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# Partial conservation of seniority and its unexpected influence on E2 transitions in $g_{9/2}$ nuclei

Chong Qi

*Department of Physics, KTH Royal Institute of Technology, 10691 Stockholm, Sweden*

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ABSTRACT

There exist two uniquely defined $v = 4$ states in systems within a $j = 9/2$ subshell, which automatically conserve seniority and do not mix with other states. Here I show that the partial conservation of seniority plays an essential role in our understanding of the electric quadrupole transitions of the semimagic nuclei involving $j = 9/2$ subshells, including the long-lived $8^+$ isomer in $^{94}$Ru. The effects of configuration mixing from neighboring subshells on the structure of those unique states are analyzed. It is shown that a sharp transition from pure seniority coupling to a significant mixture between the $v = 2$ and $v = 4$ states may be induced by the cross-orbital non-diagonal interaction matrix elements. Such strong mixture is essential to explain the observed E2 transition properties of $N = 50$ isotones $^{96}$Pd and $^{94}$Ru.

One of the greatest challenges in nuclear physics is to understand the regular and simple patterns that emerge from the complex nuclear structure. Among those one can mention the shell structure as a consequence of the strong spin-orbit coupling, which is characterized by nucleons occupying orbitals with different $lj$ values. While the original shell model is mostly built upon independent particle motion, the concept of seniority symmetry has been applied implicitly to account for the strong pairing correlation. The seniority quantum number refers to the minimum number of unpaired particles in a single-$j$ shell for a given configuration $|j^n; I\rangle$ with total angular momentum $I$ [1]. The seniority coupling has shown remarkable success in describing the spectroscopy and electromagnetic transition properties of semi-magic nuclei restricted to a single $j$ shell. Of particular interest are nuclei that can be well approximated by the seniority coupling in high $j$ orbitals like $0f_{7/2}$. For heavier systems, we can mention the neutron-rich $^{70-78}$Ni isotopes [2], the $N = 50$ and 82 [3] isotones in the $0g_{9/2}$ proton subshell, neutron-rich isotopes $^{134-140}$Sn with in the $1f_{7/2}$ subshell [4] as well as $^{210-218}$Pb in the $1g_{9/2}$ neutron subshell [5].

Seniority remains a good quantum number within a subshell when $j \leq 7/2$. All states in such systems can be uniquely specified by the total angular momentum $I$ and seniority $v$. The interaction matrix elements have to satisfy a number of constraints in order to conserve seniority when $j > 7/2$. For a subshell with $j = 9/2$, where all but one two-body matrix elements conserve seniority, the condition reads [1,6–10]

$$65V_2 - 315V_4 + 403V_6 - 153V_8 = 0, \tag{1}$$

where $V_J = \langle j^2; J|\hat{V}|j^2; J\rangle$ denotes a two-body matrix element and $J$ the angular momentum of a two-particle state $|j^2\rangle$. The symmetry is broken for most effective interactions (see, e.g., Ref. [11]) in subshells with $j \geq 9/2$ where the eigenstates would be admixtures of states with different seniorities. For a system with $n = 4$ identical fermions in a $j = 9/2$ shell, there are three $I = 4$ (and also $I = 6$) states, which may be constructed so that one state has seniority $v = 2$ and the other two have seniority $v = 4$. In principle, those seniority $v = 4$ states are not uniquely defined and any linear combination of them would result in a new set of $v = 4$ states. However, it was noticed that in the $j = 9/2$ shell two special $v = 4$ states with $I = 4$ and 6 have good seniority for any interaction [12]. They have vanishing matrix elements with the other $v = 2$ and $v = 4$ states, irrespective of two-body interactions used. In other words, those two special $v = 4$ states are uniquely specified and are eigenstates of any two-body interaction. In the following we those special states and the $v = 4$ states orthogonal to them as $|\alpha\rangle$ and $|\beta\rangle$, respectively. Detailed descriptions of the problem can be found in Refs. [10,12–19]. An analytical proof for such partial conservation of seniority is also given in Refs. [15,18].

