PHYSICAL REVIEW C VOLUME 55, NUMBER 6 JUNE 1997

Yrast superdeformed band in ^{194}Pb: J^{π} and E_x

K. Hauschild, L. A. Bernstein, J. A. Becker, D. E. Archer, and R. W. Bauer
Lawrence Livermore National Laboratory, Livermore, California 94550

D. P. McNabb, J. A. Cizewski, K.-Y. Ding, and W. Younes*
Rutgers University, New Brunswick, New Jersey 08903

R. Krücken, R. M. Diamond, R. M. Clark, P. Fallon, I.-Y. Lee, A. O. Macchiavelli, R. MacLeod, G. J. Schmid,
M. A. Deleplanque, and F. S. Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

W. H. Kelly
Iowa State University, Ames, Iowa 50011

(Received 26 November 1996)

The yrast superdeformed band in ^{194}Pb has been populated using the ^{174}Yb(^{25}Mg,5n)^{194}Pb reaction at $E_{\rm beam}=130$ MeV. Decay γ rays were detected using the GAMMASPHERE array at the 88-Inch Cyclotron. Twelve γ-ray transitions have been observed directly linking three members of the ^{194}Pb yrast superdeformed band to low-lying normal deformed levels. Anisotropy measurements indicate that these linking decays include $E1$, $M1$, and mixed $M1/E2$ multipolarities. The radiative widths deduced are very inhibited, typically $B(E1)\sim10^{-8}$ Weisskopf units (W.u.) and $B(M1)\sim10^{-5}$ W.u. Without recourse to *a priori* assumptions $J^{\pi}=6^{+}$ and $E_x=4878.4(3)$ keV have been unambiguously assigned to the lowest-lying observed superdeformed state (the state populated by the 170-keV intraband transition). The intensity of the observed primaries accounts for 21(2)% of the superdeformed band population. [S0556-2813(97)03105-1]

PACS number(s): 21.10.Re, 23.20.Lv, 25.70.Gh, 27.80.+w

I. INTRODUCTION

The observation of one-step ''primary'' gamma-ray transitions directly linking the superdeformed (SD) states to the normal deformed (ND) low-lying states of known excitation energies (E_x), spins, and parities (J^{π}) is crucial to determining the E_x and J^{π} of the SD states. With this knowledge one can begin to address some of the outstanding problems associated with SD nuclei, such as the identical band issue, and one can also place more stringent restrictions on theoretical calculations which predict SD states and their properties. This information may also lead to a more detailed understanding of the deexcitation of hot nuclei and other processes involved in the decay of SD bands to the ND states.

The resolving power of the new generation of 4π γ-ray spectrometers allows the prospect of realizing this goal. Brinkman *et al.* used the early implementation of the GAMMASPHERE spectrometer array (32 detectors) and proposed a single candidate γ ray linking the ^{194}Pb yrast SD band to the low-lying ND states in ^{194}Pb [1]. Using 55 detectors in the GAMMASPHERE array Khoo *et al.* observed multiple links between the yrast SD band in ^{194}Hg and the low-lying level scheme and conclusively determined values for E_x and J of the yrast SD states [2]. Here we report on an experiment in which GAMMASPHERE with 88 detectors was used: The E_x and J^{π} values of the yrast SD states in ^{194}Pb were uniquely determined. Twelve single-step linking transitions between the yrast SD band and low-lying states in ^{194}Pb have been identified, including the transition proposed by Brinkman. These transitions have been placed in the level scheme of ^{194}Pb using coincidence relationships and agreements between the energies of the primary transitions and the energy differences in level spacings. Furthermore, measurements of angular asymmetries have yielded the multipolarities of the primaries which have allowed J^{π} assignments of the ^{194}Pb SD states to be unambiguously determined for the first time without *a priori* assumptions about the character of SD bands. A study performed in parallel to our work using the EUROGAM-II array reports similar, but less extensive results [3].

II. EXPERIMENTAL DETAILS

The experiment was performed at the Lawrence Berkeley National Laboratory 88-Inch Cyclotron facility. High-spin states in ^{194}Pb were populated following the ^{174}Yb(^{25}Mg, $5n$) reaction at $E(^{25}{\rm Mg})=130$ MeV. Coincident γ rays emitted during the decay of these high-spin states were detected using the GAMMASPHERE array [4] which, for this experiment, consisted of 88 large-volume ($\sim$75% efficient) Compton-suppressed Ge detectors. The detectors were located in rings at 17 different angles with respect to the beam: $\Theta=17.3(162.7)°$, $31.7(148.3)°$, $37.4(142.6)°$, $50.1(129.9)°$, $58.3(121.7)°$, $69.8(110.2)°$, $79.2(100.8)°$, $80.7(99.3)°$, and $90.0°$. The isotopically enriched ($>$98%) ^{174}Yb target was 1.21 mg/cm^2 thick, and evaporated directly onto a 6.13-mg/cm^2 Au backing. The signal-to-noise ratio of the SD primary γ rays is enhanced when a thick backing is

---

*Present address: Lawrence Livermore National Laboratory, Livermore, California 94550.

