NUCLEAR GROUND STATE SPIN OF ^{185}Au AND MAGNETIC MOMENTS OF $^{187},^{188}\text{Au}$
FURTHER EVIDENCE FOR COEXISTING NUCLEAR SHAPES IN THIS MASS REGION

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ABSTRACT

Hyperfine structure measurements have been performed in some neutron-deficient gold isotopes, using on-line atomic-beam magnetic resonance (ABMR) techniques at the ISOLDE facility, CERN. The following results have been obtained : ^{185}Au , $I = 5/2$; ^{187}Au , $\Delta\nu = 44.35(60)$ GHz, $\mu = 0.72(7)$ n.m. and ^{188}Au , $\Delta\nu = \pm 2992(30)$ MHz. A discussion of the influence of hyperfine anomaly is included. With due regard to this effect, the magnetic moments of ^{188}Au may be given as $\mu = \pm 0.07(3)$ n.m. The experimental data are compared with the results from calculations based on the particle-asymmetric rotor model. Strong evidence for coexisting nuclear shapes in ^{185}Au and for a much larger ground state deformation in ^{185}Au than in ^{187}Au is presented.

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NUCLEAR MOMENTS (static) ^{185}Au ; measured J. ^{187}Au
measured a and μ . ^{188}Au ; measured a, deduced μ .
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1. INTRODUCTION

In order to test different theoretical descriptions of nuclei in the transition region between the strongly deformed rare-earths and the spherical nuclei around ^{208}Pb , experimental data are of greatest importance. In a previous paper ¹⁾, we reported on spin measurements in gold isotopes in the mass range $A = 186-189$. These measurements were performed at ISOLDE using conventional off-line ABMR techniques. By introducing an intermittent experimental procedure, it has been possible to extend the measurements to include the nuclear spin of ^{185}Au , the magnetic moment of ^{187}Au and the hyperfine separations of ^{187}Au and ^{188}Au .

2. EXPERIMENTAL PROCEDURE AND RESULTS

The radioactive gold isotopes were obtained as daughter products of mercury produced in spallation reactions when irradiating a molten lead target of the ISOLDE isotope separator with 600 MeV protons from the CERN synchro-cyclotron. The ion-beam from the isotope separator was focused on the on-line oven of the atomic-beam apparatus ²⁾. The oven was in these measurements operated in an intermittent mode; collection on a cold foil of molybdenum followed by a delay period to allow the gold activity to grow in, heating of the oven foil to about 1000°C to evaporate the remaining mercury activity and finally the atomic-beam experiment, evaporating gold out of the foil at a temperature of about 1600°C . The different time intervals used for the experiments in ^{185}Au , ^{187}Au and ^{188}Au are indicated in table 1. It is evident that only a few exposures could be made per hour.

The activity transmitted through the atomic-beam apparatus was measured in well shielded NaI(Tl) detectors, sensitive to the K X-rays following the EC decay.

The experiments were performed in the $^2\text{S}_{1/2}$ electronic ground state of gold, having the splitting factor $g_J = 2.0033115(40)$ ³⁾. The procedure for spin and moment measurements in elements with a $J = \frac{1}{2}$ electronic ground state is described in our previous papers on gold ¹⁾ and cesium ⁴⁾.

In ^{185}Au , resonance signals corresponding to a nuclear spin $I = 5/2$ were observed at three different settings of the external magnetic field; $\mu_B B/h = 2.060$, 2.941 and 4.455 MHz. No signal were observed other half-integer spin values up to $I = 11/2$. The decay curve of a spin $I = 5/2$ resonance signal is shown in fig. 1. The half-life corresponds to that reported for the nuclide ^{185}Au ⁵⁾; 4.3 ± 0.2 min.

The nuclear ground state spins of ^{187}Au and ^{188}Au were measured in a previous experiment ¹⁾ to be $I = 1/2$ and $I = 1$, respectively.

A frequency scan for resonance signals of ^{187}Au in an external magnetic field of $\mu_B B/h = 65,5$ MHz indicated a very large hyperfine separation, $\Delta\nu \approx 50$ GHz, between the hyperfine levels $F = 1$ and $F = 0$. It was then realized that a direct measurement of the nuclear magnetic moment would be possible, by observing the double-quantum transition $(F, m_F), (1, 1) \rightarrow (1, -1)$ in addition to the hyperfine separation $\Delta\nu$ or dipole constant a , obtained from the single-quantum transition $(1, 0) \rightarrow (1, -1)$.

A power expansion of the Breit-Rabi formula to second order shows that the frequencies of the single and double-quantum transitions may be written :

$$\nu_I = \frac{1}{2} \frac{\mu_B B}{h} (g_J - g_I') + (g_J + g_I')^2 \left(\frac{\mu_B B}{h}\right)^2 \frac{1}{4\Delta\nu} \quad (1)$$

$$\nu_{II} = \frac{1}{2} \frac{\mu_B B}{h} (g_J - g_I') \quad (2)$$

where g_I' denotes the nuclear g-factor expressed in Bohr magnetons.

In order to reduce systematic errors due to different tuning of the rf-system, an external magnetic field of $\mu_B B/h = 231$ MHz was chosen for the experiment. At this field, the potassium calibration frequency as well as the ^{187}Au resonance frequencies are expected close to 231 MHz. A careful frequency scan was performed, the result of which is shown in fig. 2. The experimental transition frequencies, shown in table 2, have been assigned an error of a quarter of the FWHM line widths. The contribution of g_I' to the double-quantum transition is only about 90 kHz, thus limiting the accuracy to which the magnetic moment may be determined.

A least-squares fit of the experimental data to the full Breit-Rabi formula gives independent values of the dipole constant and the magnetic moment of ^{187}Au . The results of the fit is displayed in fig. 3, showing the minimum and the ellipses corresponding to one standard deviation. The errors in a and μ have been increased to account for the tilted error ellipses.

The final experimental values for ^{187}Au are given in table 3. The magnetic moment has been corrected for diamagnetic shielding, using the correction factor 1.0157 from ref. 6).

