UCRL-103001
PREPRINT

Received by OSTI

JUL 0 5 1990

**LEVEL SPIN AND MOMENTS OF INERTIA IN
SUPERDEFORMED NUCLEI NEAR $A = 194$** **J.A. Becker, N. Roy, E.A. Henry, S.W. Yates,
and A. Kuhnert (LLNL)****J.E. Draper, W. Korten, C.W. Beausang,
M.A. Deleplanque, R.M. Diamond,
F.S. Stephens, W.H. Kelly and F. Azaiez (LBL)****J.A. Cizewski and M.J. Brinkman (Rutgers)****This paper was prepared for submittal to the proceedings
of the Conference on Nuclear Structure
in the Nineties
Oak Ridge, TN - April 23-27, 1990****April 1990** The logo of the Lawrence Livermore National Laboratory, featuring a stylized, layered V-shape or corner design. The layers are represented by different patterns: a white outer layer, a grey stippled middle layer, and a solid black inner layer. The text "Lawrence Livermore National Laboratory" is written diagonally across the white layer.
Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

LEVEL SPIN AND MOMENTS OF INERTIA IN SUPERDEFORMED NUCLEI NEAR $A = 194$

DE90 013477

J. A. Becker, N. Roy, E. A. Henry, S. W. Yates, A. Kuhnert

Lawrence Livermore National Laboratory, Livermore, California 94550

J. E. Draper, W. Korten, C. W. Beausang, M. A. Deleplanque*

R. M. Diamond, F. S. Stephens, W. H. Kelly, F. Azaiez

Lawrence Berkeley Laboratory Berkeley, California 94720

J. A. Cizewski, M. J. Brinkman

Rutgers University, New Brunswick, New Jersey 08903

Experimental transition energies in the superdeformed (SD) bands near $A = 190$ are least-squares fit to rotational model formulae in order to extract level spin. The data set includes 16 SD bands, which show no evidence of either irregular behavior near the bottom of the bands or abrupt angular momentum alignment at low $\hbar\omega$. The 9 transitions lowest in energy in each band are well described by the formulae. The fitted spin of the final state in the γ -ray cascade is within $\pm 0.1\hbar$ of an integer or half-odd integer for 13 of the bands. The weight of the evidence suggests that meaningful level spins corresponding to these transitions can be inferred. The moment of inertia at $\omega = 0$ is correlated, with $\mathcal{J} = 88.3(5)\hbar^2/\text{MeV}$ and $\mathcal{J} = 93.4(5)\hbar^2/\text{MeV}$ for the strong and weak bands, respectively.

1. Introduction

The experimental evidence supporting the existence of a new region of superdeformation near $A = 190$ has been steadily and rapidly accumulating. Presently the list of nuclei where γ -ray cascades characteristic of a superdeformed nuclear shape have been measured includes ^{190}Hg , ^{191}Hg , ^{192}Hg , ^{193}Hg , ^{194}Hg , ^{193}Tl , ^{194}Tl , ^{194}Pb , and ^{196}Pb [Ref. 1, 2-3, 4-5, 6, 6-8, 9, 10, 11-12, 11, respectively]. The more intense SD transitions produced in the reaction are consistent with multipolarity $L = 2$ [e.g. Ref. 2, 4, 5]. Transition energies of the SD cascades have a general trend: within a band they vary from ~ 200 to 850 keV, and the difference in transition energy decreases smoothly from ~ 40 to 30 keV with increasing transition energy.

The regular behavior and spacing of the transition energies, together with other measured properties of the SD bands, suggest that they follow rotational formulae. These elongated nuclei are well deformed and are expected to obey the strong coupling scheme, i.e., the single particle angular momenta are coupled to the nuclear symmetry axis, and the energy spectrum is given by $E = \hbar^2/2\mathcal{J} \cdot (I(I+1) - K^2)$. The Coriolis-interaction matrix elements are small compared to the level splitting of the single-particle energies for different Ω since the splitting of the Nilsson levels increases linearly with β , while the quantity $\hbar^2/2\mathcal{J}$, which multiplies the Coriolis matrix elements, decreases as β increases.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The nuclear alignment $i \rightarrow 0$ as $\hbar\omega \rightarrow 0$.

