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Contribution of quasiparticle-phonon, recoil and coriolis interactions in describing low-lying states of ^{133}Nd isotope

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Abstract. A quasiparticle-phonon coupling based on one quadrupole phonon is developed. The coupling is constructed by using a deformed average field of Nilsson, a monopole pairing interaction and a quadrupole-quadrupole force. Microscopic structure of the quadrupole phonon is given from the Tamm-Dancoff Approximation. The two effects of recoil and Coriolis forces are included with the assumption of a symmetric rotational motion. Since theoretical treatment is performed for an odd-A nuclei the configuration of intrinsic states should contain both one-quasiparticle and quasiparticle-phonon components. This method is applied to describe the level scheme of ^{133}Nd for which an agreement with experimental data is obtained. The results are also found similar to previous calculations obtained by the Particle plus Triaxial Rotor Model.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 21.10.Re Collective levels – 21.30.Fe Forces in hadronic systems and effective interactions – 27.60.+j $90 \leq A \leq 149$

1 Introduction

Over the last decade several experimental investigations have been made for the low-lying states in $A \sim 130$ mass of transitional region. Most of these have given important information about the characterization of both collective and intrinsic excitations for odd-A nucleus (see for example [1–3]). For transitional nuclei it is well known that the level scheme is more complicated than that of spherical or deformed nuclear shape. Usually, these types of nuclei are dominated by a triaxial shape with moderate deformation and softness. The softness with respect to the γ asymmetry arises from the interplay of the valence protons and neutrons occupying respectively low-lying and high-lying Nilsson orbitals within the $h_{11/2}$ j-shell [4].

Several models have been used to describe the level scheme for the transitional nuclei. The most popular is the Particle plus Triaxial Rotor Model (PRTM) [5]. It was first used to give an interpretation of high-spin for $^{129,131}Ce$ [6], ^{129}Ba [7] and ^{125}Ba [8] and it was recently used at low-spin to treat ^{133}Nd isotope [3,9]. With this model, the intrinsic states in ^{133}Nd have been identified but their order and splitting of excited states were not deduced as the same experimental arrangement. Another model which is useful in the study of odd nuclei is the Interacting Boson Fermion Model (IBFM) [10]. By assuming γ-softness a good result was obtained in the transitional region, particularly for $^{125,127}Xe$ [11], $^{127,129,131}Ce$ [2] and ^{133}Nd [9].

As an alternative to these models, we propose another method based on the quasiparticle-phonon coupling. This type of method has already been applied into treatment of the excited states in odd-A nuclei by supposing spherical [12–14] or deformed [15] shapes. However, as an attempt to give a new description to the structure of the level scheme in a transitional nucleus, we have limited our study to a simple case where a microscopic picture is considered for the quadrupole phonon by means of Tamm-Dancoff Approximation (TDA) [16]. This method is microscopic in the sense that it provides two-quasiparticle structure of the quadrupole vibrational core (γ-phonon) in contrast to the phenomenological model [17] in which the question of phonon structure is a priori excluded. Furthermore, it has the feature of basing the description on the choice of residual interaction. Thus, to obtain intrinsic states we have used a deformed average field of Nilsson, a monopole pairing and a quadrupole-quadrupole interaction [16]. The states of rotational bands are determined by inclusion of both recoil and Coriolis effects which came from a treatment of the axially symmetric rotational motion.

Theoretical formulation of the total Hamiltonian has been developed in Sect. 2 with a discussion of the intrinsic eigenvalue problem. In Sect. 3, the results of calculations are performed and compared to experimental data in ^{133}Nd which is taken as an example of typical nucleus from the $A \sim 130$ transitional region. Finally, in Sect. 4 some conclusions are drown.

2 Description of the model

2.1 Outline of the total Hamiltonian

For the theoretical description of the low-lying states in odd-A nuclei, we take the standard assumption that the Hamiltonian can be separated into a rotational part and an intrinsic motion. Thus we may write the total Hamiltonian as

$$H = H_{rot} + H_{intr} \tag{1}$$

The H_{rot} is the collective kinetic energy associated with the rotation of the nucleus as a whole and which is described relative to the Laboratory system. The next term H_{intr} includes the additional modes of excitation (individual and vibrational) and is treated relative to the intrinsic system. This approach for an odd-A nucleus is related to a system of an extra-nucleon coupled to an even-even core. The physical idea behind the formulation of H_{intr} is the belief that the intrinsic motion can be described in a rather simple terms with a one-body deformed potential field H_{sp} plus a two-body residual interaction composed by a short range constant pairing force H_P and a quadrupole part H_Q of the long range multipole-multipole force.

To write in more detail Hamiltonian (1), we start with the kinetic energy of rotational motion which takes the form

$$H_{rot} = A_1 R_1^2 + A_2 R_2^2 + A_3 R_3^2 \tag{2}$$

here R_k is the component of the collective angular momentum along the axis of the intrinsic system. The A_k is the corresponding rotational parameter defined as $A_k = \frac{\hbar^2}{2\Im_k}$ with the moment of inertia parameter $\Im_k$ around the three principal axis $k = 1, 2, 3$ of the nuclear mass distribution.

In (2) we have given a general triaxial form. However, in this paper we limit our analysis to the case of a nucleon coupled to an axially symmetric rotor [18]. The rotational Hamiltonian can then be deduced by

$$H_{rot} = \frac{\hbar^2}{2\Im}\left(R_1^2 + R_2^2\right) \tag{3}$$

with the same moment of inertia $\Im$ along the two axis with $k = 1, 2$, and perpendicular to symmetric axis $k = 3$. The total angular momentum $\vec{I}$ is composed of two terms, the collective rotation of the core $\vec{R}$ and the angular momentum of the extra-nucleon $\vec{J}$; $\vec{I} = \vec{R} + \vec{J}$. Since $\vec{I}$ is a conserved quantity, $\vec{R}$ in (3) is replaced by $\vec{I}$ and $\vec{J}$ so that the total Hamiltonian (1) will take the following expression

$$H = H_{intr} + H_I + H_C \tag{4}$$

where

$$\begin{aligned} H_{intr} &= H_{sp} + H_P + H_Q + H_J \\ H_I &= A_R\left(I^2 - I_3^2\right) \\ H_C &= -A_R\left(I_+ J_- + I_- J_+\right) \\ H_J &= A_R\left(J^2 - J_3^2\right) \end{aligned} \tag{5}$$

with $I_\pm = I_1 \pm iI_2$, $J_\pm = J_1 \pm iJ_2$ and $A_R = \frac{\hbar^2}{2\Im}$. The total Hamiltonian H is thus separated into three terms, the intrinsic term H_{intr}, the rotational term H_I and the Coriolis term H_C which couples the intrinsic and rotational motions.

The intrinsic Hamiltonian is more interesting from a physical point of view. It is separated into four parts. The first, H_{sp}, contains the deformed potential field which governs the independent motion of nucleons. In this sense, we prefer to use the Nilsson harmonic oscillator model [19] which is rather simple and is more performed to describe a deformed nucleus. Using second quantization, H_{sp} takes the simple form

$$H_{sp} = \sum_{\nu\tau} e_{\nu\tau} a^+_{\nu\tau} a_{\nu\tau} \tag{6}$$

$a^+_{\nu\tau}$ ($a_{\nu\tau}$) is the operator that creates (destroys) a particle of nucleon type τ (neutron or proton) in a Nilsson orbital and with an energy $e_{\nu\tau}$. The quantum number ν stands for the asymptotic quantum numbers $[Nn_3l_3]$ with the projection Ω_ν of the particle angular momentum along the symmetric axis.

