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Symmetry between particle and hole level systems in ^{189}Au[†]

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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 particle-hole symmetry valid for triaxial odd-A rotors.

[NUCLEAR STRUCTURE ^{189}Au, $h_{11/2}$ and $h_{9/2}$ bands, triaxial rotor description.]

I. INTRODUCTION

The excited states of ^{189}Au have recently been studied[1] at UNISOR and some of the structural features observed have been the subject of a short communication.[2] We discuss here the experimental details relating to the $h_{11/2}$ and $h_{9/2}$ level systems and a simple and remarkable interpretation of their unique behavior in ^{189}Au. These negative parity bands are known in a number of odd-mass 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.[3] More recently this model has been generalized[4] for triaxially deformed cores. 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 excited states of ^{189}Au were populated through the β^+ decay of high spin ($J^\pi = \frac{13}{2}^+$) ^{189}Hg^m ($T_{1/2} = 9$ min) and low spin ($J^\pi = \frac{3}{2}^-$) ^{189}Hg^g ($T_{1/2} = 8$ min). During the course of this work, two other studies of the excited states of ^{189}Au have appeared in the literature: one, of the β^+ decay of ^{189}Hg^{m,g} which was predominantly the high-spin isomer (Ref. 5); the other, of the reaction ^{181}Ta(^{12}C, $4n$)^{189}Au using in-beam γ-ray spectroscopy (Ref. 6). The major features of all these studies are in agreement. We present more extensive details of the $h_{11/2}$ and $h_{9/2}$ band structures than Refs. 5 and 6 and demonstrate that, if scaled, the two bands have almost identical energy spacings and therefore display particle-hole symmetry in a very striking way.

II. ^{189}Au LEVEL SCHEME

Mass-separated samples of ^{189}Hg^{m,g} were obtained from the UNISOR isotope separator[7] operated on line to the Oak Ridge isochronous cyclotron (ORIC). The high-spin ($J^\pi = \frac{13}{2}^+$) ^{189}Hg^m isomer was produced via the ^{181}Ta(^{16}O, $p7n$) reaction with 140 MeV ^{16}O^{5+} ions. The low-spin ($J^\pi = \frac{3}{2}^-$) ^{189}Hg^g was produced through electron capture and β^+ decay of ^{189}Tl(1.4 min), obtained in the (^{16}O, $8n$) reaction in the same bombardment. The UNISOR in-beam target/ion-source arrangement[7] permits the control of the relative yield of Tl to Hg activity through 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 ^{189}Hg^m and ^{189}Hg^g, this provides a powerful technique for distinguishing clearly between the γ rays deexciting 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, for the two choices of the isomer yield ratio described above.

The system of $h_{9/2}$ and $h_{11/2}$ levels deduced from the UNISOR experiments is shown in Fig. 1. We make some limited commentary on our characterization of the bands to amplify the details given in Fig. 1. When referring to corresponding members

