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NMR Spectra of Iminobis(methylenephosphonic acid), $HN(CH_2PO_3H_2)_2$, and Related Ligands and of Their Complexes with Platinum(II)

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Variations in chemical shift with pD have been studied for ^{31}P, ^{1}H, and ^{13}C NMR with iminobis(methylenephosphonic acid) ($idmpH_4$) and *N*-(phosphonomethyl)glycine ($impaH_3$) and for ^{31}P NMR with (methylimino)bis(methylenephosphonic acid) ($midmpH_4$) and nitrilotris(methylenephosphonic acid) ($ntmpH_6$) and discussed in terms of the successive deprotonation equilibria. ^{31}P, ^{15}N, ^{195}Pt, and ^{13}C NMR spectra have been used to study the reactions in solution of each of the ligands with *cis*-$Pt(^{15}NH_3)_2(H_2O)_2^{2+}$. Under acid conditions, $idmpH_4$, $midmpH_4$, and $ntmpH_6$ each initially coordinate through phosphonate O, with subsequent formation of a N,O-chelate. With impa, the chelate complex with carboxylate bound is stable in acid, and the isomer with phosphonate bound is stable in alkali. $idmpH_4$ with $PtCl_4^{2-}$ in acid gives $PtCl_2(idmpH_3\text{-}N,O)^-$, which with base gives $PtCl(idmp\text{-}N,O,O)^{3-}$, with the ligand coordinated meridional and tridentate. The *N*-methyl analogue behaves similarly. In acid, impa forms $PtCl_2(impaH_2\text{-}N,O)^-$, with carboxylate oxygen bound. At higher pH, $PtCl(impa\text{-}N,O,O)^{2-}$ forms.

Introduction

We have recently reported results of an NMR study of the reactions of (aminoalkyl)phosphonic acids $NH_2(CH_2)_nPO_3H_2$ (n = 1-3) with *cis*-$Pt(NH_3)_2(H_2O)_2^{2+}$ (I).[1] In this work, the study has been extended to more complex ligands containing nitrogen and two or three methylenephosphonic acid groups:[2] iminobis(methylenephosphonic acid), $HN(CH_2PO_3H_2)_2$ ($idmpH_4$); (methylimino)bis(methylenephosphonic acid), $CH_3N(CH_2PO_3H_2)_2$ ($midmpH_4$); nitrilotris(methylenephosphonic acid), $N(CH_2PO_3H_2)_3$ ($ntmpH_6$).

These molecules are formal analogues of iminodiacetic acid ($idaH_2$), (methylimino)diacetic acid ($midaH_2$), and nitrilotriacetic acid ($ntaH_3$), which form a variety of complexes with platinum(II).[3-5] *N*-(Phosphonomethyl)glycine, $HN(CH_2PO_3H_2)(CH_2COOH)$ ($impaH_3$) (from which the herbicide Roundup (Monsanto) is derived), has also been included in this work, to allow a direct comparison between the tendencies of the phosphonate and acetate "arms" to form chelate rings.

From potentiometric studies with labile metal ions,[6-8] it is clear that these ligands readily form coordination complexes, but probably because of their high solubility, few well-defined solids have been prepared and no structural data are available. ^{31}P NMR provides a useful tool for characterization of complexes in solution. When the ligands are reacted with *cis*-$Pt(^{15}NH_3)_2(H_2O)_2^{2+}$, ^{15}N and, in some cases, ^{195}Pt NMR can also provide useful information on reactions in solution.[1,4,9-11]

As a preliminary to this work, it was necessary to be able to identify peaks due to the free ligand at different pH values. A study of the effect of pH on ^{31}P spectra was carried out for all of the ligands and on ^{13}C and ^{1}H spectra as well for idmp and impa, similar to the study previously reported for $NH_2(CH_2)_nPO_3H_2$ (n = 1-3).[12] This also allowed the protonation state of the ligands to be determined at each pH.

Experimental Section

Starting Materials. *cis*-$Pt(^{15}NH_3)_2(ONO_2)_2$ was prepared as previously described.[10,11] $^{15}NH_4Cl$ (99.0% ^{15}N) was supplied by Novachem, Melbourne, Australia. Literature methods were used to prepare iminobis(methylenephosphonic acid)[13] and (methylimino)bis(methylenephosphonic acid).[14] Nitrilotris(methylenephosphonic acid) was supplied by Ega-Chemie as a 50% aqueous solution. To obtain the solid, the volume of the solution was reduced on a steam bath. Ethanol was added, and the resultant oil was triturated under ethanol. The solid was recrystallized by dissolving it in a minimum volume of hot water and then reprecipitating it by addition of ethanol. A solution of the herbicide Roundup was donated by Monsanto Ltd. *N*-(phosphonomethyl)glycine was obtained by acidifying this solution with 1 M HCl and allowing the free acid to crystallize.

NMR Techniques. Instrumentation and general methods were as previously described.[1,11,12] All chemical shifts are reported with lower shielding positive and with the following references: ^{31}P (40.3 MHz), 85% H_3PO_4 in a coaxial capillary; ^{15}N (10.1 MHz), the $^{15}NH_4^+$ signal of 5 M $^{15}NH_4{}^{15}NO_3$ in 2 M HNO_3 contained in a coaxial capillary; ^{195}Pt (21.4 MHz), a separate solution of 0.5 g of Na_2PtCl_6/mL of H_2O; ^{13}C (25.0 MHz), external tetramethylsilane, with internal dioxane taken as 67.73 ppm; ^{1}H (100 MHz), the methyl resonance of 3-(trimethylsilyl)-propanesulfonate. Unless otherwise stated, spectra (except for ^{1}H) are ^{1}H-decoupled. Probe temperature was 28 °C.

pH Measurements. Merck narrow range indicator strips were used for routine measurements. More accurate measurements were made with the use of a TPS 1852 mV digitial pH meter and a combination glass/reference electrode. pD values in D_2O were obtained by application of the correction[15] pD = meter reading + 0.40.

Results

Table I lists NMR parameters for the solution obtained by dissolving the free acids in D_2O, when the principal species in solution is the zwitterion (taking H as ^{1}H or ^{2}H) $R^1R^2{}^+NH(CH_2PO_3H^-)$ (R^1 = H, R^2 = $CH_2PO_3H_2$ or CH_2CO_2H; R^1 = CH_3, R^2 = $CH_2PO_3H_2$; R^1 = R^2 = $CH_2PO_3H_2$).

Table II gives ^{31}P and ^{15}N NMR data for the platinum complexes formed with those ligands.