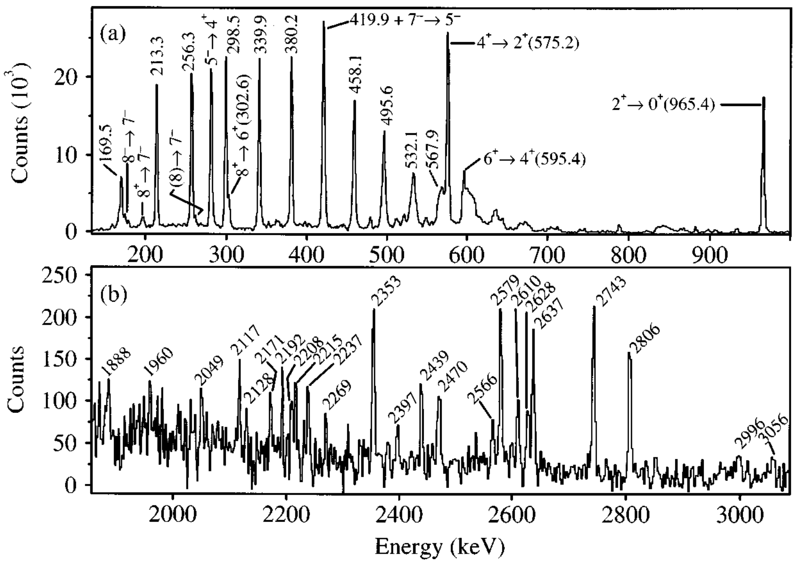

FIG. 1. Background-subtracted coincidence spectra obtained from the singly gated cube by summing all possible pairwise gate combinations of the 170–532 keV ^{194}Pb yrast SD transitions. Exclusion of the 419-keV SD line from the gate list used to create the cube results in its apparent increased intensity. The low-energy portion, panel (a), displays the yrast SD band and transitions arising from deexcitation of the low-lying ND states, while (b) presents the one-step transitions (primaries) directly linking the SD and ND states. Transition energies are labeled in keV. Yrast transitions in (a) are labeled by $J_i^\pi \to J_f^\pi$.

used because the lower-lying SD states have lifetimes that are longer than the characteristic stopping times of the evaporation residues in the Au foil. Thus, the linking transitions do not exhibit angle-dependent Doppler shifts, or broadening, and the intrinsic detector line shape is expected. Approximately 7×10^9 events were recorded with suppressed Ge fold $\geqslant 4$.

III. ANALYSIS

The search for linking transitions was performed using a triple coincidence RADWARE cube [5], gated by at least one γ ray with an energy that corresponded to a ^{194}Pb yrast SD transition energy [6–10]. The SD-gate list excluded the 419.9-keV γ ray of the SD cascade due to its proximity to the 421.1-keV $7^- \to 5^-$ low-lying transition. In addition, the γ rays were required to be in prompt coincidence with respect to the beam pulse. High fold events (fold$\geqslant$5) were incremented into the SD-gated cube following the procedure of Ref. [11]. One should note that the excited bands in ^{194}Pb reported in Ref. [12] are not expected to influence our search for linking transitions between the yrast SD and ND states. First, with the exception of the 341- and the 456-keV lines of SD band 2*b*, the transition energies of the excited bands are sufficiently separated from those of the yrast band to cause little contamination of the yrast SD-gated cube. Second, both excited SD bands in ^{194}Pb are $\sim$5% of the yrast SD band, making it highly improbable that linking transitions from the excited bands to the ND states would be observed in these data. Energy and efficiency calibrations over the range 0.100–3.548 MeV were obtained from the standard ^{56}Co, ^{152}Eu, and ^{182}Ta sources.

Figure 1 illustrates two energy regions of a triple-gated, background-subtracted spectrum for the yrast SD band in ^{194}Pb projected from this cube. All possible combinations of double gates on the SD lines between 170 and 532 keV inclusive were summed to produce this spectrum. Relative in-band intensities deduced from this spectrum are given in Table I: 56(4)%, 34(6)%, and 10(7)% of the SD band intensity decay out occurs from the three lowest observed SD states, respectively. Figure 1(a) illustrates that a number of γ-ray transitions from the low-lying ND states in ^{194}Pb [13], labeled by their corresponding $J_i^\pi \to J_f^\pi$, are in coincidence with the yrast SD cascade. Many candidates for the discrete single-step transitions feeding into these low-lying ND states can be seen in the higher-energy portion of the triple SD-gated spectrum, Fig. 1(b). These transitions have energies in

TABLE I. The in-band SD transitions in ^{194}Pb: γ-ray energies E_γ, relative intensities I_γ,[a] intensity decaying out of the band I_{out}, asymmetry ratio R_{asym}, spin and parity information J^π, multipolarities σL, and the widths Γ_{SD} and Γ_{out}.

