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Broken seniority symmetry in the semimagic proton mid-shell nucleus ^{95}Rh

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Lifetime measurements of low-lying excited states in the semimagic ($N = 50$) nucleus ^{95}Rh have been performed by means of the fast-timing technique. The experiment was carried out using γ -ray detector arrays consisting of $\text{LaBr}_3(\text{Ce})$ scintillators and germanium detectors integrated into the DESPEC experimental setup commissioned for the Facility for Antiproton and Ion Research (FAIR) Phase-0, Darmstadt, Germany. The excited

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states in ^{95}Rh were populated primarily via the β decays of ^{95}Pd nuclei, produced in the projectile fragmentation of a 850 MeV/nucleon ^{124}Xe beam impinging on a 4 g/cm^2 ^9Be target. The deduced electromagnetic E2 transition strengths for the γ -ray cascade within the multiplet structure depopulating from the isomeric $I^\pi = 21/2^+$ state are found to exhibit strong deviations from predictions of standard shell model calculations which feature approximately conserved seniority symmetry. In particular, the observation of a strongly suppressed E2 strength for the $13/2^+ \rightarrow 9/2^+$ ground state transition cannot be explained by calculations employing standard interactions. This remarkable result may require revision of the nucleon-nucleon interactions employed in state-of-the-art theoretical model calculations, and might also point to the need for including three-body forces in the Hamiltonian.

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Introduction. One of the most intriguing aspects of nuclear phenomenology is the emergence of regular and simple structural patterns from the complex nuclear many-body correlations. In particular, the vast majority of semimagic nuclei (those with either the number of neutrons, N , or the number of protons, Z , corresponding to a filled quantum shell) are characterized by the pairwise coupling of the valence nucleons in the unfilled shell [1]. The seniority quantum number, ν , is defined as the number of neutrons or protons that are not coupled in pairs to angular momentum $J = 0$ [2]. Characteristic, regular energy spectra and special patterns of the electric quadrupole transition strengths between the member states of the corresponding seniority multiplets arise as a combined effect of the strong spin-orbit coupling and residual pairing correlations in the nuclear mean field.

Even though seniority is an approximate symmetry it hence has a profound impact on the description of the spectroscopic and electromagnetic transition properties of nuclei near closed quantum shells. It is a strictly conserved quantum number for systems with identical particles in a single- j angular momentum subshell with $j \leq 7/2$ in the presence of an attractive two-body pairing force. Even for systems with higher j values, like for particles in the $g_{9/2}$, $j = 9/2$ subshell, the seniority-violating interaction matrix elements are expected to be negligible in most empirical shell model interactions. The $j = 9/2$ case has recently received particular interest with respect to the special partial conservation of seniority in systems with four proton particles/holes [3–10].

A striking consequence of seniority symmetry is that the squares of the $\Delta\nu = 0$ matrix elements of even-tensor one- and two-particle operators, such as the electromagnetic quadrupole (E2) operator, are symmetric with respect to the middle of the angular momentum subshell, i.e., when the number of particles occupying levels in the angular momentum subshell is $n_j = (2j + 1)/2$. This can be considered to be a result of the combination of particle-hole conjugation and seniority conservation, intertwined through a Berry phase [11]. The corresponding transition probabilities between such states therefore vanish when the Fermi level is situated in the middle of the subshell, as is the case for ^{95}Rh . Converseley, the seniority changing $\Delta\nu = 2$ matrix elements of the same operators, which mirror the behavior of the seniority conserving matrix elements as a function of shell filling, are maximal at midshell.