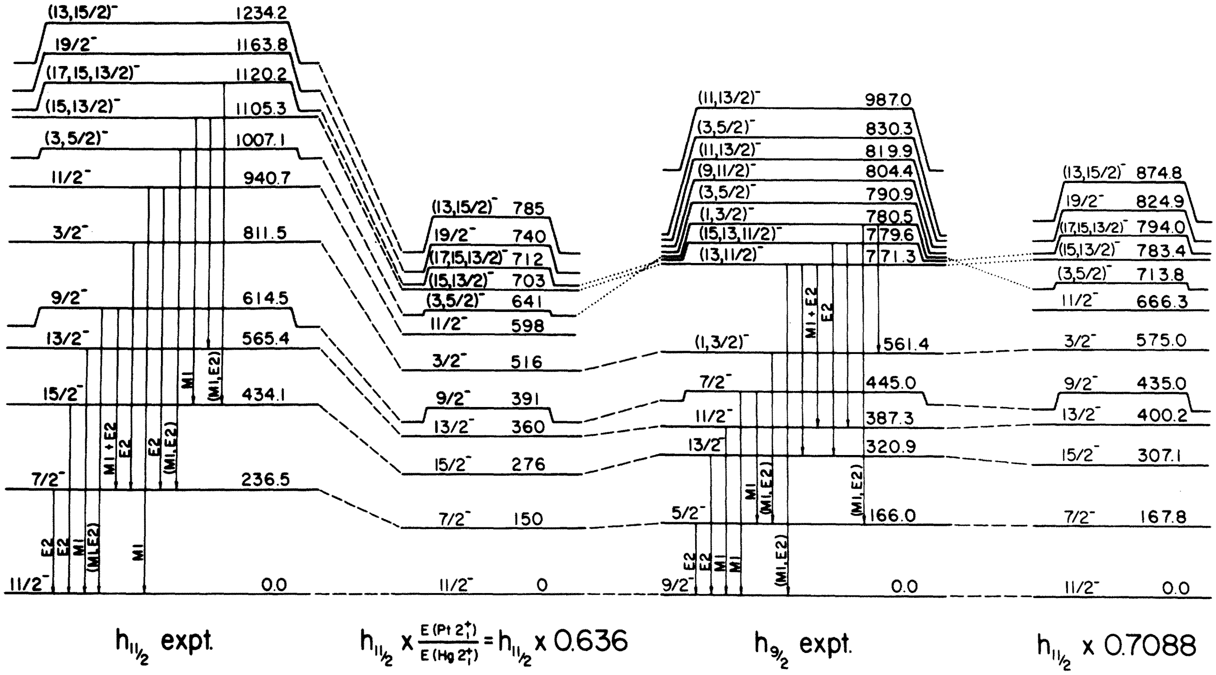

FIG. 1. The experimental $h_{11/2}$ and $h_{9/2}$ bands are based on the results of UNISOR experiments, together with the $\frac{19}{2}^-$ member assigned to the $h_{11/2}$ band in Ref. 6. Multipolarities are included where known and if ambiguous are denoted ($M1, E2$) to mean an undetermined $M1/E2$ 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 $^{189}\mathrm{Hg}^m$ ($\frac{13}{2}^+$) and $^{189}\mathrm{Hg}^g$ ($\frac{5}{2}^-$) and for the $h_{11/2}$ band, further support from the strong $h_{11/2}$ band energy systematics through $^{189-195}\mathrm{Au}$ (Ref. 2). 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 ($^{190}\mathrm{Hg}$ for $h_{11/2}$, $^{188}\mathrm{Pt}$ 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.

of each band, we designate states by their spins j, $j+1$, $j+2$, $j-1$, etc., where j is the spin of the band head. The band members with $j-2$, $j+2$, $j+1$, and $j-1$ are very well established by the UNISOR measurements and by those of Refs. 5 and 6. There are a number of differences between the UNISOR work and that of Refs. 5 and 6; however, none are crucial to our interpretation of these structures. Our identification of a $j-4$ member of the $h_{9/2}$ band is tentative, since the transition deexciting to the $j-2$ state must have pure $E2$ multipolarity and we observe $E2+20\%$ $M1$; however, we have evidence that at this energy there is more than one line in the γ-ray spectrum. The level at 1120 keV in the $h_{11/2}$ band probably has $J^\pi = \frac{17}{2}^-$ based on the stable systematic trend of the $\frac{17}{2}^-$ level through the $h_{11/2}$ bands of $^{191,193,195}\mathrm{Au}$, where it has been observed by in-beam spectroscopy[8,9] to lie just below the $\frac{19}{2}^-$ band member (see also Ref. 2). The level at 779 keV in the $h_{9/2}$ band is assigned $(\frac{11}{2}, \frac{13}{2}, \frac{15}{2})^-$, contrary to the conclusions of Refs. 5 and 6 (where it is assigned $\frac{17}{2}^-$), because intensity balances support direct β-decay feeding from the $\frac{13}{2}^+$ Hg isomer. At higher energies, members of both bands are included to illustrate the possible validity of the analogy.