In order to determine the hyperfine separation between the hyperfine levels $F = 3/2$ and $F = 1/2$ in ^{188}Au , resonance experiments were made in successively stronger external magnetic fields. The single-quantum transition $(3/2, -1/2) \leftrightarrow (3/2, -3/2)$, identified by the low r.f. power required, was observed at two settings of the external field. The resonance curves, shown in fig. 4, exhibit the same shape and width as the potassium calibration line at the two fields. The resonance frequencies, given in table 2, with errors taken to be a quarter of the line widths, were fitted to the Breit-Rabi formula, assuming either a positive or a negative sign of the nuclear g-factor. The resulting hyperfine separations were 2988(26) MHz and -2996(26) MHz, respectively. Since there was no significant difference in the goodness of the fit between the two alternatives, we give as a final result $\Delta\nu(^{188}\text{Au}) = \pm 2992(30)$ MHz.

3. EVALUATION OF THE MAGNETIC MOMENTS. INFLUENCE OF THE HYPERFINE ANOMALY.

The magnetic moments of the gold isotopes ^{187}Au and ^{188}Au may be evaluated from the experimentally determined dipole constants through a direct comparison with known values of nuclear spin, magnetic moment and dipole constant in the stable nuclide ^{197}Au . Neglecting the effects of hyperfine anomaly, the following relation holds :

$$\mu_I = \mu_{I197} \frac{a_I}{a_{197} I_{197}} \quad (3)$$

The measured quantities in ^{197}Au are :

$$\begin{aligned}\mu_{I197} &= 0.145746(9) \text{ n.m. } ^3) \\ a_{197} &= 3049.660092(7) \text{ MHz } ^3) \\ I_{197} &= 3/2 \text{ } ^7)\end{aligned}$$

The magnetic moment of ^{197}Au is corrected for diamagnetic shielding $^6)$. The resulting magnetic moments for ^{187}Au and ^{188}Au are given in table 3, column 5.

The hyperfine anomaly may, however, seriously affect the results obtained from eq. (3). In a heavy element like gold with an unpaired s-electron, the main contribution to the hyperfine anomaly arises from the distribution of nuclear magnetism over the extended nuclear volume; the Bohr-Weisskopf effect $^8)$.

In the following, we will make an analysis of the hyperfine anomaly in gold, based on some simple assumptions, in an attempt to correlate magnetic moments, hyperfine anomalies and nuclear configurations of the gold isotopes.

The hyperfine anomaly ϵ is defined by

$$a = a_{\text{pt}} (1 + \epsilon) \quad (4)$$

where a is the measured hyperfine constant and a_{pt} is the value corresponding to a point nucleus. Generally, the uncertainty associated with a_{pt} is eliminated by studying the ratio of two isotopes

$$\frac{a_1}{a_2} = \frac{a_{1\text{pt}} (1 + \epsilon_1)}{a_{2\text{pt}} (1 + \epsilon_2)} \quad (5)$$

Assuming $a_{1\text{pt}}/a_{2\text{pt}} = g_1/g_2$ one obtains

$$\frac{(a/g_I)_1}{(a/g_I)_2} = \frac{1 + \epsilon_1}{1 + \epsilon_2} \quad (6)$$

The differential hyperfine anomaly $^1\Delta^2$ is defined by

$$^1\Delta^2 = \frac{1 + \epsilon_1}{1 + \epsilon_2} - 1 \quad (7)$$

which for small values of ϵ equals

$${}^1\Delta^2 = \epsilon_1 - \epsilon_2 \quad (8)$$

The hyperfine constants and magnetic moments measured in the gold isotopes ${}^{196,197,198,199}\text{Au}$ ^{9,10)} allow a determination of the differential hyperfine anomalies. In table 4 they are given relative ${}^{197}\text{Au}$. Also included in the table is the value for ${}^{187}\text{Au}$, although the 10% error in the magnetic moment is as large as the effects to be discussed below.

Moskowitz and Lombardi ¹¹⁾ have shown that the differential hyperfine anomalies in the ${}^3\text{P}_1$ atomic state of a series of mercury isotopes, including the nuclear shell model states $p_{1/2}$, $p_{3/2}$, $f_{5/2}$ and $i_{13/2}$ are well reproduced assuming the following simple relation between the magnetic moments and hyperfine anomalies.

$$\epsilon = \frac{\alpha}{\mu} \quad (9)$$

where

$$\alpha = \pm 1.0 \cdot 10^{-2} \text{ n.m. } (j = 1 \pm \frac{1}{2}) \quad (10)$$

The hyperfine anomaly due to the s-electron may be obtained by defining $\alpha_s = 1.13\alpha$ ¹¹⁾.

In a more detailed account, Fujita and Arima ¹²⁾ give the following expression for the mercury hyperfine anomalies

$$\epsilon = c_1 + \frac{\alpha}{\mu} \quad (11)$$

$$\alpha = \pm 1.2 \cdot 10^{-2} \text{ n.m. } (j = \pm \frac{1}{2}) \quad (12)$$

As a consequence of the different signs of the proton and neutron g_s -factors, the sign of α for proton states is opposite that of the corresponding neutron states.

Under the assumption (9), the value of α for the $I = 3/2$ nuclides ${}^{197,199}\text{Au}$ may be calculated using eq. (6) and the known values of dipole constants and magnetic moments. The result is

$$\alpha = 1.197(3) \cdot 10^{-2} \text{ n.m.} \quad (13)$$

If, instead, the assumption (11) is made, the value of α is almost unchanged provided the values of c_1 are small, $|c_1| < 0.02$. The absolute hyperfine anomalies, of course, strongly depend on the choice of c_1 ; those in ^{197}Au ranging between 6.0 and 10.4% for $-0.02 < c_1 < 0.02$. In the following discussion we will choose $c_1 = 0$, giving $\epsilon = 8.21\%$ for ^{197}Au and $\epsilon = 4.41\%$ for ^{199}Au . The experimental differential hyperfine anomaly is, by definition, reproduced.