In this letter we will show that the existence of partial conservation of seniority in $j = 9/2$ shells plays an essential role in our understanding of the electric quadrupole transitions of the nuclei involved. Another important objective of this paper is to explore how the unique states mentioned above, which are defined

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*E-mail address:* chongq@kth.se.

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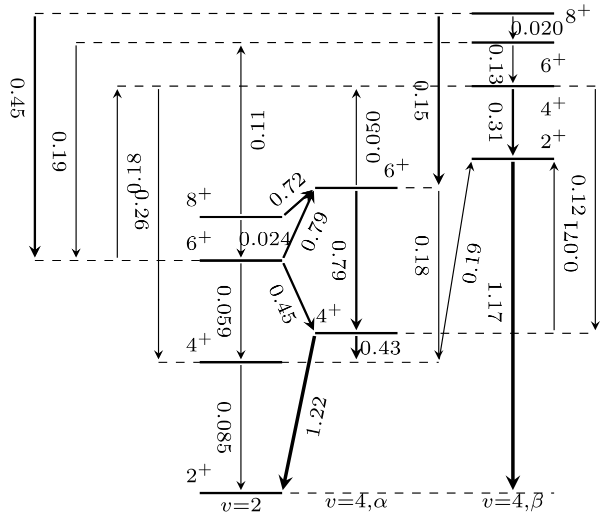

**Fig. 1.** The E2 transition strengths relative to $B(E2; 2_1^+ \to 0_1^+)$ (denoted as $B_{20}$) for a system with four particles (holes) in $j = 9/2$ shell calculated using a seniority-conserving interaction. The $0^+$ states and few weakest transitions are not shown for simplicity. One has $B(E2; 2_1^+ \to 0_2^+) = 0.044 B_{20}$ and $B(E2; 2_2^+ \to 0_2^+) = 0.19 B_{20}$. The two $v = 4$, $\alpha$ states do not mix with others for any $g_{9/2}$ interaction.

for single-$j$ systems, are influenced by configuration mixing from other neighboring subshells. We will show that a sharp transition from pure seniority coupling to significant mixing between the $v = 2$ and $v = 4, \alpha$ states may be induced by the cross-orbital non-diagonal interaction matrix elements. Such strong mixture is essential to explain the observed E2 transition properties of $N = 50$ isotones $^{96}$Pd and $^{94}$Ru. In a similar context, Ref. [20] discussed briefly the consequences of multi-shell calculations for states that are degenerate within a single-$j$ shell.

We will focus on the lightest semi-magic nuclei that involve a $j = 9/2$ orbital. These include the Ni isotopes between $N = 40$ and 50 and $N = 50$ isotones between $Z = 40$ and 50 (see Ref. [21] for a review on the structure of nuclei in this region). Those nuclei are expected to be dominated by the coupling within the $0g_{9/2}$ shell but the contribution from other neighboring orbitals (including $1p_{1/2}$, $1p_{3/2}$, $0f_{5/2}$) may also play an important role. A microscopic description of the many-body wave function is provided by the shell model full configuration interaction approach where the superposition of a sufficiently large number of many-body basis states within a given valence model space are considered. As for the $N = 50$ isotones, there has been many studies within the model spaces that include the $g_{9/2}$ orbital, the $1p_{1/2}0g_{9/2}$ orbitals as well as the $0f_{5/2}1p_{3/2}1p_{1/2}0g_{9/2}$ orbitals. All our calculations below are done numerically within the full shell model framework with exact diagonalization.