The term H_P describes the monopole pairing interaction [16] with the strength parameter G_τ and is written as

$$H_P = -\sum_{\nu\mu\tau} G_\tau a^+_{\nu\tau} a^+_{-\nu\tau} a_{-\mu\tau} a_{\mu\tau} \tag{7}$$

The next term H_Q is the quadrupole-quadrupole force [16] and is expressed by

$$H_Q = -\frac{1}{2}\chi \sum_{\tau\tau'} \left\{ Q^+_{22}(\tau) Q_{22}(\tau') + Q^+_{2-2}(\tau) Q_{2-2}(\tau') \right\} \tag{8}$$

where the quadrupole moment of mass with $\gamma = \pm 2$ is given as one-body interaction

$$Q_{2\gamma}(\tau) = \sum_{\nu\mu} \left\langle \nu\tau \left| r^2 Y_{2\gamma} \right| \mu\tau \right\rangle a^+_{\nu\tau} a_{\mu\tau} \tag{9}$$

The last term in (5) is the recoil force H_J. In many earlier works H_J was neglected with the argument that it could be absorbed in the independent nucleon motion of the potential average field [20]. Here, we have chosen to treat it in the same way as a residual interaction into the intrinsic motion. By using second quantization, H_J can be expressed as

$$H_J = \frac{1}{2} A_R \sum_{\tau\tau'} \left(J_+(\tau) J_-(\tau') + J_-(\tau) J_+(\tau') \right) \tag{10}$$

where the one-body interaction of the intrinsic momentum $J_\pm$ is written as

$$J_\pm(\tau) = \sum_{\nu\mu} \left\langle \nu\tau \left| J_\pm \right| \mu\tau \right\rangle a^+_{\nu\tau} a_{\mu\tau} \tag{11}$$

The term H_I in (4) represents the kinetic energy in the rotational motion and produces energy differences between states in a rotational band. The inclusion of the Coriolis force H_C requires the matrix of the model Hamiltonian H to be constructed and diagonalized within the space of symmetrized functions [20].

$$|IMK_\rho\rangle = \sqrt{\frac{2I+1}{16\pi^2}}\left\{D^I_{MK}\,|K_\rho\rangle + (-)^{I+K}\,D^I_{M-K}\,|\overline{K_\rho}\rangle\right\} \tag{12}$$

here ρ is the quantum number of a given intrinsic states with a projection K of the intrinsic angular momentum along the symmetric axis. $|\overline{K_\rho}\rangle$ is the time reversal of an intrinsic state $|K_\rho\rangle$ which can be obtained by resolution of the secular problem

$$H_{intr}\,|K_\rho\rangle = (H_{sp} + H_P + H_Q + H_J)\,|K_\rho\rangle = E^{intr}_{K_\rho}\,|K_\rho\rangle \tag{13}$$

As it is well Known, D^I_{MK} is the rotational matrix and is an eigenfunction of I^2 and I_3 with respective eigenvalue $I\,(I+1)$ and K. Thus, a diagonalization of H within the basis states (12) requires essentially to determine the matrix element of the Coriolis term H_C

$$\begin{aligned}\langle IMK'_{\rho'}\,|H_C|\,IMK_\rho\rangle = \\ -A_R\{(-)^{I+\frac{1}{2}}\,(I+\tfrac{1}{2})\,\langle K'_{\rho'}\,|J_+|\,\overline{K_\rho}\rangle\,\delta_{K'\frac{1}{2}}\delta_{K\frac{1}{2}} \\ +\sqrt{(I\mp K)\,(I\pm K+1)}\,\langle K'_{\rho'}\,|J_\pm|\,K_\rho\rangle\,\delta_{K',K\pm1}\}\end{aligned} \tag{14}$$

As we can see from the above equations, the solutions must be obtained in a two-step process. First, the intrinsic eigenvalue equation (13) when solved gives a set of intrinsic states $|K_\rho\rangle$ and intrinsic energies $E^{intr}_{K_\rho}$. From these states, different rotational wave functions of the form given in (12) are constructed. Then in a second step, a diagonalization of the Coriolis term is performed.

2.2 The intrinsic Hamiltonian

To discuss the different terms in the intrinsic eigenvalue equation (13) we must first look for a possible solution of the system. By neglecting H_J and H_Q we have a model which describes an independent nucleon motion in a Nilsson deformed potential and where is added the pairing correlations. The BCS approximation is adopted so as to transform the system to an independent quasiparticle motion. The long range interaction of quadrupole type H_Q is introduced so to account for the dynamical mode of deformation or the vibrational excitation. We work in the frame of Tamm-Dancoff approximation in order to make a microscopic structure description for the γ-phonon state. Our intrinsic Hamiltonian will contain also a residual part of the rotational motion by retaining the recoil force H_J which is independent in regard to the total angular momentum $\vec{I}$.

The BCS method is an approximate approach to treat pairing correlation by using the Bogoliubov-Valatin transformation which makes change from particle to quasiparticle operators

$$a^+_{\sigma\nu\tau} = u_{\nu\tau}\alpha^+_{\sigma\nu\tau} + \sigma v_{\nu\tau}\alpha_{-\sigma\nu\tau} \tag{15}$$

here the operator $\alpha^+_{\sigma\nu\tau}$ ($\alpha_{\sigma\nu\tau}$) creates (destroys) a quasiparticle in state $|\sigma\nu\tau\rangle$ with a σ-sign depending to time reversal symmetry. The expression deduced from $H_{sp} + H_P$ is given by

$$H_{BCS} = U + \sum_{\sigma\nu\tau} E_{\nu\tau}\alpha^+_{\sigma\nu\tau}\alpha_{\sigma\nu\tau} \tag{16}$$

where U is the BCS ground state energy ($|BCS\rangle \equiv |-\rangle$) and $E_{\nu\tau}$ is the energy of single quasiparticle

$$E_{\nu\tau} = \sqrt{(e_{\nu\tau} - \lambda - G_\tau v^2_{\nu\tau})^2 + \Delta^2_\tau} \tag{17}$$

with the Lagrange multiplicator λ and the energy gap Δ_τ.

In the same way, the transformation (15) allows the expression of quadrupole (9) and intrinsic (11) moments to change into form of quasiparticle terms

$$\begin{aligned}Q_{2\gamma}\,(\tau) = &\sum_{\sigma\sigma'=\pm1,\nu\nu'} G^{\gamma,\tau}_{\sigma\nu\sigma'\nu'}\alpha^+_{\sigma\nu\tau}\alpha_{\sigma'\nu'\tau} \\ &-\frac{1}{2}\sum_{\sigma\sigma'=\pm1,\nu\nu'}\left(\sigma' F^{\gamma,\tau}_{\sigma\nu-\sigma'\nu'}\alpha^+_{\sigma\nu\tau}\alpha^+_{\sigma'\nu'\tau}\right. \\ &\left.+\sigma F^{\gamma,\tau}_{-\sigma\nu\sigma'\nu'}\alpha_{\sigma\nu\tau}\alpha_{\sigma'\nu'\tau}\right)\end{aligned} \tag{18}$$

with

$$G^{\gamma,\tau}_{\sigma\nu\sigma'\nu'} = (u_{\nu\tau}u_{\nu'\tau} - v_{\nu\tau}v_{\nu'\tau})\,\langle\sigma\nu\tau\,|r^2Y_{2\gamma}|\,\sigma'\nu'\tau\rangle \tag{19}$$

