Supersymmetry classification of nuclear levels in odd-mass platinum isotopes

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Existing experimental data on the even-odd platinum isotopes ^{193,195,197,199}Pt are reviewed in order to classify excited states in terms of U(6/12) quantum numbers. For several of the known states new assignments are proposed which lead to an improved description of these nuclei. The excitation energies of the even-even supersymmetry partners ^{192,194,196,198}Pt are well reproduced with the parameters determined for the odd-mass isotopes.

I. INTRODUCTION

The theoretical interpretation of the negative-parity structure of the odd-mass platinum isotopes in the framework of conventional models of particle and collective motion has met with serious difficulties because in this transition region between strongly deformed and spherical nuclei, the nuclear shape and core motion are not well defined. Moreover, the unpaired neutron can occupy three energetically closely spaced single-particle orbits $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$, the energies of which sensitively depend on the shape of the core. Early attempts of Yamazaki *et al.*[1,2] to explain the level structure in terms of Nilsson orbits coupled to different cores showed that the low-lying levels of ^{195}Pt could be described with fair success by single-particle orbits coupled to an oblate core including a soft γ vibration.[1] For the isotope ^{197}Pt, however, this model failed to reproduce the experimentally observed levels.[2] When more complete experimental information was obtained on low-spin levels, $\frac{1}{2}^-$ and $\frac{3}{2}^-$, from average resonance neutron-capture experiments of Warner *et al.*[3] and Casten *et al.*[4], it was realized[3,4] that even for ^{195}Pt this model was totally inadequate to explain the level structure at low-excitation energies. In particular, the number of spin-$\frac{1}{2}$ and -$\frac{3}{2}$ levels observed in the experiment could not be reproduced.

Considerable progress was achieved when it was found that the collective excitations of low spin in the neighboring doubly even isotope ^{196}Pt can be understood in terms of the O(6) limit of the interacting boson approximation,[5] together with the development of the interacting boson fermion model[6] (IBFM) and the U(6/12) multi-j supersymmetry (SUSY) scheme[7] for the special case in which a neutron in $j=\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$ orbits is coupled to an O(6) core.[3,8] By this mechanism a fully specified complete core is automatically incorporated in the calculation. With the development of different succeeding versions,[8–12] this model has been increasingly successful in explaining the negative-parity structure of ^{195}Pt (Refs. 3 and 12) and in part of ^{197}Pt (Refs. 4, 11, and 12) and ^{199}Pt (Ref. 12).

While in the earlier version of the model[3,4] a discrepancy persisted between the experimental and theoretical levels in the relative excitation energy of the two major families of levels, this discrepancy was successfully removed by Sun *et al.*[9] by including an additional interaction term in the SUSY scheme. For levels at higher energy, however, the agreement between experiment and theory was still not satisfactory. Moreover, it was found difficult to simultaneously describe the doubly even nuclei and the odd-mass nuclei with the same set of parameters, unless a somewhat *ad hoc* higher-order interaction was introduced.[11]

New experimental information on $B(E2)$ values between excited states was obtained from a recent Coulomb excitation experiment with ^{32}S projectiles.[13,14] It was shown in Refs. 13 and 14 that the agreement between experiment and theory for the negative-parity states of ^{195}Pt can be substantially improved compared to the earlier attempts[3,10] if a new classification of the experimental levels is introduced. With the new assignments, the calculated energies for the levels of the configurations $\langle\sigma_1,\sigma_2,\sigma_3\rangle=\langle 7,0,0\rangle$, $\langle 6,1,0\rangle$ and the quantum numbers $(\tau_1,\tau_2)=(0,0)$, (1,0), and (2,0) agree with the experimental values to within less than 20 keV. Even the position of the doublet 199 keV ($\frac{3}{2}^-$) and 222 keV ($\frac{1}{2}^-,\frac{3}{2}^-$), associated with the quantum numbers $\langle 6,1,0\rangle$-(1,1)-1-$\frac{3}{2}$ and $\frac{1}{2}$, is well reproduced. Larger deviations occur only for the higher-lying levels associated with the quantum numbers $\langle 6,1,0\rangle$-(1,1) and (2,1). With this new classification the simultaneous description of the low-lying levels of ^{194}Pt and ^{195}Pt in the framework of the supersymmetry scheme is also appreciably improved.

Since a sizeable number of relative and absolute $B(E2)$ values have been determined for ^{195}Pt (Refs. 13–15), electromagnetic transition rates were also compared with the model predictions. It was seen that the calculated $E2$ branching ratios and absolute $B(E2)$ values for the decay of the (τ_1,τ_2)-$L=(2,0)$-4 levels in ^{195}Pt are well reproduced, while discrepancies occur in both the new and the old classification for the decay of the (2,0)-2 levels. A recent reevaluation of single-neutron stripping and pickup reaction data on the basis of the proposed new assignments has led to a better agreement between calculated and measured spectroscopic factors[16] for the $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$ levels, while the $\frac{7}{2}^-$ levels are found to be more strongly populated than expected from theory.