A calculation of the quantity a_{pt}/g_I using eq. (4) gives the result $a_{\text{pt}}/g_I = 29005 \text{ MHz}$ in gold. We thus have for the $^2S_{1/2}$ ground state of gold

$$\frac{a}{g_I} = 29005 (1 + \epsilon) \quad (14)$$

Using this relation, the hyperfine anomalies of ^{187}Au and $^{196,198}\text{Au}$ may be calculated. The results, shown in table 4, will be compared below with predictions based on different configuration assignments. Combining eqs. (9,13,14) we get the following expression for the magnetic moments and hyperfine anomalies of shell model single-particle states in gold :

$$\left. \begin{aligned} \mu &= \frac{a I}{29005} \pm 0.012 \text{ n.m.} \\ \epsilon &= \mp \frac{1.2}{\mu} \% \end{aligned} \right\} j = 1 \pm \frac{1}{2} \quad (15)$$

We will now use these expressions to calculate the magnetic moments and the hyperfine anomalies of the " $d_{3/2}$ " gold isotopes $^{191,193,195}\text{Au}$ from the experimental 9) dipole constants. The results, given in table 5, are very close to those of ^{197}Au , indicating similar nuclear structure of the odd-A gold isotopes $^{191,193,195,197}\text{Au}$.

The hyperfine anomalies of 8-9% obtained for $^{191-197}\text{Au}$ are of the same order, although somewhat lower than the 13% calculated within the Bohr-Weisskopf theory including configuration mixing ¹³⁾ (cf. ref. ¹⁴⁾).

In the $I = \frac{1}{2}$ nuclide ^{187}Au we have the following experimental data $\mu_I = 0.72(7) \text{ n.m.}$, $^{197}\Delta^{187} = 1.5(9.9)\%$ and $\epsilon_{187} = 6.6(9.9)\%$ (cf. table 4). At first sight one would expect the ground state of ^{187}Au to be accounted for by a $s_{1/2}$ proton.

However, the predictions $\mu = 1.6$ n.m. ¹⁵⁾ and $\epsilon = -0.75\%$ of a $s_{1/2}$ shell model state are seriously in conflict with the experimental results. The large error of the hyperfine anomaly in ^{187}Au precludes a serious test of this quantity to be made. However, the magnetic moment of ^{187}Au clearly shows that the $I = \frac{1}{2}$ ground state is not due to a pure $s_{1/2}$ proton state.

On the other hand, the magnetic moment and hyperfine anomaly of ^{187}Au may be accounted for by a combination of the $d_{3/2}$ and $s_{1/2}$ proton states. A main contribution from $d_{3/2}$ will reproduce the large hyperfine anomaly, while a small contribution from $s_{1/2}$ will serve to reduce the magnetic moment towards the experimental value. This speculation is supported by the more rigorous calculations using the asymmetric rotor model, presented in the following chapter. There it is shown that the ground state of ^{187}Au indeed is mainly of " $d_{3/2}$ " character, although the nuclear spin being $I = \frac{1}{2}$.

It may be noted that a similar effect has been observed in the nuclide ^{193}Ir ¹⁶⁾. Here the differential hyperfine anomaly between the $I = \frac{3}{2}$ ground state and the $I = \frac{1}{2}$ excited state, due to the contact field, has been determined to be $^{3/2}_{\Delta}^{1/2} = 5.8(6)\%$.

In order to analyse the doubly-odd gold isotopes we assume the main components of the ground states of the $I = 1$ nuclides $^{188,190,192,194}\text{Au}$ and the $I = 2$ nuclides $^{196,198}\text{Au}$ to be given by certain shell model configurations. The magnetic moments are then calculated according to :

$$\mu = \frac{I}{2} \left[g_{\pi} + g_{\nu} + (g_{\pi} - g_{\nu}) \frac{j_{\pi}(j_{\pi} + 1) - j_{\nu}(j_{\nu} + 1)}{I(I + 1)} \right] \quad (16)$$

The hyperfine anomalies are composed of the proton and neutron anomalies weighted by the fractional contributions to the total magnetic moment.

$$\epsilon = \epsilon_{\pi} \beta_{\pi} + \epsilon_{\nu} \beta_{\nu} \quad (17)$$

The β -values may be derived to be :

$$\beta_{\pi} = \frac{g_{\pi}}{g_I} \frac{g_I - g_{\nu}}{g_{\pi} - g_{\nu}}, \quad \beta_{\nu} = \frac{g_{\nu}}{g_I} \frac{g_I - g_{\pi}}{g_{\nu} - g_{\pi}} \quad (18)$$

where $\beta_{\pi} + \beta_{\nu} = 1$.

Depending on the coupling between the proton and neutron angular momenta, we get for the hyperfine anomalies :

$$\varepsilon = \frac{1}{\mu} (\alpha_{\pi} + \alpha_{\nu}) \quad I = j_{\pi} + j_{\nu} \quad (19)$$

$$\varepsilon = \frac{1}{\mu} \frac{I}{I+1} \left(\frac{j_{\pi}+1}{j_{\pi}} \alpha_{\pi} - \alpha_{\nu} \right) \quad I = j_{\pi} - j_{\nu} \quad (20)$$

under the assumption $\varepsilon_{\pi\nu} = \alpha_{\pi\nu}/\mu_{\pi\nu}$.

The corresponding compact expressions for the magnetic moments are :

$$\mu = \mu_{\pi} + \mu_{\nu} \quad I = j_{\pi} + j_{\nu} \quad (21)$$

$$\mu = \frac{I}{I+1} \left(\frac{j_{\pi}+1}{j_{\pi}} \mu_{\pi} - \mu_{\nu} \right) \quad I = j_{\pi} - j_{\nu} \quad (22)$$

Furthermore we adopt :

$$\alpha_{\pi,\nu} = \pm 1.2\% \text{ n.m.} \begin{cases} j_{\pi} = \ell_{\pi} \mp \frac{1}{2} \\ j_{\nu} = \ell_{\nu} \pm \frac{1}{2} \end{cases} \quad (23)$$

It may be shown that for the intermediate spin values $|j_{\pi} - j_{\nu}| < I < j_{\pi} + j_{\nu}$ the hyperfine anomalies are given by $\frac{-2.4}{\mu} < \varepsilon < \frac{2.4}{\mu}$.

