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Investigation of the decay out of superdeformed bands in ^{194}Hg by lifetime measurements

A. Dewald, R. Kühn, R. Peusquens, and P. von Brentano
Institut für Kernphysik, Universität Köln, Köln, Germany

R. Krücken,* M. A. Deleplanque, I. Y. Lee, R. M. Clark, P. Fallon, A. O. Macchiavelli, R. W. MacLeod, and F. S. Stephens
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 094720

T. L. Khoo and P. Reiter
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

K. Hauschild
Lawrence Livermore National Laboratory, Livermore, California 94550

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The lifetimes of low-lying states in the superdeformed (SD) bands of ^{194}Hg were measured by means of the recoil distance method using Gammasphere and the Cologne plunger device. The deduced transitional quadrupole moments in all three bands were found to be constant within the experimental uncertainties and equal those extracted from Doppler-shift attenuation method measurements for the higher-lying states, confirming that the decay out does not strongly affect the structure of the SD bands. The experimental findings are used to discuss the different mechanisms proposed for the decay out of SD bands.

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In recent years much experimental and theoretical work has been devoted to the interesting topic of the sudden decay out of superdeformed (SD) bands. Various theoretical concepts have been employed [1–9] to describe the mechanism involved. Besides ^{194}Pb and ^{152}Dy, the nucleus ^{194}Hg is the ideal candidate for the further investigation of the decay mechanism leading to an abrupt decay out of SD bands at low spins because only in these nuclei have direct linking transitions been observed so far [10–12,14–16]. Thus for these three nuclei the absolute excitation energies, spins, and for some cases also the parities are known. In addition to these experimental data knowledge of the absolute transition probabilities for intraband transitions as well as for transitions depopulating the SD bands are important experimental observables for testing the different mechanisms proposed.

In this article, we report on a measurement of the lifetimes of low-lying states in the SD bands in ^{194}Hg using the recoil distance method (RDM). We have successfully determined the lifetimes of the three lowest-lying states in bands SD1, SD2, and SD3, respectively. Using intraband intensities for the yrast SD band from an experiment with high statistics [17], transition quadrupole moments Q_t were deduced directly from these lifetimes. Comparison of these Q_t values with those extracted from measurements [18,19] using the Doppler-shift attenuation method (DSAM) for transitions in the upper part of the bands shows that the deformation remains constant down to the bottom of the band and is not appreciably disturbed by the decay-out process.

Superdeformed states of ^{194}Hg were populated using the reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg at a beam energy of 210 MeV. The beam was supplied by the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. The plunger target consisted of an approximately 1 mg/cm^2 ^{150}Nd layer evaporated onto a 1.47-mg/cm^2-thick tantalum foil. The recoiling nuclei had a mean velocity of 1.86(1)% c and were stopped in a 11 mg/cm^2 gold foil. Target and stopper were mounted in the Cologne plunger apparatus surrounded by 97 large-volume Compton-suppressed Ge detectors of the Gammasphere array [20]. Coincidence events with at least four Compton-suppressed gamma rays were recorded onto magnetic tape. In total, 72.8×10^9 unfolded triple events were recorded at nine target-to-stopper distances ranging from 8 to 103 μm separation of the foils.

The lifetimes of the low-lying states within the SD bands were determined using the differential decay curve method (DDCM) [21,22]. The germanium detectors at Gammasphere can be grouped into 17 rings whereby the detectors belonging to one ring have the same polar angle. Double-gated spectra with gates set on the shifted components of higher-lying SD transitions were produced for each distance and each detector ring. For the lifetime determination we could only analyze the ring spectra taken at the polar angles 17°, 35° (combination of detectors positioned at 32° and 37°), 50°, 58°, 122°, 130°, 146° (combination of detectors positioned at 143° and 148°), and 163° as the diminishing Doppler shift, proportional to cos(θ), made it impossible to distinguish between shifted and unshifted peaks for the remaining rings, which were only used to set gates. Spectra taken at forward and backward angles were modified in such a way that the Doppler-shifted peaks came to the same position as those in the spectra taken at 17° and 163°, respectively, while the position of the unshifted peaks remained fixed. This can be achieved by splitting the spectra and inserting the appropriate space between unshifted peak and Doppler-shifted peak to adjust for the polar angle. Thus we were able to add up all analyzed ring spectra for each dis-

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*Also at A.W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520.

