Level structure of ^{197}Pt, ^{199}Pt: Status of a possible multi-j supersymmetry

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A complete set of the low lying $1/2^-$ and $3/2^-$ levels of ^{197,199}Pt was obtained from measurements of the primary γ-ray spectra following average resonance neutron capture experiments at incident neutron energies centered at 2 and 24 keV. A combination of the ^{197}Pt results with those of a recent (t,p) experiment allows the further restriction of spin-parity assignments, including some for levels with $J \geq 5/2$. The results are discussed in comparison with those previously obtained for ^{195}Pt in terms of the Nilsson model and the recently proposed multi-j supersymmetry that may apply in this O(6)-like region.

[NUCLEAR STRUCTURE ^{196}Pt(n,γ), ^{198}Pt(n,γ), $E_n=2$, 24 keV; measured E_γ, I_γ; ^{197}Pt, ^{199}Pt, deduced levels, J, π. Ge(Li) detectors, enriched targets, ARC spectroscopy. Comparison with predictions of multi-j supersymmetry in the interacting boson fermion approximation model.]

I. INTRODUCTION

The empirical establishment of a nuclear symmetry in a certain region often offers the possibility to understand nearby nuclei in terms of systematic deviations from it. Classic examples of this are the treatment of even-even nuclei near the edge of the deformed rare earth region in terms of an increasing rotation-vibration coupling which breaks the axial symmetry of the rotor and, more recently, that of the Pt-Os nuclei in terms of increasing deviations[1] from the O(6) symmetry of the interacting boson approximation (IBA).

The recent successes of the IBA in even-even nuclei, in particular in terms of symmetries, has stimulated the search for the so-called supersymmetries that pertain to odd mass nuclei. The first odd mass symmetry to be elucidated theoretically[2] was that of a $j=3/2$ particle coupled to an O(6) core. Empirical evidence for this was sought[3,4] in the odd Ir isotopes. However, the shell model never provides an isolated 3/2 orbit: In an even parity shell the $d_{3/2}$ orbit is always accompanied by a nearby $s_{1/2}$ orbit, while in a negative parity shell the $p_{3/2}$ is always close to $f_{5/2}$ and $p_{1/2}$ orbits. Therefore, it was necessary to ascertain which levels in the odd Ir isotopes had $j=3/2$ parentage, that is, to empirically isolate a subset of the low lying levels and to verify that little j mixing occurred. Very recently, however, Balentekin *et al.*[5] developed a scheme incorporating multiple j orbits, one example of which is applicable to the case of particles in $j=1/2$, 3/2, and 5/2 orbits with an O(6) core. The obvious test is then to be found in the negative parity states of the odd Pt isotopes, where the underlying core has the O(6) symmetry. In a study just completed,[6] the level scheme of ^{195}Pt has been constructed and compared to this multi-j supersymmetry scheme. In this case, the lowest 16 negative parity energy levels, that is, all such levels below 600 keV, were found to be in a 1-1 correspondence with the predictions, and predicted patterns of repeated energy doublets characteristic of the supersymmetry scheme were found. Unfortunately, the data on transition rates and mutlipolarities were not sufficient to provide much additional support, but the presence of symmetry breaking could be inferred from two pairs of measured $B(E2)$ values. In addition, the relative excitation energies of the two major predicted families of levels deviated from the predictions. Nevertheless, as the first empirical test of a multi-j supersymmetry, these earlier results[6] are encouraging and provide a stimulus to further studies.

With that motivation, the present work on ^{197}Pt and ^{199}Pt is an outgrowth of the earlier study. Noting that, in the Ir nuclei, characteristics of the single-j supersymmetry rapidly disintegrated with increasing mass, it was anticipated that a similar systematics might occur here. Indeed, prior level schemes[7,8] for ^{197}Pt suggest significant differences with ^{195} Pt. The aim here was to use average resonance capture (ARC) spectroscopy to identify a complete set of $1/2^-$ and $3/2^-$ levels up to roughly 1 MeV in each nucleus and to compare these with their counterparts in ^{195}Pt to further study the status and evolution of the approximate supersymmetry scheme across this series of isotopes. The results are rather surprising. As will be shown below, the ^{197,199}Pt level schemes are, contrary to the above expectations, strikingly similar to ^{195}Pt, and the addition of the present results will be seen to pinpoint rather definitely the adequacies and difficulties of the supersymmetry scheme.

The existing low spin level scheme for ^{197}Pt is primarily the result of (d,p), (d,t), and (n,γ) studies of Yamazaki *et al.*[7] and a (t,p) study of Cizewski *et al.*[8] Cizewski *et al.*[8] have combined the results of the proposed transferred l_n values of Ref. 7 with the implications of the (t,p) data of Ref. 8 to work out a suggested set of level energies and J^π assignments reflecting existing knowledge. The combination of the present ARC data with this recent (t,p) study, however, leads to a number of spin assignments at variance with those previously suggested and to a different view of the nuclear structure of ^{197}Pt. These differences can be explained in most cases by the difficulty in assigning definite transferred orbital angular momenta in the (d,p) and (d,t) studies of Ref. 7. For ^{199}Pt, there is very little previous data, but a concurrent (n,γ) study by Davidson *et al.*[9] has centered on low energy secondary transitions and on the measurement of transition mutlipolarities. Combined with the present study, this again gives a complete set of low spin negative parity states and many definite spin assignments up to 1 MeV.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The principle of ARC spectroscopy lies in its automatic averaging over a number of capture states by virtue of the nonmonoenergetic character of the incident neutron beam. In a single resonance, the intensities of primary γ rays follow a Porter-Thomas distribution in which, typically, the intensities are scattered over several orders of magnitude and many spin-allowed $E1$ primaries are not observed. However, in ARC the local fluctuations in primary intensities are much reduced, being approximately given by $2/\sqrt{N_r}$, where N_r is the number of resonances in the energy interval of the nonmonoenergetic neutron beam. Superimposed on this band of intensities is a secular intensity decrease given approximately by $E_\gamma{}^5$. Thus, the so-called reduced intensities, $I_R = I_\gamma / E_\gamma{}^5$, should lie in a horizontal band when plotted against excitation energy. ARC studies can be carried out at the tailored beam facility of the Brookhaven High Flux Beam Reactor, where neutron beams centered on 2 and 24 keV are available through the use of Sc and Fe filters, respectively. The facility has been described in detail elsewhere.[10]

At 2 keV, s wave capture dominates so that, starting from an even-even target, capture states of $J^\pi = 1/2^+$ are formed. The dominant decay mode is $E1$ ($M1$ transitions are weaker by roughly a factor of 6) so that final states with $J^\pi = 1/2^-$, $3/2^-$ are populated. Thus, for nuclei not near closed shells, and where sufficient enriched target material is available, the averaging is usually sufficient to ensure the detection of all such levels up to some excitation energy, typically 1—1.5 MeV. In favorable cases the detection sensitivity limit may allow the disclosure of the weaker $1/2^+$, $3/2^+$ levels. At 24 keV incident neutron energy, p-wave capture also contributes strongly, leading to $1/2^-$, $3/2^-$ capture states and, in combination with the still present s-wave capture, to comparable intensities to final states of $1/2^-$, $3/2^-$ and $1/2^+$, $3/2^+$. Since $p_{3/2}$ capture followed by $E1(M1)$ transitions can lead to $5/2^{+(-)}$ states, these can be observed. Finally, the ratio of reduced intensities,

$$I_R(2\text{ keV})/I_R(24\text{ keV}) ,$$

is frequently useful as a parity indicator.

