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Theoretical Studies of the Potential Hydrolysis Products from *cis*-$Pt(NH_3)_2Cl_2$ and Acetamide

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Species resulting from the hydrolysis of *cis*-$Pt(NH_3)_2Cl_2$ with acetamide (A) and its tautomer, 1-hydroxy-1-iminoethane (I), namely *cis*-$(Pt(NH_3)_2XY)^{n+}$ (X = Cl^-, H_2O, OH^-; Y = A, I; n = 1, 2), have been investigated theoretically by using the relativistic (REX) and nonrelativistic charge-iterated extended Hückel (EHT) molecular orbital (MO) methods. Two potential centers for Pt coordination to acetamide and its iminol have been considered: the carbonyl or hydroxyl oxygen and the nitrogen. Coordination of Pt to the carbonyl O is the most favorable bonding situation. Calculational results for the related trans hydrolysis products are also available, and comparisons are made with the cis isomers. Transition energies, molar absorption coefficients, and magnetic circular dichroism (MCD) *B* terms derived from theory are presented for each of the species and are related to observed base pair binding interactions. The electronic absorption and MCD spectra of all complexes are predicted to exhibit ligand-field and charge-transfer transitions arising from excitations out of the occupied Pt 5d and ligand orbitals of n and π type into the unoccupied Pt 5d and ligand π^* type orbitals. These transitions are expected to yield intense d $\rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ absorptions in the UV spectral region. The MCD spectra of $\pi \rightarrow \pi^*$ transitions are expected to distinguish the different bonding arrangements. A correlation with available experimental data for acetamide is made. The optimized geometries and transition state have been located for acetamide and its iminol tautomer by using the GAUSSIAN 82 program.

Introduction

The biological effects of platinum complexes have led to considerable effort in understanding the nature of their interactions at the molecular level. Experimental evidence links the effectiveness of *cis*-diamminedichloroplatinum(II) (*cis*-DDP) and related Pt drugs to interactions with DNA, particularly with the base of pairs.[1] For an understanding of the inhibition mechanism of cancer cell division by these platinum compounds, it is clearly essential to establish the factors affecting platinum complex reactions and the selection of DNA target sites in aqueous solution. Structural evidence is available from studies of platinum pyrimidine "blues"[2] that indicates an amidic linkage is the key to the platinum binding sites in these compounds. In addition, proteins and other cellular species with amidic linkages may also be susceptible to attack by *cis*-DDP. However, attempts to utilize simple model compounds with amide groups such as trimethylacetamide[3] and acetamide itself[4] have not led to satisfactory structural characterization, while such complexes do develop the characteristic blue color. In addition, yellow solids that also contain amidic linkages have been extracted from many of the blue solutions, and there is evidence for species resulting from a lactim–lactam tautomeric equilibrium[3a,-7] the amides and pyrimidines. Since simple model compounds with potential for amidic bridges continue to be used to probe platinum binding sites, it is important to provide definite characterization of the species present in aqueous solution. The advantage of a molecular orbital study is in its ability to investigate various structures for these compounds and to obtain theoretical UV and MCD spectral data for comparison with available experimental data.

In the present study, we examine via molecular orbital theory the electronic structure of some likely platinum species produced in the reaction of acetamide with *cis*-DDP in aqueous solution. Isomeric species derived from *trans*-DDP are also studied for comparison. Since the acetamide (A) and its iminol tautomer, 1-hydroxyl-1-iminoethane (I), have two potential centers for coordination, namely, the carbonyl or hydroxyl oxygen and the nitrogen, we investigate different modes of platinum coordination. Therefore, results for *cis*- and *trans*-$(Pt(NH_3)_2XY)^{n+}$ (X = Cl^-, OH^-, H_2O; Y = A, I; n = 1, 2) species are considered. Special attention is focused on the calculation of electronic transition energies, intensities, and MCD *B* terms for the considered cis species. Relevant data from related platinum complex and amide tautomerism studies will be discussed.

For some simple platinum species, ground-state properties calculated with ab initio effective potentials are available.[8] A recent study including relativistic effects covered only $PtCl_4^{2-}$.[9] Thus, it is not yet practical to carry out extensive ab initio calculations on the many platinum species considered, in particular when information about the excited states is required. Therefore, the extended Hückel method is selected. In a series of papers,[10-13] this method has shown that it is capable of yielding reliable results in the treatment of planar Pt model complexes. For analysis of relativistic effects, calculations utilizing the relativistic extended Hückel method of Lohr and Pyykko[14] were also performed. For acetamide, its iminol, and their related transition state, ab initio calculations with geometry optimization were readily performed.

A preliminary look at the theoretically derived electronic and MCD spectral data suggests correlations between energy shifts and substituent effects in these species.

Computational Details

The computational procedures employed were those found in the charge-iterated extended Hückel (EHT)[15] and relativistic extended

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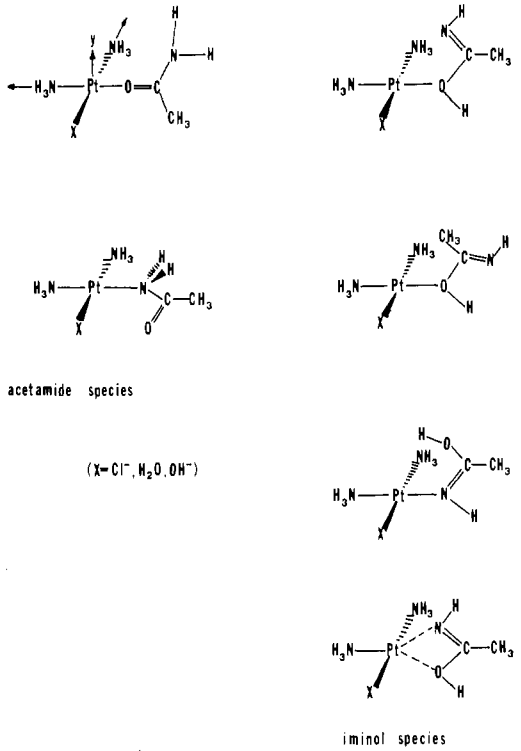

Figure 1. Lowest energy cis structures from EHT. (Trans structures arise from the exchange of X with the cis NH_3 group along the *z* axis.)