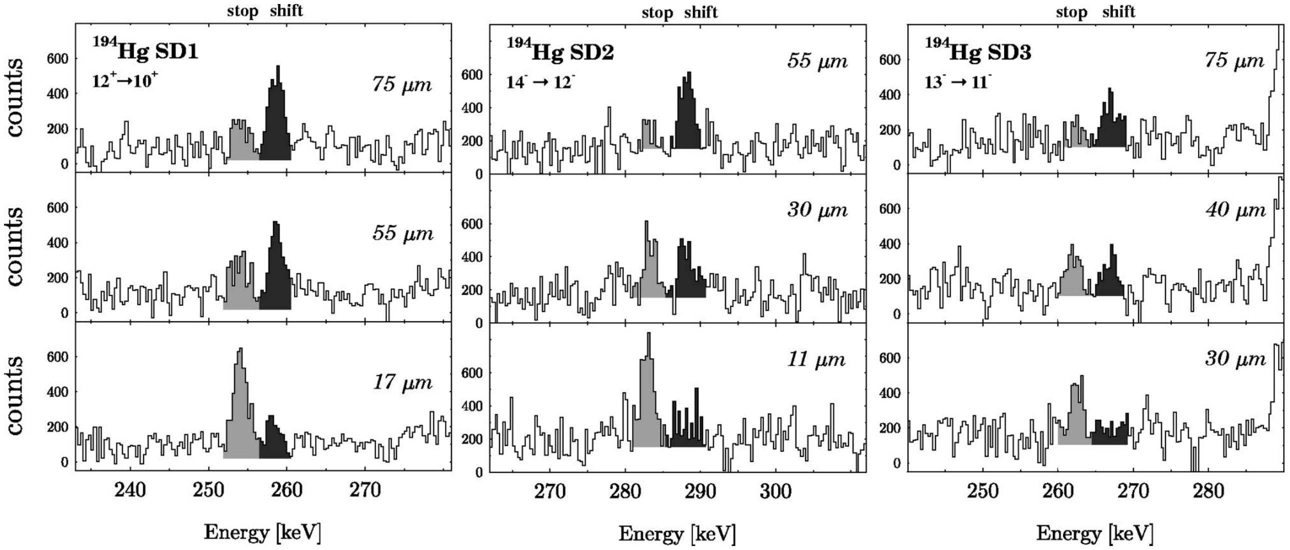

FIG. 1. Doppler-shifted and unshifted peaks of three transitions within all three SD bands in ^{194}Hg. The spectra result from double-gated spectra taken at eight different polar angles. The spectra have been modified in such way that the Doppler-shifted peaks came to the same position as those in the spectra taken at 17°, while the position of the unshifted peaks remained fixed.

tance into one single forward and one backward spectrum, respectively, which was then used to determine the shifted and unshifted intensities of the transitions of interest. So it was possible to deduce lifetimes independently from the forward and backward spectra for the transitions within the yrast SD band. For the determination of lifetimes within the excited bands, SD2 and SD3, the resulting backward spectra were reflected at the unshifted energy of the transition of interest and added to the corresponding forward spectra in order to collect the maximum statistics possible in one spectrum. Examples of the spectra are given in Fig. 1.

To determine the derivative of the intensities of the shifted components as a function of the target-to-stopper distance, a step which is necessary when applying the DDCM, these data were fitted by a series of smoothly combined second order polynomials over separate intervals.

In Table I we give our results for the lifetimes for the lowest three states in each SD band together with the corresponding transition probabilities $B(E2)$ and Q_t values for the intraband transitions. In our calculations we adopted the experimental spin assignments for bands SD1 and SD3 from Refs. [12,19] as well as the intraband intensities from Ref. [17] and considered internal conversion. The corresponding transition quadrupole moments of the yrast and the excited SD bands of ^{194}Hg are presented in Fig. 2. For means of comparison we also plotted results from previous RDM [23] and DSAM [18,19] experiments. The transition quadrupole moments from this work almost equal those deduced for higher-lying states from DSAM data [18,19]. This corroborates that the SD configurations dominate the structure of the bands down to the region of their decay out. Previous experiments have shown that this is also true for ^{192}Hg [24–27] and ^{194}Pb [28–30]. The transition quadrupole moments obtained in RDM experiments at Gammasphere (this work) and Gasp [23] for the yrast band SD1 in ^{194}Hg yield $Q_0=16.8(7)$ e b on average.

