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Molecular and Crystal Structure of a Platinum(II) Complex with Aquo and Sulfate Ligands: Aquo(*N*,*N'*-dimethylethylenediamine)(sulfato)platinum(II) Hydrate

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The molecular and crystal structure of $[Pt(N,N'\text{-dimethylethylenediamine})(H_2O)(SO_4)]\cdot H_2O$ has been determined. The compound crystallizes in the monoclinic $P2_1/c$ space group with $a = 8.472$ (3) Å, $b = 8.495$ (4) Å, $c = 15.794$ (10) Å, $\beta = 100.05$ (4)°, and $Z = 4$. Data were collected with Mo Kα radiation and a Syntex P$\bar{1}$ diffractometer. The structure was refined on 2172 observed reflections to $R = 0.037$ and $R_w = 0.039$. The square-planar environment of Pt includes the bidentate ligand, one molecule of water, and a monodentate sulfate ion bonded through an oxygen atom. The Pt–N bonds are 2.009 (6) and 2.011 (7) Å, and the Pt–O bonds are 2.078 (6) Å for the water molecule and 2.052 (5) Å for the sulfato ligand. The coordinated S–O bond is significantly longer (1.525 (6) Å) than the other three S–O bonds (1.450 (7), 1.454 (6) and 1.457 (7) Å). The crystal is stabilized by extensive hydrogen bonding. The coordinated aquo ligand is involved in two hydrogen bonds where it donates the protons. The lattice molecule of water plays a crucial role in stabilizing the crystal. The stability of the crystal was explained on the basis of Brown's valence model.

Introduction

Terminal aquo or hydroxo complexes of platinum(II) are known to occur in solution, but the existence of these compounds in the solid state has been confirmed only recently. In 1982, the crystal structures of *cis*-$[Pt(NH_3)_2(\text{1-methylcytosine})(H_2O)]^{2+}$ and *cis*-$[Pt(NH_3)_2(\text{1-methylcytosine})OH]^+$ were reported.[1] Hydroxo-bridged oligomers have been known for several years,[2-7] but compounds of platinum(II) with terminal aquo or hydroxo ligands are more difficult to isolate.

Aquo compounds are important intermediates in almost all aqueous reactions. *cis*-$[Pt(NH_3)_2(H_2O)(OH)]^+$ is probably the active intermediate in the reactions of cisplatin and related drugs in cancer chemotherapy. Cisplatin is believed to hydrolyze inside the cells and react with N(7) of two close guanine residues in DNA, forming intrastrand d(GpG) cross-links.[8]

Aquo compounds of Pt(II) can be prepared by treating the dihalo compounds with a silver salt. But these hydrolyzed systems were found to be quite complex.[9] At neutral pH, the monoaquo monohydroxo compound is formed, but it can readily be converted to hydroxo-bridged oligomers. Several crsytal structures of dimers and trimers have been reported.[2-7]

Several investigators, including ourselves, have tried to isolate $[PtA_2(H_2O)_2]^{2+}$, $[PtA_2(H_2O)(OH)]^+$, or $[PtA_2(OH)_2]$ without success. Lock et al.[10,11] tried to explain why it was not possible to isolate these monomeric hydrolyzed species. The explanation is based on a valence model of Brown,[12,13] which in turn is an extension of Pauling's valence concept. The formation of two crystalline compounds *cis*-$[Pt(NH_3)_2(\text{1-methylcytosine})(H_2O)]^{2+}$ and *cis*-$[Pt(NH_3)_2(\text{1-methylcytosine})(OH)]^+$, which were not isolated as exclusive products, were later explained on the basis of two reasons: first, the specific hydrogen-bonding properties that stabilize OH^- and H_2O ligands in the two above complexes (as predicted previously by the same authors) and, second, the poor nucleophilicity of O(2) of 1-methylcytosine toward Pt(II) in aqueous solution.[1]

