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Collective oblate bands in ^{196}Pb

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Evidence for collective oblate behavior in ^{196}Pb is presented. One irregular and two regular bands of $M1$ transitions have been observed following the ^{170}Er(^{30}Si,4n) and ^{176}Yb(^{26}Mg,6n) reactions. Transitions linking the most intense regular band to the low-lying negative-parity yrast levels are observed, establishing excitation energies, spins, and probable parities of the band members. In contrast, no such transitions have been found for the irregular band and the weaker regular band. The bands are interpreted as corresponding to collective oblate rotation, arising mainly from deformation-aligned high-j, shape-driving quasiproton excitations across the $Z = 82$ shell gap, coupled to rotation-aligned quasineutrons.

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The manner in which nuclei near closed shells develop collective excitations is a subject of considerable interest. The discovery of superdeformed (SD) bands in Hg nuclei near $A\sim190$ [1] and the subsequent search for additional SD bands in other nuclei in this region has resulted in a large data set for the singly magic Pb nuclei. This has lead to a considerable extension of the information not only on SD states [2], but also on levels in the first well of these nuclei [3]. In particular, while the low-spin excitations can be described in terms of single-particle degrees of freedom, a number of "regular" and "irregular" dipole bands[1] have been observed at higher angular momentum in both the even ^{192,194,198,200}Pb [4–10] and odd $^{197-201}$Pb [10–13] nuclei. Unfortunately, in most cases the spins and excitation energies of these bands are unknown.

These $\Delta I=1$ bands are generally characterized by large

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[1] "Regular" bands have transition energies which increase smoothly with spin; "irregular" bands do not display this behavior.

$B(M1)/B(E2)$ ratios, which are characteristic of high-K proton configurations. Furthermore, the dynamic moments of inertia $\mathcal{J}^{(2)}$ for the regular bands are found to be substantially smaller than the kinematic moments of inertia $\mathcal{J}^{(1)}$, indicating a large amount of aligned angular momentum. These experimental characteristics have been defined in recent work on oblate band structures in the $A = 120$ region [14]. The regular bands in the Pb isotopes have been interpreted as collective, or near-collective, oblate rotational structures involving quasiproton excitations across the spherical $Z = 82$ shell gap, coupled to a number of rotation-aligned high-j quasineutrons. A number of quasiproton configurations are possible, such as $\pi(i_{13/2}\otimes h_{9/2})$, $\pi(i_{13/2})^2$, or $\pi(h_{9/2})^2$ [15], whereas the rotation-aligned quasineutrons are most likely $i_{13/2}$.

In total-Routhian-surface (TRS) calculations for these configurations, collective oblate nuclear shapes with rather small quadrupole deformation (β_2 values ranging from ~ 0.10 to ~ 0.18) are present at moderate and high spins. Such high-K structures should give rise to large $M1$ matrix elements because of the large proton g factors and the additive contributions of the neutrons and protons to the component of the magnetic moment perpendicular to the angular momentum axis. Recent lifetime measurements [8] indicate that the $M1$ transitions observed in ^{198}Pb are among the strongest yet observed in nuclei, while the derived $E2$ lifetimes suggest a modest quadrupole moment.

The present Rapid Communication reports on the observation of three such bands of $M1$ transitions in ^{196}Pb. For one of these bands, spins and excitation energies have been established by the observation of linking transitions to the known yrast levels. This decay pattern provides important information regarding the configuration involved. These results were obtained in two separate experiments performed at the ATLAS facility at Argonne National Laboratory and at the 88-Inch Cyclotron facility at Lawrence Berkeley Laboratory. Preliminary results of the measurements performed at the 88-Inch Cyclotron facility have been reported recently [16]. A detailed and complete presentation of the Argonne measurement is being prepared [17].