The present experiments utilized Pt targets of 15.15 g enriched to 97.51% in ^{196}Pt and 4.67 g enriched to 95.8% in ^{198}Pt. The primary γ rays were detected in a three-crystal pair spectrometer. Energy and efficiency calibrations, as well as nonlinearity corrections, were obtained using the ^{35}Cl(n,γ) reaction[11] at thermal neutron energies. The identification of contaminant lines in the spectra is facilitated by knowledge of a well-known library of contaminants compiled from previous studies and by the empirical fact that contaminant lines arise almost solely from other Pt isotopic impurities or from thermal capture in surrounding material. The former can be identified from companion studies. The latter are easily recognized by their constancy in energy when the incident neutron energy is changed from 2 to 24 keV, whereas true γ-ray lines from the target shift upwards in energy by ≈ 22 keV since the average capture state energy increases by this amount.

Figures 1 and 2 show portions of the data for ^{197}Pt and ^{199}Pt, respectively. Peaks are labeled by nominal excitation energies of final states in these two nuclei. Tables I and II summarize the measured primary energies and reduced intensities, the deduced excitation energies, and the J^π values de-

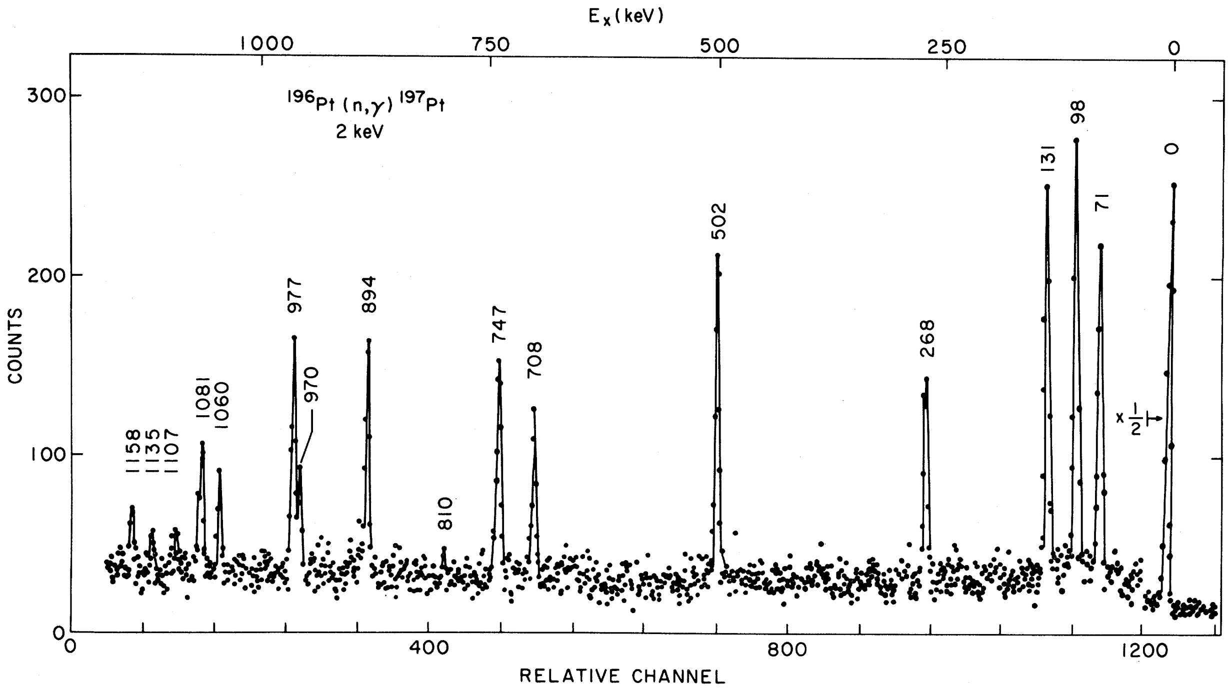

FIG. 1. Portion of an ARC spectrum for ^{197}Pt at 2 keV. Some peaks are labeled by nominal excitation energies.

duced, both directly from the ARC data, and by combination with other data.

It can be seen from these data that the averaging in the current measurements is relatively poor, due to the small level density in the two nuclei under investigation near the neutron binding energy. This feature is particularly evident in the case of the 2 keV results for ^{199}Pt. However, the broader width of the 24 keV neutron beam alleviates this problem somewhat so that it is still unlikely that any states with $J^{\pi}=1/2^{-}$, $3/2^{-}$ have been missed up to 1 MeV of excitation energy in ^{197}Pt and about 800

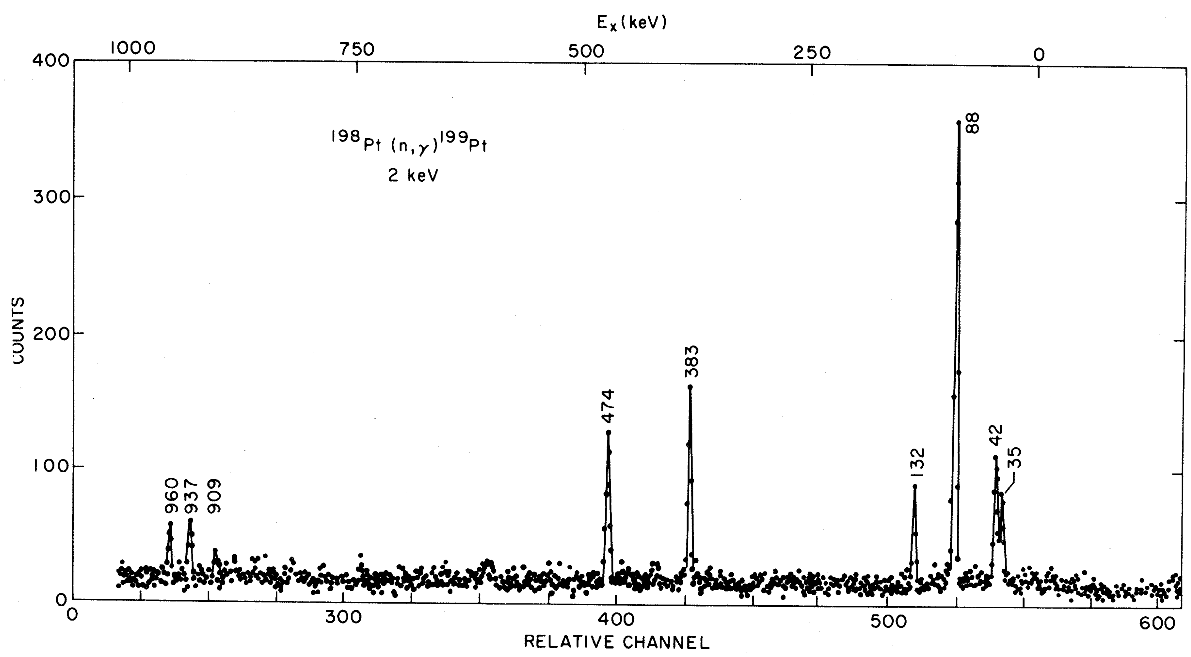

FIG. 2. Portion of an ARC spectrum for ^{199}Pt at 2 keV. Some peaks are labeled by nominal excitation energies.