The few observed exceptions from the general rule of energy level spectra and E2 transition rates following the

predictions of shell model calculations with a seniority conserving nuclear interaction are particularly interesting since they may reveal otherwise hidden details of the nuclear force. Such cases include the semimagic ($N = 50$) nuclei ^{94}Ru and ^{96}Pd , for which there are large discrepancies between the observed $4^+ \rightarrow 2^+$ electromagnetic E2 transition strengths and theoretical predictions in different directions [7,12–16]. For these nuclei, the valence protons occupy the upper half of the $N/Z = 28 - 50$ major shell which is characterized by the relative isolation of the $g_{9/2}$ subshell. Mach *et al.* reported a lower limit, $B(E2:4^+ \rightarrow 2^+) \geq 46 e^2 fm^4$ for ^{94}Ru and a value $B(E2:4^+ \rightarrow 2^+) = 3.8(4) e^2 fm^4$ for ^{96}Pd , corresponding to strongly enhanced and retarded $4^+ \rightarrow 2^+$ E2 transition strengths, respectively, compared with seniority-conserving shell model predictions [7]. They suggested that the observed anomalous E2 strengths in these $N = 50$ isotones and the inferred seniority symmetry breaking is due to residual neutron-proton interactions in combination with neutron particle-hole (ph) excitations across the $N = 50$ shell gap. Das *et al.* recently reported a value $B(E2:4^+ \rightarrow 2^+) = 103(24) e^2 fm^4$ for the same transition in ^{94}Ru [12] and proposed, alternatively, the observed seniority symmetry breaking effect in ^{94}Ru to be a result of a subtle interference between the wave functions of the initial and final states induced by cross-orbital interactions within the major valence shell. Subsequently, Pérez-Vidal *et al.* reported a value $B(E2:4^+ \rightarrow 2^+) = 38(3) e^2 fm^4$ for ^{94}Ru , differing significantly from the previously reported results [7,12], and arrived at a different conclusion, namely, that seniority is largely conserved in the first $\pi g_{9/2}$ orbital [13]. This situation requires further investigation, both from an experimental and theoretical stand point.

The nucleus $^{95}_{45}\text{Rh}_{50}$ is located exactly at the $\pi g_{9/2}$ midshell and should therefore exhibit approximate particle-hole symmetry, i.e., it can be described both as five valence protons and five proton holes in the $g_{9/2}$ orbital. A puzzling enhancement of the $B(E2)$ strength in this nucleus has previously been reported [7,14–16] for the $21/2^+ \rightarrow 17/2^+$ transition instead of the near-vanishing E2 transition rate expected from approximate seniority conservation for a $\Delta\nu = 0$ transition.

In this Letter we present lifetime measurements on the low-lying yrast states of ^{95}Rh using the direct, fast-timing method. The extracted E2 transition strengths are compared with the results from large-scale shell-model and single- j shell calculations. A strong violation of the seniority coupling scheme is observed, which cannot be reproduced by state-of-the-art

empirical shell model interactions applied in different model spaces.

Experiment details and data analysis. Lifetime measurements of low-lying yrast states of ^{95}Rh were performed using the DEcay SPECTroscopy (DESPEC) [17] setup commissioned for the Facility for Antiproton and Ion Research (FAIR) [18,19] Phase-0. The results presented here were obtained from the same measurement as those previously reported for ^{94}Ru [12].

^{124}Xe ions were accelerated to a kinetic energy of 850 MeV/u by the SIS-18 synchrotron at the GSI Helmholtzzentrum für Schwerionenforschung accelerator facility, Darmstadt, Germany, and impinged on a ^9Be target of 4 g/cm^2 areal density. Nuclear fragments produced in the reactions were identified and transported to the final focal plane of the FRagment Separator (FRS) using the $B\rho$ - ΔE - $B\rho$ and ToF- $B\rho$ - ΔE methods [20,21]. The Advanced Implantation Detector Array (AIDA) [22,23], composed of three double-sided silicon strip detectors (DSSSD), was used to stop the product nuclei and to measure their subsequent charged-particle decays. The White Rabbit (WR) [24] clock was used to save the implant timing. WR is a common clock to all DESPEC subsystems and used to synchronize these subsystems with 1 ns precision. As a result, the timing information of each implanted ^{95}Pd ion was saved as a function of its position, (x, y) , where x and y are the horizontal and vertical strip numbers of the DSSSD, respectively. After implantation of the ^{95}Pd ions, population of the $21/2^+$ isomer leads to β decay into the analog spin-parity state of the ^{95}Rh nucleus [25], which then de-excites toward the $9/2^+$ ground state via a cascade of stretched γ -ray transitions. To identify such β -delayed γ rays, β decays correlated with implants of the ^{95}Pd ions were searched for within the DSSSD pixels. The time correlation was obtained using the WR clock with a $\sim 3 \times T_{1/2}$ ($T_{1/2} = 14(1)\text{s}$ [25]) time window, within which the β -decay pixel position was validated if an ion had been implanted in the same pixel or in any of its immediate neighbors, taking into account that the highly penetrating β rays may scatter to the neighboring pixels from the implantation point depositing partial or full energy.

