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Decay from a superdeformed band in ^{194}Pb

M. J. Brinkman,[1,6] J. A. Becker,[1] I. Y. Lee,[2] L. P. Farris,[1] E. A. Henry,[1] R. W. Hoff,[1] J. R. Hughes,[1] M. A. Stoyer,[1] L. A. Bernstein,[3] J. A. Cizewski,[3] H. Q. Jin,[3] W. Younes,[3] B. Cederwall,[2] M. A. Deleplanque,[2] R. M. Diamond,[2] P. Fallon,[2] A. O. Macchiavelli,[2] F. S. Stephens,[2] W. H. Kelly,[4] D. T. Vo,[4] J. E. Draper,[5] C. Duyar,[5] and E. Rubel[5]

[1]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[2]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*
[3]*Rutgers University, New Brunswick, New Jersey 08903*
[4]*Iowa State University, Ames, Iowa 50011*
[5]*University of California–Davis, Davis, California 95616*
[6]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

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Three experiments using the ^{174}Yb(^{25}Mg,5n)^{194}Pb reaction have been undertaken at the Early Implementation of GAMMASPHERE to study the decay of known superdeformed states in ^{194}Pb. A single discrete transition with an energy of 2.746(2) MeV carrying 6(2)% of the full superdeformed band intensity has been identified. A discussion of our results and the assignment of the 2.746-MeV transition as a discrete γ ray directly connecting the superdeformed 8^+ and low-lying 6^+ levels will be presented.

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Despite the wealth of experimental information that exists on superdeformed (SD) bands in the $A\approx 190$ mass region (see [1] and references therein), a number of the most fundamental properties of these structures (e.g., the excitation energy) remain unmeasured. Direct experimental determination of these quantities requires that the decay pathways linking superdeformed and low-lying states be delineated. The most intense (yrast) SD band in ^{194}Pb [2–6] is populated using heavy-ion fusion-evaporation reactions with $\approx$1% of intensity of the normal low-lying transitions in this nucleus and an intensity pattern similar to that of the other SD bands known in this mass region. (The population of the SD band increases with decreasing spin until a plateau is reached. Following a number of transitions of roughly equal intensity, the band abruptly depopulates with the full SD band intensity observed in transitions connecting low-lying levels.) Compared with other SD bands in this mass region, there are two important differences which make ^{194}Pb an optimal case to search for SD decay pathways. First, this band extends to the lowest spin ($6\hbar$ [7]) observed for any SD band in this mass region. This favors a reduced number of distinct pathways through which the SD band can decay. Second, the singly magic ^{194}Pb will have a lower density of normal levels through which the SD band can decay and into which the SD band intensity can be concentrated following decay. Minimizing the number of distinct decay pathways should serve to maximize the intensity through a given branch.

Three experiments populating the yrast ^{194}Pb SD band were performed using the Early Implementation of GAMMASPHERE. In each of these experiments a 130-MeV ^{25}Mg beam was used to bombard three stacked thin (each $\approx$500 μg/cm^2) foils of isotopically enriched ^{174}Yb. The predominant exit channels formed in this reaction were ^{193,194,195}Pb and ^{192}Hg with relative populations approximately 10%, 60%, 20%, and 7% of the total yield, respectively. In the first experiment a total of 27 GAMMASPHERE germanium detectors [8] was used. These were divided into five rings—located at 173°, 147°, 143°, 13°, and 33° with respect to the beam—of five detectors each with two additional detectors placed at 37°. For the two following experiments five additional detectors (one at 37° and four at 90°) were installed, bringing the total to 32 detectors. In each of these experiments data were collected with a trigger condition of three or more clean germanium signals. A total of