Effects of pH on Ligand Spectra. Each of the free ligands $idmpH_4$, $midmpH_4$, $ntmpH_6$, and $impdaH_3$ showed a singlet in its ^{1}H-decoupled ^{31}P spectrum. The methylene group of $idmpH_4$ showed a doublet in the ^{1}H spectrum, and a doublet of doublets in the ^{13}C spectrum (with the larger of the two coupling constants assigned to ^{3}J(P-C-N-C); see Table I).

Figure 1 shows a plot of δ_P, δ_C, and δ_H against pD for $idmpH_4$ (D_2O was used as solvent so that ^{1}H spectra could be run on the same solution as for the other nuclei). Acid dissociation constants have previously been determined for this compound[16] and are included in Table III. By analogy with the simpler (aminoalkyl)phosphonic acids,[12] the four deprotonation steps corre-

(1) Appleton, T. G.; Hall, J. R.; McMahon, I. J. *Inorg. Chem.* preceding paper in this issue.
(2) Each of these acids normally exists in a zwitterion form, but unless this is being emphasized, they will be written in the neutral form given here.
(3) Appleton, T. G.; Berry, R. D.; Hall, J. R. *Inorg. Chem.* **1985**, *24*, 666.
(4) Appleton, T. G.; Hall, J. R.; Ralph, S. F. *Inorg. Chem.* **1985**, *24*, 673.
(5) Smith, B. B.; Sawyer, D. T. *Inorg. Chem.* **1969**, *8*, 379.
(6) Kabachnik, M. I.; Medved, T. Ya.; Dyatlova, N. M; Rudomino, M. V. *Usp. Khim.* **1974**, *43*, 1554; *Russ. Chem. Rev. (Engl. Transl.)* **1974**, *43*, 733).
(7) Lundager Madsen, H. E.; Christensen, H. H.; Gottlieb-Petersen, C. *Acta Chem. Scand., Ser. A* **1978**, *A32*, 79.
(8) Motekaitis, R. J.; Murase, I.; Martell, A. E. *Inorg. Chem.* **1976**, *15*, 2303.
(9) Ismail, I. M.; Sadler, P. J. In "Platinum, Gold, and other Metal Chemotherapeutic Agents"; Lippard, S. J., Ed.; American Chemical Society: Washington, DC, 1983; ACS Symp. Ser. No. 209, p 171.
(10) Boreham, C. J.; Broomhead, J. A.; Fairlie, D. P. *Aust. J. Chem.* **1981**, *34*, 659.
(11) Appleton, T. G.; Berry, R. D.; Davis, C. A.; Hall, J. R.; Kimlin, H. A. *Inorg. Chem.* **1984**, *23*, 3514.
(12) Appleton, T. G.; Hall, J. R.; Harris, A. D.; Kimlin, H. A.; McMahon, I. J. *Aust. J. Chem.* **1984**, *37*, 1833.
(13) Moedritzer, K. *Synth. Inorg. Met.-Org. Chem.* **1973**, *3*, 75.
(14) Moedritzer, K.; Irani, R. R. *J. Org. Chem.* **1966**, *31*, 1603.
(15) Glasoe, P. K.; Long, F. A. *J. Phys. Chem.* **1960**, *64*, 188.
(16) Vasil'ev, V. P.; Kumurov, M. V.; Kochergina, L. A.; Tsirul'nikova, N. V. *Zh. Obshch. Khim.* **1983**, *53*, 1990.

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Table I. NMR Parameters for Free Ligands Dissolved in D_2O[a]

		^{13}C				^1H	
compd	δ_P	assignt	δ_C	^1J(P–C)	^3J(P–C–N–C)	δ_H	^2J(P–C–H)
$idmpH_4$	9.75	N–CH_2–P	46.29	139.6	6.8	3.38	13.2
$midmpH_4$	7.93	N–CH_2–P	55.29	134.8	*b*	3.56	12.7
		N–CH_3	45.74			3.17	
$ntmpH_6$	8.11	N–CH_2–P	54.22	137.7	4.4	3.80	12.2
$impaH_3$	8.60	N–CH_2–P	45.00	138.6		3.25	12.7
		N–CH_2–C	49.96		7.8	4.00	
		–COOH	170.27				

[a] Spectra run on saturated solutions, except for $ntmpH_6$, for which 0.15 g was dissolved in 2 mL of D_2O. Under these conditions, the neutral zwitterion predominates. Coupling constants are in Hz. [b] Not resolved.

Table II. ^{31}P and ^{15}N NMR Parameters for Platinum Complexes[a]

			δ_P (J(Pt–P))		δ_N (J(Pt–N))		
compd[b]	structure	pH	coordinated phosphonate	uncoordinated phosphonate	ammine trans to O	ammine trans to N	J(P–N)[c]
$Pt(NH_3)_2(idmpH_4\text{-}O)(H_2O)^{2+}$	II	1.5	18.47 (<8)	*d*	*e* (385.7)		
$Pt(NH_3)_2(idmpH_3\text{-}N,O)^+$	VII	1.5	43.17 (102.5)	13.99 (102.7)	−82.83 (376.5)	−67.20 (303.7)	2.0
$Pt(NH_3)_2(idmp\text{-}N,O)^{2-}$	X	12.5	38.03 (70.8)	10.36 (68.4)	−79.88 (353.5)	−66.52 (293.0)	2.9
$PtCl_2(idmpH_3\text{-}N,O)^-$	XX	1.5	47.11 (124.5)	13.56 (200.2)			
$PtCl(idmp\text{-}N,O,O)^{3-}$	XXI	6.0	41.24 (102.5)				
$Pt(NH_3)_2(midmpH_4\text{-}O)(H_2O)^{2+}$	III	1.5	16.83 (<8)	*d*			
$Pt(NH_3)_2(midmpH_3\text{-}N,O)^+$	VIII	1.5	40.75 (63.4)	12.17 (58.6)	−78.38 (392.1)	−68.89 (304.2)	2.0
$Pt(NH_3)_2(midmp\text{-}N,O)^{2-}$	XI	10.5	36.69 (46.4)	9.81 (43.9)	−76.25 (370.6)	−67.56 (288.1)	1.5
$PtCl_2(midmpH_3\text{-}N,O)^-$	XXII	1.5	43.59 (53.2)	13.08 (151.4)			
$PtCl(midmp\text{-}N,O,O)^{3-}$	XXIII	6.0	41.78 (97.7)				
$Pt(NH_3)_2(ntmpH_6\text{-}O)(H_2O)^{2+}$	IV	1.5	22.28 (<8)	*d*			
$Pt(NH_3)_2(ntmpH_5\text{-}N,O)^+$	IX	1.5	41.28 (56.2)	12.53 (70.8)	−76.11 (394.5)	−69.43 (308.6)	2.0
$Pt(NH_3)_2(impaH_3\text{-}O)(H_2O)^{2+}$	XIII	1.5	18.47 (<8)	*d*			
$Pt(NH_3)_2(impaH_3\text{-}N)(H_2O)^{2+}$	XVII	1.5		22.46 (92.7)			
$Pt(NH_3)_2(impaH_2\text{-}N,O)^+$	XV	1.5	43.05 (97.7)				
$Pt(NH_3)_2(impaH_2\text{-}N,O)^+$	XVI	1.5		13.44 (87.9)	−80.07 (344.7)	−66.67 (303.2)	
$Pt(NH_3)_2(impa\text{-}N,O)^-$	XIX	11.0	38.15 (79.4)		−81.86 (349.6)	−66.53 (296.9)	
$Pt(NH_3)_2(impa\text{-}N,O)^-$	XVIII	11.0		9.81 (67.1)	−79.15 (344.8)	−66.29 (296.0)	
$PtCl_2(impaH_2\text{-}N,O)^-$	XXIV	2.0		12.11 (188.0)			
$PtCl_2(impa\text{-}N,O)^{3-}$	XXVI	10.0		9.87 (195.2)			
$PtCl(impa\text{-}N,O,O)^{2-}$	XXV	7.0	42.99 (95.2)				