TABLE I. Results of the ^{196}Pt$(n,\gamma)^{197}$Pt ARC measurements at $E_n=2$ and 24 keV.

E_x (keV)	E_γ (keV)	I_R (2 keV) $(I_\gamma/E_\gamma{}^5)$	I_R (24 keV) (I_γ/E^5)	$\frac{I_R\text{ (2 keV)}}{I_R\text{ (24 keV)}}$	$J^{\pi\,e}$ (ARC)	$L(t,p)^f$	J^π adopted
0	5848.7(3)	≡100	≡100	≡1	$1/2^-,3/2^-$	0	$1/2^-$
71.4	5777.3(3)	37.6(18)	108(10)	0.35	$1/2^-,3/2^-$	2	$3/2^-$
98.6	5750.1(3)	58.9(24)	174(13)	0.34	$1/2^-,3/2^-$	2	$3/2^-$
131.2	5717.5(3)	48.7(21)	152(11)	0.32	$1/2^-,3/2^-$	0	$1/2^-$
268.9	5579.8(3)	30.9(18)	128(9)	0.24	$1/2^-,3/2^-$	2	$3/2^-$
297.0[a]			57(14)		$5/2^\pm(1/2^+,3/2^+)$	2	$5/2^-$
502.7	5346.0(3)	53.8(26)	117(16)	0.46	$1/2^-,3/2^-$		$1/2^-,3/2^-$
708.4	5140.3(4)	32.0(24)	91(19)	0.35	$1/2^-,3/2^-$	2	$3/2^-$
747.4	5101.3(4)	50.5(34)	130(18)	0.39	$1/2^-,3/2^-$	0	$1/2^-$
810.3[a]		≈5(2)	104(18)	≈0.05	$1/2^+,3/2^+,5/2^\pm$		$1/2^+,3/2^+,5/2^\pm$
894.8	4953.9(3)	51.0(60)[b]	158(21)	0.32	$1/2^-,3/2^-$	≠0	$3/2^-$
[955.9	4892.8(13)	6.5(27)	56(17)	0.12][c]			
970.7	4878.0(4)	27.9(60)	113(21)	0.24	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$
977.9	4870.8(3)	63.6(60)	165(23)[d]	0.38	$1/2^-,3/2^-$	≠0	$3/2^-$
1060.5	4788.2(4)	29.6(32)	150(25)	0.20	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$
1081.0	4767.7(4)	43.4(35)	113(25)	0.38	$1/2^-,3/2^-$		$1/2^-,3/2^-$
1107.7	4741.0(7)	12.3(28)	115(23)	0.11	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$
1135.3	4713.4(6)	14.1(27)	56(20)[b]	0.24	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$
1158.7	4690.0(4)	15.7(40)[b]	178(27)	0.09	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$
1297.0	4551.7(5)	27.0(43)	146(34)	0.18	$1/2^\pm,3/2^\pm$		$1/2^\pm,3/2^\pm$

[a]Excitation energy taken from 24 keV data. For the 297 keV level there is no observation at 2 keV; for the 870 keV level a weak peak is observed. Except for these two levels the uncertainties on excitation energies are those on the corresponding γ-ray energies.

[b]Intensity has been corrected for a contribution from a contaminant line.

[c]Possibly all contaminant.

[d]Up to 10% is contaminant.

[e]The spin assignments are based on the following criteria:

$$J^\pi=1/2^-,3/2^- \text{ if } I_R\text{ (2 keV)}\geq 30,\ I_R(2)/I_n(24)\geq 0.24\ .$$

$$J^\pi=1/2^\pm,3/2^\pm \text{ if } 10<I_R\text{ (2 keV)}<30,\ I_R(2)/I_k(24)\leq 0.24\ .$$

$$J^\pi=1/2^+,3/2^+,5/2^\pm \text{ if } 5<I_R\text{(2 keV)}\leq 10,\text{ observed at 24 keV.}$$

$$J^\pi=5/2^\pm(1/2^+,3/2^+) \text{ if not observed at 2 keV, weak at 24 keV.}$$

[f]Data from Ref. 8. The ^{195}Pt target spin is $1/2^-$, hence $L=0$ implies $J^\pi=1/2^-$, $L=2$ implies $J^\pi=3/2^-$ or $5/2^-$. The symbol ≠ means the state was observed and, although no L value was assigned, an $L=0$ transfer can be ruled out. Above 1 MeV the association of levels in the two experiments becomes uncertain.

keV in ^{199}Pt. Of course, as always, this claim must be tempered by the realization that a pair of close lying levels of appropriate spins would appear as a single peak and might not be recognized as a doublet. By combining the present data for ^{197}Pt with the (t,p) results[8] of Cizewski *et al.*, unique J^π assignments for the levels at 53, 72, 99, 131, 269, 299, 457, 531, 708, 748, 894, and 978 keV are obtained.

In (t,p) it is trivial to distinguish $L=0$ from higher L transfers, while the differences between nonzero L transfers are less clear cut. Thus, for levels populated strongly in ARC, such that $J^\pi=1/2^-$ or $3/2^-$, a definite $3/2^-$ assignment only requires that $L=0$ transfer in (t,p) can be ruled out, not that $L=2$ transfer can be definitely inferred. It is in this sense (i.e., that $L\neq 0$) that most of the $L=2$ (t,p) results listed in Table I are used. Several other levels, for example, those at 53, 457, and 531 keV, are not observed in ARC and the spin assignment or limitation results precisely from this nonobservation which, due to the averaging process, provides as definitive results as actual observation. The 53 and 531 keV levels are assigned[7,8] $L=2$ transfers in (t,p) and $l_n=3$ transfer in both (d,p) and (d,t). The 457 keV level is likewise populated[7] by a tentative $l_n=3$ in (d,t). Similarly to the above comment for the

TABLE II. Results of the ^{198}Pt$(n,\gamma)^{199}$Pt ARC measurements at $E_n=2$ and 24 keV.