The single-particle states involved in the ground state configurations of the doubly-odd gold isotopes $^{188-196}\text{Au}$ are due to $s_{1/2}$ and $d_{3/2}$ protons and $p_{1/2}$ and $p_{3/2}$ neutrons. In the cases $^{196,198}\text{Au}$, the main configuration of the nuclear ground states is supposed to be $2^{-}(\pi d_{3/2} \nu p_{1/2})$. This configuration explains the nuclear spin $I = 2$ and gives the magnetic moment $\mu = 0.65 \text{ n.m.}$ if the g -factors of the neighbouring odd nuclei are used in eq. (16) or (21). The magnetic moment is reasonably close to the experimental values $0.5914(14) \text{ n.m.}$ and $0.5934(4) \text{ n.m.}$, respectively. According to eq. (19), the hyperfine anomaly equals to zero for the configuration $2^{-}(\pi d_{3/2} \nu p_{1/2})$. The differential hyperfine anomaly thus obtained $^{197}\Delta^{196,198} = 8.2\%$ is in close agreement with the experimental values $8.69(26)\%$ and $8.53(8)\%$, respectively, giving support to the simplified assumptions made in this analysis.

An analysis of possible configurations for the spin $I = 1$ ground states of $^{188,190,192,194}\text{Au}$ suggest either $1^{-}(\pi d_{3/2} \nu p_{1/2})$ or $1^{-}(\pi d_{3/2} \nu p_{3/2})$. The magnetic moments of these configurations, calculated from eq. (16) with the following g -factors; $g_{\pi}(d_{3/2}) = 0.10$, $g_{\nu}(p_{1/2}) = 1.10$ and $g_{\nu}(p_{3/2}) = -0.40$, become

$\mu = -0.15$ n.m. in both cases. Other configurations give magnetic moments considerably larger in magnitude.

The magnetic moments of the gold isotopes $^{188,190,192,194}\text{Au}$ may thus be calculated from the measured dipole constants using eq. (14), with the hyperfine anomaly $\epsilon = 1.6/\mu\%$ for the configuration $1^-(\pi d_{3/2} \nu p_{1/2})$ and $\epsilon = 0.8/\mu\%$ for $1^-(\pi d_{3/2} \nu p_{3/2})$. The hyperfine anomalies has the effect of reducing the magnetic moments by 0.016 n.m. and 0.008 n.m., respectively, in relation to those calculated from $a/g_I = 29005$ MHz.

However, because of the uncertainty with regard to both configuration assignment and magnitude of the hyperfine anomaly, we prefer to give as final values of the magnetic moments of $^{188,190,192,194}\text{Au}$ those calculated under the assumption of vanishing hyperfine anomaly, i.e. $a/g_I = 29005$ MHz, with errors including the "worst cases" $\epsilon = \pm 2.4/\mu\%$, i.e. ± 0.024 n.m. in the magnetic moments. These values are given in column 4 of table 5.

4. DISCUSSION

The gold isotopes, having 79 protons, are located in the transition region between the rare-earths with strongly deformed nuclear shapes and the spherical $^{208}_{82}\text{Pb}$. Due to the large span of gold isotopes, a study of the variation in deformation as a function of mass number is of particular interest. Also, different deformations may be found within the same nucleus, depending on the nuclear state populated.

The odd-proton states identified in the gold isotopes originate from the shell model states $d_{5/2}$, $h_{11/2}$, $d_{3/2}$ and $s_{1/2}$ below the $Z = 82$ shell closure and $h_{9/2}$, $f_{7/2}$ and $i_{13/2}$ above (cf. fig. 5).

The main source of information on the nuclear deformation of different states in the gold isotopes is provided by the band structures, revealed by in-beam γ -ray spectroscopy and radioactive decay works. Within the particle-rotor model including

axial asymmetry ¹⁷⁻¹⁹⁾, the decoupled band structure built on the $^{11/2^-}$ states in $^{185-195}\text{Au}$ ²⁰⁻²⁸⁾ may be interpreted as a $h_{11/2}$ proton hole coupled to the oblate-type cores with small quadrupole deformation of the corresponding even-even mercury isotopes. The stable structure of the mercury ground state bands is reflected in the $h_{11/2}$ bands, showing very small variations in band head energies and level spacings over the whole isotopic range $^{185-195}\text{Au}$. Similarly, the rotational structure of the $^{9/2^-}$ bands in $^{191-199}\text{Tl}$ ²⁹⁾ and $^{13/2^+}$ bands in $^{187-199}\text{Hg}$ ^{45,46)} may be explained by a $h_{9/2}$ proton and $i_{13/2}$ neutron, respectively, coupled to the oblate-type even-even mercury ground state cores.

The level structure built on the $^{9/2^-}$ states in $^{185-195}\text{Au}$ ^{21-23,25-27)} and on the $^{11/2^-}$ states in $^{185-191}\text{Ir}$ ³⁰⁻³²⁾ indicates that with decreasing mass number there is a continuous increase in quadrupole deformation and decrease in the asymmetry parameter, i.e. a transition from oblate-type nuclear shapes to prolate-type shapes. This behaviour reflects the association with the cores of the corresponding even-even platinum isotopes.

In the odd-A gold isotopes, the $^{9/2^-}$ band heads decrease rapidly in energy with decreasing mass number; from 1068 keV in ^{195}Au to probably a few keV in ^{185}Au . The ground state of the latter isotope, with the nuclear spin $I = 5/2$ measured in the present work, most probably belongs to the $^{9/2^-}$ band structure, giving evidence for a strong deformation of ^{185}Au .

