First Measurement of Magnetic Properties in a Superdeformed Nucleus: ^{193}Hg

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Dipole transitions linking signature partner superdeformed bands in ^{193}Hg have been observed. Measurements of the photon decay branching ratios, taken together with the average superdeformed quadrupole moment measured in neighboring nuclei, enable the absolute $M1$ strengths to be determined. From these data, using the strong coupling model, we find $(g_K-g_R)K/Q_0=-0.14\pm0.01$ $(e\,\mathrm{b})^{-1}$, $g_K=-0.65\pm0.14$ with $\Omega=2.8\pm0.8$. These data are consistent with the superdeformed neutron orbital being $[512]\frac{5}{2}^-$ as predicted by cranked Woods-Saxon calculations.

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The observation of discrete-line superdeformed cascades [1,2] has made it possible to study the behavior of the nucleus under extreme conditions of deformation and angular momentum. Measurements [3–5] of the intrinsic quadrupole moments confirmed the superdeformed nature of the states. In contrast, there is only indirect evidence regarding the single-particle microscopic structure at the superdeformed Fermi surface. This evidence gives information mainly on the high-j and high-N intruder orbitals [6,7] which determine the behavior of the dynamical moments of inertia $\mathbf{I}^{(2)}$ of the superdeformed bands. There is very little information of any kind regarding the lower N orbitals brought to the Fermi surface by the extreme deformation. These mostly medium- to high-K orbitals are of particular interest as they are involved in the configurations of the so called "identical" or "isospectral" superdeformed bands [8–11] whose properties are by no means fully understood.

In the region of superdeformed nuclei near mass $A=190$ there is a particular problem as the $\mathbf{I}^{(2)}$ moments of inertia for most bands are very similar showing that the high-N intruder configuration changes very little [5,12,13] among the known superdeformed bands. Information on the underlying configurations of the different superdeformed bands in this region comes mainly from chance band crossings [14] allowing bands with the same parity and signature to be identified.

A standard technique for establishing the single-particle properties of nuclear energy levels is to measure their g factors. For levels with short lifetimes, less than 1 ps, this has to be done either with the transient field method [15] or by measuring the strength of any $M1$ decays from the level. For superdeformed levels the former is very difficult due to the small cross sections for populating superdeformed bands and, until now, the latter has not been possible as the detection of $M1$ decays from superdeformed states has been beyond the sensitivity of the available apparatus.

In this Letter we report on the unambiguous observation of dipole transitions between the two negative parity signature partner superdeformed bands and between the two positive parity superdeformed bands in ^{193}Hg. Intensity measurements of these transitions allow the g factor for the superdeformed configuration of the negative parity structure to be deduced. The decrease in intensity of one of the positive parity bands, with decreasing spin, indicates that the $M1$ strengths are larger than those measured for the negative parity partners.

The nucleus ^{193}Hg is a spectacular example of superdeformed nuclear structure. Up to five superdeformed bands have been observed [14] in this nucleus. Comparison with theoretical calculations leads to the suggestion that the two pairs of signature partner bands are based on the $[512]\frac{5}{2}^-$ and $[624]\frac{9}{2}^+$ neutron orbitals. An additional band was thought to have the favored $j_{15/2}$ single-particle configuration. This latter band interacts strongly with one signature of the $[512]\frac{5}{2}^-$ pair of superdeformed bands allowing their parity and signature to be deduced. An intriguing property of the $[512]\frac{5}{2}^-$ signature partner bands was the observation of cross talk from one partner

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to the other. This cross talk had originally [14] only been observed in one direction and the connecting transitions were not seen. Very recently, it has been established [16] that the cross talk goes both ways. Candidates suggested for the connecting transitions imply that these dipole γ rays probably have $M1$ multipolarity. This assignment is consistent with the recent measurement of the x-ray yield by Cullen *et al.* [17].

To investigate further the nature of the transitions between the superdeformed states in ^{193}Hg, a very high statistics γ-ray coincidence experiment has been performed. In this experiment, the nucleus ^{193}Hg was populated using the ^{150}Nd(^{48}Ca,5n)^{193}Hg reaction at a beam energy of 213 MeV. The beam, supplied by the tandem Van de Graaff accelerator at the Nuclear Structure Facility, Daresbury Laboratory, was incident upon a target consisting of two self-supporting ^{150}Nd foils, each of nominal thickness μg cm^{-2}. The γ rays emitted in the decay of these high spin states were detected by the EUROGAM array, comprising 44 large-volume Compton suppressed germanium detectors [18-20]. A total of 10^9 events were recorded with an unsuppressed fold ≥ 5, where an event is defined as a coincidence between any number of suppressed γ rays.

