Six "Identical" Superdeformed Bands in ^{194}Tl

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Four new superdeformed bands have been observed in ^{194}Tl, in addition to the two already reported. These six bands consist of three signature-partner pairs, whose energies and spacings resemble closely those in the two superdeformed bands recently reported in ^{193}Tl. The transition-energy similarities and angular momentum alignments of these bands are discussed.

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One of the outstanding problems in superdeformed (SD) nuclei in the mass-190 region is the so-called "identical bands," where the transition energies are either identical (within 1 or 2 keV) to those in a reference band of another nucleus or identical to the midpoint energies or to the "quarter points" (average of a midpoint energy and a primary energy) of the reference band. These situations all correspond to cases where the (dynamical) moments of inertia are the same and the alignments are quantized in multiples of $\frac{1}{2}\hbar$. In this mass region, many cases have been found where the alignment is quantized in this way.[1] To understand these properties, pseudospin alignment and triplet pairing have been introduced,[1] and will be discussed briefly later. We report the observation of four new SD bands in ^{194}Tl, in addition to the two previously reported.[2] This is the first time so many SD bands have been observed in a single nucleus, and it may be related to its odd-odd nature. All these bands have a quantized alignment of 0 or 1 unit with respect to the ^{193}Tl bands used as a reference, and these properties will be discussed further.

The experiments were carried out at the Lawrence Berkeley Laboratory 88-Inch Cyclotron using the DESY Hadron-Electron Ring Accelerator (HERA) facility. HERA consists of twenty Compton-suppressed Ge detectors and a 40-bismuth-germanate-element, 4π inner ball. The fusion reaction $^{18}O+^{181}Ta$ at beam energies of 95, 100, and 104 MeV was used to populate states in ^{195,194,193}Tl via the $4n$, $5n$, and $6n$ evaporation channels. The target consisted of three stacked foils of ^{181}Ta, each about 0.5 mg/cm^2 thick. γ-ray coincidences were measured; all threefold and higher coincidences between Ge detectors were recorded event by event on magnetic tape, together with the sum (H) and multiplicity (K) information from the inner ball. Twofold Ge coincidences were recorded only when they were in coincidence with at least six inner-ball detectors. Under these conditions, about 20% of the total coincidences recorded were threefold or higher. Approximately 660×10^6 coincidence events were recorded, with about equal numbers at each beam energy.

For each set of beam energies, E_γ-E_γ correlation matrices were produced with various K and H requirements. Analysis of the coincidence matrices first revealed two SD bands in ^{194}Tl, as reported previously.[2] These are labeled 1a and 2a in Fig. 1. It was pointed out in that report that, according to their spins and transition energies, these two bands are not signature partners. Since that time, searches for their signature partners were carried out and two new SD bands were identified. These are shown in Fig. 1 as bands 1b and 2b. Bands 2a and 2b display striking similarities to the negative-signature SD band,[3] ^{193}Tl($-$). Their transition energies fall within ±1 keV on the quarter and three-quarter points between adjacent transition energies in ^{193}Tl($-$). These similarities provided clues for finding still another pair of bands in ^{194}Tl which show the same behavior when compared to the positive-signature SD band,[3] ^{193}Tl(+). This third pair of bands is labeled 3a and 3b in Fig. 1. For all these bands, only very few lines were not contaminated by the intense normal γ-ray transitions. Therefore, extensive studies of the threefold and higher Ge coincidences were used to establish the mutual coincidences between all members in each band.

These six bands show properties characteristic of SD bands in the mass-190 region. Their moments of inertia increase regularly from $100\hbar^2$/MeV to $120\hbar^2$/MeV with increasing rotational frequency. The strongest band is 1a, with an intensity of about 1.5% of the total ^{194}Tl yield for $K>10$ and $H>5$ MeV. Under the same conditions, bands 1b, 2a, 2b, 3a, and 3b were found to have intensities of approximately 70%, 60%, 40%, 40%, and 50%, respectively, of band 1a. Because of these low intensities and the fact that very few clean gates were available, the angular correlations of only the strongest transitions in bands 1a and 1b could be determined. These correlations indicated that the transitions involved