Recently, a decoupled band built on the $^{13/2^+}$ state at 851 keV in ^{185}Au was identified ^{25,27)} and interpreted as arising from the coupling of an $i_{13/2}$ proton to the prolate-type core of ^{184}Pt .

The brief description above of the band structures of high spin proton states in gold in terms of a quasiparticle coupled to a triaxial rotor is the one most commonly found in the literature. However, it may be noted that the experimental data may be explained as well by the cluster-vibration coupling model ³³⁾ and the pseudo SU(3) coupling scheme ³⁴⁾. Furthermore, the level structure built on the low-spin positive parity states $^{1/2^+}$ and $^{3/2^+}$ in gold is reproduced with similar quality within a particle-asymmetric rotor ³⁵⁾ and a cluster-vibration ³³⁾ description.

Below we will discuss some aspects of the nuclear structure of the gold isotopes mainly in the light of model calculations using a particle-asymmetric rotor formalism ³⁶⁾. Previously, this model has been applied to the positive parity states in ¹⁹³⁻¹⁹⁹Au ³⁵⁾ and to the $h_{11/2}$ level systems in ^{189,193,195}Au ¹⁹⁾.

The calculations were performed in three steps. First the modified oscillator model ^{37,38)} was employed to calculate the single-particle wave functions and energies. In a second step, the odd proton, allowed to occupy a number of single-particle states close to the Fermi surface, was coupled to an asymmetric rotor to give the total nuclear wave functions and the corresponding level energies. These wave functions were then used, in the third step, to calculate the electromagnetic properties of the coupled system.

Considering first the structure of the $^{11/2^-}$ bands in the gold isotopes ¹⁸⁵Au and ¹⁸⁷Au, we may simply refer to the calculations reported by Vieu et al. ¹⁹⁾ on the heavier isotopes ¹⁸⁹Au, ¹⁹³Au and ¹⁹⁵Au. This is due to the fact that the $^{11/2^-}$ band structure remains practically unchanged in the range ¹⁸⁵⁻¹⁹⁵Au. By including the four upper proton orbitals in the $h_{11/2}$ shell (the levels 16-19 in fig. 5) at the deformation $\epsilon = 0.15$ and $\gamma = 35^\circ$, a satisfactory description of the $^{11/2^-}$ level structure as well as the electromagnetic properties is obtained.

The $h_{9/2}$ bands in the gold isotopes ¹⁸⁵⁻¹⁹⁵Au show a continuous variation from strongly coupled to decoupled structure with decreasing mass number (cf. fig. 6). Within the particle-asymmetric rotor model, this behaviour may be understood as a change in nuclear shape from oblate-type ($\gamma > 30^\circ$) to prolate-type ($\gamma < 30^\circ$).

In our calculations we included, in addition to all levels from the $h_{9/2}$ shell, also the two lowest ones from $f_{7/2}$. The coupling between the $h_{9/2}$ and $h_{11/2}$ shells was verified to be negligibly small, thus justifying the assumption that these systems can be treated independently of each other. Indeed, in order to account for the " $h_{9/2}$ " levels experimentally observed it was found sufficient to include only the two lowest levels from $h_{9/2}$ and the lowest one from $f_{7/2}$ (the levels 20, 21 and 22 in fig. 5). Note, however, that we do not refer to the pure j-shells but to

the perturbed ones as calculated from the modified oscillator potential at the deformation in question. For example, at $\gamma = 20^\circ$, the two negative parity levels denoted 21 and 22 in fig. 5 are strongly mixed with about equal amplitudes of $h_{9/2}$ and $f_{7/2}$.

The energy spacings in the favoured band $9/2^-$, $13/2^-$, $17/2^-$, ... are mainly determined by the corresponding core spectrum, or alternatively by the nuclear shape given by the deformation parameters ϵ and γ . Other levels, like $5/2^-$, $7/2^-$, $11/2^-$, $15/2^-$, ... are, on the other hand, more sensitive to the single-particle structure around the Fermi surface.

The ground state spin $I = 5/2$, measured in ^{185}Au , gives evidence for a large nuclear deformation. This is due to the fact that for small deformations, the strong Coriolis matrix elements within the $h_{9/2}$ shell will dominate and place the $9/2^-$ state lowest in energy. Also the $7/2^-$ state, located at 100 keV, adds important information on the single-particle structure of ^{185}Au . To reproduce the low excitation energy, we have found that the Fermi level must be located well above the lowest $h_{9/2}$ orbital (20 in fig. 5). This fact also requires a rather large deformation. Somewhat similar results were obtained in ref. ²⁵⁾, and if the Fermi level is placed in a way consistent with the 79 protons present, a deformation of about $\epsilon = 0.25$ is needed. In the calculations presented below, we have used this ϵ -value together with an asymmetry parameter $\gamma = 20^\circ$. The rather large γ -value is mainly needed to reproduce the higher spin states. If a variable moment of inertia is used, similar results are obtained for $\gamma = 0$ (cf. ref. ²⁵⁾).

The theoretical level structure of ^{185}Au calculated with the "standard $A = 187$ parameters" ³⁷⁾ is shown to the left in fig. 6. Except for the $7/2^-$ level, the agreement between theory and experiment is quite good. The disagreement for the $7/2^-$ state may be understood from the fact that the Fermi level is close to the lowest $h_{9/2}$ orbital. It was, however, found in ref. ³⁹⁾ that the energies for nuclei around ^{208}Pb are better reproduced if a smaller μ -value, $\mu(N \geq 6) = 0.73 \mu_{\text{standard}}$, is used for the higher shells. This will have no influence on the orbitals included in the rotor+particle calculations for the $h_{9/2}$ system but, by raising the $i_{13/2}$

shell in energy, it will decrease the level density around the Fermi surface, and thus lift the Fermi level by about 200 keV. With this improved single-particle spectrum the agreement between experiment and theory becomes better, as shown in fig. 6. However, a further raise of the Fermi energy of about 300 keV is required to reproduce the experimental energy of the $7/2^-$ state (cf. fig. 6). It might also be important to mention that a second $7/2^-$ is calculated to be at about 400 keV, and that both $7/2^-$ states are mixtures of the orbitals 21 and 22 of fig. 5. In this case it is difficult to isolate the contributions from the different j-shells, while at $\epsilon = 0.25$ and $\gamma = 0^\circ$, where similar results are obtained, the lowest $7/2^-$ level comes mainly from $f_{7/2}$ and the higher one from $h_{9/2}$.