Apart from these remaining discrepancies in the $B(E2)$ values and spectroscopic factors, which most likely will be the subject of further studies, the encouraging results of the new classification for ^{195}Pt, as far as the level energies are concerned, immediately raise the question as to whether the description of the neighboring isotopes ^{193}Pt, ^{197}Pt, and ^{199}Pt within the same dynamical symmetry can also be improved by a revised classification of their levels. The simultaneous description with their even-mass neighbors ^{192}Pt, ^{196}Pt, and ^{198}Pt also deserves a reinvestigation. Of particular interest in the case of an improved description of the level structure is the variation of the parameters of the SUSY scheme with mass number A. It should be emphasized that the assumption that a dynamical symmetry Hamiltonian is applicable for all these isotopes is made in order to simplify the analysis. In principle, one could consider admixtures of SU(3) and U(5) terms in the Hamiltonian within the U(6/12) symmetry,[17] in order to achieve a more detailed description, which would involve, however, a larger number of parameters.

With the above-mentioned objectives in mind we proceed to review the experimental data from the literature for the platinum isotopes.

II. THEORETICAL LEVEL ORDER AND QUANTUM NUMBERS

The theoretical level energies for the even-odd isotopes are calculated using the eigenvalue equation of Ref. 10 (chain II),

$$E(h_1h_2;\sigma_1\sigma_2;\tau_1\tau_2;L;J)=A[h_1(h_1+5)+h_2(h_2+3)]-(A''/4)[\sigma_1(\sigma_1+4)+\sigma_2(\sigma_2+2)]$$
$$+(B/6)[\tau_1(\tau_1+3)+\tau_2(\tau_2+1)]+CL(L+1)+C''J(J+1)\ . \quad (1)$$

The quantum numbers of Eq. (1) have been discussed in several papers.[8,9] For the case of one uncoupled fermion the U(6) quantum numbers $[h_1,h_2]$ are either $[N+1,0]$ or $[N,1]$, where N is the number of bosons in the doubly even core. The SO(6) quantum numbers $\langle\sigma_1,\sigma_2\rangle$ can take the values $\langle N+1,0\rangle$, $\langle N-1,0\rangle$, $\langle N-3,0\rangle,\ldots,$ etc. for $[h_1,h_2]=[N+1,0]$, and the values $\langle N,1\rangle,\langle N-2,1\rangle,\ldots,$ etc., or $\langle N-1,0\rangle,\langle N-3,0\rangle,\ldots,$ etc. for $[h_1,h_2]=[N,1]$. For the $\langle\sigma,0\rangle$ configurations the SO(5) quantum numbers (τ_1,τ_2) can take the values $\tau_2=0$, $\tau_1=0,1,2,3,\ldots,\sigma$, while for $\langle\sigma,1\rangle$ configurations two groups exist, with $\tau_2=0$, $\tau_1=1,2,3,\ldots,\sigma$ and $\tau_2=1,2,3,\ldots,\sigma$. The pseudo-orbital angular momentum of the boson-fermion system L does not correspond to the angular momentum of the core states alone.[8] For $\tau_2=0$ it takes the values of the usual O(5)$\supset$O(3) reduction, which are, for the lowest cases, $L=0$ for $\tau_1=0$, $L=2$ for $\tau_1=1$, $L=2,4$ for $\tau_1=2$, and $L=0,3,4,6$ for $\tau_1=3$. In the case of $\tau_2=1$, $L=1,3$ is possible for $\tau_1=1$, and $L=1,2,3,4,5$ for $\tau_1=2$. Finally, the pseudo-spin $S=\frac{1}{2}$ is coupled to each L to give the total spin of the level $J=L+\frac{1}{2}$ or $J=L-\frac{1}{2}$, which is an experimentally observable quantity.

A schematic representation of the levels of the above eigenvalue equation is given in Fig. 1 with parameters appropriate for the platinum region. By comparison with Eq. (1), it is seen that the separation of the different multiplets within a configuration $[h_1,h_2]-\langle\sigma_1,\sigma_2\rangle$ is determined by the parameter $B/6$ and the quantum numbers (τ_1,τ_2), the separation of the L members of a (τ_1,τ_2) multiplet depends on the parameter C, and C'' determines the spin splitting for constant L. In particular, the level spacing for corresponding multiplets is the same for the $\langle N+1,0\rangle$ and $\langle N,1\rangle$ configurations. The parameters A and $A''/4$ determine the separation of the different families of levels. For the separation of the $\langle N+1,0\rangle$ and $\langle N,1\rangle$ groups the parameters enter only in the combination $(2N+2)(A-A''/4)$. A and $A''/4$ can separately be determined, when in addition the configuration $\langle N-1,0\rangle$ is considered.

For the doubly even platinum isotopes, we use the interacting boson approximation in the O(6) limit, for which the eigenvalue equation is[5]

$$E(\sigma,\tau,J)=(A''/4)(N-\sigma)(N+\sigma+4)$$
$$+(B/6)\tau(\tau+3)+CJ(J+1)\ . \quad (2)$$

The quantum numbers τ,σ correspond to τ_1,σ_1 of Eq. (1).

