INTERMEDIATE COUPLING VIBRATIONAL DESCRIPTIONS OF ODD MASS GOLD ISOTOPES

Ch. Vieu*, V. Paar** and J.S. Dionisio*

*C.S.N.S.M. (IN2P3) 91406 Campus Orsay, FRANCE

**Institute "Ruder Boskovic", Zagreb, Yugoslavia

Abstract. The theoretical analysis of $^{193-195}$Au levels is semi qualitatively performed in the frame of the intermediate coupling vibrational models of Kisslinger-Sorensen and Alaga. From the comparison between the experimental data and the corresponding predictions of the two models, conclusions are drawn on the influence of the clusters and broken pairs.

1. Introduction

Striking similarities and continuities of nuclear structure were brought in evidence in the transitional odd mass gold isotopes [1-12]. The smooth variation of the excitation energies and electromagnetic properties with the neutron number can be used fruitfully to test the predictions of the available nuclear models. In the present study, the most significant experimental data, collected on the best known 193 and 195 gold isotopes, will be compared to the theoretical results obtained with the Kisslinger-Sorensen [13] or the Alaga [14, 15] vibrational models (one quasi particle or three holes clusters coupled to an harmonic quadrupole vibrator). The theoretical predictions of both models for positive as well as negative parity states will be analysed semi qualitatively in order to bring in evidence the influence of the clusters and to connect more easily these vibrational descriptions to those derived from rotational models which offer another challenge for the interpretation of these transitional nuclei [16].

The following theoretical analysis can be used for the negative parity states built on the $11/2^-_1$ isomeric level in lighter or heavier gold isotopes. Indeed this system remains pratically unchanged from one odd mass gold isotope to another. However, higher or lower coupling strength must be choosen for the theoretical description of positive parity states in $^{189-191}$Au or $^{197-199}$Au.

2. Level excitation energies and theoretical interpretations.

The experimental excitation energies of $^{193-195}$Au levels, with definite spin and parity assignments, are given in table 1 in keV units. They are compared to the theoretical energies calculated with the one quasi particle (1QP) model (using the same parametrization adopted by Kisslinger and Sorensen [13]) and the three holes clusters (3HC) model (using two different parameter sets 3HC1 and 3HC2). Indeed, the differences observed between the experimental and theoretical one quasi particle energies of a few levels cannot be reduced choosing a different parameter set. On the contrary, a better agreement with the experimental level schemes is obtained in the Alaga model adopting the 3HC1 parameter set where the $\varepsilon(2d_{3/2})$ and $\varepsilon(2d_{5/2})$ single proton hole energies are smaller than those measured in ^{207}Tl (3HC2 parameter set [17]). Moreover, such ε variations do not change in general the predictions of the model.

In the 1QP (3HC) model, the $3/2^+_1$ and $1/2^+_1$ states are mainly the $2d_{3/2}|00>3/2$ (or $[(3s_{1/2})^{-2}0, 2d_{3/2}^{-1}]3/2|00>3/2$) and the $3s_{1/2}|00>1/2$ (or $[(2d_{3/2})^{-2}0, 3s^{-1}_{1/2}]1/2|00>1/2$) one quasi particle (or cluster) states coupled to zero phonon vibration. The $5/2^+_1$, $7/2^+_1$ and $9/2^+_1$, $11/2^+_1$ levels are identified to the one and two phonon vibrational states built on the $3/2^+_1$ ground state. Such similar and well developped band structure based on $1/2^+_1$ level does not exist. Indeed, the possible $2d_{3/2}|12>$ interpretation for the $3/2^+_2$ level in the 1QP model does not account satisfactorily upon the experimental excitation energies. In the 3HC model, a good agreement with the experimental data is obtained identifying the $3/2^+_2$ level to a complex collective state where the $[(2d_{3/2})^{-2}2, 3s_{1/2}^{-1}]5/2$ broken pair has a noticeable (36 %) influence. From its main component, the $5/2^+_2$ state can be considered as the one phonon vibrational state built on $1/2^+_1$ level. The $7/2^+_2$, $9/2^+_2$, $11/2^+_2$ states are very complex and cannot be related to any band structure. Finally, according to the 1QP model, the lowest negative parity states can be identified to the one or two phonon vibrational states built on the $11/2^-_1$ isomeric level. Such simple multiplet pattern no longer exists in the 3HC model. Indeed, the lowest negative parity levels are cluster states in the zeroth order ($a=0$). However, for $a=0.4$ MeV coupling strength, strong mixing occurs not only between different cluster states but also with the higher excited N phonons multiplets. Then, a qualitative treatment of these levels cannot be derived from the analysis of their wave function.