$$F^{\gamma,\tau}_{\sigma\nu\sigma'\nu'} = (u_{\nu\tau}v_{\nu'\tau} + v_{\nu\tau}u_{\nu'\tau})\,\langle\sigma\nu\tau\,|r^2Y_{2\gamma}|\,\sigma'\nu'\tau\rangle \tag{20}$$

and

$$\begin{aligned}J_\pm\,(\tau) = &\sum_{\sigma\sigma'=\pm1,\nu\nu'} M^{\pm,\tau}_{\sigma\nu\sigma'\nu'}\alpha^+_{\sigma\nu\tau}\alpha_{\sigma'\nu'\tau} \\ &-\frac{1}{2}\sum_{\sigma\sigma'=\pm1,\nu\nu'}\left(\sigma' N^{\pm,\tau}_{\sigma\nu-\sigma'\nu'}\alpha^+_{\sigma\nu\tau}\alpha^+_{\sigma'\nu'\tau}\right. \\ &\left.-\sigma N^{\pm,\tau}_{-\sigma\nu\sigma'\nu'}\alpha_{\sigma\nu\tau}\alpha_{\sigma'\nu'\tau}\right)\end{aligned} \tag{21}$$

with

$$M^{\pm,\tau}_{\sigma\nu\sigma'\nu'} = (u_{\nu\tau}u_{\nu'\tau} + v_{\nu\tau}v_{\nu'\tau})\,\langle\sigma\nu\tau\,|J_\pm|\,\sigma'\nu'\tau\rangle \tag{22}$$

$$N^{\pm,\tau}_{\sigma\nu\sigma'\nu'} = (u_{\nu\tau}v_{\nu'\tau} - v_{\nu\tau}u_{\nu'\tau})\,\langle\sigma\nu\tau\,|J_\pm|\,\sigma'\nu'\tau\rangle \tag{23}$$

By introducing these new expressions respectively in (8) and (10), the quadrupole and the recoil forces can be decomposed as in the form $H_{00} + H_{11} + H_{20} + H_{22} + H_{31} + H_{40}$ [16] where the subscript refer to the number of quasiparticle creation and annihilation operators. In this picture, we note that both one-body and two-body interactions should be considered.

In the frame of Tamm-Dancoff Approximation [16] the creation operator of γ-phonon is defined as

$$B^+_\gamma = \frac{1}{2}\sum_{\nu\mu\tau}\left(X^\tau_\gamma\right)_{\nu\mu}\alpha^+_{\nu\tau}\alpha^+_{\mu\tau} \tag{24}$$

This expression permits a microscopic structure description for the quadrupole vibrational core (γ-phonon state) by showing the X-amplitudes which are related to two-quasiparticle excitations.

2.3 The intrinsic eigenvalue problem in odd-A nuclei

The resolution of (13) for an odd-A nucleus is perfected by a diagonalization within a basis formed by one-quasiparticle states (1-qp) and quasiparticle-phonon coupling states (qp-Ph$_\gamma$). If we retain only the terms that do not have a zero matrix element within the states of this basis, the intrinsic Hamiltonian is then reduced to

$$H_{intr} = H_{BCS} + H_{11}^{Q} + H_{20}^{Q} + H_{22}^{Q} + H_{31}^{Q} + H_{11}^{J} + H_{20}^{J} + H_{22}^{J} + H_{31}^{J} + H_{22}^{'P} \quad (25)$$

The Q and J Terms are related respectively to quadrupole and recoil forces. The last term $H_{22}^{'P}$ is a residual pairing interaction which was neglected in BCS approximation.

The interaction between two 1-qp states and two qp-Ph$_\gamma$ states are given respectively by L_{11} and L_{22} matrix elements and that between 1-qp and qp-Ph$_\gamma$ states by L_{31}. They are written as follows (detailed expressions are given in the Appendix)

$$L_{11} = \left\langle - \left| \alpha_{k'\tau} \left(H_{BCS} + H_{11}^{Q} + H_{11}^{J} \right) \alpha_{k\tau}^{+} \right| - \right\rangle \quad (26)$$

$$L_{22} = \left\langle - \left| B_{\gamma'} \alpha_{k'\tau} \left(H_{BCS} + H_{11}^{Q} + H_{11}^{J} + H_{22}^{Q} + H_{22}^{J} + H_{22}^{'P} \right) \alpha_{k\tau}^{+} B_{\gamma}^{+} \right| - \right\rangle \quad (27)$$

$$L_{31} = \left\langle - \left| B_{\gamma} \alpha_{k'\tau} \left(H_{20}^{Q} + H_{20}^{J} + H_{31}^{Q} + H_{31}^{J} \right) \alpha_{k\tau}^{+} \right| - \right\rangle \quad (28)$$

The eigenvalue problem is written in matrix form

$$\begin{pmatrix} L_{11} & L_{31} \\ L_{31} & L_{22} \end{pmatrix} \begin{pmatrix} C_k^{\rho} \\ D_{k\gamma}^{\beta} \end{pmatrix} = E_{K_\rho}^{intr} \begin{pmatrix} C_k^{\rho} \\ D_{k\gamma}^{\beta} \end{pmatrix} \quad (29)$$

in which C_k^{ρ} represents the 1-qp component and $D_{k\gamma}^{\rho}$ the qp-Ph$_\gamma$ component. The intrinsic eigenvalue $E_{K_\rho}^{intr}$ corresponds to the eigenvector

$$|K_\rho\rangle = \left(\sum_{\nu} C_\nu^{\rho} \delta_{K\Omega_\nu} \alpha_{\nu\tau}^{+} + \sum_{\nu\gamma} D_{\nu\gamma}^{\rho} \delta_{K=\Omega_\nu+\gamma} \alpha_{\nu\tau}^{+} B_{\gamma}^{+} \right) |-\rangle \quad (30)$$

The overlap between the 1-qp and the qp-Ph$_\gamma$ states is always zero. However, the overlap between two different qp-Ph$_\gamma$ states can be non-zero so as they can form a non-orthogonal basis set

$$S_{ij} = < i|j > = \left\langle - \left| B_{\gamma'} \alpha_i \alpha_j^{+} B_{\gamma}^{+} \right| - \right\rangle = \delta_{ij}\delta_{\gamma'\gamma} - \sum_{\lambda} \left(X_{\gamma'}\right)_{j\lambda} \left(X_{\gamma}\right)_{i\lambda} \quad (31)$$

where $|i\rangle$ is the qp-Ph$_\gamma$ state. To solve this rather eigenvalue problem we adopt the method where we first solve the eigenvalue equation for the S_{ij} overlap matrix

$$\sum_j S_{ij} w_j^h = n_h w_i^h \quad (32)$$

the eigenvectors obtained can be written in the basis $\{|i\rangle\}$ as

$$\left|\widetilde{i}\right\rangle = \frac{1}{\sqrt{n_h}} \sum_i w_i^h |i> \quad (33)$$

