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Observation of a superdeformed band in ^{190}Pb

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Abstract. A superdeformed band has been observed in the $N = 108$ isotope ^{190}Pb. This is the most neutron-deficient Pb isotope in which superdeformed states have been observed. Several theoretical approaches have predicted that $N = 108$ will mark the limit of observable superdeformation in the Pb isotopes. The band, which consists of five (possibly six) transitions, is observed to feed at least one isomeric level in its decay to the ground state. This decay pattern supports a spin assignment of 10 $\hbar$ for the lowest observed level.

PACS. 21.10.Re Collective levels – 23.20.-g Electromagnetic transitions – 27.80.+w $190 \leq A \leq 219$

1 Introduction

The first experimental evidence for superdeformation in nuclei with $A \approx 190$ came with identification of γ-rays associated with a superdeformed (SD) rotational band in ^{191}Hg [1] in 1989. Since then, 83 such bands have been identified in 25 isotopes of Au, Hg, Tl, Pb, Bi and Po.

Unfortunately, the difficulties associated with identifying discrete transitions involved in the decay-out of these structures have meant that the fundamental properties of the bands such as absolute excitation energy, spin and parity have been measured in only a very small number of cases [2–7].

Without measurement of these basic properties, systematic comparisons of the data with predictions of the SD well excitation energies cannot be made. Thus, it has not been possible to distinguish which of the various theoretical approaches (which include the Strutinsky method with Woods-Saxon potential [8], Hartree-Fock-Bogoliubov (HFB) with a Skyrme force [9], HFB with a Gogny force [10] and relativistic HFB [11]) predicts excitation energies and well depths most accurately. However, there are other aspects of the calculations that can be tested and which provide useful insights into their applicability. One of these is simply the range of nuclei in which the SD minimum is sufficiently stable to be observed. Exploring the limits of the island of SD nuclei with $A \approx 190$ will give information on the factors stabilizing the extremely deformed shape and also provide a test for the existing predictions of the limits of the $A \approx 190$ island of superdeformation.

The present work reports on the observation of an SD band in the $N = 108$ nucleus ^{190}Pb, the most neutron-deficient Pb isotope in which evidence for superdeformation has been found. Although recent calculations have tended to focus on superdeformation in isotopes of Hg, Pb and Po with $N \geq 110$, two of the earliest examples of macroscopic [8] and microscopic [9] approaches predict that ^{190}Pb may be the most neutron-deficient Pb isotope which supports a stable SD shape.

The observation of this SD band has been made following a reaction which imparts relatively low angular momentum to the ^{190}Pb residue. The fact that an SD band is populated under such circumstances may support the predictions of both macroscopic and microscopic calculations that the excitation energy of the SD well in this nucleus will be low.

2 Experimental details and initial analysis

An experiment was performed at the Lawrence Berkeley National Laboratory using the Gammasphere multi-detector array. A target consisting of a 1 mg/cm^2 layer of

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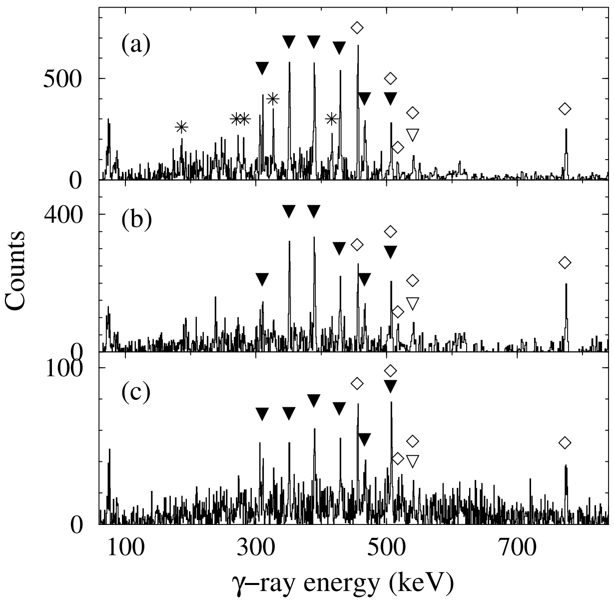

Fig. 1. (a) Spectrum created by double-gating on all pairs of γ-rays in the list (309.7 keV, 350.3 keV, 388.8 keV, 427.9 keV, 466.0 keV). (b) Spectrum created by double-gating on clean pairs only. (c) Triple-gated spectrum, created using the same gate list as (a). See text for details.