In one of the experiments, high-spin states in ^{196}Pb were investigated with the ^{170}Er(^{30}Si,4n) reaction. The Si beams were provided by the Argonne superconducting linear accelerator, ATLAS. Measurements were performed at beam energies of 142, 146, and 151 MeV using thin targets (stacks of two 500 μg/cm^2 isotopically enriched foils). The γ rays were detected with the Argonne–Notre Dame bismuth germanate (BGO) γ-ray facility which consists of 12 Compton-suppressed Ge detectors and a 50-element BGO inner array. The on-line event trigger was defined by requiring a prompt coincidence between at least two suppressed Ge detectors and a minimum of four array elements. With this requirement, approximately 3×10^8 γ-γ coincidence events were accumulated in the three experiments. In addition to the energy and time information from the Ge detectors, the γ-ray sum-energy and the prompt and delayed multiplicities recorded in the BGO array were written to magnetic tape. By appropriate gating on the multiplicity distributions, coincidence matrices were produced where at least 80% of all events belonged to ^{196}Pb for each beam energy.

In the other experiment, a study of the ^{176}Yb(^{26}Mg,6n) reaction at a beam energy of 138 MeV was made at the Lawrence Berkeley Laboratory 88-Inch Cyclotron. The target consisted of 1 mg/cm^2 of ^{176}Yb evaporated on a 10 mg/cm^2 Au backing. The data were collected using the high-energy-resolution array (HERA) which consists of 20 Compton-suppressed Ge detectors and a 4π inner ball of 40 BGO elements. All threefold and higher-fold events were recorded, together with sum-energy and multiplicity information from the array. Twofold events were recorded only when four or more BGO elements were in prompt coincidence. Approximately 4.8×10^8 expanded twofold events were collected. By appropriate gating on multiplicity and sum energy, a matrix was produced where 60% of events belonged to ^{196}Pb.

The data analyses from both experiments revealed three bands in ^{196}Pb. In the thick-target data, the transitions in each band are in coincidence with the known cascade of transitions depopulating the 11^- isomer to the 5^- isomer [18]. A partial level scheme showing these bands, together with previously identified [18] single-particle low-spin states, is presented in Fig. 1. Two bands, labeled 1 and 2 in Fig. 1, appear to be rotational in character with regular energy spacings, while the third band (band 3) is characterized by rather irregular energy spacings. Ratios of γ-ray intensities obtained from angular correlation analyses of both data sets were used to assist in the assignment of transition multipolarities. This information was extracted from two-dimensional E_γ-E_γ matrices constructed from coincidences between detectors at forward/backward angles and those at angles close to 90°. The inband γ rays exhibit intensity ratios consistent with values expected for stretched $\Delta I = 1$ transitions for both the Argonne–Notre Dame array [19] and HERA [20]. Unfortunately, the statistical accuracy of these data is not sufficient to extract mixing ratios (δ) reliably. Figure 2 presents thin-target coincidence spectra showing most of the transitions of interest as well as the associated intensity ratios. In fact, a consistent intensity pattern for the band members is obtained only if the dipole transitions are assumed to be $M1$. The observation of several $\Delta I = 2$ crossover transitions in two of the bands supports this assignment. Further support for the assignment comes from the analogy noted above with similar structures observed in neighboring Pb isotopes.

Transitions linking the newly observed $M1$ bands with the known yrast states were only established for band 2. This band decays to the 11^- isomeric state through a cascade which includes transitions of 503, 606, and 856 keV. In parallel with the 856-keV γ-ray, a 309–546 keV decay branch (Fig. 1) is also observed, in agreement with the work of Plompen *et al.* [21]. (The 11^- isomer has a 72±4 ns half-life [22].) The extracted intensity ratios are consistent with a stretched quadrupole character for the 606- and 856-keV transitions, and with a stretched dipole character for the 503-keV transition. Thus the lowest observed level of band 2 has been assigned spin and probable parity, $I^{(\pi)} = 16^{(-)}$. The negative parity is suggested on the basis of comparison with neighboring nuclei. The spins and excitation energies of bands 1 and 3 are uncertain, since no clear linking paths to the lower spin states were identified. The coincidence relationships in the thick-target data, between the 193- and 315-keV γ-rays of band 3, and the 606-keV transition, however, suggest that the state of lowest energy in band 3 lies in the range $4464 < E_x < 4657$ keV. Similarly, the γ rays in band 1 are in coincidence with transitions below the $I^\pi = 16^{(-)}$ state, placing a lower limit of $E_x \geq 5160$ keV on the excitation energy. In both cases, however, the intensities of these yrast transitions in gates set on band members are much reduced from that expected for direct feeding, possibly indicating the presence of long-lived states along the decay paths. The intensities of bands 1, 2, and 3 with respect to the $2^+ \rightarrow 0^+$ transition are found to be $\sim 9\%$, $\sim 15\%$, and $\sim 30\%$, respectively, in the thick-target experiment, when corrected for detector efficiency and internal conversion.

