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Linear Polarization Measurement of Interband Transitions in Superdeformed ^{190}Hg: Model-Independent Evidence for Octupole Vibrational Structures

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The linear polarization of γ rays between excited and yrast superdeformed (SD) states in ^{190}Hg was measured using the four-element CLOVER detectors of the EUROBALL IV γ-ray spectrometer. This measurement shows in a model-independent way that the interband transitions which compete with the highly collective in-band quadrupole transitions are largely enhanced electric dipoles. Not only do these results represent the first measurement of the multipolarity of transitions between different SD states, but they also provide strong evidence for the interpretation of the structures in the SD minimum of the $A \sim 190$ region in terms of octupole excitations.

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The nature of the lowest excitations available to superdeformed (SD) nuclei is still a matter of great debate [1,2]. It has been suggested that both in the mass $A \sim 190$ and 150 regions, collective vibrational states might occur in the same excitation energy range as quasiparticle and single-particle excitations [3–7]. More specifically, octupole correlations are predicted to be associated with some of the lowest collective modes of the nucleus when it is SD because of the inherent presence of several intruder orbitals near the Fermi surface (this results in a close proximity of states with opposite parity and $\Delta l = 3$ which favor octupole-reflection-asymmetric-shapes vibrations). Random phase approximation (RPA) calculations performed by Nakatsukasa [7] even suggest that in the even-even mass 190 SD nuclei, all the lowest excited states, previously interpreted as quasiparticle excitations, can be explained in terms of octupole vibrations. In order to distinguish between these two different interpretations, it is necessary to obtain an unambiguous experimental signal. The clearest experimental signature for the octupole vibration phenomenon arises from the presence of an anomalously large transition dipole moment associated with the charge asymmetry of this kind of vibration. This is expected to manifest itself in enhanced electric dipole strengths, allowing competition between interband $E1$ transitions and the highly collective in-band $E2$ transitions.

A large variety of data has been collected over the years on excited states in the mass 190 region. Excited SD bands with peculiar $\Im^2$ dynamical moments of inertia were observed in ^{190}Hg [8–10], ^{194}Hg [11], and ^{196}Pb [12] nuclei. With the increasing efficiency of the large γ-ray spectrometers, it was found that the states belonging to these bands decay directly to the yrast SD states via a series of discrete transitions. In the case of ^{190}Hg, angular correlations proved the dipole nature of these interband transitions [8,9]. Branching ratios and lifetime measurements [10] suggested that they were most likely electric rather than magnetic dipole transitions. For ^{194}Hg, evidence for the difference in parity between the yrast SD band and the excited band, which decays into the yrast one, arose from the observation of discrete, single-step transitions linking these bands to different parity states in the normal deformed well [11]. Tentative evidence for similar interband decays from the excited to yrast SD states has also been found in ^{196}Pb. An additional proof for octupole vibrations in the ^{190,194}Hg nuclei is given by the initial signature splitting of the excited SD bands [13] (the odd spin band being favored) which is well reproduced by the RPA calculations. However, the properties of the excited states in the SD core nucleus of the region, ^{192}Hg, do not seem to fit in this "octupole paradise" picture. The situation is therefore not so clear since no direct evidence of the electric nature of the

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interband transitions is available in any of these nuclei and the octupole vibration scenario remains open to doubt.

We report here on the results of a measurement of the linear polarization of the transitions observed between the first excited SD band (band 2) and the yrast SD band (band 1) in ^{190}Hg (see Fig. 1d). Such a measurement distinguishes between electric and magnetic transitions. Combined with angular distribution data (providing information on the multipolarity of the transitions), these results allow us to make a definitive statement regarding the nature of the transitions and also the states which they deexcite.

The experiment was performed using the EUROBALL-IV γ-ray spectrometer array [14] at IReS, Strasbourg. High-spin states in ^{190}Hg were populated in the ^{160}Gd(^{34}S, $4n$) reaction. The beam of ^{34}S, provided by the Vivitron accelerator at an energy of 156 MeV, was incident on a target consisting of a stack of two thin (500 μg cm^{-2}), self-supporting foils of ^{160}Gd for a period of 144 hours. The array consisted of 30 coaxial, 25 four-element CLOVER and 15 seven-element cluster Ge detectors arranged in rings at forward, central, and backward angles with respect to the beam direction, respectively. An inner ball of 210 bismuth germanium oxide scintillator detectors designed to provide a measure of the multiplicity and total energy of the reaction was positioned inside the EUROBALL-IV array, around the target. Events were written to magnetic tape when a minimum of five Ge detectors and five elements of the inner ball fired in coincidence; Compton and pileup suppression were performed off-line.