In the theoretical spectra of ^{185}Au , shown in fig. 6, one observes low-lying $1/2^-$ and $3/2^-$ states. These states have up to now not been observed experimentally, and would certainly be of great importance as a test of the calculations.

The steep increase in energy of the levels $5/2^-$ and $7/2^-$ with increasing mass number of the gold isotopes (cf. fig. 6) gives evidence for a reduced quadrupole deformation and increased asymmetry parameter. The sequence of $11/2^-$ states belonging to the $h_{9/2}$ system in $^{185-195}\text{Au}$ is relatively constant in energy; increasing from about 300 keV in ^{185}Au , reaching a maximum of 400 keV in ^{189}Au , to decrease again to 300 keV in ^{195}Au . The energies are given relative to the lowest level in the $h_{9/2}$ system. This behaviour may be understood as an interplay between decreasing quadrupole deformation, which tends to raise the $11/2^-$ level, and increasing asymmetry, which acts in the opposite direction. The deformation parameters obtained for the $h_{9/2}$ system in the nucleus ^{195}Au are $\epsilon = 0.15$ and $\gamma = 35^\circ$. A pattern similar to that of the $11/2^-$ states is observed also for the corresponding $15/2^-$ states in $^{185-191}\text{Au}$.

In conclusion, the results for the nucleus ^{185}Au give strong evidence that, within the $h_{9/2}$ system of levels, the deformation is considerably larger than for the heavier gold isotopes $^{191-195}\text{Au}$. This fact accounts to a large extent for the low energy of the $h_{9/2}$ system (cf. ref. ⁴¹); the $5/2^-$ level being the ground state in ^{185}Au . However, the low energy may be partly caused by a reduced energy of the entire $h_{9/2}$ shell as discussed by Goodman ⁴²). This lowering of the $h_{9/2}$ shell

is supported by the fact that we had to arbitrarily raise the Fermi energy by 300 keV to get a good agreement between theory and experiment. As mentioned above, for the $h_{11/2}$ system, the band structure is about the same independent of neutron number, and the deformation is expected to be rather constant around $\epsilon = 0.15$ and $\gamma = 35^\circ$. It is thus evident that coexistent shapes are present in ^{185}Au in a similar way as has recently been clearly shown for the isobar $^{185}\text{Hg}^{43)}$ (see also ref. $^{44)}$).

In ^{185}Au , a decoupled $^{13/2}^+$ band, originating from the $i_{13/2}$ shell, has been observed with a band head energy of 851 keV $^{25,27)}$. In our calculations, assuming the same deformation parameters as for the $h_{9/2}$ system and with the standard $A = 187$ parameters we calculate the band head to be at about 150 keV. The reduction of μ -value for the higher shells, mentioned above, will have the effect of lifting the $i_{13/2}$ shell, raising the $^{13/2}^+$ state in ^{185}Au to about 450 keV. A realistic hexadecapole deformation of $\epsilon_4 = 0.04$ $^{37)}$ will further increase the $^{13/2}^+$ band head energy by about 200 keV, while it will have a minor influence on the level structure within the " $h_{9/2}$ " system.

The positive parity levels in $^{193-199}\text{Au}$ as well as in $^{187-193}\text{Ir}$ have been extensively discussed within the present model $^{35,40)}$. Although being remarkably stable, the level structure built on the low-spin positive parity states exhibit some changes towards the lighter masses in gold. A slight compression of the spectra is observed, and in $^{187,189}\text{Au}$ the nuclear ground state spins are $I = 1/2^{1)}$ as compared to $I = 3/2$ of the heavier odd-A gold isotopes.

Vieu et al. $^{35)}$ obtained a best fit to the level structure and electromagnetic properties of $^{193-199}\text{Au}$ using the deformation parameters $\epsilon = 0.17$ and $\gamma = 27^\circ$. In order to reproduce the level structure in ^{187}Au , particularly the $I = 1/2$ ground state, slightly modified values have to be used; $\epsilon \approx 0.18$ and $\gamma \approx 35^\circ$.

In fig. 7a we have collected the known magnetic moments of $^{1/2}^+$ and $^{3/2}^+$ states in iridium, gold and thallium isotopes. It is immediately seen that the magnetic moments of the $^{1/2}^+$ states in ^{187}Au , $^{191,193}\text{Ir}$ and ^{197}Au have a character different from those in the thallium isotopes $^{195-205}\text{Tl}$. The latter have been

shown to be due mainly to a $s_{1/2}$ proton state ^{15).}

We have tried to reproduce the magnetic moments of the $1/2^+$ and $3/2^+$ states in gold within the particle-asymmetric rotor model. The magnetic moment of the $I = 1/2$ ground state of ^{187}Au , measured in this work, and that of the $I = 3/2$ first excited state, obtained from systematics (cf. fig. 7a), are given in figs. 8a and 8b, together with the results from the calculations. The theoretical moments of fig. 8a are given as a function of the asymmetry parameter γ , and for three values of the quadrupole deformation; $\epsilon = 0.16, 0.18$ and 0.20 , and for $g_s = 0.8 g_s^{\text{free}}$. A good agreement is obtained with the deformation parameters $\epsilon = 0.18$ and $\gamma = 35^\circ$. The rapid decrease of the magnetic moment of the $I = 1/2$ state with increasing asymmetry makes possible a rather accurate determination of the γ -parameter. The decrease is associated with the reduced influence of the level 23 originating from the $s_{1/2}$ shell model state (cf. fig. 5).

In fig. 8b, the influence of g_s -factors ranging from 0.6 to $1.0 g_s^{\text{free}}$ is analysed for a constant value of the quadrupole deformation; $\epsilon = 0.18$. Again, a rather narrow window may be set for the γ -parameter.