^{166}Er on a 5 mg/cm^2 Pb backing was placed at the focal point of the array, which at the time consisted of 102 Ge detectors. A beam of ^{28}Si was provided at an energy of 143 MeV by the 88″ Cyclotron. An event was written to tape when at least three signals were obtained from the Ge detectors after escape suppression. Detector identification, incident energy and time (relative to the RF signal of the Cyclotron) were written to tape. A total of 6.3×10^8 such events were collected.

In the initial analysis, the data were sorted into a γ-γ-γ cube in the format suitable for analysis with the RADWARE [12] package. Only those γ-rays which occurred within ± 30 ns of a primary beam pulse ("prompt" γ-rays) were incremented into the cube. A search of the cube for regular structures revealed a cascade of γ-rays with energies 309.7(8), 350.3(7), 388.8(8), 427.9(8), 466.0(9) and 504(1) keV. Figure 1(a) shows the spectrum obtained by setting double gates on all combinations of pairs of these γ-rays except those including the 504 keV line, which is strongly contaminated by a low-lying transition in ^{190}Pb. Gamma rays which are firmly identified as part of the SD cascade are marked with filled triangles. A transition at 539(1) keV is tentatively identified as belonging to the band; this peak is marked with an open triangle. Gamma rays in coincidence with the band which are associated with the decay of known low-lying states in ^{190}Pb [13] are marked with open diamonds. Contaminant peaks are marked with asterisks.

A series of gated spectra were then produced in order to verify this structure. Because of the strong yrast transitions with energies 507 and 540 keV, it was not possible to use the 504 and 539 keV in-band transitions as gates. Figure 1(b) shows the results of double-gating only on clean combinations of the γ-rays used to create fig. 1(a) [$309.7 \otimes (388.7, 427.9, 466.0)$; $350.3 \otimes (427.9, 466.0)$; $388.8 \otimes 466.0$; $427.9 \otimes 466.0$]. In this spectrum, the contaminant lines evident in fig. 1(a) are much reduced but the yrast lines from the normal decay of ^{190}Pb remain clear, verifying the assignment of the band to that nucleus. Figure 1(c) shows the results of triple-gating on all transitions from 309.7 keV to 466.0 keV. The small number of possible gate combinations and low average fold of the data lead to low statistics, but the band is clearly present.

The low-lying transitions associated with the decay of ^{190}Pb observed in coincidence with the newly identified cascade allow a firm assignment to this nucleus. It is estimated that this structure is populated with 0.5% or less of the intensity of the ^{190}Pb reaction channel.

3 Properties of the cascade

3.1 Transition multipolarities

In order to establish whether the cascade identified above consists of quadrupole or dipole radiation, a Directional Correlations from Oriented nuclei (DCO) [14] analysis was performed. The Gammasphere array consists of 17 rings of detectors at angles θ of 17.3°, 31.7°, 37.4°, 50.1°, 58.3°, 69.8°, 79.2°, 80.7°, 90.0°, 99.3°, 100.8°, 110.2°, 121.7°, 129.9°, 142.6°, 148.3° and 162.7° with respect to the beam direction. For the purposes of this analysis, the detectors were divided into two groups: those around 90° ($69.8° \leq \theta \leq 110.2°$), and those at forward/backward angles ($\theta \leq 58.3°$ and $\theta \geq 121.7°$). Background-subtracted, double-gated spectra were created by gating on γ-rays detected at the forward/backward angles. One spectrum was incremented with all other γ-rays detected at forward/backward angles, and another was incremented with γ-rays detected at angles around 90°. The areas of particular peaks were measured in both spectra and the ratio R_{DCO} extracted:

$$R_{\mathrm{DCO}} = \frac{I_{\gamma,\mathrm{fb}}}{I_{\gamma,90°}} \qquad (1)$$

Values of R_{DCO} were measured in spectra double-gated on the five SD transitions with energies between 309.7 and 466.0 keV.

