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Abstract

We try to determine to what extent an axial prolate rotor + 1 or 2 quasiparticle model succeeds in describing the transitional odd and odd-odd Ir and Au nuclei. The relative location of the excited states as well as the properties of the ground and isomeric states, particularly the magnetic and spectoscopic quadrupole moments, are compared to the predictions of the model.

1 Introduction

The structure of the low-lying states in Ir and Au is very discussed: these nuclei belong to a region of shape instability and various theoretical approaches setting or not axial symmetry have been used with success to interpret specific states [1-20]. Recently, both isotope series have been studied by laser spectroscopy [21-24] providing the nuclear moments of the ground and isomeric states and the change in the mean square charge radius ($\delta <r_c^2>$). The magnetic moment (μ) gives information on the structure of the state whereas, assuming axial symmetry, the deformation of the nucleus can be extracted from $\delta <r_c^2>$ and Q_S. On the other hand, electron spectroscopy measurements recently performed in the odd-odd ^{182}Ir and ^{184}Au nuclei [25, 26] have brought decisive information to define the structure of the low-energy levels, especially concerning the neutron and proton configurations involved in the description of these states.

The aim of this paper is to determine to what extent an axial prolate rotor + 1 or 2 quasiparticle approach succeeds in describing these transitional odd and odd-odd nuclei, and particularly the recent data obtained by laser and nuclear spectroscopy. The properties of the low-lying states observed in Ir and Au are presented and similarities between these two isotope series are underlined. The main characteristics of the model are recalled and the predictions of the model are compared with the experimental results analysing *(i)* the relative location of the excited states in the odd nuclei and *(ii)* the properties of the ground and isomeric states (namely the behaviour of the associated rotational bands, the values of the magnetic and spectroscopic quadrupole moments) taking as an example ^{191}Ir for the heavier odd nuclei, ^{185}Ir for the lighter odd ones, ^{184}Ir and ^{184}Au for the odd-odd isotopes.

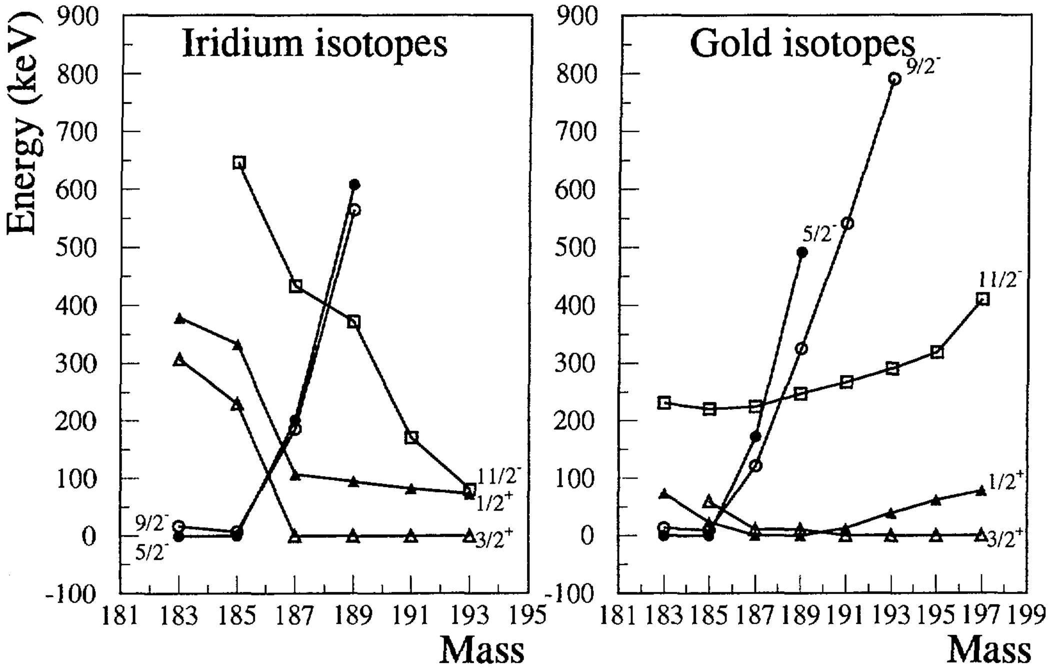

Figure 1: Low-lying states observed in Ir and Au odd nuclei.