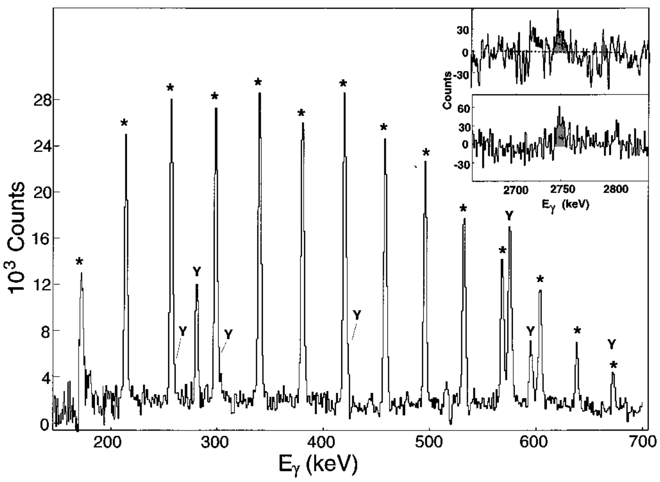

FIG. 1. Background subtracted spectrum of the ^{194}Pb superdeformed band generated by double gating the unfolded threefold events using all unique combinations of superdeformed band members. The superdeformed band members are denoted by * with the Y denoting low-lying transitions known to be in coincidence with the superdeformed band. This spectrum was background subtracted and logarithmically smoothed. The effects of the smoothing can be seen by comparing the region below 200 keV (not smoothed) with the remainder of the spectrum. The insets show the spectrum in the region of 2.75-MeV (with the 2.746-MeV peak denoted by shading) using two different background subtractions. The upper inset is the continuation of the large spectrum, while the lower inset was background subtracted using a normalized total projection and the data averaged over two channels. The upper inset also shows a typical fit to the peak (dashed line) to a Gaussian with an appropriate width. Note that the 2.746-MeV transition is the only peak with an appropriate shape that appears in both spectra.

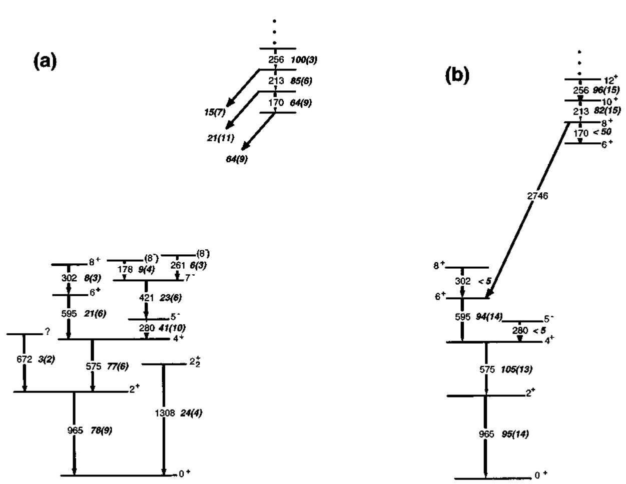

FIG. 2. (a) The low-lying level scheme in coincidence with the SD band. The italicized bold values denote the relative intensities of the associated transitions normalized to 100 for the average of the 256.4-, 298.8-, 340.3-, and 380.0-keV SD transitions. (b) The low-lying level scheme in coincidence with the 2.746-MeV transition. The italicized bold values denote the relative intensities of the associated transitions normalized to 100 for the average of the 298.8- and 340.3-keV SD transitions. The intensity for the 170-keV SD γ ray could not be extracted; an upper limit is quoted.

1.95×10^9 (3.5×10^8) unfolded threefold (fourfold) events meeting the trigger condition was recorded to tape. A preliminary report of this work is presented in Ref. [9].

During the initial analysis the data collected in the three experiments were kept separate, minimizing systematic errors arising from differences in array characteristics for the three runs. In Fig. 1 we present the background subtracted spectrum which was obtained from the second data set (containing $\approx 2/3$ of the total statistics) by summing all unique pairwise combinations of gates set on the known yrast SD band members in ^{194}Pb. A summary of the relative intensities for the lowest energy SD and all other transitions in this spectrum is provided in Fig. 2(a). Using these results we have determined the average spin at which the SD band decays and the average spin of low-lying levels populated by this decay. The average spin at which the SD band depopulates is found to be $7.0\pm1.1\hbar$. We have also conducted a search for a peak near 125 keV which would correspond to a SD $6\rightarrow4$ transition. In contrast with what was reported in Ref. [6] we find no evidence for this transition with an upper limit of $\leqslant 3\%$ of the SD band intensity.

The level scheme of ^{194}Pb reported in Ref. [10] was used as a basis to determine the average spin fed by the decay of the ^{194}Pb SD band. This analysis was complicated by two factors. (1) The low-lying 8^+ level from which the 302-keV transition originates is a short-lived isomeric state with a half-life of 17(4) ns [10]. Using an earlier (backed target) data set described by Willsau and collaborators [11] we determined that 8(3)% of the SD band intensity populates this level. The apparent intensity of this transition in our data was reduced by $\approx 1/3$ due to the isomeric lifetime of the 8^+ level. (2) The primarily forward-backward geometry of GAMMASPHERE Early Implementation enhanced the detection of $L=2$ transitions. By gating on known cascades of $L=1$ transitions, the detection probability for these γ rays was found to be 0.64(8) that for quadrupole transitions. The uncertainty in this measure strongly affects the relative intensity of the low-lying $5^-\rightarrow4^+$ transition which is known to be in coincidence with the SD band. Taking these factors into account, the average spin at which the intensity of the SD band reenters the normal states is $4.9\pm1.2\hbar$. The difference of approximately $2\hbar$ of angular momentum between the decay and the reentrance of the intensity of the SD band is in excellent agreement with similar values found in studies of the decay of other SD bands in the $A\approx190$ mass region [12,13].