Table I. Experimental Details of the X-ray Study of $[Pt(NH(CH_3)C_2H_4NH(CH_3))(H_2O)(SO_4)]\cdot H_2O$

compd	$C_4H_{16}N_2O_6SPt$
fw	415.336
space group	$P2_1/c$
a	8.472 (3) Å
b	8.495 (4) Å
c	15.794 (10) Å
β	100.05 (4)°
vol	1119.2 (10) Å^3
Z	4
$F(000)$	784
ρ_{calcd}	2.464 g cm^{-3}
ρ_{exp}(flotation, CCl_4–CH_2Br_2)	2.46 g cm^{-3}
λ(Mo Kα)	0.71069 Å
μ(Mo Kα)	128.50 cm^{-1}
transmission factor range	0.081–0.236
2θ max	60°
quadrants	$h,k,\pm l$
scan technique	$2\theta/\theta$
std reflcns	400, 141, 41$\bar{3}$
temp	22 °C
no. of independent reflcns	3265
no. of obsd reflcns ($I > 2.5\sigma(I)$)	2172
no. of refined parameters	128

Hollis and Lippard[14,15] have reported the crystal structure of a very interesting Pt(III) compound, containing also a Pt–H_2O bond. This complex $[Pt_2(NH_3)_4(C_5H_4NO)_2(H_2O)(NO_3)](NO_3)_3\cdot 2H_2O$ contains a metal–metal bond with α-pyridonate ligands in a head-to-head arrangement. The coordinated water molecule is also involved in hydrogen bonding with a nitrate anion and with a lattice water molecule. Another Pt(III) compound $K_2[Pt_2(SO_4)_4(H_2O)_2]$ was reported,[16] but no information on the environment of the water molecules is available. One Pt(IV) compound $[Pt(\text{bipyridine})(\text{triaminocyclohexane})(H_2O)]Cl_2$, containing a coordinated water ligand, was also reported.[17] Again the water molecule fully utilizes its hydrogen-bonding capabilities.

We have recently attempted to prepare hydroxo-bridged oligomers from the reaction of $[Pt(N,N'\text{-dimethylethylenediamine})X_2]$ with a silver salt. When silver sulfate was used, we isolated a sulfate monomer, which was analyzed by X-ray diffraction. The results have shown that the chosen crystal was $[Pt(NH(CH_3)C_2H_4NH(CH_3))(SO_4)(H_2O)]\cdot H_2O$, with a molecule of water and a monodentate sulfate ligand bonded to Pt(II).

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Table II. Final Refined Coordinates and Temperature Factors ($\times 10^4$)

atom	x	y	z	U_{eq},[a] Å^2
Pt	2577.6 (3)	912.5 (3)	14.5 (2)	270
S	1894 (2)	−1093 (2)	−1696 (1)	328
N(1)	2016 (7)	−541 (8)	921 (4)	332
N(2)	3737 (7)	2189 (8)	1004 (4)	368
O(1)	1212 (6)	−328 (6)	−964 (3)	336
O(2)	2856 (6)	−2448 (7)	−1364 (4)	441
O(3)	513 (7)	−1558 (8)	−2324 (4)	544
O(4)	2880 (7)	74 (7)	−2034 (4)	495
O(5)	3176 (7)	2403 (6)	−924 (4)	405
C(1)	3277 (11)	1580 (11)	1832 (6)	456
C(2)	3105 (10)	−153 (11)	1759 (5)	402
C(3)	2018 (12)	−2279 (10)	723 (6)	528
C(4)	3447 (14)	3941 (10)	897 (8)	660
O(6)	1175 (8)	217 (7)	3766 (4)	565

[a] $U_{eq} = {}^1/_3\sum_i\sum_j U_{ij}a^*_i a^*_j \bar{a}_i \cdot \bar{a}_j$.

This is the first example of a Pt(II) compound containing monodentate sulfate in its coordinating sphere. A few Pt(III) and Pt(IV) compounds containing a Pt–Pt bond and bridging sulfato ligands have been reported.[16,18] The crystal structure of the compound $[Pt(NH(CH_3)C_2H_4NH(CH_3))(SO_4)(H_2O)]\cdot H_2O$ is described below.

