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Identification of ^{181}Hg and shape coexistence in odd-A Hg isotopes

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Abstract

In-beam γ-ray transitions in ^{181}Hg, the lightest odd-A Hg isotope known thus far, have been identified from fragment mass-γ and γ-γ coincidence measurements. Five prolate deformed rotational bands were placed in the level scheme. A decoupled band built on the strongly prolate deformed $1/2^-[521]$ ground state was observed up to $29/2^-$. A $5/2^-[512]$ configuration is suggested for a pair of strongly coupled bands displaying no signature splitting. The other two bands are also signature partner bands. They are populated with the largest intensity and exhibit splitting. They have been associated with the mixed neutron $i_{13/2}$ orbitals and are proposed to decay to an $i_{13/2}$ isomeric state associated with an oblate state. © 1997 Published by Elsevier Science B.V.

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The coexistence of level structures associated with prolate and oblate shapes of moderate deformation has been well established in the even-even Hg isotopes $^{180-190}$Hg [1–3], and very recently in ^{178}Hg [4]. These nuclei are only two protons away from the

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Z = 82 shell closure, and exhibit an small oblate deformation ($\beta_2 \sim -0.15$) in the ground state. The excited prolate shape ($\beta_2 \sim 0.25$) corresponds to a structurally very different configuration with at least two protons excited to the $h_{9/2}$ shell, which is not occupied in the oblate configuration. Furthermore, in the prolate configuration 2 or 4 (depending on the neutron number) more $i_{13/2}$ neutron orbitals are occupied than at the oblate shape [5,6]. On the other hand, the ground states of the odd-A isotopes ^{181,183,185}Hg are strongly prolate deformed, as was first determined from their surprisingly large nuclear charge radii measured in isotope shift (IS) experiments [7,8]. Such a dramatic effect implies the presence of a very strong driving force towards well deformed shapes by the odd particle when the neutron number decreases below N = 107. A coexisting, weakly oblate deformed $i_{13/2}$ isomer was also found in ^{185}Hg and heavier odd-A Hg isotopes from IS measurements [9,10], and in ^{183}Hg from an α-decay study [11]. It is crucial to obtain information on the one-quasiparticle excitations of these odd-A nuclei as these excitations form the basis for the multi-quasiparticle states which are responsible for the levels seen in the neighboring even-even neighbors.

It is only recently that rotational bands built on various prolate structures were identified through in-beam γ-ray spectroscopy in ^{185}Hg [12] and ^{183}Hg [13–15] together with the weakly oblate deformed $i_{13/2}$ isomeric state. In ^{185}Hg, two excited energy levels built upon this oblate state were also observed. These results allowed for a more detailed examination of the orbitals involved. Another interesting finding was the observation that the $7/2^-[514]$ bands in ^{183}Hg and in ^{185}Hg have identical energies in their E2 cascades and M1 crossing transitions. This was attributed to the very similar behavior of the transitions of the excited prolate bands in their respective ^{182,184}Hg cores and to the absence of Coriolis interactions [13]. In order to acquire a better understanding of the nuclear landscape in this region, it is necessary to obtain spectroscopic information for ^{181}Hg as well. In particular, information should be obtained about (i) which neutron orbitals are involved in the yrast and near-yrast excitations, (ii) the associated deformations, and (iii) the persistence or disappearance of the identical bands in ^{181}Hg.

Prior to this work, the only excited state known in ^{181}Hg was an 81 keV excitation above the $1/2^{(-)}$ ground state which had been obtained from an α-decay study [16]. In a subsequent study of the same kind, the existence of this state was confirmed and three additional α-decay branches were reported [17]. However, because of ambiguities in the measurements [11], the new results seemed uncertain and additional levels could not be firmly established. In this paper we report on the first detailed in-beam study of ^{181}Hg, the lightest odd-A Hg isotope studied thus far.

