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Decay-out from low-lying superdeformed bands in Pb isotopes: Tunneling widths in a two-level mixing model

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A recently developed two-level mixing model of superdeformed decay is applied to evaluate the tunneling width between the superdeformed and normally deformed potential wells in ^{192}Pb and ^{194}Pb. Estimates are made of level densities and γ decay widths for levels in the normally deformed well, which are required for evaluation of the model. Experimental quasicontinuum results are used to suggest a spin-dependent reduction of the energy gap in the level spectrum, resulting in approximately constant level densities and decay widths in the normal well over the decay-out region for each isotope. However, it transpires that the model's prediction of the tunneling width is nearly independent of the normally deformed state widths for both isotopes. This observation is used to extract potential barrier heights for the two nuclei that depend mainly on experimentally determined values.

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Superdeformed (SD) bands have been observed in many different regions of the nuclear chart [1]. Although each region displays characteristic features depending on the underlying structure (i.e., the nature of the single-particle orbitals driving the nucleus to large deformation), there are some features which are common to all SD bands: (i) each consists of a sequence of γ-ray transitions with very regular energy spacing (indicating highly collective rotational motion) and (ii) the decay to levels of normal deformation (ND levels) occurs rather abruptly, over only two to three SD levels, and before the bandhead is reached.

By definition, the SD band is associated with a distinct second minimum in the nuclear potential energy surface at large prolate deformation. In order to decay out of that minimum, a SD state mixes with one or more states of normal deformation (ND states) at the same excitation energy and spin, thus allowing a decay branch from SD to lower-lying ND states. However, in the few cases where measurements have been possible, the experimental lifetimes of the SD levels from which the decay occurs indicate that the SD shape is retained to the lowest spins, suggesting that the ND component in the SD wave function is small. We must therefore ask, what is it that enhances the probability of decay so dramatically as the spin decreases? Various mechanisms including pairing [2] and chaos [3] have been suggested, but as yet there is no clear solution to the problem.

The SD bands in the $A\approx 190$ region of superdeformation are of particular interest for several reasons. First, like the SD nuclei with $A\approx 150$, they can be considered as one of the "classic" islands of superdeformation in the nuclear chart. That is, for these nuclei, "superdeformed" is used to imply (a) that the nucleus adopts an ellipsoidal shape with a major:minor axis ratio close to 2:1 and (b) that the deformation is caused by "superintruder orbitals" from the next major shell. In addition, the SD minimum in nuclei in this region is predicted (by many different calculations) to persist to spin $I=0\hbar$. This suggests that the abrupt decay-out, which occurs at significantly higher spins than the bandhead, cannot be explained simply in terms of a vanishing barrier.

It is natural to formulate the decay-out probability in terms of the widths of the states in the ND and SD wells and a matrix element V which describes the interaction between ND and SD states. This matrix element can itself be related to a *spreading* or *tunneling* width, $\Gamma^{\downarrow}$, which describes the probability for escape through the potential barrier separating the SD and ND wells and hence reflects the height of that barrier. In this paper, we apply a recent model to examine the decay-out of the yrast SD bands in ^{192}Pb and ^{194}Pb. We show that, *within this model*, the decay-out in both nuclei is predominantly governed by the properties of the SD band and the potential barrier, and is almost insensitive to the properties of the ND states. Although the available data are insufficient to determine whether the model is correct, the present analysis provides valuable insights into some of its implications.

In order to identify what drives the sudden decay out of the SD well, it should be helpful to describe the decay process in a manner such that the unknown factors can be separated from known quantities. For any initial SD level, both the fraction of intensity that remains within the SD band (F_{SD}) and the width for γ decay within the SD minimum (Γ_{SD}) can be measured. The average ND level spacing D and decay width Γ_{ND}, on the other hand, can only be estimated. In order to make such estimates with any degree of confidence, it is essential that the excitation energy and spin of the SD band at the point of decay are established; it is also necessary to make some assumptions about the size of the backshift parameter which represents the energy gap due to low-spin pairing correlations. In the following, we make use of experimentally determined SD excitation energies and a spin-dependent parametrization of the backshift parameter to

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obtain reasonable estimates of D and Γ_{ND} at the appropriate spins and excitation energies in ^{192,194}Pb.