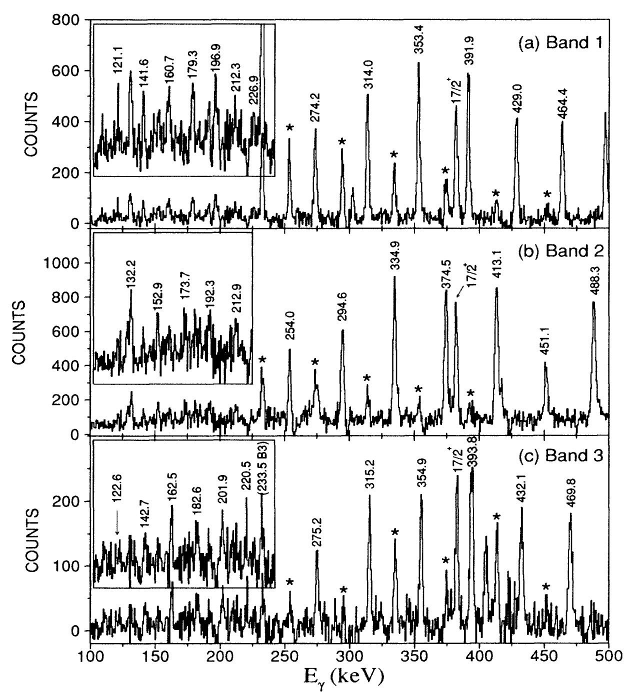

FIG. 1. Spectra of superdeformed bands 1, 2, and 3 in ^{193}Hg. These spectra are from quadrupole coincidences showing γ rays in coincidence with three γ rays that are in the band of interest. (a) Band 1 with members of band 2 (2a) denoted ★, and interband dipoles (inset). (b) Band 2 with members of band 1 denoted ★, and interband dipoles (inset). (c) Band 3 with members of band 2 (2b) denoted ★, and interband dipoles (inset).

An experimental difficulty with the study of the signature partner superdeformed bands in ^{193}He is that the negative and positive parity bands have identical γ-ray energies below 400 keV. The negative parity, negative signature band (band 1 of the [512]$\frac{5}{2}^-$ configuration) is crossed by the favored signature $j_{15/2}$ superdeformed band (band 4), at $\hbar\omega = 0.27$ MeV. This interaction perturbs the levels in band 1 and, at high frequencies, allows them to be clearly resolved from transitions in the positive parity, negative signature band (band 3) of the [624]$\frac{9}{2}^+$ configuration. Thus the negative parity band 1 can be separated from band 3 by gating on γ rays above 400 keV. The positive signature partners of these bands (band 2, 2a for negative parity and 2b for positive parity) have the same γ-ray energies within the resolution and are therefore not directly separable.

Figure 1(a) shows a spectrum which is a sum of gates demanding at least three of the coincident γ rays to be in band 1. In this spectrum, transitions in band 2 can clearly be seen, up to 451 keV. This confirms the observation of cross talk by Cullen *et al.* [14]. In addition, dipole transitions connecting band 1 to 2 with energies 121.1, 141.6, 160.7, 179.3, 196.9, 212.3, and 226.9 keV are observed at low energy (inset). In Fig. 1(b), a similar spectrum is shown for band 2. In this spectrum the situation is reversed and transitions in band 1 and/or band 3 are seen. Once more, interband γ rays are observed (inset) with energies 132.2, 152.9, 173.7, 192.3, and 212.9 keV. These data enable us to connect bands 1 and 2a as shown in Fig. 2(a).

In order to measure the nuclear g factor, the γ-ray photon $M1/E2$ branching ratios have been measured, to give $(g_K - g_R)K/Q_0$, for levels in band 1 where there is no ambiguity in the decay. These are shown in Fig. 3(a) where they are fitted as a linear function of A, where A

