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Exotic Superdeformed Structure in A $\sim$ 190 Nuclei observed using Eurogam2

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EXOTIC SUPERDEFORMED STRUCTURES IN A ~ 190 NUCLEI OBSERVED USING EUROGAM2

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Abstract

Dipole transitions between superdeformed rotational bands are only very rarely observed due to the competition from the very strong in-band E2 decays. We have carried out two experiments with the EUROGAM2 γ-ray spectrometer, situated at the Vivitron tandem accelerator at CRN Strasbourg, in September and October 1994. In the first experiment we observe M1 dipole transitions between the signature partner yrast superdeformed bands in $^{193}T\ell$. This measurement gives a mean value of $(g_K$-$g_R)$ K/Q_o = 0.135 ± 0.010 μ_N/eb identifying the bands as belonging to the [642]5/2 single particle orbital. We also observe 5 additional new superdeformed bands in $^{193}T\ell$, whoes structures are discussed. In the second experiment we observe three transitions, at 911, 865 and 831 keV, which link an excited superdeformed band in ^{190}Hg to the yrast superdeformed band. The data suggest that these are stretched dipole transitions with E1 multipolarity and strengths of about 10^{-3}Wu. The excited band has a very large dynamic moment-of-inertia and RPA calculations suggest that it is mainly a K=2 octupole vibration at zero rotational frequency which becomes mixed with the other octupole configurations at $\hbar\omega \approx 0.3$ MeV. This is the first observation of a collective vibration of the superdeformed mean field. We also observe two new superdeformed bands in ^{190}Hg.

I. INTRODUCTION

The aim of an experimental scientist is, generally speaking, to observe new phenomena or to greatly increase the accuracy and sensitivity of previous measurements so that something can be learnt that we did not know before. Beautiful and powerful new instruments like EUROGAM2, which has been very well described in the previous talk[1] by Nadine Redon, give us great scope for learning new things about nuclei. In this talk I will report on initial results from two experiments with EUROGAM2, both concerned with observing rare dipole decays from superdeformed states.

For dipole transitions to be able to compete with the very strong 2,500 Wu in-band E2 transitions, special conditions have to exist. Either the superdeformed bands have to extend down to low γ-ray energies and low spins so that M1 transitions can compete with the in-band E2s, in the case that the superdeformed bands have high K, a signature partner and a large g-factor. Or the superdeformed band has to be at a sufficiently high excitation energy above the lowest superdeformed band of opposite parity, that E1 decay can compete if there is strong electric dipole moment D_o associated with an octupole vibration or deformation.

II. M1 TRANSITIONS IN $^{193}T\ell$

The first experimental hint that dipole transitions between superdeformed bands might be observed was from evidence [2] that one superdeformed band in ^{193}Hg was in coincidence with a second superdeformed band. As the connections could only be observed in one direction it was thought that the connections might be E1 transitions between identical bands [3,4] in the same nucleus having opposite parity. It was pointed out by Walker[5] and then by Semmes, Ragnarsson and Aberg [6] that, in favourable circumstances, M1 transitions could occur when the single particle orbital had a large g-factor. These M1 transitions would have energies below 200 keV and would be very strongly converted. These large electron conversion coefficients would mean that the M1 photons would be very difficult to observe. An experiment by Cullen et al. [7] to measure the enhanced X-ray intensity in coincidence with ^{193}Hg superdeformed bands showed that the linking transitions were probably M1. This conclusion was supported by data [8] from the early implimentation of Gammasphere that both signatures of the superdeformed bands were in coincidence with the lower levels of the superdeformed band of opposite signature. Joyce et al. [9], using EUROGAM1, were able to observe and measure the branching ratios of M1 transitions between the superdeformed bands in