3. Electromagnetic properties

The BM1 and BE2 experimental reduced transition probabilities deexciting levels with known half-lives [9,10] are compared, in table 2, to the corresponding 1QP and 3HC1 theoretical values. The A, B, C, D, E matrix elements are defined in these models [3,14]. All the BM1 and BE2 values are expressed in $(n.m.)^2$ and $(eb)^2$ units respectively.

3.1. Reduced transition probabilities.

All the electromagnetic properties quoted in table 2 are well accounted in the 1QP and the 3HC models. Indeed, the $1/2^+_1 \to 3/2^+_1$ M1 transition is $\Delta\ell=2$ forbidden on account of the initial and final state interpretations. This explains the observed hindrance factor (F_W = $BM1_{sp}/BM1_{exp}$ = 1600). The E2 component of the same transition has sizeable particle (A) and collective (B) matrix elements in the 1QP and 3HC model. The relative importance of the term A reflects the single quasi particle or cluster character of the $1/2^+_1$ and $3/2^+_1$ states. Moreover, the collective term B has the same sign than A and is the sum of the coherent contributions of the zero, one and two phonon components of the $1/2^+_1$ and $3/2^+_1$ wave functions. This leads to the moderately enhancement of this E2 component ($A_W = BE2_{exp}/BE2_{sp} = 29$).

The $5/2^+_1 \to 3/2^+_1$ transition takes place between a one phonon vibrational level and the state on which it is based. The $\Delta N=1$ forbiddness of the M1 component is partly removed due to the influence of second order components ($F_W=83$). The enhanced E2 component of the same transition ($A_W=105$) has strong collective matrix elements in the 1QP or 3HC models. However, the particle matrix element A is not negligible in the 3HC model due to the coherent contributions of the $[(3s_{1/2})^{-2}0, 2d_{3/2}^{-1}]3/2|N=0(1),R=0(2)>3/2(5/2)$ and $[(2d_{3/2})^{-2}2, 3s_{1/2}^{-1}]5/2|N=1(0),R=2(0)>3/2(5/2)$ initial and final wave function components. Then, even in the groundstate, a relatively small influence of broken pairs has noticeable effect in the theoretical electromagnetic properties.

TABLE 1 : Experimental and theoretical $^{193,195}Au$ excitation energies

I^{π}	^{193}Au	^{195}Au	1QP	3HC1	3HC2
$3/2^{+}_{1}$	0	0	0	0	0
$1/2^{+}_{1}$	38.24	61.46	100	61	116
$3/2^{+}_{2}$	224.81	241.53	510	241	356
$5/2^{+}_{1}$	258.00	261.77	366	215	251
$11/2^{-}_{1}$	290.21	318.60	318	[304]	[304]
$5/2^{+}_{2}$	381.60	439.51	493	495	660
$7/2^{-}_{1}$	508.22	525.70	742	601	523
$7/2^{+}_{1}$	538.99	549.34	334	499	510
$7/2^{+}_{2}$	687.51	703.3*	755	722	831
$15/2^{-}_{1}$	697.84	706.47	746	664	581
$9/2^{+}_{1}$	808.63	817.8*	763	743	742
$3/2^{+}_{3}$	827.64	841.24	526	899	980
$13/2^{-}_{1}$	863.41	878.82	670	896	782
$9/2^{-}_{1}$	890.79	894.18	905	865	798
$9/2^{+}_{2}$	929.11	-	907	1009	1316
$7/2^{+}_{3}$	1004.10	-	901	1020	1010
$3/2^{-}_{1}$	1089.25	1110.70	1232	1241	1077
$(3/2^{+}_{4})$	1118.97	(1082.92)	781	1073	1191
$11/2^{+}_{1}$	1153.47	1177.7*	727	1271	1254
$11/2^{-}_{2}$	1284.79	1280.54	867	1097	1109
$13/2^{-}_{2}$	1355.46	1404.6	1345	1249	1249
$17/2^{-}_{1}$	1373.0	1365.0*	1175	1390	1233
$11/2^{+}_{2}$	1380.0	1396.8*	1343	1525	1623
$11/2^{-}_{3}$	1400.35	1346.17	1226	1206	1208
$9/2^{-}_{2}$	1413.10	-	1209	1232	1223
$19/2^{-}_{1}$	1419.0*	1424.9*	1933	1317	1154
$13/2^{+}_{1}$	1433.54	-	1312	1490	1520
$15/2^{-}_{2}$	1455.20	-	1149	1435	1320
$(7/2^{-}_{2})$	1477.10	-	1380	1414	1307
$13/2^{+}_{2}$	1477.7*	1489.5*	1451	1961	2414
$(7/2^{-}_{3})$	1514.10	-	1484	1516	1439
$(11/2^{+}_{3})$	1572.50	-	1440	1892	1919
$13/2^{-}_{3}$	1575.50	1559.6	1430	1472	1358
$(3/2^{-}_{2})$	1603.4	-	1933	2226	2092
$13/2^{-}_{4}$	1630.25	-	1933	1523	1579
$17/2^{-}_{2}$	1733.4	-	1933	1817	1766

