PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

Neutron blocking and delayed proton pair alignment in superdeformed ^{195}Pb

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(Received 8 November 1994)

Four new superdeformed bands have been observed in ^{195}Pb, the first time superdeformation has been observed in an odd-A Pb nucleus. Two of the bands have a dynamic moment of inertia that is nearly constant as a function of $\hbar\omega$. This is the first time that bands with such behavior have been observed in an odd-A nucleus in the $A\approx190$ region and it is interpreted as the result of the blocking of the alignment of neutron pairs.

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

We report here the observation and interpretation of four superdeformed (SD) bands in ^{195}Pb, the first time superdeformation has been identified in an odd-A Pb nucleus. It is also the first time that bands with constant dynamic moments of inertia ($\mathscr{J}^{(2)}$) have been observed in an odd-A nucleus in the $A\approx190$ region [1]. SD bands have been reported and extensively investigated in experimental studies of the even-A Pb nuclei, ^{192,194,196,198}Pb [2–15], and in the isotones of ^{195}Pb, namely ^{193}Hg [16–20] and ^{194}Tl [21]. Despite previous extensive searches for SD states in odd-A Pb nuclei, none had been identified. However, there appeared to be no theoretical reason why they should not support superdeformation.

SD bands in odd-A Pb nuclei provide a means to examine the effects of Pauli blocking and of specific neutron orbitals on SD properties. The similarity of the yrast SD bands in ^{192}Hg [11,22,23] and ^{194}Pb [2,4,11] suggests that the added protons in ^{194}Pb do not change the SD rotational properties in the observed frequency range [24]. Thus, SD bands in odd-A Pb might be expected to have similar properties to their Hg isotones.

Four new SD bands have been observed in ^{195}Pb using GAMMASPHERE. Two of these bands have $\mathscr{J}^{(2)}$ values that are approximately constant with $\hbar\omega$, and we propose that they are the favored and unfavored signatures of the $N=7$ neutron orbital. The other two bands have $\mathscr{J}^{(2)}$ values that are similar to that of the yrast SD band in ^{194}Pb, and are proposed to be signature partners built upon the deformation aligned $\nu[624]9/2$ orbital. Six new SD bands have also been observed in ^{193}Pb, which form three signature partner pairs, and which have been assigned to the configurations with the odd neutron in the $N=7$ favored and unfavored signature intruder orbitals, the [512]5/2, and the [624]9/2 orbitals. The bands built upon the $N=7$ orbital have approximately constant $\mathscr{J}^{(2)}$ for ^{193}Pb as well. The results for ^{193}Pb will be presented in a separate article [25]. In both instances, there are important differences in the rotational properties of the SD bands in the odd-A Pb nuclei and their lighter mass isotones, as will be presented below for ^{195}Pb.

This experimental study was performed at the Lawrence Berkeley Laboratory 88-Inch Cyclotron, with the early implementation configuration of GAMMASPHERE (29 Compton-suppressed, 75% efficient germanium detectors). The ^{195}Pb nuclei were produced with the reaction ^{174}Yb(^{26}Mg,5n) at a beam energy of 130 MeV. The target was a stack of three foils of ^{174}Yb, each approximately 500 μg/cm^2 thick. A total of 400×10^6 events with a coincidence requirement of three or more "clean" γ rays were recorded onto magnetic tape for off-line analysis. Doppler shift corrections were made on-line during the data accumulation. ^{152}Eu and ^{56}Co sources were counted to obtain information on the ADC nonlinearity and the detector singles efficiency in the energy region of interest. The energies of previously known low-lying transitions in ^{195}Pb [26,27] were obtained to within 0.1 keV with the resulting energy calibration.