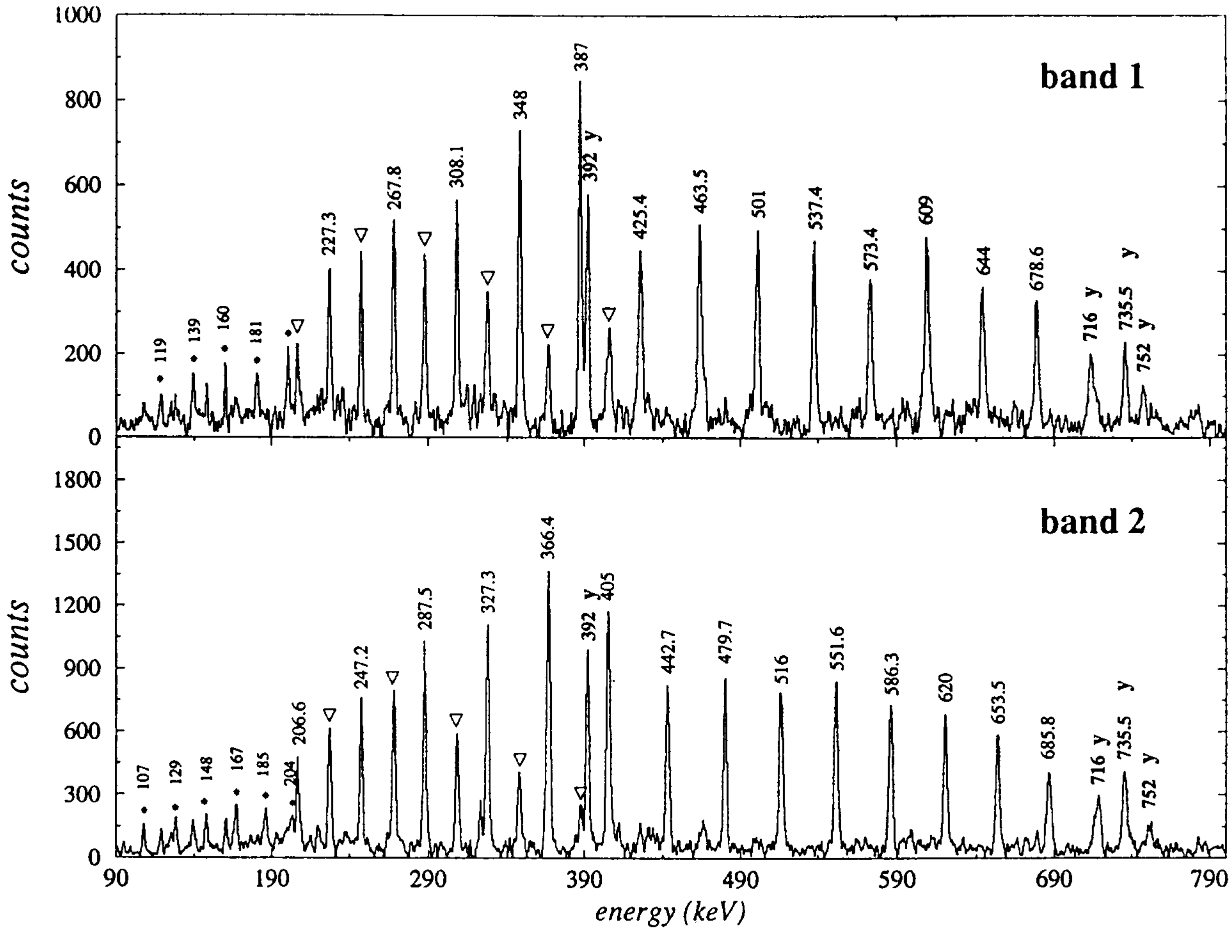

Fig.1 Spectra of the yrast signature partner superdeformed bands in ^{193}Tℓ. Gates have been set on combinations of three γ-rays in the superdeformed band. Peaks of the signature partner, populated by the cross-feeding, are marked with an inverted triangle and the cross-band M1 transitions are marked with a star. γ-rays from the normal deformed yrast levels are indicated by a y.

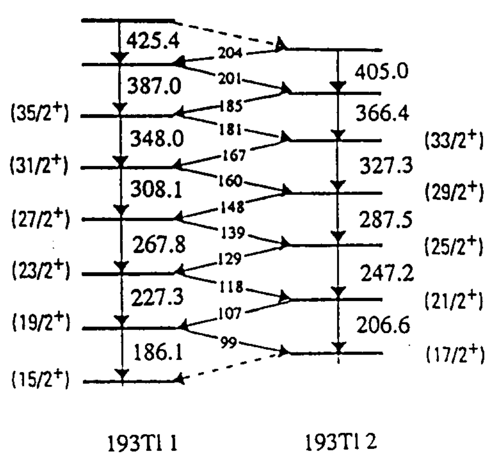

Fig.2 Decay scheme of the bottom of the signature partner superdeformed bands in ^{193}Tℓ showing the cross-band M1 transitions.

^{193}Hg. Their result gave the first quantitative measurement of the magnetic properties of a superdeformed nucleus. The experimental value of the g-factor they obtained showed that the odd neutron was in a $[514]5/2^-$ orbital. Another pair of superdeformed bands were shown to probably be based on the $[642]5/2^+$ orbital.

In a different experiment, cross-talk between signature partner superdeformed bands was observed [10,11] in the odd proton nucleus ^{195}Tℓ. Again, the spectrometer used was EUROGAM1, and the measured g-factor was consistant with the proton being in the $[642]5/2^+$ orbital.

A review of the data on M1 transitions in ^{193}Hg and ^{195}Tℓ was given at last year's Bormio Conference by Faical Azaiez [12]. These data showed that the single particle levels, predicted to be at the superdeformed Fermi surface by several different calculations [13-16] were in agreement with experiment. Indeed, the observation or non-observation of M1 transitions and cross-talk between signature partner bands could be used [17] as a very useful spectroscopic tool in superdeformed nuclei in the mass 190 region of the nuclear chart.

The motivation for the present work was to make the most accurate possible measurement of a g-factor for a superdeformed orbital. There has been discussion [18,19] of whether or not the effective M1 operator should be the same for superdeformed and normal deformed nuclei. Clearly an accurate measurement for a superdeformed orbital would give the best test for any change in the renormalization of the M1 operator. The cleanest case, where a superdeformed orbit is well separated experimentally from other orbits, is outside closed superdeformed neutron and proton shells, is easily accessible with good statistics and has a large g-factor, is the case of the yrast superdeformed proton orbit π $[642]5/2^+$ in ^{193}Tℓ. This is the same orbital whoes g-factor has been measured [10] in ^{195}Tℓ. The advantage of ^{193}Tℓ is that both the superdeformed neutron and proton shells close at N=112 and Z=82 respectively [13]. Also it is easier to reach experimentally as it is less neutron rich.

We have used the ^{181}Ta(^{18}O,6n)^{193}Tℓ reaction at a beam energy of 110 MeV. Two self supporting foils of ^{181}Ta, nominal thickness 500 μg cm^{-2}, were used without any backing so that the recoiling ^{193}Tℓ nuclei had the full centre-of-mass velocity. A total of 0.8×10^9 γ-ray coincidence events were recorded to tape for which at least 5 unsuppressed Ge detectors had fired in the EUROGAM2 array.

After unfolding [20], a total of 8×10^9 quadruple suppressed γ^4 coincidences was obtained. In fig.1 spectra of the signature partner yrast bands [21] in ^{193}Tℓ are shown. These spectra are γ-rays in coincidence with combinations of three γ-rays in that su-

TABLE I : *Energies of γ-rays in superdeformed bands observed in $^{193}T\ell$ given in keV. The relative intensities of the bands, with respect to band 2 taken as 100 % are : band 1 (100 ± 15 %), band 3 (50 ± 15 %) band 4,525 ± 20 %), bands 6,7 (10 ± 7 %)*

Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
Lowest Level $15/2^+$	Lowest Level $17/2^+$	Lowest Level $15/2^{(+)}$	Lowest Level 21/2	Lowest Level 23/2	Lowest Level 19/2	Lowest Level 25/2
186.1(2)	206.6(2)	188.2(2)	250.7(4)	271.5(4)	228.8(3)	
227.3(2)	247.2(2)	230.8(2)	292.5(4)	313.3(4)	270.3(4)	293.0(4)
267.8(2)	287.5(2)	272.7(2)	332.7(4)	353.9(3)	311.2(4)	334.0(4)
308.1(2)	327.3(2)	314.3(2)	372.6(4)	393.0(3)	351.8(3)	374.0(4)
348.0(2)	366.4(2)	355.1(2)	411.8(4)	432.5(3)	391.7(3)	414.0(4)
387.0(2)	405.0(2)	395.0(2)	450.6(4)	469.9(3)	430.0(3)	452.0(4)
425.4(2)	442.7(2)	434.5(2)	488.0(4)	507.6(3)	468.5(3)	486.3(4)
463.5(2)	479.7(2)	472.9(2)	524.8(4)	543.4(3)	504.3(3)	522.5(4)
501.0(2)	516.0(2)	510.5(5)	561.0(4)	579.7(3)	540.5(3)	557.2(4)
537.4(2)	551.6(2)	547.5(2)	596.5(4)	614.2(3)	575.5(3)	593.2(4)
573.4(2)	586.3(2)	583.3(2)	631.5(4)	649.7(4)	610.3(3)	628.0(4)
609.0(2)	620.0(2)	618.5(3)	666.0(4)	684.2(4)	644.3(4)	661.5(4)
644.0(2)	653.5(2)	652.9(3)			678.0(4)	694.0(4)
678.6(2)	685.8(3)	686.5(3)				
713.2(3)	718.6(3)	720.5(4)				
746.9(3)	750.8(3)					