The results of this analysis are shown in fig. 2. Values of R_{DCO} could not be obtained for the 466, 504 and 539 keV transitions, the former because of low statistics and the latter two because of both poor statistics and overlap with transitions in other parts of the level scheme. All in-band transitions for which R_{DCO} could be measured yielded values which are consistent with the average R_{DCO} obtained for known stretched quadrupole transitions, strongly suggesting that they are of $E2$ character.

3.2 Dynamic moment of inertia and spin assignments

Although the data were obtained with a backed target, there are insufficient statistics to measure the lifetimes

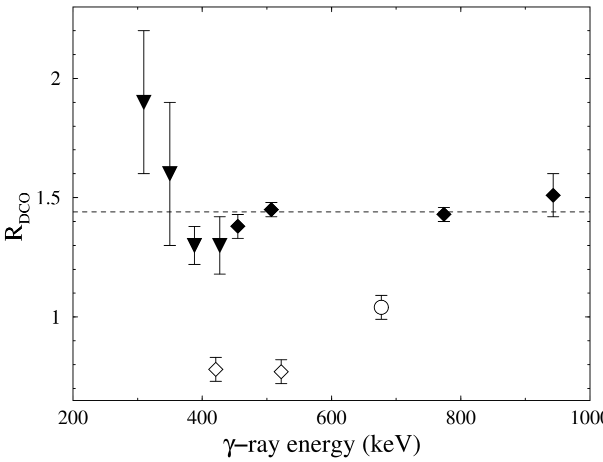

Fig. 2. R_{DCO} extracted for in-band transitions (filled triangles), known stretched $E2$ transitions (filled diamonds), known stretched $M1$ transitions (open diamonds) and a known $E1$ transition (open circle). The average value for the known stretched $E2$ transitions is indicated by the dashed line.

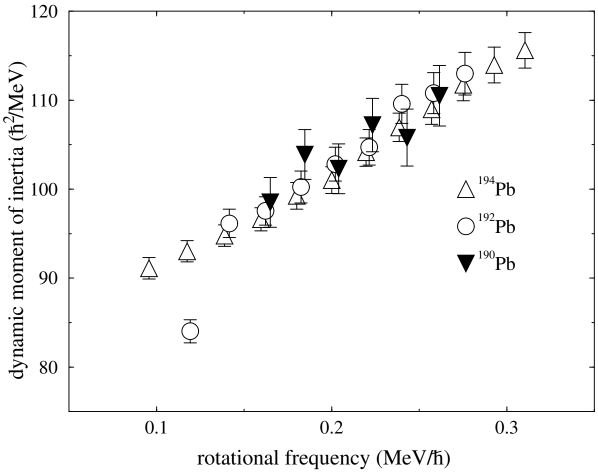

Fig. 3. The dynamic moment of inertia $\mathcal{J}^{(2)}$ of the band in ^{190}Pb, compared with those of the yrast SD bands in ^{192}Pb and ^{194}Pb.