The parameters of this equation are connected to those of Eq. (1) in the SUSY scheme by the relations

$$A''_{\text{even-even}}=A''_{\text{even-odd}},B_{\text{even-even}}=B_{\text{even-odd}}\ ,$$

and

$$C_{\text{even-even}}=C_{\text{even-odd}}+C''_{\text{even-odd}}\ .$$

Note that up to terms depending only on N, this is

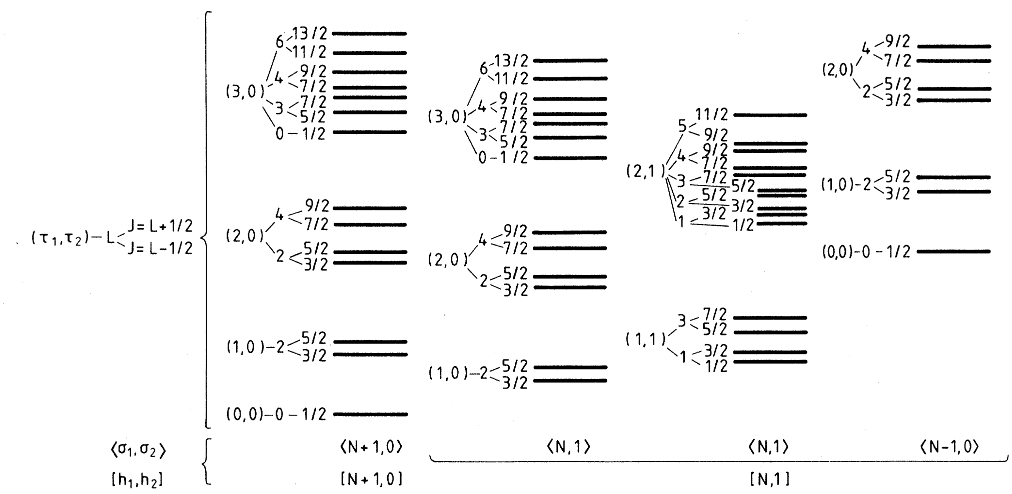

FIG. 1. Schematic level scheme and quantum numbers for the IBFM according to the eigenvalue equation (1). For the parameters A, $A''/4$, $B/6$, C, and C'' values appropriate for the negative-parity states of the odd-platinum isotopes have been taken.

equivalent to taking Eq. (1) with the even-even quantum numbers

$$[h_1,h_2]=[N,0],\quad \langle \sigma_1,\sigma_2\rangle=\langle \sigma,0\rangle ,$$

$$(\tau_1,\tau_2)=(\tau,0) \text{ and } J=L ,$$

so we can say we use Eq. (1) for both the even-even and even-odd partners.

It should be noted that the supersymmetry scheme connects nuclei with a constant sum of boson and fermion numbers, $n_b+n_f=\text{const}=N_0$. If an even-even nucleus with mass A has N_0 active bosons ($n_b=N_0$, $n_f=0$), its SUSY partner is an odd-mass nucleus with mass $A\pm1$ and the boson and fermion numbers $n_b=N=N_0-1$, $n_f=1$, where the positive sign applies if the valence neutrons and protons are both particle like or hole like and the negative sign to the case where one is particle like and the other hole like.[7,8]

III. CLASSIFICATION OF EXPERIMENTAL LEVELS IN TERMS OF THE U(6/12) QUANTUM NUMBERS

For the isotope ^{195}Pt new quantum numbers were assigned on the ground of characterictic $B(E2)$ values and energy systematics.[13,14] For the other even-odd nuclei, the classification, presented in the following sections, is predominantly based on energy systematics. Where known, $E2$ branching ratios and analogies in experimental spectroscopic factors of nucleon-transfer experiments with those for ^{195}Pt are taken into account.

In our analysis the parameters A, $A''/4$, $B/6$, C, and C'' of the eigenvalue equation are obtained by a least-squares fit of the excitation energies

$$E(h_1h_2;\sigma_1\sigma_2;\tau_1\tau_2;L;J)-E_{\text{gs}}$$

of the lowest-lying $(\tau_{,}\tau_2)=(0,0)$, $(1,0)$, and $(2,0)$ levels of the even-odd isotopes to the corresponding experimental values. The energies of levels in the doubly even isotopes are calculated with Eq. (2) using the same parameters. The experimental data and the results of the analysis for the different isotopes are given below.

^{195}Pt

This nucleus has been treated in detail in Refs. 13 and 14. We therefore only give a short summary. The existing level scheme for ^{195}Pt is the result of β-decay studies of Jansen *et al.*[19] (d,p) and (d,t) experiments of Yamazaki and Sheline,[1] (p,d) experiments of Smith *et al.*[20] and Berrier-Ronsin *et al.*,[21] $(^3\text{He},\alpha)$ experiments of Thornsteinsen *et al.*,[22] average resonance neutron-capture investigations of Warner *et al.*,[3] neutron inelastic scattering experiments of Ghatak-Roy and Yates,[23] (n,e^-) experiments of Casten *et al.*,[24] and Coulomb excitation studies of Bruce *et al.*[15] and Mauthofer *et al.*[13,14] The experimentally observed levels and spin parities are listed in Table I, together with previous assignments of U(6/12) quantum numbers, the classification proposed in Refs. 13 and 14, and the energies calculated in that classification using Eq. (1). The parameters for ^{195}Pt, determined by a least-squares fit to the experimental level energies, are $A=64.38$ keV, $A''/4=56.69$ keV, $B/6=50.21$ keV, $C=1.15$ keV, and $C''=5.40$ keV. In setting up the new classification scheme, we were led by electromagnetic properties as observed in the Coulomb excitation experiment of Refs. 13 and 14, together with newly observed levels in that investigation. The resulting level scheme for ^{195}Pt is shown in Fig. 2. The levels of ^{194}Pt are taken from Lederer.[25]

^{197}Pt

The experimental energies and spin parities again are mainly derived from nucleon-transfer and neutron-capture experiments. They are taken from Refs. 2, 4, 20–22, and 25–27, in most of which also other platinum isotopes are investigated.