[a] Chemical shifts in ppm to lower shielding; coupling constants in Hz. [b] In ammine compounds, ammonia is ^{15}N-substituted. All ammine complexes are cis. [c] Coupling between ammine ^{15}N and ^{31}P in chelate ring, when resolved. [d] Not resolved from peak due to free ligand. [e] ^{15}N peaks obscured by those from I. J(Pt–N) from ^{195}Pt spectrum.

sponding to these values would be expected to be as shown in Table III.

The plot for each of the nuclei shows a "break" corresponding to deprotonation of a $-PO_3H_2$ group at pD <2. The second and third deprotonations, of $-PO_3H^-$ groups, give a single "break" centered near pD 5.5. The last deprotonation, from the amine group, gives a well-defined "break" at pD 11 for each nucleus. In each of the ^1H and ^{13}C plots, each deprotonation produces a change in the same direction. For ^{31}P, the first three deprotonations shift δ_P to higher shielding, while deprotonation of the nitrogen causes a much more pronounced deshielding of the phosphorus nucleus. A similar pronounced deshielding was observed when $^+NH_3(CH_2)_nPO_3^{2-}$ was deprotonated to $NH_2(CH_2)_nPO_3^{2-}$ (n = 1–3). This was interpreted as indicating that the zwitterions existed in solution in conformations in which the phosphonate group can be strongly influenced by the positively charged amine group. At high pH, the methylene protons of $idmp^{4-}$ slowly exchanged with solvent deuterium. The pK_a values in D_2O would be expected to differ significantly from those in H_2O determined potentiometrically.

The ^1H spectrum of the *N*-methyl analogue, $midmpH_4$, showed a doublet from the methylene protons and a singlet from the methyl group. The ^{13}C spectrum also showed a doublet and singlet, with long-range carbon–phosphorus couplings unresolved. Only for the ^{31}P nucleus was a detailed study carried out of the effect of pH (in H_2O) on chemical shift. The shape of the plot of δ_P against pH was very similar to that for $idmpH_4$.

The ^1H spectrum of $ntmpH_6$ showed the expected doublet. The ^{13}C spectrum gave a doublet of triplets, with the P–C–N–C coupling just resolved. A plot of δ_P against pH for nitrilotris(methylenephosphonic acid) $ntmpH_6$ is shown in Figure 2. As

Table III. pK_a Values for Ligands

	pK_a		
species deprotonated	in D_2O (from NMR)	in H_2O (lit.)	ref
$H_2N^+(CH_2PO_3H_2)(CH_2PO_3H^-)$ ($idmpH_4$)	1.7	1.4	16
$H_2N^+(CH_2PO_3H^-)_2$ / $H_2N^+(CH_2PO_3H^-)(CH_2PO_3^{2-})$	5.5	5.5	16
$H_2N^+(CH_2PO_3^{2-})_2$	11.0	11.6	16
$CH_3N^+H(CH_2PO_3H_2)(CH_2PO_3H^-)$ ($midmpH_4$)	1.0		
$CH_3N^+H(CH_2PO_3H^-)_2$ / $CH_3N^+H(CH_2PO_3H^-)(CH_2PO_3^{2-})$	5.5		
$CH_3N^+H(CH_2PO_3^{2-})_2$	12.0		
$HN^+(CH_2PO_3H_2)_2(CH_2PO_3H^-)$ ($ntmpH_6$) / $HN^+(CH_2PO_3H_2)(CH_2PO_3H^-)_2$	1.0		
$HN^+(CH_2PO_3H^-)_3$	4.0		
$HN^+CH_2PO_3H^-)_2(CH_2PO_3^{2-})$ / $HN^+(CH_2PO_3H^-)(CH_2PO_3^{2-})_2$	5.5		
$HN^+(CH_2PO_3^{2-})_3$	11.5		
$H_2N^+(CH_2COOH)(CH_2PO_3H_2)$ ($impaH_4^+$)	<1		
$H_2N^+(CH_2COOH)(CH_2PO_3H^-)$	2.0	2.27	20
$H_2N^+(CH_2CO_2^-)(CH_2PO_3H^-)$	5.5	5.58	20
$H_2N^+(CH_2CO_2^-)(CH_2PO_3^{2-})$	10.5	10.25	20

with the bis(methylenephosphonate) compounds, there is a decrease in δ_P with increasing pD near pD 1, corresponding to the first two deprotonations of $HN^+(CH_2PO_3H^-)(CH_2PO_3H_2)_2$, and a sharp increase in δ_P with increasing pD at pD 11.5, corresponding to the last deprotonation of $HN^+(CH_2PO_3^{2-})_3$. The shape of the curve of the pD 3–6 region is interesting. There is a small but definite shift to lower shielding as the pD increases through 4, followed by a larger shift to higher shielding at pD 5.5. Depro-