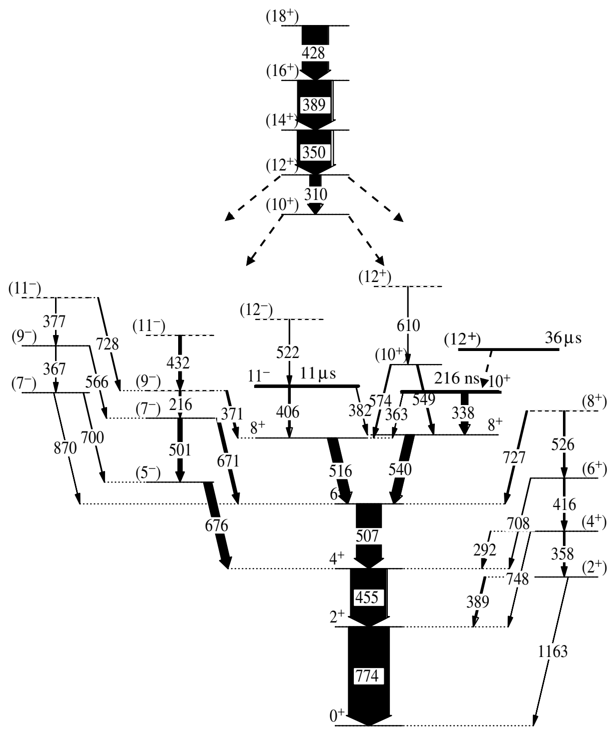

Fig. 4. Partial level scheme of ^{190}Pb showing the SD band and the low-lying transitions [13] with which it is in coincidence. Levels which are only tentatively identified as part of the decay path are marked with dashed lines.

of the states via the Doppler shift method, and therefore the deformation of the nucleus cannot be obtained experimentally. However, the energy spacing (≈ 40 keV) of the γ-rays is typical of SD bands in this mass region. The dynamic moment of inertia $\mathcal{J}^{(2)}$ shown in fig. 3 is similar to the $\mathcal{J}^{(2)}$ of the SD bands in the neighbouring even-even Pb isotopes ^{192}Pb and ^{194}Pb, increasing from 98 $\hbar^2\text{MeV}^{-1}$ to 113 $\hbar^2\text{MeV}^{-1}$ over the observed spin range. In this mass region, the SD shape is stabilized by $i_{13/2}$ proton and $j_{15/2}$ neutron intruder orbitals, and the smooth rise in the $\mathcal{J}^{(2)}$ moment of inertia observed in most SD bands in even-even isotopes of Hg, Pb and Po is attributed to the gradual alignment with increasing spin of pairs of these high-j orbitals. This trend appears to be followed by ^{190}Pb. There is some evidence for an oscillation in the $\mathcal{J}^{(2)}$, a feature which has previously been interpreted as evidence for either hexadecapole deformation [15] or band-crossing effects [16]. However the uncertainties on the data points are too large to determine whether this staggering is a real effect.

While there is no direct experimental evidence allowing a parity assignment to the structure, it can be assumed that the yrast SD band of an even-even nucleus will be built on the SD quasi-vacuum and will have $K^\pi = 0^+$. For this reason, we tentatively assign the band positive parity.

Becker *et al.* [17] suggested a method of estimating the spins of levels in an SD band from a fit to the dynamic moment of inertia using a Harris parameterization. Because the number of data points is small, the fit in this case has a relatively large uncertainty. However, restricting the possible level spins to even integer values (as would be required for a $K^\pi = 0^+$ band) results in an assignment of $I = 10\ \hbar$ for the level fed by the 309.7 keV transition.

Figure 4 shows a partial level scheme for ^{190}Pb, indicating the levels fed by the band. Transitions de-exciting yrast levels of spins up to $I = 12\hbar$ have been tentatively observed in coincidence with the band. This is consistent with the proposed spin assignment.

3.3 Population of low-lying isomers by the decay of the band

As indicated in fig. 4, there are three previously identified long-lived states in the normal decay of ^{190}Pb [13], at spins 10^+, 11^- and 12^+, which may be fed by decays

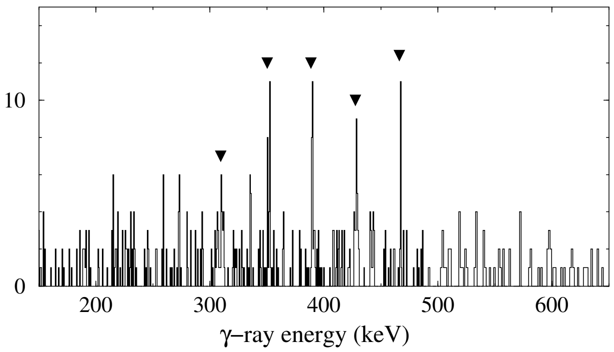

Fig. 5. Spectrum created by double-gating on all pairs of prompt γ-rays in the list (309.7 keV, 350.3 keV, 388.8 keV, 427.9 keV, 466.0 keV), where a delayed coincidence with a transition below the 10^+ state is also required.

from the SD band. Because the experimental conditions only allowed for detection and correlation of γ-rays up to ≈ 800 ns after any particular beam pulse, decays via the long-lived 11^- and 12^+ isomers cannot be isolated in the present data. However, an estimate of the fraction of the decay of the SD band which occurs via these states may be obtained by measuring the intensity of the 774 keV $2^+ \to 0^+$ (ground-state) transition in prompt, SD gated spectra.