2 Experimental properties of Ir and Au nuclei

Figure 1 shows the levels located at low energy in the odd Ir and Au nuclei and interpreted as bandheads. Three groups of levels can be defined in both isotopes series. The first one is formed by the $\frac{3}{2}$ and $\frac{1}{2}$ positive parity states which are very close in energy. The $\frac{3}{2}^+$ state arising from the $2d_{\frac{3}{2}}$ subshell is the ground state down to A = 187 in Ir and down to A = 191 in Au. The $\frac{1}{2}^+$ state arising from the $3s_{\frac{1}{2}}$ subshell becomes the ground state in ^{187,189}Au. The second group of states is formed by the $\frac{11}{2}^-$ levels originating from the $1h_{\frac{11}{2}}$ subshell and the third group by the two negative parity states which are the intruder states arising from the $1h_{\frac{9}{2}}$ subshell; the $\frac{5}{2}^-$ state becomes the ground state in the A $\leq$ 185 Ir and Au nuclei. Figure 2 shows $\delta <r_c^2>$, μ and Q_S obtained for the Ir and Au ground and isomeric states. Great similarities between the two isotope series can be noted. In both cases, there is an increase in $\delta <r_c^2>$ at A = 186, and when the spin of the state has the same value in Ir and Au, the magnetic moment as well as the spectroscopic quadrupole moment have similar values. This is particularly true for the $\frac{3}{2}^+$ state.

3 The rotor + 1 or 2 quasiparticle models

These models have been developed by M. Meyer *et al.* [27] and L. Bennour *et al.* [28]. In a first step, Hartree-Fock + BCS calculations are performed for the even-even cores using the Skyrme III force and the constant G approximation for the pairing correlations. Axial symmetry is assumed. Here the core is constrained to the deformation found experimentally from the $\delta <r_c^2>$ measurements in Ir and Au. This first step provides us with the single-particle wave functions.

In a second step, one or two quasiparticle states are coupled to an axial rotor with the

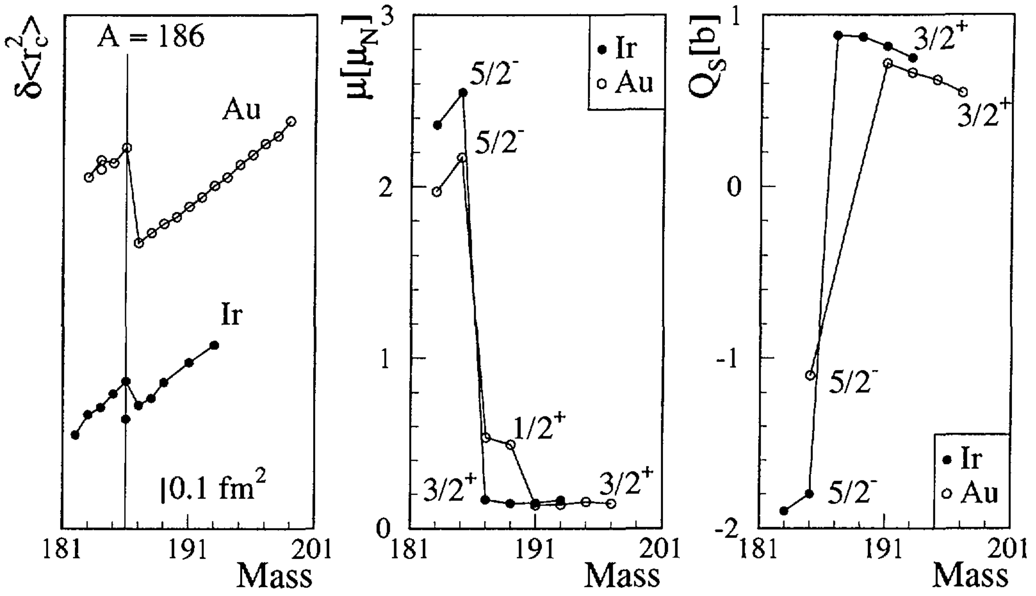

Figure 2: $\delta < r_c^2 >$, μ and Q_S measured in Ir and Au.

variable moment of inertia determined from the experimental energy sequence observed in the even-even core. In this approach, the Coriolis term is calculated exactly. The particle number is not conserved, which means that two cores can be used to describe an odd nucleus and four cores to describe an odd-odd nucleus. However using the occupation probabilities which are directly related to the location of a state above or below the Fermi level, we can determine the most suitable core to represent a given configuration. In the rotor + 2 quasiparticle approach, the proton-neutron residual interaction (V_{pn}) is calculated using the Skyrme III force, i.e. the same force as that used to determine the neutron and proton quasiparticle wave functions.

To describe the gold and iridium nuclei, such calculations have been performed using Hg, Pt and Os cores.