The experimental data, previous quantum number assignments, proposed new assignments, and calculated energies using the new assignments are listed in Table II. The least-squares fit to the experimental data results in the parameters $A=85.14$ keV, $A''/4=63.12$ keV, $B/6=65.48$ keV, $C=5.29$ keV, and $C''=3.89$ keV. The experimental levels and their spin parities, together with their quantum number assignments and the theoretical levels are shown in Fig. 3. The data for ^{196}Pt are taken from Ref. 14.

TABLE I. Energies, spin parities, and IBFM classification of levels in ^{195}Pt.

Experimental energy (keV)	Spin parity	IBFM classification $\langle\sigma_1,\sigma_2,\sigma_3\rangle$-$(\tau_1,\tau_2)$-$L$-$J$ Previous[a]	This work	Calculated energy[b] (keV)
0	$\frac{1}{2}^-$	$\langle 7,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	$\langle 7,0,0,\rangle$-(0,0)-0-$\frac{1}{2}$	0
99	$\frac{3}{2}^-$	$\langle 6,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 6,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	116
130	$\frac{5}{2}^-$	$\langle 6,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	$\langle 6,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	143
199	$\frac{3}{2}^-$	$\langle 6,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	$\langle 6,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	212
211	$\frac{3}{2}^-$	$\langle 7,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 7,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	224
222	$\frac{1}{2}^-$	$\langle 6,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	$\langle 6,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	195
239	$\frac{5}{2}^-$	$\langle 7,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	$\langle 7,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	251
389	$\frac{5}{2}^-$	$\langle 6,1,0\rangle$-(1,1)-3-$\frac{5}{2}$	$\langle 6,1,0\rangle$-(1,1)-3-$\frac{5}{2}$	250
420	$\frac{3}{2}^-$	$\langle 7,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	$\langle 6,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	417
450	$(\frac{7}{2}^-)$	$\langle 6,1,0\rangle$-(1,1)-3-$\frac{7}{2}$	$\langle 6,1,0\rangle$-(1,1)-3-$\frac{7}{2}$	288
455	$\frac{5}{2}^-$	$\langle 7,0,0\rangle$-(2,0)-2-$\frac{5}{2}$	$\langle 6,1,0\rangle$-(2,0)-2-$\frac{5}{2}$	444
508	$\frac{7}{2}^-$	$\langle 7,0,0\rangle$-(2,0)-4-$\frac{7}{2}$	$\langle 6,1,0\rangle$-(2,0)-4-$\frac{7}{2}$	498
525	$\frac{3}{2}^-$	$\langle 6,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	$\langle 7,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	525
544	$\frac{5}{2}^-$		$\langle 7,0,0\rangle$-(2,0)-2-$\frac{5}{2}$	552
563	$\frac{9}{2}^-$	$\langle 7,0,0\rangle$-(2,0)-4-$\frac{9}{2}$	$\langle 6,1,0\rangle$-(2,0)-4-$\frac{9}{2}$	547
591	$\frac{3}{2}^-$	$\langle 5,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	$\langle 6,1,0\rangle$-(2,1)-1-$\frac{3}{2}$	513
613	$\frac{7}{2}^-$		$\langle 7,0,0\rangle$-(2,0)-4-$\frac{7}{2}$	606
630	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 7,0,0\rangle$-(3,0)-0-$\frac{1}{2}$	$\langle 6,1,0\rangle$-(2,1)-1-$\frac{1}{2}$	497
632	$\frac{5}{2},\frac{7}{2}^-$			
664	$(\frac{5}{2},\frac{7}{2}^-)$			
667	$(\frac{9}{2}^-)$		$\langle 7,0,0\rangle$-(2,0)-4-$\frac{9}{2}$	655
678	$(\frac{7}{2}^-)$			
695	$(\frac{7}{2}^-)$			
739	$\frac{1}{2},\frac{3}{2}^-$			
749	$\frac{1}{2},\frac{3}{2}^-$			
765	$(\frac{5}{2},\frac{7}{2})^-$			
780	$(\frac{1}{2},\frac{3}{2})^-$			
815	$\frac{9}{2}^-$			
883	$(\frac{5}{2},\frac{7}{2})^-$			
927	$\frac{1}{2}^-,\frac{3}{2}^-$		$\langle 5,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	912
930	$(\frac{9}{2}^-)$			
980	$(\frac{5}{2},\frac{7}{2})^-$			
1016	$(\frac{5}{2},\frac{7}{2})^-$			
1033	$(\frac{5}{2},\ldots,\frac{11}{2})$			
1055	$(\frac{5}{2},\frac{7}{2})^-$			
1092	$(\frac{5}{2},\ldots,\frac{13}{2})$			
1096	$\frac{1}{2},\frac{3}{2}^-$			
1103	$(\frac{1}{2},\frac{3}{2})^-$			
1132	$\frac{1}{2}^-,\frac{3}{2}^-$		$\langle 5,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	1136
1137	$\frac{1}{2},\frac{3}{2}^-$			
1156	$\frac{5}{2}^-$		$\langle 5,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	1164

[a]Reference 3.
[b]Calculated with Eq. (1) and the parameters given in the text.