In the $A \approx 190$ region, discrete linking transitions have been observed in three nuclei: ^{194}Hg [5,6], ^{194}Pb [7,8], and ^{192}Pb [9]. The determination of precise SD excitation energies in the two Pb isotopes allows a direct comparison of the decay properties of these neighboring nuclei. Although the SD excitation energies in these two nuclei ($\approx 2-3$ MeV above yrast at the point of decay) are consistent with the predictions of both macroscopic and microscopic potential energy surface calculations (e.g., Refs. [10,11]), they are much lower than is generally assumed in models describing the decay out of the SD minimum. However, their decay-out profiles are remarkably similar both to each other and to those of the more highly excited SD bands in the Hg isotopes and heavier Pb nuclei. The implications for ND level densities and decay widths in the decay-out region thus need to be explored for these nuclei, and their effect on the decay-out probabilities examined.

A recent resurgence of theoretical interest has produced several detailed studies of the decay-out problem. In response to some apparent drawbacks and restrictions of the earliest approaches [12,13] (such as the unexpected result of spreading widths smaller than widths of the ND states), Gu and Weidenmüller [14] proposed a fully statistical treatment of the mixing and decay. (A parallel approach providing an equivalent treatment in the overlapping resonance region has been developed by Sargeant *et al.* [15].) An alternative approach, based on a two-level mixing model, has been proposed [16,17] and further refined by Cardamone, Stafford, and Barrett [18]. We choose to apply the latter model, hereafter referred to as the CSB model, to ^{194}Pb and ^{192}Pb for three main reasons: (i) the low level density expected at the relatively low excitation energies of the SD bands suggests that the SD-ND mixing could indeed be dominated by only one ND level; (ii) Cardamone *et al.* interpret the spreading width of the CSB model as a "real physical rate" for tunneling between the two SD and ND states; and (iii) because the CSB model is amenable to straightforward interpretation. In the following, the CSB model is used to estimate the barrier height in the even-even Pb isotopes ^{192}Pb and ^{194}Pb over a range of spins spanning the decay-out region, thus allowing a comparison of the well depths in the two nuclei.

In the CSB model, the ND states are described by the Gaussian orthogonal ensemble, which provides a set of complex, "structure-free" levels. Mixing is modeled between one SD and only one ND state and the tunneling part of the decay is described using a Green's function approach. This model provides a simple, closed formula for F_{SD} [18],

$$F_{SD} = \frac{\Gamma_{SD}}{\Gamma_{SD} + \Gamma_{ND}\Gamma^{\downarrow}/(\Gamma_{ND} + \Gamma^{\downarrow})}. \quad (1)$$

(Here we use F_{SD}, rather than its complement $F_{ND}=1-F_{SD}$, as this is the directly measured quantity.) The spreading width $\Gamma^{\downarrow}$ is related to the interaction matrix element V between the unmixed ND and SD states by

$$\Gamma^{\downarrow} = 2\Gamma_{ave}V^2/(\Delta^2 + \Gamma_{ave}^2), \quad (2)$$

where $\Gamma_{ave}=(\Gamma_{SD}+\Gamma_{ND})/2$ and Δ is the difference in energy of the two states in the SD and ND wells. As this cannot be measured, the average value $\overline{\Delta}=D/4$ can be used in Eq. (2) to extract an average matrix element $\langle V \rangle$ when $\Gamma_{ave} \ll D$ [18].

A Fermi gas model density of states can be used to estimate D: we follow the usual approach and use the cranking model formula [4],

$$\rho(U,I) = \frac{\sqrt{\pi}}{48}a^{-1/4}U^{-5/4}\mathrm{e}^{\sqrt{4aU}}. \quad (3)$$

Here, a is the level density parameter (taken to be 22 MeV^{-1}) and U is the excitation energy above yrast minus a backshift parameter G (that is, $U=E_{SD}-E_{\mathrm{yr}}-G$). The backshift parameter accounts for the energy gap above yrast in even-even nuclei due to low-spin pairing correlations, and is usually taken to be 1.4 MeV in SD decay studies in the $A \approx 190$ region. However, analyses of the quasicontinuum component of the SD decay in both isotopes considered here [19] suggested that reduced backshift parameters of 0.4 MeV and 0.95 MeV should be adopted for ^{192}Pb and ^{194}Pb, respectively, at the decay-out spins, and that perhaps no backshift parameter should be used at higher spins. In fact, the size of the energy gap in the level spectrum should decrease with increasing angular momentum, and it will also depend on the degree of deformation and underlying structure of the nucleus. The normal deformations and structures of the two Pb isotopes are very similar; it thus seems reasonable to take the values obtained for ^{192}Pb and ^{194}Pb by McNabb *et al.* [19] and extract a function describing the spin dependence of the backshift parameter common to both nuclei. As those quasicontinuum analyses did not select decay from a unique SD level, we have assumed that the measured values of G correspond to the average decay-out spins, weighted by the intensity leaving the bands at each level. These (somewhat limited) data show G decreasing rapidly with increasing angular momentum. We find the linear expression G (in MeV) $=1.6-0.087I$ provides a good description of the data. Without more precise measurements, and information about the gap at higher spin, it is not possible to distinguish the true form of the spin dependence, but the linear form should provide reasonable values for $G(I)$ in the decay-out region.