E_x (keV)[a]	E_γ (2 keV)	I_R (2 keV) $(I_\gamma/E_\gamma{}^5)$	I_R (24 keV) (I_γ/E^5)	$\frac{I_R\text{ (2 keV)}}{I_R\text{ (24 keV)}}$	J^{π}[e] (ARC)
			85(22)[b]		$5/2^-$
$\equiv$35.5	5522.6(4)	$\equiv$100(5)	$\equiv$100	$\equiv$1	$3/2^-$
42.0	5516.1(3)	205(15)	142(18)	1.44	$1/2^-,3/2^-$
88.1	5470.0(3)	676(30)	277(20)	2.44	$3/2^-$
132.5	5425.6(3)	173(13)	236(20)	0.73	$1/2^-,3/2^-$
383.5	5174.6(3)	375(20)	287(26)	1.30	$1/2^-,3/2^-$
474.6	5083.5(4)	362(21)	129(26)	2.81	$1/2^-,3/2^-$
647.1[c]	c	c	103(29)		$5/2^{\pm}(1/2^+,3/2^+)$
887.9	4670.2(7)	83(18)	$\approx$125[d]	$\approx$0.66	$1/2^{\pm},3/2^{\pm}$
909.5	4648.6(5)	99(22)	185(37)	0.54	$1/2^{\pm},3/2^{\pm}$
937.9	4620.2(4)	301(25)	200(40)	1.50	$1/2^-,3/2^-$
960.7	4597.4(4)	190(25)	146(37)	1.30	$1/2^-,3/2^-$

[a]Assumes the γ rays of 5522.6 and 5545.6 keV populate the 35.5 keV level. This gives a separation energy $S(n)=5556.1\pm0.5$ keV. Uncertainties on excitation energies are those on the corresponding γ-ray energies.
[b]Questionable observation in ARC.
[c]No peak observed at 2 keV. E_x from 24 keV.
[d]Peak partially obscured by a contaminant line.
[e]The criteria for J^π assignments from the ARC data are as follows:

$J^\pi=1/2^-,3/2^-$ if $I_R(2)>100$ and $I_R(2)/I_R(24)>0.7$.

$J^\pi=1/2^{\pm},3/2^{\pm}$ if $1\le I_R(2)<100$ and $I_R(2)/I_R(24)\le0.7$.

$J^\pi=5/2^{\pm}(1/2^+,3/2^+)$ if level is observed at 24 keV but not at 2 keV.

Further restrictions follow from the multipolarity assignments of Ref. 9 (see text).

(t,p) reaction, it is difficult to distinguish between $l_n=1$ and 3 transfers in these single nucleon transfer reactions. However, one can rather easily distinguish either of these from other l_n transfers and, therefore, the (d,p) and (d,t) results are still of use in suggesting the final state parity. The nonobservation of the 53, 457, and 531 keV levels in ARC, which implies that they are not $1/2^{\pm},3/2^{\pm}$, coupled with both the (t,p) and the (d,p) and (d,t) results, suggests $5/2^-$ assignments for each. For the 457 keV level, a proposed[12] decay branch to a $1/2^-$ level confirms the $5/2^-$ assignment. The 595 keV level is assigned[8] $L=4$ transfer in (t,p). This suggests $J^\pi=7/2^-$ or $9/2^-$ which, again, is consistent with its nonobservation in ARC. In these cases more explicit use has been made of the detailed angular distribution data of Refs. 7 and 8 and therefore the specific spin assignments should be considered somewhat more tentative.

Some spin assignments differ from those arrived at in Ref. 8 using the data of Ref. 7. Specifically, in ^{197}Pt, the state at 299 keV, previously suggested as $3/2^-$ on the basis of population by $l_n=1$ transfer in (d,t) combined with $L=2$ population in (t,p), now can be assigned $5/2^-$. The (d,t) data suggest negative parity as does the $L=2$ transfer in (t,p). Then the nonobservation at 2 keV in ARC, coupled with weak observation at 24 keV, and decay to a $1/2^-$ level leaves only $5/2^-$ as a plausible assignment. The 481 keV level was previously assigned tentative $1/2^-$, $3/2^-$ spin parity because of probable $l_n=1$ population in (d,p). However, this level was not observed in ARC at 2 keV (as is evident at a glance in Fig. 1) or 24 keV and so must be $J\ge5/2$ if indeed it exists. [It has also not been observed[7,8,12] in (t,p), decay, or by a primary transition in thermal capture.] As mentioned above, the explanation of these apparent discrepancies with the single nucleon transfer results presumably lies in the near indistinguishability of $l_n=1$ and $l_n=3$ transfers in those reactions at the low incident energy (13.5 MeV) utilized in Ref. 7 (see Figs. 3 and 4 of Ref. 7). The level at 426 keV, reported to be populated by a thermal primary transition in (n,γ) in Ref. 7, was not seen in the present study (see Fig. 1), nor has it been observed in (d,p), (d,t), β decay (Ref. 12), or (t,p), nor were any deexciting secondary γ rays found to depopulate it in Ref. 7. It seems that its existence must be regarded as doubtful and that the primary transition of 5420 keV to this level in Ref. 7

may be a contaminant line. Its energy does coincide with a line from sulfur often observed in (n,γ) studies at BNL. It is noteworthy that these results lower by three the number of low lying $1/2^-$, $3/2^-$ states and, as will be seen below, this radically changes the interpreted structure of ^{197}Pt.

In ^{199}Pt, the spin assignments or limitations result by combination of the present ARC data with the low energy γ ray placements and multipolarities of Davidson *et al.*[9] Previous results are so fragmentary here that it is pointless to discuss differences with them. The present work, and that of Davidson *et al.*, thus provide the first firm set of extensive J^π values for ^{199}Pt.

The thermal neutron binding energy can be deduced from the energy of a primary transition following 2 keV capture. In this way binding energies of 5846.7±0.5 and 5556.1±0.5 keV for ^{197}Pt and ^{199}Pt, respectively, were deduced where the highest energy primary transition has been used in each case. These values are consistent with, but provide more accurate values than, those of 5849.7±2.9 and 5571±19 keV from the compilation of Wapstra and Bos.[13]

III. DISCUSSION

The low lying negative parity levels of ^{197,199}Pt (below ≈900 keV) are summarized in Fig. 3 and compared with those already established[6] in ^{195}Pt. The dashed lines indicate a suggested correspondence between levels in the three nuclei, based primarily on the observed level sequences and in particular, for the low lying levels, on single neutron transfer data.[7,14] In their study, Yamazaki *et al.*[7] discussed at length the difficulties in understanding the four low lying $1/2^-$ or $3/2^-$ states in ^{197}Pt at 0, 72, 99, and 131 keV in terms of the Nilsson scheme with oblate deformation. Since all four states have relatively large (d,p) or (d,t) cross sections, the possible Nilsson assignments are restricted to the $1/2^-$ [530] and $3/2^-$ [532] orbits. However, this only provides three $1/2^-$, $3/2^-$ states and, from the Nilsson wave functions, only two with appreciable single nucleon transfer strength. Moreover, attempts[7] to interpret ^{197}Pt with an asymmetric rotor or a rotor-vibrator model core have not been successful. However, all these efforts dealt with a ^{197}Pt level scheme rather different from the one disclosed by the present study. Therefore it is of interest to see if a reanalysis in the general Nilsson framework is now more successful.