The β -delayed γ rays were registered using an array of six triple-cluster germanium detectors [19], and an array of 36 $\text{LaBr}_3(\text{Ce})$ detectors. The latter, with its much faster time response, is known as the FAst TIMing Array (FATIMA) [26–28]. The WR timestamps were used to find β - γ correlations, where the slow time response of the decay amplifier in AIDA (read-out time $\sim 2\mu\text{s}$) opens up a wide time correlation window. The β - γ events lie within the peak of the time distribution, δT , of γ rays detected in FATIMA relative to the β -decay time registered in AIDA, see Fig. 1(b). Clean mutual coincidences could be obtained between the 381 keV($21/2^+ \rightarrow 17/2_1^+$), 716 keV($17/2_1^+ \rightarrow 13/2^+$), and 1351 keV($13/2^+ \rightarrow 9/2^+$) γ lines below the seniority isomer in ^{95}Rh [25]. The presence of transitions decaying to the $13/2^+$ state could be observed in the 1351 keV gated spectra of β - γ - γ events in Fig. 1(a). The reported energies were measured using the germanium detectors and agree with the previous assignments [15,16,29].

The FATIMA $\text{LaBr}_3(\text{Ce})$ detectors were used to measure direct γ - γ time differences, with a resolution of 25 ps least significant bit [17]. Mean level lifetimes (τ) for the yrast

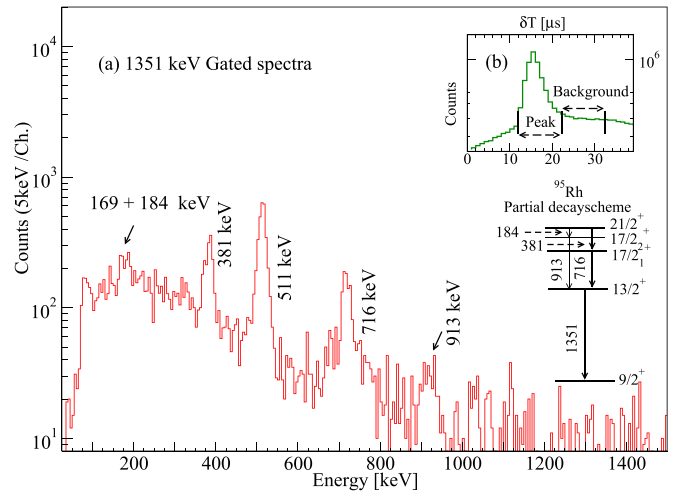


FIG. 1. (a) The γ energies of β - γ - γ events in coincidence with 1351 keV transition. The decay of $I^\pi = 21/2^+$ is depicted at the inset, while the 169 keV transition is coming from the decay of the $I^\pi = 17/2^-$ isomer. (b) The WR time difference between AIDA and FATIMA for the β -decay events from ^{95}Pd .

