# Direct Decays from Superdeformed States in $^{192}$Pb Observed Using Time-Correlated $\gamma$-Ray Spectroscopy

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Correlations of decays above and below isomeric states in the normally deformed minimum of $^{192}$Pb have been used to identify discrete transitions in the decay of the superdeformed (SD) band. The data establish the absolute excitation energy of the lowest observed SD level as 4.425 MeV. Extrapolation to the bandhead indicates that the excitation energy of the superdeformed well in $^{192}$Pb is 0.5 MeV lower than in the heavier isotope $^{194}$Pb. The results confirm the trend to decreasing excitation energy with decreasing neutron number predicted by both a macroscopic Strutinsky method approach and microscopic mean field calculations.

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The observation of rotational bands associated with extremely elongated nuclear shapes has generated a great deal of interest over the last 15 years. An intensive experimental campaign has resulted in the observation of more than 250 such superdeformed bands in several regions of the nuclear chart [1], with around 175 such bands observed in nuclei in the $A \approx 150$ and $A \approx 190$ mass regions. In spite of the wealth of data in these two mass regions, very few measurements have been made of the fundamental properties of these states, such as excitation energy, spin, and parity. This lack of information arises from the difficulty in identifying the very weak discrete transitions linking superdeformed states with levels at normal deformations. The present work reports on the application of time-correlated $\gamma$-ray spectroscopy in order to identify such linking transitions in $^{192}$Pb.

One of the common features of these bands is the abrupt nature of their decay: in general, the entire flux leaves the band from only two or three levels. In addition, measurements of the lifetimes of superdeformed (SD) states in nuclei with $A \approx 190$ [2] indicate that the enhanced collectivity, and therefore the shape, is retained to the lowest observed spins. Because these states are associated with a distinct, excited minimum in the potential energy of the nucleus, they can decay out of that minimum only by tunneling through the barrier which separates it from the normal-deformed (ND) well. If the tunneling probability is sufficiently high, SD states can mix with ND states at the same excitation energy, giving rise to significant transition rates for decays to other normal states. If the second well is at a large excitation energy, the density of surrounding states in the first well will be high, and for this reason a statistical description of the decay out process has been proposed [3]. The decay is expected to consist of a quasicontinuous component, but with the strength distribution exhibiting fluctuations which may result in a small number of *resolvable* single-step transitions which directly feed yrast states (the lowest state of a given spin) in the normal well. However, long-standing predictions [4,5] for Hg and Pb isotopes suggest that the excitation energy of the SD well in this region decreases rapidly with a decreasing neutron number, with a stable minimum in $^{192}$Pb only 3–4 MeV above the ground state. Given that the SD minimum comes closer to yrast with increasing spin, the excitation energy at the point of decay will be still lower, and the decay may not be purely statistical.

To date, single-step linking transitions have been identified in only three nuclei in the $A \approx 150$ and $A \approx 190$ regions: $^{194}$Hg [6,7], $^{194}$Pb [8,9], and, very recently, $^{152}$Dy [10]. This is despite enormous effort, with experiments carried out using high-efficiency multidetector arrays such as Gammasphere and Euroball. A few tentative identifications have been made, but unambiguous evidence has not been obtained in any other nuclei. McNabb *et al.* [11] performed a study of $^{192}$Pb in which they observed a peak at 2059 keV associated with the SD decay; however, they were unable to firmly place this $\gamma$ ray in the level scheme. In the present work, $^{192}$Pb has been reinvestigated using the techniques of time-correlated $\gamma$-ray spectroscopy to study the decay of the SD band.

The experiment was carried out using the Gammasphere array at Lawrence Berkeley National Laboratory. High-spin states in $^{192}$Pb were populated in the reaction $^{168}$Er($^{29}$Si, $5n$)$^{192}$Pb. The target consisted of a 1.1 mg/cm$^2$ layer of $^{168}$Er on a 5 mg/cm$^2$ Pb backing. The beam was provided by the 88″ Cyclotron at an energy of 154 MeV. An event was accepted when, after Compton suppression, signals were obtained from at least four of the 102 Ge detectors in the array. The time of detection (relative to the 15.5 MHz rf pulse of the Cyclotron) was recorded as well as the energy of each $\gamma$ ray in an event. The experimental setup allowed $\gamma$ rays to be detected and correlated up to $\approx 800$ ns after any particular beam pulse. Data were collected for 3 d, during which time $1.5 \times 10^9$ events were recorded.

