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Author
Wood, J.L.

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J. L. Wood, R. W. Fink, and J. Meyer-ter-Vehn

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SYMMETRY BETWEEN PARTICLE AND HOLE LEVEL SYSTEMS IN ^{189}Au*

J. L. Wood and R. W. Fink
School of Chemistry
Georgia Institute of Technology
Atlanta, Georgia 30332

and

J. Meyer-ter-Vehn†
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The $h_{11/2}$ and $h_{9/2}$ level systems have been studied experimentally and theoretically in ^{189}Au. If multiplied by a constant scaling factor, the two systems display identical relative energy spacings. This is in agreement with a particle-hole symmetry valid for triaxial odd-A rotors.

The $h_{11/2}$ and $h_{9/2}$ level systems in ^{189}Au have been studied both experimentally and theoretically. These negative parity families are now known in a number of odd-A Ir, Au, and Tl isotopes and are attributed to a hole in the $h_{11/2}$ shell and a particle in the $h_{9/2}$ shell, respectively. Going from ^{187}Ir to ^{195}Au, for example, the ordering of levels in these families indicates that the coupling to the core undergoes smooth changes as follows:

$h_{9/2}$ particle: decoupled → strongly coupled

$h_{11/2}$ hole: strongly coupled → decoupled.

The different ordering of the levels has been explained in terms of the particle-rotor model.[1] More recently this model has been generalized for triaxially deformed cores.[2] The complementary behavior of the particle and the hole bands in ^{189}Au can be understood as a manifestation of the particle-hole symmetry underlying this model. The objective of this letter is to evaluate the available experimental data on the two level systems in ^{189}Au and to show that if scaled, they have almost identical energy spacings and therefore display this symmetry in a very striking way.

The excited states of ^{189}Au have been studied recently at UNISOR,[3,4] and at Orsay[5] by population through the β^+-decay of ^{189m}Hg(9m) and ^{189g}Hg(8m) and at Orsay[6] by in-beam spectroscopy using the reaction ^{181}Ta(^{12}C,4n)^{189}Au. Since there are some differences between the UNISOR and Orsay level schemes, and since not all of the UNISOR data are published, we present some of the details of the UNISOR experiments and discuss the differences between the UNISOR and Orsay level schemes.

Mass-separated samples of ^{189m,g}Hg were obtained using the UNISOR isotope separator[7] operated on-line to the Oak Ridge Isochronous Cyclotron (ORIC). The high-spin ($J^\pi = 13/2^+$) ^{189m}Hg isomer was produced via the (^{16}O,p7n) reaction by bombardment of ^{181}Ta targets with 140 MeV ^{16}O^{5+} ions. The low-spin ($J^\pi = 13/2^-$) ^{189g}Hg was produced through electron capture and β^+-decay of ^{189}Tl(1.4m), which was obtained via the (^{16}O,8n) reaction in the same bombardment. The UNISOR in-beam target/ion-source arrangement[7] permitted the control of the relative yield of Tl to Hg activity by different choices of recoil catcher foil; a tenfold increase in this ratio was made by using graphite felt in place of tantalum foil. In view of the close similarity in half-lives and the very complex decay schemes of ^{189m}Hg and ^{189g}Hg, this provides a powerful technique for distinguishing clearly between the γ-rays de-exciting the high- and low-spin levels in ^{189}Au. The energy levels, their spins and parities, the γ-ray transitions and their branching ratios, and the transition multipolarities were established by γ-γ, γ-electron and γ-x vs. time coincidence measurements and γ-ray and conversion electron multiscaling, combined with two choices of the isomer yield ratio, as described above. The system of $h_{9/2}$ and $h_{11/2}$ levels deduced from the UNISOR experiments is shown in Fig. 1.