E_γ (keV)	I_γ (%)	I_{out} (%)	R_{aysm}	σL	Favored σL	$J_i^\pi \to J_f^\pi$	Γ_{SD} (eV) $\times 10^{-5}$	Γ_{out} (eV)
380.20(5)	91(4)	-	1.42(5)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$18^+ \to 16^+$		
339.90(5)	92(4)	-	1.40(5)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$16^+ \to 14^+$		
298.49(3)	94(4)	-	1.47(5)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$14^+ \to 12^+$		
256.32(3)	100(5)	-	1.40(5)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$12^+ \to 10^+$		
213.26(3)	90(5)	10(7)	1.45(4)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$10^+ \to 8^+$	6.9(9)	0.8(1)
169.52(4)	56(4)	34(6)	1.48(8)	$L=1,\Delta J=0$ or $L=2,\Delta J=2$	$E2$	$8^+ \to 6^+$	2.8(4)	1.7(3)
-	-	56(4)					1.2(1)[b]	15(4)[b]

[a] Corrected for detector efficiency and electron internal conversion, and normalized to the intensity of the 256.3-keV transition.

[b] Assumes smooth extrapolation of E_γ^{SD} [$E_\gamma^{\text{SD}}(6+ \to 4+) = 124.4$ keV] and $I_\gamma(6+ \to 4+) = 0.04\%$.

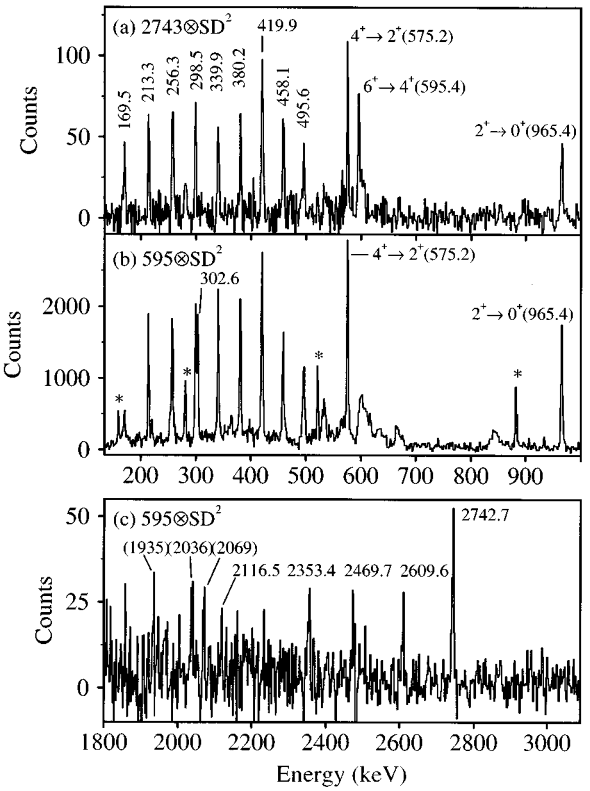

FIG. 2. Coincidence spectra projected from an SD gated cube obtained from the summation of pairwise gates between the yrast SD band and (a) the 2743-keV transition and (b),(c) the 595-keV yrast $6^+ \rightarrow 4^+$ transition. An asterisk denotes a contaminant from ^{193}Pb brought in by the 213⊗595 keV gate. Transition energies are labeled in keV.

the range corresponding to those expected for the primary linking γ rays [14].

Coincidence relationships between these candidate primaries, the low-lying γ rays, and the yrast SD transitions in ^{194}Pb were used to verify which, indeed, are linking transitions, and to place them in the ^{194}Pb level scheme. We give two examples. For the first example, coincidence relationships for the 2743-keV primary transition were deduced from the background-subtracted spectra shown in Fig. 2. Figure 2(a) was obtained by summing all triple-gate combinations between the 2743-keV transition and two of the yrast SD band in ^{194}Pb. From this spectrum we determined that the 2743-keV γ ray depopulates the band below the 170-keV intraband SD transition since the 170-keV line is observed. Another important feature is the enhancement of the 595-keV $6^+ \rightarrow 4^+$ low-lying yrast transition in comparison with Fig. 1(a). This indicates that the 2743-keV transition decays into, or above, the state from which the 595-keV line depopulates. As a second example, in Figs. 2(b) and 2(c) we present partial spectra obtained by a summation of triple gates on the 595-keV and any two in-band SD transitions. It is apparent from these figures that the 595-keV γ ray is in coincidence with the SD band, the 303-keV $8^+ \rightarrow 6^+$ transition, and the 2117-, 2353-, 2470-, 2610-, and 2743-keV primary transitions.