Experimental Section

Synthesis. The compound was synthesized from the aqueous reaction of $[Pt(NH(CH_3)C_2H_4NH(CH_3))I_2]$ with Ag_2SO_4 (1:1 ratio). After the AgI precipitate was filtered out, the filtrate was concentrated under reduced pressure (40 °C) and left to crystallize slowly. The isolated compound was recrystallized from water.

Collection and Reduction of X-ray Data. A brown plate was selected after examination under a polarizing microscope for homogeneity. The crystal was mounted along the a axis. Precession photographs showed that the crystal was monoclinic with the systematic absences of $P2_1/c$. The unit cell parameters were obtained by least-squares refinement of angles 2θ, ω, and χ for 15 well-centered reflections (2θ range 10–22°) on a Syntex P$\bar{1}$ diffractometer using graphite-monochromatized Mo Kα radiation. Crystal data and other information are summarized in Table I. Scan rates and data treatment have been described.[19] Corrections were made for absorption and Lorentz-polarization effects. Anomalous dispersion terms were also included in calculations.

Solution of the Structure. The coordinates of the platinum atom were found from a three-dimensional Patterson synthesis. The positions of all the other non-hydrogen atoms were obtained by structure factor and Fourier-map calculations. The refinements were done by using full-matrix least squares minimizing $\sum w(F_o - F_c)^2$. Isotropic secondary-extinction corrections[20] were included in the calculations. The H atoms were fixed at the calculated positions with isotropic $B = 6.0$ Å^2 (N–H = 0.85 Å and C–H = 0.95 Å). Individual weights $w = 1/\sigma^2(F)$ were applied. The refinement of the scale factor, coordinates, and anisotropic temperature factors of all atoms converted to $R = 0.037$ and $R_w = 0.039$. The ratio of maximum least-squares shift to esd in final refinement cycle was <0.18. There were a few residual peaks (<0.9 e Å^{-3}) in the close environment of the Pt atom. The calculations were done on a Cyber 830 with programs already described.[19] A listing of final observed and calculated structure factors (Table S5) is available as supplementary material.

Discussion

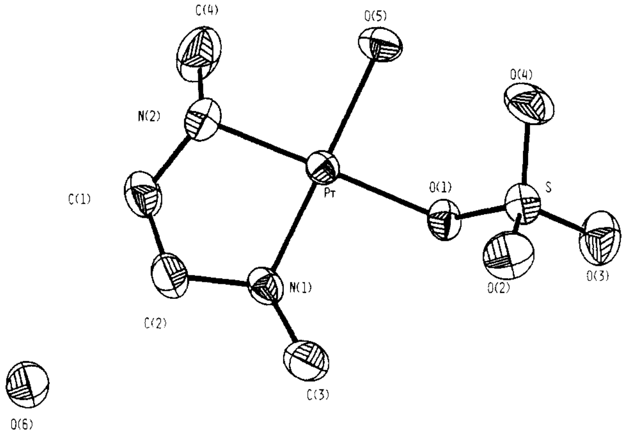

Figure 1. Labeled diagram of the molecule $[Pt(NH(CH_3)C_2H_4NH(CH_3))(H_2O)(SO_4)]\cdot H_2O$.

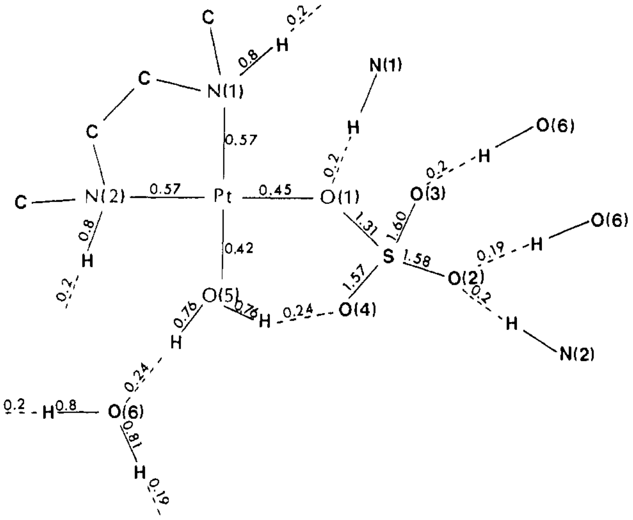

Figure 2. Bond valence assignment (Brown's theory) in the crystal $[Pt(NH(CH_3)C_2H_4NH(CH_3))(H_2O)(SO_4)]\cdot H_2O$.