They have the propriety of being mutually orthogonal, have a norm equal to unity and form a complete set. With these new states we construct an orthogonal complete basis $\left\{ \alpha_j^{+} |-\rangle, \left|\widetilde{i}\right\rangle \right\}$ in which the matrix element of H_{intr} is diagonalized. The intrinsic wave function contains then two kinds of amplitudes C_j^{ρ} for 1-qp and g_h^{ρ} for normalized qp-Ph$_\gamma$ $\left|\widetilde{i}\right\rangle$. The amplitudes D_ν^{ρ} in (30) are then calculated from the g-amplitudes in the following way

$$D_\nu^{\rho} = \sum_h \frac{1}{\sqrt{n_h}} g_h^{\rho} w_\nu^h \quad (34)$$

3 Results and discussions

The theoretical calculations are performed for ^{133}Nd which has recently been most investigated at low and high-spin [3,9]. The eigenvalue problem (29) is solved and the intrinsic energies E_ν^{intr} with the corresponding amplitudes C_ν and D_ν are obtained by using the following set of parameters. For the Nilsson deformed average field, the last parametrization [21] adapted for the transitional region around the mass $A = 130$ is used. Deformation parameter for the even-even core ^{132}Nd is taken equal to $\varepsilon_2 = 0.267$ [22]. Twenty Nilsson orbitals positioned equally below and above the Fermi level are considered in the BCS calculation. The pairing gap are fixed for proton and neutron by the well known phenomenological relation $\Delta_p = \Delta_n = \frac{12}{\sqrt{A}}$ [23]. The inertia parameter is obtained by using the phenomenological relation of Grodzins $\left(\varepsilon_2^2 \approx 11176 \left[A^{7/3}(6\frac{\hbar}{2\Im})\right]^{-1}\right)$ [24]. The parameter of quadrupole force χ is fitted so as to reproduce the experimental energy of quadrupole vibrational core, for $^{132}Nd : E_{2_\gamma^+} = 824\ KeV$. We take to note that since our method based upon quasiparticle-phonon coupling is microscopic without any free adjustable parameters for odd nuclei (all parameters are given by the even-even core), the intrinsic energies obtained are not expected to approach exactly the experimental values. Some discrepancies must also be expected because we have limited our study to only γ-phonon excitation by neglecting the other multipole modes of vibration (β-phonon, g-phonon, ...) and the multiphonon correlations which may be important in some nuclei from the transitional region [25].

We refer to Fig. 1 in order to demonstrate the contribution of each term in the intrinsic Hamiltonian (25) for the

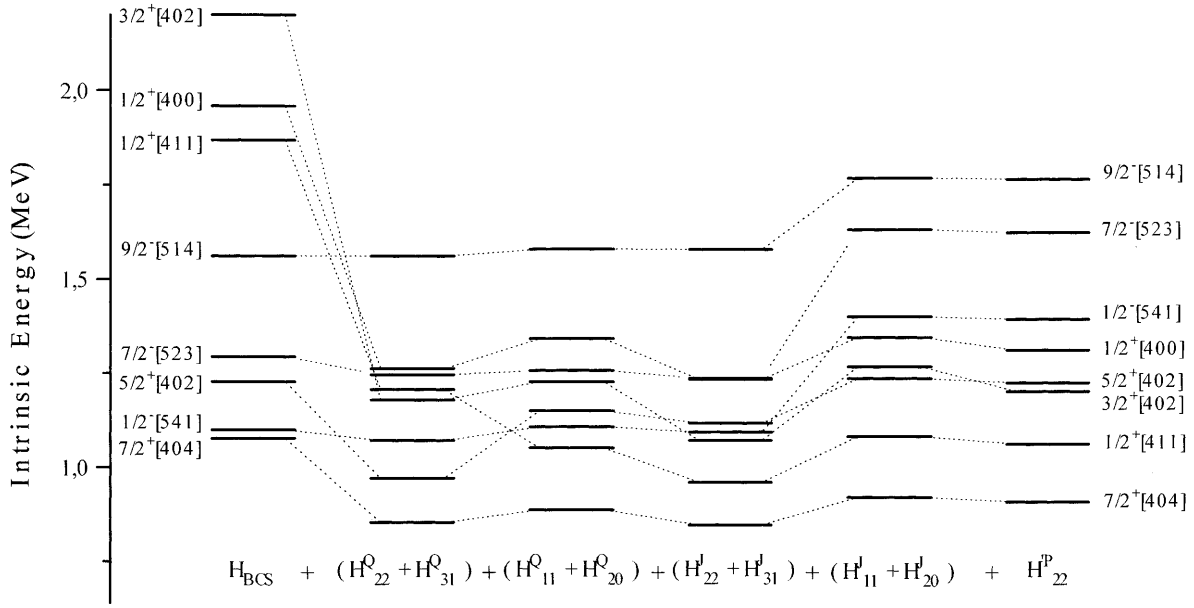

Fig. 1. Energy evolution of intrinsic states in ^{133}Nd caused by including successive interaction terms of quadrupole and recoil forces to the initial pairing interaction

Table 1. Energy ($\leq 1\ MeV$) and structure of intrinsic states in ^{133}Nd

K^π	Energy, KeV Exp.	Structure Th.	1-qp	C_k	qp-Ph$_\gamma$	D_k
$7/2^+$	0	0	$7/2^+[404]$	0.94	$3/2^+[402] + Q_{22}$	−0.32
$1/2^+$	128	153	$1/2^+[411]$	0.89	$3/2^+[411] + Q_{2-2}$	0.31
					$5/2^+[413] + Q_{2-2}$	0.31
$3/2^+$	—	293	$3/2^+[402]$	0.77	$1/2^+[400] + Q_{2-2}$	0.40
					$7/2^+[404] + Q_{2-2}$	−0.55
$5/2^+$	291	316	$5/2^+[402]$	0.93	$1/2^+[400] + Q_{22}$	−0.22
			$5/2^+[413]$	−0.12	$9/2^+[404] + Q_{2-2}$	0.20
$1/2^+$	—	402	$1/2^+[400]$	0.83	$3/2^+[402] + Q_{2-2}$	−0.57
$1/2^-$	—	484	$1/2^-[541]$	0.96	$3/2^-[532] + Q_{2-2}$	−0.13
			$1/2^-[530]$	−0.21		
$7/2^-$	—	714	$7/2^-[523]$	0.99	$3/2^-[541] + Q_{22}$	0.11
$5/2^+$	—	758	$5/2^+[413]$	0.65	$1/2^+[411] + Q_{22}$	0.74
			$5/2^+[402]$	0.14		
$3/2^+$	—	845	$3/2^+[411]$	−0.57	$1/2^+[411] + Q_{2-2}$	0.82
$9/2^-$	—	856	$9/2^-[514]$	0.99		

energy evolution of intrinsic states (assigned by the dominant one-quasiparticle configuration or Nilsson orbital) and which are positioned near the Fermi level in ^{133}Nd isotope. Here, we can see that by adding quadrupole and recoil forces to pairing interaction a new arrangement of intrinsic energies is obtained. Thus, for the quadrupole force we notice that both two-body and one-body terms exhibit important interaction for positive parity states than negative parity ones. The influence is so high as states have a small spin. This situation changes with the recoil force which preferentially influences the negative parity states. The effect due to the last term $H_{22}^{'P}$ in (25) is in general small.

The results of calculations obtained by considering all terms of the intrinsic Hamiltonian are given in Table 1. The low-lying intrinsic states in ^{133}Nd with a calculated energy up to 1 MeV are presented. Only components C_ν or D_ν which contribution to the normalization of wave function is more than 1 % are shown. The calculated energy position reproduce the observed positive parity bandhead. Also, an important contribution from the quasiparticle-phonon coupling is established for the configuration of positive parity wave functions. However, for the negative parity wave function, the configuration indicate a large component related to only a one-quasiparticle excitation. One can then consider the negative parity intrinsic states in ^{133}Nd as been a pure one-quasiparticle excitation without any contribution from the vibrational excitation mode.