For the odd nuclei, the magnetic and spectroscopic quadrupole moments have been calculated using the procedure described in ref. [29]. For the odd-odd nuclei, the magnetic moments have been evaluated following the method given in ref. [30]:

$$\mu = \frac{K}{I+1}\left[g_{K_p}K_p + g_{K_n}K_n + g_R\frac{I^2+I-K^2}{K}\right],$$

with the g_{K_p} and g_{K_n} factors extracted from the theoretical magnetic moments obtained in the rotor + 1 quasiparticle approach for the given neutron and proton configurations.

4 Comparing theory with experiment

4.1 Systematics of the bandheads

Figure 3 shows the theoretical bandheads calculated with the rotor + 1 qp model using the Os and Pt cores. The theoretical states are labelled by their main component on the quasiparticle state basis using the asymptotic notation. The main differences between the results obtained with the Os and Pt cores are: *i)* the $\frac{5}{2}^+[402]$ state calculated above 500 keV with the Pt cores appears to be the ground state with the $^{182-190}$Os cores, and

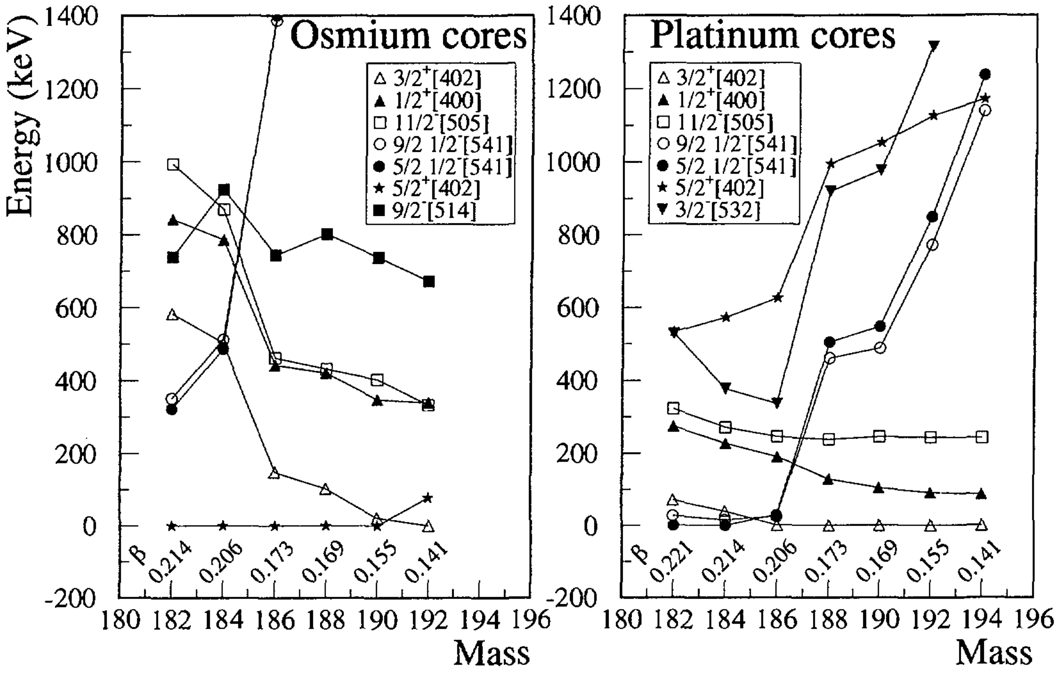

Figure 3: Theoretical states calculated with the Os and Pt cores. β indicates the deformation obtained from the δ $<r_c^2>$ measurements in Ir.

ii) the $\frac{9}{2}^-[514]$ state located above 1.4 MeV with the Pt cores is predicted to lie below 1 MeV with the Os cores. However, for both states, the occupation probabilities indicate full states, which means that, for these configurations, the Os cores describe the Re odd nuclei rather than the Ir ones. The $\frac{5}{2}^+[402]$ state is actually the ground state in the odd $^{179-189}$Re nuclei, and the $\frac{9}{2}^-[514]$ state is found at low energy ($E \leq 263$ keV) in $^{181-189}$Re [31].

The other theoretical states can be classified into two groups: the first one is formed by the $\frac{3}{2}^+[402]$, $\frac{1}{2}^+[400]$ and $\frac{11}{2}^-[505]$ levels with an energy decreasing when the mass of the core increases, and the second group by the $\frac{5}{2}^-\frac{1}{2}[541]$ and $\frac{9}{2}^-\frac{1}{2}[541]$ states originating from the $h_{\frac{9}{2}}$ subshell with an energy increasing with the mass of the core. The result is that the ground state is expected to be the $\frac{3}{2}^+[402]$ state in the heavier odd Ir and Au nuclei, and the $\frac{5}{2}^-\frac{1}{2}[541]$ state in the lighter odd ones. This is in agreement with the experimental data (see figure 1).