The number of $1/2^-$, $3/2^-$ levels now established for ^{197}Pt below 800 keV is eight, of which either three or four are $1/2^-$. If one assumes that the levels can all be grouped into reasonably well-behaved rotational bands, this implies either three $K=1/2^-$ bands and two $K=3/2^-$ bands or four $K=1/2^-$

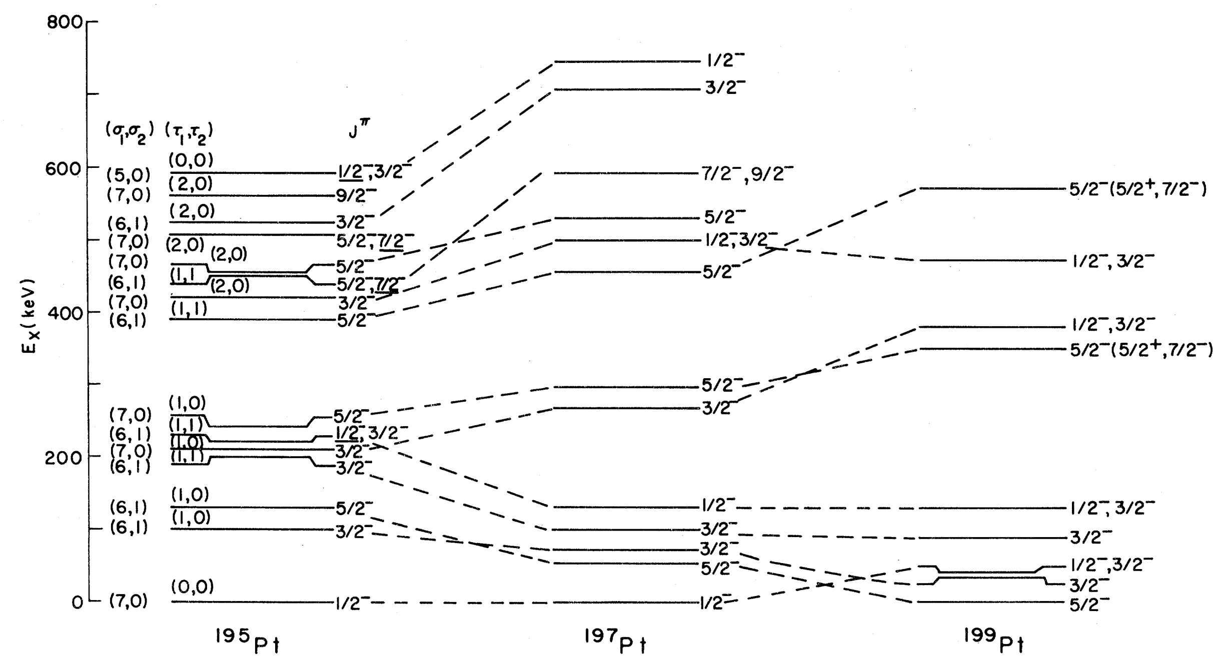

FIG. 3. Comparison of the levels of ^{195,197,199}Pt. Results for ^{195}Pt are from Ref. 6. The supersymmetry quantum numbers (σ_1,σ_2) and (τ_1,τ_2) assigned to the levels of ^{195}Pt in Ref. 6 are shown at the left. Spins that are underlined are the choices consistent with the prediction of the supersymmetry. Results for ^{197,199}Pt are from the present work and that of Refs. 7–9.

bands and no $K=3/2^-$ bands. Since, in this Nilsson context it seems impossible to avoid the $3/2^-$ [532] orbital, that is to say, at least one low lying $K=3/2^-$ band, the former possibility is favored. This then requires five $3/2^-$ levels and, perforce, suggests that the 502 keV level, assigned $1/2^-$, $3/2^-$, is indeed $3/2^-$.

There is, indeed, another reason for preferring the $3/2^-$ choice from the ARC results themselves. Since the data provide a full set of $1/2^-$ and $3/2^-$ levels and since any $1/2^-$ bandhead must be accompanied by a nearby $3/2^-$ rotational state (barring very large decoupling parameters which are not expected for the orbits in this region), the isolation of the 502 keV state from possible $3/2^-$ states argues rather strongly that it cannot be a $1/2^-$ state.

This new level scheme of ^{197}Pt, with five $K=1/2^-$ or $3/2^-$ bands, which seems mandated by the data, is no easier to explain in a Nilsson context than the previous scheme, since the Nilsson model exhibits at most four such bands in this region, unless one includes the strongly upsloping $1/2^-$ [550] band from the $p_{1/2}$ orbital. Indeed, a stronger statement can be made based on the comparison of the new level sheme for ^{197}Pt with that for ^{195}Pt. Whereas the results of Refs. 7 and 8 implied a considerably larger number of low lying $1/2^-$, $3/2^-$ levels in ^{197}Pt compared to ^{195}Pt, the present results in fact show an equal number, that is, an exact 1-1 correspondence of levels. Indeed, this correspondence extends into ^{199}Pt as well, up to the energy where definite negative parity spin assignments can be made (i.e., ≤ 800 keV). Moreover, it is interesting that the analogy of levels suggested in Fig. 3 again suggests the assignment of the 502 keV level as $3/2^-$. The systematics of level shifts is also interesting. The first two $3/2^-$ levels, the lowest $5/2^-$ state, and the lowest excited $1/2^-$ all drop in energy from ^{195}Pt to ^{197}Pt and either continue this trend or remain constant in energy into ^{199}Pt. All the other excited low spin negative parity levels increase in energy. (Note that, as a consequence of the completeness assured by ARC spectroscopy, the levels in ^{199}Pt which would be analogous to the 708 and 747 keV levels of ^{197}Pt must be above 800 keV.)

Owing to the 1-1 correspondence between ^{195}Pt and ^{197}Pt, it is now easy to assess the applicability of the Nilsson scheme to ^{197}Pt by asking whether it works in ^{195}Pt, and this question was in fact addressed in Ref. 6. Some years ago, Yamazaki and Sheline[14] carried out an extensive interpretation of ^{195}Pt in terms of an oblate Nilsson potential and with considerable apparent success. However, the ARC data of Ref. 6 disclosed new $1/2^-$ or $3/2^-$ levels at 222, 419, and 590 keV, whose existence, as *extra*, low lying states that do not fit into the rotational bands proposed in Ref. 14, vitiate that interpretation. Given the 1-1 level correspondence with ^{197}Pt (and ^{199}Pt) the same difficulties with a Nilsson interpretation must arise in these nuclei as well. (This incidentally is a classic example of the virtues of "complete spectroscopy" in the ARC sense of the disclosure of all levels: While a full structure interpretation demands more information than can be provided by ARC spectroscopy, the mere disclosure of new levels can often force the reexamination of an accepted interpretation.)