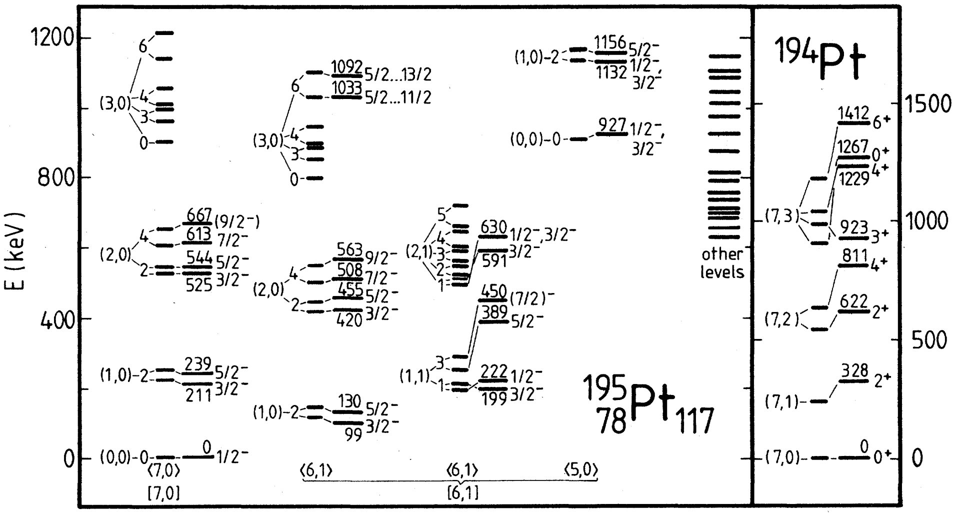

FIG. 2. Comparison of experimental levels to the theoretical energies and quantum numbers of the SUSY scheme for the isotopes ^{195}Pt and ^{194}Pt ($n_b+n_f=7$). The parameters are given in the text. Notice the different energy scales for the even-odd and even-even isotopes. The excitation energies and spin parities for other levels are given in Table I. Levels in the even-even nucleus are labeled by (σ,τ).

^{199}Pt

The experimental level energies and spin parities listed in Table III are taken from Refs. 4 and 28. The theoretical energies in the last column of Table III are calculated with the parameters $A-A''/4=36.7$ keV, $B/6=78.67$ keV, $C=8.69$ keV, and $C''=-5.19$ keV, obtained by fitting the theoretical energies of Eq. (1) to the experimental levels. Figure 4 shows a comparison of theory and experiment. The level energies for the doubly even neighbor ^{198}Pt are taken from Ref. 25.

^{193}Pt

The level energies and spin parities listed in Table IV are taken from Nuclear Data Sheets,[29] the Table of Iso-

TABLE II. Energies, spin parities, and proposed IBFM classification of levels in ^{197}Pt.

Experimental energy (keV)	Spin parity	Classification $\langle\sigma_1,\sigma_2,\sigma_3\rangle$-$(\tau_1,\tau_2)$-$L$-$J$ Previous[a]	This work	Calculated energy[b] (keV)
0	$\frac{1}{2}^-$	$\langle 6,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	$\langle 6,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	0
53	$\frac{5}{2}^-$	$\langle 5,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	$\langle 5,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	61
72	$\frac{3}{2}^-$	$\langle 5,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 5,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	41
99	$\frac{3}{2}^-$	$\langle 5,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	$\langle 5,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	151
131	$\frac{1}{2}^-$	$\langle 5,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	$\langle 5,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	139
269	$\frac{3}{2}^-$	$\langle 6,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 6,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	305
299	$\frac{5}{2}^-$	$\langle 6,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	$\langle 6,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	325
425[c]	$\frac{1}{2}^-,\frac{3}{2}^-$		$\langle 5,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	434
457	$(\frac{5}{2}^-)$	$\langle 5,1,0\rangle$-(1,1)-3-$\frac{5}{2}$	$\langle 5,1,0\rangle$-(2,0)-2-$\frac{5}{2}$	453
481	$(\frac{1}{2}^-,\frac{3}{2}^-)$	$\langle 6,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	$\langle 5,1,0\rangle$-(2,1)-1-$\frac{1}{2}$	532
502	$\frac{1}{2}^-,\frac{3}{2}^-$		$\langle 5,1,0\rangle$-(2,1)-1-$\frac{3}{2}$	543
530	$\frac{5}{2}^-,\frac{7}{2}^-$	$\langle 6,0,0\rangle$(2,0)-2-$\frac{5}{2}$	$\langle 5,1,0\rangle$-(2,0)-4-$\frac{7}{2}$	555
595	$\frac{7}{2},\frac{9}{2}$	$\langle 5,1,0\rangle$-(1,1)-3-$\frac{7}{2}$	$\langle 5,1,0\rangle$-(2,0)-4-$\frac{9}{2}$	590
708	$\frac{3}{2}^-$	$\langle 5,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	$\langle 6,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	689
713	$\frac{5}{2}^-$			
748	$\frac{1}{2}^-$		$\langle 4,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	748
825	$\frac{1}{2}^-,\frac{3}{2}^-$			
852	$\frac{5}{2}^-,\frac{7}{2}^-$		$\langle 6,0,0\rangle$-(2,0)-4-$\frac{7}{2}$	818

[a]Reference 4.
[b]Calculated with Eq. (1) and the parameters given in the text.
[c]Existence of level questionable, see Ref. 4.