The construction and diagonalization of the total Hamiltonian matrix are performed by using the basis function (12). The energies and wave functions of rotational bands based upon the dominant intrinsic states are determined for each value of the total angular momentum and parity.

A comparison of the experimental spectrum with energy levels obtained from the Coriolis-mixing calculations in ^{133}Nd is shown in Fig. 2. Although, the structure of intrinsic states is given by two components - the dominant one-quasiparticle component and the quasiparticle-phonon component - it is the first of these that provides a direct matching to the experimental bands. This is a particularly simple process since bands in ^{133}Nd have already been assigned by the dominant Nilsson configuration on the basis of experimental properties [3], systematic of the region and comparison with calculations [9]. The results obtained by our calculations agree with the previous assignments and reproduce well the experimental energy position. We give in the following an analysis of the structure related to each band.

The band $7/2^+$ [404] is the ground state band. Its rotational structure agrees well with experimental data and with PTRM description [9] obtained by assuming a large triaxiality ($\gamma = -22°$). Triaxiality with static deformation or softness with dynamic deformation (assumed by the quasiparticle-phonon coupling) appears as an excellent description that can be given for ^{133}Nd, in particularly for the ground state band.

The $1/2^+$, $3/2^+$, $5/2^+$, ... band is a mixed $s_{1/2} + d_{3/2}$ structure as found in the IBFM calculations [9]. More precisely, it is assigned by our method as dominated by $1/2^+$ [411] and their states are determined in agreement with PTRM calculation as mixture of the two intrinsic states $1/2^+$ [411] and $1/2^+$ [400]. In this band, the Coriolis interaction have caused an energy rapprochement between the neighboring excited levels ($1/2^+$ and $3/2^+$), ($5/2^+$ and $7/2^+$), ... The same effects were also established by PTRM results with $\gamma = -22°$. We have presented in Fig. 2 two bands without any comparison with experimental data. These bands are assigned respectively by one dominant intrinsic state $3/2^+$ [402] and $1/2^+$ [400] and have low energy positions. They may be candidates to an eventual identification for several positive parity levels that have not yet a well specification of experimental spin [3].

The band dominated by the intrinsic state $5/2^+$ [402] reproduces well the experimental band structure. The agreement indicates a favor contribution coming from inclusion of quadrupole force and both recoil and Coriolis interactions. This contribution has allowed to deduce the energy position of the bandhead $K^\pi = 5/2^+$ relatively to the ground state $K^\pi = 7/2^+$ (see Fig. 1) and to determine the regularity of excited energy levels as seen in Fig. 2.

The negative parity structure assigned by $1/2^-$ [541] indicates an energy shift of the excited level $I^\pi = 3/2^-$ under the bandhead $K^\pi = 1/2^-$. The calculated energy of excited levels agrees well with those positions reported in [3]. Furthermore, a level with spin $1/2^-$ was recently observed at energy $E_{1/2^+} = 387\ KeV$ above the level $3/2^-(E_{3/2^+} = 354\ KeV)$ [9]. This structure is then well established in ^{133}Nd as been a decoupled band dominated by the intrinsic state $1/2^-$ [541].

Table 2. Calculated energies (KeV) and Coriolis-mixing amplitudes of the negative parity $7/2^-$[523] band in ^{133}Nd

I^π	$E_{Th.}$	$5/2^-$[532]	$7/2^-$[523]	$9/2^-$[514]	$11/2^-$[505]
$7/2^-$	646	4.4%	95.0%	–	–
$9/2^-$	570	4.2%	52.6%	42.5%	–
$11/2^-$	683	6.1%	51.4%	40.2%	1.0%
$13/2^-$	874	7.9%	50.5%	38.0%	1.8 %

By assuming a large triaxiality [9], the $9/2^-$, $11/2^-$, $13/2^-$, ... band has been identified as a mixture of intrinsic orbitals from the intruder $h_{11/2}$ neutron j-shell with a dominant $9/2^-$ [514] component. But in our calculations we have found that it is more dominated by $7/2^-$ [523] state. The Coriolis-mixing components for this negative parity band are given in Table 2. One can see an equivalent mixing between the two intrinsic states $7/2^-$ [523] and $9/2^-$ [514] for the excited levels that have a spin $I^\pi \geq 9/2^-$. Only the level $K^\pi = 7/2^-$ has a pure configuration $7/2^-$ [523] and is determined at an energy position above the excited state $I^\pi = 9/2^-$. The level $K^\pi = 7/2^-$ has never been observed experimentally for ^{133}Nd but the existence of a similar one has recently been confirmed in the neighboring isotone ^{131}Ce [2]. Furthermore, in Fig. 2 appear a disagreement between the calculated $7/2^-$ [523] band and the experimental energy levels. It is caused by the high relative energy of the calculated intrinsic state (or bandhead). However, as seen in Fig. 1 the two intrinsic states $7/2^-$ [523] and $9/2^-$ [514] are less influenced by the quadrupole force and only the one-body interaction from the recoil force contributes significantly to their energy positions. The assumption that they can be considered as one-quasiparticle intrinsic states allows to adopt the possibility of neglecting the recoil term in the resolution of the intrinsic eigenvalue problem. In order to examine the influence of adding or neglecting recoil and/or Coriolis forces into the treatment of $7/2^-$ [523] band, we have reported in Fig. 3 the evolution of relative energy obtained by four independent calculation cases. From this, it is clear that by neglecting the recoil force and including the Coriolis interaction the arrangement obtained reproduces better the experimental data but it can not resolve entirely the splitting of energy position.

4 Conclusions

In this work, we have added to pairing interaction the quadrupole and recoil forces so as to construct an intrinsic Hamiltonian having the ability of considering all terms of residual interactions. This method has been developed with the attention to give a microscopic description for the low-lying states of odd-A nuclei. The influence of quadrupole and recoil interactions to reproduce energy arrangement of intrinsic states has been presented. We have

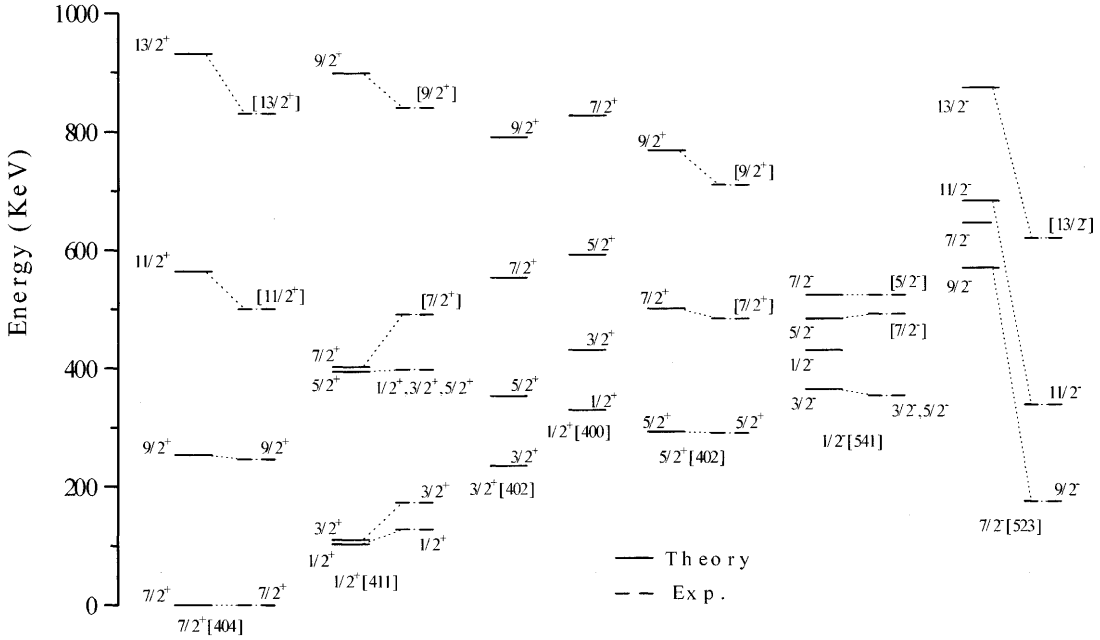

Fig. 2. Comparison of experimental levels of ^{133}Nd with the calculated excited states obtained by the quasiparticle-phonon coupling method plus recoil and Coriolis forces. (experimental assignments are conform to that given in [3])