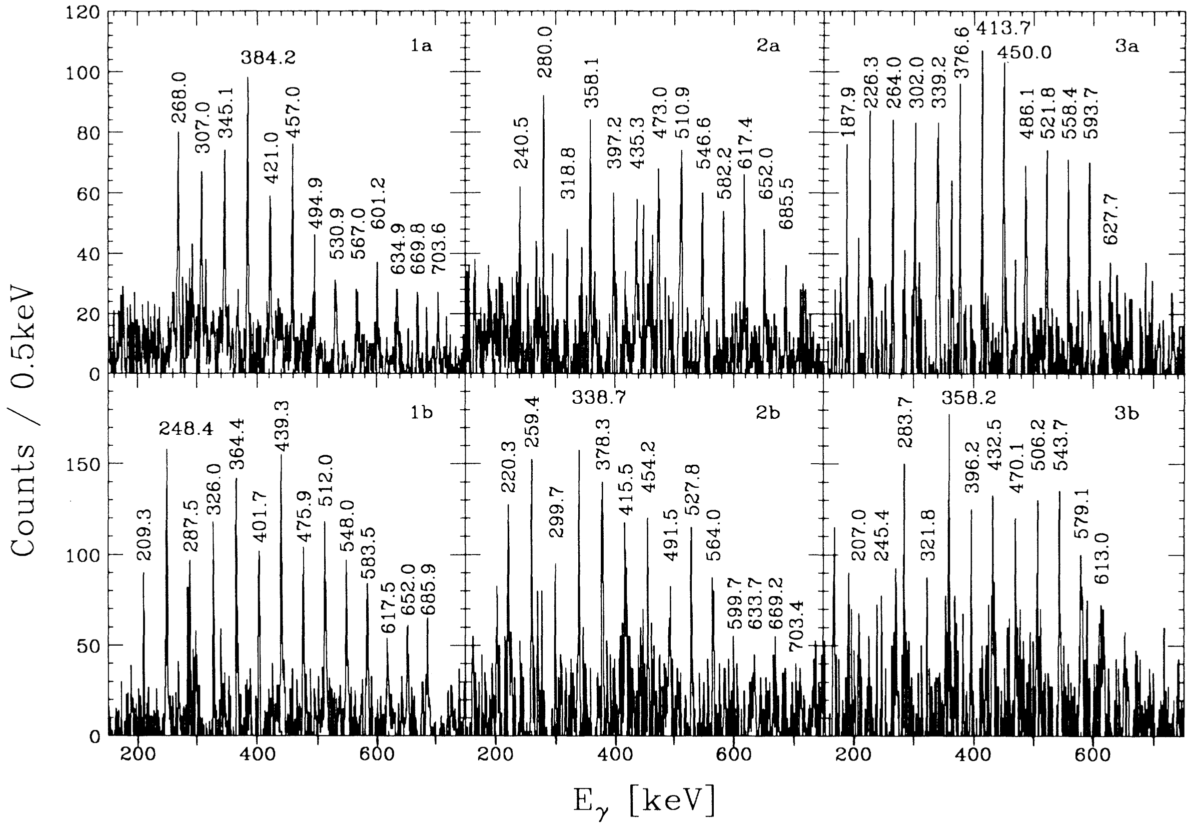

FIG. 1. Triple-coincidence spectra of the six SD bands in ^{194}Tl, obtained by adding spectra from different double-gate combinations in a given band. The uncertainties in the transition energies range from 0.3 to 1.0 keV. The ordinate scale should be multiplied by the factors $\frac{1}{2}$, $\frac{2}{5}$, $\frac{3}{5}$, and $\frac{2}{3}$ for spectra 2*a*, 2*b*, 3*a*, and 3*b*, respectively.

are stretched quadrupole in character. The relative intensities of the transitions in these SD bands show the same behavior as those in the Hg nuclei, namely, a slow increase of intensity with decreasing transition energy, followed by a region where the intensities stay roughly constant, and finally a rapid depopulation of the bands within one or two transitions at the low-energy end.

With these very weak bands, the contamination of the lines and the background subtraction were too critical to establish the mass assignment from the observation of coincidences between normal[4] and SD transitions. Therefore, the mass assignments were based on excitation-function studies. The six SD bands were mainly observed in the data taken with ^{18}O at 100- and 104-MeV bombarding energies, where the dominant reaction products are ^{193}Tl and ^{194}Tl. We compared the yields of the normal and SD bands with a high-multiplicity cut ($K \geq 16$). This did not affect the SD bands appreciably, but eliminated the lower-spin population of normal bands, making their excitation functions much more similar to the SD bands in their respective nuclei. With this high-multiplicity condition, the ratio of the yield at 104 MeV to the yield at 100 MeV varies between 0.9 and 1.5 for the six bands, with a typical uncertainty of 0.3 to 0.4. This ratio is 1.0 ± 0.2 for normal ^{194}Tl transitions and 3.5 ± 0.5 for those of ^{193}Tl. With the same high-multiplicity condition, the normal ^{195}Tl transitions become vanishingly small in the data taken at 104 MeV. We have therefore assigned these six SD bands to ^{194}Tl. An additional argument for the mass assignment comes from a comparison of the excitation of SD bands in neighboring isotopes using the same reaction. The two SD bands in ^{193}Tl reported by the Argonne group[3] have been seen only very weakly populated in the 104-MeV data, whereas a SD band[5] in ^{195}Tl has been identified, also very weakly populated, but only in the 95-MeV data.