Figure 1 shows the level densities obtained using the formula given with a fixed and varying backshift. It is clear that the use of spin-dependent backshift parameters results in significantly higher level densities for both isotopes. In addition (and perhaps equally important) the behavior of ρ as a function of spin is modified. If ρ is calculated using a fixed G, it decreases rapidly with increasing spin. In contrast, if a spin dependent G is adopted, ρ is approximately constant over much of the spin range of interest.

Similarly, the choice of backshift parameter has a marked effect on estimates of the width for γ decay from the ND states. One can estimate Γ_{ND} with the formula [20]

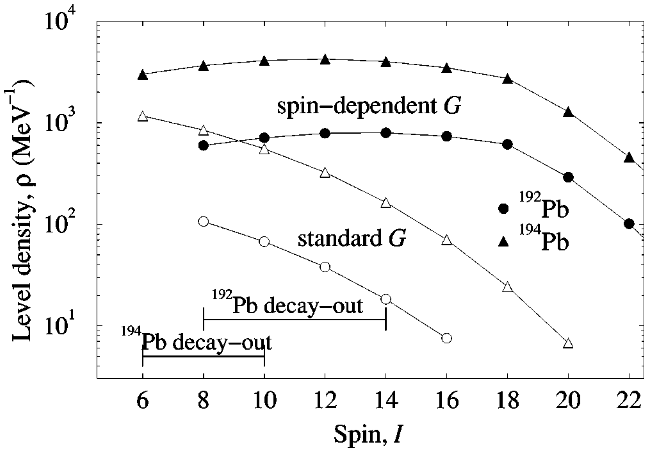

FIG. 1. Level densities calculated with fixed $G=1.4$ MeV (open symbols) and G linearly decreasing with increasing spin (filled symbols).

$$\Gamma_{ND} = \Gamma_{E1}^{\text{stat}} = (0.15 \times 2.3 \times 10^{-11}) NZA^{1/3}(U/a)^{5/2}, \quad (4)$$

which combines the Fermi gas model level density estimates with the tail of the giant dipole resonance strength function. This reflects the assumption that the nonyrast ND states will decay predominantly via fast, statistical $E1$ transitions rather than via collective $E2/M1$ or single-particle transitions. As the SD bands observed in ^{192}Pb and ^{194}Pb are only 2–3 MeV above yrast at the point of decay, it is necessary to ask whether this assumption is valid. A first order justification is provided by a check that $\Gamma_{E1}^{\text{stat}} \gg \Gamma_{ND}^{\text{coll}}$, where $\Gamma_{ND}^{\text{coll}}$ is the width for collective decay ($E2$ or $M1$) from a ND state. In general, $\Gamma_{ND}^{\text{coll}}$ can be estimated by $\Gamma_{E2,ND}$, the width for $E2$ decay within a rotational band, since this is expected to be significantly larger than competing collective $M1$ and single-particle decays. We estimate values of $\Gamma_{E2,ND}$ by assuming a band with a moment of inertia obtained from a fit to the excitation energies of the observed ND yrast states in the range $14\hbar \geq I \leq 34\hbar$. Figure 2 shows