Four new SD bands have been identified in our experiment (Fig. 1). The transition energies are listed in Table I. The spectra display the typical behavior of SD bands in the $A\approx190$ region. The γ-ray transitions are regularly spaced in energy, with $\Delta E_\gamma\approx40$ keV at the bottom of the bands. All of these bands have their last transitions near 200 keV, similar to the last transitions in ^{194}Pb and ^{196}Pb. We were not able to assign multipolarities to these transitions, normally determined using DCO ratios, because there were no detectors at $\theta=90°$ degrees in this experiment; we assume these transitions are of $E2$ multipolarity. The 162-, 203-, and 244-keV transitions of band 2 appear in coincidence with band 1, while the 182- and 222-keV gamma rays of band 1 appear in coincidence with band 2. Similarly, the 214-, 258-, and 298-keV transitions of band 4 are in coincidence with band 3, and the 198- and 235-keV transitions of band 3 are in coincidence with band 4. We take this crosstalk as evidence that

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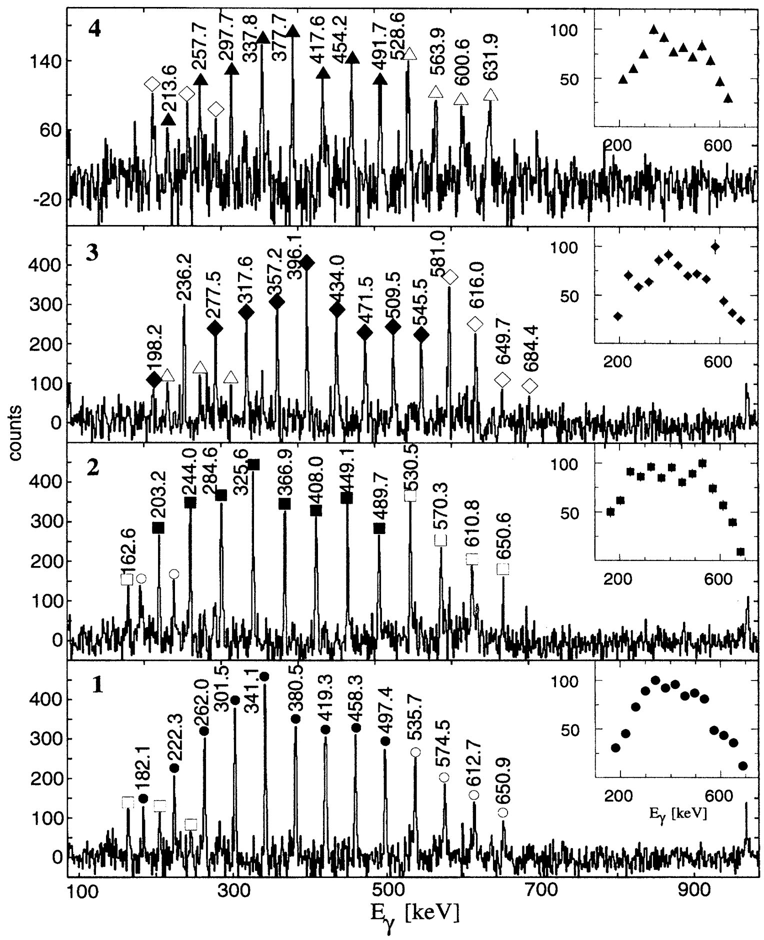

FIG. 1. Double-gated triples spectra of superdeformed bands in ^{195}Pb. SD band γ rays are labeled by ○—band 1, □—band 2, ◇—band 3, and △—band 4. Filled symbols indicate gate transitions. Insets give the relative intensities of peaks in the spectra as a percentage of the largest peak intensity in the band.

bands 1 and 2, and bands 3 and 4 share the same basic structures and are signature partner pairs.

The relative intensities of the transitions in the four bands as determined from the spectra in Fig. 1 are plotted in the insets. These relative intensities are not corrected for the effects of gating, and are plotted to show the similarity in the relative intensities between these bands and SD bands in other $A \approx 190$ nuclei. It is difficult to determine the intensities of the bands as a fraction of the $5n$ channel that populates ^{195}Pb, as they are weakly populated, and several known long-lived isomers in ^{195}Pb complicate the normalization to the total production in the $5n$ channel. Therefore, we estimate the relative yields of the ^{195}Pb SD bands through a comparison with data rates in our ^{194}Pb experiment [14]. In this way, we estimate that band 1, the most intense SD band observed in ^{195}Pb, comprises about 0.25% of the total ^{195}Pb γ-ray flux. The least intense band, band 4, comprises about 0.1%.