The levels schemes based on the Orsay work differ from Fig. 1 in that, with reference to the Orsay schemes: the level at 1007.1 keV in the $h_{11/2}$ band is assigned $11/2^-$ (note that the energies of the levels within each band are specified relative to the band head); the $17/2^-$ member of the $h_{11/2}$ band is placed at 1472.6 keV; and no spin assignments are made to the levels at 1105.3, 1120.2, and 1234.2 keV. Further, in the $h_{9/2}$ band, the Orsay schemes do not contain the levels at 561.4, 780.5, 790.9, 830.3, and 987.0 keV; they have an assignment of $17/2^-$ to the 779.6 keV level; and they have no spin assignment for the level at 771.3 keV. Finally, in the $h_{9/2}$ band, the 395.4 keV γ-line (the transition between the $1/2^-$ and $5/2^-$ levels in the UNISOR scheme) is reported in the Orsay work to be M1 multipolarity. Other discrepancies include insufficient evidence in the UNISOR work to support the level reported in the Orsay measurements at 990.6 keV in the $h_{9/2}$ band and minor ambiguities such as the assignment of γ-lines to more than one location. We make the following specific arguments in support of the assignments which are at variance with the Orsay work: The level at 1007.1 keV in the $h_{11/2}$ band is clearly populated by the ^{189g}Hg($3/2^-$) β^+-decay, based on the coincidence data obtained with target/ion-source conditions favouring Tl production (see above) and thus has low spin. Similar data support the existence of the low-spin levels at 561.4, 780.5, 790.9, and 830.3 keV in the $h_{9/2}$ band. The level at 1120.2 keV in the $h_{11/2}$ band is assigned $17/2^-$ based on the strong systematic trend of this level through the $h_{11/2}$ bands of ^{191,193,195}Au, where it has been observed by in-beam spectroscopy[8,9] to lie just below the $19/2^-$ band member ($E_{19/2} - E_{17/2} = 34.8$, 45.5, and 59.9 keV, respectively). The level at 779.6 keV in the $h_{9/2}$ band is assigned $(11/2, 12/2, 15/2)^-$, based on the strong intensity of the transition de-exciting this level to the $13/2^-$ state at 320.9 keV and the absence of coincidences between this transition and γ-lines other than the 320.9 keV transition: these latter data suggest that the level at 779.6 keV is directly fed in the β^+-decay of ^{189m}Hg($13/2^+$), and thus a $17/2^-$ assignment is unlikely. Finally, our data suggest that the 395-4 keV γ-line has more than one component and that the multipolarity of the composite line is E2 + 20% M1. The 395K and 395L electrons in coincidence with the 166 keV γ-line are not strong enough in our data to resolve the multipolarity of the proposed $1/2^- \to 5/2^-$ component. This is the most serious uncertainty in our proposed scheme, since the assignment of $1/2^-$ to the 561.4 keV level in the $h_{9/2}$ band clearly requires pure E2 character for the 395 keV transition.

The analogy between the scaled $h_{9/2}$-particle and $h_{11/2}$-hole band spacings is quite remarkable for the R = 2 multiplet (R - core spin) states with spins j-2, j-1, j+1, j+2, all of which are very well characterized by both the Orsay and the UNISOR experiments. It is premature to discuss the extension of the analogy to the j-4 state until this member of the $h_{9/2}$ band has a more reliably established spin. At higher energies, members of both bands are included to illustrate the possible validity of the analogy in these regions. Although the candidates for the j-3 states do not correspond too closely, there is a possibility that the pairs 17.2^-(1120.2 keV, $h_{11/2}$) -$(11/2, 13/2, 15/2)^-$(779.6 keV, $h_{9/2}$) and $(13.2,15/2)^-$(1105.3 keV, $h_{11/2}$) -$(11/2,13/2)^-$(771.3 keV, $h_{9/2}$) are analogs. An interesting prediction of the scheme is the energy of the 17.2^- member of $h_{9/2}$ band, which should lie 518±13 keV above the $13/2^-$ member and this conceivably its de-excitation could be concealed by the annihilation peak. Although it appears that the analogy begins to break down in the region of the j+4 states and above, it would be interesting to test the j+6 states for this behavior. (Since we do not concur with the Orsay results for the $17/2^-$ (j +4) member of the $h_{9/2}$ band, we must necessarily question their assignment of j+6 and j+8 members. In this respect, their $23/2^-$ (j+6) member of the $h_{11/2}$ band fits the systematics of this state through $^{191-195}$Au[8,9] and would predict, from our particle-hole analogy, a $21/2^- \to 17/2^-$ transition energy of 561.5 keV in the $h_{9/2}$ band.)

The theoretical interpretation of these results is based on the model of a particle (or hole) coupled to a triaxially deformed core.[2] It has been shown that the model describes well the low-energy unique parity states of transitional odd-A nuclei in the A = 190 mass region.[2] The model spectrum $E_I(\beta,\gamma,\lambda_F)$ depends on the deformation β, the shape asymmetry γ, and the Fermi energy λ_F. (The subscript I is the nuclear spin.) Particle and hole spectra are connected by the symmetry relation

$$E_I(\beta,\gamma,\ j\text{-particle}) = E_I(\beta,\gamma,\ j\text{-hole})$$

where λ_F is located well below the j-shell of the odd nucleon for the particle spectrum and well above the j-shell for the hole spectrum. This condition is essentially met in the Au isotopes with respect to the $h_{9/2}$ shell (λ_F below) and the $h_{11/2}$ shell (λ_F above). Taking into account that E_I is weakly dependent on j and depends on β strongly only through a scale factor $1/\beta^2$, but much less otherwise, we have approximately

$$\beta^2_{h_{9/2}} \cdot E_I(\gamma,\ h_{9/2}\ \text{particle}) = \beta^2_{h_{11/2}} \cdot E_{I+1}(60-\gamma,\ h_{11/2}\ \text{hole}).$$

