NUCLEON ALIGNMENT IN ^{191}Hg. A COMPETING MECHANISM AT MODERATE SPINS

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Detailed spectroscopic studies of the discrete γ-rays feeding and deexciting a $41/2^-$, 4.6 MeV level in ^{191}Hg are reported. The resulting decay scheme indicates single-particle nature for the states above the $41/2^-$ level. At moderate spin, the corresponding particle alignment mode competes favorably with collective oblate rotation. It is suggested that this sequence is associated with a non-collective prolate shape ($\epsilon_2 = 0.1$–0.15, $\gamma \simeq -120°$).

The nucleus ^{191}Hg has proven to be an excellent testing ground for the study of collective motion near the $Z = 82$ closed shell. At the ground state, this nucleus is characterized by a small oblate deformation ($\epsilon_2 \simeq 0.2$, $\gamma = -60°$), and the sequences of states observed in (HI,xn) reactions [1] have been interpreted in terms of bands built on configurations with different numbers of rotation-aligned quasiparticles [1,2]. Cranked shell model (CSM) calculations have been applied successfully to the Hg isotopes, and it has been recognized that these nuclei are good cases for detailed tests of the CSM on rotating oblate systems. Recently, a superdeformed band of 12 transitions was reported in ^{191}Hg by Moore et al. [3]. Superdeformed minima in a great number of nuclei with $Z \geqslant 80$ were originally predicted by Tsang and Nilsson [4] at spin $I = 0\,\hbar$ and later confirmed in several other calculations. From general expectations (e.g. ref. [5]), these minima survive and come closer to the yrast line with increasing spin. This is in agreement with a recent theoretical study of ^{187}Au [6] and a new survey for $Z = 74$–86 performed with the cranked Strutinsky approach [7]. The data of ref. [3] indicate that the superdeformed ^{191}Hg nucleus has a prolate shape with an axis ratio of 1.65:1 ($\epsilon_2 \simeq 0.5$), in excellent agreement with the predictions.

The calculations of ref. [6] have also suggested that the collective oblate states ($\gamma = -60°$) will terminate in prolate non-collective states ($\gamma = -120°$) in ^{187}Au and in neighboring nuclei. The driving force towards $\gamma = -120°$ is provided by the presence of several quasi-holes in high-j orbitals in the same way as quasiparticles in high-j shells drive the neutron deficient $A = 150$–160 nuclei towards oblate non-collective rotation [8]. We report here on the discovery of a sequence of levels with properties indicative of single-particle character. This is the first observation in the heavy Hg nuceli of "non-collective" angular momentum generation (i.e. gain of angular momentum by alignment of the spins of nucleons along the symmetry axis). This finding makes the ^{191}Hg nucleus a good example for a rich variety of phenomena indicative of different nuclear shapes (oblate-collective, superdeformed and prolate non-collective), and analogies can be drawn with the level structure of ^{152}Dy where particle alignment resulting in a non-collective oblate shape as well as rotation associated with small and very large (superdeformed) deformations have been reported [9–11],

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The results presented below were derived from the data used in the superdeformation search outlined in ref. [3] where most of the relevant experimental details can be found. Two sets of data were available: one set was obtained with a thin ^{160}Gd target consisting of two isotopically enriched 500 μg/cm^2 self-supporting foils stacked together while the other used a 1 mg/cm^2 ^{160}Gd target on which 14 mg/cm^2 Au was evaporated in order to stop the recoiling evaporation residues. In both measurements the (^{36}S,5n) reaction was used at an effective beam energy at the middle of the target of 169 MeV. The experiments were performed at the ATLAS accelerator with the Argonne–Notre Dame BGO γ-ray facility which consists of 50 hexagonal BGO elements surrounded by 12 Compton suppressed Ge spectrometers. Data were accumulated in an event-by-event mode with a requirement that at least 4 detectors of the inner BGO array fire in coincidence with two suppressed Ge detectors.

Final γ–γ coincidence matrices with a total of 9.5×10^7 and 6.9×10^7 events from the thin and thick target measurements, respectively, were used in the analysis. These matrices were obtained with a proper selection of events with high γ-ray multiplicity: a threshold of 14 was placed on the number of array detectors required to fire in prompt coincidence with the suppressed Ge detectors. Information on the multipolarity of the transitions was derived mainly from directional correlation ratios (DCO) described in ref. [12]. In several cases it was possible to distinguish between M1 and E1 transitions on the basis of the intensity balance between the γ-rays involved.