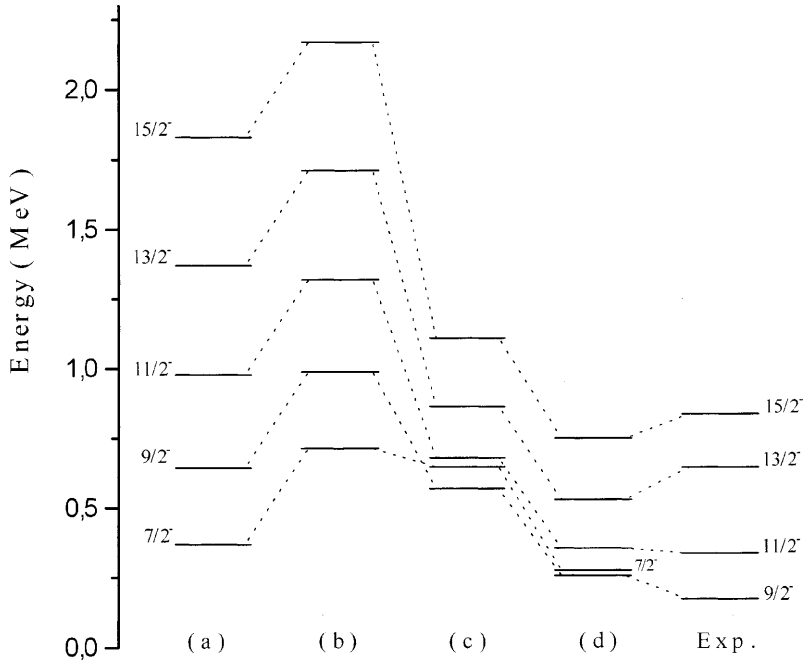

Fig. 3. Calculations of excited states for the collective structure built upon negative parity intrinsic state $7/2^-$ [523]. (a) with only rotation relation $A_R(I(I+1)-K^2)$. (b) with rotation plus recoil force. (c) with rotation plus both recoil and Coriolis forces. (d) with rotation and Coriolis force, no recoil

shown for ^{133}Nd that the contribution of quasiparticle-phonon coupling is more important for positive parity states than negative parity ones. At low-spin the excited states have been obtained by including the Coriolis mixing force. The calculations of negative parity rotational structure built upon the intrinsic state $7/2^-$ [523] have been revised by neglecting the recoil force.

Using this quasiparticle-phonon coupling method we have analyzed the low-lying excited levels in ^{133}Nd. We have confirmed some parity and experimental spin assignments and predict two new bands. In general our results agree also with previous calculations, particularly those obtained with the Particle plus Triaxial Rotor Model.

Appendix

Detailed expressions of L-matrix elements are written for each interaction term of the intrinsic Hamiltonian (see (25)).

Between two one-quasiparticle states, the L_{11} matrix elements are given by

$$\left(H_{BCS}\right)_{11} = E_{k\tau}\delta_{k'k} \tag{A1}$$

$$\left(H^{Q}_{11}\right)_{11} = +\tfrac{\chi}{2}\sum_{\lambda}\left(F^{2\tau}_{k'\lambda}F^{2\tau}_{k\lambda} + F^{2\tau}_{\lambda k'}F^{2\tau}_{\lambda k} - G^{2\tau}_{k'\lambda}G^{2\tau}_{k\lambda} - G^{2\tau}_{\lambda k'}G^{2\tau}_{\lambda k}\right) \tag{A2}$$

$$\left(H^{J}_{11}\right)_{11} = -\tfrac{A_R}{2}\sum_{\lambda}\left(N^{+\tau}_{k'\lambda}N^{+\tau}_{k\lambda} + N^{+\tau}_{\lambda k'}N^{+\tau}_{\lambda k} - M^{+\tau}_{k'\lambda}M^{+\tau}_{k\lambda} - M^{+\tau}_{\lambda k'}M^{+\tau}_{\lambda k}\right) \tag{A3}$$

Between two quasiparticle-phonon states, the L_{22} matrix elements are given by

$$\begin{aligned}(H_{BCS})_{22} = {} & E_{k\tau}\delta_{k'k}\delta_{\gamma'\gamma} \\ & -\sum_{\lambda}(E_{k'\tau}+E_{k\tau}+E_{\lambda\tau})(X^{\tau}_{\gamma'})_{k\lambda}(X^{\tau}_{\gamma})_{k'\lambda} \\ & +\sum_{\nu\lambda t}E_{\nu t}(X^{t}_{\gamma'})_{\nu\lambda}(X^{t}_{\gamma})_{\nu\lambda}\delta_{k'k}\end{aligned} \tag{A4}$$

$$\begin{aligned}&(H^{Q}_{11})_{22} = \\ &\tfrac{1}{2}\chi\sum_{\lambda}(F^{2\tau}_{k\lambda}F^{2\tau}_{k'\lambda}+F^{2\tau}_{\lambda k}F^{2\tau}_{\lambda k'}-G^{2\tau}_{k\lambda}G^{2\tau}_{k'\lambda}-G^{2\tau}_{\lambda k}G^{2\tau}_{\lambda k'})\delta_{\gamma'\gamma} \\ &-\tfrac{1}{2}\chi\sum_{\nu\mu\lambda}(F^{2\tau}_{k\nu}F^{2\tau}_{\mu\nu}+F^{2\tau}_{\nu k}F^{2\tau}_{\nu\mu}-G^{2\tau}_{k\nu}G^{2\tau}_{\mu\nu}-G^{2\tau}_{\nu k}G^{2\tau}_{\nu\mu}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{k'\lambda} \\ &-\tfrac{1}{2}\chi\sum_{\nu\mu\lambda}(F^{2\tau}_{\mu\nu}F^{2\tau}_{k'\nu}+F^{2\tau}_{\nu\mu}F^{2\tau}_{\nu k'}-G^{2\tau}_{\mu\nu}G^{2\tau}_{k'\nu}-G^{2\tau}_{\nu\mu}G^{2\tau}_{\nu k'}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{k\lambda}(X^{\tau}_{\gamma})_{\mu\lambda} \\ &-\tfrac{1}{2}\chi\sum_{\nu\mu\lambda}(F^{2\tau}_{\nu\lambda}F^{2\tau}_{\mu\lambda}+F^{2\tau}_{\lambda\nu}F^{2\tau}_{\lambda\mu}-G^{2\tau}_{\nu\lambda}G^{2\tau}_{\mu\lambda}-G^{2\tau}_{\lambda\nu}G^{2\tau}_{\lambda\mu}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{k\mu}(X^{\tau}_{\gamma})_{k'\nu} \\ &+\tfrac{1}{2}\chi\sum_{\nu\mu\lambda ht}(F^{2t}_{\nu h}F^{2t}_{\mu h}+F^{2t}_{h\nu}F^{2t}_{h\mu}-G^{2t}_{\nu h}G^{2t}_{\mu h}-G^{2t}_{h\nu}G^{2t}_{h\mu}) \\ &\quad\cdot(X^{t}_{\gamma'})_{\mu\lambda}(X^{t}_{\gamma})_{\nu\lambda}\delta_{k'k}\end{aligned} \tag{A5}$$