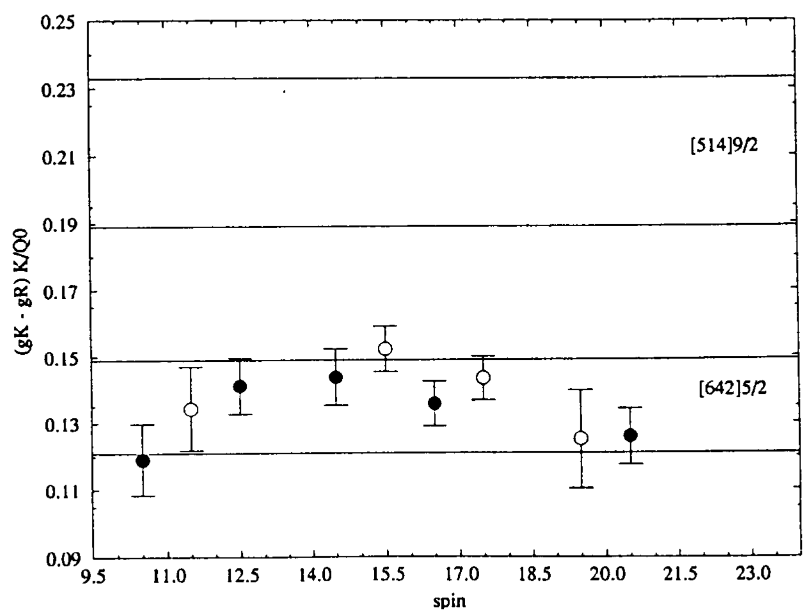

Fig.3 Values of $(g_K\text{-}g_R)K/Q_o$ for bands 1 and 2 in $^{193}T\ell$. The values are determined from the cross-feeding strengths using the method describd by Duprat et al [10,11]. The data show that the single proton, outside the superdeformed ^{192}Hg core, is in the $[642]5/2^+$ orbit.

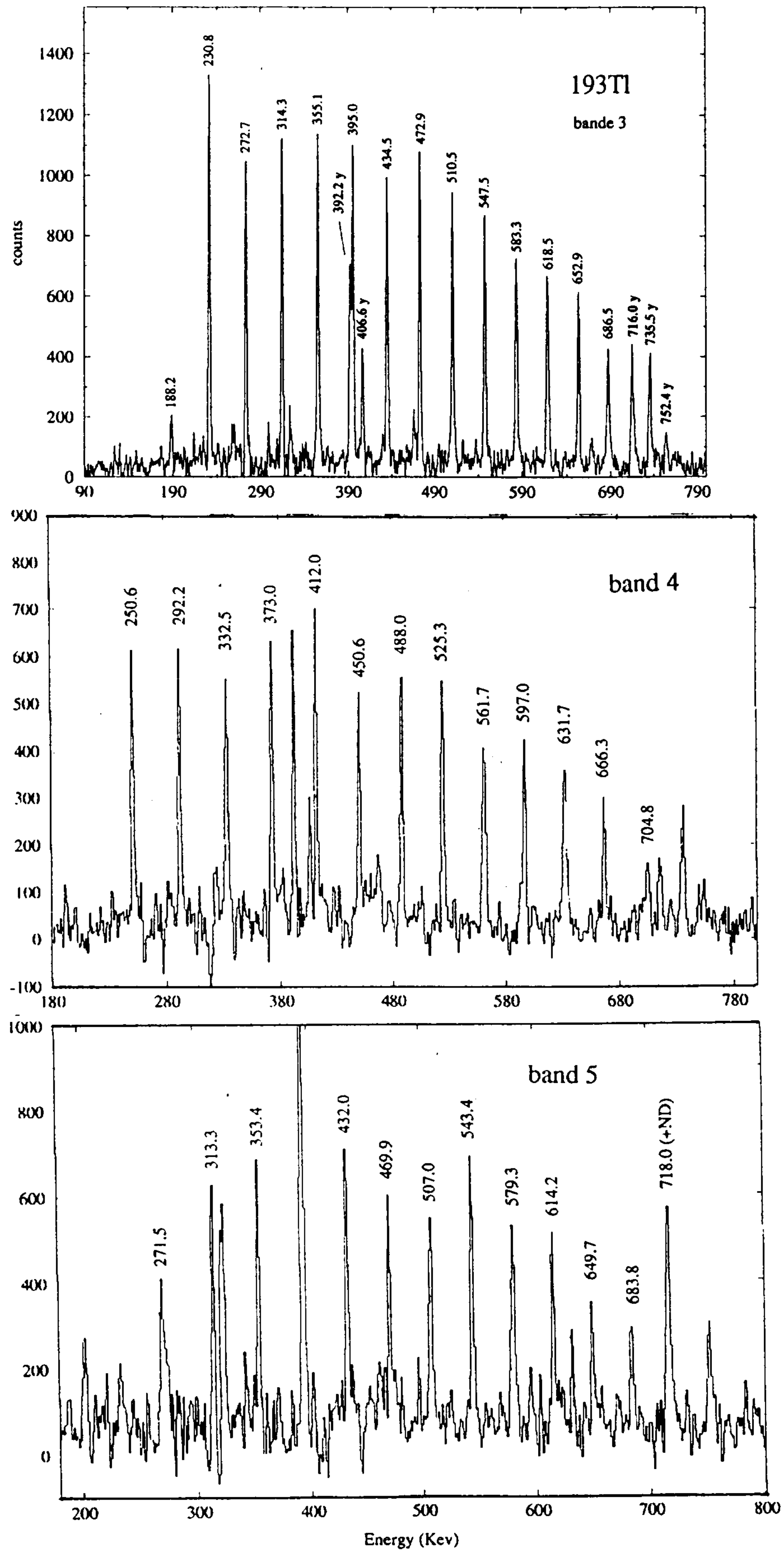

Fig.4 Spectra for the excited superdeformed bands 3,4 and 5 in $^{193}T\ell$. Quadruple coincidences have been used.

perdeformed band. Peaks from the decay of known normal deformation yrast states at low spin are indicated by bold type **y** after the γ-ray energy. The peaks of the signature partner superdeformed band populated by the cross-feeding are marked with an inverted triangle. The linking M1 transitions themselves are marked with a star. The decay scheme for these bands, over the region for which M1 linking transitions have been observed, is shown in fig.2.