A total of 14 different band structures has been established in ^{191}Hg from this experiment, and a detailed level scheme will be presented in a forthcoming publication [13]. Here we give in fig. 1 the partial level scheme relevant to the discussion below. A new sequence of levels at excitation energies between 4587 and 8669 keV was observed. The level ordering as well as the spin and parity assignments in the new sequence are rather firmly established because the gamma decay usually proceeds through several pathways. Further confirmation of the placement of the transitions was provided by the analysis of data obtained at a lower beam energy of 163 MeV where the levels with the highest excitation energies and spins are no longer populated. The 41/2 spin at the bottom of the new structure is established mainly on the basis of the DCO ratios of the 629.9 and 1158.2 keV transitions which are consistent with dipole and quadrupole character, respectively. The information available for all other transitions involved in the decay of the 4587 state is also consistent with this assignment. Under the multiplicity conditions outlined above, 15% of all decays in ^{191}Hg proceed through the $41/2^-$ level.

The decay out of the $41/2^-$ state is fragmented in a large number of branches, some of which have been reported in earlier work [1]. We note that this decay proceeds through states with negative parity only. Close inspection of coincidence spectra with yrast transitions between positive parity states indicate that any possible decay branch towards these states must be less than 2% of the 268.8 keV line. Finally, the measurements with the backed target indicated that all transitions in the new level sequence are emitted after the ^{191}Hg nuclei are fully stopped. This result implies that the lifetimes of the states or of the transitions feeding them are longer than a few picoseconds.

A noticeable feature of the level structure above the 41/2 level (fig. 1) is that the transition energies vary greatly, and a large number of dipole and quadrupole transitions compete in the decay. This feature together with the fact that the band decays towards several rotational structures indicates that the new levels differ greatly in character from the rotational yrast states at lower excitation energy. These properties are very similar to those observed in nuceli with $A \simeq 150$. For example, the yrast lines of ^{152}Dy [9] or ^{148}Gd [12] are irregular and several isomers with decay rates typical of single-particle transitions are present. In these cases, the angular momentum is generated by the alignment of the spins of individual nucleons along a symmetry axis and the overall nuclear shape resulting from this "particle-alignment mode" is oblate. We propose that the new level structure in ^{191}Hg is also of single-particle character on the basis of this similarity, and we note that the lifetimes of the states discussed above are consistent with this interpretation. The present data represent the first experimental observation of this mode in the Hg nuclei. Preliminary data by Becker et al. [14] indicate that a similar structure may be present in the neighboring ^{193}Hg nucleus.