Initially seven linking transitions could be placed with the adopted level scheme of ^{194}Pb compiled by Browne and Singh [13]. A full resolution RADWARE cube [5] was, therefore, sorted to build a more complete low-lying excitation spectrum. The resulting level scheme (see Fig. 3) is essentially that of Refs. [15] and [16] with the addition of the 664- and 672-keV transitions observed in Ref. [17]. These two transitions depopulate states with $E_x = 2800$ and 2914 keV, respectively. Also, the 283-, 479-, 722-, and 788-keV transitions observed in Ref. [17] were placed at an $E_x =$ 2525, 2299, 3522, and 2609 keV, respectively. Additional states were added at 3374 and 3471 keV and a previously unobserved 867-keV γ ray at $E_x = 2408$ keV. Twelve of the candidate primaries were placed with the aid of the new decay scheme of ^{194}Pb. We have also established that 12 further transitions are in coincidence with yrast SD band. These γ rays are listed in Table II. However, these transitions are too weak to be uniquely placed in the ^{194}Pb level scheme; they could form part of the multiple-step decays between SD and ND states.

Multipolarities of the SD lines and the linking transitions were deduced from an empirical asymmetry ratio R_{asym}. Matrices were constructed which contained γ-γ coincidences between any detector with (1) detectors located at the three most "forward" and "backward" angles ($\Theta = 17.3°$, $31.7°$, $37.4°$ and $142.6°$, $148.3°$, $162.7°$ with respect to the beam line) and, (2) detectors at $\overline{90°}$ ($\Theta = 69.8°$, $79.2°$, $80.7°$, $90.0°$, $99.3°$, $100.3°$, and $110.2°$ with respect to the beam line). The asymmetry ratio $R_{\mathrm{asym}}(E_{\gamma}) = I_{\gamma}(\text{forward}+\text{backward})/I_{\gamma}(\overline{90°})$, multiplied for convenience by the ratio of the number of detectors at $\overline{90°}$ to the number at the forward and backward angles, was deduced for relevant γ rays in these matrices. R_{asym} values of known low-lying stretched $L=2$ and $L=1$ transitions are given in Table III. The mean values are 1.35(3) and 0.71(2), respectively.

The R_{asym} values obtained for the SD and linking transitions are given in Tables I and IV, respectively. One should note that with these R_{asym} ratios it is not possible to distinguish between (1) $L=1$, $\Delta J=1$ and $L=2$, $\Delta J=0$ and (2) $L=1$, $\Delta J=0$ and $L=2$, $\Delta J=2$ transitions. Nevertheless, these measurements can be used to place *restrictions* on the primary multipolarities and, since J_f^{π} is known, limits on J_i^{π}. On comparing the possible J^{π} values deduced for each SD level from the measured angular anisotropies of the linking transitions (Table IV, column 6) one finds that the two lowest SD states can only be assigned $J^{\pi} = 6^+$ and $J^{\pi} = 8^+$, respectively. These assignments have been made without *any* assumptions about the nature of the SD band and are in agreement with those calculated in Ref. [18]. In addition, a mean value of $R_{\mathrm{asym}} = 1.43(2)$ was measured for the intraband SD transition, consistent with the above J^{π} assignments, confirming their $E2$ character (see Table I).

These results have allowed the excitation energy of the yrast 6^+ SD state in ^{194}Pb to be unambiguously determined; we find $E_x(6^+)_{\mathrm{SD}} = 4878.4(3)$ keV, in agreement with [3]. Assuming a smooth extrapolation to $J=0$ [18], the bandhead of the SD band is estimated to have $E_x \simeq 4640.7(4)$ keV. This is in very good agreement with the axial Hartree-Fock-Bogoliubov + BCS calculations of Krieger *et al.* [14], performed with the Skm* effective interaction which predict $E_x(0^+_{\mathrm{SD}}) = 4.86$ MeV. For comparison, $E_x(0^+_{\mathrm{SD}})$ is estimated