The spectrum shown in Fig. 1(a) is obtained by double-gating on the SD band and requiring that all transitions occur within $\pm 30$ ns of the primary beam pulse (i.e., that they are *prompt*). Although the SD band is only weakly populated (0.6% of the intensity of the $^{192}$Pb channel), the quality and quantity of the data allow it to be easily observed. Unfortunately, the experimental difficulties associated with looking for the very weak SD-ND linking transitions are exacerbated in studies of heavy neutron-deficient nuclei by the large background arising from fission and other reaction channels. Because of overlaps between the energies of SD transitions and strong transitions in other structures, and additional constraints brought in by Doppler broadening effects, there are very few clean double-gate combinations. Triple gates are less affected, but there is still some contamination, and the reduction in statistics is significant. Figure 1(b) shows part of the prompt spectrum obtained by setting 35 triple-gate combinations on seven transitions (262–499 keV). The energy range covers the region where single-step links might be expected. The 2059 keV $\gamma$ ray observed by McNabb *et al.* is visible, but the level of background fluctuations is high and "bumps" in the spectrum associated with random coincidences with very strong background lines remain. It has not been possible to place this transition in the SD decay from data constrained by only the prompt time condition.

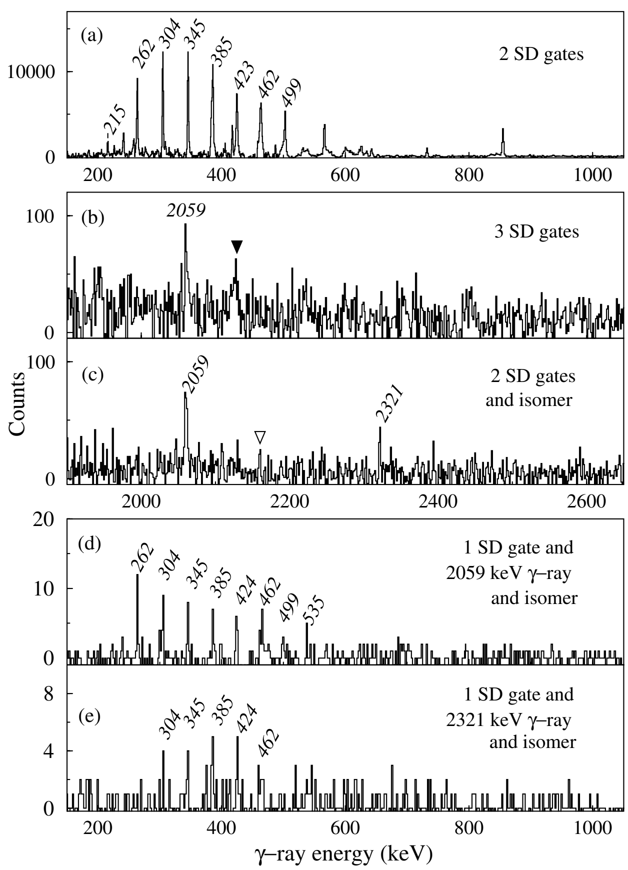


FIG. 1. Spectra of prompt data gated by (a) any two of the six SD transitions (262 − 462 keV); (b) any three of the seven SD transitions (262 − 499 keV); (c) any two of the seven SD transitions plus $\geq 1$ delayed transition; (d),(e) any one of the seven SD transitions *and* a delayed transition *and* the 2059/2321 keV $\gamma$ ray. The filled and open triangles mark the wide peak at ~2120 keV and the energy 2160 keV.