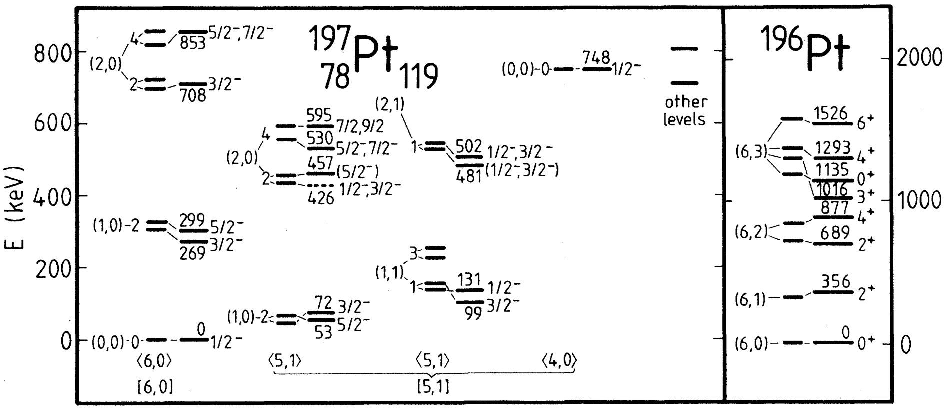

FIG. 3. Same as Fig. 2, but for the isotopes ^{197}Pt and ^{196}Pt ($n_b+n_f=6$).

topes,[25] internal conversion electron studies of the decay of ^{193}Au of Svahn *et al.*,[30] (p,d) experiments of Smith *et al.*,[20] (p,t) data of Rotbard *et al.*,[31] and (^{3}He,α) data of Thorsteinsen *et al.*[22] The energies listed in the last column of Table IV are calculated using Eq. (1) with the parameters $A-A''/4=12.27$ keV, $B/6=46.37$ keV, $C=-1.27$ keV, and $C''=10.35$ keV. Theory and experiment are compared in Fig. 5. The energies of levels in ^{194}Pt are taken from Ref. 25.

IV. DISCUSSION

Even-odd nuclei

^{195}Pt. In Ref. 13 arguments are given for a change of the level classification against earlier assignments.[3] They mainly depend on electromagnetic matrix elements between excited states, obtained in that reference, and on selection rules of the model. The changes concern the interchange of some levels between the families $\langle 7,0\rangle$ and $\langle 6,1\rangle$, and $\langle 6,1\rangle$ and $\langle 5,0\rangle$ (see Table I).

As is seen in Fig. 2, the eigenvalue equation [Eq. (1)] reproduces the experimental levels rather well for the low-lying states. This is particularly true for the multiplet separations of the configurations $(\tau_1,\tau_2)=(1,0)$ and (2,0) of the $\langle 7,0\rangle$ and $\langle 6,1\rangle$ families of levels. For the configurations with $\tau_2=1$ of the $\langle 6,1\rangle$ family the situation is less favorable. However, at least the (1,1) group is reproduced (with an inversion of the 199- and 222- keV states). For excitation energies above 600 keV a classification has been tried only for a few levels which were close in energy and had compatible spin to those predicted by theory based on the parameters determined at lower energy. In particular, three experimental levels at 927 keV ($\frac{1}{2}^-,\frac{3}{2}^-$), 1132 keV ($\frac{1}{2}^-,\frac{3}{2}^-$), and 1156 keV ($\frac{5}{2}^-$) have the correct relative separation of a $(\tau_1,\tau_2)-L=(0,0)$-0/(1,0)-2 structure. Their classification as members of the [6,1]-$\langle 5,0\rangle$ family has the conse-

TABLE III. Level energies, spin parities, and possible IBFM quantum number assignments for ^{199}Pt.

Experimental energy (keV)	Spin parity	Classification $\langle\sigma_1,\sigma_2,\sigma_3\rangle$-$(\tau_1,\tau_2)$-$L$-$J$ Previous[a]	This work	Calculated energy[b] (keV)
0	$\frac{5}{2}^-$	$\langle 4,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	$\langle 4,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	0
35	$\frac{3}{2}^-$	$\langle 4,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 4,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	26
42	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 5,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	$\langle 5,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	42
88	$\frac{3}{2}^-$	$\langle 4,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	$\langle 4,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	149
132	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 4,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	$\langle 4,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	165
355	$(\frac{5}{2}^-)$		$\langle 5,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	367
384	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 5,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	$\langle 5,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	393
475	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 5,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	$\langle 4,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	472
570	$\frac{5}{2}^-$	$\langle 4,1,0\rangle$-(1,1)-3-$\frac{5}{2}$		
647	$(\frac{5}{2}^+,\frac{7}{2}^+)$ $\frac{5}{2}^\pm$ $(\frac{1}{2}^+,\frac{3}{2}^+)$			
888	$\frac{1}{2}^-,\frac{3}{2}^-$	$\langle 3,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	$\langle 5,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	865

[a]References 4 and 12.

[b]Calculated with Eq. (1) and the parameters given in the text.