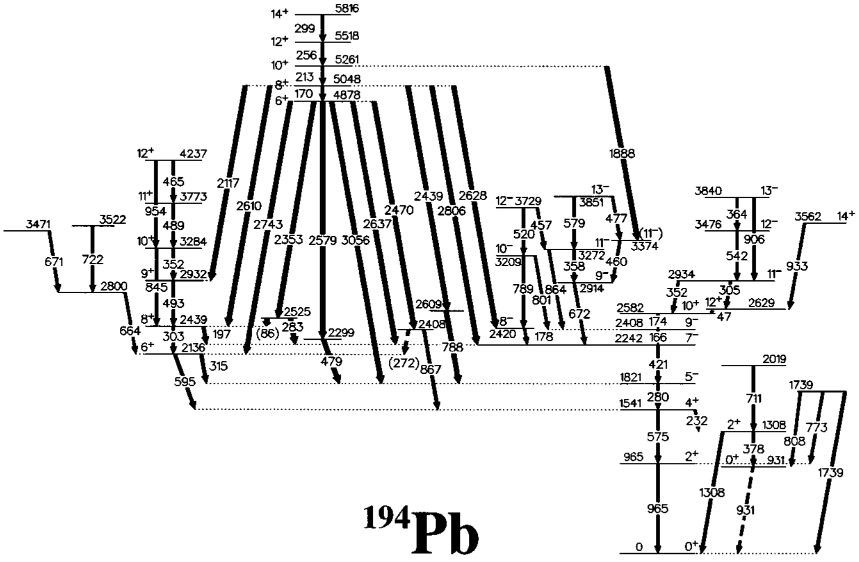

FIG. 3. Decay paths out of the ^{194}Pb yrast SD band. Levels are labeled by E_x in keV and J^π. Transition energies are labeled in keV. For clarity, only states in the immediate E_x and J^π region of the lowest observed SD levels are shown.

to be 6.017 MeV in ^{194}Hg [2], the only other example in the $A\sim190$ region of an SD cascade to have been unambiguously linked into the low-lying level scheme via primary transitions. In this case, the same calculations predict the bandhead of ^{194}Hg to lie at 5.00 MeV, a significant disagreement. The calculations do not include the nonaxial degree of freedom or configuration mixing, which are expected to be more important in ^{194}Hg than in ^{194}Pb. Inclusion of these effects may ameliorate the discrepancy. An alternate self-consistent calculation by Girod [19], with the $D1S$ effective interaction, yields 6.49 and 4.55 MeV, respectively, for these two nuclei. These calculations, while also axial, include configuration mixing effects through the solution of the Bohr-Hamiltonian, an approximation to the generator coordinate method (GCM) equation. The better agreement of this calculation for ^{194}Hg, without loss of agreement in ^{194}Pb, may imply the importance of configuration mixing for ^{194}Hg or the efficacy of the $D1S$ effective interaction in this region of the periodic table. However, both more experimental values and improved calculations will be required to decide this technically important point.

Reduced transition probabilities $B(\sigma L)$ (where σ represents either electric or magnetic radiation and L is the multipolarity) for the primary decays have been calculated by relating the branching ratio of each primary to the in-band $B(E2)$ value assuming a constant in-band transition quadrupole moment $Q_t=20.6(13)$ e b, derived from both Doppler shift attenuation [20] and recoil distance [21] measurements. $B(\sigma L)$ values are given in Table IV. Obtaining $B(\sigma L)$'s for the primaries depopulating the 6^+ SD state required the following additional assumptions about the unobserved $6^+\rightarrow4^+$ intraband transition. First, the energy (124.4 keV) was calculated from a smooth extrapolation of known transition energies. Second, the intensity of this transition is estimated to be $\leqslant4\%$. The resulting transition strengths indicate that the decay out of the SD states is highly retarded—typical values were found to be $B(E1)\sim10^{-8}$ Weisskopf units (W.u.) and $B(M1)\sim10^{-5}$ W.u.

TABLE II. Transitions observed in coincidence with the yrast ^{194}Pb SD band in addition to those placed into the level scheme of Fig. 3. Transition energies in keV. Errors are ~1 keV.

Transitions observed in coincidence with $8^+_{\mathrm{SD}}\rightarrow6^+_{\mathrm{SD}}$ 170-keV line	 $10^+_{\mathrm{SD}}\rightarrow8^+_{\mathrm{SD}}$ 213-keV line[a]
1960	2128
2049	2208
2171	2215
2192	2269
2237	2397
	2566
	2996

[a]Not observed in coincidence with the $8^+_{\mathrm{SD}}\rightarrow6^+_{\mathrm{SD}}$ 170-keV transition.

Similarly retarded transition strengths were obtained for the primary ($E1$) decays from SD states in ^{194}Hg, as summarized in Table V. However, there are a number of striking differences between the character of the linking transitions observed in these two cases. From a comparison of Tables IV and V it is immediately apparent that many more primaries are observed in ^{194}Pb—12 linking transitions have been placed in the level scheme of ^{194}Pb compared to 4 in ^{194}Hg. Also, in contrast to ^{194}Hg in which only $E1$'s have been observed, the linking transitions in ^{194}Pb are of $E1$, $M1$, and mixed $M1/E2$ multipolarities. That we observe both $E1$ and $M1$ transitions depopulating the ^{194}Pb SD band is not unexpected. In average resonance neutron capture [23], $M1$ strengths are typically 1/7 of the $E1$ strengths and both $E1$ and $M1$ transitions routinely depopulate highly excited

TABLE III. Asymmetry ratios obtained from the present data for known stretched $L=1$ and $L=2$ transitions in ^{194}Pb.