The assignment of these four bands to ^{195}Pb is based on a comparison of the data obtained in the present experiment with those data obtained from our other experiments on neighboring nuclei. The known yrast SD band of ^{196}Pb is observed at approximately the same intensity as band 4 of ^{195}Pb in the data from this experiment, while the SD yrast band in ^{194}Pb is not observed. In a large data set optimized for ^{194}Pb (8.1×10^8 three- and higher-fold events), the bands assigned to ^{195}Pb are observed, but not the ^{196}Pb band. Similarly, we have searched in the present data for known SD bands in ^{194,195}Tl and ^{192,193}Hg, which are predicted to be the most intense charged-particle channels, and have not found them. Thus we assign these four bands to ^{195}Pb. Low-lying ^{195}Pb transitions are observed in coincidence with the bands.

TABLE I. Energies of ^{195}Pb SD transitions in keV. Errors reflect only statistical errors.

γ no.	Band 1	Band 2	Band 3	Band 4
1	182.13±0.21	162.58±0.18	198.19±0.40	213.58±0.39
2	222.33±0.14	203.22±0.16	236.19±0.14	257.66±0.23
3	261.97±0.10	243.99±0.11	277.47±0.13	297.70±0.17
4	301.52±0.09	284.63±0.09	317.60±0.12	337.83±0.16
5	341.09±0.09	325.64±0.09	357.22±0.11	377.68±0.17
6	380.54±0.10	366.91±0.10	396.08±0.13	417.59±0.19
7	419.29±0.16	407.99±0.11	434.02±0.13	454.21±0.14
8	458.26±0.09	449.14±0.09	471.52±0.15	491.68±0.20
9	497.38±0.09	489.70±0.08	509.46±0.14	528.60±0.29
10	535.69±0.15	530.51±0.13	545.51±0.16	563.93±0.34
11	574.52±0.18	570.32±0.16	581.04±0.17	600.55±0.42
12	612.68±0.29	610.75±0.23	615.97±0.31	631.92±0.39
13	650.88±0.35	650.58±0.31	649.65±0.53	
14			684.41±0.81	

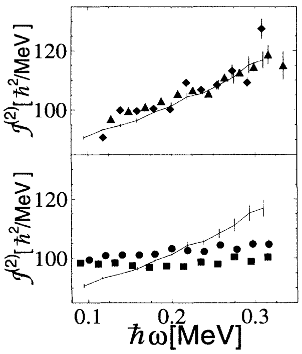

FIG. 2. The $\mathcal{J}^{(2)}$ moments of inertia for the four bands in ^{195}Pb. (●—band 1, ■—band 2, ♦—band 3, ▲—band 4, no symbol—^{194}Pb.)

However, their intensities vary greatly with the manner in which the background is subtracted. The only consistent coincidence is with the Pb x rays.

The $\mathcal{J}^{(2)}$'s for the four bands are plotted in Fig. 2 as a function of $\hbar\omega$. Also shown in Fig. 2 for comparison is the $\mathcal{J}^{(2)}$ for the yrast SD band in ^{194}Pb. Bands 3 and 4 have $\mathcal{J}^{(2)}$'s that are similar to those of ^{194}Pb and most other SD bands in the $A\approx190$ region. However, the $\mathcal{J}^{(2)}$'s for bands 1 and 2 are quite constant as a function of frequency. Other SD bands in the $A\approx190$ region that display this feature are bands 3 and 4 in the odd-odd nucleus ^{192}Tl [28], and ^{190}Hg band 2 [29]. The mean value of $\mathcal{J}^{(2)}$ for bands 1 and 2 in ^{195}Pb are 102.1(8) and 98.8(8) $\hbar^2\mathrm{MeV}^{-1}$, respectively, compared with 107 $\hbar^2\mathrm{MeV}^{-1}$ for the ^{192}Tl bands. The angular momenta of the lowest observed levels in the ^{195}Pb SD bands are estimated to be $I_f=15/2\hbar$, $13/2\hbar$, $15/2\hbar$, and $17/2\hbar$, for bands 1 through 4, respectively. These estimates are based on the rotational model by extrapolating from the two lowest energy transitions for each band. The K values used in this estimate are derived from the asymptotic values of Ω for the orbitals to which the bands are assigned.