In order to extract the g-factors for these bands, the same proceedure has been used as in ref.[10]. The results are shown in fig.3. The average value obtained is $(g_K\text{-}g_R)K/Q_o$ $= 0.135 \pm 0.010$. This is already more accurate than measurements of Q_o by the DSAM, which is limited by the best error of 10 % on stopping powers.

III. EXCITED BANDS IN $^{193}T\ell$

In the $^{193}T\ell$ data set we have been able to observe five new excited superdeformed bands. Spectra for the bands we have labelled bands 3, 4 and 5 are shown in fig.4. Band 3 does not have an observable signature partner in our data and must belong to an orbit showing strong signature splitting and hence a low value of Ω. Bands 4 and 5 are signature partners. Band 6 has energies almost identical to the known [22] superdeformed band ^{191}Au. Band 6 and band 7 are signature partners whereas no signature partner was found in ^{191}Au. However bands 6 and 7 are distinctly in coincidence with $T\ell$ X-rays, have not been observed in either $^{192}T\ell$ or $^{194}T\ell$ and are in coincidence with normal deformation γ-rays in $^{193}T\ell$. We conclude that they are in $^{193}T\ell$ and are not in ^{191}Au populated by the (^{18}O, α 4n) reaction. All the energies of the superdeformed transitions we have observed in $^{193}T\ell$ are collected in Table 1.

Comparison with calculations [14,15,16] shows that the most obvious configuration for band 3 is the favoured $\alpha = 1/2$ signature of the $\pi[411]1/2^+$ (proton hole) orbital.

We would also expect bands 4/5 and bands 6/7 to involve proton excitations because similar, fairly strong excitations across the neutron N=112 gap have not been observed in ^{192}Hg [23,24]. An obvious candidate for either pair of bands would be the next predicted proton orbital with high K, as no signature splitting is observed in either pair of bands. This orbital would be the $\pi[514]9/2^-$ (proton particle) configuration. However this orbital is predicted [6,17] to have a large g_K giving B(M1) = 1.9 and hence strong cross-band transitions. Our experimental results suggest that crossband transitions are very weak for bands 4/5 (fig.4) ruling out the $\pi[514]9/2^-$ orbital. In fig.5(a) we show the incremental alignments [25] of bands 3,4,5 with respect to the yrast SD bands in the core nuclei ^{192}Hg (particles) and ^{194}Pb (holes)[26]. It can be seen that the incremental

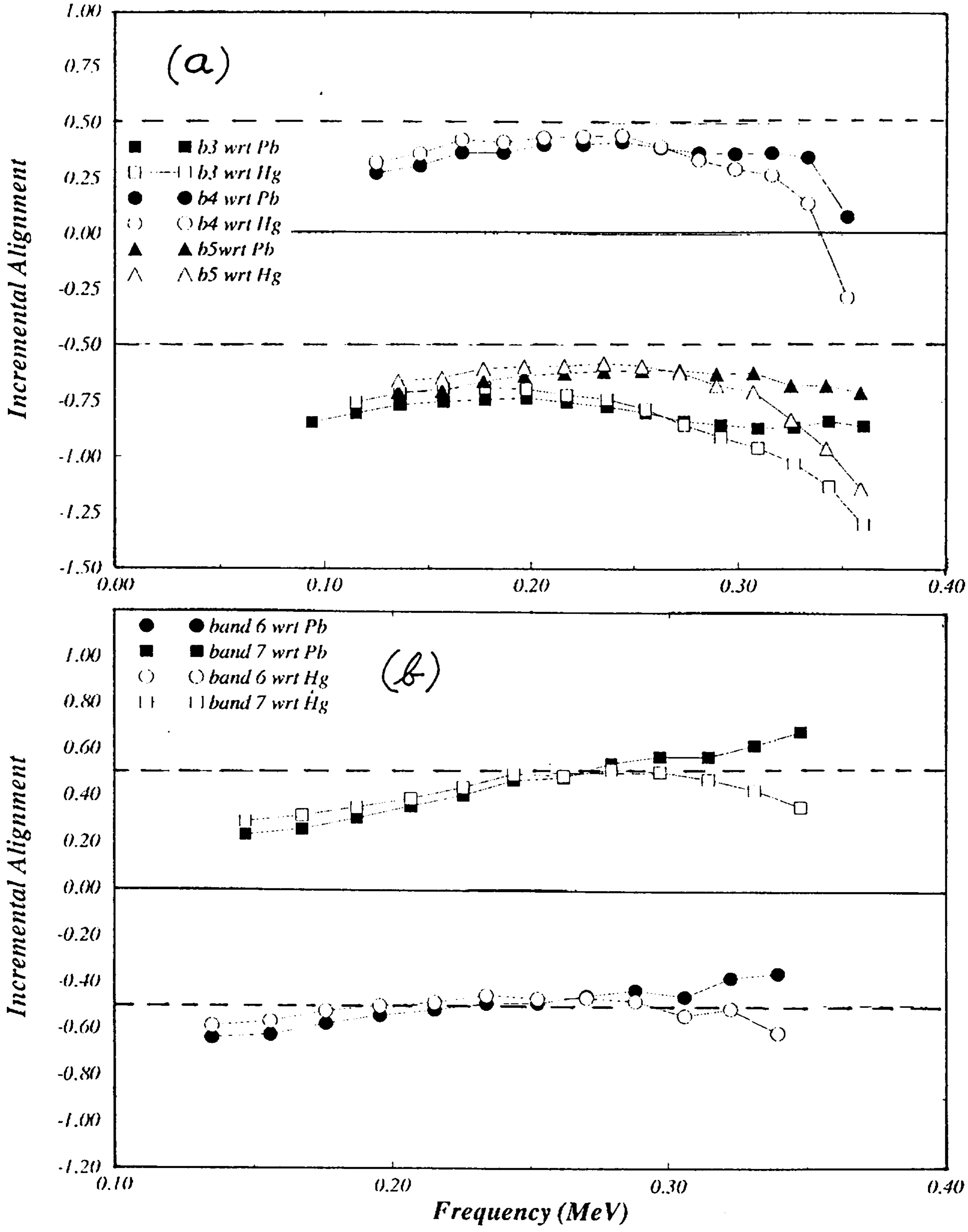

Fig.5 Incremental alignments for the excited superdeformed bands in $^{193}_{81}T\ell$ with respect to the yrast bands in $^{192}_{80}Hg$ (open symbols) and $^{194}_{82}Pb$ (full symbols).