One of the unique capabilities of the EUROBALL-IV array is the possibility to use the CLOVER detectors as Compton polarimeters [15,16]. Thus, the main aim of the experiment was to obtain a measurement of the linear polarization of the γ rays which had previously been observed to link states in band 2 in SD ^{190}Hg with states in band 1 [8,9]. These transitions carry only a tiny fraction

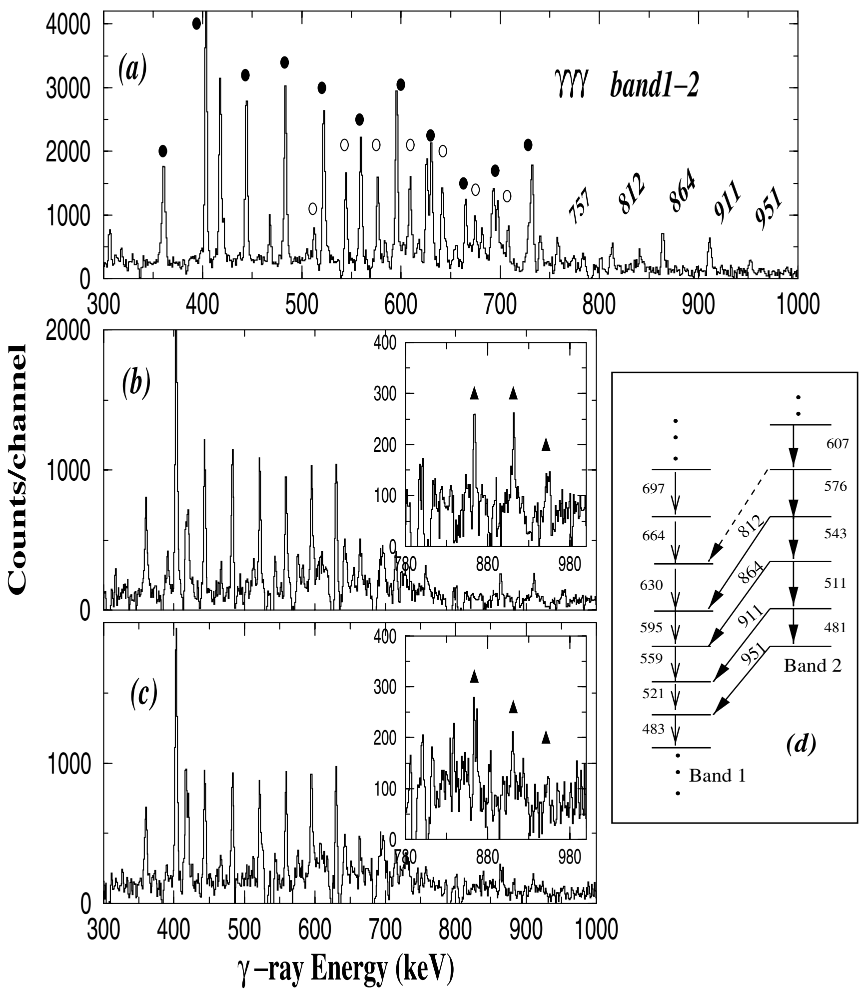

FIG. 1. Spectra showing γ rays in coincidence (a) with at least three transitions from either band 1 or band 2. Transitions from SD band 2 are marked with open circles and transitions from band 1 with filled circles. The interband transitions around 800 keV are labeled by their energies. The lower portion of the figure shows the γ rays in coincidence with at least two transitions which were detected as (b) vertically and (c) horizontally scattered γ rays in the CLOVER detectors. The high energy portion of these spectra is detailed in the insets in which the interband transitions are visible with filled triangles. Panel (d) shows the relevant portion of the level scheme for bands 1 and 2.

($\sim$0.01%) of the intensity of the ^{190}Hg reaction channel and, thus, the high efficiency of the EUROBALL-IV array was necessary to allow such a measurement to be made. In addition, the improved statistics collected over previous experiments [8–10] allow a more precise measurement of the angular distributions associated with these transitions. After escape suppression, add back of events Compton scattered between neighboring elements of the composite CLOVER and cluster detectors and the setting of prompt time gates, a total of 1.76×10^9 events of fold 3 and greater were obtained. Of these, $\sim$12% contained information concerning γ rays which had scattered between neighboring (nondiagonal) elements of the CLOVER detectors.

These data were then unpacked and sorted into two asymmetric matrices, both gated on transitions from the lower portion of band 1 (360, 443, 483, 521, 558, and 594 keV) and band 2 (511, 543, 576, 607, 643, and 676 keV). In both cases, all γ rays detected in prompt coincidence with one of these gates (except those which had scattered between CLOVER elements) were incremented on one axis: the energies of all coincident vertically scattered γ rays were incremented on the second axis of the first matrix, and the energies of all coincident horizontally scattered γ rays on the second axis of the second matrix. Gates were then set on the cleanest transitions in both bands and projections were made onto the vertical/horizontal axes. In this way, spectra were created which contained only those γ rays which had scattered either horizontally or vertically in the CLOVER detectors and which were in coincidence with a minimum of two γ rays from SD bands 1 and 2.