For the two excited bands SD2 and SD3 we find average quadrupole moments of $Q_0=19.0(20)$ e b and $Q_0=18.8(25)$

TABLE I. Level lifetimes τ, reduced transition probabilities $B(E2)$, and transition quadrupole moments Q_t for intraband transitions of low-lying states in the three SD bands in ^{194}Hg.

Band	E_x (keV)	I^π ($\hbar$)	E_γ (keV)	τ (ps)	$B(E2)$ (10^3 W.u.)	Q_t (e b)
SD1	6883.1	12^+	253.9	3.47(63)	$1.7\ (^{+0.5}_{-0.3})$	$18.1\ (^{+2.5}_{-1.9})$
	7179.1	14^+	296.0	2.98(55)	$1.6\ (^{+0.4}_{-0.3})$	$17.6\ (^{+2.0}_{-1.5})$
	7516.3	16^+	337.2	1.96(25)	$1.3\ (^{+0.2}_{-0.2})$	$15.9\ (^{+1.2}_{-1.0})$
SD2	$443.8+E_{8^-}$	12^-	242.3	4.3(12)	$2.1\ (^{+1.0}_{-0.6})$	$20.8\ (^{+4.5}_{-3.0})$
	$726.9+E_{8^-}$	14^-	283.1	3.94(93)	$1.5\ (^{+0.5}_{-0.3})$	$17.4\ (^{+2.6}_{-1.8})$
	$1050.4+E_{8^-}$	16^-	323.5	1.91(77)	$1.7\ (^{+1.2}_{-0.5})$	$18.1(^{+5.4}_{-2.9})$
SD3	7715	13^-	262.3	3.0(10)	$2.4\ (^{+1.5}_{-0.7})$	$22.0\ (^{+5.9}_{-3.5})$
	8018	15^-	302.7	3.01(84)	$1.4\ (^{+0.8}_{-0.4})$	$16.9\ (^{+3.9}_{-2.5})$
	8360	17^-	342.5	2.00(66)	$1.1\ (^{+0.7}_{-0.4})$	$14.8\ (^{+4.0}_{-2.4})$