In the following the $\frac{5}{2}^-\frac{1}{2}[541]$ and $\frac{9}{2}^-\frac{1}{2}[541]$ states will be labelled as originating from $h_{\frac{9}{2}}$. Indeed, the analysis of the wave functions describing these states shows a K mixing due to the Coriolis interaction, and this K mixing becomes stronger as the deformation increases. This point is illustrated by the wave function obtained for the $\frac{5}{2}^-$ state using the ^{186}Pt core constrained to various deformation values:

$$\Psi(\tfrac{5}{2}^-, \beta = 0.155) = 80.5\% \ \tfrac{5}{2}^-\tfrac{1}{2}[541] + 18.8\% \ \tfrac{5}{2}^-\tfrac{3}{2}[532] + \ldots$$
$$\Psi(\tfrac{5}{2}^-, \beta = 0.268) = 59.5\% \ \tfrac{5}{2}^-\tfrac{1}{2}[541] + 39.8\% \ \tfrac{5}{2}^-\tfrac{3}{2}[532] + \ldots$$

4.2 The $\frac{3}{2}^+[402]$ and $\frac{1}{2}^+[400]$ bands

Experimentally the ground state is a $\frac{3}{2}^+$ state in $^{187-193}$Ir and $^{191-195}$Au, and a $\frac{1}{2}^+$ state in ^{187,189}Au. The bands built on these two states are known and rather similar in all these

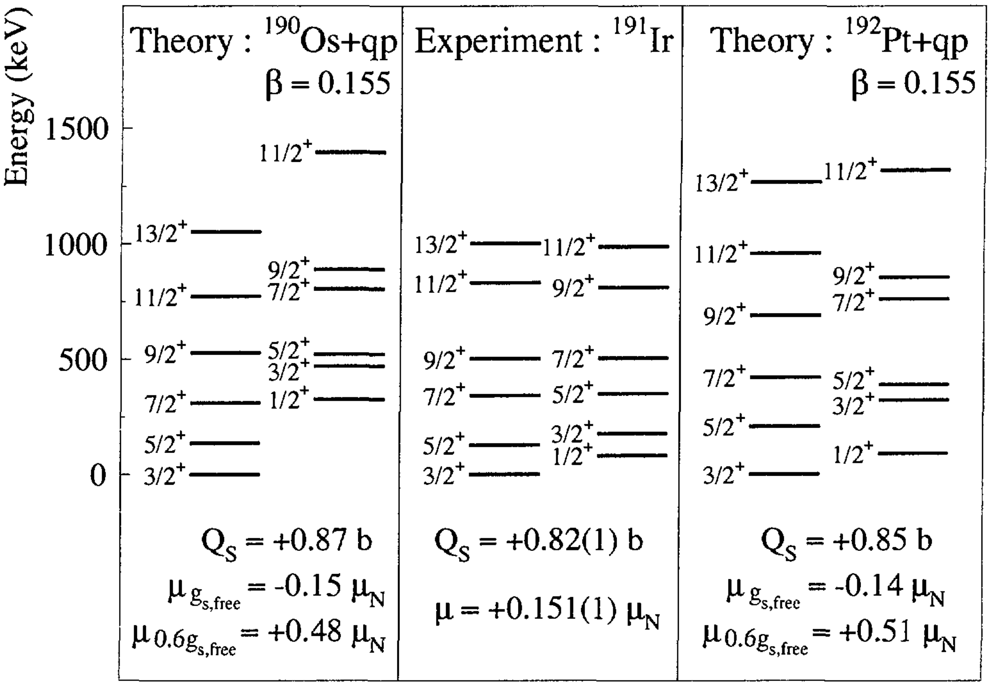

Figure 4: $\frac{3}{2}^+[402]$ and $\frac{1}{2}^+[400]$ bands calculated with the ^{190}Os and ^{192}Pt cores compared with the experimental data in ^{191}Ir. The moments for the $\frac{3}{2}^+$ state are also indicated.

nuclei. Figure 4 shows as an example the experimental data obtained in ^{191}Ir and the theoretical results obtained with the rotor + 1 qp model using the ^{190}Os and ^{192}Pt cores constrained to the deformation found experimentally for the ^{191}Ir ground state from the $\delta <r_c^2>$ measurements. The band built on the $\frac{3}{2}^+$ state is quite well reproduced by the calculations, in particular with the ^{190}Os core. Moreover the experimental μ value lies between the values calculated using $g_s = g_{s,free}$ and $0.6\times g_{s,free}$, and the spectroscopic quadrupole moment is in fair agreement with the theoretical values (see fig. 4). Thus we can consider that the model succeeds in describing this $\frac{3}{2}^+$ ground state in the heavier Ir and Au nuclei. On the contrary, the experimental pattern of the band built on the $\frac{1}{2}^+$ state differs strongly from the predictions. Moreover, the magnetic moment measured for the $\frac{1}{2}^+$ state, for example in ^{189}Au, $\mu_{exp}(^{189}\mathrm{Au}) = +0.494(14)\ \mu_N$, is much smaller than the values calculated for the $\frac{1}{2}^+[400]$ state using the ^{188}Pt core with $\beta = 0.150$: $\mu^{th}_{g_{s,free}} = +2.66\ \mu_N$ and $\mu^{th}_{0.6\times g_{s,free}} = +1.57\ \mu_N$.