Two in-beam gamma-ray spectroscopy experiments were carried out at the Argonne National Laboratory ATLAS facility using the reaction ^{144}Sm(^{40}Ar, 3n)^{181}Hg. In the first experiment, a 500 μg/cm^2 self-supporting ^{144}Sm target, placed in front of the Fragments Mass Analyzer (FMA) [18], was bombarded with an 175 MeV ^{40}Ar beam. Prompt γ-rays were measured by ten Compton-suppressed germanium spectrometers (CSS) surrounding the target chamber. The compound nuclei, recoiling into the FMA, were separated from the primary beam and detected by a multi-wire proportional counter at the focal plane. Their x- and y-positions, energy loss and time information were determined. A two-dimensional mass spectrum was then obtained at the focal plane for residues with charge states of 19^+ and 20^+ (which were found to produce the maximum yield for mass 181 nuclei). Three types of coincidence events, mass-γ, γ-γ, and mass-γ-γ, were recorded and stored on magnetic tape for off-line analysis. Most data were collected with a 10 μg/cm^2 carbon reset foil placed 3 cm behind the target and only a short run was taken without the reset foil. The mass-181 gated γ-ray spectra taken with and without the reset foil were compared to help identify the ^{181}Hg transitions. This experimental technique was discussed in detail in a previous paper where it was used to facilitate the identification of γ transitions in $_{183}$Hg [13]. Mass 181 and 182 nuclei were found to be the dominant reaction products with mass 181 nuclei populated roughly twice as much as those with mass 182. It can also be seen from the mass-181 gated γ-ray spectrum in Fig. 1a that ^{181}Au was populated more strongly than ^{181}Hg. The γ-γ coincidence matrices with and without mass-181 gating were built. A preliminary level scheme was established based on the analysis of the observed γ-ray coincidence relationships. However, with only 30 million γ-γ coincidence events, some weak γ rays could not be placed in the level scheme.

In order to improve the statistics and to obtain angular correlation information, a second experiment was performed using the full Argonne-Notre Dame BGO γ-ray facility, which consists of 12 CSS and a multiplicity filter of 50 BGO detectors. The beam energy was raised to 180 MeV and the target thickness was 8 mg/cm^2. An event was taken when at least two BGO elements and two CSS fired in prompt coincidence. Thus, the peak-to-background ratio of the γ-ray spectra was improved as the low-multiplicity events were suppressed. Extra care was taken to search for possible low-energy transitions during the experiment by setting the threshold of the detection system at ~ 35 keV. A total of 40 million events were collected and sorted into a γ-γ coincidence matrix. This matrix was added to the γ-γ coincidence matrix obtained from the first experiment. Another matrix was built to analyze the directional correlation information (DCO ratio) of γ rays for spin and parity assignments. In this matrix, the γ rays collected by the four 90° detectors were sorted onto one axis and those collected by the other detectors (located at 35° and 145°) onto the other. Known transitions in ^{182}Hg [19] and ^{181}Au [20] were used to check the sensitivity of the DCO measurements. The DCO ratios of stretched E2 and M1 transitions have the values of 1.0 and 0.7, respectively.

A level scheme, shown in Fig. 2, was established from the γ-ray coincidence relationships and the measured intensities. The spin and parity assignments were based on the measured DCO ratios with further help from the available systematics of heavier Hg isotopes. Transitions were assigned to ^{181}Hg according to their coincidence relationship with the mass-181 recoils in the first experiment and with the characteristic Hg X rays. An illustrative coincidence spectrum, obtained by gating on transitions in band 2, is shown in Fig. 1b.

At the expected prolate deformation ($\beta_2 \approx 0.26$)