$$\begin{aligned}&(H^{J}_{11})_{22} = \\ &-\tfrac{1}{2}A_R\sum_{\lambda}(N^{+\tau}_{k\lambda}N^{+\tau}_{k'\lambda}+N^{+\tau}_{\lambda k}N^{+\tau}_{\lambda k'} \\ &\quad - M^{+\tau}_{k\lambda}M^{+\tau}_{k'\lambda}-M^{+\tau}_{\lambda k}M^{+\tau}_{\lambda k'})\delta_{\gamma'\gamma} \\ &+\tfrac{1}{2}A_R\sum_{\nu\mu\lambda}(N^{+\tau}_{k\nu}N^{+\tau}_{\mu\nu}+N^{+\tau}_{\nu k}N^{+\tau}_{\nu\mu}-M^{+\tau}_{k\nu}M^{+\tau}_{\mu\nu}-M^{+\tau}_{\nu k}M^{+\tau}_{\nu\mu}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{k'\lambda} \\ &+\tfrac{1}{2}A_R\sum_{\nu\mu\lambda}(N^{+\tau}_{\mu\nu}N^{+\tau}_{k'\nu}+N^{+\tau}_{\nu\mu}N^{+\tau}_{\nu k'}-M^{+\tau}_{\mu\nu}M^{+\tau}_{k'\nu}-M^{+\tau}_{\nu\mu}M^{+\tau}_{\nu k'}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{k\lambda}(X^{\tau}_{\gamma})_{\mu\lambda} \\ &+\tfrac{1}{2}A_R\sum_{\nu\mu\lambda}(N^{+\tau}_{\nu\lambda}N^{+\tau}_{\mu\lambda}+N^{+\tau}_{\lambda\nu}N^{+\tau}_{\lambda\mu}-M^{+\tau}_{\nu\lambda}M^{+\tau}_{\mu\lambda}-M^{+\tau}_{\lambda\nu}M^{+\tau}_{\lambda\mu}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{k\mu}(X^{\tau}_{\gamma})_{k'\nu} \\ &-\tfrac{1}{2}A_R\sum_{\nu\mu\lambda ht}(N^{+t}_{\nu h}N^{+t}_{\mu h}+N^{+t}_{h\nu}N^{+t}_{h\mu}-M^{+t}_{\nu h}M^{+t}_{\mu h}-M^{+t}_{h\nu}M^{+t}_{h\mu}) \\ &\quad\cdot(X^{t}_{\gamma'})_{\mu\lambda}(X^{t}_{\gamma})_{\nu\lambda}\delta_{k'k}\end{aligned} \tag{A6}$$

$$\begin{aligned}&(H^{Q}_{22})_{22} = \\ &-\chi\sum_{\nu\mu\lambda}(F^{2\tau}_{k-\nu}F^{2\tau}_{k'-\mu}+F^{2\tau}_{-\nu k}F^{2\tau}_{-\mu k'})(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{\nu\lambda} \\ &-\tfrac{1}{2}\chi\sum_{\nu\mu\lambda t}(F^{2\tau}_{k-\nu}F^{2t}_{\lambda-\mu}+F^{2\tau}_{-\nu k}F^{2t}_{-\mu\lambda}) \\ &\quad\cdot(X^{t}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{k'\nu}\sigma_\nu\sigma_\mu \\ &-\tfrac{1}{2}\chi\sum_{\nu\mu\lambda t}(F^{2\tau}_{k'-\nu}F^{2t}_{\lambda-\mu}+F^{2\tau}_{-\nu k'}F^{2t}_{-\mu\lambda}) \\ &\quad\cdot(X^{\tau}_{\gamma'})_{k\nu}(X^{t}_{\gamma})_{\mu\lambda}\sigma_\nu\sigma_\mu \\ &-\tfrac{1}{4}\chi\sum_{\nu\mu\lambda ht't}(F^{2t}_{h-\nu}F^{2t'}_{\lambda-\mu}+F^{2t}_{-\nu h}F^{2t'}_{-\mu\lambda}) \\ &\quad\cdot(X^{t}_{\gamma'})_{h\nu}(X^{t'}_{\gamma})_{\lambda\mu}\sigma_\nu\sigma_\mu\delta_{k'k} \\ &+\chi\sum_{\nu\mu\lambda}(G^{2\tau}_{k\mu}G^{2\tau}_{k'\nu}+G^{2\tau}_{\mu k}G^{2\tau}_{\nu k'})(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{\nu\lambda} \\ &+\chi\sum_{\nu\mu\lambda}(G^{2\tau}_{k\mu}G^{2\tau}_{\lambda\nu}+G^{2\tau}_{\mu k}G^{2\tau}_{\nu\lambda})(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{k'\nu} \\ &+\chi\sum_{\nu\mu\lambda}(G^{2\tau}_{k'\mu}G^{2\tau}_{\lambda\nu}+G^{2\tau}_{\mu k'}G^{2\tau}_{\nu\lambda})(X^{\tau}_{\gamma'})_{k\nu}(X^{\tau}_{\gamma})_{\mu\lambda} \\ &+\tfrac{1}{2}\chi\sum_{\nu\mu\lambda ht}(G^{2t}_{h\mu}G^{2t}_{\lambda\nu}+G^{2t}_{\mu h}G^{2t}_{\nu\lambda})(X^{t}_{\gamma'})_{h\nu}(X^{t}_{\gamma})_{\lambda\mu}\delta_{k'k}\end{aligned} \tag{A7}$$

$$
\begin{aligned}
&(H^J_{22})_{22} = \\
&A_R \sum_{\nu\mu\lambda}(N^{+\tau}_{k-\mu}N^{+\tau}_{k'-\nu}+N^{+\tau}_{-\mu k}N^{+\tau}_{-\nu k'})(X^{\tau}_{\gamma'})_{\nu\lambda}(X^{\tau}_{\gamma})_{\mu\lambda} \\
&-A_R \sum_{\nu\mu\lambda}(M^{+\tau}_{k\nu}M^{+\tau}_{k'\mu}+M^{+\tau}_{\nu k}M^{+\tau}_{\mu k'})(X^{\tau}_{\gamma'})_{\nu\lambda}(X^{\tau}_{\gamma})_{\mu\lambda} \\
&-A_R \sum_{\nu\mu\lambda}(M^{+\tau}_{k\mu}M^{+\tau}_{\lambda\nu}+M^{+\tau}_{\mu k}M^{+\tau}_{\nu\lambda})(X^{\tau}_{\gamma'})_{\mu\lambda}(X^{\tau}_{\gamma})_{k'\nu} \\
&-A_R \sum_{\nu\mu\lambda}(M^{+\tau}_{k'\mu}M^{+\tau}_{\lambda\nu}+M^{+\tau}_{\mu k'}M^{+\tau}_{\nu\lambda})(X^{\tau}_{\gamma'})_{k\nu}(X^{\tau}_{\gamma})_{\mu\lambda} \\
&-\frac{1}{2}A_R \sum_{\nu\mu\lambda ht}(M^{+t}_{h\nu}M^{+t}_{\lambda\mu}+M^{+t}_{\nu h}M^{+t}_{\mu\lambda})(X^{t}_{\gamma'})_{h\mu}(X^{t}_{\gamma})_{\lambda\nu}\delta_{k'k}
\end{aligned}
\tag{A8}
$$

