Ultrafast-timing lifetime measurements in ^{94}Ru and ^{96}Pd: Breakdown of the seniority scheme in $N = 50$ isotones

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The advanced time-delayed $\gamma\gamma(t)$ method has been applied to determine half-lives of low-lying states in the $N = 50$ isotones ^{94}Ru and ^{96}Pd. The inferred experimental $E2$ strengths for the $4^+ \to 2^+$ transitions in the two nuclei show a dramatic deviation with respect to the shell model predictions in the $(f_{5/2}, p, g_{9/2})$ proton hole space in ^{100}Sn. The anomalous behavior can be ascribed to a breakdown of the seniority quantum number in the $\pi g_{9/2}^n$ configuration due to particle-hole excitations across the $N = Z = 50$ shell as confirmed by large-scale shell model calculations.

I. INTRODUCTION

In nuclear structure calculations the seniority v is a well-defined quantum number in any n-particle configuration j^n of like particles. This is a direct consequence of the short-range nature of the nucleon-nucleon interaction [1]. It has been shown for various empirical interactions [2–4] and is exhibited by G-matrix based realistic interactions [5,6], that the seniority mixing matrix elements are very small, in the order of tens of keV. This imposes a few symmetry rules, which can favourably be exploited in nuclear structure applications [1,7,8]. The most important among these are (i) excitation energies are independent of shell occupation n; (ii) $\Delta v = 0$ matrix-elements of even-tensor one- and two-particle operators are symmetric to midshell except for a sign change, and they vanish for $n = (2j + 1)/2$ creating

long-lived isomers; (iii) $\Delta v = 2$ matrix elements of even-tensor one-body operators are symmetric to particle-hole (ph) conjugation with a maximum in midshell; (iv) odd-tensor one- and two-particle operators are diagonal in seniority. Distortion of good seniority in semimagic nuclei may be caused by three effects, namely (i) by mixing due to a seniority nonconserving interaction, (ii) by configuration mixing with neighboring orbits, and (iii) by core excitation across the shell gap which implies seniority nonconserving proton-neutron interaction. Theoretically the $g_{9/2}^n$ system has recently received increased interest with respect to seniority [9–11], symmetry [12], and aligned proton-neutron pairs [13,14].

Experimentally, well-developed seniority schemes have been established in many isolated proton (π) and neutron (v) high-spin orbitals ($j \geqslant 7/2$), such as $v\pi f_{7/2}^n$ in the Ca isotopes [1,15], $vg_{9/2}^n$ in the Ni isotopes [16–18], $\pi g_{9/2}^n$ in the $N = 50$ isotones [19], $vh_{11/2}^n$ in the Sn isotopes [20], $\pi h_{11/2}^n$ in the $N = 82$ isotones [21], and $\pi h_{9/2}^n$ in the $N = 126$ isotones [5,22]. The specific features of the various sequences of nuclei are subject to change due to the presence of

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close-lying subshells and peculiarities of the interactions. Thus (i) the constancy of excitation energies is affected by increased pairing when approaching neighboring shells as observed in the $N = 50$ [23] and $N = 126$ [5] isotones, (ii) the symmetry of $E2$ transitions with respect to midshell is distorted in all known cases [19–23] by premature or delayed filling in the presence of other orbitals at the Fermi surface, and (iii) for $n \geqslant 4$ the yrast states have not always the lowest seniority. The latter effect, besides the well-known case of $\nu f_{7/2}^n$ in the Ca isotopes, was established for the Ni isotopes where the isomerism of the $\nu g_{9/2}^n, I^\pi = 8^+$ state disappears in midshell [24]. The effect was clearly attributed to a well bound $I^\pi = 2^+$ two-body matrix element, i.e., a small $I^\pi = 2^+$ excitation energy [25,26]. In spite of these distortions of the seniority scheme, the seniority v is pure and a well-defined quantum number, even in the heavily distorted $N = 126$ case [5].