It seems, therefore, that one faces substantial difficulties interpreting ^{197}Pt in a conventional framework. It is apparent from the large number of $1/2^-$, $3/2^-$ states that a possibly fruitful approach would therefore consist in enlarging the number of core states available for coupling to quasiparticle excitations. The difficulties mentioned earlier with asymmetric rotor interpretations further suggest that it is not sufficient to include only the γ band states.

These comments suggest an attempt to utilize the IBFA (interacting boson-fermion approximation) model in which the fully specified complete core is automatically incorporated. While, in the general multi-j situation this can be a complex, multiparameter approach, the possibility of a supersymmetry scheme in the Pt-Ir region presents a much simpler, analytically describable, alternative. Moreover, as pointed out above, this scheme has been worked out[5] for an O(6) core coupled to a fermion which can occupy $j=1/2$, $3/2$, or $5/2$ orbits and has already been applied,[6] with some degree of success, to ^{195}Pt. There is no need to repeat a detailed description of it here and the following concise summary should suffice. The low lying levels of this supersymmetry scheme, as shown in Fig. 4, fall into several representations denoted by a major-family pair of quantum numbers (σ_1,σ_2), the former of which is closely related to the σ quantum number of the O(6) core. If we denote by Σ the maximum σ value of the core, that is,

$$\Sigma=\sigma_{\max_{\rm core}}=N ,$$

then the lowest families of levels in the supersymmetry are characterized by (σ_1,σ_2) quantum numbers $(\Sigma+1,0)$, $(\Sigma,1)$, and $(\Sigma-1,0)$. For ^{195}Pt, whose core is ^{196}Pt with $N_B=6$, the lowest representations are $(\sigma_1,\sigma_2)=(7,0)$, (6,1), and (5,0). For ^{197}Pt, they would be (6,0), (5,1), and (4,0). Within a (σ_1,σ_2) representation the levels are split and distinguished by quantum numbers (τ_1,τ_2), where again the first of these is closely related to the τ

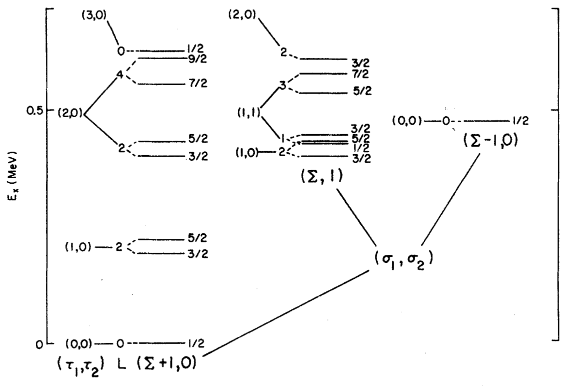

FIG. 4. Lowest levels of the multi-j supersymmetry $O(6)\times(j=1/2,3/2,5/2)$. Based on Ref. 5 and adapted from Ref. 6.

quantum number of the O(6) limit of an even even nucleus. The lowest few (τ_1,τ_2) multiples are included in Fig. 4.

To fully specify the levels, two additional quantum numbers are needed, called L and J, where the latter is simply the level spin. The former is a pseudo-orbital angular momentum quantum number describing the combined boson-fermion system, so that J is simply given by $L+1/2$ or $L-1/2$. Thus the levels of the resultant level scheme always (except for $1/2$ states with $L=0$) appear in pairs, grouped as $(1/2,3/2)$, $(3/2,5/2)$, $(5/2,7/2)$, and so on, according to whether $L=1,2,3\ldots$. Moreover, a given spin pair should always have the same energy splitting, given solely by a $J(J+1)$ term. In ^{195}Pt this was nicely illustrated by the $(3/2,5/2)$ $L=2$ pairs of which three examples were found, with spacings of 30, 28, and 35 keV. Note that this characteristic spacing is too small to be characterized as a typical rotational spacing in this region [which would be $\hbar^2/2\mathscr{I}=E(2^+)/6\approx 60$ keV].

The energy eigenvalue expression for the supersymmetry is

$$E(\Sigma;(\sigma_1,\sigma_2,\sigma_3);(\tau_1,\tau_2),L,J)=-\frac{A}{4}\Sigma(\Sigma+4)-\frac{A''}{4}[\sigma_1(\sigma_1+4)+\sigma_2(\sigma_2+2)+\sigma_3{}^2] +\frac{B}{6}[\tau_1(\tau_1+3)+\tau_2(\tau_2+1)]+CL(L+1)+C''J(J+1)\ . \quad (1)$$

All the levels discussed in Ref. 6 correspond to the same (maximum) value of Σ: Therefore, for relative excitation energies, the first Σ term $-(A/4)\Sigma(\Sigma+4)$ is of no consequence. The term $C''J(J+1)$ gives the energy splitting within the level couplets discussed above. σ_3 is zero in the present discussion and in Ref. 6. In Fig. 3, the quantum numbers assigned to levels in ^{195}Pt are given.

A characteristic feature of the scheme is seen from Eq. (1). The ground state family has $(\sigma_1,\sigma_2)=(\Sigma+1,0)$ and successive $[(\tau_1,\tau_2),L]$ values of $[(0,0),0]$ for the ground state and $[(1,0),2]$ for the first excited couplet. Thus the lowest two excited states of this family have $J=3/2$ and $5/2$ and excitation energies

$$E[\Sigma;(\Sigma+1,0);(1,0),2,J] =\frac{2B}{3}+6C+C''[J(J+1)-3/4]\ . \quad (2)$$

Similarly, the lowest couplet of the next σ family, $(\sigma_1,\sigma_2)=(\Sigma,1)$, has $[(\tau_1,\tau_2),L]=[(1,0),2]$ and spins $3/2$ and $5/2$. Their energies are given by

$$E[\Sigma;(\Sigma,1);(1,0),2,J]=(A''/2)(\Sigma+1)+\frac{2B}{3}+6C +C''[J(J+1)-3/4]\ . \quad (3)$$

Since the spins are the same in Eqs. (2) and (3), the $C''J(J+1)$ terms are identical. It follows then that the lowest levels of the $(\sigma_1,\sigma_2)=(\Sigma,1)$ group must lie at an energy equal to or greater than the first excited couplet [with $(\tau_1,\tau_2)=(1,0)$, $J=3/2,5/2$] of the $(\sigma_1,\sigma_2)=(\Sigma+1,0)$ group. Within the context of an unbroken supersymmetry this cannot be avoided by any choice of parameters as long as A'' is positive. Inspection of the level assignments for ^{195}Pt in Fig. 3 shows, however, that, empirically, it is violated. The 3/2 and 5/2 levels at 99 and 131 keV, both members of the (6,1) group, are below the 3/2 and 5/2 members of the (7,0) group at 211 and 239 keV. This may give some indication of the symmetry breaking.