In order to understand the results of this experiment, comparisons are made to appropriate theoretical calculations for quasiparticles at SD shapes in the $A\approx190$ region: the calculations of Gall *et al.* [30], who use the cranked Hartree-Fock-Bogoliubov method with the Lipkin-Nogami prescription for the treatment of pairing (CHFBLN) to calculate quasiparticle levels and Routhians for $^{190-194}$Hg and ^{194}Pb; and a cranked Woods-Saxon calculation (CWS) [31] for ^{195}Pb. The quasineutron Routhians for ^{194}Pb in the CHFBLN model, and for ^{195}Pb in the CWS model, are plotted in Figs. 3(a) and 3(b), respectively. The main differences between them, relevant to the experimental data, are that the $N=7$, $\alpha=+1/2$ signature orbital is the second lowest energy orbital in the CWS model, and that interactions occur over a much broader frequency range in the CHFBLN model. At $\hbar\omega=0$, three low-lying quasiparticle neutron states are within 300 keV of each other in both calculations: [512]5/2, [624]9/2, and an $N=7$ orbital. The following features are evident in the quasineutron Routhian plots: (a) the [624]9/2 orbital and the [512]5/2 orbitals lie within 50 keV of each other at $\hbar\omega=0$, and show no signature splitting over the frequency range calculated; (b) the next quasiparticle orbital, the $N=7$, crosses the [512]5/2 orbital at fairly low frequency

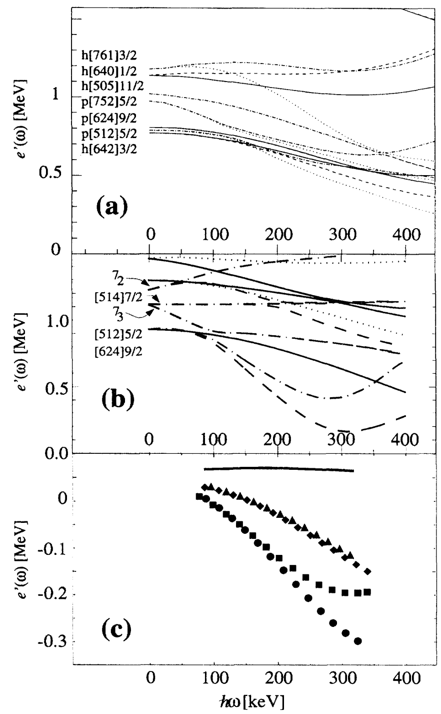

FIG. 3. (a) CHFBLN quasineutron Routhians for ^{194}Pb (reproduced from Ref. [30]) (π,α): solid=(+,+1/2), dashed=(+,–1/2), dash-dotted=(–,+1/2), dotted=(–,–1/2). (b) The CWS quasineutron Routhians for ^{195}Pb with deformation parameters $\beta_2=0.47$, $\beta_4=0.05$, and $\gamma=0$. The orbitals are labeled by their asymptotic Nilsson quantum numbers, except for the $N=7$ orbitals, which are labeled 7_1, 7_2, ..., in order of increasing energy. (π,α): solid=(+,+1/2), dotted=(+,−1/2), dash-dotted=(−,+1/2), dashed=(−,−1/2). (c) Experimental Routhians for the ^{195}Pb SD bands. $\mathcal{J}=88.5+100\omega^2$ $\hbar^2\mathrm{MeV}^{-1}$ is used for the reference. An arbitrary offset is applied to each Routhian, so that all bands extrapolate to $e'=0$ at $\hbar\omega=0$. ●—band 1, ■—band 2, ♦—band 3, ▲—band 4, no symbol—^{194}Pb.

($\hbar\omega\approx100$ keV in the CWS calculations, and over a broader frequency range of approximately 100 to 250 keV in the CHFBLN); (c) after the crossing, the lower energy orbital, now principally of $N=7$ character, shows significant signature splitting starting at $\hbar\omega\approx150$ keV in the CWS model, and at $\hbar\omega\approx200$ keV in the CHFBLN.

The experimental Routhians for the bands are plotted in Fig. 3(c). We note that bands 1 and 2 are sharply downsloping, relative to bands 3 and 4 and the yrast SD band in ^{194}Pb, with signature splitting that increases with frequency. At low $\hbar\omega$, the transitions of band 2 are at the midpoints between the transitions of band 1, but diverge from this relationship at higher frequencies. Under the assumption that at $\hbar\omega\approx0$ these bands have the same energy, we observe a signature splitting in the Routhians of approximately 100 keV at $\hbar\omega\approx$ 300 keV. This is consistent with bands 1 and 2 being built upon the $N=7$ intruder orbital. Comparison of the experimental and theoretical Routhians suggests that band 1 is built upon the $\alpha=-1/2$ favored signature, and band 2 upon the unfavored signature. Since the $N=7$ favored signature orbital is calculated to be the lowest energy orbital in the region of $\hbar\omega$ in which the bands are populated, we expect the band built upon it to be the most intensely fed band, which is consistent with our assignment of band 1 to this orbital. These assignments are consistent with the assigned spins for these bands. Also, the intensity of the observed crosstalk is consistent with that expected for a $j_{15/2}$, $\Omega = 5/2$ orbital.