4.3 The $h_{\frac{9}{2}}$ structure

This structure is known and built on the ground state in the lighter Ir and Au nuclei. Figure 5 shows its pattern in ^{185}Ir, as well as the results obtained with the rotor + 1 qp model using the ^{184}Os and ^{186}Pt cores. The agreement between experiment and theory is quite good, in spite of some differences in the order of appearance of the levels. Table 1 shows the moments measured for the $\frac{5}{2}^-$ ground state in ^{185}Ir and ^{185}Au, as well as the theoretical values obtained for the various cores for deformations close to the values found experimentally from the $\delta <r_c^2>$ measurements. With the Pt and Os cores, the wave function of the $\frac{5}{2}^-$ state has $K = \frac{1}{2}$ as main component but with the Hg core

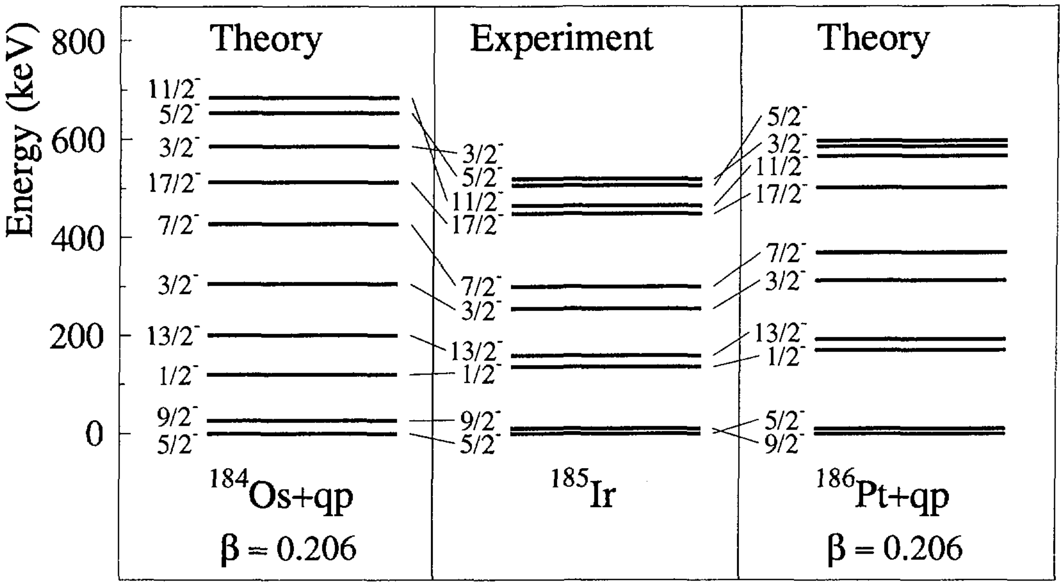

Figure 5: The $h_{\frac{9}{2}}$ structure calculated with the ^{184}Os and ^{186}Pt cores compared with the experimental data in ^{185}Ir.

the wave function shows a strong K($\frac{3}{2}$ and $\frac{1}{2}$) mixing. This strong K mixing does not affect the values obtained for the theoretical magnetic moments but strongly increases the theoretical spectroscopic quadrupole moments (see table 1). Therefore the change in the Q_S values between ^{185}Ir and ^{185}Au appears to be related to the change in the K mixing in the wave function describing the ground state. This K-mixing change is due to the variation of the deformation and of the Fermi level location between ^{185}Ir and ^{185}Au. Since it is quite well reproduced by the calculations, we can conclude that for this proton configuration the Coriolis effects are well accounted for by the axial rotor + 1 quasiparticle model.

Table 1: Experimental moments measured for the $\frac{5}{2}^-$ ground state in ^{185}Ir and ^{185}Au compared with the values calculated for the $\frac{5}{2}^-$ state of the $h_{\frac{9}{2}}$ structure.