Examples of gated coincidence spectra are presented in Fig. 1: Panel (a) shows the relevant portion of the spectrum obtained by triple gating on band 1 and band 2 (from the list given above). Panel (b) shows the spectrum obtained for vertically scattered γ rays in the CLOVER detectors in coincidence with any two transitions from the list given above. Panel (c) was created under the same conditions but shows the spectrum obtained for horizontally scattered events. Expanded sections of these spectra, showing the region in which the interband transitions are observed, are presented in the insets of Figs. 1(b) and 1(c), respectively. In both cases, a normalized spectrum obtained under the same conditions but with only one gate requirement have been used to substract a background.

In order to measure the linear polarization of photons, one has to determine the number of counts I_H and I_V of Compton scattered events parallel and perpendicular to a reference plane to which the polarization P is defined [17]. The experimental asymmetry is defined by the ratio,

$$A(E_\gamma) = \frac{I_V - I_H}{I_V + I_H}, \quad (1)$$

where I_V and I_H represent the number (efficiency corrected) of vertically and horizontally scattered events, respectively. This ratio is proportional to the degree of polarization P and depends on the photon energy,

$$A(E_\gamma) = Q(E_\gamma)P(E_\gamma), \quad (2)$$

where the quality factor Q corresponds to the polarization sensitivity of the polarimeter [16].

This is sufficient to unambiguously identify whether a transition is electric or magnetic in character. In effect, unmixed stretched electric transitions give rise to a positive and magnetic transitions to a negative value of P. A "calibration" of the polarization values was performed by analyzing known pure magnetic transitions in the level scheme of ^{190}Hg (the M1 of 389 keV $10^- \rightarrow 9^-$) and ^{189}Hg (the $M1s$ of 474 keV $\frac{15}{2}^+ \rightarrow \frac{13}{2}^+$, 707 keV $\frac{19}{2}^+ \rightarrow \frac{17}{2}^+$ transitions reported in [18]).

It was not possible to obtain a value of $P(E_\gamma)$ for all SD and interband transitions due to the low intensity of the corresponding peaks and their contamination from transitions deexciting states in the normal-deformed well. The results for $P(E_\gamma)$ are shown in Fig. 2(a). It is immediately obvious that both the in-band and interband transitions give

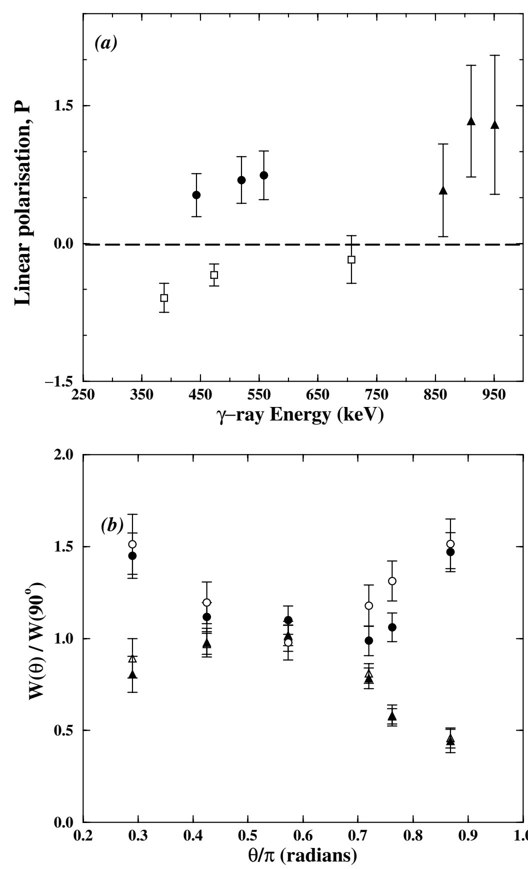

FIG. 2. (a) The values of the ratio P (see text) obtained in the present data for the interband, SD (in-band), and known transitions from the decay of normal deformed states of ^{190}Hg. The in-band SD transitions are indicated by filled circles; the interband SD transitions are indicated by filled triangles. The values of P obtained for the known $M1$ transitions are indicated by open squares. (b) Angular distributions obtained for in-band (543 and 607 keV marked by circles) and interband (864 and 911 keV marked by triangles) transitions.