In addition to delineating the average spin at which the ^{194}Pb SD band depopulates/reenters, a search was undertaken for discrete transitions which depopulate the SD band. Since this search took place at the limit of experimental sensitivity, four criteria were established to ensure that a candidate peak corresponded to a viable linking transition. (1) The full-width at half-maximum of the candidate, corrected for the energy of the transition, was required to be consistent with the measured value for other peaks in ^{194}Pb. (2) The peak was checked to ensure that it was not visible in a total projection of the data, to minimize artifacts caused by inadequate background subtraction. (3) The intensity of a candidate was required to track the intensity of the SD band under different gating conditions and variations in the background subtraction. (4) Any proposed candidate was required to ap-

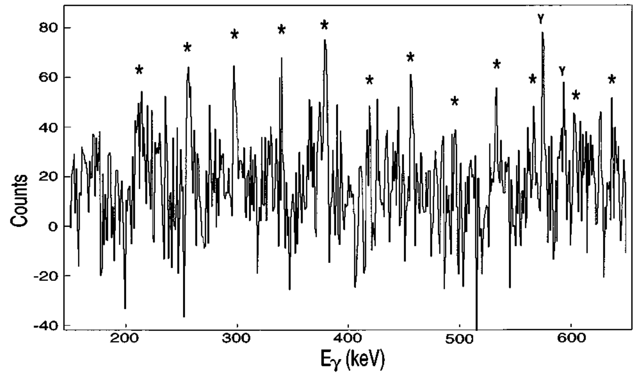

FIG. 3. The background subtracted spectrum associated with a 10-keV wide gate at 2.746 MeV. The ^{194}Pb yrast superdeformed band members are denoted by $*$ with a Y denoting the known low-lying transitions known to be in coincidence with the SD band and observed in this spectrum. The spectrum is compressed by a factor of 2 to smooth out fluctuations.

pear in each of the three experimental data sets, with any variations in its intensity consistent with changes in the SD band intensity.

Of the four criteria listed above, the fourth proved to be the most important to our analysis. By initially keeping the data collected from the three runs separate, we were able to place stringent limits on discrete transitions depopulating the SD band. While a large number of possible candidates was suggested by the data collected in the first experiment, by applying the fourth criterion to subsequent data sets only a *single* candidate remained. No evidence has been found for any other discrete transition in coincidence with the SD band in the energy range of 2 MeV $\leqslant E_\gamma \leqslant$ 4 MeV. Summing the three data sets, an upper limit of $\leqslant 3\%$ ($\leqslant 5\%$) can be placed on the intensities of a $L=2$ ($L=1$) discrete transition with an energy of 3 MeV. Folding in the detection efficiency of the Early Implementation of GAMMASPHERE, this corresponds to limits of $\leqslant 2\% (\leqslant 3\%)$ and $\leqslant 4\% (\leqslant 7\%)$ for discrete $L=2$ ($L=1$) transitions at $E_\gamma = 2$ and 4 MeV, respectively.

The sole discrete transition found in our analysis has an energy of 2.746(2) MeV and was originally observed in the first data set at a level of 3σ statistical significance. This transition was confirmed in the second (third) data set at the 4σ (3σ) level. By summing the three data sets the significance of the 2.746(2)-MeV transition increased to slightly less than 5σ in accordance with the increased statistics. Due to limited statistics we have been unable to measure the multipolarity of the 2.746-MeV transition using standard techniques. Assuming that the 2.746-MeV γ ray is an $L=2$ transition, it carries 6(2)% of the intensity of the SD band.