(a) Superdeformed bands 3,4 and 5

(b) Superdeformed bands 6 and 7

alignments are much flatter for all 3 bands for the ^{194}Pb reference than for the ^{192}Hg reference. This observation strongly suggests that the three bands are proton holes in ^{194}Pb. Similar plots for bands 6, 7, shown in fig.5(b), tend towards the opposite result: the alignments are flatter for the ^{192}Hg reference than for ^{194}Pb. We conclude that bands 6, 7 are probably a particle excitation, above the [642]5/2$^+$ orbit, outside the ^{192}Hg core. Perhaps bands 6, 7 are in the "missing" [514]9/2$^+$ orbit ?

IV. THE HIGH $\mathcal{J}^{(2)}$ BAND IN ^{190}Hg

Recently an excited band has been found [27] in ^{190}Hg that has a very large and relatively constant dynamical moment-of-inertia $\mathcal{J}^{(2)} \sim 120\hbar$ MeV^{-1}. There was strong evidence that this band, labelled band 2, decayed to the yrast superdeformed band, band 1. The nature of this decay is quite different from the M1 decays between signature partner bands that we have been discussing in the previous section II of this contribution. Firstly the decay occurs only from the excited band 2 to the yrast band. Secondly the yrast band is expected to be a K=0 vacuum band and therefore the excited band 2 cannot be its signature partner. Thirdly, the intensity in the excited band is emptied entirely from band 2 into band 1 over 3 to 4 linking transitions. Fourthly the very large $\mathcal{J}^{(2)}$ for band 2 makes it quite unique compared to the systematics of all other superdeformed bands [28]in this mass region.

The nucleus ^{190}Hg was calculated [29] at an early stage to be the nucleus whose superdeformed shape was likely to be softest to octupole vibrations. RPA calculations [30,31] suggested that the K=2 vibrational phonon would lie lowest in energy for the even Hg superdeformed isotopes. Rotations built on a K=2 phonon would cause a splitting of the two signature components, of which the odd spin ($\alpha = 1$) component would be lowest. The even spins, with α=0, would lie at higher energies. All single octupole phonon excitations of a positive parity vacuum state will have negative parity themselves. Hence any decays from an octupole vibrational state to the vacuum would be expected to go via E1 transitions with ΔJ=1 or 0. Of course the rotation will mix states of different K but having the same signature. All phonon vibrational states will mix with particle-hole states with the same intrinsic quantum numbers as the rotational frequency increases. The octupole phonons can be identified experimentally by their ability to give an electric dipole moment to the nucleus enhancing [32] the probability of E1 decays to strengths above 10^{-3}Wu.

The original experiment [27], which revealed band 2 and its unique properties, was not geared to efficient detection of streched dipole transitions which are emitted pref-

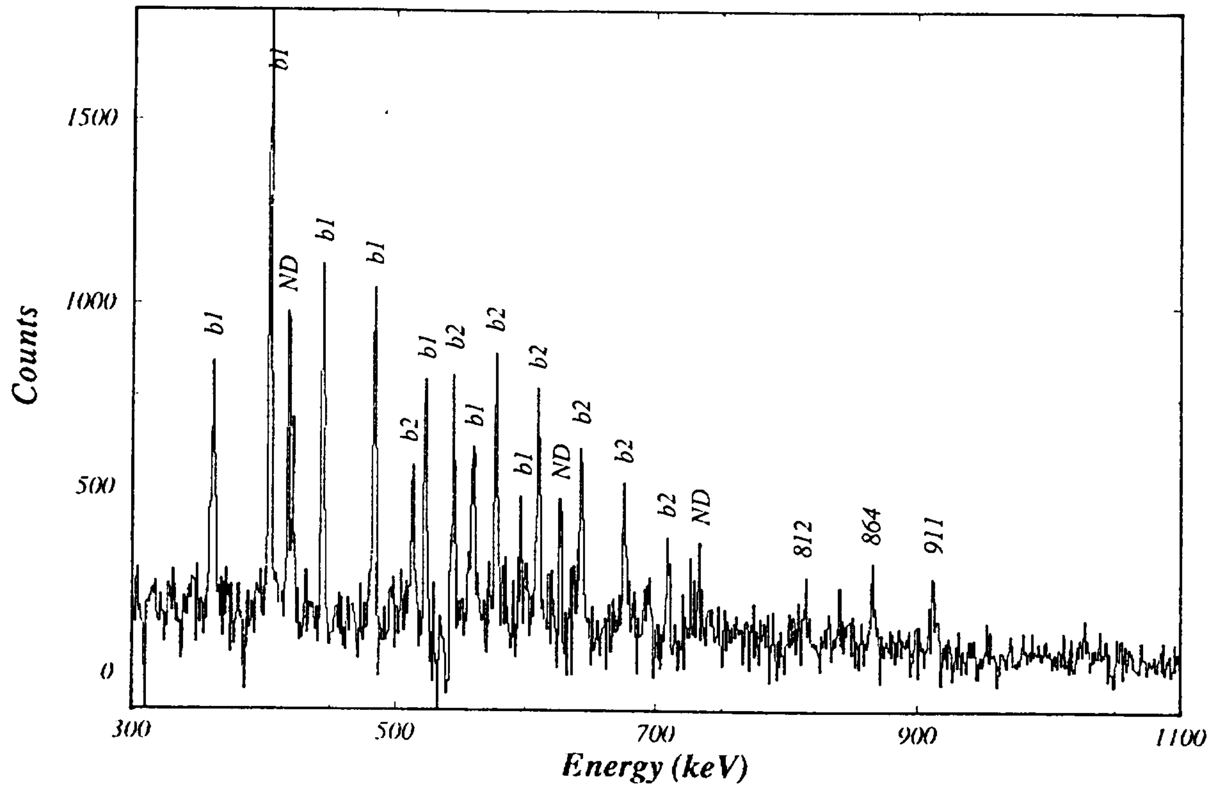

Fig.6 Spectrum of γ-rays in the superdeformed band 2 (b2) in ^{190}Hg showing the yrast superdeformed band 1 (b1) transitions that are fed and the linking transitions between band 2 and band 1 at 911, 864 and 812 keV. Gates have been set, in triple coincidences, on both combinations of two γ-rays in band 2 and on combinations of one γ-ray in band 2 and one γ-ray in band 1.