Hückel (REX)[16] programs for the platinum species. Platinum and chloride basis sets and valence-state ionization potentials were from Cotton and Harris,[17] and similar nitrogen data were generated by employing Herman–Skillman potentials.[18] These parameters are summarized in our earlier paper.[19] Values for orbital exponents and valence-state ionization potentials were taken from Burns.[20] The *K* term was adjusted to 1.8 in the EHT program, while standard parameters[16] were used in REX. In addition, Hartree–Fock calculations with the 3-21G basis set were performed on acetamide, iminol, and the transition state arising from a 1,3-hydrogen shift, using an GAUSSIAN 82 series of programs.[21] The geometries of A and I were optimized, and the geometry for I was used for the Pt complexes; the acetamide crystal structure was used for the Pt–A complexes.[22]

Molecular configurations and bond lengths for *cis*- and *trans*-DDP were taken from X-ray determinations.[23] The Pt–N bond lengths were taken from X-ray data for monoadducts.[24] Pt–O(A) and Pt–Cl distances were fixed at 2.04 and 2.33 Å, respectively, in accordance with related studies.[25] Experimental geometries were chosen for NH_3, H_2O, and OH^-.[26] Pt–(OH_2) and Pt–(OH) bond lengths were 2.04 and 1.96 Å, respectively, with OH bonds oriented perpendicular to or in the molecular plane with tetrahedral H–O–Pt angles. Carbonyl O bonded Pt species containing acetamide and the pyramidalized amide N bonded Pt complexes as well as hydroxyl O bonded and imine N bonded Pt species of I were studied with EHT and REX both in the molecular plane with and perpendicular to it, as shown in Figure 1. Two planar O-bonded structures were considered for the cis species, one with the nitrogen-containing group in A or I located near the non-ammine ligands and the other with this group directed 180° away from the ammine ligands. Similar planar arrangements were prepared with the N-bonded structures. One planar form was used for the trans species. The calculated properties are relatively insensitive to the in- and out-of-plane variations. The perpendicular arrangement was energetically preferred, and the significance of this result is discussed below. Bidentate binding was tried in a trigonal-bipyramidal geometry having Pt–N and Pt–O bond lengths of 2.0 Å, as shown in Figure 1.

Table I. HF/3-21G and EHT Total Energies for Acetamide Species

species	HF/3-21G[a] (RE)[b]	EHT[c] (RE)[b]
acetamide	−206.815 80 (0.0)	−447.883 47 (0.0); −447.699 20[d]
acetamide, perpendicular $-NH_2$	−206.782 70 (20.8)	−447.016 97 (20.0)
transition state	−206.715 52 (62.9)	−442.882 63 (115.3)
iminol	−206.786 91 (18.1)	−445.488 92 (55.2)

[a] In Hartrees. [b] Relative energy in kcal/mol. [c] In eV; with HF/3-21G optimized geometry. [d] Crystal structure.[22]

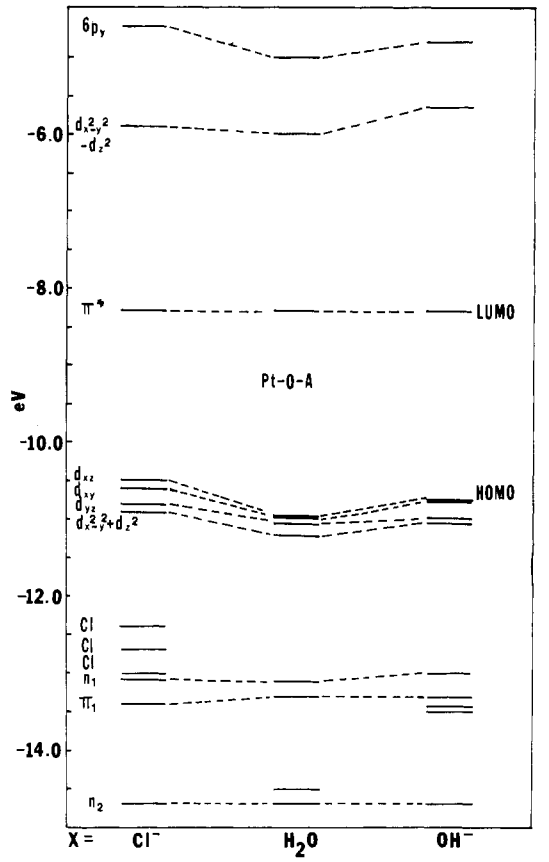

Figure 2. EHT orbital energy diagrams for the cis Pt–O-bonded acetamide species.

The computer program used to evaluate oscillator strengths and *B* terms from molecular orbital coefficients and energies was discussed in our previous paper.[10] Oscillator strengths were converted to maximum molar absorption coefficients (ϵ_{max}) by assuming a bandwidth of 4000 cm^{-1}.[27] ϵ_{max} values were available from related experiments. The excited-state energies were estimated from simple orbital energy differences. The *B* term calculation involves in principle a summation that should include all electronic states. For practical purposes, this was limited to the 12–15 excited states lying closest to the transition under consideration.