$$
\begin{aligned}
&(H^{'P}_{22})_{22} = \\
&2G_\tau u_{k\tau}v_{k\tau}u_{k'\tau}v_{k'\tau}\sum_{\lambda}(X^{\tau}_{\gamma'})_{k\lambda}(X^{\tau}_{\gamma})_{k'\lambda} \\
&+2G_\tau(u_{k\tau}v_{k\tau}+u_{k'\tau}v_{k'\tau})\sum_{\lambda}u_{\lambda\tau}v_{\lambda\tau}(X^{\tau}_{\gamma'})_{k\lambda}(X^{\tau}_{\gamma})_{k'\lambda} \\
&-2G_\tau u_{k\tau}v_{k\tau}\sum_{\nu\lambda}u_{\lambda\tau}v_{\lambda\tau}(X^{\tau}_{\gamma'})_{\lambda\nu}(X^{\tau}_{\gamma})_{\lambda\nu}\delta_{k'k} \\
&-\sum_{\nu\lambda t}G_t u_{\nu t}v_{\nu t}u_{\lambda t}v_{\lambda t}(X^{t}_{\gamma'})_{\lambda\nu}(X^{t}_{\gamma})_{\lambda\nu}\delta_{k'k}
\end{aligned}
\tag{A9}
$$

Between one-quasiparticle and quasiparticle-phonon states, the L_{31} matrix elements are given by

$$
\begin{aligned}
(H^Q_{20})_{31} = \frac{1}{2}\chi\sum_{\nu\mu}&(F^{2\tau}_{k'\nu}G^{2\tau}_{-\mu\nu}+G^{2\tau}_{k'\nu}F^{2\tau}_{-\mu\nu} \\
&+F^{2\tau}_{\nu k'}G^{2\tau}_{\nu-\mu}+G^{2\tau}_{\nu k'}F^{2\tau}_{\nu-\mu})(X^{\tau}_{\gamma})_{\mu k}\sigma_\mu
\end{aligned}
\tag{A10}
$$

$$
\begin{aligned}
(H^J_{20})_{31} = \frac{1}{2}A_R\sum_{\nu\mu}&(N^{+\tau}_{k'\nu}M^{+\tau}_{-\mu\nu}+M^{+\tau}_{k'\nu}N^{+\tau}_{-\mu\nu} \\
&-N^{+\tau}_{\nu k'}M^{+\tau}_{\nu-\mu}-M^{+\tau}_{\nu k'}N^{+\tau}_{\nu-\mu})(X^{\tau}_{\gamma})_{\mu k}\sigma_\mu
\end{aligned}
\tag{A11}
$$

$$
\begin{aligned}
(H^Q_{31})_{31} = &\chi\sum_{\nu\mu}(G^{2\tau}_{k\mu}F^{2\tau}_{k'-\nu}+G^{2\tau}_{\mu k}F^{2\tau}_{-\nu k'})(X^{\tau}_{\gamma})_{\nu\mu}\sigma_\nu \\
&+\frac{1}{2}\chi\sum_{\nu\mu}(G^{2\tau}_{kk'}F^{2\tau}_{\nu-\mu}+G^{2\tau}_{k'k}F^{2\tau}_{-\mu\nu}) \\
&\cdot(X^{\tau}_{\gamma})_{\nu\mu}\sigma_\mu
\end{aligned}
\tag{A12}
$$

$$
\begin{aligned}
(H^J_{31})_{31} = &-A_R\sum_{\nu\mu}(M^{+\tau}_{k\mu}N^{+\tau}_{k'-\nu}-M^{+\tau}_{\mu k}N^{+\tau}_{-\nu k'}) \\
&\cdot(X^{\tau}_{\gamma})_{\nu\mu}\sigma_\nu
\end{aligned}
\tag{A13}
$$

The intrinsic matrix element $\langle K'_{\rho'}|J_+|K_\rho\rangle$ in (14) can be obtained by substituting the wave function (30). The deduced expression is written as

$$
\begin{aligned}
&\langle K'_{\rho'}|J_+|K_\rho\rangle = \\
&\sum_{\nu\mu}C^{\rho'}_{\mu}C^{\rho}_{\nu}\delta_{k'\Omega_\mu}\delta_{k\Omega_\nu}\langle-|\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}|-\rangle \\
&+\sum_{\nu\mu\gamma'}D^{\rho'}_{\mu\gamma'}C^{\rho}_{\nu}\delta_{k'=\Omega_\mu+\gamma'}\delta_{k\Omega_\nu}\langle-|B_{\gamma'}\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}|-\rangle \\
&+\sum_{\nu\mu\gamma}C^{\rho'}_{\mu}D^{\rho}_{\nu\gamma}\delta_{k'\Omega_\mu}\delta_{k=\Omega_\nu+\gamma}\langle-|\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}B^+_{\gamma}|-\rangle \\
&+\sum_{\nu\mu\gamma\gamma'}D^{\rho'}_{\mu\gamma'}D^{\rho}_{\nu\gamma}\delta_{k'=\Omega_\mu+\gamma'}\delta_{k=\Omega_\nu+\gamma}\langle-|B_{\gamma'}\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}B^+_{\gamma}|-\rangle
\end{aligned}
\tag{A14}
$$

where

$$
\langle-|\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}|-\rangle = M^{+\tau}_{\mu\nu} \tag{A15}
$$

$$
\langle-|B_{\gamma'}\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}|-\rangle = \sum_{\lambda}N^{+\tau}_{\mu-\lambda}(X^{\tau}_{\gamma'})_{\nu\lambda}\sigma_\lambda \tag{A16}
$$

$$
\langle-|\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}B^+_{\gamma}|-\rangle = \sum_{\lambda}N^{+\tau}_{-\lambda\nu}(X^{\tau}_{\gamma})_{\lambda\mu}\sigma_\lambda \tag{A17}
$$

$$
\begin{aligned}
&\langle-|B_{\gamma'}\alpha_{\mu\tau}J_+\alpha^+_{\nu\tau}B^+_{\gamma}|-\rangle = \\
&M^{+\tau}_{\mu\nu}\delta_{\gamma'\gamma}-\sum_{\lambda h}M^{+\tau}_{h\nu}(X^{\tau}_{\gamma'})_{h\lambda}(X^{\tau}_{\gamma})_{\mu\lambda} \\
&-\sum_{\lambda h}M^{+\tau}_{\mu h}(X^{\tau}_{\gamma'})_{\nu\lambda}(X^{\tau}_{\gamma})_{h\lambda}-\sum_{\lambda h}M^{+\tau}_{h\lambda}(X^{\tau}_{\gamma'})_{h\nu}(X^{\tau}_{\gamma})_{\lambda\mu}
\end{aligned}
\tag{A18}
$$

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