A spectrum was created containing those γ-rays detected in prompt coincidence with any two of the 389, 428 and 466 keV in-band transitions. In this spectrum, the intensity of the 774 keV transition was found to be 73(5)% of the 350 keV in-band transition. This indicates that the remaining 27(5)% of the intensity must be accounted for in decay paths in which the $2^+ \to 0^+$ transition is *not* in prompt coincidence with the band. The path via the direct decay of the excited 2_2^+ state at 1163 keV to the ground state accounts for less than 1% of the SD band intensity. It is therefore highly likely that the rest of the "missing" intensity populates one or more of the isomeric states.

As mentioned above, the experimental conditions preclude the direct correlation of γ-rays across the long-lived 11^- and 12^+ isomers. However, there is some evidence of a peak at 522 keV in the spectra gated on the band. The 11^- isomer is fed by a 522 keV transition de-exciting a (12^-) state, so this peak may be evidence that the SD decay does indeed feed this isomer. However, this cannot be confirmed without time-correlated information. No transitions known to feed the 12^+ state were observed in the SD gated spectra.

The shorter lifetime of the 10^+ level (216 ns) allows transitions feeding and de-exciting this state to be correlated. A cube was created which contained only those prompt γ-rays which were detected in coincidence with a delayed transition in the low-lying part of the ^{190}Pb level scheme. That is, prompt γ-rays were incremented into the cube if one of the 774, 455, 507, 516, 540 or 338 keV transitions was detected in a delayed period 45–800 ns after the primary beam pulse in the same event. Double-gating on the transition energies used to produce fig. 1(a) resulted in the spectrum shown in fig. 5.

The spectrum shows that the SD band is present, albeit weakly. This strongly suggests that the 10^+ state is fed in the decay from the SD band.

4 Discussion

4.1 The stability of the superdeformed minimum

Of the many theoretical studies of the nuclear potential energy surfaces and the properties of SD states which have been carried out to date, only a small number have considered nuclei with $A \approx 190$ and $N < 110$. These few include the Woods-Saxon calculations of Satula *et al.* [8] and the HFB calculations of Krieger *et al.* [9] and Bender *et al.* [18].

Satula *et al.* [8] employed the Strutinsky shell correction method and an average Woods-Saxon potential to predict the depths and excitation energies of the SD well in nuclei in this mass region. These calculations indicated that the SD minimum might be expected to persist at spin $I = 0$ in isotopes of Hg and Pb with $N \geq 110$, but that rotation is required to stabilize the shape for nuclides with $N = 108$. A true second minimum in ^{190}Pb and ^{188}Hg is predicted only for rotational frequency $\hbar\omega > \hbar\omega_{\min} = 0.12$ MeV.

Microscopic calculations also predict a reduction in the depth of the SD well for the light Pb isotopes. For example, Krieger *et al.* have performed Hartree-Fock-Bogoliubov (HFB) calculations using a Skyrme interaction [9] which also predict well depths and excitation energies at $I = 0$; their calculations suggest that the depth of the SD minimum in ^{190}Pb is only 90 keV.

The results of both these approaches suggest that ^{190}Pb will mark the limit of observable superdeformation for the neutron-deficient Pb isotopes.

More recently, Bender *et al.* [18] have employed the SLy6 Skyrme interaction with a density-dependent zero-range pairing force to investigate the potential landscapes of light Pb isotopes. These calculations indicate a well depth of around 1 MeV for ^{190}Pb. As with the earlier calculations, they also suggest that this will be the lightest Pb isotope in which a distinct SD minimum occurs. However, it should be noted that a deformation of $\beta_2 \geq 0.7$ is predicted for the SD minimum by this approach. This is significantly higher than the values of $\beta_2 \approx 0.47$ which are both inferred from experimental quadrupole moment measurements and predicted by other methods.