Results and Discussion

Hartree–Fock (HF/3-21G) and EHT total energies for the acetamide species are listed in Table I. The EHT and REX total

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Table II. EHT and REX Energies (eV) for the Platinum Species

species	Pt–O binding		Pt–N binding	
	EHT	REX	EHT	REX
cis-$Pt(NH_3)_2Cl(A)^+$	−997.184 44	−1011.247 07	−992.297 56	−1010.948 97
trans-$Pt(NH_3)_2Cl(A)^+$	−997.192 53	−1011.563 23	−992.302 93	−1011.018 31
cis-$Pt(NH_3)_2H_2O(A)^{2+}$	−1039.552 29	−1047.216 55	−1034.727 57	−1046.974 61
trans-$Pt(NH_3)_2H_2O(A)^{2+}$	−1039.690 85	−1047.401 86	−1034.762 47	−1047.042 97
cis-$Pt(NH_3)_2OH(A)^+$	−1022.589 66	−1042.468 99	−1017.776 20	−1042.188 72
trans-$Pt(NH_3)_2OH(A)^+$	−1022.745 29	−1042.758 54	−1017.842 87	−1042.283 20
cis-$Pt(NH_3)_2Cl(I)^+$	−994.931 72	−1009.714 60	−994.787 03	−1010.649 90
trans-$Pt(NH_3)_2Cl(I)^+$	−994.903 52	−1009.851 07	−994.760 47	−1010.778 56
cis-$Pt(NH_3)_2H_2O(I)^{2+}$	−1037.353 96	−1045.704 10	−1037.178 39	−1046.664 55
trans-$Pt(NH_3)_2H_2O(I)^{2+}$	−1037.475 56	−1045.805 60	−1037.233 38	−1047.002 69
cis-$Pt(NH_3)_2OH(I)^+$	−1020.372 94	−1040.950 93	−1020.224 08	−1041.883 06
trans-$Pt(NH_3)_2OH(I)^+$	−1020.504 36	−1041.123 29	−1020.319 04	−1042.027 59

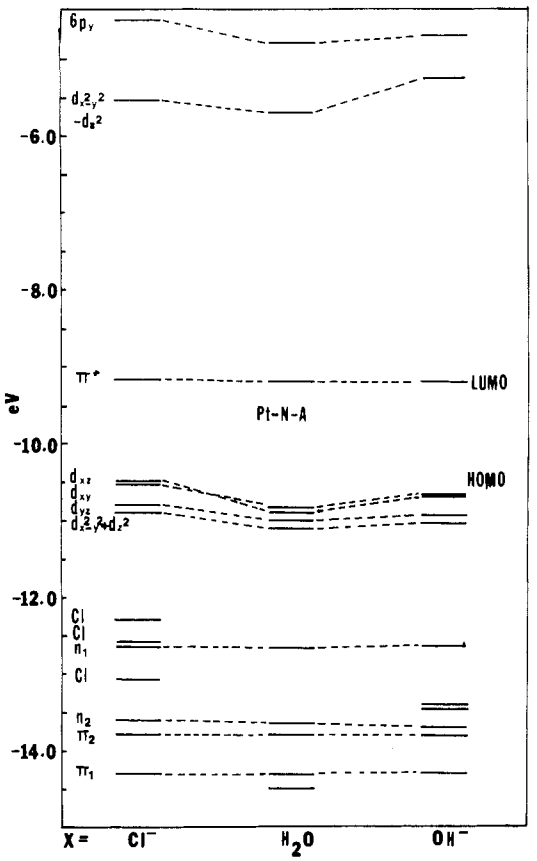

Figure 3. EHT orbital energy diagrams for the cis Pt–N-bonded acetamide species.

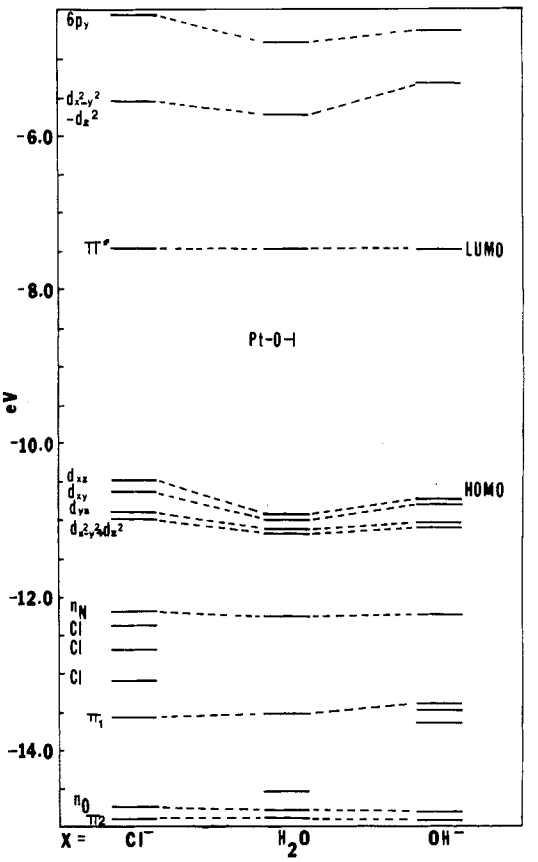

Figure 4. EHT orbital energy diagrams for the cis Pt–O-bonded iminol species.

energies for the platinum species are reported in Table II. All ground-state configurations are singlets. The molecular orbital (MO) energy levels for the proposed products in aqueous solution are plotted for the cis isomeric Pt–O-bonded acetamide species in Figure 2. Pt–N-bonded acetamide cis species are presented in Figure 3. Included in Figures 4 and 5 are the relevant Pt–O- and Pt–N-bonded iminol species, respectively. Trans species diagrams are available upon request. Results from relativistic calculations on the aquo substituted Pt–O- and Pt–N-bonded species are in Figure 6.

Electronic transition energies, molar absorption coefficients, and MCD *B* terms were calculated for all singlet excited states by using the EHT method. Transition energies were also found for the Pt complexes from REX. MO calculations with EHT or REX generate the same relative ordering of the d orbitals and predict the same d → d transitions but show differences in the relative energies of the d → d, d → π*, and Cl → d transitions. These variations have been noted[9,10] and will be discussed below. These data can be found in Table III for the acetamide species and Table S1 (supplementary material) for the Pt species, along with spectral assignments. Rationale for these assignments and possible features of a UV–visible and MCD spectral study are presented below.