Nucleus	$\mu^{exp}[\mu_N]$ Q_S^{exp}[b]	Core β_2 main component	$\mu^{th}[\mu_N]^{a)}$ Q_S^{th}[b]	Core β_2 main component	$\mu^{th}[\mu_N]^{a)}$ Q_S^{th}[b]
^{185}Ir	$+2.55(7)$ $-1.8(6)$	^{184}Os 0.206 85%$\frac{1}{2}$[541]	μ_1=+1.38 μ_2=+2.06 -1.46	^{186}Pt 0.206 78.4%$\frac{1}{2}$[541]	μ_1=+1.39 μ_2=+2.10 -1.42
^{185}Au	$+2.17(7)$ $-1.1(1)$	^{184}Pt 0.245 76%$\frac{1}{2}$[541]	μ_1=+1.32 μ_2=+2.00 -1.65	^{186}Hg 0.242 65%$\frac{3}{2}$[532]	μ_1=+1.31 μ_2=+1.94 -1.01

[a] calculated with $g_s=g_{s,free}$ (μ_1) and $g_s=0.6\times g_{s,free}$ (μ_2)

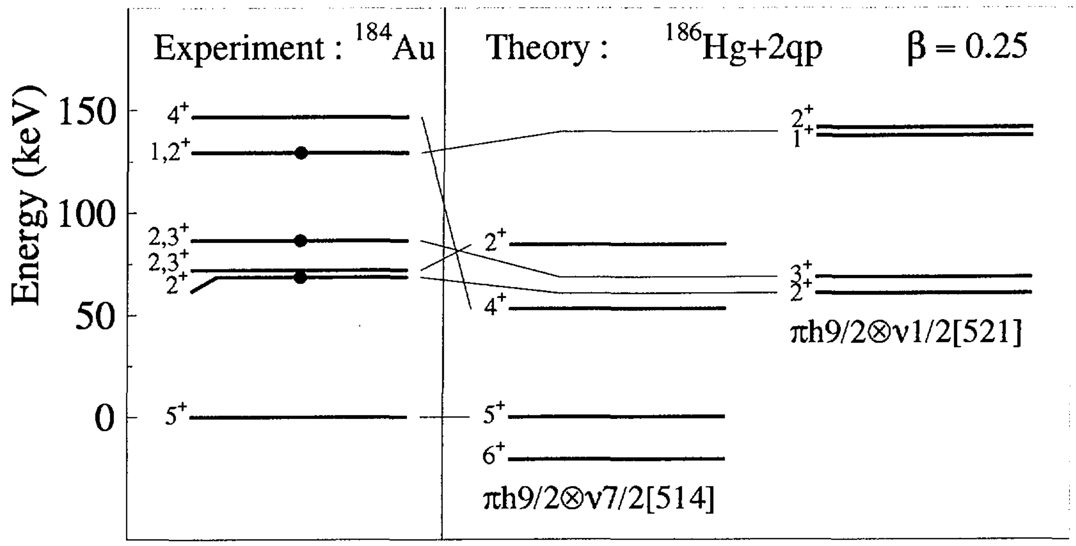

Figure 6: The $\pi h_{\frac{9}{2}}\otimes\nu\frac{7}{2}^{-}[514]$ and $\pi h_{\frac{9}{2}}\otimes\nu\frac{1}{2}^{-}[521]$ configurations calculated with the ^{186}Hg core compared with the experimental data in ^{184}Au.

4.4 The $\pi h_{\frac{9}{2}}\otimes\nu\frac{7}{2}^{-}[514]$ and $\pi h_{\frac{9}{2}}\otimes\nu\frac{1}{2}^{-}[521]$ configurations in ^{184}Au

From the intrinsic states observed in the neighbouring odd-neutron and odd-proton nuclei, the configurations expected in ^{184}Au for the $I^\pi = 5^+$ ground state and for the $I^\pi = 2^+$ isomeric state are the following: $\pi h_{\frac{9}{2}}\otimes\nu\frac{7}{2}^{-}[514]$ and $\pi h_{\frac{9}{2}}\otimes\nu\frac{1}{2}^{-}[521]$ [32]. As $\pi h_{\frac{9}{2}}$ stands for $\pi\frac{1}{2}[541]$ and/or $\pi\frac{3}{2}[532]$, the possible K values are : K = 4, 3 and/or 5, 2 for the ground state and K = 1, 0 and/or 2, 1 for the isomeric state. Figure 6 represents the experimental levels which have been interpreted as members of these $\pi\otimes\nu$ configurations [32], as well as the theoretical states obtained in the frame of the rotor + 2 quasiparticle model using

Table 2: Experimental moments measured for the ground and isomeric states in ^{184}Au compared with the values calculated for the $\pi h_{\frac{9}{2}}\otimes\nu\frac{7}{2}^{-}[514]$ and $\pi h_{\frac{9}{2}}\otimes\nu\frac{1}{2}^{-}[521]$ configurations.