Parameter sets

1QP $\varepsilon_{1/2}=0.00$; $\varepsilon_{3/2}=0.33$; $\varepsilon_{5/2}=1.22$; $\varepsilon_{7/2}=3.00$; $\varepsilon_{11/2}=0.89$; $\hbar\omega=0.42$; G=0.12 ; a=0.40 MeV

3HC1 $\varepsilon_{1/2}=0.00$; $\varepsilon_{3/2}=0.20$; $\varepsilon_{5/2}=1.00$; $\varepsilon_{7/2}=3.50$; $\varepsilon_{11/2}=1.34$; $\hbar\omega=0.50$; G=0.12 ; a=0.40 MeV

3HC2 $\varepsilon_{1/2}=0.00$; $\varepsilon_{3/2}=0.35$; $\varepsilon_{5/2}=1.67$; $\varepsilon_{7/2}=3.50$; $\varepsilon_{11/2}=1.34$; $\hbar\omega=0.50$; G=0.12 ; a=0.40 MeV

TABLE 2 : Experimental and theoretical $^{193,195}Au$ reduced transition probabilities.

Initial State	Final State	$BM1_{exp}$ { ^{193}Au / ^{195}Au }	$BE2_{exp}$ { ^{193}Au / ^{195}Au }	Model	$BM1_{th}$	C	D	E	$BE2_{th}$	A	B
$1/2^+_1$	$3/2^+_1$	0.0021 ± 0.0004	0.32 ± 0.008	1QP	0.00046	0.112	− 0.123	0.111	0.046	0.032	0.080
		0.0035 ± 0.0007	0.26 ± 0.007	3HC	0.0013	− 0.057	0.082	− 0.025	0.172	− 0.061	− 0.155
$5/2^+_1$	$3/2^+_1$	0.024 ± 0.013	0.20 ± 0.12	1QP	0.048	0.477	− 0.713	0.237	0.159	− 0.038	− 0.300
		0.022 ± 0.006	0.112 ± 0.056	3HC	0.066	0.283	− 0.514	0.231	0.295	− 0.181	− 0.322
$5/2^+_1$	$1/2^+_1$	−	0.088 ± 0.064	1QP	−	−	−	−	0.032	0.030	0.108
		−	0.054 ± 0.018	3HC	−	−	−	−	0.032	0.063	− 0.188
$7/2^-_1$	$11/2^-_1$	−	0.31 ± 0.004	1QP	−	−	−	−	0.139	0.019	0.338
		−	−	3HC	−	−	−	−	0.221	0.127	0.358

The $5/2^+_1 \rightarrow 1/2^+_1$ transition connects a collective level and a state on which it is not based. Both the 1QP and the 3HC models predict the observed moderate enhancement (A_W = 13) of this E2 transition. However, the $5/2^+_1$ and $1/2^+_1$ zero and one phonon components account for 80 % and 60 % of the matrix elements A and B in the 1QP model. On the other way, the main (63 %) contribution in the three holes cluster A matrix element comes from the $[(2d_{3/2})^{-2}2,\ 3s_{1/2}{}^{-1}]5/2$ and $[(2d_{3/2})^{-2}\,0,\ 3s_{1/2}{}^{-1}]1/2$ clusters in the initial and final wave functions. In the same model, the B matrix element is a sum of many coherent contributions. Then similar results obtained in the 1QP or 3HC models do not reflect the same physical situation.