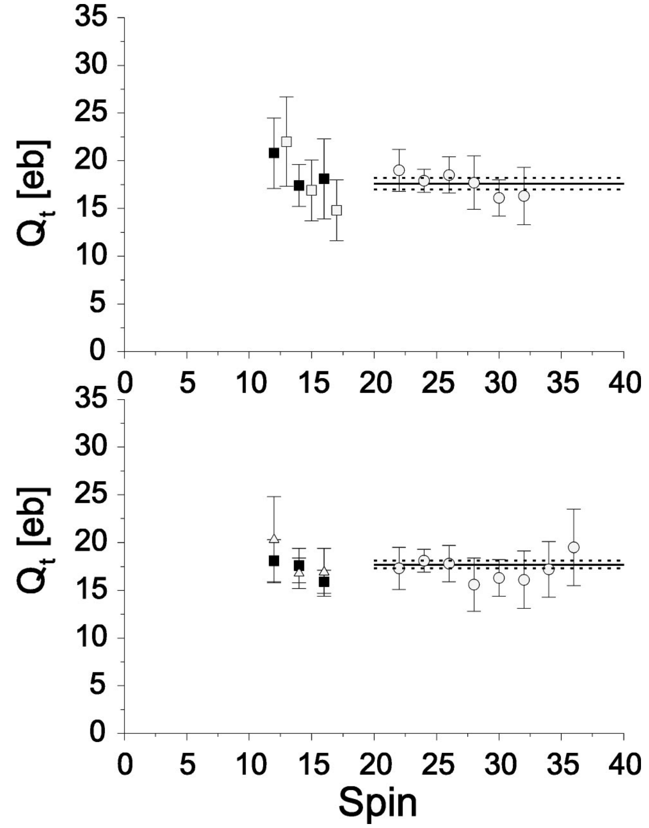

FIG. 2. Transition quadrupole moments the SD bands in ^{194}Hg. Top: Q_t values from this RDM experiment for the excited bands SD2 (solid squares) and SD3 (open squares) in comparison with values from a DSAM line shape analysis for band SD2 [18] and the average quadrupole moment determined by Moore *et al.* [19] (solid line for average, dotted lines for uncertainties). Bottom: Q_t values for bands SD1 from this RDM experiment (solid squares) and Kühn *et al.* [23] (open triangles) in comparison with values from a DSAM line shape analysis [18] and the average quadrupole moment determined by Moore *et al.* [19] (solid line for average, dotted lines for uncertainties).

e b, respectively. The equality of these values with the one found for SD1 within their experimental errors reveals the stability of the SD potential minimum for ^{194}Hg since the band SD3 is about 800 keV higher in excitation energy. For the band SD2 no link to other states has been observed so far. It was suggested by Riley *et al.* [31] that SD2 and SD3 are signature partners of a neutron two-quasiparticle (2qp) configuration. After the observation of links for SD3 to ND states as well as connecting $E1$ transitions between SD3 and SD1, Hackman *et al.* [13] assigned negative parity to band SD3. It was further suggested that this band might be a octupole vibrational band since a 2qp configuration was expected to lie higher in excitation energy and also the estimated $B(E1)$ transition probabilities would support the octupole vibrational assignment.

From the present work it is now possible to determine the $B(E1)$ value of the transition depopulating the 13^- state of SD3. The measured lifetime of 2.4 ps, together with the branching ratio from Ref. [13], yields an $E1$ strength of $8(3)\times 10^{-5}$ Weisskopf units (W.u.) This is significantly weaker than the $B(E1)$ strength found in the case ^{190}Hg where $B(E1)$ values of the order of 10^{-3} W.u. were found [33–35]. Values of this size have been found in octupole bands, e.g., ^{176}Hf [46], as well as for transitions between 2qp states and the ground state [32]. Thus the lifetime does not provide conclusive evidence as to the nature of the band SD3.

In the following we will discuss the mechanism for the decay out of the SD bands in ^{194}Hg on the basis of our results. Recently several works have been devoted to the interesting problem of the abrupt transition from superdeformed to normal deformed states which was observed in many SD bands in different mass regions [5–9]. From the experimental point of view observables such as excitation energy, spin, lifetimes, and branching ratios of SD states are of special importance. These quantities are suited to test the different theoretical approaches which have been proposed to describe the decay out of SD bands. Since ^{194}Hg is one of the rare cases where two SD bands could be connected to the normal deformed level scheme, this nucleus is of special interest to get deeper insight into this interesting phenomenon.

It is of course an open question if the mechanism underlying the transition from SD to ND states is the same in all mass regions where SD bands have been observed. In ^{194}Hg it is evident that the nucleus has to undergo a major change in deformation, e.g., from $\beta\approx 0.6$ to $\beta\approx 0.2$, like in the mass-150 region. This is different in the mass-130 region where the so-called highly deformed bands (HD's) ($\beta\approx 0.4$) decay to states with $\beta\approx 0.26$ and where the decay is very well described by level mixing [36–38].

An approach to describe the decay out of SD bands based on level mixing between ND and SD states was proposed by Vigezzi *et al.* [2] and has been frequently applied in the $A=150$ and $A=190$ mass regions [9,23–25,39–42]. The total probability N_{out} that a SD state decays to a ND state is given by

$$N_{out}(I)=\sum_m |c_m|^2\frac{(1-|c_m|^2)\Gamma_N}{(1-|c_m|^2)\Gamma_N+|c_m|^2\Gamma_S}, \tag{1}$$

where Γ_N and Γ_S are the decay width in the ND and SD potential minima, respectively. c_m are the mixing amplitudes of a SD state with a set of ND states assumed to form a Gaussian orthogonal ensemble (GOE). These amplitudes are assumed to depend on the ratio $|v|/D_N$ where v is the coupling matrix element and D_N is the average level spacing of the ND states. v is related to the tunneling width $\Gamma^{\downarrow}$ representing the penetration through the potential barrier separating the SD and ND potential minima using Fermi's "golden rule":

$$\Gamma^{\downarrow}=\frac{2\pi v^2}{D}. \tag{2}$$

Recently, Gu and Weidenmüller [7] elaborated a more general expression for N_{out} based on a statistical model de-