E_γ (keV)	$J_i^\pi\rightarrow J_f^\pi$	σL	R_{aysm}
195.8	$8^+\rightarrow7^-$	$E1$	0.66(12)
280.2	$5^-\rightarrow4^+$	$E1$	0.71(2)
302.6	$8^+\rightarrow6^+$	$E2$	1.33(12)
595.4	$6^+\rightarrow4^+$	$E2$	1.30(8)
575.2	$4^+\rightarrow2^+$	$E2$	1.34(4)

TABLE IV. The primary SD decay data in ^{194}Pb: E_{γ}, I_{γ}, R_{asym}, J^{π}, σL, and reduced transition probabilities $B(\sigma L)$. I_{γ} is given as a percentage of the SD band population.[a]

E_{γ} (keV)	I_{γ} (%)	R_{aysm}	σL	J_f^{π}	J_i^{π}	Favored σL	$B(\sigma L)$ (W.u)
Decays out of the third lowest SD level ($J_i^{\pi}=10^+$)							
1887.9(3)	1.0(4)	0.9(1)	$L=1,\Delta J=1$; $L=2,\Delta J=0$	(11^-)	$(10^{\pm},11^-,12^{\pm})$	$(E1)$	$5(2)\times10^{-8}$
Decays out of the second lowest SD level: $J_i^{\pi}=8^+$							
2116.5(4)	0.9(5)	0.3(1)	mixed $M1/E2$	9^+	$8^+,9^+,10^+$	$M1/E2$	
2438.5(4)	0.9(4)	1.0(2)	mixed $M1/E2$	-	-	-	
2609.6(4)	1.7(6)	1.4(3)	$L=1,\Delta J=0$; $L=2,\Delta J=2$	8^+	$6^+,8^{\pm},10^+$	$M1$	$2.3(9)\times10^{-6}$
2627.9(4)	1.3(6)	1.4(3)	$L=1,\Delta J=0$; $L=2,\Delta J=2$	8^-	$6^-,8^{\pm},10^-$	$E1$	$1.6(8)\times10^{-8}$
2806.1(3)	1.7(5)	0.7(1)	$L=1,\Delta J=1$; $L=2,\Delta J=0$	7^-	$6^{\pm},7^-,8^{\pm}$	$E1$	$1.7(6)\times10^{-8}$
Decays out of the lowest SD level: $J_i^{\pi}=6^+$							
2353.4(3)	2.8(6)	0.8(1)	$L=1,\Delta J=1$; $L=2,\Delta J=0$	-	-	-	
2469.7(4)	1.5(6)	1.4(3)	$L=1,\Delta J=0$; $L=2,\Delta J=2$	-	-	-	
2579.1(2)	3.0(6)	0.7(1)	$L=1,\Delta J=1$ $L=2,\Delta J=0$	-	-	-	
2636.6(2)	1.8(6)	0.8(2)	$L=1,\Delta J=1$; $L=2,\Delta J=0$	7^-	$6^{\pm},7^-,8^{\pm}$	$E1$	$\geqslant12(5)\times10^{-8}$
2742.5(2)	3.3(6)	1.1(2)	mixed $M1/E2$	6^+	$5^+,6^+,7^+$	$M1$	$\geqslant22(7)\times10^{-6}$
3056.4(12)	0.8(5)	-	-	5^-	-	$E1$	$\geqslant4(2)\times10^{-8}$

Total $I_{\gamma}=21(2)\%$ of SD band intensity accounted for by the above primaries.

[a] The relative intensities were obtained from a triple-gated, background-subtracted spectrum for which the 170-, 213-, and 256-keV lines, in addition to the 420-keV line, were not included in the SD gate list, corrected for detector efficiency and normalized to the intensity of the 256.3-keV SD line. Angular dependence of γ-ray emission has not been corrected for; it is not expected to be important because of the 4π coverage of GAMMASPHERE.

normal states, for example, in ^{114}Sn [24]. One should also note that the decay of the shape isomers in ^{236}U [25] and ^{238}U [26] is also very different; the predominant γ branches are $E1$ and $E2$, respectively.

A surprisingly large proportion of the ^{194}Pb band intensity, 21(2)%, is accounted for by the one-step decays compared to the recent results in ^{194}Hg which indicate that only ~5% of the yrast SD band intensity is attributed to the one-step links [2]. The root cause of these differences reflects the greater phase space for decay available in ^{194}Hg compared to ^{194}Pb. The factors that contribute to this are the following: (1) The excitation energies of the SD bandheads in ^{194}Pb and ^{194}Hg are estimated to be 4.640 and 6.017 MeV, respectively. (2) The spin of the SD states at deexcitation is higher in ^{194}Hg. (3) The E_x of the ND states into which the primaries decay is ~2.4 and ~2.8 MeV for ^{194}Pb and ^{194}Hg, respectively. (4) In addition, ^{194}Pb is spherical at low excitation energy, while coexisting oblate and prolate minima at further increase the density of ND states in ^{194}Hg compared to ^{194}Pb. These distinctions result in an order of magnitude difference in the level densities of states at the point of deexcitation in ^{194}Hg, leading to a more fragmented decay.