The $7/2^-_1 \rightarrow 11/2^-_1$ enhanced E2 transition (A_W = 21) is strongly collective in the 1QP model. Indeed the $7/2^-_1$ and $11/2^-_1$ levels are identified respectively to $1h_{11/2}$ proton hole coupled to one and zero phonon in the zero order. For increasing coupling strength, the influence of these configurations are decreased but sizeable admixtures of $1h_{11/2}|22 > 7/2$ and $1h_{11/2}|12 > 11/2$ configurations are introduced in the $7/2^-_1$ and $11/2^-_1$ wave functions. These configurations and the former ones have coherent contributions which explain the strong collective B matrix element in the 1QP model. Similar effects are observed in the 3HC model where the $7/2^-_1$ and $11/2^-_1$ levels are identified to the $[(2d_{3/2}{}^{-1},\ 3s_{1/2}{}^{-1})2,\ 1h_{11/2}{}^{-1}]7/2\ |\ 00 > 7/2$ and $[(3s_{1/2})^{-2}0,\ 1h_{11/2}{}^{-1}]11/2|00 > 11/2$ states in the zero order (allowed E2 transtion predicted by GVISR [14]). For increasing a value, the $[(2d_{3/2})^{-2}0,\ 1h_{11/2}{}^{-1}]11/2|NR > 7/2$ and $[(3s_{1/2})^{-2}0,\ 1h_{11/2}{}^{-1}]11/2|N'R' > 11/2$ configurations are introduced in the $7/2^-_1$ and $11/2^-_1$ wave functions. They have coherent contributions not only in the collective term B but also in the particle term A.

3.2. Gamma transition rates and Δ mixing ratios.

For levels with unknown half lives but deexciting through two (M1, E2 or M1+E2) transitions at least, valuable tests for the interpretations can be derived from the analysis of the relative gamma transition rates and the Δ mixing ratios (see table 3).

For example, it appears clearly that the 1QP model does not account satisfactorily for the relative gamma transtion rates of the $3/2^+_2$ level. Such failure is overcamed in the 3HC model where the $[(2d_{3/2})^{-2}2,\ 3s_{1/2}{}^{-1}]5/2|12>1/2$ or 3/2 and the $[(3s_{1/2})^{-2}0,\ 2d_{3/2}{}^{-1}]3/2|12>1/2$ or 3/2 initial and final wave function components have coherent contributions in the preponderant <L> matrix elements of the intense $3/2^+_2 \rightarrow 1/2^+_1$ M1 transition. This fact explains the better agreement for the relative γ intensity rates and the Δ mixing ratios of the $3/2^+_2$ deexciting transitions.In both models, the identification of the $7/2^-_1$ level to a vibrational state based on the $3/2^+_1$ ground state accounts for the strong $7/2^+_1 \rightarrow 3/2^+_1$ E2 transition. Similarly, both models predict the $7/2^+_1 \rightarrow 5/2^+_1$ M1 transition with incoherent contributions of the L and S operators. However, a better agreement with the experimental relative γ transition rates is obtained by the 3HC model where a noticeable contribution in the E matrix elements (S operator) comes from the $[(2d_{3/2}{}^{-1},\ 3s_{1/2}{}^{-1})2,\ 2d_{5/2}]7/2|00>7/2 \times [(2d_{3/2})^{-2}2,\ 3s_{1/2}{}^{-1}]5/2|00>5/2$ broken pair components in the initial and final wave functions. The analysis of other more complex positive or negative parity states will not be performed in this study.