TABLE I. Transition energies, branching ratios, lifetimes [10], and corresponding $E1$ strengths for transitions in SD bands 1 and 2 in ^{190}Hg.

$E_\gamma(E2)$ (keV)	$E_\gamma(E1)$ (keV)	BR	τ (fs)	$B(E1)$ (mW.u.)
576	757	0.23 (4)	110 (20)	1.6 (4)
543	812	0.35 (4)	130 (30)	1.5 (3)
511	864	0.83 (8)	100 (20)	3.8 (8)

positive values of P, and that they are clearly separated from the known magnetic transitions which result in negative value for P. This provides the first evidence of the electric nature of the interband γ rays.

As stated above, the electric character of the interband transitions is not a sufficient proof of the nature of the excitation upon which band 2 is based. The previous measurements of the directional correlations from oriented nuclei (DCO) ratios [8,9] indicated that they were dipole transitions. The present experiment has allowed a precise measurement of the angular distributions of the interband transitions. Figure 2(b) shows examples of the anisotropy obtained for in-band SD transitions and the interband transitions for which a measurement was possible. The angular distribution coefficients obtained from these measurements are $A_2 = -0.35(12)$ and $A_2 = 0.31(10)$ for the interband and in-band transitions, respectively. Such angular distributions indicate that the interband transitions are pure stretched dipoles, confirming and strengthening the evidence provided by the previous DCO ratios [8,9]. Based on our results, we assign unambiguously the three interband transitions as being stretched electric dipoles.

The highly collective nature of the $E2$ transitions deexciting a SD band (typical transition strengths are of the order of 1800 W.u.) means that, in order for the interband transitions to be competitive, they must also have an anomalously large strength. Branching ratios for the interband and in-band decays from specific levels in band 2 are given in Table I. The corresponding $E1$ strengths deduced from these measurements are also given. These strengths are consistent with those obtained from the previous experiments [9,10], being of the order of 10^{-3} W.u. They are similar to those observed in normal deformed nuclei in which octupole deformation or vibrations play a part in defining the nuclear structure [19,20].

In summary, taking all of the above experimental information into account, it is possible to state for the first time that the interband transitions connecting the first excited SD band in ^{190}Hg to the yrast SD band are of electric dipole character. They compete strongly with the in-band $E2$ transitions: the branching ratios and the previously measured lifetimes [10] indicate transition strengths corresponding to a significant charge asymmetry in the nucleus. The only situation in which such large $B(E1)$s are likely to occur is if there is an octupole component associated with the nuclear wave function. These results suggest strongly that the octupole paradise scenario described by Nakatsukasa *et al.* [7] is correct; they imply that other excited SD bands in neighboring nuclei may, by extension, also be interpreted as vibrational states. This is the first time that it has been possible to demonstrate unambiguously that an excited SD band in any mass region is not based on a quasiparticle excitation.

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[1] P.-H. Heenen and R. V. F. Janssens, Phys. Rev. C **57**, 159 (1998), and references therein.
[2] J. Libert, M. Girod, and J.-P. Delaroche, Phys. Rev. C **60**, 054301 (1999), and references therein.
[3] J. Dudek *et al.,* Phys. Lett. B **248**, 235 (1990).
[4] J. Skalski *et al.,* Nucl. Phys. **A551**, 109 (1993).
[5] S. Mizutori, Y.R. Shimizu, and K. Matsuyanagi, Prog. Theor. Phys. **83**, 666 (1990).
[6] J. Meyer *et al.,* Nucl. Phys. **A588**, 597 (1995).
[7] T. Nakatsukasa *et al.,* Phys. Rev. C **53**, 2213 (1996).
[8] B. Crowell *et al.,* Phys. Lett. B **333**, 320 (1994); Phys. Rev. C **51**, R1599 (1995).
[9] A. N. Wilson *et al.,* Phys. Rev. C **54**, 559 (1996).
[10] H. Amro *et al.,* Phys. Lett. B **413**, 15 (1997).
[11] G. Hackman *et al.,* Phys. Rev. Lett. **79**, 4100 (1997).
[12] S. Bouneau *et al.,* Z. Phys. A **358**, 179 (1997).
[13] P. Fallon *et al.,* Phys. Rev. C **55**, R999 (1997).
[14] J. Simpson, Z. Phys. A **358**, 139 (1997); Nucl. Phys. **A654**, 178c (1999).
[15] P. M. Jones *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **362**, 556 (1995).
[16] G. Duchêne *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **443**, 90 (1999).
[17] B. Schlitt *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **337**, 416 (1994).
[18] I. G. Bearden *et al.,* Nucl. Phys. **A576**, 441 (1994).
[19] I. Ahmad and P. A. Butler, Annu. Rev. Nucl. Part. Sci. **43**, 71 (1993).
[20] P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1995).