Turning now to ^{197}Pt we can inspect the two features of the sypersymmetry just discussed, namely the 3/2-5/2 couplet spacings and the relative energies of the σ groups. As for the former, the empirically observed 1-1 level correspondence of ^{195}Pt and ^{197}Pt noted above implies that, again, three (3/2,5/2) couplets must appear in ^{197}Pt. The spacings are now, respectively, -18, 29, and 31 keV. These are similar to ^{195}Pt but there is an order reversal in the lowest couplet. In ^{199}Pt the couplet structure breaks down further. Two are reversed and the spacing in the highest candidate for a couplet is nearly 100 keV.

Concerning the σ groups, inspection of Fig. 4 shows that the $(\sigma_1,\sigma_2)=(\Sigma+1,0)$ group contains no low lying excited $1/2^-$ states whereas the excited group $(\sigma_1,\sigma_2)=(\Sigma,1)$ does, as part of the four state multiplet at the base of this representation. Thus, one is led to assign the 3/2, 1/2 pair of levels at 98 and 131 keV in ^{197}Pt to the $(\Sigma,1)$ family. There should, then, be a nearby pair of $[(\tau_1,\tau_2),L]=[(1,0),2]$ levels with spins 3/2 and 5/2. These in fact occur at 53 and 71 keV. This in turn implies that the first excited couplet of the $(\Sigma+1,0)$ family is associated with the levels at 268 and 299 keV and that the violation of the eigenvalue expression (1) for the relative energies of the $(\Sigma+1,0)$ and $(\Sigma,1)$ representations is even stronger than in ^{195}Pt. Of course, pending more detailed transition multipolarity information, it cannot be completely ruled out that the quantum numbers of two low lying pairs of 3/2, 5/2 levels could be interchanged but this would then destroy any semblance of the correct level spacings *within* each σ family.

The next four levels at 457, 502, 531, and 595 keV contain two 5/2 levels, one level which is 1/2 or 3/2, and one which is tentatively 7/2 or 9/2. If one adopts 3/2 for the 502 keV level, as has been argued above, and chooses 7/2 for the 595 keV level, this quartet of levels is precisely that in the supersymmetry scheme where there is a (3/2,5/2) couplet in the $(\Sigma+1,0)$ group and a (5/2,7/2) couplet of the $(\Sigma,1)$ group.

The continuation of these level assignments in terms of the supersymmetry scheme into ^{199}Pt is even more highly speculative. The association suggested in Fig. 3 seems the most plausible given that the set of $1/2^-$ and $3/2^-$ levels in ^{199}Pt is empirically complete.

Viewing the level associations in Fig. 3 and the implied associations of levels in ^{197}Pt and ^{199}Pt with the supersymmetry scheme, three major conclusions emerge. First, there seems to be a 1-1 correspondence between empirical and predicted low spin states. This is not a trivial result since other models (e.g., Nilsson or asymmetric rotor) do not contain the same set of low lying levels. Second, there is a clear and serious discrepancy between the observed and predicted relative energies of the two lowest (σ_1,σ_2) groups. Significantly, the $(\Sigma,1)$ representation appears too low in energy in all three odd Pt nuclei and, indeed, the discrepancy increases with mass, so much so that if the associations in Fig. 3 are believed, the ground state in ^{199}Pt belongs to the $(\Sigma,1)$ group. The only way to force agreement with the data for the relative energies of the lowest two (σ_1,σ_2) representations would be to choose A'' negative and growing in absolute value with decreasing boson number (increasing mass). However, such a behavior would be at variance with that deduced for the corresponding parameter in the even mass nuclei in this region.

Third, despite this difficulty, the agreement of theoretical and experimental level energies *within each representation* is rather good, particularly so for the $(\Sigma+1,0)$ group. To isolate this feature more clearly, Fig. 5 shows the comparison of experimental and theoretical energies for the low lying levels of each family in ^{195,197}Pt, but separately for the two families. For the theoretical levels in Fig. 5, the parameters C and C'' of Eq. (1) were kept the same for the two nuclei at the value of 6 keV adopted in Ref. 6. The values of B were chosen to approximately fit the levels of the $(\Sigma+1,0)$ group. The first feature one notices in Fig. 5 is one that has been mentioned above but now appears much more evidently, namely the remarkable similarity of ^{195}Pt and ^{197}Pt, for both families of levels. As just intimated, the agreement for the $(\Sigma+1,0)$ representation is excellent in both ^{195,197}Pt. It can be noted that a larger B value is needed in ^{197}Pt than in ^{195}Pt. This may reflect a well known trend[1] in the even Pt isotopes wherein the coefficient of the τ term steadily increases with increasing mass. For the $(\Sigma,1)$ representation the empirical levels are greatly expanded relative to the predictions. Plotted as it is in Fig. 5, with the lowest state of each representation assigned zero relative energy theoretically and experimentally, it seems as if the higher levels of the $(\Sigma,1)$ representation are too high. However, for two reasons it is probably more accurate to reverse this assessment. First, if one views the symmetry breaking as due to mixing of the supersymmetry levels rather than to the neglect of some other degrees of freedom, it is difficult to envision a mechanism for *increasing* the energy of a low lying group of levels. Second, as seen in Fig. 4, the $[(\tau_1,\tau_2),L]=[(1,1),3]$ couplet for the $(\Sigma,1)$ group is expected to occur near the [(2,0)] multiplet of the $(\Sigma+1,0)$ representation. Empirically, as shown in Fig. 3, this prediction is approximately verified, especially in ^{195}Pt. The discrepancies for the $(\Sigma,1)$ group therefore, in fact, arise rather from the depressed energy of the lowest couplets [(1,0),2] and [(1,1),1] of this representation.

Any account of the origin of the symmetry breaking should therefore aim at reproducing this lowering. The even-even core, ^{196}Pt, is rather well described by the O(6) limit up to ≈ 2 MeV and the $j=1/2$, 3/2, and 5/2 set of fermion orbits is rather well isolated in this mass region. Therefore, it is probable that the origin of this symmetry breaking is to be found not in extra core or single particle degrees of freedom but in the selective inadequacy of one or more of the basic assumptions required to achieve the supersymmetry. The most obvious can-