states of ^{95}Rh were deduced using the generalized centroid difference (GCD) method [30,31]. The centroid difference for a coincident γ -ray pair, ΔC , is directly related to τ , following the relation

$$\Delta C(\Delta E_\gamma) = \Delta PRD(\Delta E_\gamma) + 2\tau, \quad (1)$$

with the symmetry conditions [31]

$$\begin{aligned} \Delta C(\Delta E_\gamma) &= -\Delta C(-\Delta E_\gamma), \\ PRD(\Delta E_\gamma) &= -PRD(-\Delta E_\gamma), \end{aligned} \quad (2)$$

where ΔE_γ is the energy difference between the feeding and the decaying γ rays of the level, and PRD is the prompt response difference [30]. The calibration measurement of the PRD function for the present setup has been described in Ref. [12].

The delayed and antidelated time distributions obtained for the $13/2^+$ and $17/2_1^+$ states are shown in Figs. 2(a) and 2(d), respectively, from which the generalized time centroids [32] were obtained. The background contribution to the time distribution was subtracted according to the method described in Ref. [33]. The time spectra due to background coincidences are shown in Figs. 2(b) and 2(c) and Figs. 2(e) and 2(f) for the $13/2^+$ and $17/2_1^+$ states, respectively. The PRD values of $-321(\pm 6 \pm 14 \pm 16)$ ps and $-290(\pm 6 \pm 14 \pm 15)$ ps were obtained from the fit shown in Fig. 2(b) of Ref. [12], for the $13/2^+$ and $17/2_1^+$ states, respectively. The PRD errors in bracket include the time uncertainty introduced by the large energy width of LaBr_3 detectors, along with the fit residual errors for start and stop energies, respectively. One may note that this is the only source of systematic errors built into the GCD method [30]. The cancellation of systematic errors from different sources therefore makes it advantageous over other fast-timing methods. The obtained lifetime values are $\tau(13/2_1^+) = 36(15)$ ps and $\tau(17/2_1^+) = 8(18)$ ps, the latter corresponding to a limit $\tau(17/2_1^+) \leq 26$ ps with 1σ uncertainty. The uncertainties include uncorrelated errors added

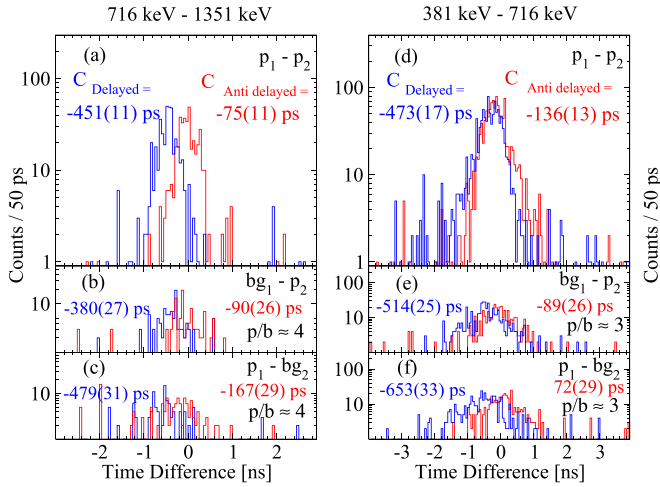


FIG. 2. Delayed and antidelayed time distributions for the (a) 381 keV (p_1)–716 keV (p_2) transitions, where (b) and (c) depict peak-to-background (p - bg) coincidences. Delayed and antidelayed time distributions for the (d) 716 keV–1351 keV transitions, where (e) and (f) depict peak-to-background coincidences.