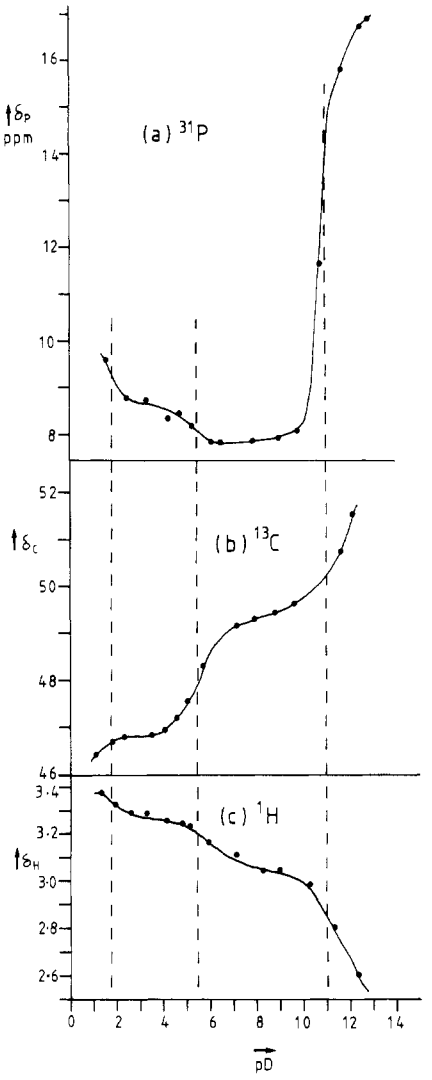


Figure 1. Variation with pD of (a) δ_P, (b) δ_C, and (c) δ_H for a solution of iminobis(methylenephosphonic acid) (idmpH_4) in D_2O.

tonation of one of the hydrogen phosphonate groups of $HN^+(CH_2PO_3H^-)_3$ will increase shielding of the phosphorus nucleus directly concerned but will also affect the other two phosphorus nuclei in phosphonate groups that remain protonated. If this "remote effect" has the same sign as the much greater effect of nitrogen deprotonation, it will cause a decrease in phosphorus shielding. Because the protonation equilibria are fast, the observed shift will be a weighted average for the three nuclei. When one proton is removed from $HN(CH_2PO_3H^-)_3$ at pH 4, the magnitude of the "remote effect" outweighs that of the "direct effect" in the weighted average, and there is a shift to lower shielding. For the subsequent phosphonate deprotonations, the "direct effect" predominates.

Plots of δ_P, δ_C, and δ_H against pD for *N*-(phosphonomethyl)-glycine, impaH_3, are shown in Figure 3. Since pK_a values indicate that fully protonated phosphonic acid groups ($-PO_3H_2$) are usually more acidic than carboxylic acid groups ($-CO_2H$), the favored zwitterion form for the free acid would be expected to be $H_2N^+(CH_2CO_2H)(CH_2PO_3H^-)$. X-ray crystal structure determinations[17-19] have shown that the solid acid exists in this form, and our plots are consistent with its presence in solution also. pK_a values for impaH_3 have been reported[20] (see Table III).

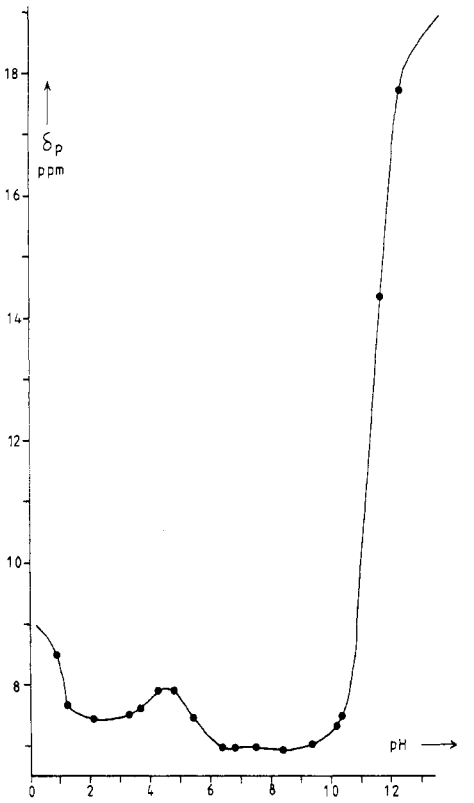


Figure 2. Variation of δ_P with pH for a solution of nitrilotris(methylenephosphonic acid) (ntmpH_6) in H_2O.

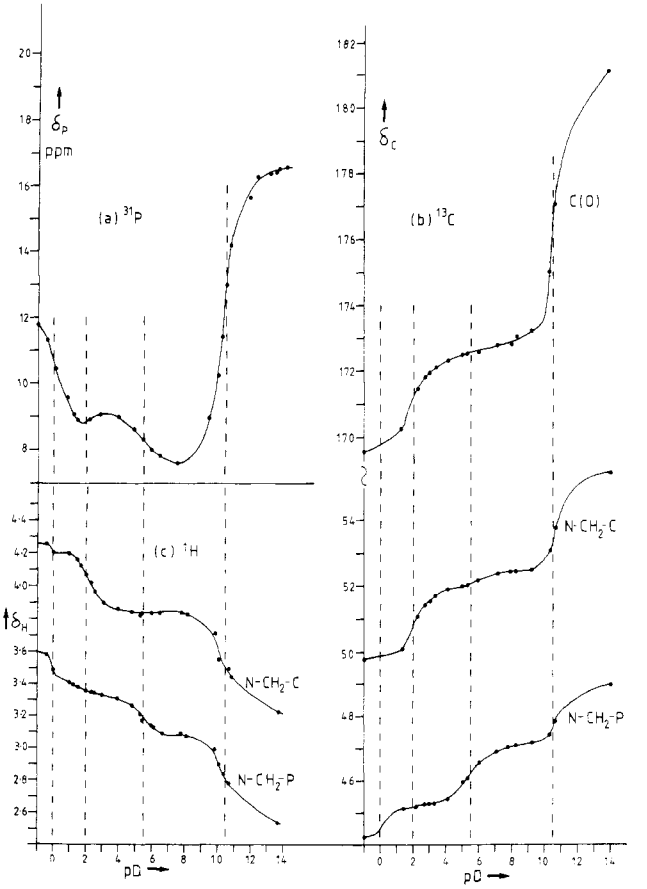
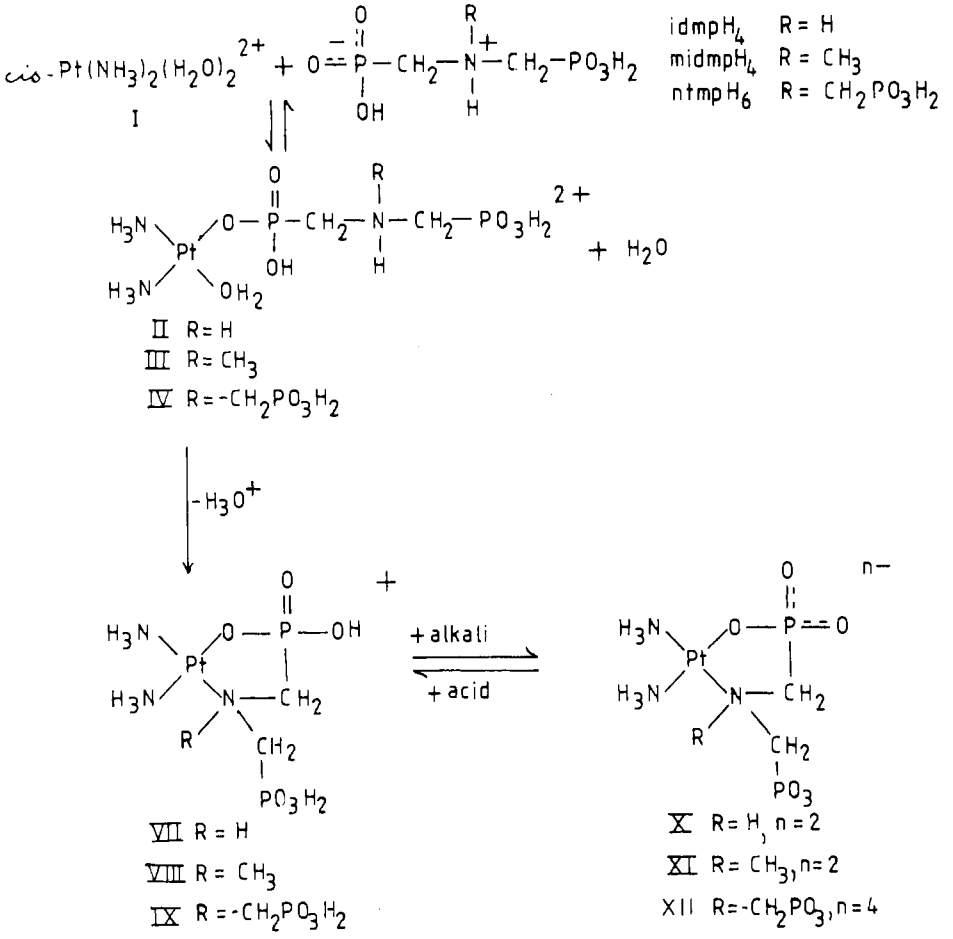