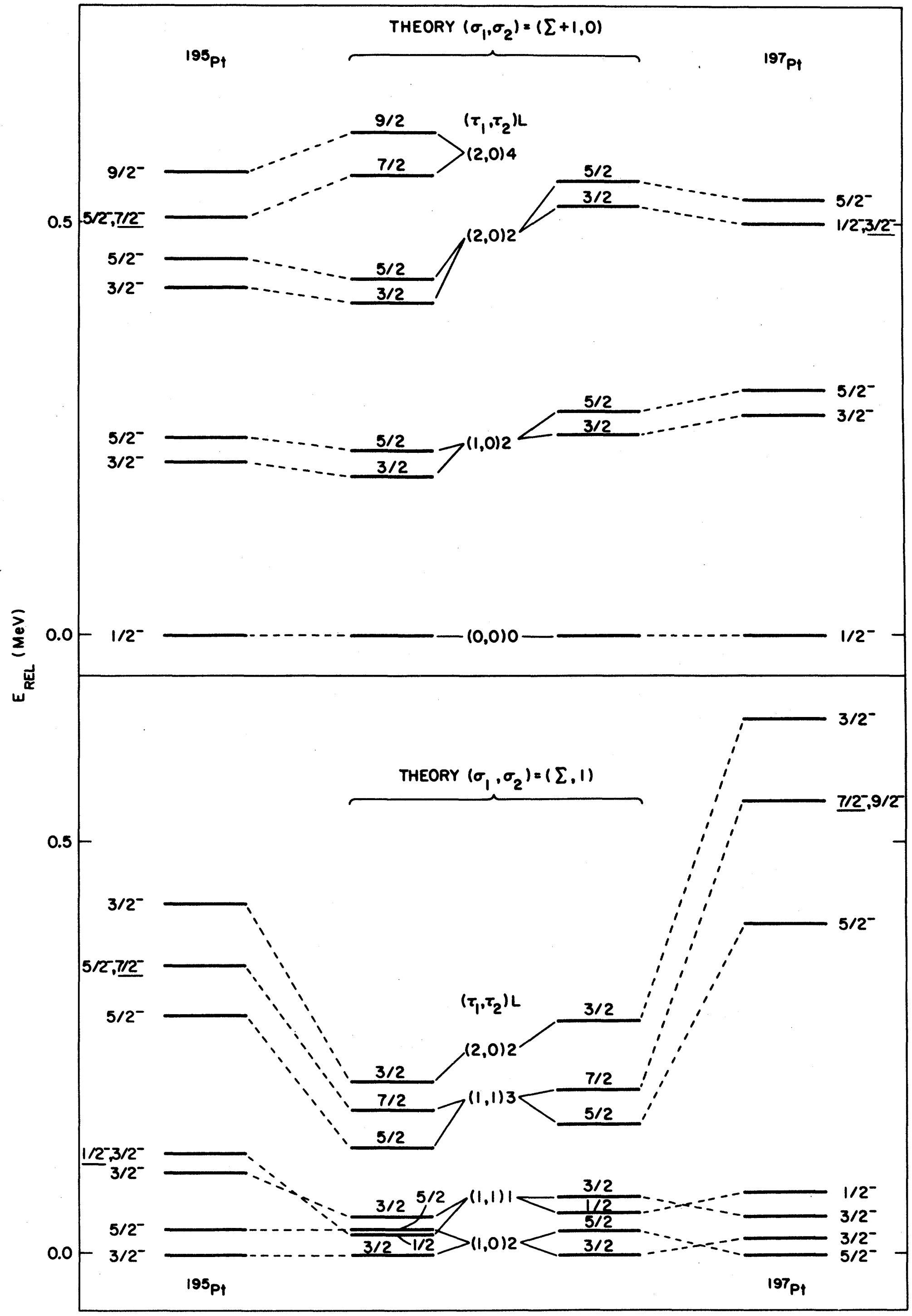

FIG. 5. Comparison of the predictions of the multi-j supersymmetry with the levels of ^{195,197}Pt. The parameters for ^{195}Pt are $A''/4=15$ keV, $B/6=35$ keV, and $C=C''=6$ keV (from Ref. 6). For ^{197}Pt, $A''/4$, C and C'' were kept at the same values while $B/6=47$ keV. The comparison is done separately for the $(\sigma_1,\sigma_2)=(\Sigma+1,0)$ and $(\Sigma,1)$ families (top and bottom, respectively). In each case the lowest experimental and theoretical levels of each representation are assigned zero relative energy.

didates are the specific assumption of a definite set of relative quasiparticle energies inherent in the supersymmetry, and the assumption of a specific interaction (quadrupole-quadrupole) between core and particle degrees of freedom. The fact that there appears to be a smooth systematic change in the relative positions of the lowest two (σ_1,σ_2) representations from ^{195}Pt to ^{199}Pt perhaps points to a Fermi surface location which is at variance with the assumption of the supersymmetry and which shifts further and further from its required position with increasing mass.

It is premature at this stage to speculate further, but the present data for ^{197,199}Pt, coupled with those for ^{195}Pt, provide a new systematics for this region; along with the above preliminary analysis, it is hoped that this may offer a focus for future, more detailed studies, especially of $B(E2)$ values and single particle transfer reaction cross sections, that will lead to a more precise understanding of whether or not the supersymmetry scheme is adequate, for this region. If it is adequate, then the identification herein of the specific levels wherein the symmetry breaking seems to be concentrated may have provided appropriate clues to its origin.

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[1]R. F. Casten and J. A. Cizewski, Nucl. Phys. A309, 477 (1978).
[2]F. Iachello and S. Kuyucak, Ann. Phys. (N.Y.) 136, 19 (1981).
[3]J. L. Wood, in *Interacting Bose-Fermi Systems in Nuclei*, edited by F. Iachello (Plenum, New York, 1981), p. 381.
[4]J. A. Cizewski, D. G. Burke, E. R. Flynn, Ronald E. Brown, and J. W. Sunier, Phys. Rev. Lett. 46, 1264 (1981).
[5]B. Balentekin, I. Bars, R. Bijker, and F. Iachello, report, 1982; F. Iachello, *Proceedings of the 1982 Institute for Nuclear Study (INS) International Symposium on Dynamics of Nuclear Collective Motion, Mt. Fuji, Japan, 1982* (University of Tokyo, Tokyo, 1982), p. 373; F. Iachello, private communication.
[6]D. D. Warner, R. F. Casten, M. L. Stelts, H. G. Borner, and G. Barreau, Phys. Rev. C 26, 1921 (1982).
[7]Y. Yamazaki, R. K. Sheline, and E. B. Shera, Phys. Rev. C 17, 2061 (1978).
[8]J. A. Cizewski, E. R. Flynn, R. E. Brown, and J. W. Sunier, Phys. Rev. C 26, 1960 (1982).
[9]W. F. Davidson, J. S. Dionisio, W. Watzig, H. Faust, K. Schreckenbach, G. Barreau, D. D. Warner, C. H. Atwood, and R. K. Sheline, in *Proceedings of the International Conference on Nuclear Structure, Amsterdam, 1982*, edited by A. Vander Woude and B. J. Verhaar, (European Physical Society, Amsterdam, 1982), Vol. 1, p. 275; W. F. Davidson, private communication.
[10]M. L. Stelts and J. C. Browne, Nucl. Instrum. 133, 35 (1976).
[11]M. L. Stelts and R. E. Chrien, Nucl. Instrum. 155, 253 (1978); B. Krusche, K. P. Lieb, H. Daniel, T. von Egidy, G. Barreau, H. G. Borner, R. Brissot, C. Hofmeyr, and R. Rascher, Nucl. Phys. A386, 245 (1982).
[12]R. F. Petry, D. S. Shirk, and J. C. Hill, Bull. Am. Phys. Soc. 21, 558 (1976), quoted in B. Harmatz, Nucl. Data Sheets 20, 73 (1977).
[13]A. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177 (1977).
[14]Y. Yamazaki and R. K. Sheline, Phys. Rev. C 14, 531 (1976).