Table III. Interatomic Distances (Å) and Angles (deg)

Pt–O(1)	2.052 (5)	S–O(4)	1.457 (7)
Pt–O(5)	2.078 (6)	N(1)–C(2)	1.512 (11)
Pt–N(1)	2.009 (6)	N(1)–C(3)	1.509 (11)
Pt–N(2)	2.011 (7)	N(2)–C(1)	1.519 (11)
S–O(1)	1.525 (6)	N(2)–C(4)	1.513 (11)
S–O(2)	1.454 (6)	C(1)–C(2)	1.482 (13)
S–O(3)	1.450 (7)		
O(1)–Pt–O(5)	87.2 (2)	N(1)–C(2)–C(1)	108.7 (7)
O(1)–Pt–N(1)	92.8 (2)	N(2)–C(1)–C(2)	107.9 (7)
O(1)–Pt–N(2)	175.0 (2)	C(1)–N(2)–C(4)	111.7 (7)
O(5)–Pt–N(1)	179.5 (2)	C(2)–N(1)–C(3)	111.8 (6)
O(5)–Pt–N(2)	94.5 (2)	O(1)–S–O(2)	109.0 (3)
N(1)–Pt–N(2)	85.5 (3)	O(1)–S–O(3)	105.5 (3)
Pt–O(1)–S	123.5 (3)	O(1)–S–O(4)	107.7 (3)
Pt–N(1)–C(2)	107.8 (5)	O(2)–S–O(3)	111.4 (4)
Pt–N(1)–C(3)	116.4 (5)	O(2)–S–O(4)	110.5 (4)
Pt–N(2)–C(1)	108.7 (5)	O(3)–S–O(4)	112.3 (4)
Pt–N(2)–C(4)	113.3 (6)		

The refined atomic parameters are listed in Table II. A labeled diagram of the molecule is shown in Figure 1. As expected, the coordination around the platinum(II) atom is square planar. The sulfate ligand is monodentate and is bonded through O(1). Besides the diamine ligand, one molecule of water, O(5), occupies the fourth position in the platinum(II) coordinating plane. The deviations (Å) from the weighted best plane are as follows: Pt, 0.0004 (3); N(1), 0.012 (6); N(2), −0.101 (6); O(1), −0.063 (5); O(5), 0.006 (6). The angles around the platinum atom are close to the expected values of 90 and 180° (Table III), but there are a few deviations caused by a slight strain inside the chelate ring. The chelate angle N(1)–Pt–N(2) is only 85.5 (3)°, while the angles O(1)–Pt–N(1) and O(5)–Pt–N(2) are slightly larger than normal (92.8 (2) and 94.5 (2)°), as observed in other platinum(II) chelates. The Pt–N bond distances (2.009 (6) and 2.011 (7) Å) are normal, and the two methyl groups on the bidentate ligand have the trans configuration (Figure 1). The torsion angles have been calculated (Table S2, supplementary material).

The SO_4 ligand is bonded to platinum(II) through one of its oxygen atoms. The bond distance Pt–O(1) is 2.052 (5) Å. The sulfate ligand is monodentate, and the coordinated S–O(1) bond

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Table IV. Distances and Angles of Atoms Possibly Involved in Hydrogen Bonds

atoms	transformn (on 2nd atom)	dist, Å	atoms	angle, deg
N(1)---O(1)	$-x, -y, -z$	2.845 (8)	Pt–N(1)---O(1)	101.9 (3)
			C(2)–N(1)---O(1)	111.4 (5)
			C(3)–N(1)---O(1)	107.1 (5)
			N(1)–H(1)---O(1)	172.3 (5)
N(2)---O(2)	$1 - x, -y, -z$	2.851 (8)	Pt–N(2)---O(2)	122.5 (3)
			C(1)–N(2)---O(2)	104.9 (5)
			C(4)–N(2)---O(2)	94.9 (5)
			N(2)–H(2)---O(2)	158.4 (5)
O(5)---O(6)	$x, {}^1/_2 - y, z - {}^1/_2$	2.629 (8)	Pt–O(5)---O(6)	111.8 (3)
O(5)---O(4)	x, y, z	2.627 (8)	Pt–O(5)---O(4)	90.6 (2)
O(6)---O(2)	$x, -{}^1/_2 - y, {}^1/_2 + z$	2.776 (8)		
O(6)---O(3)	$-x, -y, -z$	2.719 (9)	O(2)---O(6)---O(3)	119.7 (3)