The low γ -ray transition energies suggest that they are near the bottom of the cascade where level spin I can be extracted reliably based on a comparison with simple rotational formulae predictions. The percentage change in E_γ with increasing spin is largest at the bottom of the band because for rotational band transitions $\Delta E_\gamma/E_\gamma \sim -dI/I$. For example, the lowest observed γ ray in the most intense SD ^{194}Hg cascade, which we label $^{194}\text{Hg}(2)$, has $E_\gamma = 201.2$ keV. With the γ -ray energy spacing $\Delta E_\gamma \sim 43$ keV and the transition multipolarity $L = 2$, the above expression implies $I = 10$.

The suggestion that level spins could be assigned to SD band members was made in Ref. 4, where the SD band in ^{192}Hg was discussed. Level spin determination is fundamental to understanding the physics of this new regime of deformation. It has already led to new insights in nuclear structure through the study of nuclear alignments^{13,14}.

2. Rotational Formulae

Harris¹⁵ has presented expansions for the nuclear rotational energy E in terms of even powers of the rotational frequency (ω) and for the nuclear spin I in terms of odd powers of ω . The expansion for level spin as a function of ω (up to ω^5) is

$$J = 2\alpha\omega + \frac{4}{3}\beta\omega^3 + \frac{6}{5}\gamma\omega^5 \quad (1)$$

(where $\hbar = 1$). In these equations α , β , and γ are expansion parameters with evident inertial interpretations, $J = \sqrt{I(I+1)}$ is the intermediate nuclear spin, and $\hbar\omega \approx E_\gamma/2$. The corresponding expansion for the dynamic moment of inertia $\mathcal{J}^{(2)}$ is [Be90]

$$\mathcal{J}^{(2)} = 2\alpha + 4\beta\omega^2 + 6\gamma\omega^4. \quad (2)$$

The appropriate value of $\hbar\omega$ in Eq. 2 is the average of the transition energies from which $\mathcal{J}^{(2)}$ is computed. Results presented here emphasize the least-squares fitting of the extracted $\hbar\omega$ to Eq. 1, assuming quadrupole transitions. This procedure takes best advantage of the statistical uncertainties in the measured data set. In general, least-squares fits were made to both Eq. 1 and Eq. 2 throughout our work and have produced consistent results. Draper, et al.,¹⁶ have emphasized the use of Eq. 2 directly.

3. The Least-Square Fits

The $\hbar\omega$ of each SD band were least-squares fit to Eq. 1 in the following fashion: All γ -ray transitions were assumed to be $L = 2$. Then, for each $\hbar\omega$, J of Eq. 2 was replaced by $J_f, J_f + L, J_f + 2L, \dots, J_f + nL$, where J_f is the baseline spin. Frequency independent alignment (such as might arise for $\Omega = 1/2$ bands) is included in J_f , and frequency dependent alignment is absorbed in the higher order terms of the expansion over the frequency range important for these fits. For these strongly coupled nuclei, nuclear alignment $i \rightarrow 0$ as $\hbar\omega \rightarrow 0$. Thus J_f , α , β , and γ are the fitting parameters in Eq. 1. Results are reported in terms of $I_f = J_f - 1$, which we identify with the spin

of the final state in the cascade. We also compute $\mathcal{J}^{(2)}$ with the fitted parameters, and compare this to the data through the use of Eq. 2.

The first 9 transitions of the SD bands (counting from low E_γ) were used in the fits in an effort to maintain consistency across the data sets. Data reported by the first reference listed in Table I were used. In general, reported errors were multiplied by a factor ~ 1.5 to obtain a χ^2/ν value near 1. The $\gamma\omega^5$ term in Eq. 1 did not improve the fit and it was set to 0. After an initial fitting, least-squares solutions to Eq. 1 were obtained for each band over a range of $I_f(\min) \pm 4\hbar$ in steps of $0.1\hbar$. Representative results of the plots of χ^2/ν vs I_f are presented in the insets of Figs. 1-2 for the three bands observed in ^{194}Hg and ^{191}Hg , respectively. The 95% confidence level is indicated by the horizontal line in the figure inset. It is clear that Eq. 1 describes the data well (with $\gamma = 0$), and that the least-squares solution produces values of $I_f(\min)$ which are sharp and approximately multiples of half integers. The expansion we have used results in a ratio $\beta/\alpha \sim 2 \times 10^{-6}$.