The excitation energies and spins associated with band 2 have been experimentally determined, making the interpretation somewhat more straightforward. The transition energies of band 2 (starting at spin $16\hbar$) vary smoothly with spin as would be expected for a rotational band. Furthermore, the odd and even spin states do not display any signature splitting. From the two $E2$ crossover transitions observed in this band, the average $B(M1)/B(E2)$ ratio is 15(5) $(\mu/e\,\mathrm{b})^2$. These characteristics suggest that band 2 is a rotational band built on a high-K configuration. Information regarding the configuration can be obtained from the decay pattern of the band: Indeed, most of the flux out of band 2 proceeds through the 11^- isomeric level at 3.195 MeV. Based on the measured g factor and excitation en-

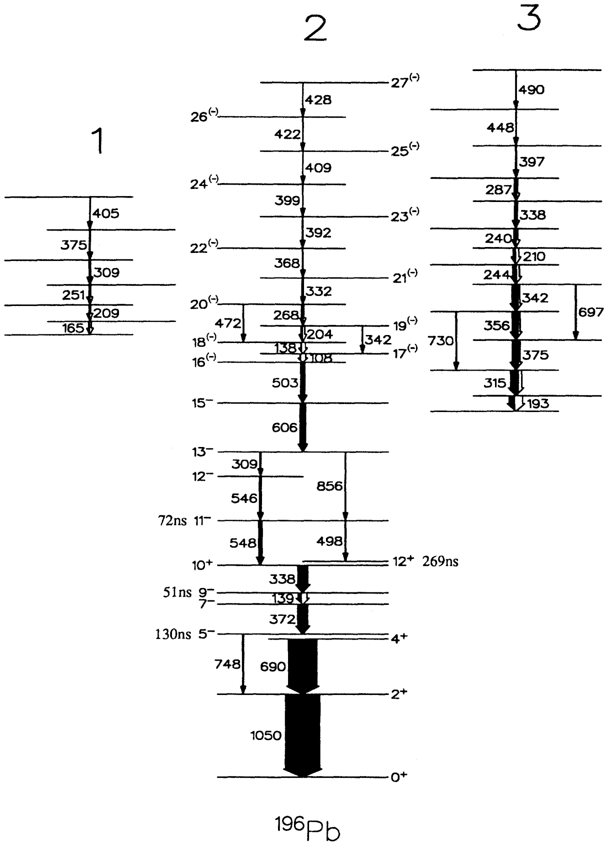

FIG. 1. Partial level scheme for ^{196}Pb deduced from this work. The γ rays are labeled by energy (in keV), and the width of the arrows represents the relative intensities.

