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Decay of the ^{194}Pb Superdeformed Band

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Abstract: Three experiments using the ^{174}Yb(^{25}Mg,5n) reaction at a beam energy of 130 MeV have been performed utilizing the Early Implementation of GAMMASPHERE. The goal of these experiments was to study the decay of the known superdeformed states in ^{194}Pb to the normal low–lying levels in this nucleus. The statistical decay of this band appears to be suppressed with respect to its ^{194}Hg isobar. A single discrete transition at 2.746(2) MeV in coincidence with both the superdeformed band and the normal states through which it decays has been identified in these experiments. The evidence for this transition and a discussion of its placement will be presented.

1. Introduction

Despite a wealth of experimental information on the superdeformed (SD) nuclei in the A ~ 190 mass region [Fi94], a number of the most fundamental properties of these structures remain unmeasured. Macroscopic quantities such as the excitation energy and the well depth of the second minimum and the width of the barrier separating the SD and the low–lying ground state minima remain unmeasured quantities as do fundamental microscopic parameters such as the spins and the parities of the SD levels. Direct experimental measurement of these quantities requires the that the decay pathways linking SD and low–lying normal states be observed.

The SD bands in the A ~ 190 mass region all have a similar intensity curve. The intensity of the SD bands increase with decreasing spin at the top of the bands until an intensity plateau is reached at intermediate spins. The intensity of the bands then stay approximately constant until they abruptly depopulates within one to two transitions. The SD band intensity non–preferentially populates a number of the low–lying normal states. This observation, coupled with the fact that previous experiments which have attempted to identify the SD decay pathways in the A ~ 190 mass region have been unsuccessful, has served as the primary piece of experimental evidence that the SD states decay via a statistical process.

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The ^{194}Pb nucleus was chosen as an optimal candidate for observing discrete decay of a SD band for five reasons. 1) ^{194}Pb has a well–studied, strongly populated ground state SD band [Br90,Th90,Hü90]. 2) All Pb isotopes are singly magic in the ground state serving to reduce the level density in the continuum through which decay of the SD band will proceed. 3) The ^{194}Pb SD band exists to low angular momentum which reduces the number of possible decay pathways. 4) The low–lying nuclear structure of ^{194}Pb is well understood from both HI,xn [Fa91,Br91] and β–decay studies [vD87]. 5) Long–lived isomers isolate the low spin ($\leq 12\ \hbar$) normal states from the high spin structures.

2. Experimental Details

Three experiments were performed using the Early Implementation of Gammasphere. In each of these three experiments three thin (~500 $\mu g/cm^2$ each), stacked self–supporting foils of isotopically enriched ^{174}Yb were bombarded by a 130–MeV ^{25}Mg beam. The predominant channels in this reaction were ^{193,194,195}Pb and ^{192}Hg with approximate relative production yields of 10%, 60%, 20%, and 7%, respectively. Of particular importance is the relatively low yield of ^{192}Hg created in this reaction because the most intense ^{192}Hg superdeformed band has energies that are identical (within ~0.5 keV) to those in the ^{194}Pb band over a range of angular frequencies from 100 keV to 280 keV.

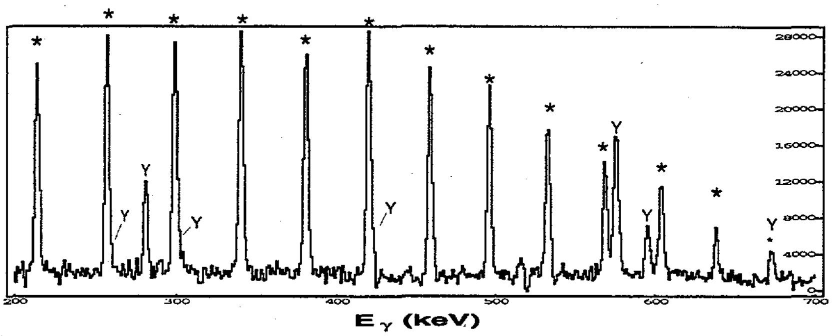

Figure 1: The ^{194}Pb SD band in a double–gated triples spectrum. The SD band members are denoted by *'s and the known low–lying yrast lines in coincidence with the SD band are denoted by Y's.