In the $N = 50$ isotones a puzzling result has been long known in the $\pi g_{9/2}$ midshell nucleus ^{95}Rh. For the half-filled shell the $\Delta v = 0 \, 21/2^+, v = 3 \rightarrow 17/2^+, v = 3 \; E2$ strength should be small or zero and the $\Delta v = 2 \; 21/2^+, v = 3 \rightarrow 17/2^+, v = 5$ transition is expected to be strong. Experimentally, however, both branches are observed with comparable strengths [19,27,28]. This cannot be explained by mixing within the proton model space since both the odd- and even-tensor two-body matrix elements vanish in midshell owing to the seniority conserving interaction [19]. Therefore neutron core excitation across $N = 50$ has been invoked as a possible explanation [23,28]. The importance of excitations of the ^{100}Sn core for $E2$ strengths has been demonstrated for the two-proton hole nucleus ^{98}Cd [29] with the result that the net effect of ph excitation may be absorbed in an increased effective charge. On the other hand it is well known that the proton-neutron interaction destroys good seniority. Therefore in the present work lifetime measurements for low-lying, low-spin states in the four-particle and four-hole $\pi g_{9/2}^n$ nuclei ^{94}Ru and ^{96}Pd were performed.

II. EXPERIMENT AND DATA ANALYSIS

Lifetime experiments in the $N = 50$ isotones for levels below the 8^+ isomers are largely hampered by the delayed feeding from this state. The ultrafast $\gamma\gamma(t)$ timing technique [30–33] enabled for the first time access to lifetime measurements of the lower-lying states. The experiment was performed at the LISE3 [34] spectrometer in GANIL following fragmentation of a ^{112}Sn beam with an energy of $64A$ MeV on a ^{9}Be target. The A and Z identification of the fragments was obtained from the energy loss, total kinetic energy, and the time of flight of the residues, which were implanted into a stack of four Si detectors placed at the focal plane of the spectrometer [24]. Selected reaction products were passing through the first two detectors and finally were stopped in the third one. The implantation detector was surrounded in close geometry by a γ-ray detection system including an array of four fast timing BaF$_2$ scintillators and a Ge spectrometer. The BaF$_2$ detectors were prepared and their time response calibrated at the OSIRIS separator at Studsvik. The system

allowed for determination of lifetimes in the range from ~ 20 ns down to ~ 10 ps using time-delayed $\gamma\gamma(t)$ coincidences between any pair of BaF$_2$ detectors. A specific isomeric decay was selected by gating the $\gamma\gamma(t)$ event within a specific time
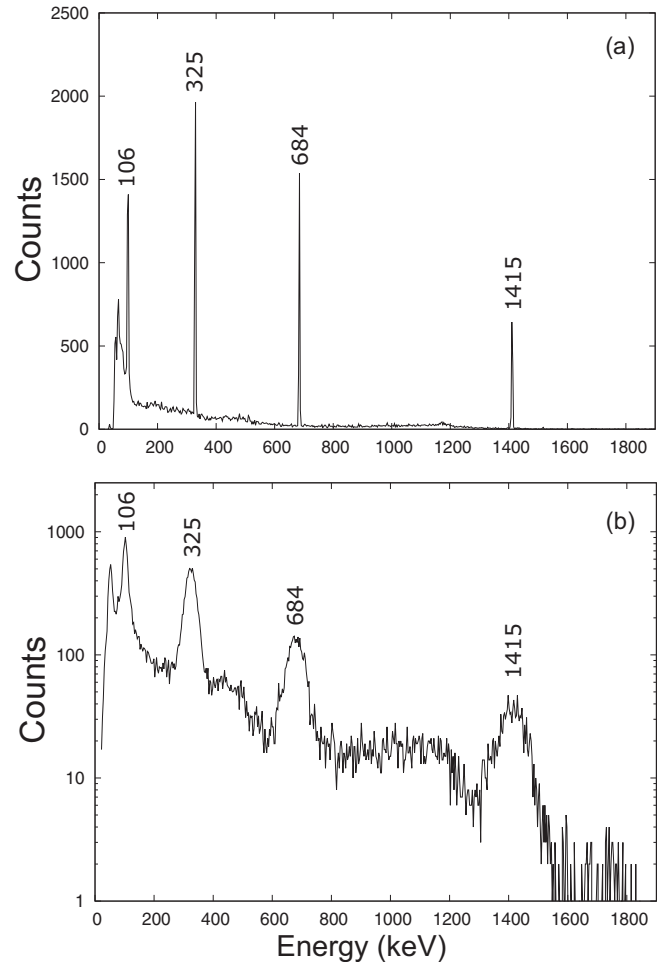

FIG. 1. Total projections of the energy spectra in the Ge (a) and BaF$_2$ (b) detectors and partial decay scheme of ^{96}Pd (c).

window after an implantation of a fragment of interest. In the off-line analysis data for a given nucleus were selected in the form of a matrix representing time-delayed $\gamma\gamma(t)$ coincidences between individual BaF_2 detectors, from which energy and time spectra under various start-stop conditions could be projected. A similar $\gamma\gamma$ matrix between Ge detector and BaF_2

detectors was also constructed to verify the subsequent gating conditions.