Table III. Experimental and Theoretical Absorption and MCD Spectral Results for Acetamide Species

complex	abs ν, μm^{-1} (ϵ_{max}, cm^{-1} M^{-1}) exptl	abs ν, μm^{-1} (ϵ_{max}, cm^{-1} M^{-1}) calcd	MCD[a] B ($10^4 D^2\beta$) calcd	assignt[b]
acetamide[c]	4.35 (60)	3.36 (43)	−12	$n_1 \rightarrow \pi^*$
	5.49 (7600)	3.74 (6800)	31	$\pi_1 \rightarrow \pi^*$
		4.53 (34)	10	$n_2 \rightarrow \pi^*$
		5.08 (33 000)	−66	$\pi_2 \rightarrow \pi^*$
iminol		3.55 (2)	0.0	$n_N \rightarrow \pi^*$
		4.11 (24 000)	−29	$\pi_1 \rightarrow \pi^*$
		4.81 (140)	26	$n_O \rightarrow \pi^*$
		5.28 (13 000)	−27	$\pi_2 \rightarrow \pi^*$
		5.69 (29)	0.0	$n_3 \rightarrow \pi^*$

[a] For MCD conventions, see ref 37. [b] Assume singlet–singlet transitions unless otherwise noted. [c] Reference 28.

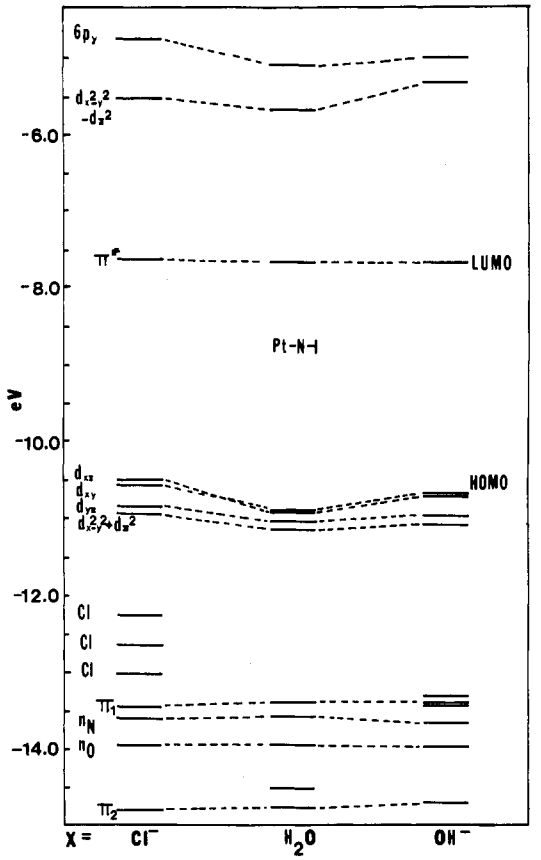

Figure 5. EHT orbital energy diagrams for the cis Pt–N-bonded iminol species.

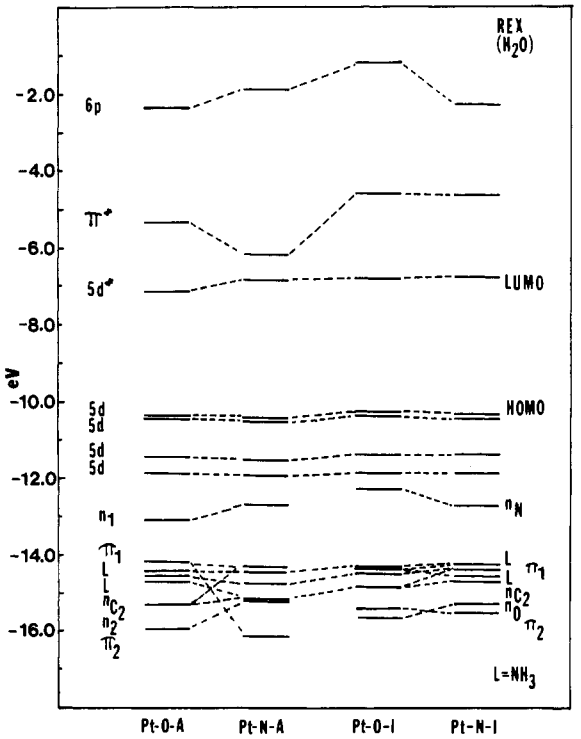

Figure 6. REX orbital energy diagrams for the aquo-substituted *cis* Pt–O- and Pt–N-bonded species.

Acetamide Species. UV spectal data[28] and theoretical calculations[29] are available for acetamide. These and our results confirm

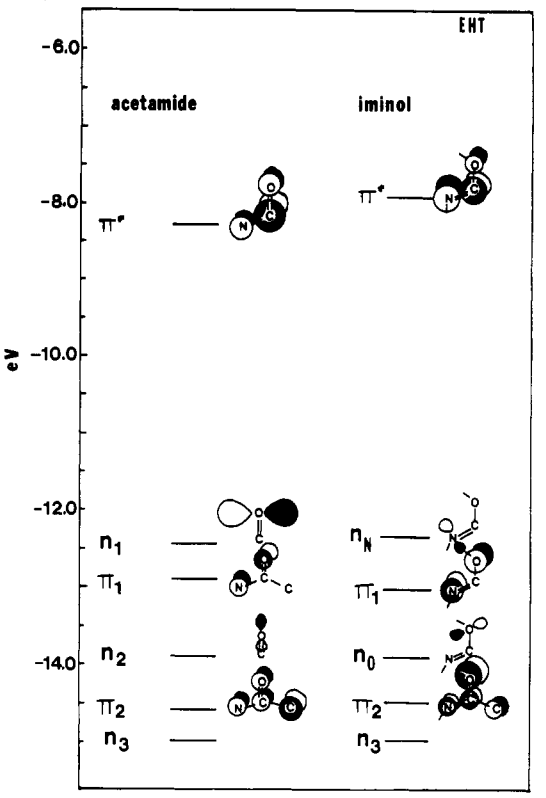

Figure 7. EHT orbital energy diagrams for the relevant n, π, and π^* molecular orbitals of acetamide and iminol.