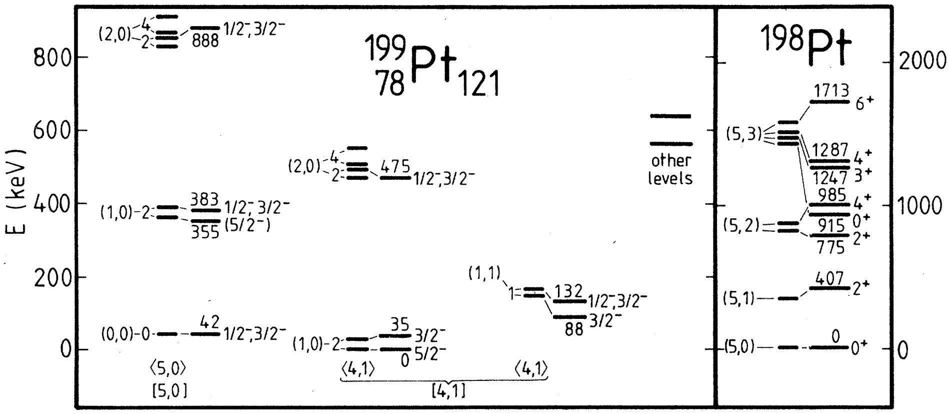

FIG. 4. Same as Fig. 2, but for the isotopes ^{199}Pt and ^{198}Pt ($n_b+n_f=5$).

quence that the parameters A and $A''/4$ can separately be determined. Levels which have not been classified are shown on the right side of Fig. 2 as "other levels." It should be noted that the theory would provide an equivalent number of levels with the configurations $\langle 7,0\rangle$-(3,0), $\langle 6,1\rangle$-(3,0), and $\langle 6,1\rangle$-(2,1).

^{197}Pt. Less experimental information is available for ^{197}Pt than for ^{195}Pt. In particular, no electromagnetic matrix elements are known with which selection rules of the theory could have been applied for the classification. Figure 3 shows, however, that the experimentally known states can be reasonably well arranged to reproduce the theoretical structure. Our classification differs from the earlier one[4] in the assignment of states to the $\langle 6,0\rangle$ and

TABLE IV. Level energies, spin parities, and proposed IBFM classification for ^{193}Pt.

Experimental level energy (keV)	Spin parity	Proposed classification $\langle\sigma_1,\sigma_2,\sigma_3,\rangle$-$(\tau_1,\tau_2)$-$L$-$J$	Calculated energy[a] (keV)
0	$\frac{1}{2}^-$	$\langle 8,0,0\rangle$-(0,0)-0-$\frac{1}{2}$	0
1.6	$\frac{3}{2}^-$	$\langle 7,1,0\rangle$-(1,0)-2-$\frac{3}{2}$	13
14	$\frac{5}{2}^-$	$\langle 7,1,0\rangle$-(1,0)-2-$\frac{5}{2}$	64
114	$(\frac{3}{2}^-)$	$\langle 7,1,0\rangle$-(1,1)-1-$\frac{3}{2}$	110
121		$\langle 7,1,0\rangle$-(1,1)-1-$\frac{1}{2}$	79
188	$\frac{3}{2}^-$	$\langle 8,0,0\rangle$-(1,0)-2-$\frac{3}{2}$	208
232	$\frac{5}{2}^-$	$\langle 8,0,0\rangle$-(1,0)-2-$\frac{5}{2}$	260
270	$\frac{3}{2}^-$	$\langle 7,1,0\rangle$-(2,0)-2-$\frac{3}{2}$	291
330	$(\frac{9}{2},\frac{11}{2})^-$		
415	$(\frac{5}{2},\frac{7}{2})^-$		
425	$\frac{5}{2}^-,\frac{7}{2}^-$	$\langle 7,1,0\rangle$-(2,0)-4-$\frac{7}{2}$	397
439	$(\frac{3}{2}^-)$	$\langle 8,0,0\rangle$-(2,0)-2-$\frac{3}{2}$	487
460	$(\frac{1}{2},\frac{3}{2})^-$ $(\frac{5}{2},\frac{7}{2})^-$	doublet	
491	$\frac{5}{2}^-$	$\langle 8,0,0\rangle$-(2,0)-2-$\frac{5}{2}$	538
522	$(\frac{3}{2},\frac{5}{2})^-$		
530	$(\frac{1}{2},\frac{3}{2})^-$		
544	$(\frac{5}{2},\frac{7}{2})^-$		
563	$(\frac{1}{2},\frac{3}{2})^-$		
599	$\frac{5}{2}^-,\frac{7}{2}^-$	$\langle 8,0,0\rangle$-(2,0)-4-$\frac{7}{2}$	593
630	$(\frac{5}{2},\frac{7}{2})^-$		
700	$(\frac{1}{2},\frac{3}{2})^-$		
701	$(\frac{5}{2},\frac{7}{2})^-$		
728	$(\frac{5}{2},\frac{7}{2})^-$		
755	$(\frac{5}{2},\frac{7}{2})^-$		

[a]Calculated with Eq. (1) and the parameters given in the text.