Figure 3. Variation with pD of (a) δ_P, (b) δ_C, and (c) δ_H for a solution of *N*-(phosphonomethyl)glycine (impaH_3) in D_2O.

The ^{1}H NMR spectrum of a solution of impaH_3 in D_2O showed a singlet and a doublet. It was assumed that the doublet coupling corresponded to $^2J(P-CH_2)$, so the doublet was assigned to the

(17) Knuuttila, P.; Knuuttila, H. *Acta Chem. Scand., Ser. B.* **1979**, *B33*, 623.
(18) Sheldrick, W. S.; Morr, M. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1981**, *37*, 733.
(19) Shkol'nikova, L. M.; Porai-Koshits, M. A.; Dyatlova, N. M.; Yaroshenko, G. F.; Rudomino, M. V.; Kolova, E. K. *Zh. Strkt. Khim.* **1982**, *23*, 98.
(20) Wauchope, D. *J. Agric. Food Chem.* **1976**, *24*, 717.

Scheme I



methylene group adjacent to phosphonate and the singlet to methylene adjacent to carboxyl (Table I). The ^{1}H-decoupled ^{13}C spectrum showed a singlet at lower shielding assigned to the carboxyl carbon atom and two doublets in the methylene region. The doublet with the larger splitting (139 Hz) was assigned to the methylene group adjacent to phosphonate, and the doublet with the smaller splitting (8 Hz) was assigned to the methylene group adjacent to carboxyl (Table I). A singlet was observed in the ^{1}H-decoupled ^{31}P spectrum.

In very strong acid solutions, the Hammett acidity function, H_0,[21] was used to give approximate values for log [D$^+$] to allow the plots to be extended into these areas. As acid concentration increased, the phosphorus nucleus and the protons of the adjacent methylene group were deshielded and the carbon nucleus of this methylene group was shielded. The other carbon atoms and protons were not affected significantly. These changes correspond to protonation of the free acid impaH_3 to impaH_4^+ in strong acid.

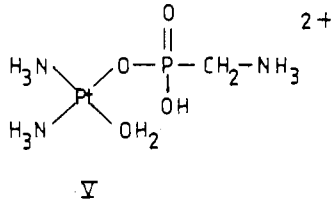
As the pD increases through 2.0, there is significant deshielding of the carbonyl carbon atom and of the adjacent methylene carbon atom. There is a corresponding shielding of the protons of this methylene group. The signals due to the methylene group adjacent to phosphonate are not affected. These changes are therefore due to the deprotonation of the carboxyl group.

The effect of δ_P of this deprotonation is to cause a small shift to lower shielding (cf. the "remote effect" in deprotonation of $HN^+(CH_2PO_3H^-)$ discussed above).

The next deprotonation, at pD 5.5, causes shielding of the phosphorus nucleus and affects the signals from the methylene group adjacent to phosphonate much more than those from the other methylene group. This reaction therefore corresponds to loss of the remaining phosphonic acid proton.

The last deprotonation, from nitrogen, at pD 10.5 affects both methylene groups and causes marked deshielding of both the phosphorus and carboxyl carbon nuclei.

Reactions of *cis*-Pt$(NH_3)_2(H_2O)_2^{2+}$ (I) with Ligands RN$(CH_2PO_3H_2)_2$ (R = H, CH_3, $-CH_2PO_3H_2$) (Scheme I). When solutions of I and idmpH_4 in H_2O were mixed at pH 1.5, the ^{1}H-decoupled ^{31}P NMR spectrum showed initially, in addition to a peak due to free ligand, a singlet without resolved platinum satellites at 18.47 ppm. If ^{15}N-substituted ammine was used in I, the ^{1}H-decoupled ^{195}Pt, NMR spectrum showed a sharp triplet at −1479.4 ppm, with triplet separation of 386 Hz. This platinum shift corresponds to a platinum atom coordinated by two nitrogen and two oxygen donors.[9-11] In the corresponding reaction between I and (aminomethyl)phosphonic acid (ampH_2), the initial compound formed was *cis*-Pt$(^{15}NH_3)_2$(ampH_2-*O*)$(H_2O)^{2+}$ (V), which



V

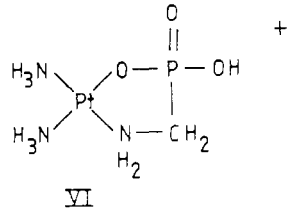
gave a triplet at −1490.8 ppm (separation of 383 Hz) in its ^{195}Pt spectrum and a singlet without resolved platinum coupling at 20.83 ppm in its ^{31}P spectrum.[1] This initial complex with idmp was therefore assigned as *cis*-Pt$(^{15}NH_3)_2$(idmpH_4-*O*)$(H_2O)^{2+}$ (II).[22] The ^{31}P spectrum of II would be expected to show an additional singlet due to the uncoordinated phosphonic acid group. This was not observed, but was presumably coincident with the peak from free idmpH_4 at 9.75 ppm. The ^{15}N resonances from II, like those of V, would be expected to be close to those of I. II underwent

(21) Rochester, C. H. "Acidity Functions"; Academic Press: London, 1970; pp 9–68.