that ground-state acetamide is a planar molecule with restricted rotation around for the C–N bond due to π resonance. The UV spectrum is characterized by an $n \rightarrow \pi^*$ transition at 4.35 μm^{-1} arising when an electron is promoted from an in-plane oxygen 2p orbital to an antibonding π^* orbital having predominantly C p orbital contributions. Both the n and π^* orbitals are shown in Figure 7. At 5.49 μm^{-1}, a $\pi \rightarrow \pi^*$ transition is observed originating from a π antibonding orbital between the O and N atoms to the π^* orbital described above. A negative *B* term is expected for the $n \rightarrow \pi^*$ transition followed at higher energy by a positive *B* term for the $\pi \rightarrow \pi^*$ transition. Good qualitative agreement between experiment and EHT theory for spectral data is seen in Table III.

Two modes of binding to the Pt complex are considered for acetamide. Little structural change within acetamide occurs with Pt binding to the carbonyl oxygen. However, for Pt to bind with the amidic N, structural rearrangement involving pyramidalization of $-NH_2$ is necessary to achieve favorable Pt–N bonding. The C–N rotational barrier is 20.8 kcal/mol, at the HF/3-21G level,[30] in agreement with 17.3 kcal/mol from experimental results.[31] In addition, after a 90° rotation around the C–N bond, attempts were made to pyramidalize the $-NH_2$ group and produce a stable nonplanar acetamide with N–H bonds directed trans to the carbonyl oxygen, in line with the structural arrangements found in amidic linkages. These trials failed and led to increasing energies, and no such secondary minimum could be located. A nonplanar acetamide has been calculated to be 17 kcal less stable than the planar form with N–H bonds directed cis to the carbonyl oxygen.[32] At the HF/3-21G level, we found this is to be a transition state with pseudorotation to the planar form. Therefore, a net energy increase for Pt–N bonding is expected without solvent

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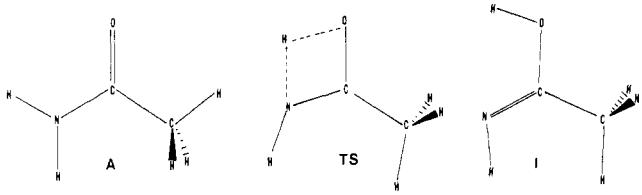
interactions. Bidentate bonding of acetamide was proposed. However, this bonding is expected to involve pyramidalization of the $-NH_2$ group and can be considered as unfavorable for the same reason as that for Pt–N bonding.

Controversy surrounds the existence of the iminol tautomer of acetamide. Related tautomers have been implicated from X-ray, NMR, and IR data.[3,33] At the HF/3-21G basis level, I is 18.1 kcal/mol less stable than A. The I form may be obtained from A through a 1,3-hydrogen shift interconverting A and I and passing through a planar transition state located more than 60 kcal/mol above A at the HF/3-21G level. From these theoretical



results, which do of course represent gas-phase data, it might seem unlikely that I is available in any appreciable concentration in solution for interaction with the Pt complex. However, solvent effects,[34] decrease in pH as the reaction proceeds,[35] metal complex catalysis, and utilization of ^{15}N NMR[33] are all proposed alternatives for preparing and detecting the iminol tautomer. In contrast, tautomers of purines and pyrimidines are accessible and Pt complexes of these tautomers have been structurally characterized.[36]

The theoretical UV and MCD spectra for I are expected to exhibit an $n \rightarrow \pi^*$ transition with a small positive *B* term originating from a N lone-pair orbital to an antibonding π^* orbital having C and N contributions (Figure 7). This is followed by an intense $\pi \rightarrow \pi^*$ transition similar to that in acetamide except with a negative *B* term. An $n \rightarrow \pi^*$ transition with a positive *B* term arising from an oxygen lone-pair orbital is still higher in energy followed by a second $\pi \rightarrow \pi^*$ transition with a negative *B* term. $\pi \rightarrow \pi^*$ transitions in both A and I can probably be used as markers, particularly in the Pt complexes. They are intense and may be distinguished, since the signs of the MCD *B* terms are noted to be different. These transitions in I are shifted only slightly higher in energy relative to those in acetamide.

Pt–Acetamide Species. For all cis and trans species, platinum bonded to the acetamide carbonyl oxygen is energetically more favorable than to the pyramidalized amide nitrogen at these geometries. Trans species are more stable than the cis species. This bonding scheme agrees with a recent NMR study[4a] of *cis*-$Pt(NH_3)_2(H_2O)_2^{2+}$ with acetamide. Moreover, the molecular plane of acetamide for both N and O bonding prefers to be perpendicular to the Pt-complex plane, as in Figure 1. This predicted structure for acetamide compares favorably with that established for the amidic-bridged species of the "platinum blues" and may prepare the groundwork for the delayed appearance of a blue species in the acetamide study.

The perpendicular structure can be explained by overlap interaction of the Pt $6p_y$ orbital with the in-plane lone-pair $2p_y$ orbital on the carbonyl oxygen, as shown in Figure 7. The bonding combination is more favorably in the perpendicular position. A rotation of acetamide into the Pt molecular plane destabilizes this bonding and stabilizes the antibonding $6p_y$ combination.