In Fig. 1 the background-corrected projected energy spectra for ^{96}Pd registered with the Ge and BaF_2 detectors are shown along with a partial decay scheme. The spectra are pure and show only γ-ray lines from the decay of the 2.2 μs [35] isomer
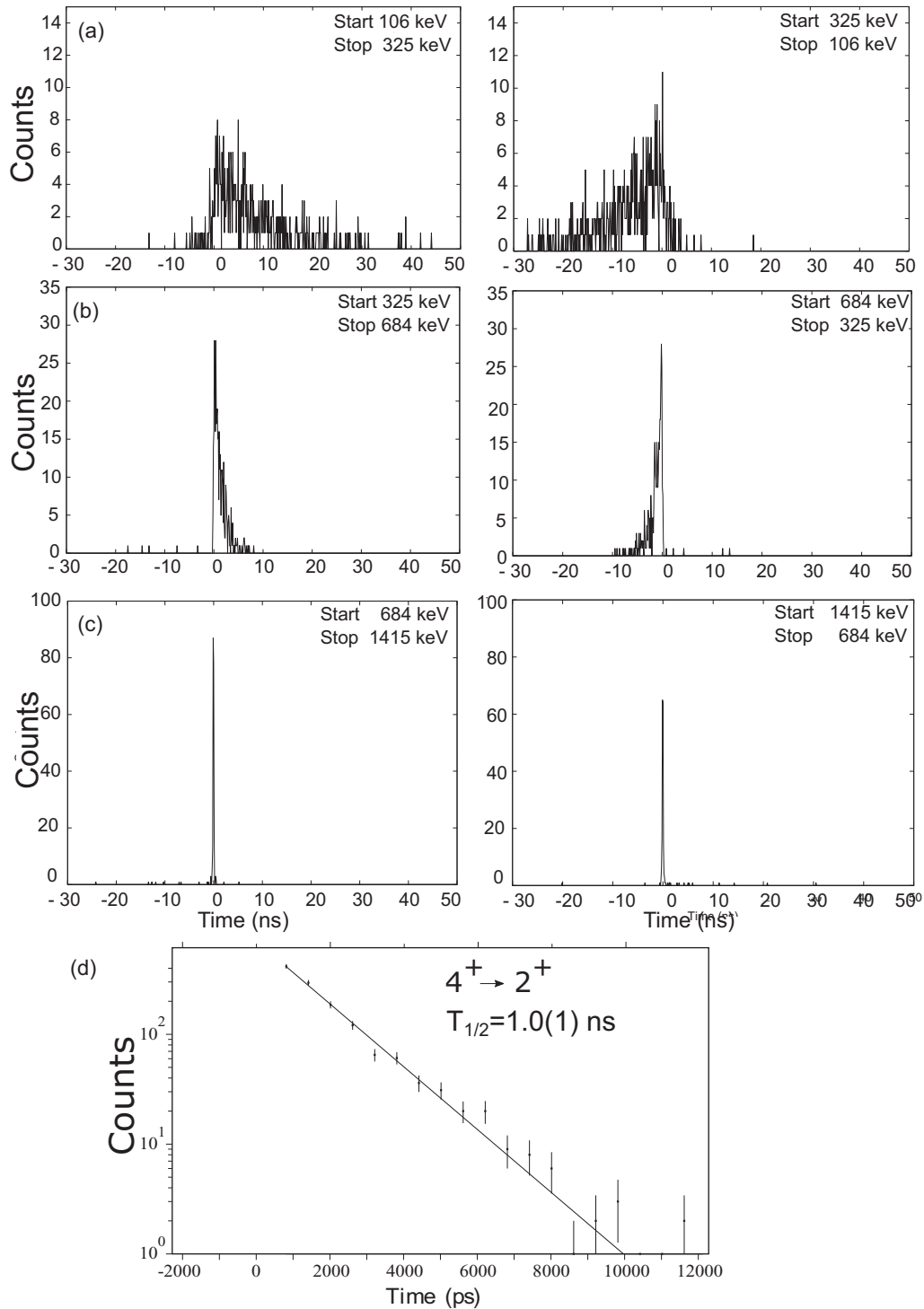