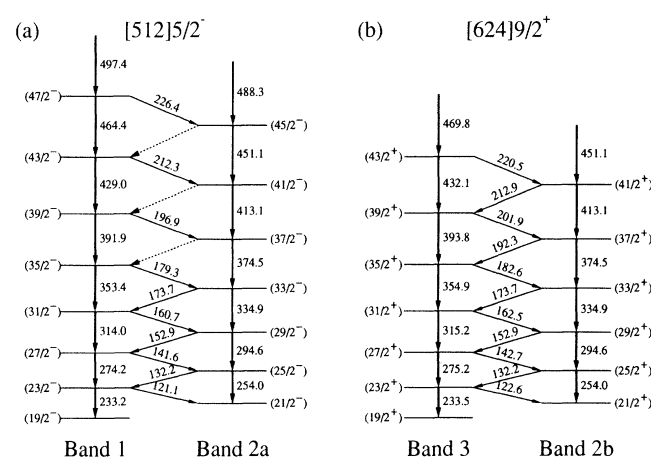

FIG. 2. Level schemes for the negative and positive parity structures. The energies of the dipoles are assigned maximum errors of 0.5 keV: (a) Bands 1 and 2a showing interband dipoles and (b) bands 3 and 2b showing interband dipoles.

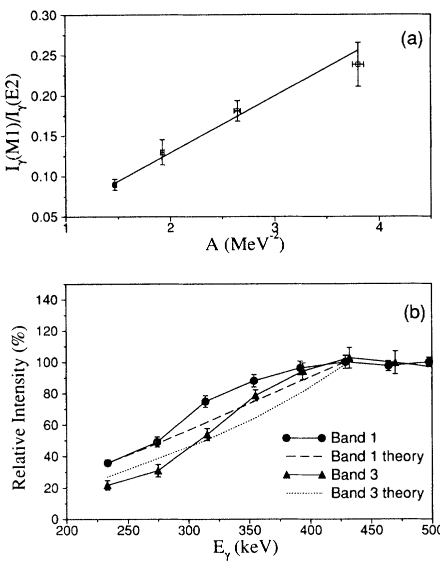

FIG. 3. (a) Measurements of the $M1/E2$ branching ratios taken on band 1 only, plotted as a function of A, where A is given by

$$A = \frac{E_\gamma(M1)^3 \langle IK10|I-1K\rangle^2}{E_\gamma(E2)^5 \langle IK20|I-2K\rangle^2}\,.$$

A least squares fit to the data is also presented, the gradient of which is used to determine $(g_K - g_R)K/Q_0$. (b) Intensity measurements of bands 1 and 3 measured relative to the 429.0 keV and 432.1 keV transitions, respectively. The variation in intensity down bands 1 and 3, using theoretical branching ratios determined from their respective single parity assignments of $[512]\frac{5}{2}^-$ and $[624]\frac{9}{2}^+$, is also included.

takes account of the dependence on energy and Clebsch-Gordan coefficients of the branching ratio:

$$A = \frac{E_\gamma(M1)^3 \langle IK10|I-1K\rangle^2}{E_\gamma(E2)^5 \langle IK20|I-2K\rangle^2}\,.$$

The formulas used are those given by Semmes *et al.* [21] and taking $g_s^{\mathrm{eff}} = 0.8 g_s^{\mathrm{free}}$. The quadrupole moment $Q_0 = 19 \pm 2$ eb of band 1 is assumed to be the same as that measured for the core nucleus ^{192}Hg [22,23]. A least squares fit is made to the data giving $(g_K - g_R)K/Q_0 = -0.14 \pm 0.01$ $(e\mathrm{b})^{-1}$ so that $g_K = -0.65 \pm 0.14$. This large value for g_K shows that the band 1 neutron orbital must have $\langle s_z \rangle = \Sigma = +\frac{1}{2}$ as suggested in Ref. [21]. The measured g factor is in very good agreement with $g_K = -0.61$ given by the strong coupling model for the proposed $[512]\frac{5}{2}^-$ neutron orbital. Alternatively, using the expression

$$B(M1) \approx 0.021(\Omega + 3.69)^2 \mu_N^2$$

for neutron orbitals obtained from Semmes *et al.* [21] using $g_s^{\mathrm{eff}} = 0.8 g_s^{\mathrm{free}}$, we obtain $\Omega = 2.8 \pm 0.8$ by fitting our data. Once again, this is in excellent agreement with the assigned configuration.