4. Conclusions

The present theoretical analysis gives evidence that a complete and satisfactory description of positive and negative parity states in $^{193-195}Au$ is achieved with the 3HC model. In particular, besides the quasi rotational band built on the $3/2^+_1$ ground state, the other positive parity levels have, in general, complex wave functions. Indeed the mixing of different cluster configurations explains their deexcitation modes which does not correspond to any clear $1/2^+$ band structure. On the other side, the negative parity states, built on the $11/2^-_1$ isomeric level, form a very stable pattern in the different odd mass gold isotopes. Such nuclear stability with the neutron number suggests that the $1h_{11/2}$ proton

TABLE 3 : Experimental and theoretical $^{193,195}Au$ gamma transition rates and mixing ratios.

Initial state	Final state	Gamma transition rates ^{193}Au	^{195}Au	1QP	3HC	Δ Mixing ratios ^{193}Au	^{195}Au	1QP	3HC	Notes
$1/2^+_1$	$3/2^+_1$	2.6 ± 0.2	17.5 ± 3.3	138	7.2	0.12 ± 0.03	0.17 ± 0.01	0.41	0.25	1
$3/2^+_2$	$3/2^+_1$	0.068 ± 0.018	0.036 ± 0.006	3.57	0.056	0.86 ± 0.10	0.83 ± 0.11	0.98	0.95	
"	$1/2^+_1$	1	1	1	1	0.064 ± 0.016	0.024 ± 0.010	0.77	1.13(-2)	
$5/2^+_1$	$3/2^+_1$	10.2 ± 4.4	8.65 ± 2.50	5.42	13.2	0.27 ± 0.03	0.19 ± 0.06	0.24	0.13	2
"	$1/2^+_1$	0.58 ± 0.39	0.22 ± 0.06	0.053	0.034	1.0	1.0	1.0	1.0	
"	$3/2^+_2$	-	-	0.128	0.032	-	-	2.51(-2)	1.38(-3)	
$5/2^+_2$	$3/2^+_1$	1	1	1	1	0.61 ± 0.18	0.018 ± 0.027	1.79(-2)	1.62(-3)	
"	$1/2^+_1$	-	0.21 ± 0.09	0.011	0.065	-	-	1.0	1.0	
"	$3/2^+_2$	-	-	0.000	0.018	-	-	1.81(-3)	2.03(-2)	
"	$5/2^+_1$	-	-	0.004	0.271	-	-	1.24(-3)	0.86	
$7/2^+_1$	$3/2^+_1$	1	1	1	1	-	0.86 ± 0.20	1.0	1.0	
"	$3/2^+_2$	0.031 ± 0.021	-	0.006	0.002	-	-	1.0	1.0	
"	$5/2^+_1$	0.15 ± 0.16	0.22 ± 0.07	0.000	0.475	0.31 ± 1.38	-	1.63(-2)	2.98(-4)	
"	$5/2^+_2$	0.04 ± 0.02	-	0.424	0.000	-	-	5.84(-3)	5.26(-5)	
$7/2^-_1$	$11/2^-_1$	1.86 ± 0.20	-	23.6	6.32	1.0	1.0	1.0	1.0	2
$13/2^-_1$	$11/2^-_1$	358 ± 123	131 ± 15	65	13	0.49 ± 0.14	0.0	6.85(-2)	0.19	
"	$15/2^-_1$	1	1	1	1	≤ 0.39	≤ 0.16	6.20(-4)	5.94(-3)	
$9/2^-_1$	$11/2^-_1$	1	1	1	1	0.66 ± 0.15	0.39 ± 0.07	2.16(-2)	0.18	
"	$7/2^-_1$	1.0 ± 0.3	1.4 ± 0.3	0.027	0.178	0.20 ± 0.20	≤ 0.15	3.62(-3)	8.95(-3)	
"	$13/2^-_1$	-	-	0.000	0.000	-	-	1.0	1.0	
$11/2^-_2$	$11/2^-_1$	1	1	1	1	1.00 ± 0.12	0.15 ± 0.32	0.36	0.29	
"	$7/2^-_1$	0.46 ± 0.20	0.28 ± 0.06	0.000	0.039	-	0.88 ± 0.21	1.0	1.0	
"	$15/2^-_1$	-	-	0.000	0.003	-	-	1.0	1.0	
"	$13/2^-_1$	-	0.080 ± 0.024	0.580	0.267	-	-	2.74(-3)	8.15(-3)	
"	$9/2^-_1$	1.63 ± 0.39	1.25 ± 0.34	0.003	0.391	0.26 ± 0.14	≤ 0.18	1.66(-4)	4.17(-3)	
$13/2^-_2$	$11/2^-_1$	0.20 ± 0.14	-	0.012	0.106	-	-	5.84(-5)	0.83	
"	$15/2^-_1$	1	-	1	1	-	-	3.19(-2)	5.25(-4)	
"	$13/2^-_1$	-	-	0.132	0.004	-	-	2.78(-2)	4.14(-3)	
"	$9/2^-_1$	-	-	0.025	0.000	1.0	-	1.0	1.0	
"	$11/2^-_2$	-	-	0.008	0.000	-	-	5.55(-3)	8.15(-5)	