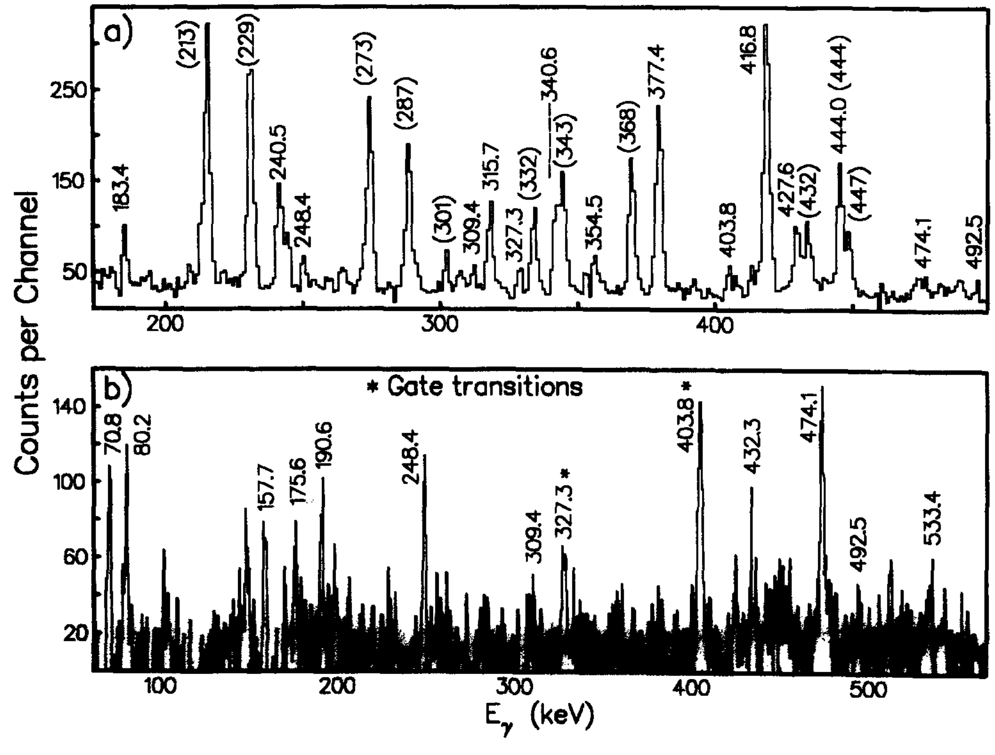

Fig. 1. a) Mass-181 gated γ-ray spectrum, ^{181}Au transitions [20] are shown in parentheses. b) Gamma-ray coincidence spectrum of band 2, the weakest band in the level scheme.

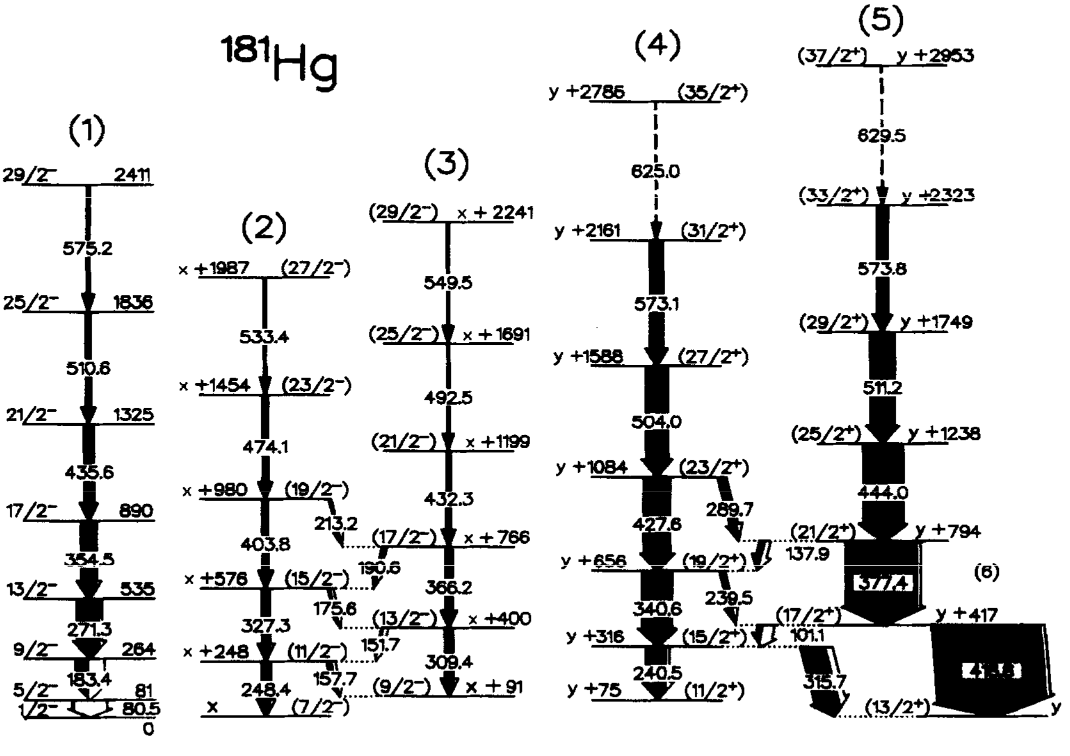

Fig. 2. The ^{181}Hg level scheme derived from the present measurements.