As shown in Fig. 3, a background subtracted gate set at 2.746 MeV on the raw E_γ–E_γ matrix was found to be in coincidence with all 11 members of the ^{194}Pb SD band with energies in the range 200 keV $\leqslant E_\gamma \leqslant$ 640 keV. Similar gates were set 20 keV above and below the 2.746-MeV candidate transition. For the spectra gated 20 keV below (above) 2.746 MeV a total of 2 (4) peaks were found with energies corresponding to the 11 SD band members, 6 (3) regions were negatively correlated with the SD band members, and 3 (4) regions had counts consistent with the average background. Thus, the 2.746-MeV transition is in true coincidence with the SD band, and this coincidence is not a general feature of this energy region. Furthermore, in this gate all of the SD transitions from 200 keV to 500 keV have relative intensities consistent with the full population of the SD band, as would be expected if the 2.746-MeV transition corresponds to a γ ray associated with the decay of the band. We are unable to definitively claim that the lowest-energy transition in the ^{194}Pb SD band (at 170 keV) is not in coincidence with the 2.746-MeV transition due to contaminants in this region of the spectrum. If the 170-keV SD transition is in coincidence with the gate, however, it would have a relative intensity less than half that of the SD band.

In Fig. 3 we have also marked the energies corresponding to low-lying transitions known to be in coincidence with the SD band. The low-lying $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions with energies of 595 and 575 keV (and the 965-keV $2^+ \rightarrow 0^+$ transition which is not shown) are clearly coincidence with the 2.746-MeV transition. The normalized intensities for both the low energy SD and normal transitions in coincidence with the 2.746-MeV γ-ray is summarized in Fig. 2(b). Of particular interest is the lack of evidence for the $8^+ \rightarrow 6^+$ and $5^- \rightarrow 4^+$ transitions that feed and run parallel to the $6^+ \rightarrow 4^+$ transition, respectively. Furthermore, within errors, the 595-, 575-, and 965-keV transitions contain the full intensity of the SD band contained within this gate. Therefore, we propose that the 2.746-MeV transition directly feeds the low-lying 6^+ level. Finally, gates set on the low-lying $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ peaks show an intensity of the 2.746-MeV γ ray which is consistent with it originating *solely* from the decay of the SD band.

Since the 2.746-MeV transition feeds the low-lying 6^+ level directly we can eliminate the possibility that this transition corresponds to the first step of a purely statistical cascade, which would populate all of the low-lying levels known to be in coincidence with the SD band. Furthermore, since the initial level for this transition appears to be populated solely via the decay of the SD band, the anomalously large intensity carried by the 2.746-MeV γ ray is also inconsistent with it being the final step in a multitransition statistical decay cascade. Thus, it appears that the 2.746-MeV transition is a γ ray that directly links the SD level fed by the 213-keV transition and the 6^+ level in the first well.

Although the multipolarity of the 2.746-MeV transition cannot be determined directly, from intensity balance arguments it is apparent that this transition does not depopulate an isomeric level. Should the initial level have a relatively long lifetime (on the order of the 17 ns of the low-lying 8^+ level), the intensity of the low-lying normal states in coincidence with the 2.746-MeV transition would be measurably less than that of the SD band. Under the standard assumption that prompt γ rays are either electric or magnetic dipoles or electric quadrupoles, the high-lying level depopulated via the 2.746-MeV transition must have $4 \leqslant I \leqslant 8$. Furthermore, by decaying solely to the low-lying 6^+ and not to the 4^+ state, the more probable assignment for this level is $J^\pi = 7^\pm, 8^+$. Since the yrast SD band in ^{194}Pb has no known signature partner, it is assumed to be built upon a $K=0$ bandhead, which means that the originating level for the 2.746-MeV transition would have $J^\pi = 8^+$. Therefore, we have experimentally determined that the yrast SD band has positive parity, and—since the 213-keV is the final SD transition clearly seen in coincidence in the gate at 2.746 MeV—we have directly confirmed the spin assignment made in Ref. [7].

Since the low-lying 6^+ level has an excitation energy of 2.135(1) MeV, the excitation energy of the 8^+_{SD} level is 4.881(2) MeV. Using the values provided in Ref. [7], the SD band head energy can be determined by extrapolating the fitted parameters to a spin of $0\hbar$. The SD band head then has an excitation energy of 4.471(6) MeV in reasonable accordance with various theoretical calculations. For example, the ^{194}Pb SD excitation energy is estimated to be 4.86 MeV [14] from Hartree-Fock calculations and 3.8 MeV [15] using the Strutinsky method built on a Woods-Saxon average potential. Since the energies and relative intensities of the competing $8^+_{\mathrm{SD}}\to 6^+_{\mathrm{SD}}$ and 2.746-MeV transitions are known we can estimate the reduced matrix element $B(E2)$ for the 2.746-MeV transition. Assuming that the $B(E2)$ for the $8^+_{\mathrm{SD}}\to 6^+_{\mathrm{SD}}$ transition is 2000 W.u. (as measured for the $10^+_{\mathrm{SD}}\to 8^+_{\mathrm{SD}}$ γ ray in this band [16]), the 2.746-MeV transition has $B(E2)=4\times 10^{-4}$ W.u.