The present data cannot determine whether there is a distinct SD minimum in ^{190}Pb at spin $I = 0$. However, it is clear that the SD shape is indeed stable at higher spins and rotational frequencies. It would be interesting to search for SD states in the $N = 106$ isotope ^{188}Pb to further test the validity of the calculations.

4.2 Population of the superdeformed band

One feature common to most theoretical predictions of superdeformation in the Hg and Pb isotopes is that the excitation energy of the SD well $E_{\rm SD}$ decreases with decreasing neutron number. While the present data do not allow a measurement of $E_{\mathrm{SD}}(^{190}\mathrm{Pb})$, the angular momentum imparted to the residue may indicate a relatively low value.

It has been suggested [19] that SD bands are populated with "high" intensities (1–2% of the reaction channel intensity) only when the fusion-evaporation reaction imparts sufficient angular momentum so as to populate spins higher than the spin at which the SD band crosses the normal yrast line (*i.e.* in the so-called "magic triangle" of the spin-excitation energy plane). (This idea has recently been revived in connection with the search for hyperdeformation [20].) The measured excitation energies of the lowest-energy SD bands in ^{194}Pb [4,5] and ^{192}Pb [6] allow the spins at which this crossing takes place to be determined as $I_{\mathrm{crit}}(^{194}\mathrm{Pb}) \approx 28.5\ \hbar$ and $I_{\mathrm{crit}}(^{192}\mathrm{Pb}) \approx 25.3\ \hbar$. The observation of these bands to spins of 38 $\hbar$ and 32 $\hbar$, respectively, confirms that the reactions used to populate them achieve maximum spins $l_{\max}$ significantly higher than I_{crit}.

Because the normal yrast lines, as well as the SD bands, have very similar moments of inertia in the Pb isotopes, the spin at which the SD band becomes yrast in each case is determined predominantly by the excitation energy of the SD band. Thus, if the SD band in ^{190}Pb were at the same excitation energy as that in ^{194}Pb, it would be expected that $I_{\mathrm{crit}}(^{190}\mathrm{Pb}) = I_{\mathrm{crit}}(^{194}\mathrm{Pb}) \approx 28.5\ \hbar$; similarly, if the excitation energy were the same as the band in ^{192}Pb, it would be expected that $I_{\mathrm{crit}}(^{190}\mathrm{Pb}) = I_{\mathrm{crit}}(^{192}\mathrm{Pb}) \approx 25.3\ \hbar$.

Assuming that each evaporated neutron removes $\approx 2\ \hbar$ from the compound system, the present reaction can be estimated to leave the ^{190}Pb evaporation residues which survive the fusion process with $l_{\max} \approx 26\ \hbar$. This is consistent with the experimental observation of SD and normal states up to $I = (24)\ \hbar$ and $I = 22\ \hbar$ [21], respectively. This estimate of $l_{\max} \leq 26\ \hbar$ is *lower* than $I_{\mathrm{crit}}(^{194}\mathrm{Pb})$ and approximately equal to $I_{\mathrm{crit}}(^{192}\mathrm{Pb})$.

In the present reaction, the SD band accounts for $\approx 0.5\%$ of the total ^{190}Pb cross-section. If the picture of population in the "magic triangle" were correct, this level of population would suggest that $I_{\mathrm{crit}}(^{190}\mathrm{Pb})$ is less than or close to 26 $\hbar$. This would in turn imply a bandhead energy close to that of ^{192}Pb, which has the lowest excitation energy measured for an SD band [6] in this mass region.

5 Conclusions

A superdeformed band has been observed in the $N = 108$ isotope ^{190}Pb. This is the most neutron-deficient isotope of Pb in which evidence for superdeformation has been found, and is likely to represent the neutron-deficient edge of the $A \approx 190$ island of superdeformation. The relatively low angular momentum imparted in the reaction suggests that the superdeformed band in this nucleus may be at an excitation energy similar to that of the superdeformed band in the neighbouring nucleus ^{192}Pb.

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