[8,13], the Nilsson neutron orbitals located closest to the Fermi surface are: the $1/2^-[521]$ orbital from the $p_{3/2}$ subshell, the $5/2^-[512]$ level from the $h_{9/2}$ subshell and the $7/2^+[633]$ orbital from the $i_{13/2}$ subshell. The ground state spin of ^{181}Hg was measured to be $1/2^{(-)}$ from an optical pumping experiment [8]. Band 1 is suggested to be built on the ground state configuration. The γ-ray transition at the bottom of this band has an energy of 80.5 keV which overlaps with the $K_{\beta 1}$ line of the characteristic Hg X rays. The observation that the intensity of this 80.5 keV line is larger than that of the 70.8 keV $K_{\alpha 1}$ line confirms the assignment of the transition as a combination of the $K_{\beta 1}$ line and the $5/2^- \to 1/2^-$ deexcitation in the band. This γ-ray transition energy is consistent with the results of α-decay studies, and is comparable to the lowest excitation energy in ^{183,185}Hg nuclei and in neighboring N = 101 isotones, e.g. ^{179}Pt [21], ^{177}Os [22], ^{175}W [23], and ^{173}Hf [24]. The moment of inertia of band 1 is consistent with a strongly prolate deformed shape. The angular momentum alignment (Fig. 3a) is very gradual over the observed range of rotational frequencies as expected for a band built on a low-j intrinsic state. The first band crossing in this configuration has been observed in several neighboring nuclei (see Fig. 3a) but at frequencies around 0.3 MeV, which are beyond the highest frequency observed here. The unfavored signature partner of this band was not observed. It was populated weakly in ^{183}Hg [14] and not observed in ^{185}Hg [12], presumably because of the large signature splitting expected for rotational bands built on this configuration.

Bands 4 and 5, the bands with the highest intensity, are very similar in behavior to the mixed $i_{13/2}$ neutron bands reported earlier in ^{183,185}Hg and ^{187}Hg [25]. While in the latter three nuclei the bands were believed to be associated mainly with the $9/2^+[624]$ configuration, the $7/2^+[633]$ configuration is most likely the predominant one in ^{181}Hg, as its neutron

Fermi surface is lower. This positive-parity structure feeds an oblate deformed $i_{13/2}$ isomeric state in ^{185}Hg and in heavier odd-A Hg isotopes. Experimental results support the same scenario in ^{183}Hg [11,14] even though the lifetime and the γ decay of the isomer were not observed. There was no previous experimental evidence for the existence of an $i_{13/2}$ isomer in ^{181}Hg. The anomalous 416.8 keV transition energy at the bottom of band 5 can be taken as an indication of a transition from the prolate deformed band 5 to the oblate isomeric state. This crossing causes a sharp increase of alignment at $\hbar\omega \approx 0.2$ MeV (Fig. 3a), very similar to that seen in ^{183,185}Hg nuclei. This 416.8 keV crossing transition is lower in energy than the corresponding 429 keV line in ^{183}Hg or 442 keV γ ray in ^{185}Hg. At higher frequency, bands 4 and 5 have constant alignments of 3 and 4 $\hbar$, respectively, similar in magnitude to that seen in other N = 101 isotones (which, however, do not have the sharp increase in their alignment curves at low frequencies). The excitation energy of the bandhead remains unknown as no linking transition with the ground state was found. This could be caused by the long lifetime of the isomeric state. Significant signature splitting exists in bands 4 and 5, similar to that seen in neighboring odd-A Hg isotopes and in the N = 101 isotones, as can be seen in Fig. 3b. This splitting is expected for the $7/2^+[633]$ orbital, as the K value is not very high. Other possibilities, such as the presence of some degree of triaxiality or the mixing of the wave function of the $7/2^+[633]$ level with the oblate structure of the same $\nu i_{13/2}$ subshell, may also be partly responsible for the splitting. Overall, the data are consistent with the systematic picture of shape coexistence in light odd-A mercury isotopes. The levels built on the oblate structures above the $i_{13/2}$ isomers in ^{181,183}Hg are too weakly populated to be observed in current experiments. It is particularly important to locate in future work the coexisting oblate states, the low-spin extension of the prolate band and the γ-ray transitions between these bands since this would allow an empirical determination of the energy difference between the unperturbed prolate and oblate configurations, as well as of the strength of the interaction between states in the two