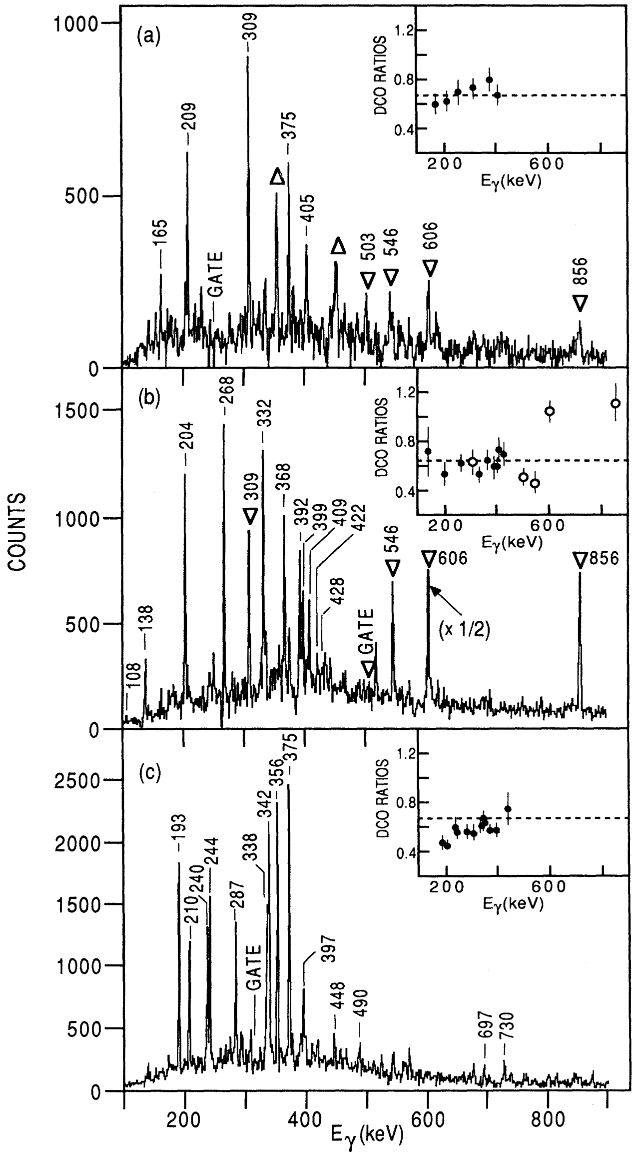

FIG. 2. Coincidence γ-γ spectra gated by the (a) 251-, (b) 503-, and (c) 315-keV transitions in bands 1-3, respectively. Transitions are labeled by energy in keV. γ rays labeled with ∇ correspond to transitions below the 16^- level, while those labeled with Δ correspond to strong identified contaminants in the gate of interest. Intensity ratios from an angular correlation analysis [19] are shown (inset). Band members are represented by •, and other ^{196}Pb transitions by ○. The dashed line represents the expected value for dipole transitions (see text for details).

ergy, this state has been assigned [18,23,15] a deformed oblate $\pi([505]9/2^- \otimes [606]13/2^+)_{K=11}$ configuration [i.e., $\pi(h_{9/2} \otimes i_{13/2})$].

We have examined the available TRS [24] calculations and performed cranked shell model (CSM) calculations, in order to investigate which configurations can be coupled to this 11^- state and provide suitable quasiparticle excitations. Similar calculations have been utilized previously to discuss the $M1$ sequences observed in ^{192,198}Pb [4,9] and ^{197}Pb [11]. The TRS calculations show that stable minima develop on the oblate collective axis ($\gamma = -60°$) for the two-quasiproton configuration, $\pi(h_{9/2} \otimes i_{13/2})$, but only at frequencies higher than $\hbar\omega \sim 0.20$ MeV, when at least one pair of $i_{13/2}$ quasineutrons has aligned. This oblate minimum persists to frequencies $\hbar\omega > 0.40$ MeV, and is only affected slightly by the alignment of a second pair of quasineutrons at $\hbar\omega \sim 0.34$ MeV: The calculated deformation parameters vary from $\beta_2 \sim 0.15$ at $\hbar\omega = 0.24$ MeV to $\beta_2 \sim 0.13$ at $\hbar\omega = 0.40$ MeV. These values are intermediate to those found for the same configuration in the lighter and heavier Pb isotopes ($\beta_2 \sim 0.18$ for ^{192}Pb, ~ 0.12 for ^{200}Pb).

From this discussion it is then proposed that band 2 is built on the $\pi(h_{9/2} \otimes i_{13/2}) \otimes \nu(i_{13/2})^2$ configuration. This band possesses a large amount of aligned angular momentum [$(12 - 15)\hbar$], consistent with the proposed assignment. This feature explains the observation that the $\mathcal{J}^{(2)}$ in band 2 is much smaller than the kinematic moment of inertia $\mathcal{J}^{(1)}$. Detailed CSM calculations for this configuration are able to account for the measured alignment. Finally, the CSM calculations also predict the alignment of a second pair of $i_{13/2}$ quasineutrons at a rotational frequency $\hbar\omega \sim 0.34$ MeV, in agreement with the sharp increase in the $\mathcal{J}^{(2)}$ observed at the highest frequencies in band 2.