Determination of the spin in the bands was made using the two methods already described.[6] Using the even-mass nature of the nucleus, the spins were taken to be the closest integers to the values determined. All three SD bands labeled *a* in Fig. 1 were found to have even spins, with the $14 \rightarrow 12$ transitions being the 268.0-, 280.0-, and 264.0-keV γ rays, and the bands labeled *b* to have odd spins, with the $13 \rightarrow 11$ transitions being the 248.4-, 259.4-, and 254.4-keV γ rays. According to their transition energies and spins, we conclude that bands 1*a*, 2*a*, and 3*a* are the (signature 0) partners, respectively, of the (signature 1) bands 1*b*, 2*b*, and 3*b*.

In trying to understand superdeformed bands in the mass-190 region, plots of alignment[1] relative to ^{192}Hg versus rotational frequency (half the γ-ray transition energy) have been discussed.[1] Figure 2(a) shows such a plot for the six bands in ^{194}Tl and the two in ^{193}Tl. It is apparent that the ^{194}Tl bands comprise three signature pairs and that those in ^{193}Tl are signature partners that develop some signature splitting at frequencies above 0.2 MeV. The added proton in ^{193}Tl has been assigned[3] as the $\frac{5}{2}$ [642] configuration, which seems consistent with such a splitting. The points are basically along a horizontal line in Fig. 2(a) (at least for the middle frequencies), as is the case for many of the superdeformed bands in Hg nuclei, and this indicates (dynamical) moments of inertia very similar to those of ^{192}Hg. Quite surprisingly the alignments have been found[1] to be "quantized" for many of the bands in this region (as well as some in the mass-150 region), i.e., to have integer or half-integer values. One could argue that some of these Tl bands behave in this way. Above frequencies of 0.2 MeV, bands 3*a* and 3*b* in ^{194}Tl and the band ^{193}Tl(+) are rather close to half-integer values in Fig. 2(a), and bands 1*a* and 1*b* in ^{194}Tl come rather close to an integer value for the middle frequencies. However, this kind of behavior is not really expected for this proton orbital, as it has an intruder, rather than a natural-parity, character. Furthermore, a better classification is suggested by the similarity in shape of bands 1*a*,1*b* and 2*a*,2*b* in ^{194}Tl to ^{193}Tl(−), and bands 3*a*,3*b* in ^{194}Tl to ^{193}Tl(+). The bands in ^{193}Tl are clearly better references for the bands in ^{194}Tl than is ^{192}Hg. Thus in Fig. 2(b) we have used the ^{193}Tl bands suggested above as references for the bands in ^{194}Tl. All these cases involve the effects of adding the 113th neutron, and ^{193}Hg compared to ^{192}Hg is another such case; therefore, the two bands in ^{193}Hg referred to ^{192}Hg have been included in Fig. 2(b).