TABLE V. The primary decay data for ^{194}Hg. E_{γ}, I_{γ}, and σL taken from [2].

E_{γ} (keV)	I_{γ} (%)	σL	$B(\sigma L)$ W.u.[a]
Decays from the $J^{\pi}=12^+$ superdeformed state			
3489.3	1.4	$E1$	$2.7(6)\times10^{-8}$ [a]
3709.6	0.7	$E1$	$1.1(3)\times10^{-8}$ [a]
4195.2	1.2	$E1$	$1.3(3)\times10^{-8}$ [a]
Decays from the $J^{\pi}=10^+$ superdeformed state			
4485.3	1.5	$E1$	$1.1(3)\times10^{-7}$ [b]
Total $I_{\gamma}=4.8\%$			

[a] These values correct an error in Ref. [2].

[b] Assumes $E_{\gamma}^{\mathrm{SD}}(10^+\rightarrow8^+)=211.7$ keV and $I_{\gamma}^{\mathrm{SD}}(10^+\rightarrow8^+)=3\%$ [22].

It has been suggested that the decay of the SD to ND states is statistical and governed by the mixing between SD and ND levels at similar excitation energies [27]. In this scenario, the pattern observed in the decay of the SD states reflects the decay of the ND component and the retarded decay-out transition strengths result from a small admixture of ND components into the SD wave function. An order of magnitude calculation of the squared amplitude a_n^2 of the ND admixture has been performed using the method outlined by Krücken *et al.* [28]. These calculations relate the out-of-band transition probability λ_{out} to the $E1$ ND-ND transition probability $\lambda_{\mathrm{stat}}^{E1}$, which is estimated using a standard back-shifted spin-dependent level density formula [29] and the Brink-Axel giant dipole resonance (GDR) strength function [30,31] with Lorentzian parameters taken from [32]. The $a_n^2 = \lambda_{\mathrm{out}}/\lambda_{\mathrm{stat}}^{E1}$ values obtained are 1.0(1)%, 1.8(3)%, and 7(2)% for the 10^+, 8^+, and 6^+ SD states, respectively, assuming a constant in-band Q_t (errors have been determined from the experimentally deduced λ_{out} only). The increase in a_n^2 with decreasing spin reflects the competition between the in-band and out-of-band decay. Even if the Lorentzian function accurately modeled the dipole transition strength below ~3 MeV, one should note that a factor of 4 uncertainty in a_n^2 arises using published extremum values of the level density parameter a, $a = A/7.5$ [33] to $a = A/13.5$ [34]. Further uncertainties arise from a limited knowledge of the level density itself, and the peak cross section, energy, and width of the GDR for neutron-deficient Pb isotopes.

IV. SUMMARY

In summary, 12 discrete one-step γ-ray transitions have been observed linking three members of the ^{194}Pb yrast SD band to low-lying ND levels. A further 12 high-energy transitions have also been identified to be in coincidence with the yrast SD band. Anisotropy measurements have determined that the linking decays include $E1$, $M1$, and mixed $M1/E2$ transitions. $J^\pi = 6^+$, $E_x = 4878.4(3)$ keV and $J^\pi = 8^+$, $E_x = 5047.8(3)$ keV have been unambiguously assigned to the two lowest-lying observed superdeformed states without making assumptions about the properties of SD bands. These results represent the first experimentally self-consistent J^π assignments to an SD band.

Here 21(2)% of the ^{194}Pb yrast SD band intensity has been observed to decay out through the one-step linking transitions. At first glance this is a suprisingly large proportion of the SD flux when compared to the ~5% observed for the ^{194}Hg yrast SD band [2]. A more highly fragmented decay in ^{194}Hg is to be expected from simple arguments based on level density considerations at the point of SD decay, combined with the different low-lying ND structure of ^{194}Hg and ^{194}Pb. Evidently each case is different and any generalizations about the nature of the primary decays based on a single case must be viewed cautiously.

Calculations by Døssing *et al.* [35] estimate the branching ratio of single-step links to be ~5% compared to the unresolved statistical decays. However, these calculations have been ‘‘tuned’’ for ^{194}Hg and it is not clear how one would extrapolate to the different excitation energies and level densities of the ^{194}Pb case. The decay-out pattern of the yrast SD bands in has also been calculated by Bonche *et al.* [36]. These calculations reproduce qualitatively the SD band intensity profile, but for simplicity only treated $E2$ transitions. Both calculations need refinement.

Greater understanding of these properties is anticipated with the improved resolving power of the ‘‘complete’’ GAMMASPHERE and EUROBALL arrays, for example, excited bands and their decay properties. A unique determination of the J^π and E_x values of SD bands is needed to place more stringent restrictions upon theoretical calculations which predict the SD states and their properties, in particular, the excitation energy of the SD bandheads. In addition, this knowledge will help to address the phenomena of ‘‘identical’’ bands—for the first time the spins of states emitting γ rays of similar energies could be compared and configurations assigned to the SD bands with greater certainty.