Based on this relation, the close resemblance of the proportionally scaled $h_{9/2}$ and $h_{11/2}$ systems in ^{189}Au (see Fig. 1) indicates that $\gamma_{h_{9/2}} = 60° - \gamma_{h_{11/2}}$. This includes the possibility of axially symmetric shapes, e.g. a prolate ($\gamma = 0°$) shape for the $h_{9/2}$ and an oblate ($\gamma = 60°$) shape for the $h_{11/2}$ system, and also permits an asymmetric shape with the same $\gamma_{h_{9/2}} = \gamma_{h_{11/2}} = 30°$ for both systems. The actual level spacings of the $h_{11/2}$ spectrum, which appear to be almost identical for $^{189-195}$Au,[2,3] indicates $\gamma_{h_{11/2}} = (37\pm2)°$. Consequently, we deduce $\gamma_{h_{9/2}} = (23\pm2)°$ for ^{189}Au. These values should be compared with $\gamma = (24\pm2)°$ derived from the ^{188}Pt spectrum and $\gamma = (38\pm2)°$ derived from the ^{190}Hg spectrum, specifically from the first and second 2^+ energies. Also, the ratio of the first 2^+ energies $E_2(^{188}\text{Pt})/E_2(^{190}\text{Hg}) = 0.64$ is close to the scaling ratio $E_I(h_{9/2})/E_{I+1}(h_{11/2}) = 0.7088$, which is found to give the best match in ^{189}Au (see Fig. 1).

From these results it is concluded that the $h_{9/2}$ and $h_{11/2}$ systems in ^{189}Au are based on different shapes (asymmetric-prolate and asymmetric-oblate) which are essentially those of the ^{188}Pt and ^{190}Hg cores, respectively. In the Orsay experiments[5] it was observed that the M1 transition between the $h_{9/2}$ and $h_{11/2}$ band heads is retarded by a factor 15000 relative to the Weisskopf single-particle estimate, and the relationship of these bands to the neighbouring doubly-even cores was recognized. Interpreted within the frame of the triaxial particle-core model, the striking similarity in the level spacings of the two systems reflects a basic particle-hole symmetry and follows from the fact that the γ-values in ^{188}Pt and ^{190}Hg happen to lie symmetrically about $\gamma = 30°$. (It should be noted that the triaxial rotor spectrum of a doubly-even nucleus has reflection symmetry about $\gamma = 30°$ and thus, the odd-A spectrum must be used to determine whether the nuclear shape is prolate or oblate.) Comparing this model with the Alaga model, which also describes the $h_{11/2}$ spectra well in odd-A Au isotopes,[10] one notices that a corresponding symmetry relating the $h_{11/2}$ levels as 3-proton hole clusters coupled to phonons in closed-shell Pb and should treat (not done so far) the $h_{9/2}$ levels as 4-holes-1-particle clusters. The microscopic model of Hecht, based upon the pseudo SU$_3$ coupling scheme[11] appears to have the same limitation. The particle-hole symmetry arises under the assumption that the open-shell nuclei ^{188}Pt and ^{190}Hg are stable enough to be used as effective cores: this is done in the particle-core model by treating the core correlations in terms of triaxial shapes. The ^{189}Au spectrum provides strong evidence that such a treatment is justified and further, that the shapes of the even-A nuclei in this mass region--or at least their averaged parameters--are relatively stable, in contrast to general belief.

FOOTNOTES AND REFERENCES

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FIGURE CAPTION

Fig. 1. The experimental $h_{11/2}$ and $h_{9/2}$ bands are based on the results of UNISOR experiments, together with the $10/2^-$ member assigned to the $h_{11/2}$ band in Ref. 6. Discrepancies between these data and those of Refs/ 5,6 are discussed in the text. Multipolarities are included where known and if ambiguous are denoted (M1,E2) to mean an undertermined M1/E2 admixture, the ambiguity generally being due to the complexity of the spectra. Possible spin assignments rely mainly on multipolarities, population systematics from the decays of ^{189m}Hg($13/2^+$) and ^{189g}Hg($3/2^-$) and for the $h_{11/2}$ band, further support from the strong $h_{11/2}$ band energy systematics through $^{189-195}$Au.[3] The energy scale compression factors (0.636 and 0.7088) for the $h_{11/2}$ band are determined by the energy ratio of the 2_1^+ states in the effective cores (^{190}Hg for $h_{11/2}$, ^{188}Pt for $h_{9/2}$) and by an ad hoc ratio that gives the closest analogy for the two bands, respectively. In the region of the j+4 states, the particle-hole symmetry is less clear and transitions are only included for levels that have tentatively identified analogs: these levels are connected by dots instead of dashes.