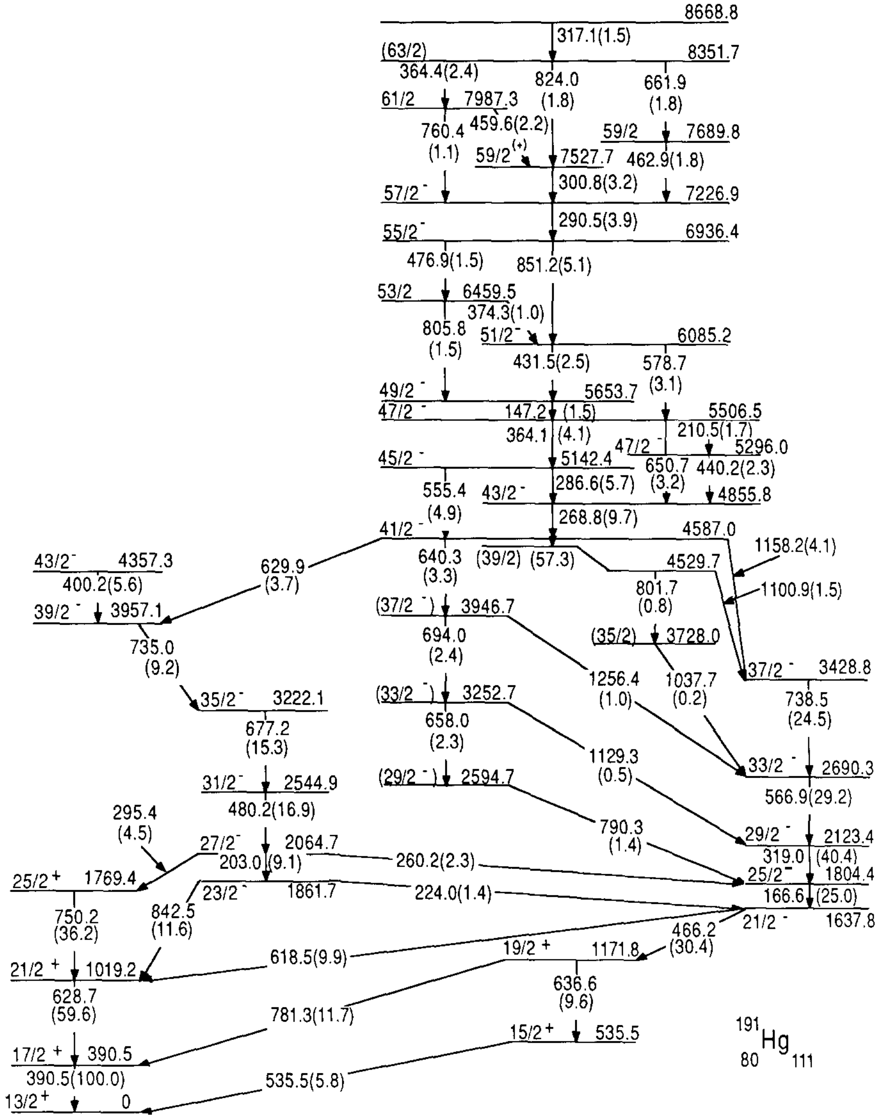

Fig. 1. Partial level scheme of ^{191}Hg showing the new level structure discussed in the text. The uncertainty on the γ-ray energy varies from 0.2 keV for the strong transitions to 0.5 keV for the weakest lines. Gamma-ray intensities normalized to 100 for the 390.5 keV transition are given in parenthesis for all levels associated with the new level sequence. Excitation energies are relative to the $13/2^+$ level.

The data are presented in an energy versus $I(I+1)$ plot in fig. 2 together with other states in ^{191}Hg with the exception of the members of the superdeformed band for which the excitation energies and spins are currently unknown [3]. The levels of the new structure exhibit a scatter about an average linear behavior up to the highest observed states. A similar behavior has been noted for the single-particle states in the $A\sim150$ region, see e.g. ^{152}Dy [12]. A straight line fit to all the levels with $I\geqslant41/2$ yields an effective moment of inertia $(2\mathscr{F}/\hbar^2)$ of 151 MeV^{-1} which is larger than the corresponding values for all other bands in ^{191}Hg with the exception of the superdeformed band. As a consequence, the new structure

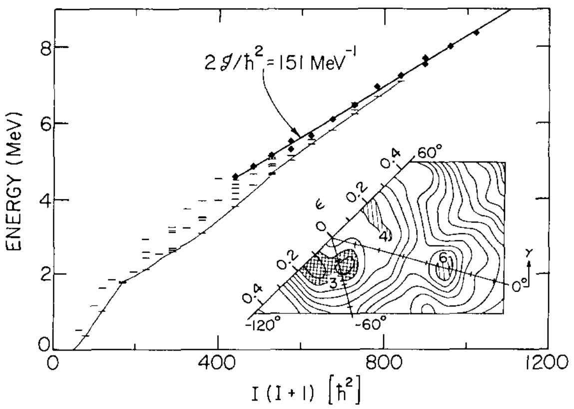

Fig. 2. Plot of energy versus $I(I+1)$ for states identified in ^{191}Hg. All known levels with the exception of the superdeformed states are given as lines in the figure (see text for details). The diamonds represent the new structure under discussion. One of the two lines in the figure joins the yrast states while the other is a straight line with a slope corresponding to $2\mathscr{F}/\hbar^2=151$ MeV^{-1}. The inset presents a deformation energy surface at spin 51/2$^-$ for the lowest lying $(\pi,\alpha)=(-,-1/2)$ configuration. Consecutive contour lines differ in energy by 1 MeV. Note that the surface shows that the collective and non-collective minima coexist in the same spin region as indicated by the data.

becomes yrast at the highest spins, a feature which might account for its relatively large population (at higher spin $I\geqslant 40$ ħ, the superdeformed band is calculated to become yrast). The effective moment of intertia is smaller than that of a rotating spherical rigid body by 15%, but to close to that of a prolate spheroid with $\epsilon_2\sim 0.2$ rotating rigidly about its symmetry axis. However, this consideration does not establish the nuclear deformation as the moment of inertia is known to be very sensitive to the actual microscopic shell structure.