For all Pt species considered regardless of Pt to ligand bonding type, additional variation in the position of the $6p_y$ orbital once the A or I geometry is determined arises from the overlap interaction of this orbital with the p_y orbitals of the Cl^-, OH^-, and

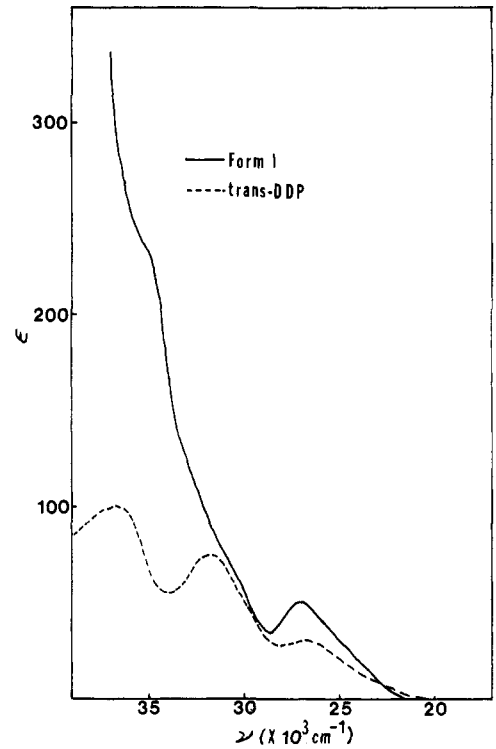


Figure 8. Absorption spectra for *trans*-$Pt(NH_3)_2Cl_2$ (*trans*-DDP) and *trans*-$Pt(TMA)_2Cl_2$ (form I).

H_2O ligands. The position of the empty $6p_y$ type orbital is determined by the amount of antibonding p_y character contributed by the ligand. The ability of these ligands to stabilize the unoccupied $6p_y$ orbital follows the trend $H_2O > OH^- > Cl^-$, corresponding to an increase in antibonding p_y character, $H_2O < OH^- < Cl^-$. Moreover, the magnitude of the splitting between filled d orbitals and the empty d orbitals of the Pt complexes is also $H_2O > OH^- > Cl^-$, reflecting a similar trend in the spectrochemical series.

For Pt–O acetamide species, the n_1 orbital (or in-plane O $p\pi$ orbital) of A is stabilized in bonding to Pt, as is the π_1 and the lone-pair O orbital directed toward the Pt. The π^* orbital varies insignificantly. Therefore, the acetamide type transitions, $n_1 \rightarrow \pi^*$, $\pi_1 \rightarrow \pi^*$, and $n_2 \rightarrow \pi^*$, are blue-shifted but have similar intensities and magnitudes of MCD terms compared to the related acetamide transitions.

In EHT, $d \rightarrow \pi^*$ transitions precede $Cl \rightarrow \pi^*$, $d \rightarrow d$, and N, $\pi \rightarrow \pi^*$ transitions. The weak $d \rightarrow d$ and $n \rightarrow \pi^*$ transitions are likely to be masked by the remaining strong transitions. The ordering contrasts with REX results that predict $d \rightarrow d$ transitions followed by $d \rightarrow \pi^*$, n, Cl, $\pi \rightarrow d$, and n, Cl, $\pi \rightarrow \pi^*$ transitions. Our experience with REX for $PtCl_4^{2-}$ and related complexes[10,11] indicates this method will produce transition energy orderings in close agreement with experimental results. As an example, the only experimental absorption spectra available for comparison are shown in Figure 8. In *trans*-DDP, the low-lying peaks are assigned as two triplet $d \rightarrow d$ transitions followed by a singlet $d \rightarrow d$ transition. Similarly, in form I, a species that involves Pt–N bonding of the iminol form of trimethylacetamide (TMA), the first band is likely to be a triplet $d \rightarrow d$ transition followed by intense bands indicative of metal and ligand orbital transitions with the π^* orbital. While the intensity of a particular transition should remain the same, it is expected that sums in the MCD *B* term expression will change if the order of transition energies is changed. We found this to be true, but in general, the signs of the *B* terms did not change, only the magnitudes. The transisomeric species exhibit transitions very similar to those for the cis species.

A comparison between Pt–O and Pt–N species indicates little difference in the $6p_y$ position as a result of bonding differences. However, the π^* orbital of the Pt–N-bonded species is stabilized

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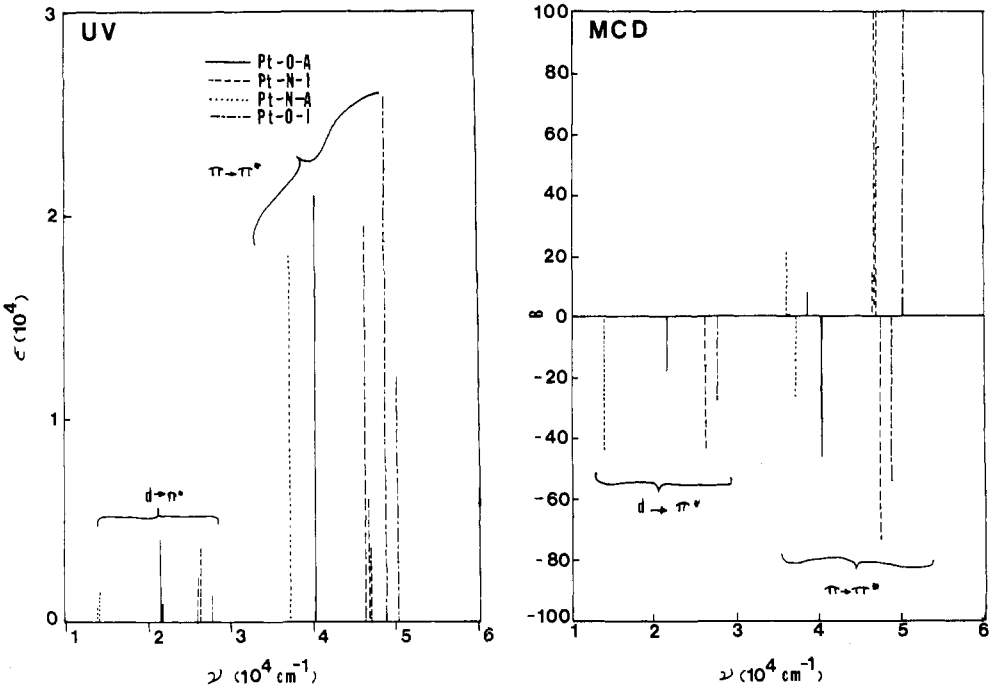