Fig. 1. $\mathcal{J}^{(2)}(\circ)$ and $\mathcal{J}^{(1)}(\circ)$ for $^{194}\text{Hg}(2)$. Data points represented by filled circles correspond to the γ -ray transitions used in the least-squares fit (1-9). The solid line drawn through the data points represents $\mathcal{J}^{(2)}$ calculated with Eq. 2. For comparison, the dot-dash and dash lines represent $\mathcal{J}^{(2)}$ calculated with $I_f(\min) \pm 1/2$.

Numerical results of the least-squares parameters α , β , and I_f resulting from a fit of Eq. 1 to the data sets are presented in Table I. The SD bands are identified by the lowest E_γ observed and with the arbitrary labels (1), (2), (3) ... when multiple bands have been observed in a particular nucleus. Errors are statistical only. $I_f(\min)$ is within $0.1\hbar$ of an integer or half-odd integer (as is appropriate for Z, A) for 13 of the 16 bands considered. The exceptions are $^{191}\text{Hg}(1)$, $^{193}\text{Hg}(1)$ and $^{194}\text{Tl}(2)$. There are alternative solutions for $^{191}\text{Hg}(1)$, $I_f = 29/2$ or $31/2$. Considered as separate trials, the weighted

mean of the difference between $I_f(\min)$ and the appropriate spin (integer or half-odd integer depending on Z, A) is 0.04(3), -0.12(07), 0.19(10), and 0.02(3) for the even-even, odd-A, odd-odd, and combined data sets, respectively.

Experimental and computed (Eq. 2) values of $\mathcal{J}^{(2)}$ are also illustrated in Figs. 1-2 for $^{194}\text{Hg}(2)$ and $^{191}\text{Hg}(1)$, respectively. The α and β values used were obtained from a least-squares fit to Eq. 1, with I_f fixed to the (half)integer nearest to $I_f(\min)$. A study of the figures illustrates that (1) there is no sudden alignment at low $\hbar\omega$ (frequencies where alignment is in any case expected to be approaching 0), (2) there is no particular sensitivity to the number of data points at low (or high) $\hbar\omega$ included in the fits, and (3) the expansion breaks down at high $\hbar\omega$ ($\sim 400\text{keV}$). The kinematic moment of inertia $\mathcal{J}^{(1)}$ vs $\hbar\omega$ is also illustrated in Figs. 1-2.

Fig. 2. $\mathcal{J}^{(2)}(\circ)$ and $\mathcal{J}^{(1)}(\circ)$ for $^{191}\text{Hg}(1)$. Data points represented by filled circles correspond to γ -ray transitions used in the least-squares fit (1-9). The solid line drawn through the data points represents $\mathcal{J}^{(2)}$ calculated with Eq. 3. For comparison, the dot-dash and dash lines represent $\mathcal{J}^{(2)}$ calculated with $I_f(\min) \pm 1$.

4. Discussion

The values of I_f deduced from the present data set are (half)integer for 13 of 16 cases within probable experimental error. Alignment is not quantized at low angular momentum, and it is unlikely that the cases presented here, which include even-even, odd-A, and odd-odd nuclei, would have the fitting parameter I_f an (half)integer unless the frequency independent alignment = 0. There is no strong evidence for alignment independent of frequency. We note that the two of the three exceptions are $^{191}\text{Hg}(1)$ and $^{193}\text{Hg}(1)$. Frequency dependent alignment over the fitting range is smooth and accommodated within Eq. 1. Therefore these results suggest that we are determining directly the nuclear spin

of the final state observed in the cascade as a result of our least-square fits to Eq. 1. The values of I resulting from this procedure are consistent with all spin assignments that have been inferred from the deexcitation of the SD band to the yrast states assuming a small number of linking transitions [Ref. 1, 4-5, 7-8].