Finally, we have undertaken analyses similar to that presented by Atac and co-workers for the decay of the SD band in ^{143}Eu [17]. Summing the three data sets, single gates were set on each of the SD band members in unfolded threefold (fourfold) events, and the remaining two (three) transitions were summed to search for double (triple) step statistical decays depopulating the SD band. No statistically significant candidate cascades were found in these analyses. A series of Monte Carlo simulations were undertaken (in a manner similar to work first done for ^{194}Hg by one of us, I.Y.L.) to estimate the upper limit for the intensity that can be carried by unobserved multistep decay pathways using the Atac analysis method. Conservative estimates of two and four times that associated with the search for $L=1$ discrete decays (for two- and three-step cascades, respectively) have been established. Therefore, the most intense multistep cascades would be expected to have intensities lying slightly below the sensitivity of our experiment provided that the low-lying states are populated via multistep decay cascades in ratios consistent with their final intensity.

In summary, a series of three experiments using the ^{25}Mg(^{174}Yb,5n) ^{194}Pb reaction have been undertaken using the Early Implementation of GAMMASPHERE. A total of 1.95×10^9 unfolded threefold events was collected and used to study the decay of yrast SD band in this nucleus. The ^{194}Pb SD band decays at an average spin of $7.0\pm 1.1\hbar$ and its intensity reenters the normal low-lying levels at an average spin of $4.9\pm 1.2\hbar$. We searched for one-, two-, and three-step cascades depopulating the SD band. A single γ ray with an energy of 2.746(2) MeV depopulating the SD band has been identified in these analyses. The most consistent interpretation of this γ ray is that it is a stretched $E2$ transition directly connecting the 8^+_{SD} level with the 6^+ state in the first well. This transition carries 6(2)% of the full SD band intensity and has a $B(E2)=4\times 10^{-4}$ W.u. Using this assignment the excitation energy of the SD band head lies at 4.471(6) MeV, consistent with theoretical estimates. Upper limits of $\leqslant 3\%$ and $\leqslant 5\%$ of the SD band intensity can be placed on additional single-step $L=2$ and $L=1$ decay transitions, respectively, with an energy of 3 MeV, and these upper limits can be scaled as a function of energy with the efficiency of the array. Although it is difficult to determine similar values for the unobserved two- and three-step decay pathways, conservative limits two and four times that of single-step $L=1$ decays have been estimated. Clearly further experimental work aimed at fully characterizing the 2.746-MeV γ ray, measuring the $B(E2)$ value for the $8^+_{\mathrm{SD}}\to 6^+_{\mathrm{SD}}$ transition, and (most importantly) locating the remaining 94(2)% of the SD decay intensity is required.

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[1] H.-L. Hanand C.-L. Wu, At. Data Nucl. Data Tables **52**, 43 (1992).
[2] K. Theine *et al.*, Z. Phys. A **336**, 113 (1990).
[3] M. J. Brinkman *et al.*, Z. Phys. A **336**, 115 (1990).
[4] H. Hübel *et al.*, Nucl. Phys. **A520**, 125c (1990).
[5] W. Korten *et al.*, Z. Phys. A **334**, 475 (1993).
[6] B. J. P. Gall *et al.*, Phys. Lett. B **345**, 124 (1995).
[7] J. A. Becker *et al.*, Phys. Rev. C **46**, 889 (1992).
[8] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[9] M. J. Brinkman, *Proceedings of the Conference on Physics from Large γ-Ray Detector Arrays*, Berkeley, California, 1994 (unpublished), p. 242.
[10] P. van Duppen, E. Coenen, K. Deneffe, M. Huyse, and J. L. Wood, Phys. Rev. C **35**, 1861 (1987).
[11] P. Willsau *et al.*, Z. Phys. A **344**, 351 (1993).
[12] T. L. Khoo *et al.*, Nucl. Phys. **A557**, 83c (1993).
[13] R. G. Henry *et al.*, Phys. Rev. Lett. **73**, 777 (1994).
[14] S. J. Krieger, P. Bonche, M. S. Weiss, J. Meyer, H. Flocard, and P. H. Heenen, Nucl. Phys. **A542**, 43 (1992).
[15] W. Satula, S. Cwiok, W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A529**, 289 (1991).
[16] R. Krücken *et al.*, Phys. Rev. Lett. **73**, 3359 (1994).
[17] A. Atac *et al.*, Nucl. Phys. **A557**, 109c (1993).