Notes : 1 - Gamma transition rate in 10^6 photons per second.
2 - Gamma transition rate in 10^9 photons per second.

hole is coupled with the other paired or unpaired proton holes and the remaining nucleons with such polarization effects that the resulting even-even core has many similarities with the even-even mercury isotopes. Indeed, one observe that the $3s_{1/2}$, $2d_{3/2}$ and $2d_{5/2}$ proton pair configurations are those used in the theoretical description of the even-even mercury isotopes [18]. Moreover, the theoretical vibrational energy ($\hbar\omega$ = 0.5 MeV) is constant for the $11/2^-$ system of levels in the different odd mass isotopes and its value is near the excitation energy of the first 2^+ level in the even-even mercury isotopes ($E(2^+_1,Hg) \simeq 0.41$ MeV). Finally, another system of negative parity levels, based on the $9/2^-_1$ level and weakly feeded in $^{193-195}Au$ [1-3], is not described in the present 3HC model. Indeed, the theoretical description of a $1h_{9/2}$ particle state would necessitate its coupling with four proton holes.

References

[1] V. Berg, C. Bourgeois and R. Foucher, Journ. Phys. 36 (1975) 613

[2] V. Berg, R. Foucher, A. Hoglund, Nucl. Phys. A244 (1975) 462

[3] Ch. Vieu, Thesis Orsay (1974)

[4] Ch. Vieu, A. Peghaire and J.S. Dionisio, Rev. Phys. Appl. 8 (1973) 231

[5] E. Barnard, J.A.M. de Villiers C.A. Engelbrecht and D. Reitmann, Nucl. Phys. A167 (1971) 511

[6] K. Okano, Y. Kawase, S. Uehara and T. Hayashi, Nucl. Phys. A136 (1969) 321.

[7] F.K. Mc. Gowan, W.T. Milner, R.L. Robinson and P.H. Stelson, Ann. Phys. 63 (1971) 549

[8] A. Bäcklin, B. Fogelberg and S.G. Malmskog, Nucl. Phys. A103 (1967) 337

[9] B. Fogelberg, A. Bäcklin, V. Berg and S.G. Malmskog, Nucl. Phys. A153 (1970) 301

[10] A. Bäcklin, V. Berg and S.G. Malmskog, Nucl. Phys. A156 (1970) 647

[11] P.O. Tjøm , M.R. Maier, D. Benson Jr., F.S. Stephens and R.M. Diamond, Nucl. Phys. A231 (1974) 397

[12] 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 n°2 (1975) 159.

[13] L.S. Kisslinger and R.A. Sorensen, Rev. Mod. Phys. 35 (1963) 853

[14] V.Paar, Problems of vibrational nuclei, G. Alaga, V. Paar and L. Sips ed. (1975) 15

[15] Ch. Vieu, J.S. Dionisio and V. Paar, Fisika vol. 7 suppl. 2 (1975) 192

[16] Ch. Vieu, S.E. Larsson, G. Leander, I. Ragnarsson, W. de Wieclawik and J.S. Dionisio, Contribution to the present Conference.

[17] S. Hinds, R. Middleton, J.H. Bjerregaard, O. Hansen and O. Nathan, Phys. Lett. 17 (1965) 302

[18] G. Alaga and V. Paar, private communication.