TABLE II. Quantities relevant for the decay out of the SD bands in ^{194}Hg. Given are the branching of the decay out N_{out}, the estimated average level spacing D_N and the electromagnetic width Γ_N of the ND states, and the electromagnetic width Γ_S of the pure SD states as well as the squared admixture c^2 of ND components into the observed SD states. Values for the tunneling width $\Gamma^\downarrow$ calculated in the framework of Gu and Weindemüller ($\Gamma_W^\downarrow$) [7] using Eqs. (3)–(6) and Vigezzi ($\Gamma_V^\downarrow$) [2] using the approximation (8). An upper limit $\Gamma_{\max}^\downarrow$ for the tunneling width extracted from Eq. (14) is also given.

Band	I ($\hbar$)	N_{out}	D_N (eV)	Γ_N (meV)	Γ_S (meV)	$1-c^2$ (%)	$\Gamma_W^\downarrow$ (meV)	$\Gamma_V^\downarrow$ (meV)	$\Gamma_{\max}^\downarrow$ (meV)
SD1	12	0.40	16.3	4.8	0.100	1.3	22	53	332
	10	>0.92	26.2	4.1	0.039	9.9	>1700	>210	4074
SD3	15	0.10	26.5	4.0	0.230	0.7	6	18.5	336
	13	0.16	19.9	4.5	0.110	0.6	11	30.3	354
	11	>0.93	7.2	6.4	0.048	7.6	>400	>21.5	478
SD2	12	0.25	30[a]	4[a]	0.080	0.7		37.5	311
	10	0.50	30[a]	4[a]	0.036	1.0		67.5	449

[a] Arbitrary, since the excitation energy is not known.

scribing the ND states. In this approach the mean SD intraband intensity $\overline{I_{in}}$ is determined as the sum of two components,

$$\overline{I_{in}} = \overline{I_{in}^{av}} + \overline{I_{in}^{fl}}, \tag{3}$$

and is related to N_{out} by

$$N_{out} = (1-\overline{I_{in}}). \tag{4}$$

$\overline{I_{in}^{av}}$ is obtained directly from the quantities $\Gamma^\downarrow$ and Γ_S from

$$\overline{I_{in}^{av}} = \frac{1}{1+\dfrac{\Gamma^\downarrow}{\Gamma_S}}. \tag{5}$$

The second term, the fluctuation contribution $\overline{I_{in}^{fl}}$, has to be calculated numerically. In Refs. [7,43] it was shown that this term cannot be neglected as was done in an earlier publication [5] and that it can be approximated by the expression

$$\overline{I_{in}^{fl}} = \left[1-0.9139\left(\frac{\Gamma_N}{D}\right)^{0.2172}\right] \times \exp\left\{-\frac{\left[0.4343\ln\left(\dfrac{\Gamma^\downarrow}{\Gamma_S}\right)-0.45\left(\dfrac{\Gamma_N}{D}\right)^{-0.1303}\right]^2}{\left(\dfrac{\Gamma_N}{D}\right)^{-0.1477}}\right\}. \tag{6}$$

It was also shown that $\overline{N_{out}}$ calculated by Vigezzi *et al.* agrees well with $\overline{N_{out}}$ obtained in Ref. [7] for cases where the following two conditions are fulfilled:

$$\Gamma_N/D_N \ll 1 \quad \text{and} \quad \Gamma_N/D_N \leq \Gamma^\downarrow/\Gamma_S. \tag{7}$$