Dracoulis *et al.* [12] have provided a detailed characterization of three isomers of $I^\pi = 10^+$, $12^+$, and $11^-$ in the ND well of $^{192}$Pb, which have excitation energies 2.581, 2.623, and 2.743 MeV, respectively. Their mean lives (238 ns, 1.6 $\mu$s, and 1.09 $\mu$s, respectively) are sufficiently short to allow correlations across them in this experiment. The current data show that $(29 \pm 2)\%$ of the SD decay occurs via these isomers (consistent with $\leq$ 28% [11]). Figures 1(c)–1(e) show the effect of selecting the subset of prompt data correlated with delayed transitions in this nucleus by requiring that at least one of seven strong delayed transitions (connecting yrast levels of spins $I \leq 9$) was detected after a delay of 45–800 ns. (It should be noted that, because the delayed time region after any primary pulse contains uncorrelated data from subsequent beam pulses, only those decays occurring in periods between pulses could be included in the delayed gate, effectively excluding around 50% of the delayed data.) Figure 1(c) is double-gated on the same seven SD transitions as Fig. 1(b). The peak at 2059 keV is clearly visible, with a considerable enhancement in the peak-to-background ratio, and a second peak can be seen at 2321 keV.

The presence of the 2059 keV peak in data correlated with delayed transitions indicates that it feeds either an isomeric state or a higher-lying level which decays via an isomer. The spectra shown in Figs. 1(d) and 1(e) were obtained by setting pairs of gates on the SD transitions and the 2059 and 2321 keV $\gamma$ rays, respectively. Although the number of counts is low, the band is clear in both spectra. All band members except the 215 keV transition are visible in Fig. 1(d), while the 262 and 215 keV transitions are both missing in Fig. 1(e). The difference in energy ($2321 - 2059 = 262$) strongly suggests that they feed the same level. The transitions feeding the isomers are well established, and so the lack of any peaks in the spectra which correspond to these decays (or indeed any other peaks at all) suggests that these are single-step decays which directly link levels in the SD band with one of the isomeric levels in the ND well.

The delayed spectra with which these transitions are correlated show that they feed either the $10^+$ or $12^+$ isomer. The different lifetimes of these two states (238 ns and 1.6 $\mu$s) can be used to distinguish between them: Fig. 2(a) shows the decay curve for the level fed by the 2059 keV $\gamma$ ray. The data are consistent only with the

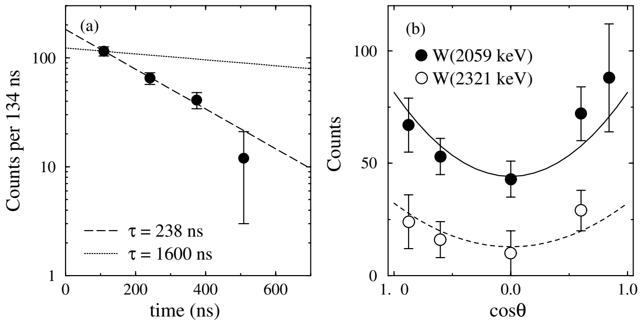


FIG. 2. (a) Decay curve associated with the state fed by the 2059 keV $\gamma$ ray. (b) Angular distributions for the prompt 2059 and 2321 keV $\gamma$ rays. The peak areas were measured in spectra gated by two SD band members and a delayed coincidence.

lifetime of the $10^+$ level, indicating that the 2059 keV $\gamma$ ray directly feeds this state and giving an energy of 4640 keV for the initial level.

The identification of these two paths enables the placement of other $\gamma$ rays in the level scheme to be confirmed. There is a wide peak around 2120 keV which is marked with a filled triangle in Fig. 1(b) but is not visible in Fig. 1(c), which is correlated with delayed decays. Coincidence relationships show that it consists of two $\gamma$ rays of 2119 and 2125 keV which link the 4640 keV SD level to the $8^+$ and $9^-$ ND levels at 2521 and 2514 keV, both of which are below the isomers. A weak 2079 keV $\gamma$ ray which is observed in prompt coincidence with the 262 keV SD transition and transitions below the isomers is placed as connecting the 4640 keV level to the $8^+$ at 2563 keV. Last, a 2160 keV $\gamma$ ray is observed in double-SD gated spectra. This transition is not in coincidence with the 262 keV SD transition, and the data also indicate that it is not in prompt coincidence with transitions below the isomers. Together with these coincidence relationships, energy sums suggest that it connects the 4902 keV SD level to the $11^-$ isomer at 2743 keV. Because the 800 ns delay period allowed by the coincidence overlap window is relatively short compared to the lifetimes of the $12^+$ and $11^-$ isomers, time correlations are less efficient for these cases, and the low intensity of this peak in Fig. 1(c) (marked with an open triangle) is therefore not inconsistent with the suggested placement of this transition.