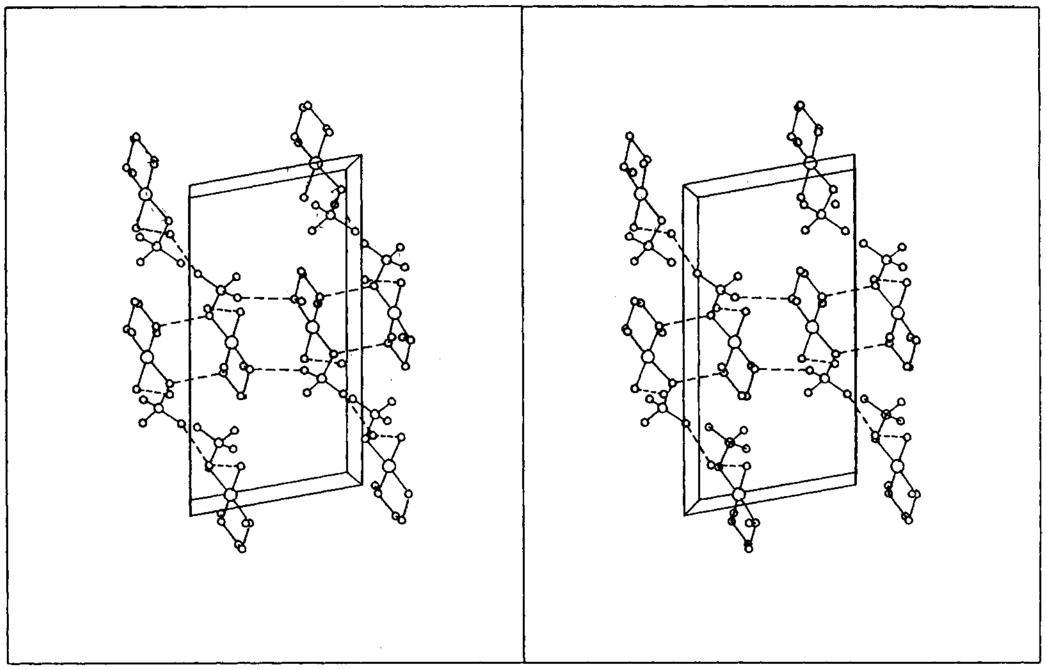

Figure 3. Packing of the molecules in the crystal $[Pt(NH(CH_3)C_2H_4NH(CH_3))(H_2O)(SO_4)]\cdot H_2O$ (z axis vertical; down y axis).

is significantly longer (1.526 (6) Å) than the other three S–O bonds (1.450 (7), 1.454 (6), 1.457 (7) Å). The six O–S–O angles vary from 105.5 (3) to 112.3 (4)°. The plane defined by atoms S–O(1)–Pt makes an angle of 120° with the platinum coordination plane so that the sulfate group is twisted away from the methyl carbon C(3). The S–O(1)–Pt angle of 123.5 (3)° clearly reduces local anion symmetry below C_{3v}. This is the first report of a crystal structure of a monomeric platinum(II) compound with coordinated sulfate ion. But this geometry of the sulfate ligand has been observed in other metal complexes as in $[Cu(N(CH_3)_2C_2H_4N(CH_3)_2)(SO_4)(H_2O)_2]$.[21]

