfunctions of the operator $\hat{j}$. This results in a characteristic doublet character of the rotational bands. The larger the decoupling parameter, the stronger the perturbation of the rotational bands. Figure 5 shows the rotational band in ^{103}Ag [39] based on the proton state $g_{9/2}$. Let us limit ourselves to the single-orbit approximation [40]. As the decoupling parameter is proportional to $(-)^{j+1/2}$, this leads to a negative value of $a(\pi g_{9/2})$. Therefore, the levels with the spins $I_0{+}1, I_0{+}3, \ldots$ (I_0 is the spin of the band head) are shifted up and the levels with the spins $I_0{+}2, I_0{+}4, \ldots$ are shifted down.

For odd-odd nuclei, the sign-changing diagonal matrix elements equivalent to (18) do not exist. Nevertheless, the examination of the rotational part of Hamiltonian (2) shows that a similar role is played by the non-diagonal matrix elements of the Coriolis interaction coupling the

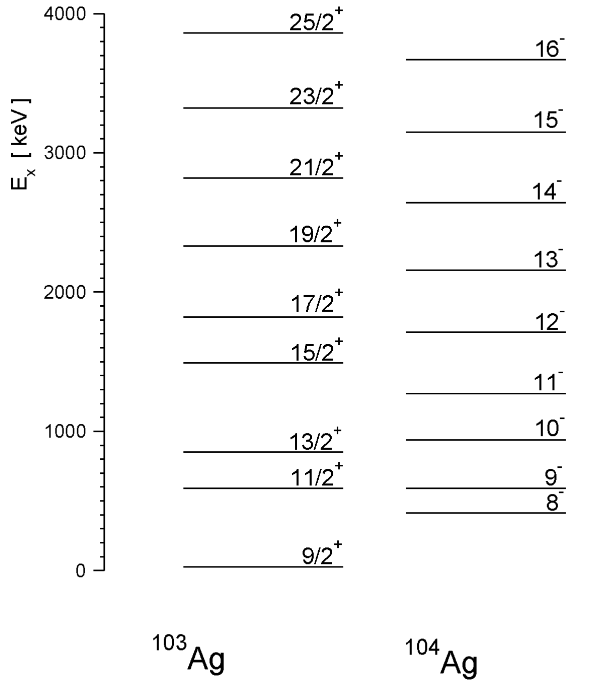

Fig. 5. Comparison of the energy spectra of the rotational bands in the odd-odd nucleus ^{104}Ag and in the odd nucleus ^{103}Ag. The positions of the bands are shifted to the same energy for $11/2^+$ and 9^- levels

states with $K = 1$ and $K = 0$ [5, 39]:

$$\langle K = 1 \mid \hat{H}_c \mid K = 0\rangle =$$

$$= -A[a_p + (-)^{I+1}a_n][I(I + 1)]^{1/2}. \tag{22}$$

Let us consider the "weakly conflicting" state $(\nu h_{11/2} \otimes \pi g_{9/2})$ in the odd-odd isotopes of Ag, where the proton Fermi-level lies between the orbitals $[413]7/2^+$ and $[404]9/2^+$ [3]. As $a(\pi g_{9/2}) < 0$, $a(\nu h_{11/2}) > 0$, and $a_n > a_p$ (the neutron is decoupled), the sign of the matrix elements (19) is determined by the term $(-)^{I+1}a_n[I(I + 1)]^{1/2}$. Therefore, the situation is opposite to that in the odd isotopes of Ag: the levels with spins $I_0 + 1, I_0 + 3, \ldots$ are shifted down, while the levels with spins $I_0 + 2, I_0 + 4, \ldots$ are shifted up.

The reduction of the energy intervals between the low-lying levels in ^{104}Ag as compared with the corresponding levels in the odd ^{103}Ag can be explained in a similar way as for the case of the extreme "conflicting" coupling, namely by the different orientations of the total angular momenta.

5. Conclusion

The approximation based on the quasiclassical limit of the model "axial rotor + two quasiparticles" allowed us to establish that the rotational band in odd-odd nuclei based on the "conflicting" state can be considered as the rotational excitations of the neighboring odd nucleus, in which the odd strongly coupled particle is the one entering the "conflicting" configuration in the odd-odd nucleus. However, the decoupled particle in the odd-odd nucleus cannot be considered simply as a spectator, as in the decoupled band in the odd nucleus. Its presence leads to a change of the orientation of the total angular momentum in the odd-odd nucleus as compared with that in the odd nucleus and to a modification of the moment of inertia, which can be expressed by a geometric factor. This is the reason for the reduction of the low-lying energy-intervals between the band levels in an odd-odd nucleus relative to those in an odd nucleus. For the high-lying states, the bands are very similar, because the geometric factor approaches 1.

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КОНФЛІКТНИЙ ЗВ'ЯЗОК НЕСПАРЕНИХ НУКЛОНІВ І СТРУКТУРА КОЛЕКТИВНИХ СМУГ В НЕПАРНО-НЕПАРНИХ ЯДРАХ

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Р е з ю м е

Розглянуто конфліктний зв'язок неспарених нуклонів в непарно-непарних ядрах. Запропоновано просте пояснення стискання нижніх енергетичних рівнів ротаційних смуг в непарно-непарних ядрах у випадку конфліктного зв'язку непарних протона і нейтрона порівняно з ротаційними смугами, побудованими на стані сильно зв'язаного нуклона в сусідньому непарному ядрі, тим же, що входить в конфліктний стан.