(22) At pH 1.5, the fully protonated form, II, will be in equilibrium with species that have lost some of the phosphonate protons. The exact protonation state of this and related species at this pH is not known.

further reaction too quickly (see below) to allow an ^{15}N spectrum to be obtained of sufficient quality to resolve these peaks. As with V and related complexes,[1] the ^{195}Pt spectrum of II showed a triplet rather than a doublet of doublets because of the similarity of ^1J(Pt–N) for the two nonequivalent ammine groups. Formation of II as the initial complex in solution is also analogous to the formation of *cis*-$Pt(NH_3)_2$(midaH_2-*O*)$(H_2O)^{2+}$ from I and midaH_2.[4]

At pH 1.5, *cis*-$Pt(NH_3)_2$(ampH_2-*O*)$(H_2O)^{2+}$ (V) very slowly undergoes a ring closure reaction to the chelate complex Pt-$(NH_3)_2$(ampH-*N*,*O*)$^+$ (VI).[1] The analogous ring closure reaction



VI

of II to give $Pt(NH_3)_2$(idmpH_3-*N*,*O*)$^+$ (VII) occurred much more quickly. Peaks due to VII were easily detectable within 30 min and within several hours had become (apart from peaks due to excess free ligand or I) the only significant peaks in the spectra, at the expense of those from II.

For $Pt(NH_3)_2$(ampH-*N*,*O*)$^+$ (VI), the ^{31}P NMR spectrum showed a singlet with satellites at 45.96 ppm (J(Pt-P) = 119.6 Hz).[1] Such large Pt–P coupling constants were observed only when nitrogen was bound to the metal, giving a Pt–N–C–P coupling pathway. The low shielding of the phosphorus nucleus is characteristic of phosphorus incorporated in a five-membered ring.[23] The ^{31}P NMR spectrum of $Pt(NH_3)_2$(idmpH_3-*N*,*O*)$^+$ (VII) is shown in Figure 4a. It showed two singlets with satellites. Both Pt–P coupling constants were large (approximately 103 Hz). The resonance to lower shielding (43.17 ppm) was assigned to the phosphorus atom in the chelate ring, and that to higher shielding (13.99 ppm) was assigned to the uncoordinated phosphonic acid group.

The ^{195}Pt NMR spectrum of VII showed a broad multiplet at −2125 ppm. The broadening results from partial decoupling of platinum from the quadrupolar ^{14}N nucleus of idmp.[24] The shift corresponds to platinum coordinated by three N atoms and one O donor.[4,19]

The ^{15}N NMR spectrum of $Pt(^{15}NH_3)_2$(ampH-*N*,*O*)$^+$ (VI) showed two singlets with satellites (−65.12 ppm, ^1J(Pt–N) = 306.6 Hz, trans to ligand nitrogen; −87.04 ppm, ^1J(Pt–N) = 362.6 Hz, trans to phosphonate oxygen).[1] If the ^1H-decoupled ^{15}N spectrum of VII was run at low resolution, it was as expected, showing a signal at −67.20 ppm (^1J(Pt–N) = 303.7 Hz) from ammine trans to nitrogen, and at −82.83 ppm (^1J(Pt–N) = 376.5 Hz) from ammine trans to phosphonate. When the spectrum was run at higher resolution, the signal due to ammine trans to nitrogen showed a splitting of 2 Hz (Figure 4b). The splitting was not resolved in the satellite peaks, which were, as usual in these complexes, slightly broader than the central peaks, probably because of relaxation of the platinum nucleus induced by chemical shift anisotropy.[25] The origin of this splitting will be discussed below.

Addition of alkali to a solution of VII caused its deprotonation to $Pt(^{15}NH_3)_2$(idmp-*N*,*O*)$^{2-}$, with corresponding changes in the NMR spectra (Table II), which included a large reduction in J(Pt–P), and a decrease in ^1J(Pt–N) trans to phosphonate O. The splitting in the ^{15}N peak due to ammine trans to nitrogen remained.

The reactions of (methylimino)bis(methylenephosphonic acid), midmpH_4, and nitrilotris(methylenephosphonic acid), ntmpH_6, with I were similar to those of idmpH_4. Details of spectra are given in Table II. For $Pt(NH_3)_2$(ntmpH_5-*N*,*O*)$^+$ (IX), the ^{31}P NMR showed two singlets with satellites, with the peak at higher shielding (12.53 ppm) twice as intense as that at lower shielding (41.28 ppm). This confirms the general assignment of peaks near 40 ppm to phosphorus in a five-membered chelate ring.