The first experiment was used to provide potential candidates for discrete transitions connecting the superdeformed and normal states. The second experiment provided an independent verification of the candidate transitions, while the third was used as a final cross–check. During all times in our analysis we have kept separate the three data sets. The discussion that follows will focus on the results from the largest data set (i.e., the second experiment).

Thirty–two Compton–suppressed detectors were in place for the second experiment with 15 located a backward angles (three rings of five detectors each at 173°, 147°, and 143° with respect to the beam), 13 detectors at forward angles (two rings of five detectors at 13° and 33°, and three detectors at 37°), and four detectors at 90°. The second experiment was consisted of twenty eight–hour shifts of beam time during which 1.3 x 10^8 unfolded triples events were recorded.

In Figure 1, we present the background subtracted spectrum produced by summing all unique pairwise combinations of gates set on the known members of the ^{194}Pb SD band from the second experiment. In this spectrum the most intense SD transitions have approximately 40,000 counts. Also seen in coincidence are a number of low–lying normal states through which the SD band depopulates.

3. Simple Observables

There are two observables that can be extracted from the data in a relatively straightforward manner. These are the average spin at which the SD band depopulates and the average spin at which the SD intensity reenters the low–lying level scheme. In Table 1, we summarize the relative intensities of all known transitions in coincidence with the ^{194}Pb SD band. From the results presented in Table 1 the value of the average depopulating spin is found to be 7.0 ± 1.1 $\hbar$. The average spin at which the SD band intensity re–enters the normal states is found to be 5.3 ± 1.2 $\hbar$. The difference of approximately 2 $\hbar$ angular momentum between the SD depopulation and the re-entrance of its intensity is in good agreement with similar values found in other studies [He94] and is in qualitative agreement with what is expected from both statistical and discrete decay processes from the SD band.

4. Statistical Decay

Recently an Argonne led collaboration has undertaken studies of the complete spectrum of γ–rays associated with the decay of the SD bands in the Hg isotopes to study the statistical decay properties of the SD bands [He94,Kh94]. Of particular interest is a "noticeable bump" between 1.3 and 2.2 MeV that has been associated with the final step in the decay of the SD bands.

We have undertaken a grossly simplified version of this type of analysis in order to make qualitative comparisons between the decay of the ^{194}Pb SD band and its isobaric complement ^{194}Hg. The method we have

Table I:

E_γ (keV)[a]	$J^\pi_i \rightarrow J^\pi_f$[b,c]	I(SD)[d]	I (2746)[e,f]
170.7	$8 \rightarrow 6$	64 (9)	?[g]
178	$(8^-) \rightarrow 7^-$	9 (4)	—
214.1	$10 \rightarrow 8$	85 (6)	82 (15)
257.3	$12 \rightarrow 10$	100 (3)	96 (15)
261	$(8^-) \rightarrow 7^-$	6 (3)	—
281	$5^- \rightarrow 4^+$	41 (10)	—
299.2	$14 \rightarrow 12$	99 (2)	98 (10)
302	$8^+ \rightarrow 6^+$	~8	—
340.3	$16 \rightarrow 14$	98 (2)	103 (14)
380.7	$18 \rightarrow 16$	101 (2)	124 (18)
420.2	$20 \rightarrow 18$	100 (2)	75 (22)
421	$7^- \rightarrow 5^-$	23 (6)	—
458.4	$22 \rightarrow 20$	78 (3)	84 (13)
496.0	$24 \rightarrow 22$	82 (3)	47 (12)
532.6	$26 \rightarrow 24$	64 (2)	65 (12)
568.8	$28 \rightarrow 26$	55 (5)	60 (13)
576	$4^+ \rightarrow 2^+$	77 (6)	105 (13)
595	$6^+ \rightarrow 4^+$	21 (6)	94 (14)
603.7	$30 \rightarrow 28$	33 (4)	55 (18)
638.3	$32 \rightarrow 30$	34 (4)	45 (19)
672	$? \rightarrow 2^+$	3 (2)	—
672.6	$34 \rightarrow 32$	18 (2)	22 (14)
965	$2^+ \rightarrow 0^+$	78 (9)	95 (14)
1308	$2_2^+ \rightarrow 0^+$	24 (4)	—

a) Superdeformed bands members given to 0.1 keV
b) Putative spins of SD band members from spin fit analysis [Be90]
c) Spins and parities of low–lying normal levels from reference [VD87]
d) Relative intensity from double–gated triples spectrum normalized to the 257.2–, 299.2– 340.3, and 380.7–keV transitions
e) Relative intensity in the background subtracted gate on the 2746–keV transition normalized to the 299.2– and 340.3–keV transitions.
f) — denotes a state for which an upper limit of ≤ 5% can be placed.
g) Data does not allow a determination whether this transition is seen.