III. DISCUSSION AND CONCLUSIONS

The theoretical interpretation of these results is based on the model[4] of a particle (or hole) coupled to a triaxially deformed core. It has been shown[4] that the model describes well the low-energy unique parity states of transitional odd-A nuclei in the $A=190$ mass region. 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

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

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 $\gamma_{h_{9/2}} = 60^\circ - \gamma_{h_{11/2}}$. This includes the possibility of axially symmetric shapes, e.g., a prolate ($\gamma = 0^\circ$) shape for the $h_{9/2}$ and an oblate ($\gamma = 60^\circ$) shape for the $h_{11/2}$ system, and also permits an asymmetric shape with the same $\gamma_{h_{9/2}} = \gamma_{h_{11/2}} = 30^\circ$ for both systems. The actual level spacings of the $h_{11/2}$ spectrum, which appear to be almost identical for $^{189-195}$Au (Refs. 2 and 4), indicates $\gamma_{h_{11/2}} = (37 \pm 2)^\circ$. Consequently, we deduce $\gamma_{h_{9/2}} = (23 \pm 2)^\circ$ for ^{189}Au. These values should be compared with $\gamma = (24 \pm 2)^\circ$ derived from the ^{188}Pt spectrum and $\gamma = (38 \pm 2)^\circ$ 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 $E_I(h_{9/2})/E_{I+I}(h_{11/2}) = 0.7088$, 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 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 15 000 relative to the Weisskopf single-particle estimate, and the relationship of these bands to the neighboring 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 $\gamma = 30^\circ$. (It should be noted that the triaxial rotor spectrum of a doubly-even nucleus has reflection symmetry about $\gamma = 30^\circ$ 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,[10] which also describes the $h_{11/2}$ spectra well in odd-A Au isotopes, one notices that a corresponding symmetry relating the $h_{11/2}$ and $h_{9/2}$ systems is not apparent there. This is because the Alaga model describes the $h_{11/2}$ levels as three-proton hole clusters coupled to phonons in closed-shell Pb and should treat (not done so far) the $h_{9/2}$ levels as four-holes–one-particle clusters. The microscopic model of Hecht,[11] based upon the pseudo SU$_3$ coupling scheme 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 correlation 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.

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[1] J. L. Wood, E. F. Zganjar, and UNISOR co-workers (unpublished).

[2] E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, C. R. Bingham, B. D. Kern, J. L. Weil, J. H. Hamilton, A. V. Ramayya, E. H. Spejewski, R. L. Mlekodaj, H. K. Carter, and W. D. Schmidt-Ott, Phys. Lett. 58B, 159 (1975).

[3] F. S. Stephens, Rev. Mod. Phys. 47, 43 (1975).

[4] J. Meyer ter Vehn, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 32, 1383 (1974); J. Meyer ter Vehn, Nucl. Phys. A249, 111, 141 (1975).

[5] V. Berg, R. Foucher, and Å. Höglund, Nucl. Phys. A244, 462 (1975).

[6] M. A. Deleplanque, C. Gerschel, N. Perrin, and V. Berg, Nucl. Phys. A249, 366 (1975).

[7] E. H. Spejewski, R. L. Mlekodaj, H. K. Carter, W. D. Schmidt-Ott, E. L. Robinson, R. W. Fink, J. M. Palms, W. H. Brantley, B. D. Kern, K. J. Hofstetter, E. F. Zganjar, A. R. Quinton, F. T. Avignone, W. M. Bugg, C. R. Bingham, F. Culp, J. Lin, J. H. Hamilton, A. V. Ramayya, M. A. Ijaz, J. A. Jacobs, J. L. Duggan, W. G. Pollard, R. S. Livingston, C. E. Bemis, E. Eichler, N. R. Johnson, R. L. Robinson, and K. S. Toth, in Proceedings of the International Conference on Low Energy Acceleration and Mass Separators, Skövde, Sweden, edited by G. Anderson and G. Holmén, 1973 (unpublished), p. 318.

[8] P. O. Tjøm, M. R. Maier, D. Benson, Jr., F. S. Stephens, and R. M. Diamond, Nucl. Phys. A232, 397 (1974).

[9] R. M. Lieder (private communication).

[10] V. Paar, Ch. Vieu, and J. S. Dionisio (unpublished).

[11] K. T. Hecht, Phys. Lett. 58B, 253 (1975).