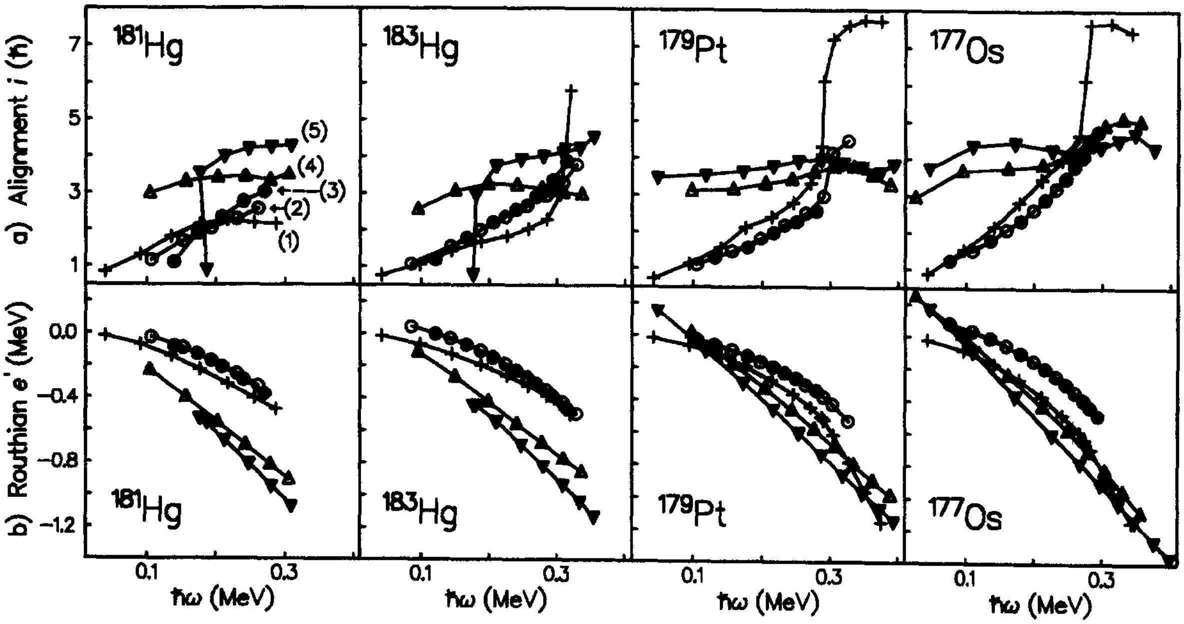

Fig. 3. a) Aligned angular momenta and b) Routhians for the bands in ^{181,183}Hg and the N = 101 isotones ^{179}Pt and ^{177}Os. The reference parameters of $J_0 = 28.0\ \hbar^2/(\mathrm{MeV})$ and $J_1 = 160\ \hbar^4/(\mathrm{MeV})^3$ are used for the alignment plots in ^{181}Hg. The vertical positions of the excited bands in ^{181,183}Hg are uncertain as the bandhead energies are unknown. Figure legends: crosses (+) for the ground state bands, circles for the $7/2^-[514]$ band in ^{183}Hg and $5/2^-[512]$ bands in the other isotopes, and the triangles for the $i_{13/2}$ mixed neutron bands.

wells, as shown by recent phenomenological band-mixing calculations [15].

Bands 2 and 3, consisting of stretched E2 transitions as well as M1 intraband crossover transitions, were populated very weakly: the strongest γ ray, the 248.4 keV transition, has an intensity of only ~ 7% relative to the strongest γ ray in the level scheme (416.8 keV). No signature splitting and very gradual angular momentum alignment (Fig. 3) are observed in this structure. These features, except for the signature dependence of the alignment, are very similar to those seen in the $5/2^-[512]$ configuration of the neighboring N = 101 isotones where the bandheads have excitation energies of 100–150 keV and lifetimes of ~ 50 ns [22,23]. These bandheads decay to the ground state structure through low-energy γ rays. The excitation energy of band 2 in ^{181}Hg is unknown as no linking transition to the ground state was observed, presumably because of the very low transition energy involved and the corresponding high conversion coefficient. On the other hand, a pair of bands built on the $7/2^-[514]$ configuration was found in ^{183}Hg [13] and ^{185}Hg [12], and this configuration cannot be entirely ruled out on the basis of systematics.