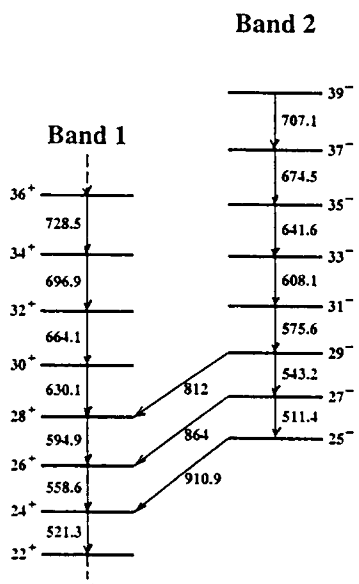

Fig.7 Decay scheme showing the linking transitions connecting superdeformed band 2 to superdeformed band 1 in ^{190}Hg.

TABLE 2 : *Energies, branching ratios, partial half-lifes and B(E1) transition probabilities for the linking transitions between band2 and band 1 in ^{190}Hg. A quadrupole moment Q_o = 18 ±3 eb has been assumed for band 2.*

E_γ (keV)	Branching ratio of link %	Partial half-life (+s)	B(E1) (Wu $\times 10^{-3}$)
910.9(4)	> 50	< 200	> 1.4
864(1)	35(4)	260(60)	1.2(3)
812(1)	29(4)	260(70)	1.5(4)

TABLE 3 : *Energies in keV of the superdeformed bands in ^{190}Hg.*

Band 1	Band 2	Band 3	Band 4
316.9(4)	511.4(4)	279.0(3)	446.3(4)
360(1)	543.2(3)	318.4(3)	466.5(4)
402.3(1)	575.6(2)	359.3(3)	486.7(4)
443.0(1)	608.1(3)	397.4(3)	515.0(4)
482.7(1)	641.6(3)	435.9(3)	547.7(4)
521.3(1)	674.5(5)	474.0(8)	582.7(4)
558.6(1)	707.1(6)	510.6(3)	617.7(4)
594.9(1)		547.7(8)	653.6(4)
630.1(1)		582.9(7)	689.6(6)
664.1(1)		617.9(7)	723.3(6)
696.9(1)		651.5(5)	760.4(6)
728.5(4)			791.2(6)
757.4(4)			
783.5(6)			

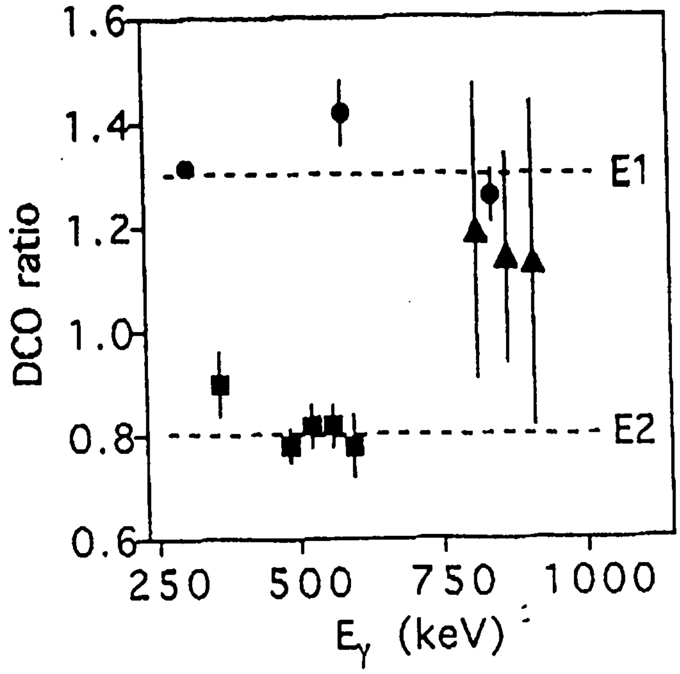

Fig.8 DCO ratios for transitions in ^{190}Hg. The data are for E1 transitions between normally deformed states (circles), E2 transitions in superdeformed band 1 (squares) and the linking transitions between the superdeformed band 2 and band 1 (triangles).

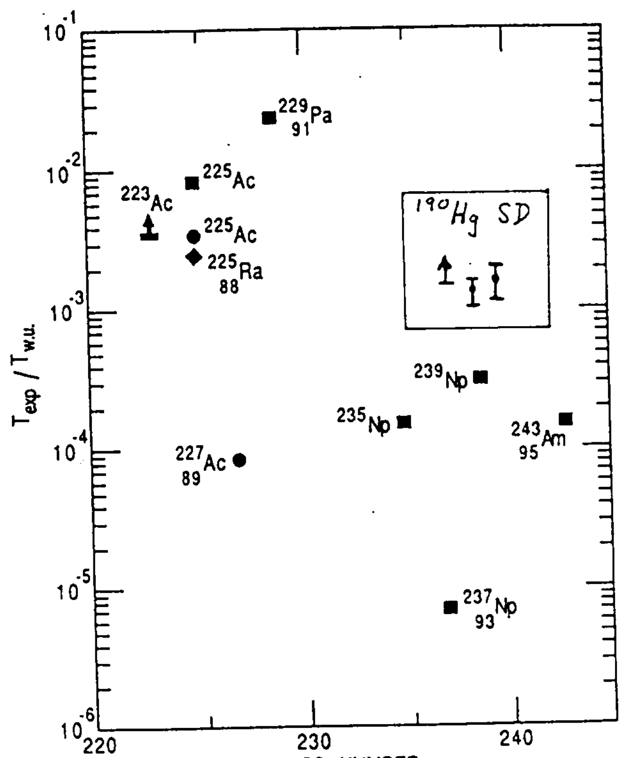

Fig.9 E1 transition probabilities compiled by Ahamad and Butler [32] for actinide nuclei. Transitions associated with octupole deformations have probabilities greater than 10^{-3} Wu (Weisskopf single particle units) whereas E1 transition probabilities without this association are found to be less than 3 $\times 10^{-4}$Wu. The E1 strengths of the linking transitions in ^{190}Hg are shown for comparison.

erentially at 90° to the beam direction. The spectrometer, Early Implementation of Gammasphere, had 15 detectors at both forward and backward angles but only four detectors near 90°. Clearly EUROGAM2 is considerably move sensitive to such emmissions having 24 "clover" detectors near 90°.