ACKNOWLEDGMENTS

We would like to thank Torben Lauritsen for help with data acquisition and David Radford for RADWARE. We acknowledge often useful conversations with Mort Weiss. Joanne Heagney of MicroMatter fabricated the targets. The 88-Inch Cyclotron crew are thanked for faultless operation. This work has been funded in part by the U.S. Department of Energy, under Contracts Nos. W-7405-ENG-48 (LLNL) and AC03-76SF00098 (LBNL), and the National Science Foundation (Rutgers and Iowa State).

---

[1] M. J. Brinkman, in Proceedings of the Conference on Physics from Large γ-Ray Detector Arrays, Berkeley, California, 1994 (unpublished), p. 242; Phys. Rev. C **53**, R1461 (1996).

[2] T. L. Khoo *et al.*, Phys. Rev. Lett. **76**, 1583 (1996).

[3] A. Lopez-Martens *et al.*, Phys. Lett. B **380**, 18 (1996).

[4] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).

[5] D. C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 306 (1995).

[6] K. Theine *et al.*, Z. Phys. A **336**, 113 (1990).

[7] M. J. Brinkman *et al.*, Z. Phys. A **336**, 115 (1990).

[8] H. Hübel *et al.*, Nucl. Phys. **A520**, 125c (1990).

[9] W. Korten *et al.*, Z. Phys. A **334**, 475 (1990).

[10] B. J. P. Gall *et al.*, Phys. Lett. B **345**, 124 (1995).

[11] C. W. Beausang, D. Prevost, M. H. Bergstrom, G. deFrance, B. Haas, J. C. Lisle, Ch. Theisen, J. Timàr, P. J. Twin, and J. N. Wilson, Nucl. Instrum. Methods Phys. Res. A **364**, 560 (1995).

[12] J. R. Hughes *et al.*, Phys. Rev. C **50**, R1265 (1994).

[13] E. Browne and B. Singh, Nucl. Data Sheets **79**, 277 (1996).

[14] S. J. Krieger, P. Bonche, M. S. Weiss, J. Meyer, H. Flocard, and P.-H. Heenen, Nucl. Phys. **A542**, 43 (1992).

[15] D. Metha *et al.*, Z. Phys. A **345**, 169 (1993).

[16] M. G. Porquet *et al.*, J. Phys. G **20**, 765 (1994).

[17] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse, and J. L. Wood, Phys. Rev. C **35**, 1861 (1987).

[18] J. A. Becker *et al.*, Nucl. Phys. **A520**, 187 (1990).

[19] M. Girod (private communication).

[20] P. Willsau *et al.*, Z. Phys. A **344**, 351 (1993).

[21] R. Krücken *et al.*, Phys. Rev. Lett. **73**, 3359 (1994).

[22] M. P. Carpenter *et al.*, in Proceedings of the Workshop on GAMMASPHERE Physics, Berkeley, California, 1995 (unpublished).

[23] W. F. Davidson *et al.*, J. Phys. G **7**, 445 (1981).

[24] S. Raman, T. A. Walkiewicz, E. T. Jurney, J. Sa, Z. Gasci, J. L. Werl, K. Allaart, G. Bonsignon, and J. F. Shriner, Jr., Phys. Rev. C **43**, 521 (1991).

[25] J. Schirmer, J. Gerl, D. Habs, and D. Schwalm, Phys. Rev. Lett. **63**, 2196 (1989).

[26] J. Kantele, W. Stöffl, L. E. Ussery, D. J. Decman, E. A. Henry, R. J. Estep, R. W. Hoff, and L. G. Mann, Phys. Rev. C **29**, 1693 (1984).

[27] E. Vigezzi *et al.*, Phys. Lett. B **249**, 163 (1990); Y. R. Shimizu *et al.*, Nucl. Phys. **A557**, 99c (1993).

[28] R. Krücken, A. Dewald, P. von Brentano, D. Bazzacco, and C. Rossi-Alvarez, Phys. Rev. C **54**, 1182 (1996).

[29] A. Gilbert and A. G. W. Cameron, Can. J. Phys. **43**, 1446 (1965).

[30] D. M. Brink, Ph.D. thesis, Oxford University, Oxford, England, 1955.

[31] P. Axel, Phys. Rev. **126**, 671 (1962).

[32] S. S. Dietrich and B. L. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).

[33] U. Facchini and E. Saetta-Menichella, Energ. Nucl. (Italy) **15**, 54 (1968).

[34] A. Richter, *Nuclear Spectroscopy and Reactions* (Academic Press, New York, 1974), Vol. 40-B, p. 343.

[35] T. Døssing *et al.*, Phys. Rev. Lett. **75**, 1276 (1995).

[36] P. Bonche, J. Dobaczewski, H. Flocard, P-H. Heenen, S. J. Krieger, and M. S. Weiss, Nucl. Phys. **A519**, 509 (1990).