The large $B(M1)/B(E2)$ ratios mentioned above can be qualitatively understood in terms of the semiclassical model proposed by Dönau and Frauendorf [25]. Large $B(M1)$ values arise from the large component of the magnetic moment perpendicular to the angular momentum, resulting from coupling deformation-aligned high-K quasiprotons with rotation-aligned quasineutrons. The average value of the $B(M1)/B(E2)$ ratio for ^{196}Pb (band 2) also fits the smooth systematic trend observed in the other Pb isotopes. The decrease in this ratio from $\sim 40(10)$ $(\mu/e\,\mathrm{b})^2$ in ^{199}Pb to $\sim 15(5)$ $(\mu/e\,\mathrm{b})^2$ in ^{196}Pb can be interpreted as being due to a small increase in the quadrupole deformation as the middle of the neutron shell is approached. It is noted that all these observations also apply to most of the regular $M1$ bands in the other Pb isotopes, for which similar configurations have been proposed.

The intrinsic structures of bands 1 and 3 are more difficult to establish since the spins and excitation energies cannot be determined from the present experiments. Nevertheless, the facts that (i) band 1 is also regular and that (ii) only dipole transitions have been observed suggest that this band is built on a high-K proton configuration similar in character to that of band 2. The TRS calculations show that an oblate minimum with deformation parameters similar to those obtained for the $\pi(h_{9/2} \otimes i_{13/2}) \otimes \nu(i_{13/2})^2$ configuration also exist when quasiprotons or quasineutrons occupy other high-j orbitals located near the Fermi surface. Measured excitation energies and spins in band 1 are however necessary to suggest which precise proton-neutron configuration is involved.

In contrast to bands 1 and 2, band 3 does not form a well-defined rotational pattern, i.e., the transition energies vary in an irregular manner with spin. It is worth noting that this is the most strongly populated of the three bands. Bands with similar features have also been observed in other Pb isotopes [11]. The detailed mechanism leading to this strong irregular $M1$ band is at present not well understood. It has been proposed that this band might be associated with configurations either departing from axial symmetry or for which the potential energy surface is at least soft in the γ degree of freedom. In the case of ^{196}Pb, a possible configuration could be $\pi(d_{3/2} \otimes h_{9/2}) \otimes \nu(i_{13/2})^2$; i.e., a configuration similar to that proposed for band 2, but where the $\pi d_{3/2}$ orbital has replaced the high-j $\pi i_{13/2}$ orbital. The TRS calculations show that this particular configuration becomes the lowest two quasiproton configuration of negative parity at a spin of $\sim 18\hbar$ and corresponds to an oblate minimum with a somewhat smaller quadrupole deformation ($\beta_2 \sim 0.10$) which is also rather flat in the γ direction. The small β_2 value combined with the apparent softness in γ could result in the observed irregular energy sequence. The Dönau and Frauendorf model predicts that $B(M1)/B(E2) \sim 5$ $(\mu/e\,\mathrm{b})^2$ for such a configuration, smaller than that observed experimentally [20(5) $(\mu/e\,\mathrm{b})^2$]. We note that larger $B(M1)/B(E2)$ ratios would result if the configuration contained some $\pi s_{1/2}$ admixture. On the other hand, this prescription may not be adequate for small deformations ($\beta_2 \sim 0.10$). Finally, it is also possible that one-dimensional cranking is not the appropriate model for this band and that a more elaborate description is required. For example, tilted-axis cranking calculations such as those performed recently by Frauendorf for ^{199}Pb might be needed [26].

In conclusion, three dipole bands have been found in ^{196}Pb with properties similar to those seen in other Pb isotopes. The bands are characterized by strong $\Delta I = 1$ $M1$ transitions, and weak $\Delta I = 2$ crossover $E2$ transitions. These bands can be generally understood as high-K, collective oblate states built on configurations involving high-j, shape-driving quasiproton excitations coupled to rotation-aligned quasineutrons. A definite configuration is proposed for band 2. Further experimental studies measuring spins and energies of the other two bands are necessary for a better delineation of their detailed structures.

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