We have done calculations for different $(g_{9/2})^4$ systems within the $g_{9/2}$ orbital. The calculations are exactly the same for the spectra and E2 transition properties of the four-particle/four hole systems $^{94}$Ru and $^{96}$Pd (and $^{72}$Ni and $^{74}$Ni). In Fig. 1 a detailed calculation is given on the relative E2 transition strengths for a $(9/2)^4$ system calculated with a seniority-conserving (SC) interaction. Part of the results may also be found in Ref. [14]. The E2 transition matrix elements between states with the same seniority is related to each other as $\langle j^n vI||E2||j^n vI'\rangle = (2j+1-2n)/(2j+1-2v)\langle j^v vI||E2||j^v vI'\rangle$. As a result, the E2 transitions involve $v = 2$ are mostly weak. On the other hand, as indicated in Fig. 1, the E2 transitions between the two special $v = 4, \alpha$ states and between those states are strong and are proportional to $B(E2; 2_1^+ \to 0_1^+)$. The transitions between those $v = 4$ states and the $v = 2$ states are also expected to be strong. However, those special states are weakly connected to the other $v = 4$ states.

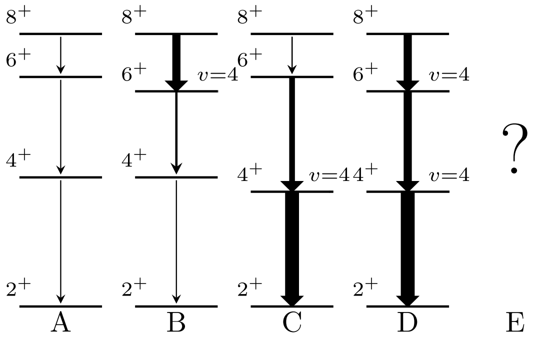

**Fig. 2.** Illustration on E2 transitions for the yrast states of a $(9/2)^4$ system in different scenarios based on E2 transitions from Fig. 1: A. All lowest excited states are dominated by seniority $v = 2$ configurations with suppressed E2 transitions below them; B. The special $v = 4$, $6^+$ state becomes yrast with a large $B(E2; 8_1^+ \to 6_1^+)$ value, in which situation the $8_1^+$ state may not be isomeric; C. Similar to B but with the special $v = 4$, $4^+$ state becomes yrast; D. Both special $v = 4$, $4^+$ and $6^+$ states become yrast where a collective-like strong inband E2 transition pattern is formed. E. One may wonder if it is possible to have a strong mixture between the $v = 2$ and 4 states (see text for details).

The lowest-lying spectra for such semi-magic nuclei are usually dominated by low seniority states. The seniority coupling is also associated with the existence of long-lived isomeric states with aligned spin $I = 2j - 1$ and seniority $v = 2$ in relation to the diminishing energy gap between the isomer and the $I = 2j - 3$ state and the suppressed E2 transition between the two. The suppression is expected to be maximum when the subshell is half-occupied. A systematic study on those E2 transitions may be found, e.g., in Ref. [22]. The situation for $(9/2)^4$ systems can be much more complicated since the two $\alpha$ states are also expected to have rather low excitation energies. Analytic expressions have been derived for their energies which depend on the strengths of the matrix elements $\langle 0g_{9/2}^2|V|0g_{9/2}^2\rangle_J$ with $J \neq 0$ [14].

A schematic plot for the influence of the relative positions of low-lying states on the yrast E2 transition properties are shown in Fig. 2. The low-lying spectroscopy of $^{72}$Ni including the $4_2^+$, $6_2^+$ and $8_1^+$ states was reported in Ref. [2]. The $B(E2; 4_1^+ \to 2_1^+)$ value for $^{72}$Ni was measured to be 50(9) e$^2$fm$^4$ in Ref. [23], which indicates that the $4_1^+$ state may be mostly of seniority $v = 4$ (see, also, Fig. 4 in Ref. [10]). As a result, the $8_1^+$ states in $^{72,74}$Ni are not expected to be isomeric [24–26].