Using the same formalism as in ref. [6], we have carried out Nilsson–Strutinsky cranking calculations for ^{191}Hg. These calculations do not include pairing and, therefore, are reliable only at high spins. However, for lower spins, they should give a good idea of the energy difference between various configurations, and these configurations can be labelled in a more straightforward way than in calculations where pairing is included. The following general features emerge: (1) for spins $I=20$–30 ħ, two minima are present in the energy surfaces corresponding to collective near-oblate configurations ($\epsilon_2\sim 0.15$, $\gamma\sim -40°$) and to aligned prolate non-collective configurations ($\epsilon_2\sim 0.1-0.15$, $\gamma\sim -120°$), respectively (see inset fig. 2); (2) the prolate non-collective configurations become favored energetically for $I>30$ ħ; (3) at spin $I\sim 40$ ħ, the valence space is essentially exhausted and a third minimum at $\epsilon_2=0.2$–0.3, $\gamma\sim 20°$ (involving $h_{9/2}$ and $i_{13/2}$ protons) becomes energetically competitive; (4) a superdeformed minimum is present at all spins with $\epsilon_2\sim 0.5$ and $\gamma\simeq 0°$ and becomes yrast for $I\sim 50$ ħ. The prolate non-collective minimum originates from the alignment (with the symmetry axis of the nucleus) of *holes* in the high-*j* shells $\pi h_{11/2}$, $\nu i_{13/2}$ and $\nu h_{9/2}$ which drive the nucleus towards $\gamma=-120°$.

The calculations reproduce the general features of the data fairly well. In particular, the coexistence of near-oblate rotational structures with single-particle, prolate non-collective states is accounted for (inset fig. 2), and the data indicate that the latter states become yrast for $I\sim 30$ ħ. Unfortunately, it is not possible to propose detailed configurations for the states reported here: most of the data cover a region where the single-particle states are not yrast and none of the highest spin states appears to be favored with respect to the others (which would facilitate an assignment).

It is instructive to make a comparison with the classic example of $\gamma=-120°$ "rotation" in Hf nuclei [15] (high-K isomers). In ^{191}Hg bandhead lifetimes are considerably shorter and rotational band members are not observed. The differences indicate that the potential energy surface in ^{191}Hg is soft in the γ direction, whereas in the Hf nuclei the surface is well localized at $\gamma=-120°$ and also at larger deformation ($\epsilon_2\sim 0.25$).

Information on the configuration of the 41/2$^-$ state can be derived from a close inspection of the decay pathways in ^{191}Hg, assuming that deexcitation from this level occurs primarily towards states with some overlap in configuration. The level structure of neighboring nuclei is also helpful. First, we note that a substantial fraction of the deexcitation proceeds through a sequence of γ-rays of almost equal energy (640–694–658 keV). This sequence is similar to band structures seen in the neighboring ^{192,194}Hg nuclei [1]. These levels may be tentatively interpreted as "quasivibrational" patterns corresponding to "terminating bands". These bands might be due to a gradual transition from $\gamma=-60°$ through the γ-plane toward the limit of $\gamma = -120°$ with the "quasi-vibrational" structure being regarded as an indication for γ-softness. In this case, the alignment of a pair of $h_{11/2}$ protons provides the required strong driving force towards $\gamma = -120°$. Secondly, the other main decay branches out of the 41/2 state reach collective structures in which one pair of aligned $i_{13/2}$ neutrons is coupled to a $p_{3/2}$ odd-neutron, and the feeding of these bands occurs in the region of the second backbend where another pair of neutrons aligns [1]. These negative-parity collective levels have corresponding states in ^{192,194}Hg with configurations initially involving an $i_{13/2}$ neutron coupled to a neutron in a negative-parity orbital. Thirdly, single-particle like structures have been observed in the even-N isotopes $^{187-195}$Au [16] with mean values of $\mathscr{F}$ very similar to the one reported above. These structures are based on states interpreted as originating from the coupling of a $h_{11/2}$ proton hole to the collective negative-parity states seen in the even Hg nuclei.

With these points in mind, we note that the negative-parity collective sequence in ^{191}Hg begins at $21/2^-$. By coupling a pair of aligned $h_{11/2}$ protons to this structure, one obtains an additional 10 units of angular momentum and reproduces the 41/2 spin of the band head. Thus, a suggestion for the configuration of the $41/2^-$ state is $(\pi h_{11/2})^{-2}_{10}\nu[(i_{13/2})^{-4}_{10}(p_{3/2})_{1/2}]_{21/2}$. In our cranked Nilsson–Strutinsky calculations, this configuration results in a prolate non-collective shape ($\epsilon_2 \sim 0.1$, $\gamma = -120°$) and a consistent interpretation in terms of a shape change from collective oblate to non-collective prolate seems to emerge.

To summarize, a new band structure with properties associated with single–particle character has been observed in ^{191}Hg. This structure becomes yrast at moderate spin. On the basis of the available evidence, it is proposed that the corresponding nuclear shape is prolate non-collective. It is hoped that the present data and the interpretation outlined above will be tested further by the search for similar band structures in the neighboring nuclei.

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