The $Pt–OH_2$ bond distance is 2.078 (6) Å. It agrees with the value of 2.052 (8) Å found for *cis*-$[Pt(NH_3)_2(H_2O)(1\text{-methylcytosine})]^{2+}$.[1] The values found for the two Pt(III) compounds are 2.122 (6) Å[14] in $[Pt_2(NH_3)_4(C_5H_4NO)_2(H_2O)(NO_3)]^{3+}$ and 2.12 Å[16] in $K_2[Pt_2(SO_4)_4(H_2O)_2]$. For the Pt(IV) compound a value of 2.001 (7) Å[17] was found in $[Pt(bipyridine)(triaminocyclohexane)(H_2O)]^{2+}$. Our value seems slightly longer than the Pt(II)–OH distances (2.027 (9) Å)[1] found in *cis*-$[Pt(NH_3)_2(OH)(1\text{-methylcytosine})]^+$ and in a Pt(IV) compound $[Pt(NH_3)_2Cl_2(OH)_2]$ (2.00 (1) Å).[22] For hydroxo-bridged oligomers, the reported Pt–O bond distances vary from 1.99 to 2.17 Å.[2-7] Therefore, the bond lengths do not give any information on the weakness of the Pt–O bonds that has been suggested by the rapid rate of reaction of square-planar d^8 complexes. It has been suggested that the rapid rate of reaction of OH and OH_2 groups on platinum was associated with a marked weakening of the Pt–O bond in the five-coordinate state.[1]

Only one aquoplatinum(II) complex, *cis*-$[Pt(NH_3)_2(H_2O)(1\text{-methylcytosine})]^{2+}$, has been reported[1] before this structure. Brown's bond-valence concept[12,13] has been used to suggest conditions under which it may be possible to obtain aquo or terminal hydroxoplatinum(II) species.[10,11] Brown's model is an extension of the Pauling bond order–bond length relationship.[23] But Brown assigned bond valences to all neighboring interactions, regardless of whether they are ionic or covalent bonds or just van der Waals interactions. The only requirement is that the sums of the bond valences should be equal to the modulus of the formal oxidation state of each atom.

The bond valences in $[Pt(NH(CH_3)C_2H_4NH(CH_3))(SO_4)(H_2O)]\cdot H_2O$ were calculated as suggested by Brown and Altermatt[24] and are shown in Figure 2. The Pt–O valences were calculated from the bond lengths, and the Pt–N values were chosen to give the correct sum at the Pt atom. Bond valences for S–O bonds were calculated from the bond lengths. The O---H–O valences were calculated from the O---O distances (sum at H = 1.0) while the O---H–N values were assumed to be 0.2 and 0.8. The atoms of the diamine ligand should be electrically neutral. The total valence used for base bonds is 2 × 0.57 = 1.14, which should equal the total valence used for acid bonds, namely 2 H

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(on N) and 10 H (on C). Since the residual valence on NH is 0.2, the residual valence on the remaining H atoms is 0.74, or 0.074 valence unit per H atom.

As suggested earlier,[11] in order to form aquo complexes of platinum, certain hydrogen-bonding requirements must be fulfilled. The coordinated water molecule must form two strong bonds, where it would donate the protons. This was observed in the structures described in the Introduction.[1,14,17] In our compound, the aquo ligand also forms two strong bonds, the first with one oxygen atom of the intramolecular sulfate ligand (O(5)- - -O(4) = 2.627 (8) Å) (Table IV) and the second with a molecule of lattice water (O(5)- - -O(6) = 2.629 (8) Å). Therefore, the lattice molecule of water O(6) plays a very important role in the stabilization of the crystalline structure. On the basis of the valence sums in Figure 2, O(3), O(4), and O(6) are underbonded (1.80, 1.81, and 1.84). Therefore, these atoms must be hydrogen bonded to the CH groups. The application of Brown's theory to the crystal structure of $[Pt(NH(CH_3)C_2H_4NH(CH_3))(SO_4)(H_2O)]\cdot H_2O$ seems very interesting, and a more detailed theoretical study, including van der Waals interactions, should improve the results.