used is to construct double–gated triples spectra of the SD band in question and an associated background spectrum. These spectra are then compressed to 16 keV per channel to eliminate statistical fluctuations, normalized to the total number of counts between 3 and 4 MeV, and the background spectrum is subtracted from the peak spectrum.

For ^{194}Hg this simplified analysis technique provides spectra that are qualitatively similar to those shown in references He94 and Kh94, with the exception of the exponential portion of the spectra at high energies which is over subtracted (by definition) in our method. In figure 2 we provide excerpts of spectra generated using our technique for both ^{194}Hg and ^{194}Pb in the region of the "noticeable bump." As can be seen in comparing these spectra, the bump which appears quite readily in the ^{194}Hg is absent from the ^{194}Pb spectrum.

The presence of the bump has been interpreted to be caused by the redistribution of energy levels due to ground state pairing. If this interpretation is correct, it is not surprising that ^{194}Pb, being singly magic, would show a marked reduction in this feature compared to ^{194}Hg. To the extent that this moderate energy bump is characteristic of the overall statistical part of the decay of the SD bands, however, the statistical contribution to the decay of the ^{194}Pb band appears to be suppressed.

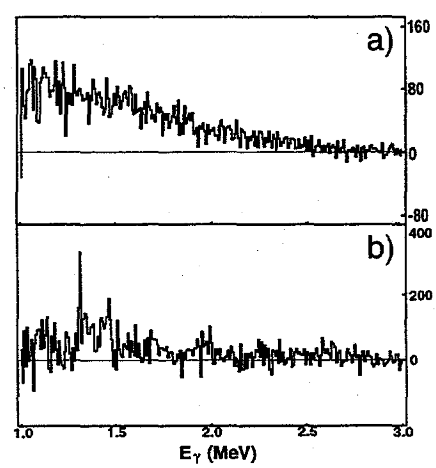

Figure 2: Spectra from 1 to 3 MeV created by the method described in Section 4 of the text. a) Spectrum associated with the ^{194}Hg SD band. b) Spectrum associated with the ^{194}Pb SD band.

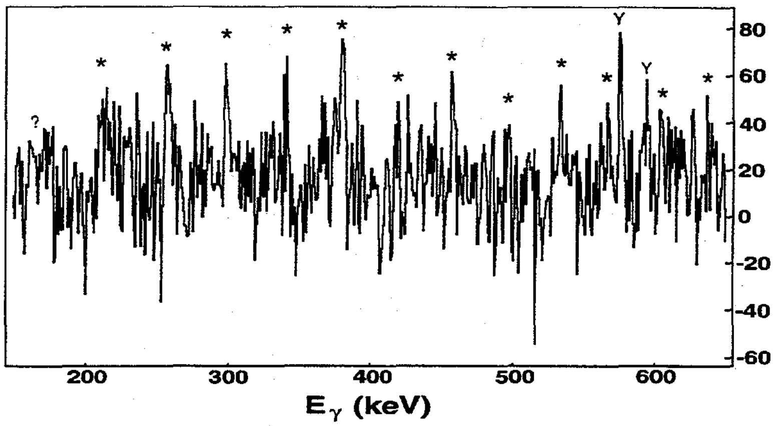

Figure 3: The ^{194}Pb SD band in coincidence with the 2.746(2)–MeV transition. The SD band members are denoted by *'s and the known low–lying yrast lines in coincidence with the SD band are denoted by Y's.