At the deformation $\epsilon = 0.18$ and $\gamma = 35^\circ$, the dominant contribution to the wave functions of both the $1/2^+$ and $3/2^+$ states is coming from level 21 with a squared amplitude of about 85%. This level, in its turn, is built up of about 50% $d_{3/2} 3/2$ and 25% $s_{1/2} 1/2$. The small hyperfine anomaly determined in this work between the $I = 1/2$ and $I = 3/2$ ground states in ^{187}Au and ^{197}Au , respectively, $^{197}\Delta^{187} = 1.5\%$, may consequently be attributed to the similarity of the nuclear wave functions. The slightly different deformation parameters obtained for the $I = 3/2$ ground state in ^{197}Au by Vieu et al.³⁵⁾ do not affect the conclusion above.

The magnetic moment of the $1/2^+$ excited state in ^{197}Au , being smaller than that in ^{187}Au , requires within the present model either larger ϵ -deformation, larger γ -asymmetry or smaller g_s -factor than in ^{187}Au (cf. figs. 7a, 8a and 8b).

The magnetic moments of the doubly-odd gold isotopes $^{188-198}\text{Au}$ are given in fig. 7b together with those of the odd-neutron states " $p_{1/2}$ " and " $p_{3/2}$ " in the

neighbouring mercury isotopes. As discussed in section 3, both the magnetic moments and the hyperfine anomalies in $^{196,198}\text{Au}$ may be explained by the configuration $2^-(\pi d_{3/2} \nu p_{1/2})$. This is consistent inasmuch the neighbouring odd-proton moments are of mainly $d_{3/2}$ character. The nuclides $^{188,190,192,194}\text{Au}$ having nuclear spin $I = 1$ and very small magnetic moments are more difficult to understand. Since the main contribution to the $I = 1/2$ and $I = 3/2$ odd-proton ground states in $^{187,189}\text{Au}$ and $^{191-195}\text{Au}$, respectively, is due to $d_{3/2}$, one may assume that this is the case also in the neighbouring doubly-odd isotopes. Combined with " $p_{1/2}$ " or " $p_{3/2}$ " neutrons, we get indeed small magnetic moments. However, a more detailed account of the configuration composition is presently not possible.

5. CONCLUSION

The main results from the present experimental and theoretical study of the light gold isotopes are that :

- i) the nuclear ground state spin $I = 5/2$ measured in ^{185}Au together with the corresponding band structure gives evidence for a strong prolate-like nuclear deformation; $\epsilon \approx 0.25$ and $\gamma < 20^\circ$ in the $h_{9/2}/f_{7/2}$ system of levels. The deformation of the $h_{11/2}$ system in ^{185}Au is shown to be considerably smaller.
- ii) the magnetic moment measured in ^{187}Au indicates a ground state of mainly $d_{3/2}$ character although the nuclear spin is $I = 1/2$. The deformation parameters derived are $\epsilon \approx 0.18$ and $\gamma \approx 35^\circ$.
- iii) the proton contribution to the ground state of the doubly-odd isotope ^{188}Au is mainly $d_{3/2}$ as evidenced by the small value of the experimental magnetic moment.

In conclusion, it is shown that a substantial decrease in the quadrupole deformation ϵ and increase in the asymmetry parameter γ occur between the ground states of the nuclides ^{185}Au and ^{187}Au . This behaviour is readily interpreted as a consequence of the different nuclear configurations involved.

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Table 1

Time sequence followed in the experiments on ^{185}Au , ^{187}Au and ^{188}Au

Isotope	Collection on cold foil	Delay	Evaporation of mercury	Evaporation of gold
^{185}Au	10 min	1.5 min	1 min	3 min
$^{187}, ^{188}\text{Au}$	12 min	2 min	2 min	4 min

Table 2

Experimentally observed transitions in ^{187}Au and ^{188}Au

Isotope	Transition (F, m_F) $\rightarrow$ ($F', m_{F'}$)	Frequency of calibration transition in ^{39}K (MHz)	$\mu_B B/h$ (MHz)	Resonance frequency (MHz)
^{187}Au	(1,0) $\rightarrow$ (1,-1)	231.239(10)	230.853(7)	232.353(12)
	(1,1) $\rightarrow$ (1,-1)	231.175(10)	230.811(7)	231.104(5)
^{188}Au	$(\frac{3}{2}, \frac{1}{2}) \leftrightarrow (\frac{3}{2}, -\frac{3}{2})$	20.115(7)	35.717(11)	24.236(7)
		39.303(7)	63.566(9)	43.668(9)

Table 3

Hyperfine structure and nuclear moment data in ^{187}Au and ^{188}Au

Isotope	Nuclear spin $I^1)$	Hfs separation $\Delta\nu$ MHz	Dipole constant a MHz	Magnetic moment μ_I n.m. (diam. corr.)	
				a)	b)
^{187}Au	$1/2$	44350(600)	44350(600)	0.706(10)	0.72(7)
^{188}Au	1	$\pm 2992(30)$	$\pm 1995(19)$	$\pm 0.0636(6)$	$\pm 0.07(3)$

a) Magnetic moments derived from eq. (3)

b) ^{187}Au ; directly measured. ^{188}Au ; cf. text.

Table 4

Experimental data on dipole constants, magnetic moments and differential hyperfine anomalies *this work*,^{9,10}, together with hyperfine anomalies derived from eq.(14).

Isotope	Nuclear spin I	Dipole constant a MHz	Magnetic moment μ_I n.m.	a/g_{Icorr}	Diff. hf anomaly $^{197}\Delta A\%$	Hf anomaly $\epsilon\%$ (eq.(14))
187	$1/2$	44350(600)	0.72(7)	30915(3000)	1.5(9.9)	6.6
197	$3/2$	3049.660092(7)	0.145746(9)	31387(2)	0	8.21
199	$3/2$	5481.36135(15)	0.2715(7)	30284(84)	3.64(29)	4.41
196	2	8538.90088(60)	0.5914(14)	28877(68)	8.69(26)	-0.44
198	2	8580.28668(16)	0.5934(4)	28919(19)	8.53(8)	-0.30

Table 5

Magnetic moments derived from experimental dipole constants ^{9, this work}.