	Experiment	Theory		
	^{184g}Au $I^\pi = 5^+$	K mixed b)	K = 5	K = 4
$\mu[\mu_N]$ a)	+2.07(2)	+2.29 +2.07	+2.36 +2.21	+2.19 +1.85
Q_S[b]	+4.7(3)	+3.4	+4.4	+1.8
	^{184m}Au $I^\pi = 2^+$	K mixed c)	K = 2	K = 1
$\mu[\mu_N]$ a)	+1.44(2)	+1.10 +1.21	+1.27 +1.41	+0.80 +1.00
Q_S[b]	+1.9(2)	+0.62	+2.2	−1.1

a) calculated with $g_s = g_{s,free}$ and $g_s = 0.6\times g_{s,free}$

b) $\Psi(5^+)$ = 47% (K = 5) + 31% (K = 4) + ...

c) $\Psi(2^+)$ = 40% (K = 2) + 37% (K = 1) + ...

the ^{186}Hg core at the deformation found experimentally for ^{184}Au from the $\delta <r_c^2>$ measurements. Except for the 6^+ state, each theoretical state can be associated with one experimental level. We can note that the 6^+ level has been observed experimentally but its energy location with respect to the 5^+ ground state is still unknown [33].
Table 2 shows the magnetic and spectroscopic quadrupole moments measured for the ground and isomeric states in ^{184}Au, as well as the theoretical values obtained assuming the K mixing given by the rotor + 2 qp calculations using the ^{186}Hg core at $\beta = 0.25$, or pure K states. The calculated μ values are not very sensitive to these various possibilities, but the experimental Q_S values indicate a pure K = 5 state for the ground state and a K = 2 component stronger than that given by the rotor + 2 qp calculation for the isomeric state. Such K values are obtained by coupling the $\pi\frac{3}{2}[532]$ state to the $\nu\frac{7}{2}^-[514]$ or $\nu\frac{1}{2}^-[521]$ state. Thus it seems that in ^{184}Au the role of the $\pi\frac{3}{2}[532]$ state is underestimated by the rotor + 2 qp calculations, which means that the K mixing due to the Coriolis interaction is overestimated.

4.5 The $\pi h_{\frac{9}{2}} \otimes \nu\frac{9}{2}^+[624]$ configuration in ^{184}Ir

In ^{184}Ir the 5^- ground state has been interpreted by the $\pi h_{\frac{9}{2}} \otimes \nu\frac{9}{2}^+[624]$ configuration [34]. The experimental levels identified as members of this configuration [35, 36] and the corresponding theoretical states obtained with the ^{184}Pt core are presented in figure 7. The agreement between experiment and theory is quite good since the same spin sequence is observed in both cases, even though the energy spacings are calculated a little smaller than observed. The wave function describing the 5^- state shows a strong mixing between the K = 5 and 4 components corresponding to the parallel and antiparallel coupling of the $\nu\frac{9}{2}[624]$ state to the $\pi\frac{1}{2}[541]$ state originating from the $\pi h_{\frac{9}{2}}$ subshell, and a weak

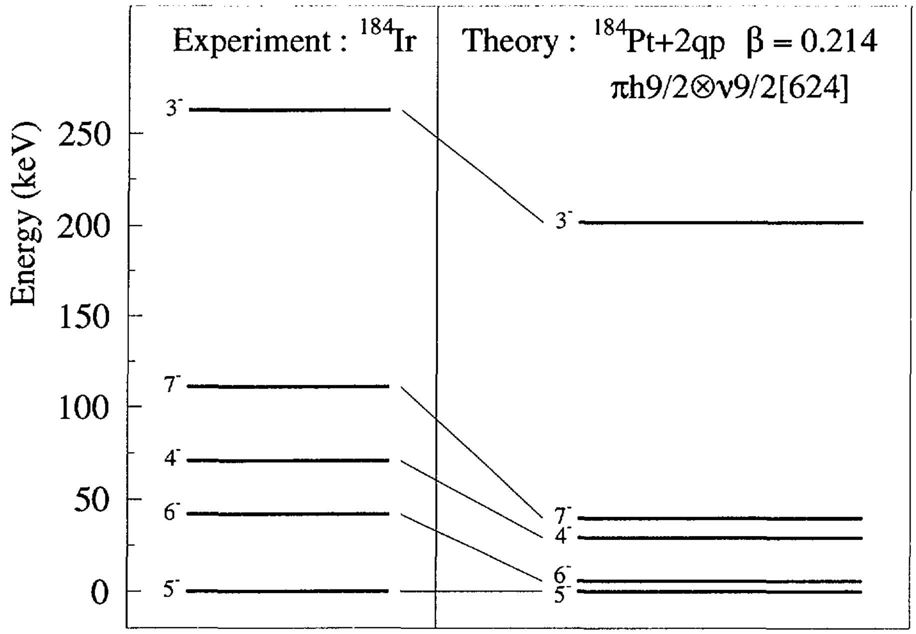

Figure 7: The $\pi h_{\frac{9}{2}} \otimes \nu\frac{9}{2}^+[624]$ configuration calculated with the ^{184}Pt core compared with the experimental data in ^{184}Ir.