in quadrature [34]. The use of the GCD method with the present experimental setup was also validated by remeasuring the mean lives of the 4_1^+ and 2_1^+ states in ^{94}Ru and ^{96}Pd from the same experiment. For ^{94}Ru , the lifetimes of the 4_1^+ and 2_1^+ states were observed to be $\tau = 32(11)$ ps and $\tau \leq 14$ ps, respectively [12], and consistent with the respective $\tau \leq 72$ ps and $\tau \leq 14$ ps limits previously established by Mach *et al.* [7]. For ^{96}Pd , Yaneva *et al.*, [35] have measured the value $\tau(4_1^+) = 1.44(7)$ ns and the limit $\tau(2_1^+) \leq 20$ ps, which also confirms the previous measurements [7]. It is to be noted that, despite the similar ΔE_γ values for the first excited states in these nuclei, the delayed nature of the $13/2_1^+ \rightarrow 9/2^+$ transition could be clearly established for ^{95}Rh . The lifetime of the $17/2_2^+$ state of ^{95}Rh [15] could not be measured in the present experiment due to insufficient statistics. The experimental results are summarized in Table I.

Discussion. To understand the observed E2 transition properties of the low-lying yrast structure in ^{95}Rh , we have carried out configuration interaction model calculations including extensive large-scale shell model (LSSM) calculations in a variety of model spaces, and compared the results with those from a pure single- j shell calculation. In Fig. 3 the experimental low-lying yrast spectrum and the associated E2 transition strengths

TABLE I. Experimental lifetimes and $B(E2)$ strengths in ^{95}Rh . The lifetime value for the $21/2^+$ state is taken from Ref. [16]. The lifetime limit for the $17/2_1^+$ state was determined with a 1 σ confidence level. See text for details.

$I_i^\pi \rightarrow I_f^\pi$	τ [ps]	$B_{\text{exp.}}(E2)$ [$e^2 \text{fm}^4$]
$21/2^+ \rightarrow 17/2_1^+$	$3.0(4) \times 10^3$	$29.0(4.0)$ [7]
$21/2^+ \rightarrow 17/2_2^+$	$3.0(4) \times 10^3$	$136(20)$ [7]
$17/2_1^+ \rightarrow 13/2_1^+$	≤ 26	≥ 167
$17/2_2^+ \rightarrow 13/2_1^+$		
$13/2_1^+ \rightarrow 9/2^+$	$36(15)$	$5.0^{+3.6}_{-1.6}$

between the members of the $\pi g_{9/2}$ seniority multiplet are compared with theoretical calculations using the single $\pi g_{9/2}$ (labeled “g”) model space with the same seniority-conserving empirical interaction as used in Ref. [36], the $\pi f_{5/2} p_{1/2,3/2} g_{9/2}$ (labeled “fpg”) model space with the jun45 interaction [37], and the $\pi \nu g_{9/2,7/2} d_{5/2,3/2} s_{1/2}$ model space (labeled “gds”), employing the SDG CD-Bonn based G-matrix renormalized SDGN interaction [7,38], limiting the model space to allow a maximum of $t = 6$ particles that can be excited across the $N = Z = 50$ major shell. Effective charges of $e_p(e_n) = 1.5e(0.5e)$ were used for the calculations in the “g” and “fpg” model spaces and $e_p(e_n) = 1.11e(0.84e)$ [39] in the “gds” model space. Numerical results are listed in Table II. The $\nu = 3$ -dominated, $17/2^+$ state is predicted to be lower in excitation energy than the $\nu = 5$ -dominated state in the “g” and “gds” model spaces, whereas an inversion between the two states is seen in the “fpg” space calculation. However, predicted energy spectra and electromagnetic transition strengths for the different model calculations are in general quite similar, in excellent agreement with approximate seniority symmetry. On the other hand, it may be immediately recognized that the calculated electromagnetic transition strengths are in stark contrast with the experimental observations. In particular, none of the calculations are even close to reproducing the experimentally observed E2 transition rate for the $13/2_1^+ \rightarrow 9/2^+$ ground-state transition.