A tentative search for the $6_2^+$ state in $^{94}$Ru was reported in Ref. [27]. For $^{94}$Ru and $^{96}$Pd, the two $\alpha$ states are expected to be just above the yrast $I = 4$ and 8 states, respectively, in most of our calculations. The $4_2^+$ states in $^{94}$Ru and $^{96}$Pd were also predicted to be lower than $6_1^+$ in the $pg$ calculations in Refs. [28,29]. Restricted calculations with the interactions from Ref. [25,30] predict the two $v = 4$ states to be yrast. When extended to the full $fpg$ space, the $6_2^+$ state is calculated to be 35 keV above the $8_1^+$ state with the jun45 interaction [30].

The nucleus $^{94}$Ru has an $8^+$ isomer at 2.644 MeV with a half-life of 71 μs [31]. The isomeric character of this level is a consequence of the significantly suppressed E2 decay and the small energy difference with the $6^+$ level below it. The E2 transition probabilities in $^{94}$Ru have been calculated in Refs. [28,32–36].

The existence of the uniquely defined $v = 4$, $\alpha$ states makes it possible to understand the suppression of $B(E2; 8_1^+ \to 6_1^+)$ in $^{94}$Ru from a very simple perspective. Since those two states do not mix with others, one can write the wave functions of the seniority $v' = 2$ (here one uses $v'$ to denote states with mixed seniorities but are dominated by the configuration with seniority $v$), $6^+$ and $8^+$ states as $|j^4, I\rangle_1 = \beta_2^I|j^4, v = 2, I\rangle + \beta_4^I|j^4, v = 4, \beta, I\rangle$ where $\beta_v^I$ denotes the amplitude. By taking $B(E2; I_i \to I_f) = e_{\rm eff}^2|M(E2; I_i \to$

$I_f)|^2/(2I_i+1)$ and $M_{v_1v_2} = M(E2; 8^+(v_1) \to 6^+(v_2))$, one can calculate the transition element as

$$\begin{aligned} &M(E2; 8_1^+ \to 6_1^+) \\ &\quad = \beta_2^8\beta_2^6 M_{22} + [\beta_4^8\beta_2^6 M_{42} + \beta_2^8\beta_4^6 M_{24}] + \beta_4^8\beta_4^6 M_{44}, \end{aligned} \tag{2}$$

where $M_{22}$ is of positive value and the rest are negative. One should expect the absolute values of $\beta_2^I$ to be much larger than that of $\beta_4^I$ since the $v = 4$, $\beta$ states lie at rather high excitation energies. Moreover, as indicated in Fig. 1, the absolute values for $M_{22}$ and $M_{44}$ are much smaller than the other two. As a result, the suppression of the transition should be mostly due to the cancellation of the first and middle two terms in the bracket where $\beta_4^I$ should have the same sign as $\beta_2^I$.

To illustrate the influence of the seniority mixing on the E2 transition property, in Fig. 3 I calculated the wave functions and transition matrix element by varying the seniority-non-conserving interaction matrix element $V_{SNC} = 65V_2 - 315V_4 + 403V_6 - 153V_8$. Only $M_{22}$ contributes for $V_{SNC}$ (or $\Delta V_8$) = 0. $\beta_4^I$ show finite values with the same sign as $\beta_2^I$ for negative $V_{SNC}$, which eventually lead to a full cancellation of $M(E2)$.

As indicated in Fig. 3, the transition $8_2^+(v' = 4) \to 6_3^+(v' = 4)$ will also be suppressed for the same reason. On the other hand, the $g_{9/2}$ matrix elements from the effective interactions for Ni isotopes (jj44Ni and jj44b) [25] also show rather large seniority non-conserving matrix element but with a different sign. In that case, as shown in Fig. 4, the predicted $B(E2; 8_{v'=2}^+ \to 6_{v'=2}^+)$ values for $^{72,74}$Ni are much larger than those from other interactions and no cancellation is expected.