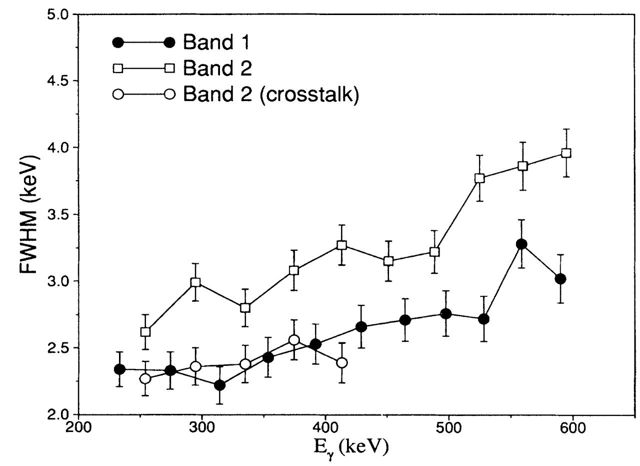

FIG. 4. Measurements of the full width half maxima (FWHM) of band 1 and band 2. Errors are assigned through consideration of the statistical variation of similar measurements made on all the superdeformed bands present in ^{193}Hg which have very similar widths to those of band 1.

An outstanding conclusion of these measurements is that band 2 is required to be two identical bands. This conclusion is confirmed by comparing the widths of the peaks for band 2 with those of band 1 (Fig. 4). It can be concluded that band 2 is indeed two superdeformed bands, with an average γ-ray separation of 1.4 ± 0.3 keV. Measurements of the widths of the component $2a$ of band 2, seen by band 1 and marked with stars in Fig. 1(a), are also shown in Fig. 4. These widths are the same as the widths for band 1 showing that band 1 only populates one component of band 2. The measured positions of the centroids of the starred peaks in Fig. 1(a) suggest that band 1 feeds the lower energy component of band 2. This is consistent with our observation that the energies of the band 1 γ rays, below 400 keV, are slightly lower than those of band 3. These data constitute the first conclusive experimental evidence for identical superdeformed bands in the same nucleus.

A spectrum of band 3 is shown in Fig. 1(c), gated on transitions above the crossing, where it is no longer identical to band 1. In this spectrum, transitions belonging to band 2 are observed up to 451 keV. The 334.9 and 413.1 keV transitions are observed to have an anomalously high intensity. At low energies, transitions linking these superdeformed bands are observed with energies 122.6, 142.7, 162.5, 182.6, 201.9, and 220.5 keV. These transitions connect band 3 and band $2b$ a shown in Fig. 2(b). Because of the gating procedure necessary to separate band 3 from band 1, these transitions are very weak. Consequently, it has not been possible to perform a conclusive g-factor measurement for the positive parity structure. However, if these connecting transitions were $M1$ and the observed cross talk was to the signature partner of band 3, then the larger Ω in this case would result in a larger $M1$ strength than is observed in the case of band 1. This would result in the intensity of the $E2$ transitions of band 3 in the region of the cross talk decreasing more rapidly, with decreasing γ-ray energy, than in the case of the band 1. Relative intensity measurement of both bands 1 and 3 are shown in Fig. 3(b), and it can be seen that this is indeed the case. Also shown in Fig. 3(b) are the results of estimating the variation in $E2$ intensity in bands 1 and 3, using the theoretical branching ratios for both the negative and positive parity band pairs, assuming neutron orbitals $[512]\frac{5}{2}^-$ and $[624]\frac{9}{2}^+$, respectively, and assuming that there is no decay from the superdeformed minimum to normal states until the bottoms of the bands are reached. Theoretical electron conversion coefficients used in this analysis are taken from Ref. [24].

To summarize: We have observed dipole transitions between the superdeformed bands 1 and $2a$ in ^{193}Hg. We measure a g factor of $g_K = -0.65 \pm 0.14$ for band 1 by fitting the $M1/E2$ photon branching ratios. This is consistent with the value of $g_K = -0.61$ predicted by the strong coupling model for a particle in an orbit with asymptotic Nilsson quantum number $[512]\frac{5}{2}^-$.

We find evidence that band 3 also decays to band $2b$ and observe transitions linking these superdeformed bands. The decrease in intensity of the $E2$ transitions in band 3 with decreasing γ-ray energy is consistent with band 3 being one signature of the $[624]\frac{9}{2}^+$ neutron orbital. The crossing of the $j_{15/2}$ neutron orbital, band 4, with band 1 and not band 3 has previously [14] shown that bands 1 and 3 have opposite parity. Taken all together, the data can only be reasonably understood if band 2 is actually a pair of "isospectral" bands of opposite parity as drawn in Fig. 2. This scenario is confirmed by the observation in this work that the peak widths of band 2 are consistently larger than those of band 1. This indicates that band 2 does indeed comprise two identical bands, that have an average γ-ray separation of 1.4 ± 0.3 keV.

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