We have carried out an experiment with EUROGAM2, using the ^{160}Gd(^{34}S,4n)^{190}Hg reaction at an estimated beam energy of 158 MeV, in order to definitely establish the energies of the cross-band transitions from band 2 to band 1 in superdeformed ^{190}Hg. Two thin foils of 500 μg cm^{-2} isotopically pure ^{160}Gd were used as the target. A total of approximately 0.5 $\times 10^9$ events were recorded to tape in which four or more escape supressed Ge counters were in coincidence. After unfolding the events 2.5 $\times 10^9$ triples γ^3 and 2.0 $\times 10^9$ quadruple γ^4 coincidences were obtained. In fig.6 we show a spectrum of γ-rays in band 2 with γ-rays in band 1 that are fed by band2. The gates for this triples spectrum require either a coincidence between any two γ-rays in band2 or a coincidence between a γ-ray in band 2 with a γ-ray in band 1. Candidates for linking transitions can clearly be seen at 910.9(4), 864(1) and 812(1) keV. The intensity pattern of the γ-rays in bands 1 and 2 in fig.6 and the Ritz combination principle immediately establishes the 911, 864 and 812 decays to be from the levels in band 2 fed by the 511.4, 543.2 and 575.6 γ-rays. A decay scheme showing these links is given in fig.7.

In order to check the multipolarity of the linking transitions, DCO ratios [33] were measured. In the case for our data we have simply taken this ratio to be the number of counts in the clover detectors, near 90°, divided by the number of counts in the single detectors nearer 0° and 180° to the beam direction and then correcting for the relative efficiencies. This ratio is plotted in fig.8 both for the linking transitions and calibrating-transitions. It can be seen that the ratio for the three linking transitions is nearer that for the calibrating streched dipole than the streched quadrupole transitions. We assume [27, 34] that the linking transitions have E1 and not M1 multipolarity. The branching ratios for the linking transitions are given in table 2. The E1 strengths may be calculated assuming that band 2 has a quadrupole moment $Q_o = 18 \pm 3$ eb equal [35] to that of band 1. We find that B(E1) $> 10^{-3}$ Wu. This value is compared in fig.9 with B(E1) values for nuclei with static octupole moments compiled by Ahmad and Butler [32]. It can be seen that the B(E1) value for the linking transitions is very comparable to B(E1) strengths found for nuclei with well established octupole correlations.

V. FURTHER EXCITED BANDS IN ^{190}Hg

We have discovered two further excited superdeformed bands in ^{190}Hg, which we label

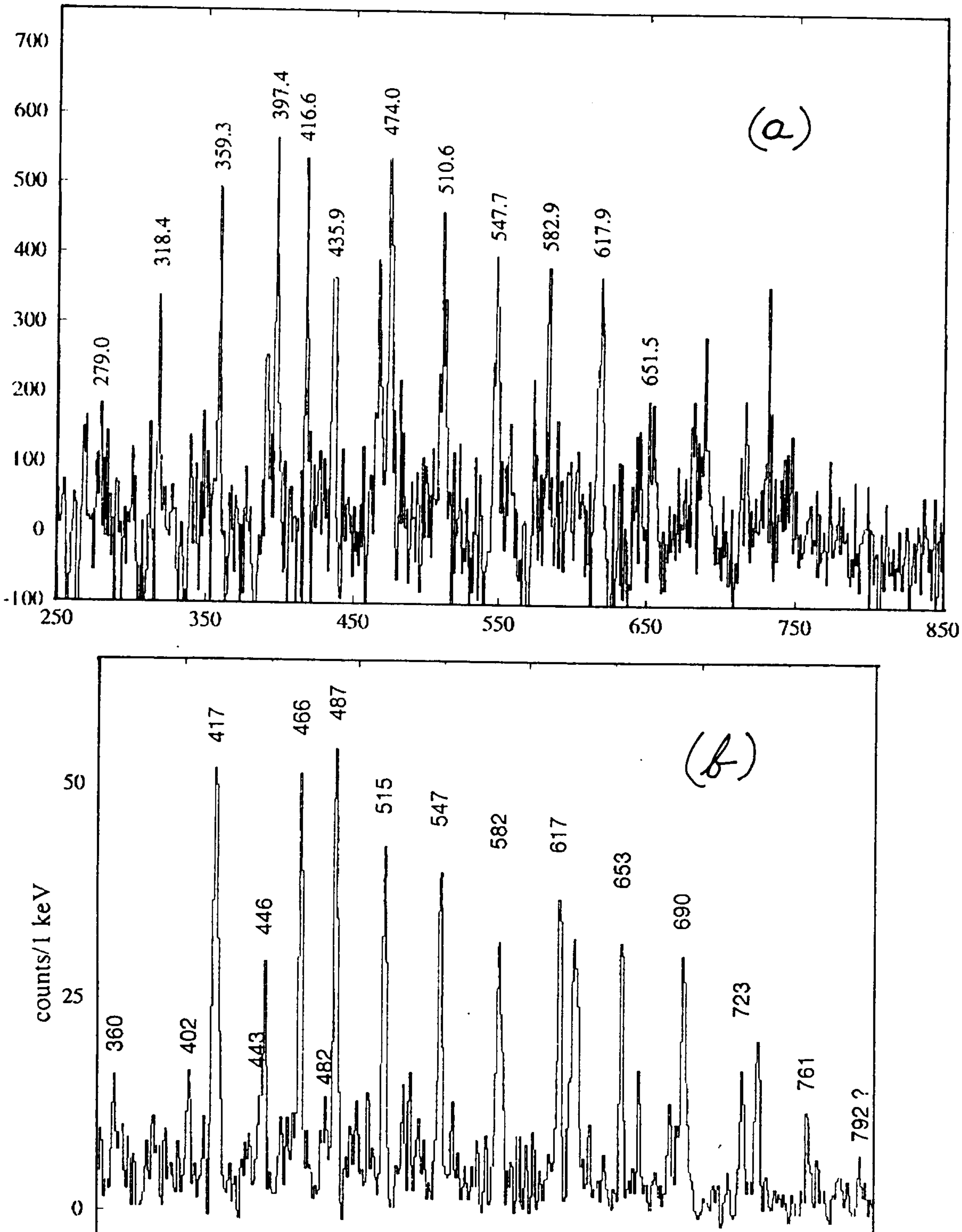

Fig.10 Spectra of the two additional excited superdeformed bands in ^{190}Hg obtained from γ^4 data (a) band 3 (b) band 4 which possibly shows connections with the yrast band 1 γ-rays at 402, 443 and 482 keV