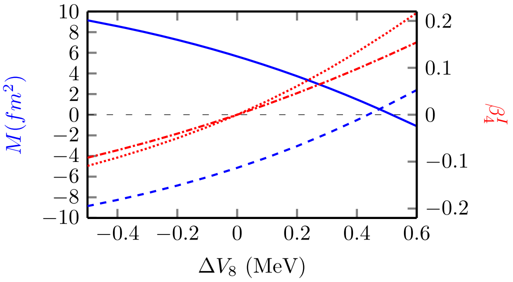

**Fig. 3.** Influence of the isospin-non-conserving matrix element on the wave functions of the $8_1^+(v' = 2)$ and $6_1^+(v' = 2)$ states in $^{94}$Ru and on the transition matrix element $M(E2; 8_1^+ \to 6_1^+)$ (blue solid line) and $M(E2; 8_2^+ \to 6_3^+)$ (blue dashed line). Calculations are done by shifting the strength of the matrix element $V_8$ of the SC interaction by an amount $\Delta v$. The red solid and red dashed lines correspond to $\beta_4^6$ and $\beta_4^8$ values for the $v' = 2$ states where it is assumed $\beta_2^I > 0$. Those two amplitudes change sign at $\Delta v = 0$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In order to explore the influence of the neighboring orbitals, in Fig. 4 I have done calculations with different effective interactions on the transitions $8_{v'=2}^+ \to 6_{v'=2}^+$ and $4_{v'=2}^+ \to 2_{v'=2}^+$ by gradually enlarging the model space. No significant influence from the mixture with those orbitals is seen for the $8_{v'=2}^+ \to 6_{v'=2}^+$ transition in $^{96}$Pd (and $^{74}$Ni). Moreover, the opening of the $N/Z = 50$ shell closures is not expected to influence the E2 transitions in the $N = 50$ isotones in a significant manner. On the other hand, if the model space is extended to include the $p_{1/2}$ orbital, the transitions for $^{94}$Ru and $^{72}$Ni can be influenced by the mixture between $|g_{9/2}^{-6}\rangle J$ and $|p_{1/2}^{-2}g_{9/2}^{-4}\rangle_J$ configurations. This is related to the cancellation as induced by the four-particle and four-hole natures of the two configurations. Such kind of cancellation does not happen for $^{96}$Pd and $^{74}$Ni. This is partly responsible for the fact that the observed transition probability $B(E2; 8_1^+ \to 6_1^+)$ for $^{96}$Pd is nearly 100 times larger than that of $^{94}$Ru. It is also noticed that, for the same reason, the measured $B(E2; 6_1^+ \to 4_1^+)$ value for $^{96}$Pd [37] is more than eight times larger than that of $^{94}$Ru.

In Ref. [37], the $B(E2; 4_1^+ \to 2_1^+)$ value for $^{96}$Pd was measured to be as small as 3.8 e$^2$fm$^4$, which is significantly suppressed by roughly a factor of seven in comparison with that predicted by a SC interaction. In contrast to those for $\to 6_1^+$ and $6_1^+ \to 4_1^+$, that value is expected to be significantly smaller than the that for $^{94}$Ru where the lower limit for $B(E2; 4_1^+ \to 2_1^+)$ is suggested to be as large as 46 e$^2$fm$^4$. Such an anomalous suppression can not be reproduced by calculations within the single $g_{9/2}$ shell but should be related to the mixing with other shells. In the following I will show that such anomalous transition is related to the unexpected mixture between $v = 2$ and $v = 4, \alpha$ which is induced by cross-orbital non-diagonal matrix elements of the two-body interaction. A detailed analysis on all related transitions will be presented in a forthcoming paper. Moreover, a dramatic increase in the $B(E2; 4_{v'=2}^+ \to 2_{v'=2}^+)$ values of $^{96}$Pd and $^{94}$Ru is seen in Fig. 4 for calculations with the jun45 interaction when the model space is extended to include $f_{5/2}$. Our detailed analysis of the corresponding wave functions shows that this calculated abrupt change is also related to the configuration mixing within $g_{9/2}$ induced by non-diagonal matrix elements involving $f_{5/2}$.