Sulfate ions are usually believed to be bidentate ligands toward Pt(II) in the solid state. In aqueous solution, ^{195}Pt NMR has shown the presence of $[PtL_2(SO_4)(H_2O)]$ species.[25,26] In crystalline $[Pt(NH(CH_3)C_2H_4NH(CH_3))(H_2O)(SO_4)]\cdot H_2O$, the hydrogen-bonding system is probably much more efficient when the sulfate ligand is monodentate and a water molecule occupies the fourth coordination site of the platinum(II) atom. The four oxygen atoms of the sulfate ligand are involved in the hydrogen-bonding system, where they accept protons from the water molecules or from the -NH groups (Table IV).

The packing of the molecues in the crystal is shown in Figure 3. It consists of layers of molecules parallel to the *bc* plane held together in the *a* direction by hydrogen bonds between the amine groups and the sulfate ligands. The N(1)- - -O(1) and N(2)- - -O(2) distances are 2.845 (8) and 2.851 (8) Å, respectively, and the angles are very favorable for hydrogen bonds (Table IV). Besides the two hydrogen bonds already mentioned, where the coordinated water molecule O(5) donates protons to a sulfate oxygen O(4) and to the lattice molecule of water O(6), there are two other hydrogen bonds where O(6) donates protons to two sulfate oxygen atoms O(2) and O(3). The angle O(2)- - -O(6)---O(3) is 119.7 (3)°. Therefore, one oxygen atom in the sulfate ligand O(2) seems to accept two protons, one from N(1) and one from the lattice molecule of water O(6).

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Supplementary Material Available: Tables S1–S4, listing anisotropic thermal parameters, torsion angles, weighted least-squares planes, and calculated hydrogen coordinates (4 pages); Table S5, listing of calculated and observed structure factors (12 pages). Ordering information is given on any current masthead page.

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Equilibrium and Kinetic Studies of Monoaquo Complexes of Platinum(II). 1. Formation from Corresponding Chloro Species by Hydrolysis

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Rate (k_1) and equilibrium constants (K_h) for the hydrolysis of *cis*(*N*,*S*)-Pt(amino acid)(dimethyl sulfoxide)Cl complexes (denoted Pt–Cl) have been determined for amino acids glycine, sarcosine, and *N*,*N*-dimethylglycine at 35 °C. K_h and k_2, the rate constant for the reverse reaction, were determined by potentiometric titration (with a chloride-sensitive electrode) of the aquo species derived from the chloro species by reaction with $AgNO_3$. Rate constants for the base hydrolysis of Pt–Cl at high pH, determined by both NMR and potentiometric techniques, correspond closely to those obtained from the low-pH titrations, indicating that the hydrolysis occurs by reaction with water solvent over a substantial pH range. For both glycine and sarcosine complexes of Pt–Cl, addition of NaOH leads to rapid establishment of an equilibrium mixture of Pt–Cl and the N-coordinated, OH-substituted species that results from opening of the chelate ring. This mixture slowly reverts to Pt–OH as the Pt–Cl is hydrolyzed by solvent water. Second-order rate constants, k_{Ag}, are also reported for the silver-assisted hydrolysis of the chloride complexes, making possible an assessment of the relative importance of the two mechanisms of hydrolysis. Variation among the three species is less than 1 order of magnitude for all four constants: $k_1 \cong 10^{-4}\ s^{-1}$, $k_2 \cong 10\ M^{-1}\ s^{-1}$, $K_h \cong 10^{-5}$ M, $k_{Ag} \cong 10^{-2}\ M^{-1}\ s^{-1}$.

Extensive investigations of the mechanism of the interaction of the anticancer drug *cis*-diamminedichloroplatinum(II) (DDP) with DNA and with simpler nucleotides and nucleosides have emphasized the importance of aquo species derived from the chloro species by hydrolysis in a low-[chloride] medium.[1,2] The acidic aquo species is readily deprotonated by bases to yield the corresponding mono- and dihydroxo species.[3,4] At pH values near the pK_a, μ-OH-bridged dimer and trimer species are readily formed from the partially neutralized aquo species.[5,6]

We have earlier reported NMR evidence for isomer assignments[7,8] and a detailed study of the mechanism of Cl^--catalyzed and Me_2SO-catalyzed isomerization of cis and trans (N,S) isomers of mixed amino acid–dimethyl sulfoxide complexes of platinum(II).[9] The equilibration studies included a comparison of rates

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