FIG. 2. Background-subtracted time-delayed $\gamma\gamma(t)$ spectra for ^{96}Pd with various start-stop conditions for the 6^+ (a), 4^+ (b), and 2^+ (c) levels and exponential fit of the sum of time spectra to the $4^+ \rightarrow 2^+$ decay (d). The second spectrum (on the right-hand side) in (c) was flipped around time = 0 before summing.

TABLE I. Experimental half-lives and $B(E2)$ strengths in comparison to various shell model predictions.

Nucleus	$I_i^\pi \rightarrow I_f^\pi$	$T_{1/2}$ [ns]	Ref.	$B_{EX}(E2)$ [e^2fm^4]	$B_{SMCC}(E2)$ [e^2fm^4]	$B_{SMLB}(E2)$ [e^2fm^4]	$B_{SDGN}(E2)$ [e^2fm^4]
^{94}Ru	$2^+ \rightarrow 0^+$	$\leqslant 0.01$		$\geqslant 9.5$	184	225	295
	$4^+ \rightarrow 2^+$	$\leqslant 0.05$		$\geqslant 46$	2.6	6.8	85.2
	$6^+ \rightarrow 4^+$	65(2)	[36]	2.89(10)	1.7	6.1	17.3
	$8^+ \rightarrow 6^+$	71000(4000)	[36]	0.090(5)	0.68	2.0	0.77
^{95}Rh	$21/2^+ \rightarrow 17/2_1^+$	2.1(3)	[27]	29(4)	1.3	0.00143	25.7
	$21/2^+ \rightarrow 17/2_2^+$			136(20)	120	221	212.8
^{96}Pd	$2^+ \rightarrow 0^+$	$\leqslant 0.017$		$\geqslant 6$	157	209	300
	$4^+ \rightarrow 2^+$	1.0(1)		3.8(4)	20	30	1.4
	$6^+ \rightarrow 4^+$	6.3(6)		24(2)	14	14.8	24.5
	$8^+ \rightarrow 6^+$	2200(300)	[35]	8.9(13)	5.4	5.25	12.3
^{98}Cd	$2^+ \rightarrow 0^+$				97	134	205
	$4^+ \rightarrow 2^+$				112	158	217
	$6^+ \rightarrow 4^+$	$\leqslant 20$	[29]	$\geqslant 80$	79	110	145
	$8^+ \rightarrow 6^+$	170(60)	[29]	35(10)	32	44	57.5

in ^{96}Pd. The excellent energy resolution of this BaF$_2$ array warrants clean gating conditions to create time-delayed $\gamma\gamma(t)$ spectra. These are shown in Fig. 2 with various start-stop conditions to select time distributions for the $I^\pi = 6^+$, 4^+, and 2^+ states, respectively. The 6^+ (a) and 4^+ (b) time spectra show clearly defined slopes, that can be fitted with single exponential fits as shown in panel (d). For the 2^+ state only a half-life limit can be extracted. The results are shown in Table I and Fig. 4. In Fig. 3 time distributions for the $I^\pi = 4^+$ and 2^+ states in ^{94}Ru are shown together with a partial decay scheme. Time spectra are shown for normal (START: feeding γ—STOP: deexciting γ) and reversed START-STOP. Half-life limits were extracted from the centroid shifts, see Table I.

III. RESULTS AND DISCUSSION

From the measured half-life values and limits, $B(E2)$ values were inferred and are summarised in Table I and Fig. 4 along with known values for the long-lived isomers, the 8^+ level in ^{96}Pd [35] and the 8^+ and 6^+ states in ^{94}Ru [36]. For comparison to shell model results and further discussion the $B(E2)$ values for the $21/2^+ \rightarrow 17/2_1^+$ and $21/2^+ \rightarrow 17/2_2^+$ transitions in the midshell ^{95}Rh [27] and for the $8^+ \rightarrow 6_1^+$ and $6^+ \rightarrow 4^+$ transitions in the two-proton hole nucleus ^{98}Cd [29] have been included in Table I.