These conditions hold very well for all known cases in the mass-190 region. Therefore, it is justified to apply the method proposed by Vigezzi *et al.* [2] where a further approximation is used, namely, a representation of the ND states by an equidistant level spectrum with a fixed level spacing of D_N rather than the GOE. For cases where $\Gamma^\downarrow/D_N \ll 1$ and

$$\Gamma^\downarrow/D_N \ll 2\pi\frac{\Gamma_S}{\Gamma_N}\frac{1}{\left(1+\dfrac{\Gamma_S}{\Gamma_N}\right)^2},$$

a simple relation between $\overline{N_{out}}$ and $\Gamma^\downarrow$ holds:

$$\overline{N_{out}} \approx \sqrt{\frac{\Gamma^\downarrow}{\Gamma_S}\frac{\Gamma_N}{D_N}}. \tag{8}$$

From this relation as well as from Eq. (3) the tunneling width $\Gamma^\downarrow$ can be calculated using the quantities $\overline{N_{out}}$, Γ_S, Γ_N, and D_N. $\Gamma^\downarrow$ values determined with both approaches discussed above are given in Table II. The quantities $\overline{N_{out}}$, Γ_S, Γ_N, and D_N are also given in Table II.

In order to determine Γ_N, only statistical $E1$ transitions were considered for the decay between the ND states, since they are expected to dominate this decay due to the high excitation energy of SD states above yrast (≈4 MeV). This assumption $\Gamma_N \approx \Gamma_N^{E1}$ is supported by the fact that at spin $12\hbar$ the statistical $E1$ transition probability is three orders of magnitude larger than the collective $E2$ decay probability [41] and one order of magnitude larger than the statistical $M1$ transition probability [44]. Notice that no $M1$ or $E2$ transitions have yet been identified considering the discrete γ transitions between SD and ND states in ^{194}Hg. The situation is different in the neighboring ^{194}Pb, where mixed $E2/M1$ radiation originating from SD states has been detected and where the excitation energies of the SD states are more than 1 MeV lower than in ^{194}Hg. Furthermore, Krücken and Lee discussed and refuted the decay via electric monopole transition applying the mixing model [42]. The $E1$ decay probability was calculated as in Ref. [9] applying a statistical model following the parametrization in Ref. [45].

In the following part of the discussion we want to determine the normal deformed admixture of the SD states from which a maximum tunneling width $\Gamma^{\downarrow}_{max}$ can be extracted. In the weak coupling limit when the conditions (7) are fulfilled only the closest ND level has to be considered to mix with a SD state. Such a situation was found, e.g., in the cases of ^{133}Nd as mentioned above and ^{194}Pb [30]. Also in ^{194}Hg these conditions hold as can be seen in Table II. Therefore, we will apply in the following discussion the two-level mixing model in order to extract the normal deformed admixture of the SD states.

In Eq. (1) the summation over m reduces now to only one term

$$N_{out}=\frac{(1-c^2)\Gamma_N}{(1-c^2)\Gamma_N+c^2\Gamma_S}, \tag{9}$$

where N_{out} is calculated from the outgoing intensity I_{out} and intraband intensity I_{in}, taken from Ref. [17]:

$$N_{out}=\frac{I_{out}}{I_{out}+I_{in}}. \tag{10}$$

The normal deformed admixture $1-c^2$ of a SD state can be determined using the level lifetime τ which is related to Γ_N and Γ_S as

$$\hbar\frac{1}{\tau}=(1-c^2)\Gamma_N+c^2\Gamma_S. \tag{11}$$

Combining Eqs. (9) and (11) one obtains the following relation for the squared mixing amplitudes $1-c^2$ for the ND admixture using, which are given in Table II:

$$c^2=1-\frac{N_{out}}{\Gamma_N}\frac{\hbar}{\tau}. \tag{12}$$

For the lowest spin values no lifetimes have yet been measured. In order to extract a squared mixing amplitude c^2 for these states, using Eqs. (11) and (12), we assume a constant transition quadrupole moment in the lower parts of the bands. We take the average of the existing Q_t values provided by RDM experiments, thus excluding uncertainties of stopping powers which may affect the lifetimes determined by the DSAM technique. Γ_S can be determined directly from the average transition quadrupole moment Q_t according to

$$\Gamma_S=1.22\hbar\frac{5\pi}{16}E_{\gamma}^5\mathrm{CL}^2Q_t, \tag{13}$$

where CL is the appropriate Clebsch Gordon coefficient.