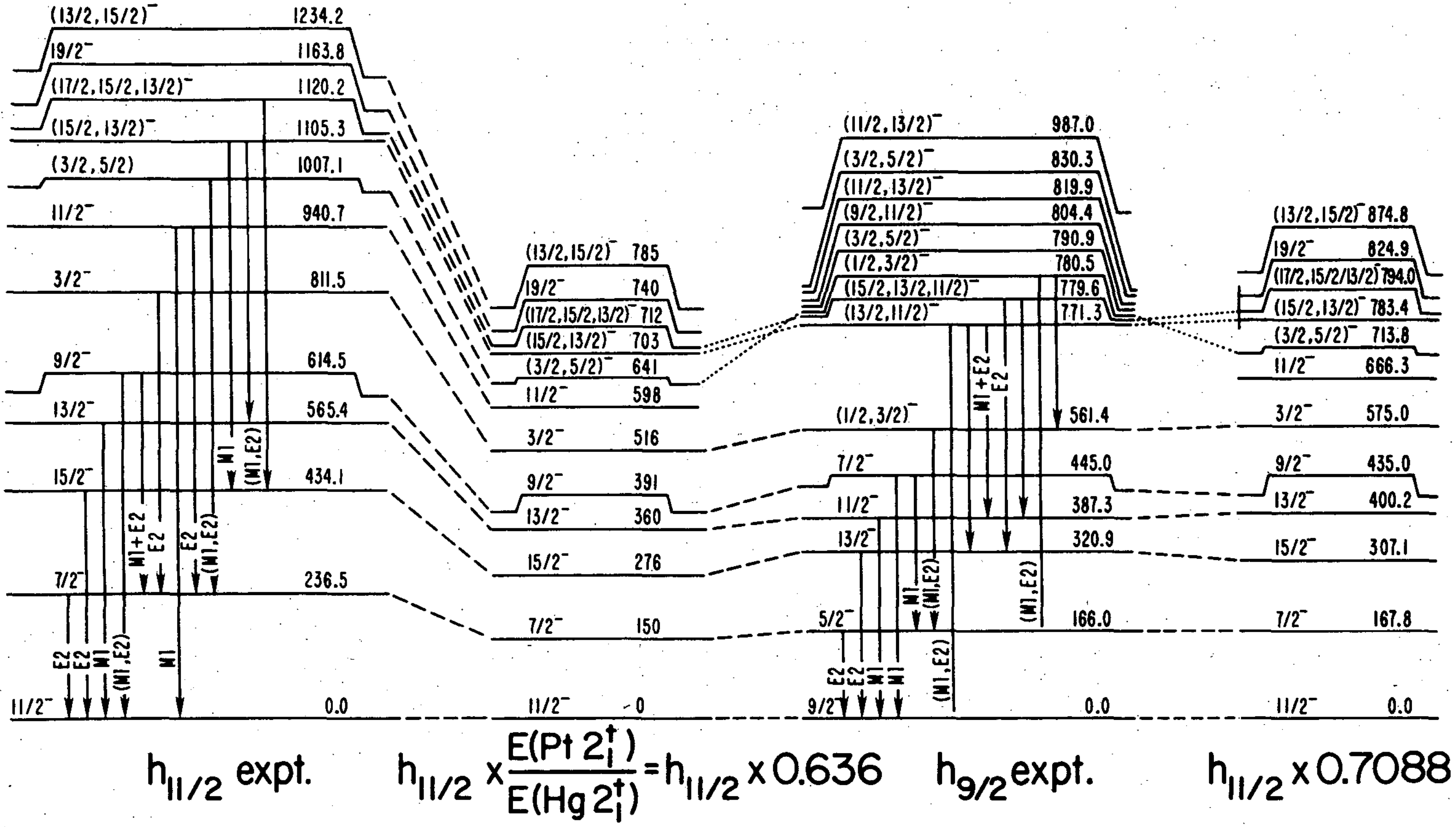

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Fig. 1

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720