A. Shell model calculations

Several shell model calculations have been performed for the $N = 50$ isotones with empirically fitted interactions in the proton $\pi(p_{1/2}, g_{9/2})$ [2,3,37] and $\pi(f_{5/2}, p, g_{9/2})$ [26,38] model spaces. For the latter model space a G-matrix based realistic effective interaction was also derived [26] from the Bonn-A nucleon-nucleon (NN) potential. All these approaches give a very good description of nuclei in the well studied $Z \geqslant 38$ region and account well for the seniority scheme in the nuclei dominated by the $\pi g_{9/2}^n$ configuration. For comparison

with experiment we have chosen three representative model approaches. The first model represents a development of the calculation of Ref. [6] in that the effective interaction is derived from the high-quality CD-Bonn NN potential and a new approach to the renormalization of the short-range repulsion is used. In this approach, which has proved to be an advantageous alternative to the usual G-matrix method, a smooth potential, $V_{\text{low-}k}$, is constructed by integrating out the high-momentum components of the original NN potential. Once the $V_{\text{low-}k}$ is obtained, the two-body matrix elements (TBME) are calculated including core polarization corrections appropriate for the $\pi(f_{5/2}, p, g_{9/2})$ hole space in ^{100}Sn. A description of this calculation can be found in [39] and references therein. As discussed in [6], single-hole energies were fitted to the most sensitive experimental levels in the upper proton shell $N = 50$ isotones. For the effective $E2$ proton charge $e_\pi = 1.35e$ was assumed. It turns out that the resulting $E2$ transition rates do not differ significantly from those obtained when using, orbitals dependent effective single-particle operators, consistently with the derivation of the two-body effective interaction. This model is marked as SMCC.

The second approach marked as SMLB [26] is based on an empirically fitted interaction in the $\pi(f_{5/2}, p, g_{9/2})$ space, which includes the single particle energies as fit parameters. $E2$ matrix elements were calculated with a general best-fit effective charge $e_\pi = 1.72e$ [40].