5. Discrete Decay

We have searched for high–energy transitions in coincidence with the known SD band members as candidates for discrete transitions connecting the SD and normal states in ^{194}Pb. Since this analysis takes place at the limits of existing experimental sensitivity, we have four independent criteria that must be met for a transition to be considered a viable candidate. 1) A proposed candidate must appear in all three data sets and its intensity must be consistent with the intensity of the SD band. 2) The candidate must track the intensity of the SD band members under a number of different gating conditions and background subtraction variations. 3) The full–width at half–maximum of the peak, corrected for the energy of the transition, must be consistent with the measured values of other peaks. 4) The peak was checked to ensure that it was not visible in the total projection to eliminate the possibility of a strong transition "leaking" through the gating and background subtraction requirements.

During the above analysis a *single* transition in the energy range of 2–4 MeV was found that met the above requirements. This transition has an energy of 2.746(2) MeV and a 4σ significance. Although not seen in a total projection (see criteria 4, above), we have set a 10 keV wide gate on this transition in a raw E_γ–E_γ coincidence matrix. Two 40 keV background gates were set starting at 60 keV below the low energy edge and 20 keV above the high energy edge of the peak gate, respectively. The spectra resulting from these two background gates were summed together and normalized to ~85% of the total number of counts in the peak spectrum. This summed and normalized spectrum was then subtracted from the peak spectrum, and a portion of the resulting spectrum is provided in Figure 3.

Clearly visible in Figure 3 are all 11 members of the ^{194}Pb SD band in the range 214.1 keV $\leq E_\gamma \leq$ 638.3 keV. We are unable to determine whether the 8 → 6 SD band transition at 170.7–keV is in coincidence with the transition at 2.746–MeV transition due to an unresolvable clump of intensity centered near the appropriate energy.

A similar procedure to the one described above was performed with the peak and background gates shifted down and up by 20 keV. For the spectra gated on 2730 keV (2770 keV) a total of 2 (4) peaks were found with energies corresponding to the SD band members, 6 (3) regions were found that were negatively correlated with the known SD band members, and the remaining 3 (4) regions were near the average background. From this study we find that the peak at 2.746 MeV is in coincidence with the SD band, and that this is not a general feature of this energy region.

In Figure 3 we have also marked the transition energies of the known low–lying normal states through which the SD band depopulates. In clear coincidence with the 2.746–MeV transition are the 595– and 576–

keV transitions corresponding to the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ low–lying transitions. Although not shown in this spectrum the 965–keV $2^+ \rightarrow 0^+$ is also in coincidence with the 2.746–MeV transition. A complete list of normalized intensities in coincidence with this transition is provided in Table 1. Of particular interest is the lack of evidence for both the 280–keV transition which runs parallel to and the 302–keV transition which directly feeds the 595–keV transition. Furthermore, within errors the 595–, 575– and 965–keV transitions each contain the full intensity of the SD band. Thus, it is clear that the 2.746–keV transition preferentially feeds the low–lying 6^+ state.

With direct experimental evidence that the 2.746–MeV transition feeds exclusively into the low–lying 6^+ state, we can eliminate the possibility that it is the first step in a purely statistical decay of the ^{194}Pb SD band, which should non-preferentially populate all low–lying normal states in coincidence with the band. While it is possible that this transition is a direct single step transition which connects the SD and normal structures, the available experimental evidence does not rule out the possibility that it is a single member of a multi–transition cascade depopulating the SD structure. If this is the case, however, the 2.746–MeV transition must lie near the final step of the cascade chain since no branching to multiple low–lying states is observed.

Since the low–lying 6^+ state has an excitation energy of 2.135(1) MeV, we can assign a minimum excitation energy for the SD level which depopulates through the 2.746–MeV transition (i.e., either the spin 8 or 6 superdeformed level) to be 4.881 (2) MeV. By extrapolating the SD band to a spin of 0 $\hbar$, the bandhead excitation energy is either 4.471 or 4.641 MeV assuming the depopulation of the SD spin 8 or 6 level, respectively.

We have been unable to measure the transition multipolarity. Assuming that the 2.746–MeV transition is a stretched E2, it carries 6(2)% of the full superdeformed band intensity. Furthermore, if this transition is in direct competition with the SD $8 \rightarrow 6$ transition, the 2.746 has a $B(E2) \approx 4 \times 10^{-4}$ Wu. Assuming $L = 1$, this transition carries 10(3)% of the band intensity and would have $B(E1) \approx 1 \times 10^{-4}$ Wu.

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