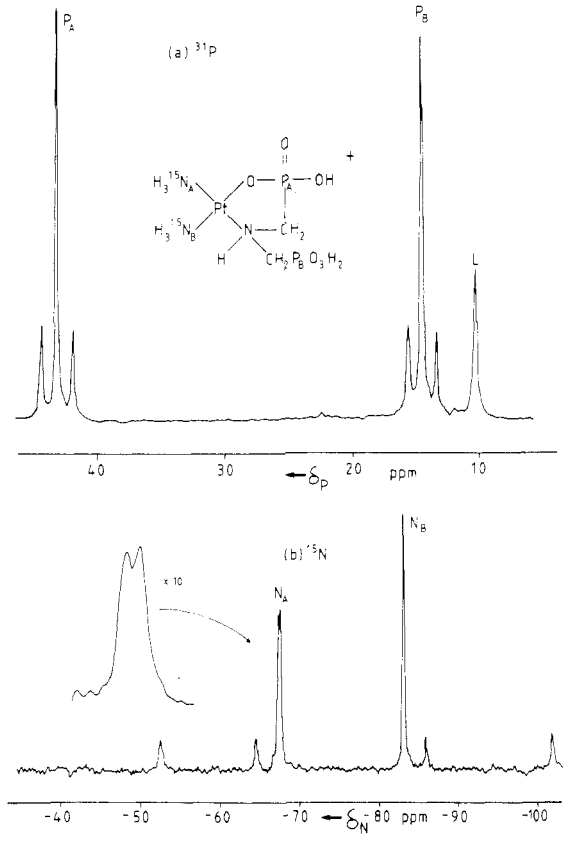


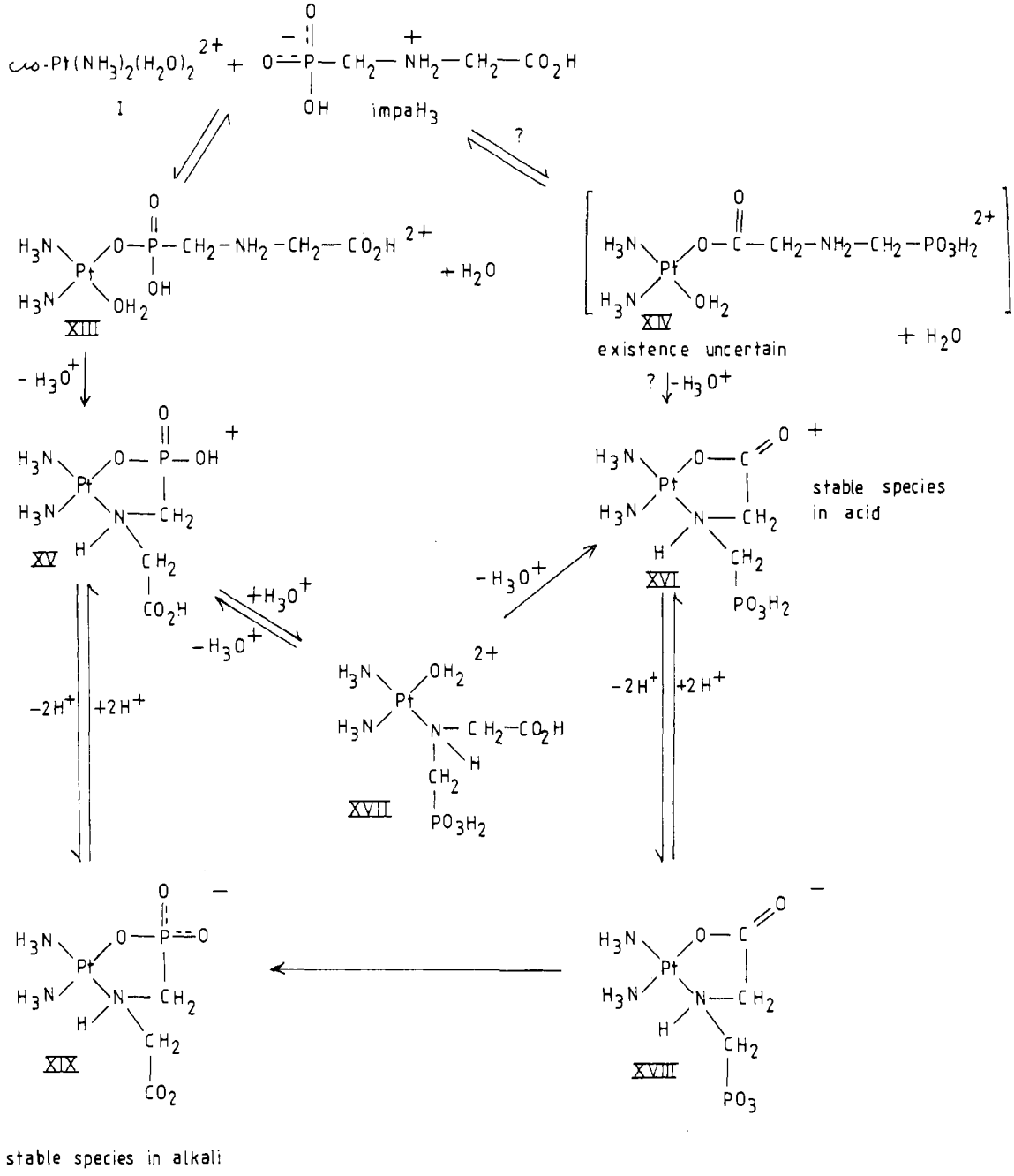
Figure 4. ^1H-decoupled NMR spectra of a solution of $Pt(^{15}NH_3)_2$-(idmpH_3-*N*,*O*)$^+$ (VII) in the presence of excess idmpH_4 (L): (a) 40.3 MHz ^{31}P; (b) 10.1 MHz ^{15}N.

The chelate complexes $Pt(^{15}NH_3)_2$(midmpH_3-*N*,*O*)$^+$ (VIII) and $Pt(^{15}NH_3)_2$(ntmpH_5-*N*,*O*)$^+$ (IX), like $Pt(^{15}NH_3)_2$(idmpH_3-*N*,*O*)$^+$ (VII), showed a small splitting (approximately 2 Hz) in the ^{15}N peak corresponding to ammine trans to nitrogen. The splitting was not affected by alteration of the conditions of the NMR experiment, including the ^1H decoupling power and frequencies. There are no geometrical isomers possible for any of these compounds. For VII and VIII there are two enantiomers, which would give identical NMR spectra. The ^{15}N spectrum of VIII was run at higher field (30.3 MHz) in an attempt to confirm that the splitting was due to spin–spin coupling. The result was inconclusive, as the splitting was no longer resolved, but the width of the singlet observed (7 Hz at half-height) made it unlikely that the separation between the unresolved peaks had increased to 5.6 Hz. The "satellite" peaks were very broad in this spectrum, owing to enhanced chemical shift anisotropy relaxation at the higher field. The only reasonable explanation for the splitting is an unusual long-range ^{15}N–Pt–N–C–^{31}P coupling. No corresponding splitting was resolved in the 40.3-MHz ^{31}P spectrum, where the lines were much less sharp (width at half-height 5 Hz) than in the 10.1-MHz ^{15}N spectrum (width 1.6 Hz). Unfortunately, we are not able to decouple ^{31}P from a ^{15}N spectrum, which would allow confirmation of this coupling. Since the corresponding ^{15}N signal is still a doublet in $Pt(^{15}NH_3)_2$(ntmpH_5-*N*,*O*)$^+$ (IX), the phosphorus atom involved must be that in the chelate ring. If the phosphorus atoms in the uncoordinated phosphonic acid groups were involved, a triplet splitting would be expected in the ^{15}N signal.

In the light of this observation, the ^{15}N spectrum of Pt-$(^{15}NH_3)_2$(ampH-*N*,*O*)$^+$ (VI) was closely reexamined. No analogous ^{15}N–^{31}P coupling was resolved, but the ^{15}N peak from ammine trans to nitrogen was slightly broader than the other ^{15}N peak.