The five protons in the $0g_{9/2}$ subshell can couple to three $I^\pi = 9/2^+$; $\nu = 1, 3, 5$, states, two $13/2^+$; $\nu = 3, 5$, and two $17/2^+$; $\nu = 3, 5$ states. The $I^\pi = 9/2^+$ ground state and the first $I^\pi = 13/2^+$ state (which is dominated by $\nu = 3$) are predicted to be well separated in energy in calculations employing a variety of standard effective interactions in different model spaces while the two $I^\pi = 17/2^+$ states can be close to each other [9]. A special property of midshell nuclei like ^{95}Rh is that the two-body interaction, operating within a single- j shell, can only mix configurations with seniority differing by $\Delta \nu = 4$. This means that the two $13/2^+$ and $17/2^+$ states with $\nu = 3$ and 5 never mix in such calculations and the seniority symmetry is strictly conserved. In general, the $13/2_2^+$ state (dominated by $\nu = 5$) is predicted at much higher excitation energy than the first $13/2_1^+$ ($\nu = 3$) state, at 3.03 MeV in the g calculation and 2.94 MeV in the fpg model space. The state is calculated to decay primarily to the $17/2^+$ $\nu = 3$ -dominated state or a $11/2^+$ state.

In general, the wave function of a state $|\alpha\rangle$ with angular momentum quantum number I can be expressed as a superposition of single- j configurations with different seniority and configurations as

$$|I, \alpha\rangle = \sum_{\nu=1,3,5} c_\nu |(0g_{9/2}^5, \nu, I)\rangle + \text{contributions from other shells.} \quad (3)$$

The three $I^\pi = 9/2^+$ configurations can mix with each other due to the allowed $\Delta \nu = 4$ mixing between the $\nu = 1$ and $\nu = 5$ configurations and interactions with the intermediate $\nu = 3$ state via mainly the close-lying $p_{1/2}$ subshell. However, the mixing between the $\nu = 1$ $I^\pi = 9/2^+$ ground state and the $\nu = 3$ and $\nu = 5$ $I^\pi = 9/2^+$ states is predicted to be quite small (1.16% and 2.14%, respectively) due to the dominance

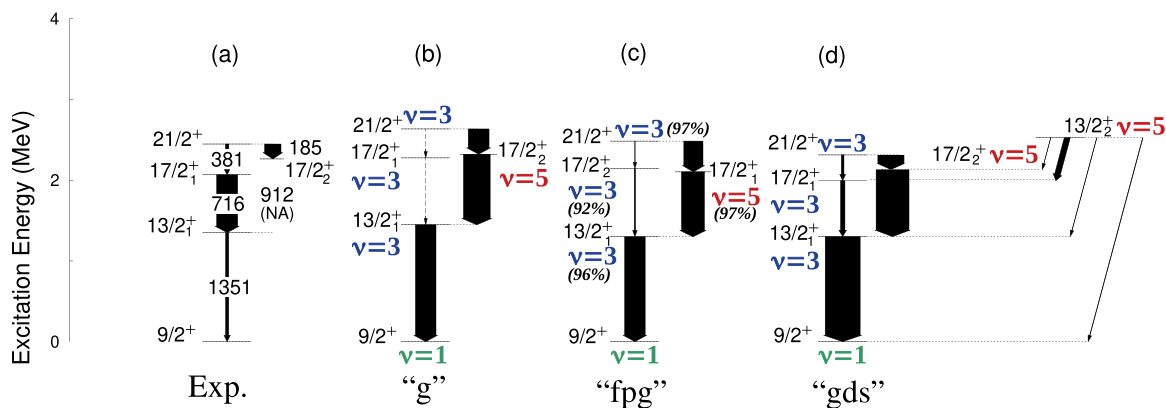


FIG. 3. Experimental and theoretical level energies and electromagnetic transition strengths for the low-lying excited states in ^{95}Rh . The widths of the arrows are proportional to the experimentally deduced (a) and calculated (b)–(d) $B(E2)$ values given in Table I and Table II. Dashed arrows correspond to a vanishing transition strength. The theoretically calculated energy levels are labeled by the dominant seniority quantum number in the wave function. For the calculation employing the jun45 interaction (c), the squared amplitude of the dominant signature component is also given.

of the pairing matrix element which increases the energy of the latter states to around 1.8 MeV and 2.3 MeV, respectively, for the calculation employing the realistic jun45 interaction [37]. The $\nu = 3$ and $\nu = 5$ admixtures in the ground state wave function are consistently zero or of similar magnitude for all the interactions and model spaces employed in this work. The same applies to the predictions for the mixing between the $13/2_1^+$ and $13/2_2^+$ states.