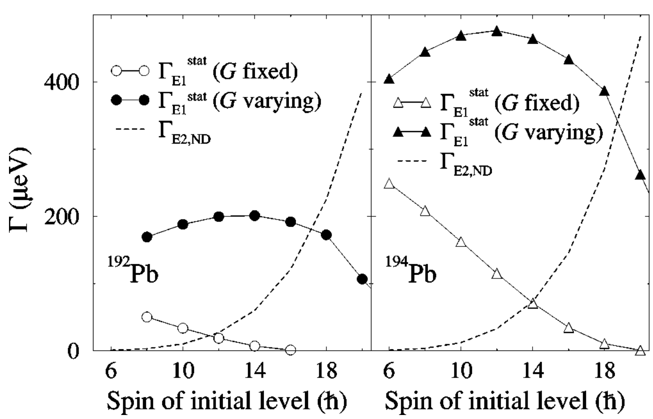

FIG. 2. Estimates of statistical $E1$ widths (calculated for ND levels of the same excitation energy as the SD level of the same spin) and collective $E2$ widths. $E1$ widths are shown for both standard (dotted lines) and decreasing (solid lines) backshift parameters. The collective $E2$ widths are for a $K=0$ band.

the behavior of $\Gamma_{E1}^{\text{stat}}$ and $\Gamma_{E2,ND}$ for states in the ND well at the same excitation energy and spin as states in the yrast SD bands in the two Pb isotopes. The estimated ND $E2$ widths are upper limits, as they have been calculated for bands with $K=0$.

With the linearly decreasing parametrization G, the statistical $E1$ width in the decay-out region is almost two orders of magnitude larger than the estimated collective $E2$ width. With the standard value, the $E1$ width is still significantly larger than the $E2$ width for ^{194}Pb, but for ^{192}Pb it is almost the same as $E2$ width. These results therefore only support the assumption that the ND width can be approximated by the statistical $E1$ width in both cases if the spin-dependent parametrization of the backshift parameter is appropriate.

The two remaining parameters are determined experimentally. F_{SD} is simply the measured fraction of intensity that remains in the SD band below the level of interest. In the following calculations, we adopt the values of F_{SD} given in Refs. [9,24]. The width for γ decay within the SD band, Γ_{SD}, is obtained through measurements of the lifetimes of the SD states. The Doppler shift attenuation method (DSAM) has been used to measure lifetimes of the high-spin SD states in ^{192}Pb [21] and ^{194}Pb [22], and the recoil distance method to measure lifetimes of low-spin SD states in ^{194}Pb [23]. The DSAM measurements do not extend to the decay-out region, but can be used to obtain an average quadrupole moment Q_t. Γ_{SD} is then given (in eV) by $\Gamma_{SD}=(8.0 \times 10^{-8}) E_\gamma^5 Q_t^2 \langle IK20|(I-2)K\rangle^2$, with E_γ in MeV, Q_t in $e$fm^2. For ^{192}Pb, values of Γ_{SD} have been obtained from the above assuming a quadrupole moment of 19.3 eb, the average of the DSAM results for decays from levels with spins $16\hbar \leq I \leq 26\hbar$ [21]. Values of Γ_{SD} for ^{194}Pb are taken from Krücken *et al.* [24].

The values of U, D, Γ_{ND}, Γ_{SD}, and F_{SD} obtained with the above prescription, using the spin-dependent backshift, are given in Table I.

Spreading widths $\Gamma^{\downarrow}$ and interaction strengths V in ^{192}Pb and ^{194}Pb have been extracted using the CSB approach and the parameters given in Table I. The lower limits on F_{SD} for the state prior to the onset of decay-out lead to upper limits for both the spreading widths and interactions; similarly upper limits on F_{SD} for the last decay-out state lead to lower limits for the widths and interaction strengths. The results of these calculations are given in Table II.

We will comment on the interactions first: we emphasize that these are average strengths only, and cannot be expected to provide exact measures for each level. This is because, in the CSB model, the interaction strength V involves the energy difference between the ND and SD states Δ, which is unknown. For these nuclei, $\Gamma_{ave} \ll D$, which means that V is given by $\Delta\sqrt{\Gamma^{\downarrow}/2\Gamma_{ave}}$. By choosing the average $\overline{\Delta}=D/4$, we extract an average $\langle V\rangle$ and we comment on the trends exhibited by the calculated *average* interactions.

For both isotopes, the spin dependence is not inconsistent with an exponentially decreasing V with increasing spin, as has been previously postulated [24]. (No value is given for the ^{192}Pb $I=10\hbar$ state due to an unphysical negative tunneling width, as will be discussed below.) Any inferred spin dependence of $\langle V\rangle$ is mainly a reflection of the spin depen-

TABLE I. Values of the fractional intensities, effective excitation energies, γ-decay widths, and level spacings used in the calculations of $\Gamma^{\downarrow}$ and V.