The fitting procedure was repeated with I , fixed at the nearest (half)integer given in Table I. Numerical results are presented in Table II. More precise values of α and β are obtained, and an interesting correlation for $J = 2 \times \alpha$ is obtained. The values of α fall into two groups. The SD bands populated most strongly in the reaction (except for ^{190}Hg) have α equal within 1%: $\alpha(\text{ave}) = 4.415(13) \times 10^{-2} \hbar^2/\text{keV}$. The 'weak' signature partner bands also show a constant and different value of α , $\alpha(\text{ave}) = 4.672(10) \times 10^{-2} \hbar^2/\text{keV}$. The grouping of the values of α suggests that the SD bands have a common starting point, depending on whether or not they are 'yrast' or two quasi-particle bands. The two exceptions are ^{190}Hg and $^{194}\text{Tl}(2)$. We can understand the departure for ^{190}Hg if we recall theoretical calculations [e.g. Ref. 17-19] which show a decreasing well depth at the second minimum and smaller barrier height for ^{190}Hg , as compared for example to $^{192-194}\text{Hg}$, although ^{190}Hg still shows a well developed second minimum. Calculations also show the second minimum occurs at a constant mass quadrupole moment Q_m^2 , where the second minimum is well developed, roughly independent of A, Z . The values reported here are in accord with the trend of the predicted values. The increased moment of inertia of the quasi-particle bands relative to the ground state band in the same nucleus likely reflects blocking near the Fermi surface by the excited quasi-particles.

Acknowledgements

Nirabendu Roy was the first to recognize that a meaningful spin assignment could be made when he analyzed the ^{182}Hg data. Communication of data prior to publication by R. Janssens (Argonne National Laboratory) is also acknowledged.

This work was supported in part by U.S. Department of Energy under Contract W7405-ENG-48 (LLNL), the SDIO/IST (LLNL), in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U. S. Department of Energy under Contract DE-AC03-76SF00098 (LBL), and in part by the National Science Foundation (Rutgers).

TABLE I. Parameters from the least-squares fit of transitions 1-9 (beginning with the lowest energy) to Eq. 1. Errors in the expansion coefficients are the standard deviation σ or uncertainty ($\sim \sqrt{\chi^2/\nu} \times \sigma$) whichever is larger. $\Delta = I_f(\min) - \text{nearest(half) integer}$.

$A Z(id)$	E_γ (keV)	$\alpha(\times 10^{-2})$ ($\hbar^2/\text{keV}$)	$\beta(\times 10^{-8})$ ($\hbar^2/\text{keV}^3$)	$I_f(\min)$ ($\hbar$)	Δ ($\hbar$)	Ref.
$^{180}\text{Hg}(1)$	360.0	4.178(31)	8.14(23)	14.16 (10)	+0.16(10)	1
$^{181}\text{Hg}(1)$	350.6	4.558(22)	5.62(17)	14.87 (7)	+0.37(7)	2
$^{181}\text{Hg}(2)$	292.0	4.689(26)	5.45(59)	12.43 (7)	-0.07(7)	3
$^{181}\text{Hg}(3)$	311.8	4.662(42)	6.45(35)	13.38 (13)	-0.12(13)	3
$^{182}\text{Hg}(1)$	214.6	4.410(8)	8.44(11)	8.10 (2)	+0.10(2)	4,5
$^{183}\text{Hg}(1)$	293.6	4.527(49)	7.81(51)	12.13 (9)	-0.37(9)	6
$^{183}\text{Hg}(2)$	234.5	4.750(87)	5.39(99)	9.73 (21)	+0.23(21)	3
$^{184}\text{Hg}(1)$	201.2	4.657(16)	6.50(23)	7.95 (4)	-0.05(4)	7,8
$^{184}\text{Hg}(2)$	254.3	4.413(13)	8.68(15)	9.95 (3)	-0.05(5)	7,8
$^{184}\text{Hg}(3)$	262.5	4.620(32)	7.07(31)	10.83 (7)	-0.17(7)	6,8
$^{194}\text{Pb}(1)$	169.7	4.408(24)	8.17(43)	6.02 (5)	+0.02(5)	11, 12
$^{196}\text{Pb}(1)$	215.8	4.392(31)	5.78(39)	8.08 (8)	+0.08(8)	11
$^{193}\text{Tl}(1)$	228.1	4.755(28)	5.37(39)	9.46 (3)	-0.05(3)	11
$^{193}\text{Tl}(2)$	248.3	4.752(32)	6.16(38)	10.44 (8)	-0.06(8)	11
$^{194}\text{Tl}(1)$	268.0	5.021(55)	3.74(60)	12.09 (15)	+0.09(15)	10
$^{194}\text{Tl}(2)$	240.5	4.873(49)	4.20(43)	10.29 (13)	+0.29(13)	10