A particularly striking feature of the electromagnetic properties of ^{95}Rh is the observed strong hindrance of the $13/2_1^+ \rightarrow 9/2^+$ transition, in contradiction to the predictions within the seniority coupling scheme as well as all of our LSSM calculations. The experimentally deduced $B(E2:13/2_1^+ \rightarrow 9/2^+)$ value of $5.0_{-1.6}^{+3.6} e^2 fm^4$ is reduced by a factor of more than 30 compared with the lowest theoretical prediction obtained in this work (Table II). This indicates a strong violation of seniority symmetry and that the two $\nu = 3$ and 5, $13/2^+$ states, unexpectedly, might be strongly mixed. We have therefore evaluated the influence of various nondiagonal matrix element contributions to Eq. (3) by varying their strengths. No significant mixing has been found in our calculations without invoking an unrealistic adjustment of those matrix elements that would lead to strong perturbations in, e.g., the predicted level energies.

We have also extended our calculations to include neutron cross-shell excitations including $d_{5/2}$ and $g_{7/2}$ configurations

as in Refs. [40,41]. However, no significant contributions to the wave functions from neutron core excitations across the $N = 50$ shell closure were found for the lowest $I^\pi = 9/2^+$, $13/2^+$, and $17/2^+$ states, primarily due to the large energy gap (~ 4 MeV) between the $g_{9/2}$ subshell and higher-lying shells. It is also noteworthy that no evidence for significant cross-shell excitations was observed for the neutron analog system, ^{213}Pb , with five neutrons in the $1g_{9/2}$ shell [11]. There is very limited experimental information on the E2 transition probabilities in similar systems. We note, however, that the deduced limits on the E2 strengths for the $2_1^+ \rightarrow 0_g^+$ transitions in the neighboring $N = 50$ isotones ^{94}Ru [7,12] and ^{96}Pd [7], which are expected to be similar to the $13/2_1^+ \rightarrow 9/2^+$ transition in ^{95}Rh , are in agreement with the predicted behavior for conserved seniority symmetry.

The observed $13/2_1^+ \rightarrow 9/2_{gs}^+$ E2 transition strength in ^{95}Rh appears to be extremely difficult to reproduce using standard effective two-body shell model interactions. Although highly challenging and beyond the current state of the art in computational capabilities, it is possible that the inclusion of three-body forces into the shell-model Hamiltonian [42,43] could elucidate the mechanism behind this unexpected observation. For a more complete picture, experimental data on similar systems are also required.

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TABLE II. Theoretical $B(E2)$ strengths in ^{95}Rh calculated in different model spaces. The states are labeled by the dominant seniority component in the wave function. See text for details.

$I_i^\pi \rightarrow I_f^\pi$	$B_{gds}(E2)$ [$e^2 fm^4$]	$B_{fpg}(E2)$ [$e^2 fm^4$]	$B_g(E2)$ [$e^2 fm^4$]
$21/2^+ \rightarrow 17/2_{\nu=3}^+$	10.7	2.8	0.00
$21/2^+ \rightarrow 17/2_{\nu=5}^+$	177.1	158.1	172.0
$17/2_{\nu=3}^+ \rightarrow 13/2_{\nu=3}^+$	18.4	10.9	0.0
$17/2_{\nu=5}^+ \rightarrow 13/2_{\nu=3}^+$	232.4	189.5	208.7
$13/2_{\nu=3}^+ \rightarrow 9/2^+$	219.2	169.7	169.3

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