Nucleus	I	F_{SD}	U (MeV)	Γ_{SD} [a] (μeV)	Γ_{ND} (μeV)	D (eV)
^{192}Pb [b]	$8\hbar$	<0.25	1.29	16	169	1681
	$10\hbar$	0.12(3)	1.34	48	188	1410
	$12\hbar$	0.66(3)	1.37	132	200	1272
	$14\hbar$	0.98(2)	1.38	266	201	1258
	$16\hbar$	>0.99	1.35	487	192	1362
^{194}Pb [c]	$6\hbar$	<0.04	1.82	3	405	333
	$8\hbar$	0.65(3)	1.89	14	445	273
	$10\hbar$	0.90(2)	1.94	45	470	244
	$12\hbar$	>0.99	1.95	125	476	236

[a]The widths of the SD in-band transitions have errors of the order of 20% due to uncertainties in the stopping powers in the DSAM measurements.
[b]Based on data given in Ref. [9].
[c]Based on data given in Ref. [24].

dences of the measured quantities F_{SD} and Γ_{SD}, since the calculated properties of the ND states do not change greatly with spin. In turn, Γ_{SD} predominantly reflects the decreasing transition energies with decreasing spin, as the quadrupole moments are taken to remain constant.

It is difficult to make a precise comparison of $\langle V\rangle$ between ^{192}Pb and ^{194}Pb because of the uncertainty in the estimates of D and Γ_{ND}; nevertheless, we can infer that the interaction is approximately two orders of magnitude larger in ^{192}Pb than in ^{194}Pb for states of the same spin.

We turn now to the calculated widths $\Gamma^{\downarrow}$. As noted by Cardamone *et al.* [18], the necessity that $\Gamma^{\downarrow}$ is positive imposes the additional constraint that $\Gamma_{ND}>\Gamma_{SD}(F_{SD}^{-1}-1)$, thus the model yields a negative value of $\Gamma^{\downarrow}$ for the $I=10\hbar$ state in ^{192}Pb. To obtain a positive width for the ^{192}Pb $I=10\hbar$ state would require that $\Gamma_{ND}>352$ μeV, which is slightly less than twice the value obtained from the prescription above.

TABLE II. Results of the analysis using the CSB approach. See text for discussion of $\Gamma^{\downarrow}_{approx}$ and B.

Nucleus	I	$\Gamma^{\downarrow}$ (μeV)	$\langle V\rangle$ (eV)	$\Gamma^{\downarrow}_{approx}$ (μeV)	B (MeV)
^{192}Pb	$8\hbar$	>67	>253	>48	<2.01
	$10\hbar$	-404		352	1.85 [a]
	$12\hbar$	103	177	68	1.97
	$14\hbar$	6	37	5	2.24
	$16\hbar$	<5	<29	<5	>2.26
^{194}Pb	$6\hbar$	>88	>39	>72	<1.99
	$8\hbar$	8	9	8	2.22
	$10\hbar$	5	6	5	2.26
	$12\hbar$	<1.3	<3	<1.3	>2.39

[a]The barrier height for the $10\hbar$ level in ^{192}Pb is calculated using $\Gamma^{\downarrow}_{approx}$ rather than $\Gamma^{\downarrow}$.

Given the uncertainties in estimating the ND widths, this is not unreasonable and the negative value cannot therefore be taken to signify a fundamental problem with the CSB approach.

The simple expression for $\Gamma^{\downarrow}$ in the CSB model allows us to make a number of enlightening observations. When $\Gamma_{ND}\gg\Gamma_{SD}$, Eq. (1) reduces to [16]

$$\Gamma^{\downarrow}_{approx}=\Gamma_{SD}(F_{SD}^{-1}-1), \tag{5}$$

which only depends on the observed fractional intensity F_{SD} and the SD decay width Γ_{SD}, which is inferred from experiment. The quantity $\Gamma^{\downarrow}_{approx}$ is evaluated in Table II and we find, perhaps surprisingly, that it is very similar to $\Gamma^{\downarrow}$ for all states considered here, even for cases where $\Gamma_{ND}\approx\Gamma_{SD}$. This can be accounted for because Eq. (5) also holds when Γ_{ND} is similar in magnitude to Γ_{SD} and $F_{SD}\approx 1$. The rough equivalence between $\Gamma^{\downarrow}$ and $\Gamma^{\downarrow}_{approx}$ for the Pb isotopes shows that, as long as the ND widths are not somewhat smaller than our estimates, $\Gamma^{\downarrow}$ in the CSB model is approximately independent of the ND state properties.