The hyperfine anomalies of the odd-A nuclides are calculated from eq.(15)

Isotope	Nuclear spin I	Dipole constants a MHz	$\epsilon\%$ (eq.(15))	Magnetic moment μ_I n.m. (corr)
191	$3/2$	2885(3)	8.74	0.137(1)
193	$3/2$	2941(5)	8.55	0.140(1)
195	$3/2$	3110(19)	8.03	0.149(1)
188	1	$\pm 1995(19)$	cf. text	$\pm 0.069(24)$
190	1	$\pm 2003(5)$		$\pm 0.069(24)$
192	1	$\pm 249.53(7)$		$\pm 0.009(24)$
194	1	$\pm 2326.577(21)$		$\pm 0.080(24)$

FIGURE CAPTIONS

- Fig. 1 : Decay of a resonance signal corresponding to the nuclear spin $I = 5/2$ in ^{185}Au . The signal was recorded in an external magnetic field of $\mu_B B/h = 2.941$ MHz.
- Fig. 2 : Resonance curves corresponding to the double-quantum $(1,1) \rightarrow (1,-1)$ and single-quantum $(1,0) \rightarrow (1,-1)$ transitions in the spin $I = 1/2$ nuclide ^{187}Au . The signals were recorded in an external magnetic field of $\mu_B B/h = 231$ MHz.
- Fig. 3 : Results for the dipole constant $\underline{a}$ and magnetic moment μ of ^{187}Au from a least-squares fit of the experimental data to the Breit-Rabi formula. The ellips corresponds to one standard deviation.
- Fig. 4 : Resonance curves of the single-quantum transition $(3/2, -1/2) \leftrightarrow (3/2, -3/2)$ in ^{188}Au , observed in the external magnetic fields $\mu_B B/h = 35.717(11)$ MHz and $63.566(9)$ MHz.
- Fig. 5 : Single-particle orbitals for protons calculated within the modified oscillator model. The parameters correspond to "A=187", $\kappa = 0.062$, $\mu = 0.614$ but, to reproduce the experimental fact that the $i_{13/2}$ shell is situated above the $f_{7/2}$ shell, the μ -value has been reduced by a factor 0.73 for the $N = 6$ shell. The left part of the figure corresponds to prolate shapes, the middle part to triaxial shapes at constant $\epsilon = 0.2$ and the right part to oblate shapes. For axial shapes, the main component at $\epsilon = 0.2$ in the asymptotic basis $|Nn_z \Lambda \Omega\rangle$ are given. If the component is different from the ultimate asymptotic state at large deformation, the latter is given within parenthesis. For triaxial shapes, the positive and negative parity orbitals, respectively, are numbered starting from the bottom of the potential well. Finally, the calculated Fermi level for 79 protons is denoted by a wavy line.
- Fig. 6 : The experimental band structure for the " $h_{9/2}$ system" in $^{185-195}\text{Au}$ together with calculated spectra for ^{185}Au . In ^{195}Au , the $9/2^-$ band head is situated 1068 keV above the ground state but with decreasing mass number, the excitation energy is continuously decreasing and in ^{185}Au , the $5/2^-$ state is the

ground state. The theoretical calculations are done for $\epsilon = 0.25$, $\gamma = 20^\circ$ and with an equivalent 2^+ energy of 120 keV ¹⁹⁾. This E_{2^+} corresponds to a moment of inertia parameter B, roughly in agreement with Grodzins relation ¹⁷⁾. The three cases can be distinguished by different positions of the Fermi surface, 6.09, 6.12 and 6.17 $\hbar\omega_0$, given above each band. In the two first cases this energy has been fixed from the BCS solution with 79 protons and for "A-187 parameters" with and without a reduction of for the higher shells, cf. fig. 5. The third calculation shows that if the Fermi energy is raised another 300 keV, the experimental $7/2^-$ state is much better reproduced. For ^{185}Au , $\hbar\omega_0 = 6.85$ MeV and the three orbitals 20, 21 and 22 of fig. 5 are, at the adopted deformation $\epsilon = 0.25$ and $\gamma = 20^\circ$, situated at 6.09, 6.19 and 6.31 $\hbar\omega_0$ respectively.

Fig. 7a : Experimental magnetic moments of low-spin odd-proton states in iridium, gold and thallium nuclides (¹⁰⁾ and this work). Note the large difference in magnetic moments between the spin $I = 1/2$ thallium isotopes and the spin $I = 1/2$ sequence ^{187}Au , $^{191,193}\text{Ir}$ and ^{197}Au .

Fig. 7b : Experimental magnetic moments of low-spin odd-neutron states in mercury and of low-spin states in doubly-odd gold isotopes (¹⁰⁾ and this work). Because of the small g-factors of the nuclides $^{188-194}\text{Au}$, the signs of the magnetic moments have not been determined.

Fig. 8 : Theoretical magnetic moments of ^{187}Au as a function of asymmetry parameter γ , compared with the experimental value of the spin $I = 1/2$ ground state and the value of the spin $I = 3/2$ excited state obtained from systematics (cf. fig. 7a). Here the "A=187" potential parameters have been used. By using a reduced μ -value for the N=6 shell, a slight reduction of the theoretical magnetic moments is obtained. The left part of the figure (a) shows the variation in moments for different deformation parameters and a fixed g_s -value, $g_s = 0.8 g_s^{\text{free}}$, while in the right part of the figure (b) the g_s -values are varied with a constant deformation parameter. A good agreement is obtained for the parameter set $\epsilon = 0.18$, $\gamma = 35^\circ$ and $g_s = 0.8 g_s^{\text{free}}$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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Fig. 7a

Fig. 7b

Fig. 8a

Fig. 8b

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