Finally a large-scale shell model (LSSM) calculation was performed in the $(0g, 1d, 2s)$ proton-neutron model space employing a G-matrix based interaction with tuned monopoles to reproduce the experimentally extrapolated single particle/hole energies in ^{100}Sn [23,29]. Polarisation charges of $\delta e_\pi = \delta e_\nu = 0.5e$ were used for both protons and neutrons to calculate $E2$ properties in this model marked here by SDGN [41]. It should be noted that the relative proton-hole energies for $p_{1/2}$ and $g_{9/2}$, which are dominating the configurations for $Z \geqslant 44$, agree within 100 keV in the SMCC and SMLB approaches. The $p_{3/2}$ energy in SMCC and SMLB agree within 200 keV,
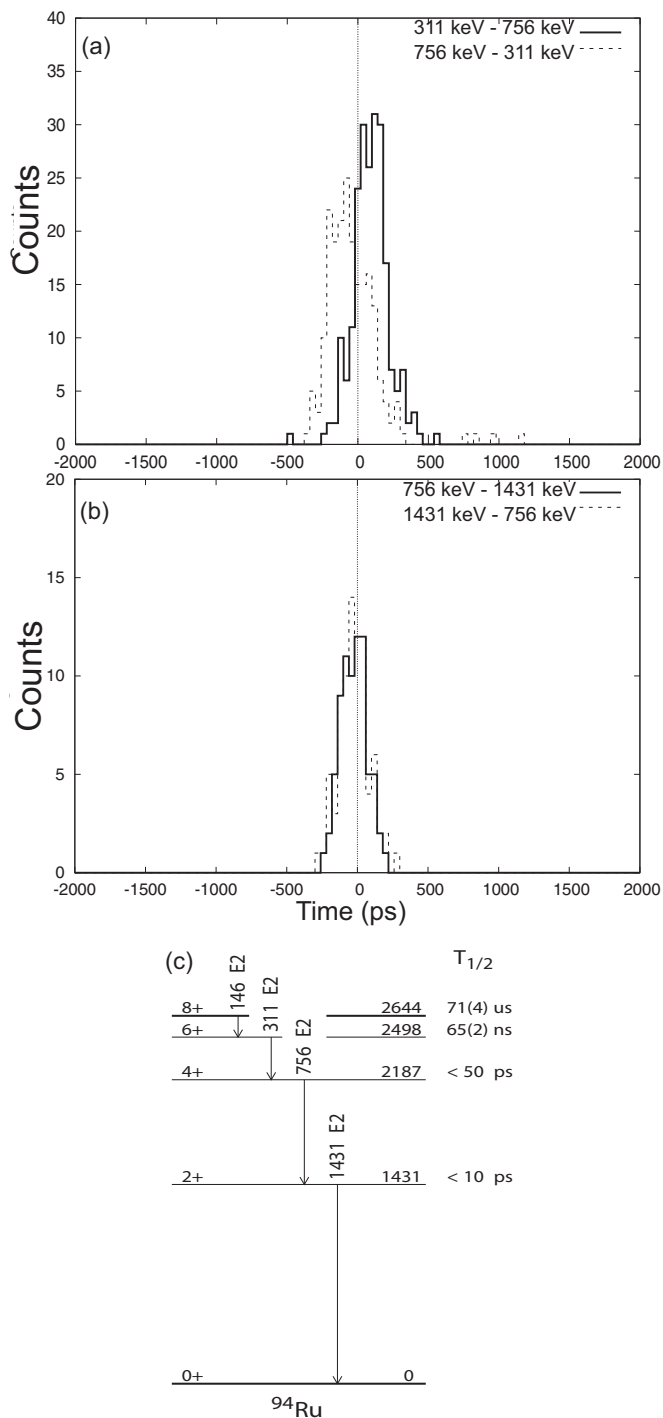
FIG. 3. Background-subtracted time spectra and centroid shift for the 4^+ (a) and 2^+ (b) levels in ^{94}Ru with various start-stop conditions and partial decay scheme (c). In order to select a particular γ-cascade decay, an additional coincidence in the HPGe detectors with the appropriate γ transition was required. A visible shift in the centroids of the time spectra (a) from the prompt position (marked by a dotted line), is due to the mean life of the $I^\pi = 4^+$ state in ^{94}Ru.

while the $f_{5/2}$ energies are deviating largely. This, however, has no bearing on the present results, and even for the lighter

$N = 50$ isotones the difference may be compensated by a different monopole part of the TBME between $f_{5/2}$ protons and the remaining orbitals.

B. Seniority scheme and core excitations

All model approaches account very well for the $8^+ \rightarrow 6_1^+$ and $6^+ \rightarrow 4^+$ transitions in the $N = 50$ isotones. These follow the expected trend for $\Delta v = 0$ transitions in the seniority scheme (Table I and Fig. 4). The deviations in the highly retarded midshell transitions can be ascribed to distortions from outside the model space.

The overestimation of the $B(E2; 6^+ \rightarrow 4^+)$ for ^{94}Ru in the SDGN model maybe explained by the fading dominance of the $g_{9/2}$ orbital relative to the remaining $(0f_{5/2}, 1p)$ orbitals with increasing distance from $Z = 50$ due to pair scattering and premature filling of $g_{9/2}$, which should affect low-spin states more strongly. Large discrepancies in different directions occur for the $4^+ \rightarrow 2^+$ transitions in ^{94}Ru and ^{96}Pd in the models SMCC and SMLB. It should be noted that any other of the pure-proton space models [2,3,37,38] fails as well in this respect, as they cannot provide the amount of seniority mixing required to reproduce the experimental data. On the other hand the SDGN model, which includes up to $4p4h$ excitations, reproduces the data perfectly (Table I). The different sign of the deviations in ^{94}Ru and ^{96}Pd can be easily understood. In the four-hole nucleus ^{96}Pd core excitations cause a destructive interference with the dominating $\pi g_{9/2}^{-4}$ transition matrix element, whereas in ^{94}Ru with a leading $\pi g_{9/2}^4$ configuration this matrix element changes sign due to ph conjugation reversing the interference to be constructive. For the midshell nucleus ^{95}Rh it was discussed in great detail that the puzzling $\Delta v = 0$, $21/2^+, v = 3 \rightarrow 17/2^+, v = 3$ and the $\Delta v = 2$, $21/2^+, v = 3 \rightarrow 17/2^+, v = 5$ $E2$ strengths cannot be explained by seniority mixing at all in a pure proton space [19]. Again the SDGN model provides almost perfect agreement (Table I). In conclusion neutron ph excitations across the $N = 50$ shell are responsible for the seniority mixing and the ensuing breakdown of the seniority scheme in the midshell $N = 50$ isotones. The decisive prerequisite for the mixing is the existence of close lying $v = 2,4$ $I^\pi = 4^+$ and $v = 3,5$ $I^\pi = 17/2^+$ valence configurations in ^{94}Ru, ^{96}Pd, and ^{95}Rh, respectively.