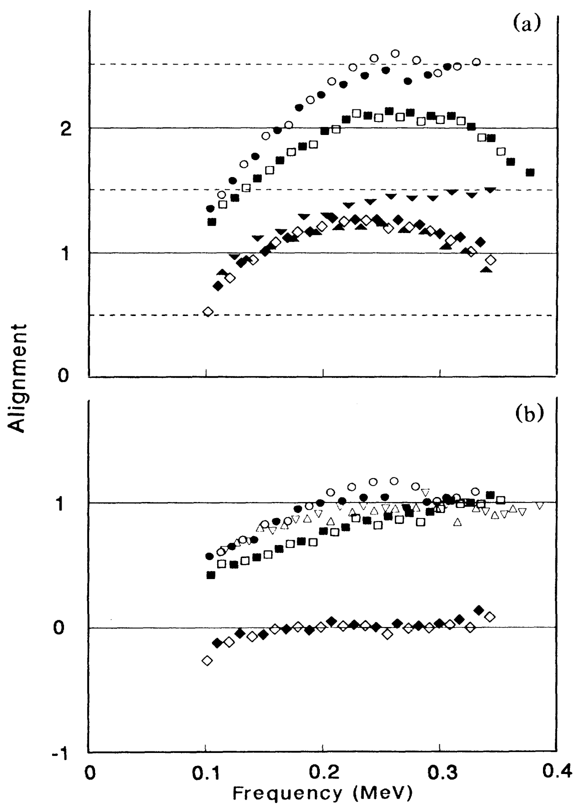

FIG. 2. (a) Alignment of the two bands in ^{193}Tl and the six bands in ^{194}Tl relative to the ^{192}Hg band: ▼, ^{193}Tl(+); ▲, ^{193}Tl(−); □, ^{194}Tl(1*a*); ■, ^{194}Tl(1*b*); ◇, ^{194}Tl(2*a*); ◆, ^{194}Tl(2*b*); ○, ^{194}Tl(3*a*); and ●, ^{194}Tl(3*b*). (b) Alignment of the six bands in ^{194}Tl relative to ^{193}Tl bands, and alignment of the two bands in ^{193}Hg relative to ^{192}Hg (see text): △, ^{193}Hg(+) and ▽, ^{193}Hg(−). The six bands in ^{194}Tl are represented by the same symbols as in (a).

The regularities are more striking in Fig. 2(b) and also much more like those already noted in other nuclei of this region—the moments of inertia are extremely similar above frequencies of 0.2 MeV [the points are horizontal in Fig. 2(b)] and the relative alignments are very close to integers. Thus the 113th neutron [Fig. 2(b)] is "better" behaved than is the 81st proton [^{193}Tl in Fig. 2(a)], as expected. Adding a neutron to each of the ^{193}Tl bands (signatures) appears to produce a pair of bands in ^{194}Tl with alignment very close to 1, just as adding the same neutron to the one band in ^{192}Hg (signature 0) produces a pair of bands in ^{193}Hg with alignment 1. While it is normal to get a pair of bands when adding a particle, the rest of this behavior is quite unexpected and not understood, as we will discuss below. Furthermore, in the case of the ^{193}Tl(−) band, there also seems to be a pair of related bands with alignment 0. This suggests that a fourth pair of bands might exist in ^{194}Tl which would be related to the ^{193}Tl(+) band, with alignment 0, but we have not yet found these bands. Whether that is because they are not there or are just too weakly populated is not clear.

The only explanation so far suggested for quantized alignments is in terms of the alignment of pseudo intrinsic spins[1,7] (pseudospin). In this picture the mixing (due to the deformation) of shell-model states that have opposite spin-orbit coupling (e.g., $h_{9/2}$ and $f_{7/2}$) results in mixed (pseudo) configurations having the average orbital angular momentum and very weak residual spin-orbit coupling (pseudo $g_{7/2,9/2}$ in the above example). The Coriolis force can then align the pseudospins leaving the pseudo orbital angular momentum strongly coupled to the symmetry axis. However, in such a scheme, one would *a priori* expect an alignment of $\frac{1}{2}\hbar$ for the addition of a single nucleon. While this probably happens in some cases in the mass-150 region,[7] the alignments in the mass-190 region are usually integers as in Fig. 2(b). Alignments of 1 are most common in this region, suggesting that two nucleons with aligned pseudospins might be involved. This has led to the speculation that there might be pairing correlations involving pairs with time-reversed orbital motion but aligned pseudospins (alignment 1), rather than the usual fully time-reversed (both l and s) configurations which have alignment 0. This could occur because there are many pairs of orbits (almost all the natural-parity ones) whose pseudospins are expected to be aligned in this way at high spins. (However, the intruder orbitals have no nearby states to mix with and thus the spin remains strongly coupled to the orbital motion, resulting in no pseudospin alignment.) Triplet pairing is indeed seen[8] in superfluid ^{3}He, though singlet superfluid ^{3}He is also expected to occur under some conditions, and the two superfluids could coexist. Triplet pairing is also thought to be important in the interior of neutron stars.[8] The relevance to the present data is that triplet-pairing correlations in nuclei might generate a vacuum that has alignment 1—thus explaining the frequent occurrence of such alignments. However, the normal (singlet) pairing vacuum would be likely to occur at energies not much different from those from the triplet pairing; thus there could also be configurations based on the normal (alignment 0) vacuum. Which vacuum lies lower in energy would depend on what levels are available to the pairing, i.e., on exactly which levels are blocked, and the two vacua might coexist at rather similar energies. This last possibility is an interesting one, and the alignment-1 and -0 pairs of bands in ^{194}Tl based on the band ^{193}Tl(−) might be the first indication of such behavior.

It is quite clear that some of the properties of superdeformed bands recently observed cannot be explained in usual nuclear-structure terms. Several new concepts seem to be required to explain the extremely similar moments of inertia and the (integer) quantized alignments sometimes observed. Pseudospin symmetry seems likely to be involved in the explanation, as does some systematic cancellation among the contributions to the moments of inertia. In addition, we have speculated above that the large deformation and the high spin may stabilize a different type of pairing (triplet) which can then compete with the Coriolis-weakened normal pairing. It appears there is much to be learned about nuclear structure from the unusual behavior of these superdeformed bands.

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