TABLE II. Parameters from the least-squares fit of transitions 1-9 (beginning with the lowest energy) with $I_f(\text{min})$ fixed at (half)integer. Data are arranged according to the value of the parameter α , which corresponds to 1/2 the moment of inertia at spin 0. Errors in the expansion coefficients are the standard deviation σ or uncertainty ($\sim \sqrt{\chi^2/\nu} \times \sigma$) whichever is larger. See Table I for references to the experimental data.

$AZ(id)$	E_γ (keV)	$\alpha(\times 10^{-2})$ ($\hbar^2/\text{keV}$)	$\beta(\times 10^{-8})$ ($\hbar^2/\text{keV}^3$)	I_f
<i>strong</i>				
$^{180}\text{Hg}(1)$	360.0	4.129(3)	8.51(6)	14
$^{191}\text{Hg}(1)$	350.6	4.444(5)	6.48(10)	29/2
$^{192}\text{Hg}(1)$	214.6	4.366(2)	9.03(8)	8
$^{194}\text{Hg}(2)$	254.3	4.430(1)	8.49(4)	10
$^{194}\text{Pb}(1)$	169.7	4.398(4)	8.33(16)	6
$^{196}\text{Pb}(1)$	215.8	4.363(5)	6.13(14)	8
<i>weak</i>				
$^{181}\text{Hg}(2)$	292.0	4.713(3)	5.21(8)	25/2
$^{191}\text{Hg}(3)$	311.8	4.709(4)	6.14(9)	27/2
$^{193}\text{Hg}(1)$	293.6	4.663(7)	6.45(18)	25/2
$^{193}\text{Hg}(2)$	234.5	4.662(8)	6.37(25)	19/2
$^{194}\text{Hg}(1)$	201.2	4.677(2)	6.23(8)	8
$^{194}\text{Hg}(3)$	262.5	4.682(4)	6.38(11)	11
$^{183}\text{Tl}(1)$	228.1	4.777(5)	5.07(2)	19/2
$^{183}\text{Tl}(2)$	248.3	4.773(4)	5.92(11)	21/2
$^{194}\text{Tl}(1)$	268.0	4.988(5)	4.08(14)	12
$^{194}\text{Tl}(2)$	240.5	4.767(8)	5.30(19)	10

References

- [1] M. W. Drigert et al., to be published.
- [2] E. F. Moore et al., Phys. Rev. Lett. 63, 360 (1989).
- [3] M. P. Carpenter et al., to be published.
- [4] J. A. Becker et al., Phys. Rev. C 41, R9(1990).
- [5] D. Ye et al., Phys. Rev. C 41, R13(1990).
- [6] E. A. Henry et al., Zeitschrift für Physik A 335, 361(1990).
- [7] C. W. Beausang et al., Zeitschrift für Physik A 335, 325(1990).
- [8] M. A. Riley et al., Nucl. Phys. A (submitted).
- [9] P. B. Fernandez et al., to be published.
- [10] F. Azaiez et al., to be published.
- [11] M. J. Brinkman et al., Zeitschrift für Physik A 336 115(1990).
- [12] K. Theine et al., Zeitschrift für Physik A 336 113(1990).
- [13] F. S. Stephens et al., Phys. Rev. Lett, submitted.
- [14] F. S. Stephens et al., Phys. Rev. Lett, submitted.
- [15] S. M. Harris, Phys. Rev. B 509, 138 (1965).
- [16] J. E. Draper et al., to be published.
- [17] P. Bonche et al., Nucl. Phys. A500, 309(1989).
- [18] R. R. Chasman, Phys. Lett. B219, 227 (1989).
- [19] J. P. Delaroche, Phys. Lett. B232, 145 (1989).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.