In order to gain more insight, the B(M1; I → I-1)/B(E2; I → I-2) ratios have been derived from the γ-ray intensities in bands 2 and 3 using the standard formula (see, e.g., Ref. [12]). The resulting experimental values are shown in Fig. 4, and are compared with the experimental values for ^{183}Hg. All of the experimental B(M1)/B(E2) values shown have been obtained assuming that the I → I-1 transitions are of pure M1 character, and thus these values are upper limits. (We note that the B(M1)/B(E2) values for ^{183}Hg were shown incorrectly in Fig. 5 of Ref [14]). Also shown in Fig. 4 are simple theoretical estimates based on the strong coupling formula [26] for the $5/2^-[512]$ and $7/2^-[514]$ orbitals. The intrinsic g_K factors, calculated from the Woods-Saxon single-particle wave functions and using $g_s = 0.70 g_s^{\mathrm{free}}$, were found to be -0.42 for the $5/2^-[512]$ orbital and +0.29 for the $7/2^-[514]$. The core g factor and the intrinsic quadrupole moment were estimated as $g_R = Z/A = 0.44$, and $Q_0 = 7.8$ eb (calculated from the deformation $\beta_2 \approx 0.26$ from Ref. [13]). In the strong coupling limit, the B(M1) value is proportional to $(g_K - g_R)^2$, and consequently much weaker M1 transitions are expected for the $7/2^-[514]$ orbital than for the $5/2^-[512]$. Note that a smaller core g_R factor should decrease the M1 strength for both configurations. The two sets of B(M1)/B(E2) values for ^{183}Hg [14,15] are both quite close to the values expected for a pure $7/2^-[514]$ band, and in fact agree with that assignment within error bars when the E2 contribution to the I → I-1 γ-ray intensity, estimated from the I → I-2 intensity and the $7/2^-[514]$ strong coupling limit, is removed [15]. In contrast, the B(M1)/B(E2) values in ^{181}Hg are clearly much larger than the ^{183}Hg experimental values, and close to the values expected for a pure $5/2^-[512]$ band. This change from a $7/2^-[514]$ band in ^{183}Hg to a $5/2^-[512]$ band in ^{181}Hg is consistent with the decreasing neutron number. Note that the lowest level observed in this structure is assigned as the 7/2 state instead of the expected 5/2 bandhead; otherwise, the static moment of inertia for this configuration would be significantly smaller than that of other configurations in ^{181}Hg, of the $5/2^-[512]$ configuration in neighboring N = 101 isotones, and

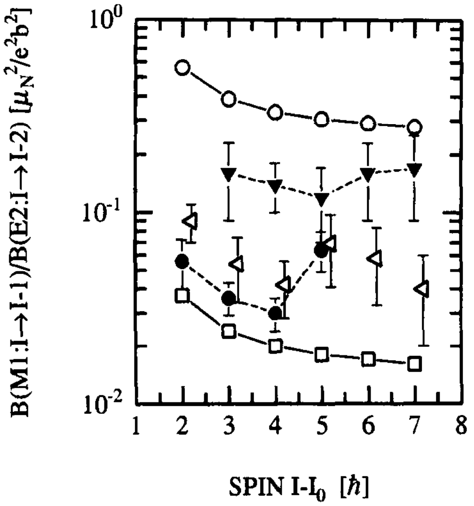

Fig. 4. The experimental $B(M1)/B(E2)$ ratios for bands 2 and 3 in ^{181}Hg (filled triangles). The open circles and the open squares give the calculated ratios assuming a $5/2^-[512]$ and a $7/2^-[514]$ band assignment, respectively. The ratios for the $7/2^-[514]$ band in ^{183}Hg (filled circles [14] and open triangles [15]) are also shown for comparison. Note that the data points for Ref. [15] were shifted to the right slightly in order to show the error bars clearly. The horizontal axis is $I - I_0$ where I_0 is the bandhead spin. See the text for a detailed discussion.

of the $7/2^-[514]$ configuration in ^{183,185}Hg. Thus, the lowest transitions in this configuration were not observed, and the situation is similar to that in the isotone ^{179}Pt [21]. This might be caused by the strong internal conversion of the low energy transitions.

Finally, the $7/2^-[514]$ bands in ^{183}Hg and ^{185}Hg were found to have ''identical'' transition energies [13]. In ^{181}Hg, the transition energies in the $5/2^-[512]$ bands, especially in the favored signature, are similar to, but not nearly as identical as those of the ''identical'' bands in ^{183}Hg and ^{185}Hg. This similarity, but lack of identicality, is consistent with the slightly larger deformation change expected when both the neutron number and the configuration change as is the case between ^{181}Hg and ^{183}Hg (between ^{183}Hg and ^{185}Hg the configuration remains unchanged [13]).

In summary, five rotational bands have been assigned for the first time to ^{181}Hg. A decoupled band was found to be built on the strongly deformed ground state, and a pair of strongly coupled bands on the $5/2^-[512]$ configuration. The strongly populated mixed neutron $i_{13/2}$ bands decay to a proposed oblate isomeric state, while the excited levels of the oblate structure remain to be identified in future experiments.

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