Figure 9. Comparison of theoretical UV and MCD spectra for the cis Pt–aquo species.

relative to that in acetamide and in the Pt–O-bonded acetamide species because the pyramidalization of the $-NH_2$ group has reduced the antibonding contribution from N in this orbital. Pyramidalization also affects the occupied π_1 orbital antibonding between O and N stabilizing it relative to the n_2 orbital and the π_2 bonding orbital destabilizing it. Hence, this π_1 orbital is involved in bonding with Pt and is now in n_N type p_z orbital. Therefore, the $\pi_1 \rightarrow \pi^*$ transition is missing in Pt–N-bonded acetamide. The in-plane n_1 orbital and the n_2 orbital are only slightly varied and are not directly involved in bonding as they were in the Pt–O acetamide species. Therefore, the $d \rightarrow \pi^*$ and the acetamide related transitions are expected to be red-shifted and occur in the order d, n_1, n_2, $\pi_2 \rightarrow \pi^*$ relative to acetamide and Pt–O species in EHT. In REX, the energy shifts are the same, but with a different ordering in the transitions as previously noted.

For Pt–O and Pt–N bonding, the $d_{xz} \rightarrow \pi^*$ transitions are predicted to have the greatest intensities among the $d \rightarrow \pi^*$ transitions with some intensity from $d_{xy} \rightarrow \pi^*$. MCD may be utilized to distinguish these two with a pseudo *A* term or a net negative *B* term. The $d \rightarrow d$ transitions for the Pt–N species are at higher energies than those of the Pt–O species, in line with the related position of NH_3 in the spectrochemical series. Trans Pt–N results are similar to cis results in EHT and REX.

Pt–Iminol Species. Cis and trans Pt complexes of I with both Pt–O and Pt–N bonding orient the molecular plane for I perpendicular to the plane of the Pt complex. All coplanar forms are considerably higher in energy. The nitrogen group in I is expected to undergo only minor structural changes to accommodate a favorable overlap with Pt. Therefore, the Pt–O- and Pt–N-bonded I species are now closer in energy than they are in the Pt–O and Pt– N acetamide cases. The Pt–O-bound species are found to be more stable than Pt–N-bound species when the H—N= group is collinear with O at EHT. The reverse is true with REX. The Pt–O-bonded forms having $-CH_3$ collinear with O are less stable than the Pt–N-bonded forms. The bidentate-bonded complexes are also unstable relative to the monodentate iminol species. All perpendicular arrangements of the iminol species are found to be more stable than the Pt–N-bound acetamide species. However, the Pt–O-bound acetamide complexes remain the most favored.

In all species, the H_2O and OH^- ligands are in the plane of the Pt complex. The OH^- bond is directed away from A or I except in one case, where it is directed toward a Pt–O-bonded iminol. This suggests intramolecular hydrogen bonding.[8b]

In the Pt–O species, the n_O lone-pair orbital of I is stabilized in bonding with Pt, as are the π_1 and π_2 orbitals to a lesser degree. The unbonded n_N orbital and the π^* orbital remain unchanged. Therefore, π_1, n_O, and $\pi_2 \rightarrow \pi^*$ transitions in the Pt complexes are blue-shifted relative to free iminol transitions, while the lowest $n_N \rightarrow \pi^*$ transitions are only slightly shifted. The dominant transitions are $d_{xz} \rightarrow \pi^*$ (negative *B* term), $Cl \rightarrow \pi^*$, $\pi_1 \rightarrow \pi^*$, and several $d \rightarrow 6p_y$ transitions. The $\pi_1 \rightarrow \pi^*$ transitions remain at the same energy in all species and have intensities and negative *B* terms similar to those of the related transition in the iminol. Pt–O-bonded A and I species may be distinguished by positions of the $\pi_1 \rightarrow \pi^*$ transitions. In both binding types, these transitions are intense but their MCD *B* terms are closely related to those transitions in A and I.

For Pt–N-bonded species, the n_N orbital is stabilized in bonding with Pt as are the π_1 and π_2 orbitals, but to a lesser degree. The π^* and n_O orbitals are changed little in the bonding. Therefore, the transitions from REX results are expected to be, in order of increasing energy, $d \rightarrow d$, d, Cl, π_1, n_N, n_O, and $\pi_2 \rightarrow \pi^*$. The ability to distinguish between the presence of the Pt–O- and Pt–N-bonded iminol species is hampered, since the $\pi_1 \rightarrow \pi^*$ transitions have similar characteristics in both species. The $n_N \rightarrow \pi^*$ transitions are expected at considerably different energies for these species but are weak and likely to be easily masked. ^{195}Pt NMR may provide an alternative means of detection.

Acetamide and iminol entities with Pt–N bonding are differentiated by both $d \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ transitions. $d \rightarrow \pi^*$ and $\pi_2 \rightarrow \pi^*$ transitions are at lower energies in A than the $d \rightarrow \pi^*$ and $\pi_1 \rightarrow \pi^*$ transitions are in I.

These predicted trends are summarized in Figure 9 for the Pt–aquo species. The UV and MCD spectra with consideration for energy and intensity variation are expected to have broad $d \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ transitions. It is noteworthy that the Pt–O–A and the P–N–I species have opposite *B* terms for the $\pi_1 \rightarrow \pi^*$ transitions.

In general, transitions for the trans counterparts are similar to those of the cis species.