The such-determined ND admixtures $1-c^2$ are relatively small and only for levels where the decay out exceeds 90% the admixtures go up to 10%. This indicates rather pure SD states until the lowest observed member of each SD band. We would like to note that the $1-c^2$ values increase steadily for successive levels with decreasing spin. Comparing the three different SD bands in ^{194}Hg we observe a very similar decay pattern despite their very different excitation energies: The onset of the decay out appears at the same spin range of $(8-12)\hbar$. The mean tunneling width $\Gamma^{\downarrow}$, determined from Eq. (1) and the maximum tunneling width [41,42]

$$\Gamma^{\downarrow}_{max}=(\pi D_N c^2)/2, \tag{14}$$

as well as the squared mixing amplitudes $1-c^2$ show a similar and monotonous behavior.

It appears to be very unlikely to obtain such regular decay patterns if accidental level mixing with a constant, spin-independent interaction v is governing the decay-out mechanism alone. The decay out by purely accidental level mixing cannot explain this behavior unless, due to the very small values of $\Gamma^{\downarrow}$, each SD state with decay to ND states would have to fall close enough to the nearest ND state with an accuracy of about $D_N/100$. At the same time this accidental degeneracy would not occur for the higher-lying SD states. All quantities related to the decay out of SD bands exhibit a very regular behavior and are comparable for states of different bands with the same spin values, although the excitation energy can be very different. This points to an interaction between SD and ND states which is strongly spin dependent. This has been pointed out already in Refs. [2–4,39,40] and was investigated in detail in Ref. [9]. The quantities determined in this work give further support for the spin exponential spin dependence of the interaction strength v first proposed by Vigezzi *et al.* [2].

Finally, we would like to mention another interesting approach to explain the decay out of SD bands as it has been suggested by Åberg [6]. In this approach, the decay goes via a doorway state with an interaction strength enhanced by the onset of chaos at a certain excitation energy to values of about $v=50$ keV. This approach describes the observed decay intensities as it varies at the bottom of the SD bands in the mass-150 region. For the mass-190 region, where the excitation energies were fixed via the observed linking transitions, the following question has to be raised: Why are the decay-out patterns for ^{194}Hg and ^{194}Pb so similar with respect to the decay-out intensities $I_{out}(I)$, although the excitation energies are different by about 2 MeV? Even the decay out of the yrast SD band and the excited band SD3 in ^{194}Hg occurs within the same spin window $8\hbar<I<12\hbar$ whereas the excitation energies differ by almost 1 MeV. If the onset of chaoticity would be governing the decay out, one would expect a significantly larger interaction strength v for the excited band and thus a very different decay-out pattern. Since this is not the case, we conclude that the decay out due to the onset of chaos seems not supported by our results.

In summary, we have measured the lifetimes of the three lowest states in each SD band in ^{194}Hg using the recoil distance method. The corresponding transition quadrupole moments Q_t agree within the experimental uncertainties with those for higher-lying transitions obtained from previous DSAM measurements [18,19], corroborating the thesis that SD configurations dominate the band structures down to the region of their decay.

In order to discuss the decay-out mechanism the measured lifetimes have been used to determine the mean tunneling width $\Gamma^{\downarrow}$ for the penetration of the potential barrier separating the SD to the ND potential minimum. We applied the level mixing approach [2] as well as an approach based on statistical model calculations [7]. It was shown that for the ^{194}Hg both variants can be employed and consistent results were obtained.

In addition the squared mixing amplitudes c^2 were determined for SD states where decay out was observed. These mixing amplitudes were found to be in the range of 0.6–10 %, thus revealing that the SD structure is essentially maintained down to the lowest observed SD states in all three SD bands of ^{194}Hg. A very regular decay pattern was found for these bands, as exhibited by the extracted $\Gamma^{\downarrow}$ and c^2 values, which is similar to that observed in other nuclei in the $A = 190$ region. The results support the assumption that the decay out of the SD bands in ^{194}Hg is dominated by a weak admixture of the nearest-neighboring ND states governed by a two level mixing process. The assumption of an exponential spin dependence of the interaction [9,43] between SD and ND states is supported as well.

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