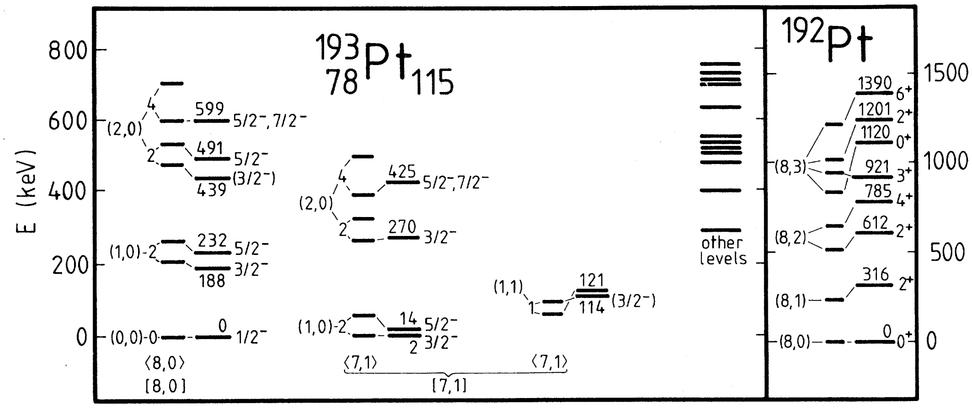

FIG. 5. Same as Fig. 2, but for the isotopes ^{193}Pt and ^{192}Pt ($n_b+n_f=8$).

$\langle 5,1 \rangle$ families of levels (see Table II).

^{199}Pt. For this nucleus 11 levels with negative parity are known up to an excitation energy of 910 keV. For only a few of them unique spin assignments exist. Nevertheless, with the IBFM quantum numbers assigned to these levels, as shown in Fig. 4, reasonable values of the relative energies are obtained. The ground-state spin of this nucleus is $\frac{5}{2}^-$, indicating a reversed spin splitting, i.e., a negative value for the parameter C''. It is of interest that the reversed order of spins is not only observed in the ground state $\langle 4,1 \rangle$-(1,0) configuration but also for the $\langle 5,0 \rangle$-(1,0)-2 and $\langle 4,1 \rangle$-(1,1)-1 couplets. Having the nonunique spin assignments in mind, the classification, although compatible with the experimental data, rests on the assumption that the spin of the 42- and 132-keV levels $(\frac{1}{2}^-,\frac{3}{2}^-)$, is $\frac{1}{2}$, and that of the 383-, 475-, and 888-keV levels $(\frac{1}{2}^-,\frac{3}{2}^-)$, is $\frac{3}{2}^-$.

^{193}Pt. For this nucleus the classification of levels is more speculative than in the other cases. Above 300 keV several levels have been observed experimentally which cannot be incorporated in the present scheme and are shown as "other levels" in Fig. 5. They may possibly arise in part from the $f_{7/2}$ or $h_{9/2}$ single-particle orbits. The levels belonging to the $(\tau_1,\tau_2)=(2,0)$ multiplets were assigned using energy systematics obtained from the (1,0) and (0,0) states and the fact that the (2,0)-4 levels are appreciably excited by stripping and pickup reactions in ^{193}Pt and ^{195}Pt as well.[16,21,31]

Figure 6 shows the systematic variation of the parameters determined by fits to the experimental data as a function of the mass number of the isotopes. It is seen that this variation is smooth and monotonous for $B/6$, C, and C'', while the parameter $(A-A''/4)$, which describes the relative spacing of the $[N+1,0]$ and $[N,1]$ families, has a minimum for ^{195}Pt.

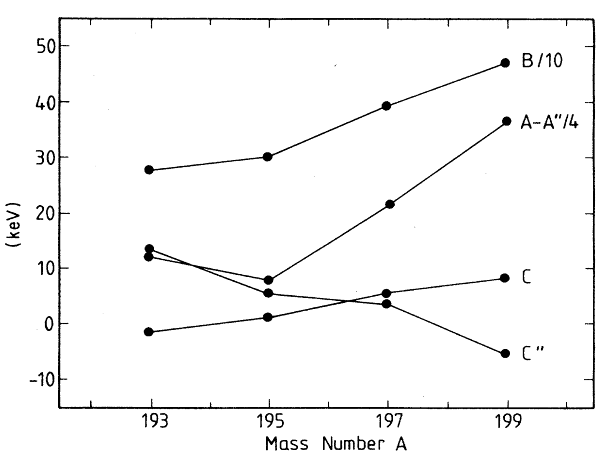

FIG. 6. Systematic variation of the SUSY parameters of the platinum isotopes with mass number A.

Energy spectra of the even-even isotopes

The spectra of the even-even isotopes, ^{192,194,196,198}Pt, which were calculated using the parameters obtained for the even-odd isotopes, are shown on the right-hand parts of Figs. 2–5. They generally agree well with the experimental values. Note the compressed energy scale as compared to the left display. The model predictions for the states with $\tau=3$ above about 1 MeV are less well reproduced by the data. This is not unexpected, however, since their energies were obtained by extrapolation from the even-odd spectra in which states up to only $\tau=2$ were taken into consideration.

The overall agreement between experimental level energies and those calculated within the SUSY scheme is appreciably improved compared to calculations using the parameters of Refs. 3 and 4. The ^{196}Pt data are particularly well reproduced. The "quality factor" R_E, which has been used in the literature[16] to characterize the deviation between the model and experiment is only 8% for all $\tau=1,2,3$ levels. It is particularly satisfactory that the parametrization within the SUSY scheme and parameters obtained by fitting ^{197}Pt offers almost as good a description of ^{196}Pt as the best fit O(6) limit for this nucleus by itself. Nevertheless, it should be pointed out that the assignments proposed for the isotopes ^{193,197,199}Pt in our study are based primarily on excitation energies and that further experiments to obtain electromagnetic matrix elements are necessary to support the proposed interpretation. To remove existing discrepancies in some of the electromagnetic moments[13–15] and spectroscopic factors[16] an extension of the model to include orbits of higher angular momentum may also be necessary.

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