The paths established between SD and ND states fix the absolute excitation energy of the SD levels, but it is also important to establish their spin and parity. Figure 2(b) shows the angular distribution of both the 2059 and 2321 keV transitions. The solid and dashed lines are fits to the data of the formula $W(\theta) = A_0[1 + A_2P_2(\cos\theta)]$; values of $A_2 = 0.44 \pm 0.19$ and $A_2 = 0.63 \pm 0.52$ are obtained, which are consistent only with $\Delta J = 2$ or $\Delta J = 0$ transitions, restricting the spins of the parent SD levels to $10^+, 8^+$ or $12^+, 10^+$. This is consistent with the assumption that the yrast SD band in an even-even nucleus will be of positive parity and even spin, corresponding to a $K = 0$ band based on the SD vacuum. Figure 3 shows the decay paths established in this work.

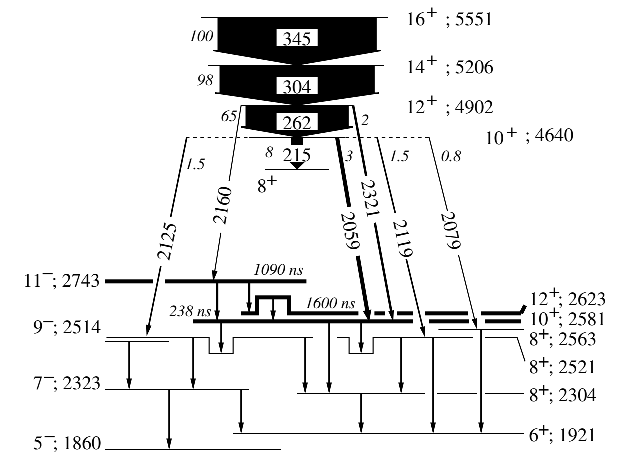


FIG. 3. Partial level scheme showing the decay of SD $^{192}$Pb. The known isomers are indicated by bold lines.

The data do not uniquely define the spins of the levels, but a $10^+$ assignment for the 4640 keV level is supported by a fit to the dynamic moment of inertia [13] and also by the absence of decays from this level to states of lower spin, such as a decay to the $8^-$ level at 2507 keV or the $7^-$ at 2323 keV. No transitions have been observed connecting the 4425 keV ($8^+$) level in the SD band with ND levels, but its single-step decays would be most likely to feed states below the isomers, and therefore the advantage of using time correlations is lost. Details of the linking transitions are given in Table I.

Figure 4(a) shows the excitation energies of states in the SD bands in $^{192}$Pb, $^{194}$Pb, and $^{194}$Hg. Rotational model fits to the data give bandhead energies of 4.011 MeV, 4.643 MeV, and 6.018 MeV respectively. Predictions of the energies of the SD well in these nuclei have been made using the Strutinsky method and an average Woods-Saxon potential [4] and also Hartree-Fock-Bogoliubov (HFB) calculations using a density-dependent Skyrme interaction [5] and a Gogny force [15]. The results of

TABLE I. Properties of the single-step links between SD and ND states.

| Transitions deexciting the 4640 keV SD level | | | | |
|---|---|---|---|---|
| $E_\gamma$ (keV) | Intensity[a] | $I_i^\pi - I_f^\pi$ | $\sigma L$ | $B(\sigma L)$ (Wu)[b] |
| 2059 | 3.0(0.3) | $10^+ \rightarrow 10^+$ | M1 | $7.4(27) \times 10^{-5}$ |
| 2079 | 0.8(0.3) | $10^+ \rightarrow 8^+$ | E2 | $1.7(9) \times 10^{-3}$ |
| 2119 | 1.5(0.3) | $10^+ \rightarrow 8^+$ | E2 | $3.0(12) \times 10^{-3}$ |
| 2125 | 1.5(0.25) | $10^+ \rightarrow 9^-$ | E1 | $5.0(19) \times 10^{-7}$ |
| Transitions deexciting the 4902 keV SD level | | | | |
| $E_\gamma$ (keV) | Intensity | $I_i^\pi \rightarrow I_f^\pi$ | $\sigma L$ | $B(\sigma L)$ (Wu) |
| 2160 | 1.0(0.5) | $12^+ \rightarrow 11^-$ | E1 | $1.6(10) \times 10^{-7}$ |
| 2321 | 2.0(0.23) | $12^+ \rightarrow 10^+$ | E2 | $8.6(32) \times 10^{-4}$ |

[a]Relative to 100 units for the intensity of the 345 keV SD transition.
[b]Calculated assuming $Q_0 = 17(3)$ $e$ b, measured for $^{193}$Pb [14]. M1 strengths assume pure M1 character and are upper limits.