The overlaps between the two special $I = 4$ and 6, $\alpha$ states with the states constructed from the coupling of two $J = 2$ pairs $|j_{J=2}^2 \otimes j_{J=2}^2\rangle_{I=4}$ and two $J = 2$ and $J = 4$ pairs $|j_{J=2}^2 \otimes j_{J=4}^2\rangle_{I=6}$ are as large as $\alpha^I = 10\sqrt{255}/\sqrt{25591} \approx 0.9982$ and $2\sqrt{6783}/\sqrt{27257} \approx 0.9977$, respectively. It means that the cross-orbital configurations of the form $|(j_1 j_2) \otimes (g_{9/2})^2\rangle_{I=4,6}$ may overlap largely with the $v = 4, \alpha$ states through the non-diagonal matrix elements $V_{j_1 j_2 g_{9/2} g_{9/2}}^{J=2,4}$. Those configurations also show nonzero non-diagonal matrix elements with the $v = 2$ states. These

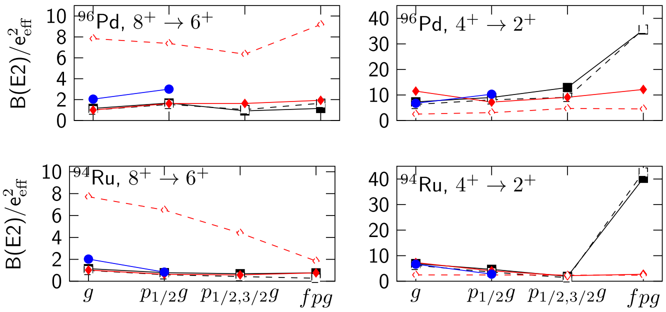

**Fig. 4.** $8_{v'=2}^+ \to 6_{v'=2}^+$ and $4_{v'=2}^+ \to 2_{v'=2}^+$ E2 transition strengths (divided by the square of the effective charge, in fm$^4$) for $^{94}$Ru, $^{96}$Pd calculated in different model spaces with effective interactions from Refs. [30] (square), [25] (diamond) and [29] (circle). The open symbols connected by dashed lines correspond to the calculations for $^{72,74}$Ni. The experimental $B(E2)$ values are 0.090 (5) and 8.9 (13) e$^2$fm$^4$, respectively, for $^{94}$Ru, $^{96}$Pd [31,37].

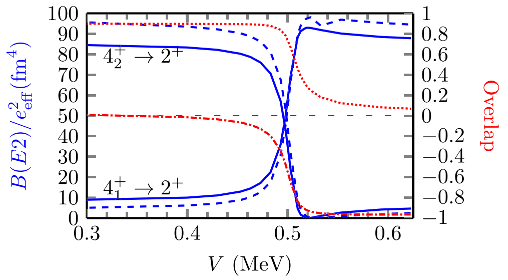

**Fig. 5.** E2 transition strengths (solid lines) for the transitions $4^+_{1,2} \to 2^+_1$ in $^{96}$Pd calculated in a minimal model space $p_{1/2,3/2}g$ calculated by varying the strength of the non-diagonal matrix element $V^{J=2}_{p_{3/2}p_{3/2}g_{9/2}g_{9/2}}$. The dashed lines correspond to the transition from $4^+_{1,2}$ to the state $|g^{-4}_{9/2}, v = 2, I = 2\rangle$. The dotted and dash-dotted lines (red) show the overlaps between $4^+_1$ and the seniority $v = 2$ and $v = 4, \alpha$ states. Calculations are done with the jun45 effective Hamiltonian by allowing at most two particles/holes in $p_{3/2}$. The original value of the matrix element is 0.453 MeV while a sharp transition occurs between 0.46 and 0.52 MeV where the main component of $4^+_1$ ($4^+_2$) change from seniority 2 (4) to 4 (2). The transition $4^+_2(v' = 2) \to 2^+_1$ vanish with $V^{J=2}_{p_{3/2}p_{3/2}g_{9/2}g_{9/2}} \approx 0.52$ MeV. With this interaction strength, a strong mixture between the $v = 2$ and $\alpha$ configurations is still expected for $4^+_{1,2}$ in $^{94}$Ru. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

matrix elements lead to a co-existence of the two $v = 2$ and 4 configurations which does not happen in calculations within the $g_{9/2}$.