Table 3: Experimental moments measured for the ground state in ^{184}Ir compared with the values calculated for the $\pi h_{\frac{9}{2}} \otimes \nu \frac{9}{2}^{+}[624]$ configuration.

	Experiment ^{184}Ir	Theory K mixed	K = 5	K = 4	K = 3
$\mu[\mu_N]^{a)}$	+0.69(3)	−0.92 −0.39	−1.41 −0.69	−0.74 −0.32	+0.07 +0.719
Q_S[b]	+2.6(4)	+2.15	+3.61	+1.44	−0.24

$^{a)}$ the theoretical values have been calculated with $g_s = g_{s,free}$ and $g_s = 0.6 \times g_{s,free}$

K = 3 component due to the coupling of the same neutron state to the $\pi\frac{3}{2}[532]$ state: $\Psi(5^-) = 46\% \ (K = 4) + 41.5\% \ (K = 5) + 6\% \ (K = 3) + \ldots$. These K percentages have been used to estimate the values of the nuclear moments presented in table 3. The experimental Q_S and μ values, as well as those calculated assuming a pure K = 5, 4 or 3 state are also shown in table 3. In the K-mixed case, the spectroscopic quadrupole moment is in rather good agreement with the experimental value, but the magnetic moment is negative contrary to what has been measured. It results from the μ values calculated assuming a pure K state that a positive value is obtained for K = 3 only. This seems to indicate that the role of the $\pi\frac{3}{2}[532]$ state is again underestimated by the rotor + 2 quasiparticle calculations. But in ^{184}Ir, unlike what has been observed in ^{184}Au, the wave function describing the ground state has to exhibit a K mixing in order to obtain a positive spectroscopic quadrupole moment.

5 Conclusions

The properties of the low-lying levels in the iridium and gold nuclei have been compared with the predictions of an axial rotor + 1 or 2 quasiparticle model assuming a prolate shape of the core and a deformation close to that extracted from the $\delta < r_c^2 >$ measurements. Since there is no adjustable parameters in the theoretical approach, we can consider that the agreement found between the theoretical and experimental results is of high quality. Concerning the positive parity states, the properties of the $\frac{3}{2}^+$ ground state in the heavier Ir and Au nuclei are quite well reproduced, but some discrepancies between theory and experiment are found for the $\frac{1}{2}^+$ state which is the ground state in ^{187,189}Au. These positive parity states have been previously discussed in the frame of this rotor + 1 quasiparticle model assuming an oblate shape of the core with the deformation parameter corresponding to the minimun of the potential energy [19]. In this case, the description of the properties of the band built on the $\frac{1}{2}^+$ state becomes better, but that of the $\frac{3}{2}^+$ level, in particular the nuclear moments, becomes worse. It remains to be seen whether the same conclusions are obtained when the calculations are constrained in deformation. On the other hand, this difficulty in reproducing the whole of the low-spin positive-parity states does not seem to be due to the axial-symmetry assumption since it has been also encountered in the recent calculations performed using the particle-triaxial-rotor model for ^{191,193}Ir [37]. On the contrary, a very good theory-experiment agreement is found for the $h_{\frac{9}{2}}$ structure built on the $\frac{5}{2}^-$ state in the lighter Ir and Au nuclei. It appears from the calculations that the more deformed is the nucleus, the more important is the $\frac{3}{2}[532]$ component in the wave function describing the $\frac{5}{2}^{-}$ state. As the deformation increases between ^{185}Ir and ^{185}Au, the differences observed in the experimental Q_S values are mainly due to the changes in the weight of the main components in the wave function describing the ground state.

As for the odd-odd nuclei, their properties are qualitatively well reproduced by the rotor + 2 quasiparticle model. The theory-experiment comparison done for ^{184}Au and ^{184}Ir indicates that the $\pi\frac{3}{2}[532]$ component is favoured when the $h_{\frac{9}{2}}$ proton is coupled to a neutron. For the configurations involving the $h_{\frac{9}{2}}$ structure, the K mixings due to the Coriolis interaction are better accounted for in the odd nuclei than in the odd-odd nuclei.

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