IV. SUMMARY AND CONCLUSION

In summary we have measured lifetimes in the ps–ns range by the ultrafast $\gamma\gamma(t)$ timing technique in the proton-rich $N = 50$ isotones populated in fragmentation reaction. This method enables lifetime measurements for low-lying states in the presence of long-lived feeding by high-spin isomers. For the first time, it was shown that in the $E2$ strengths of nonaligned spin states in midshell $N = 50$ isotones the seniority breaks down as a good quantum number due to cross shell ph excitations.
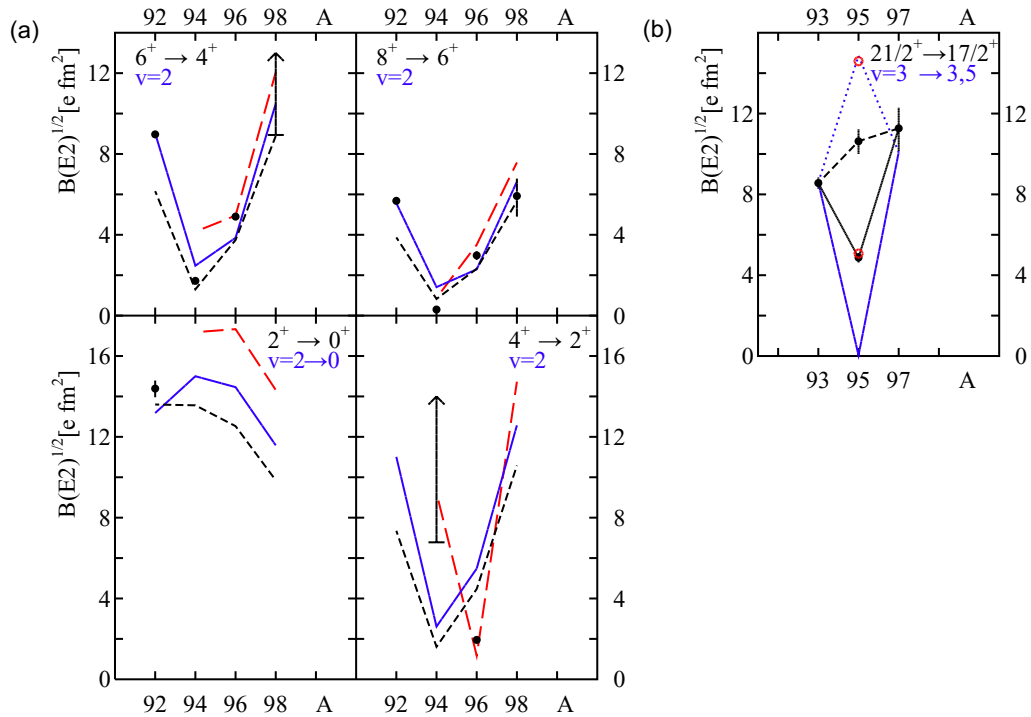
FIG. 4. Experimental $E2$ strengths $B^{1/2}(E2)$ for yrast transitions in even $N = 50$ isotones in comparison to shell model predictions in the proton $(f_{5/2}, p, g_{9/2})$ model space for the approaches SMLB (full line) and SMCC (short dashed). The calculation including excitations of the ^{100}Sn core is shown as long dashed line. Experimental values, error bars, and limits are shown in black dots and lines (a). For odd-A nuclei experimental values for transitions to the $v = 3$ and $v = 5$ $I^{\pi} = 17/2^+$ daughter states are connected by full and short dashed black lines and SMLB results by full and dotted blue lines (b). SDGN results are indicated by open red circles. Data are from present work and [36].

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