As for $I = 4$, it is found that the non-diagonal matrix elements with $j_1 j_2 = p^2_{3/2}$, $p_{1/2}p_{3/2}$, $p_{1/2}f_{5/2}$, $p_{3/2}f_{5/2}$ coupled to $J = 2$ can indeed induce significant mixture between the $v = 2$ and $v = 4, \alpha$ states. But it happens only in a relatively small window of strengths for the two-body matrix elements. As for calculations in Fig. 4, only those from the jun45 interaction (more exactly, the $V^{J=2}_{p_{3/2}f_{5/2}g_{9/2}g_{9/2}}$ element) fall in that window. That is why there is no abrupt change seen in other calculations. It should also be mentioned that those non-diagonal matrix elements $V^{J=2,4}_{j_1 j_2 g_{9/2}g_{9/2}}$ have very limited influence on the energies of the states of concern. In relation to that, it has always been a challenging task to pin down the sign and the strengths of the non-diagonal interaction matrix elements for the shell-model Hamiltonian which may be approximated from realistic nucleon–nucleon potentials.

In Fig. 5 I evaluated the overlaps between the calculated wave functions and the $v = 2$ and $v = 4, \alpha$ for the first two $4^+$ states in $^{96}$Pd in a model space containing orbitals $p_{1/2}, p_{3/2}$ and $g_{9/2}$. That is the minimal space that can induce significant mixture between the two $v = 2$ and 4 configurations. As indicated in Figs. 4 and 5, no significant mixture between the two components is seen in the calculation with the original jun45 interaction since the $V^{J=2}_{p_{3/2}p_{3/2}g_{9/2}g_{9/2}}$ interaction is slightly outside the strength window. But a strong mixture between the two $v = 2$ and 4 configurations is expected for both $4^+_{1,2}$ if the interaction got more repulsive.

The transition pattern shown in Fig. 5 gives us an unique opportunity to understand the $4^+ \to 2^+$ E2 transitions of $^{96}$Pd and $^{94}$Ru as measured in Ref. [37,38]: The E2 transition in $^{96}$Pd corresponds to a vanishing $4^+_{v'=2} \to 2^+_{v'=2}$ transition seen in right-hand side of Fig. 5 while the large E2 transition in $^{94}$Ru indicates that the nucleus is indeed located in the transitional region where the transition strength is very sensitive to the mixture of the two configurations.

To summarize, in this work I present a novel analysis on the electric quadrupole transition properties of semi-magic nuclei with four particles or four holes in the $g_{9/2}$ orbital from a partial seniority conservation perspective. This is related to the existence of uniquely defined $v = 4$ states which, for systems within a $j = 9/2$ subshell, do not mix with other states. It is shown that the diminishing $B(E2; 8^+_1 \to 6^+_1)$ in $^{94}$Ru can be mostly understood as the cancellation between few terms induced by the seniority-non-conserving interaction. Moreover, I studied the influence of the neighboring $1p_{1/2}$, $1p_{3/2}$, $0f_{5/2}$ orbitals. It is seen that the cross-orbital interaction matrix elements can induce significant mixture between the $v = 2$ and the unique $\alpha$ states. The limited experimental information available do indicate that such a sharp phase transition can be seen in nuclei like $^{96}$Pd and $^{94}$Ru. In the future, besides the measurement on the predicted states and E2 transitions mentioned in the present work, it can also be of great interest to explore other $j = 9/2$ nuclei, including the $N = 82$ isotones and neutron-rich Pb isotopes, with different two-body interaction strengths and different neighboring orbitals to get a better understanding of such phase transitions.

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