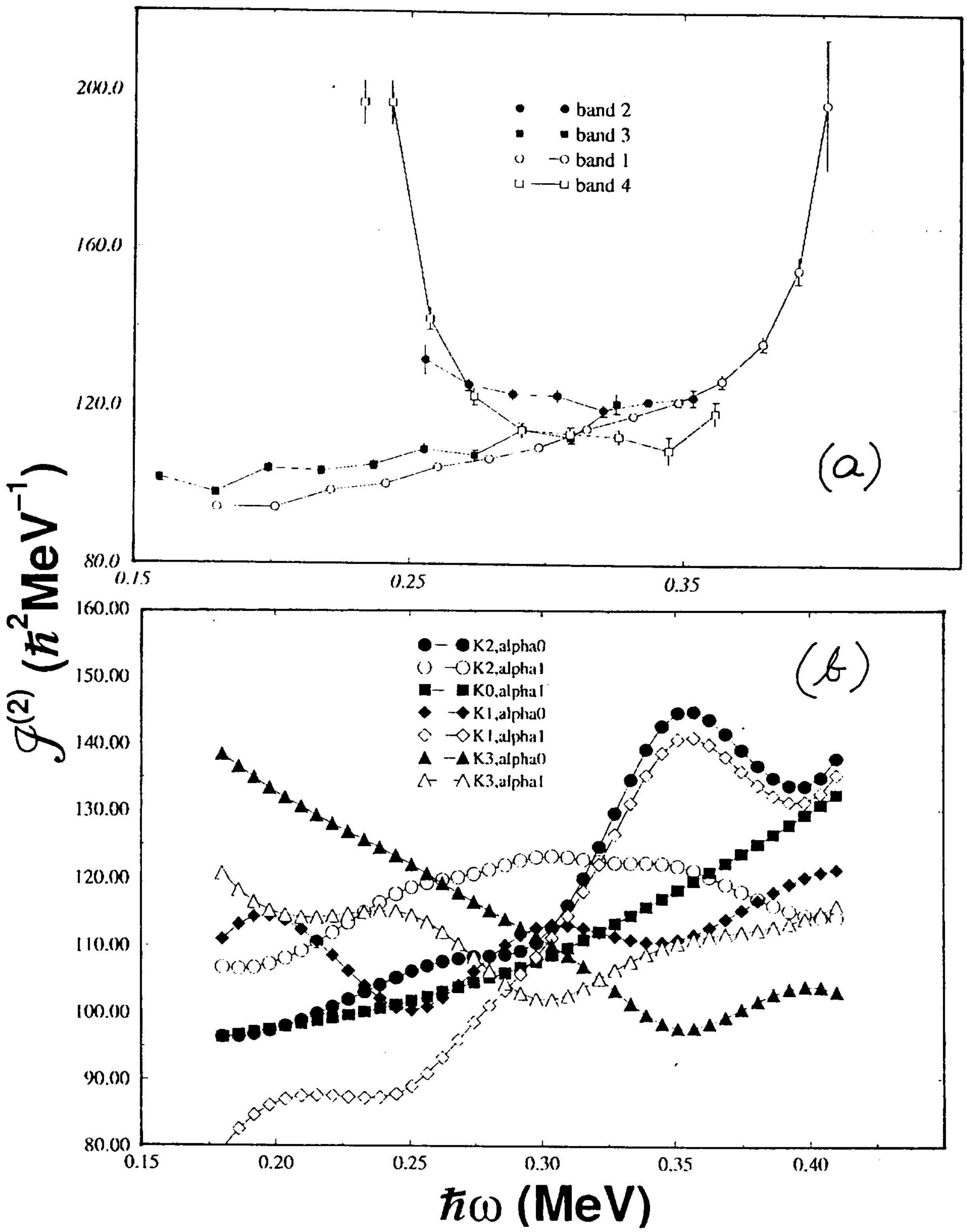

Fig.11 (a) Experimental dynamical moments of inertia $\mathcal{J}^{(2)}$ for the superdeformed bands in ^{190}Hg.

(b) $\mathcal{J}^{(2)}$ for octupole vibrational phonon states in ^{190}Hg given by RPA calculations [36]. The (K,α) = (2,1) band is predicted to be lowest in energy at $\hbar\omega$ = 0.30 MeV and may be associated with the experimentally observed band 2. The band with the next lowest energy is predicted to be the (K, α) = (2,0) band.

band 3 and band 4 ! Triple gated spectra using the γ^4 data are shown for these bands in fig.10 and the energies of all γ-rays in superdeformed bands in ^{190}Hg are collected in table 3. Band 3 has $\mathcal{J}^{(2)}$ very similar to that of the yrast superdeformed band 1 and most other superdeformed bands in the mass 190 region [28], fig. 11(a). In contrast band 4 is again, like band 2, rather atypical. It has a large and mainly constant $\mathcal{J}^{(2)}$, fig.11(a) but not quite as large as that for band 2. At the lowest frequencies band 4 shows a dramatic increase in $\mathcal{J}^{(2)}$ characteristic of a band crossing. In this case band 4 would cross another superdeformed band of lower $\mathcal{J}^{(2)}$ and lower excitation energy near $\hbar\omega = 0$. Some of our data, see fig.10(b), give a hint that band 4 may decay partially to the yrast superdeformed band 1. Our data are at the margin of statistical significance and we are not agreed amongst ourselves whether or not this intringuing decay can be established !

RPA calculations [31,36] of $\mathcal{J}^{(2)}$ are shown in fig.11 (b). The band with the lowest energy is predicted to be the K=2 (at $\hbar\omega = 0$) $\alpha = 1$ band which has the highest $\mathcal{J}^{(2)}$ and corresponds very well to our band 2. It is not quite so clear what the identification of bands 3 and 4 are. The next lowest band should have K=2 and $\alpha = 0$ and would be unlikely to decay to the vacuum band 1. Over the frequency range, for which we can observe it, band 3 has a similar $\mathcal{J}^{(2)}$ to this predicted band. No unique assignment can be made for band 4 on the basis of the calculated values of $\mathcal{J}^{(2)}$ shown in fig.11(b).

VI. CONCLUSIONS

Perhaps the most exciting result reported here is the first observation of the transitions connecting a superdeformed band, with a very atypical $\mathcal{J}^{(2)}$, to the lowest superdeformed band in ^{190}Hg. The behaviour of band 4 in ^{190}Hg is also very atypical, pointing to the fact that the excited superdeformed bands in ^{190}Hg have degrees of freedom that do not make a major impact on the properties of other superdeformed bands in this mass region. The comparison with the RPA calculations and the assumed E1 strengths between the bands we regard as very strong evidence that this is the first observation of a collective vibration of the superdeformed shape.

The data we have on ^{193}Tℓ will give an accurate measure of the magnetic properties of the [642]5/2$^+$ proton orbital in the superdeformed shape. The excited bands we observe in ^{193}Tℓ give the best data we have at present on the proton excitations across the Z=80 superdeformed shell gap. These data nicely compliment the data available [2,9,37,38,39] on the neutron orbitals in the region of the N=112 superdeformed shell gap.

It is surprising to us that these elegant superdeformed nuclei continue to reveal new properties in such abundance. It makes the task of the γ-ray spectroscopist a most pleasant and rewarding experience.

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