If we assume that the quantity $\Gamma^{\downarrow}$ in the CSB approach can be equated with a fusionlike tunneling rate, it can be associated with a barrier height. Using a semiclassical model where the SD well and the barrier potential are modeled with parabolic and inverse parabolic shapes, respectively [13,24], the relationship is

$$B=-\frac{\hbar\omega_b}{2\pi}\ln\left(\frac{2\pi\Gamma_{tunnel}}{\hbar\omega_s}\right). \tag{6}$$

Here B is the barrier height and ω_s and ω_b specify the widths of the SD well and the barrier. In the Pb isotopes, the very weak dependence of $\Gamma^{\downarrow}$ on Γ_{ND} means that, if we make the assumption that $\Gamma^{\downarrow}$ is equivalent to the tunneling width above, the CSB model gives us a means of extracting a barrier height directly from experimental results. Values of B, calculated using $\hbar\omega_s=\hbar\omega_b=0.6$ MeV [24], are given in

Table II. The barrier heights are relatively large; however, they are proportional to the value assumed for ω_b, and this is strongly affected by the shape of the barrier. In the absence of reliable predictions for the potential energy distribution, B must be taken to be schematic only. Regardless of the absolute values, there is still a significant barrier even at the lowest observed spins.

As has been observed elsewhere [18], the values of $\Gamma^{\downarrow}$ obtained in the alternative formalism developed by Gu and Weidenmüller [14] and Sargeant *et al.* [15] are several orders of magnitude larger than those given in Table II. In those models, $\Gamma^{\downarrow}$ depends strongly on Γ_{ND} and D, and thus the independence of the ND properties found for the decay-out probability above may not hold. In order to determine whether the insensitivity to these parameters in the CSB model is real, it would be of great help to acquire measurements of the excitation energies and decays of the yrast bands in the neighboring even-even isotopes ^{190}Pb and ^{196}Pb, which are expected to occur at lower and higher energies, respectively, but which will have similar SD structures and properties. A chain of SD bands in the same isotopes, spanning excitation energies such that the properties of the ND states are significantly different, might be expected to highlight any strong dependence on the ND density and γ-decay widths.

In summary, assuming that $\Gamma^{\downarrow}$ of the CSB model can be equated with the tunneling width, and using some simple assumptions about the shape of the potential, we have extracted values for the height of the barrier between the SD and ND wells in ^{192}Pb and ^{194}Pb. For the levels considered in these two nuclei, we find that $\Gamma^{\downarrow}$ is almost independent of the properties of the ND states. This suggests that, in the CSB model, the fraction of intensity leaving the SD band from any initial level is highly sensitive to the width for γ decay within the band and to small changes in the barrier height, and that the variation of the density of the ND states is not an important factor in these cases. Indeed it appears that the decay occurs because, at the same time as the potential barrier lowers with decreasing angular momentum, Γ_{SD} rapidly becomes smaller and any competing branch will be correspondingly favored.

Finally, we note that a barrier height difference between states of the same spin in ^{192}Pb and ^{194}Pb can be estimated. We define ΔB as the difference in the barrier between states of the same spin $\Delta B(I) = B_{^{194}\mathrm{Pb}}(I) - B_{^{192}\mathrm{Pb}}(I)$. From Eq. (6) it is obvious that ΔB is independent of ω_s. Although no exact comparison is available for states of the same spin in Table II, if an average ratio of ≈ 100 is assumed for $\Gamma^{\downarrow}_{^{192}\mathrm{Pb}}/\Gamma^{\downarrow}_{^{194}\mathrm{Pb}}$, we calculate $\overline{\Delta B} \approx 0.75\omega_b$ MeV, i.e., $\Delta B \approx 0.45$ MeV for $\omega_b = 0.6$ MeV. This is consistent with the fact that despite similar in-band transition strengths, the decay-out in the lighter isotope occurs predominantly over spins $8\hbar - 12\hbar$ as compared to $6\hbar - 10\hbar$ in the heavier isotope. These data thus confirm that the SD well in ^{194}Pb is more stable than that in ^{192}Pb, as would be expected if the SD "shell gap" occurs at $N = 112$.

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