Bands 3 and 4 have no signature splitting in their γ-ray energies. In the CHFBLN calculations, the only low-lying orbital which matches these properties is the $\nu[624]9/2$. In the CWS calculations, both the $\nu[624]9/2$ and the [512]5/2 match these properties, but the [624]9/2 orbital lies 200 keV lower in energy in the population region. Therefore, we propose that these bands are built upon the $\nu[624]9/2$ orbital. However, bands built on the [512]5/2 and the [624]9/2 orbitals might have nearly identical transition energies, which would require a more sensitive experiment to resolve. Bands 3 and 4 are fed more weakly than bands 1 and 2, consistent with the corresponding orbitals being higher in energy in the population region.

Let us now consider $\mathscr{J}^{(2)}$. $\mathscr{J}^{(2)}$ of the ^{194}Pb SD yrast band (Fig. 2) increases as a function of $\hbar\omega$, a property which is characteristic of most SD bands in the $A \approx 190$ region. It has been suggested that this rise in $\mathscr{J}^{(2)}$ results from the alignment of the angular momentum of paired particles in high-j, low-Ω intruder orbitals with the collective rotation, and from the gradual disappearance of pairing correlations with increasing frequency [32,33]. An odd particle will increase the value of $\mathscr{J}^{(2)}$ at low frequency, and reduce the slope in $\mathscr{J}^{(2)}$, by reducing the amount of pairing. An odd particle in the lowest low-Ω intruder quasiparticle excitation further reduces the rise in $\mathscr{J}^{(2)}$ by blocking the alignment of a pair of particles in that orbital. This is consistent with the greater slope of the $\mathscr{J}^{(2)}$ in ^{195}Pb bands 3 and 4 compared with bands 1 and 2, given the configurations assigned to these bands.

The relative values of the $\mathscr{J}^{(2)}$ for bands 1 and 2 are consistent with the predicted curvatures in the cranked Woods-Saxon quasiparticle Routhians [Fig. 3(b)]. The individual quasiparticle contributions to $\mathscr{J}^{(2)}$ are given by $-d^2e_i/d\omega^2$, where e_i are the quasiparticle Routhians. The $N=7$ unfavored signature, having a greater positive curvature than the favored signature at $\hbar\omega > 200$ keV, thus might support a band with lower $\mathscr{J}^{(2)}$ than the favored signature.

The constant value of $\mathscr{J}^{(2)}$ for bands 1 and 2 is surprising. While blocking of the neutron intruder orbital is expected to reduce the slope of $\mathscr{J}^{(2)}$, we might still expect to observe some positive slope in $\mathscr{J}^{(2)}$ as an effect of proton pair alignment in an intruder orbital. The other cases of SD bands with constant $\mathscr{J}^{(2)}$ in this mass region were ^{192}Tl [28] and ^{190}Hg [29]. In the case of ^{192}Tl the constant $\mathscr{J}^{(2)}$ was interpreted to be due to blocking of low-Ω intruder orbitals by both the odd proton and the odd neutron (double blocking). Clearly, double blocking is not likely for the lowest energy SD bands in ^{195}Pb.

Although there are no theoretical predictions of a constant $\mathscr{J}^{(2)}$ in odd-A Pb nuclei, several mechanisms can be proposed to explain the absence of the effects of proton pair alignment on $\mathscr{J}^{(2)}$ in ^{195}Pb. One possibility is that in the $A \approx 190$ region, proton pair alignment occurs at a frequency higher than we have observed for ^{195}Pb. This is consistent with SD band 5 in ^{193}Hg [20], which has been assigned to the $N=7$ unfavored signature orbital, and which has a nearly constant $\mathscr{J}^{(2)}$ in the range of $\hbar\omega$ over which the ^{195}Pb bands are observed. However, this mechanism is not consistent with the bands built on the $N=7$ favored signature orbitals in ^{189,191}Hg [33,34], or ^{193}Hg band 1 [16,18] when corrected for the interaction with ^{193}Hg band 4. In these cases, neutron pair alignment in the intruder orbital should be blocked. However, there is still a rise in $\mathscr{J}^{(2)}$, with a slightly lesser slope than for ^{192}Hg band 1.