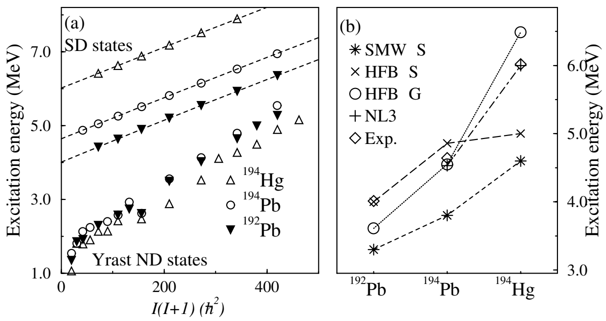


FIG. 4. (a) Excitation energies of the SD and yrast ND states in $^{192}$Pb, $^{194}$Pb, and $^{194}$Hg. The dashed lines show extrapolations to $I = 0$. (b) Comparison with various model predictions: Strutinsky method (SM-WS) [4], mean field using Skyrme (HFB-S) [5] and Gogny (HFB-G) [15] interactions, and relativistic mean field (NL3) [16].

these calculations are compared to the data in Fig. 4(b). All three approaches predict a decrease in the energy of the SD well between $^{194}$Pb and $^{192}$Pb of the right order, with the results of the Strutinsky method and the mean field calculations using the Skyrme force within 150 keV of the measured difference. On the other hand, none of the calculations consistently reproduces the absolute energies. Relativistic mean field calculations using an NL3 force [16] have successfully reproduced the excitation energies of $^{194}$Pb and $^{194}$Hg but have not been performed for $^{192}$Pb. A systematic comparison with experiment requires measurements in other nuclei, as the Strutinsky method predicts a significantly slower increase in the SD well energy with neutron number.

The data show that the SD well in $^{192}$Pb is not very far from yrast even at low spins, a fact which must be considered when describing the decay out process. It is usually assumed that the decay from the SD well will be dominated by E1 transitions. However, only two of the six transitions identified in the present work are assigned as E1s. This contrasts with the decay of SD $^{194}$Hg [6], in which only E1 transitions have been identified as single-step links between yrast SD and ND states, but is similar to that of SD $^{194}$Pb [8,9], in which states of both positive and negative parity are directly fed by single-step transitions. Reduced transition probabilities, $B(\sigma L)$, are given in Table I for the six links. They are slightly larger than those measured for $^{194}$Pb [2,9] and $^{194}$Hg [6], but all are retarded, as would be expected for such a drastic change of configuration. Not surprisingly, the data suggest that the precise detail of the decay of SD $^{192}$Pb is governed by the transition strengths of the available paths. Figure 4(a) shows that the excitation energies above yrast of the SD band in $^{192,194}$Pb are significantly lower than in $^{194}$Hg, in regions where the structure of the ND states may not be very complex. In addition, the low-lying states of $^{192}$Pb are mostly of noncollective character, while oblate and prolate minima coexist in the light Hg isotopes, producing collective rotational excitations as well as quasiparticle states. The probabilities of transitions between the excited and yrast ND states could therefore be affected by the structure of the initial and final states, with the importance of this nonstatistical factor increasing as the relative excitation energy decreases.

In summary, the presence of isomeric states in the ND well has been exploited in order to identify single-step transitions linking superdeformed and yrast levels in $^{192}$Pb. Six single-step transitions have been observed, two of which directly feed the $10^+$ isomer at 2581 keV. The data firmly establish the excitation energy and parity of the SD band and suggest the spin of the lowest level is $8\hbar$. The excitation energy above yrast confirms the decrease with decreasing neutron number predicted by both the Strutinsky method and mean field approaches and is significantly lower than is usually assumed in statistical descriptions of the SD decay. This will have important consequences for the mixing that allows the decay to take place and hence the nature of the decay.

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