Absorption and MCD Spectral Studies. The theoretically derived electronic and MCD spectra for complexes considered in this study are characterized by ligand-field ($d \rightarrow d$, $d \rightarrow 6p_y$) on Pt, charge-transfer ($d \rightarrow \pi^*$), and ligand–ligand ($n, \pi \rightarrow \pi^*$) transitions. The possibility of degenerate excited states is precluded by the low symmetry of all the complexes. Thus, only *B* terms and possibly pseudo *A* terms are expected from the MCD spectra

of these species. The UV and MCD spectra as indicated by the calculated *B* terms (Tables III and S1 and Figure 9) are characterized by prominent features that can function as markers. Strong $d_{xz} \rightarrow \pi^*$ transitions alone or coupled with nearly degenerate $d_{xy} \rightarrow \pi^*$ transitions produce negative *B* terms. $d_{xz} \rightarrow \pi^*$ transitions may be used to indicate which ligand (Cl^-, OH^-, H_2O) is present, particularly if only one type of Pt binding is found. $\pi_1 \rightarrow \pi^*$ and $\pi_2 \rightarrow \pi^*$ transitions are especially useful because their intensities in free acetamide and iminol are manifested in the Pt complexes. The signs of the MCD *B* terms are not a reliable means for establishing the ligand-related A or I transitions although in many cases the magnitudes are reproduced. One reason for this is the transitions of the complex that are close in energy to the chosen transition can mix into this transition and change the sign. Another reason may be the orientation of the A and I ligands relative to the molecular plane. $n \rightarrow \pi^*$ transitions might be expected to provide additional information, but they are weak.

Triplet transitions are anticipated for these spectral studies, as Pt possesses an appreciable spin-orbit coupling constant that allows the intermixing of singlet and triplet excited states. But it is beyond the scope of the MO methods employed to give satisfactory treatment to these conditions.

Summary

This work has indicated that there may be observed band shifts in a UV-visible and MCD spectral study of the hydrolysis of *cis*-DDP with acetamide. The energy shifts correlate well with expectations from the spectrochemical series and with orbital interaction diagrams for acetamide and its iminol tautomer. Although total and transition energies are likely to be overestimated as compared with experimental results, reasonable spectral assignments are made from the relative ordering and trends.

The Pt-O bonded acetamide complex is found to be the most stable species. Perpendicular arrangements of the acetamide moieties are more favorable than planar structures. The differences in the Pt-O- and P-N-bonding species are found particularly in their effects on ligand-ligand transitions and transitions involving $d \rightarrow \pi^*$, $d \rightarrow d$, and $d \rightarrow 6p_y$. The $\pi \rightarrow \pi^*$ transitions are of primary importance in distinguishing Pt-A and Pt-I species regardless of Pt-ligand coordination.

This preliminary examination of the acetamide system represents an essential step in the development of a reasonable picture at the molecular level for the interaction of platinum species with simple binding sites. This system appears to offer good prospects for experimental realization.

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Supplementary Material Available: Table S1, showing theoretical absorption and MCD spectral results for *cis*-$Pt(NH_3)_2Cl_2$ hydrolysis products with both acetamide and its iminol (3 pages). Ordering information is given on any current masthead page.

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Improved Synthesis of Cyclamphosphine Oxide, a Potential Bidentate Asymmetric Ligand. Synthesis and Characterization of Some of Its Rhodium Complexes. Molecular and Crystal Structure of (Cyclamphosphine oxide)dicarbonylchlororhodium(I)

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Cyclamphosphorane, $C_{10}H_{21}N_4P$ (**1**), reacts with $ONMe_3$ to give cyclamphosphine oxide, $C_{10}H_{21}N_4PO$ (**2**), a potential bidentate asymmetric ligand, quantitatively. The action of **2** on $(Rh(CO)_2Cl)_2$ gives $(C_{10}H_{21}N_4PO)Rh(CO)_2Cl$ (**5**) and $(C_{10}H_{21}N_4PO)(Rh(CO)_2Cl)_2$ (**4**) wherein **2** behaves as a monodentate ligand and as a bridging ligand, respectively. An X-ray structure determination has been achieved on **5**, which crystallizes in the monoclinic space group $P2_1/n$ with $a = 12.698$ (1) Å, $b = 9.777$ (1) Å, $c = 13.791$ (1) Å, $\beta = 93.93$ (1)°, and $Z = 4$. The structure of **5** shows that the NH site is coordinated to the rhodium atom whereas the phosphoryl site remains free. Only one diastereoisomer is formed. The P=O bond length (1.456 (2) Å) and the Rh—N bond length (2.118 (3) Å) are in the usual ranges. The six-membered ring adopts a slightly distorted boat conformation. The five-membered ring has a flattened envelope conformation. The interatomic (N)H-Cl distance of 2.306 (1) Å indicates a bent hydrogen bond. The dinuclear complex **4** can be converted into **5** by an additional 1 equiv of **2**, while **5** yields **4** in the presence of 0.5 equiv of $(Rh(CO)_2Cl)_2$.

Tricyclic tetraaminophosphine oxides were first reported in a patent by Richman in 1976.[2] They were obtained from the tetrasilylated cyclic tetraamines by reaction with PF_5 or OPF_3 and subsequent hydrolysis of the tetraaminofluorophosphorane that is formed. The same author more recently showed that these oxides, including cyclamphosphine oxide (**2**), could be obtained by hydrolyzing the corresponding ionic phosphonium chloride.[3] The first of these routes requires reagents that are neither readily available nor convenient to handle and are expensive, while neither yields nor experimental details were given for the second approach.

Moreover, the versatile ligand properties of cyclamphosphorane (**1**)[4,5] in its open tautomeric form **1b** raised the question of the coordination ability of its oxide **2**. We therefore wish to report a convenient, quantitative synthesis of **2**, in a single step from **1**, by using trimethylamine oxide as the oxidizing agent,[6,7] as well as the preparation and characterization of two rhodium complexes in which cyclamphosphine oxide behaves as a monodentate ligand through its NH site or as a bridging ligand through both its NH

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