Another possible explanation for the constant $\mathscr{J}^{(2)}$ in ^{195}Pb is that the proton pair alignment occurs at a higher frequency in Pb than in Hg and Tl. CWS quasiproton Routhian calculations suggest that proton pair alignment occurs over a wider frequency range, and at 100 keV lower frequency, for Hg than for Pb. This result is consistent with the CHFBLN calculations. In this case, one might expect (i) $\mathscr{J}^{(2)}$ has a greater slope in Hg than in Pb, at low $\hbar\omega$, and (ii) $\mathscr{J}^{(2)}$ turns over at a lower frequency in Hg than in Pb. The former is consistent with the bands with identical neutron configurations in the odd-A Hg's and Pb's. However, it is inconsistent with the similarity between the SD yrast bands in ^{192}Hg and ^{194}Pb, and (ii) is inconsistent with the observation that the band in ^{194}Pb turns over at a *lower* frequency than the band in ^{192}Hg.

Another possible mechanism for the $\mathscr{J}^{(2)}$ for bands 1 and 2 appearing to be approximately constant is an interaction between the favored $\nu N=7$ and the $\nu[512]5/2$ orbitals, as was observed for ^{193}Hg bands 1 and 4 [16,18]. However, no evidence for such an interaction was observed in ^{195}Pb.

To summarize, we have observed four new superdeformed bands in ^{195}Pb. This is the first observation of superdeformation in an odd-A Pb nucleus, and the first observation of constant $\mathscr{J}^{(2)}$ as a function of rotational frequency in an odd-A nucleus in the $A \approx 190$ region. Crosstalk between bands suggests that they form two sets of signature partner pairs. The first pair, bands 1 and 2, have approximately constant $\mathscr{J}^{(2)}$'s. Relative to ^{194}Pb, their Routhians are sharply downsloping in energy, and exhibit a signature splitting that increases to approximately 100 keV at $\hbar\omega \approx 300$ keV. We have assigned these bands to the configuration with the odd neutron in the $N=7$ orbital, band 1 to the favored signature, based on comparison to theoretical quasineutron Routhian calculations, its intensity relative to band 2, and the relative moments of inertia for bands 1 and 2. Band 2 is assigned to the $N=7$ unfavored signature. Bands 3 and 4 show little signature splitting, and have Routhians which are very similar to that of ^{194}Pb. These bands have been assigned to the two signatures of the $\nu[624]9/2$ orbital. The fitted spins for bands 1 and 2, 15/2 and 13/2, are consistent with the assigned parity and signatures.

$\mathscr{J}^{(2)}$ is constant as a function of $\hbar\omega$ for bands 1 and 2. This can be explained through blocking of the $N=7$ neutron intruder orbital, and the absence of proton pair alignment in the observed frequency range. The latter may be a result of the proton pairs aligning at a frequency higher than that observed in this work. The high frequency of the proton pair alignment might be a general feature of this mass region, or might reflect the movement of the proton SD Fermi level away from the $\pi 6_2$ and 6_1 orbitals. There are, however, counterexamples to both these possibilities, and more work needs to be done before a model consistent with all the observed data emerges.

We would like to thank P. Bonche, H. Flocard, P.-H. Heenan, and S. J. Krieger for stimulating and useful discussions, Jo Ann Heagny for making the targets, and the staff of the LBL 88-inch Cyclotron. This work was supported in part by the U.S. Department of Energy, under Contract No. W-7405-ENG-48 (LLNL) and No. DE-AC03-76SF00098 (LBL), in part by the Research Corporation Grant No. R-152 and an IPA Independent Research Agreement with the Division of Undergraduate Education of the National Science Foundation, the U.S. Department of Energy Division of High Energy and Nuclear Physics under Grants Nos. DE-FG02-92ER40692 and DE-FG02 87ER40371 (ISU), and in part by the National Science Foundation (Rutgers).

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