(23) Gorenstein, D. G. *Prog. Nucl. Magn. Reson. Spectrosc.* **1983**, *16*, 1.
(24) Ismail, I. M; Kerrison, S. J. S.; Sadler, P. J. *Polyhedron* **1982**, *1*, 57.
(25) Lallemand, J.-Y.; Soulie, J.; Chottard, J.-C. *J. Chem. Soc., Chem. Commun.* **1980**, 436.

Scheme II



Reactions of I with *N*-(Phosphonomethyl)glycine (impaH_3) (Scheme II). When solutions of I and impaH_3 were mixed at pH 1.5, the first peak detected in the ^{31}P spectrum (Figure 5a) was a singlet without resolved platinum coupling at 18.35 ppm This may be compared with the peak assigned to *cis*-Pt$(NH_3)_2$(idmpH_4-*O*)$(H_2O)^{2+}$ (II) at 18.47 ppm, also without resolved platinum coupling. This peak was therefore assigned to *cis*-Pt$(NH_3)_2$(impaH_3-*O*)$(H_2O)^{2+}$ in which the ligand is bound only through phosphonate oxygen (XIII). Because the phosphonic acid group is partly deprotonated in a solution of impaH_3 at pH 1.5 while the carboxyl group is protonated (see above), it is more likely that the phosphonate-bound complex XIII will form initially than the carboxylate-bound isomer XIV. We cannot exclude the possibility that some of isomer XIV was formed, since its ^{31}P NMR signal would probably coincide with that from the free ligand.

A singlet with satellites at 43.05 ppm (J(Pt–P) = 97.7 Hz) then appeared in the ^{31}P spectrum (Figure 5b). Its intensity passed through a maximum and then decreased. The low shielding indicated that the phosphorus atom was part of a five-membered ring, and the large Pt–P coupling showed that nitrogen was coordinated. This species was assigned as Pt$(NH_3)_2$(impaH_2-*N*,*O*)$^+$ (XV), in which the ligand is bound through the N atom and a phosphonate O atom. Because of the transitory existence of this compound under these conditions, no spectra of other nuclei were obtained, but ^{15}N spectra were run for the deprotonated complex XIX (see below).

As ^{31}P peaks due to XIV and XV decreased in intensity, a singlet with satellites at 13.44 ppm became dominant (Figure 5c,d). The large Pt–P coupling, 87.9 Hz, indicated that impa nitrogen was bound, and the high phosphorus shielding showed that the phosphorus atom was not part of a five-membered chelate ring. The ^{15}N spectrum showed singlets with satellites at –80.07 ppm (^1J(Pt–N) = 344.7 Hz) and –66.67 ppm (^1J(Pt–N) = 303.2 Hz) corresponding to ammine trans to carboxylate oxygen and ligand nitrogen, respectively (cf. Pt$(^{15}NH_3)_2$(midaH-*N*,*O*)$^+$ with δ_N trans to carboxylate –76.40 ppm, J(Pt–N) = 355.4 Hz and δ_N trans to mida N –68.90 ppm, J(Pt–N) = 306.6 Hz[3]). The ^{195}Pt spectrum showed a broad peak at –2135.3 ppm. A structure consistent with all these data is Pt$(^{15}NH_3)_2$(impaH_2-*N*,*O*)$^+$ (XVI), with impaH_2 bound through N and carboxylate O. The coordination of the carboxylate group was confirmed from the ^{13}C spectrum, which showed a peak due to the carboxyl carbon atom

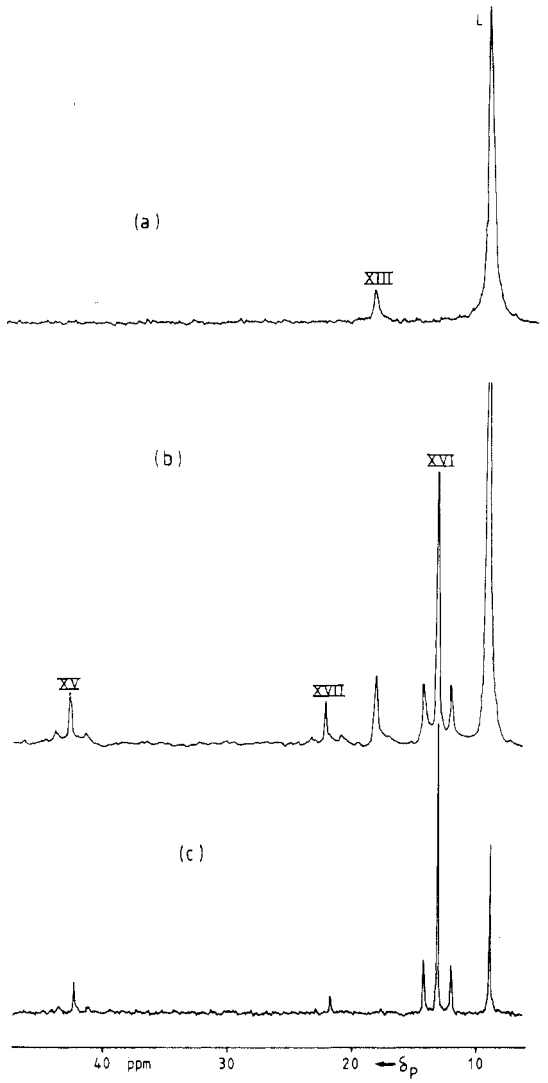


Figure 5. Changes in the ^{1}H-decoupled 40.3-MHz ^{31}P NMR spectra with time of the mixture of *cis*-$Pt(NH_3)_2(H_2O)_2^{2+}$ (I) with a small excess of *N*-(phosphonomethyl)glycine ($impaH_3$, L) in H_2O at pH 1.5: (a) 15 min; (b) 2 h; (c) 24 h. Roman numerals refer to the species shown in Scheme II.

at 187.2 ppm. If the carboxyl group were uncoordinated, the peak would be expected to higher shielding.[3,26] Other aspects of the ^{13}C spectrum were as expected for structure XVI (P–CH_2, 53.11 ppm, doublet, ^1J(P–C) = 142.6 Hz, J(Pt–C) = 16.6 Hz; C–CH_2, 58.45 ppm, doublet, ^3J(P–C–N–C) = 7.81 Hz, J(Pt–C) = 25.4 Hz; CO_2, 187.2 ppm, singlet, J(Pt–C) = 21.5 Hz).

As well as the peaks that were assigned to XIII, XV, and XVI, the ^{31}P spectra of solutions containing all of these species also showed a weak singlet at 22.46 ppm, with satellites (J(Pt–P) = 92.7 Hz). As peaks from XVI eventually dominated the spectrum, these transitory peaks disappeared. The high shielding indicates that this is not a complex with the phosphonate group in a chelate ring, and the large Pt–P coupling indicates that nitrogen is bound to the metal. These peaks are therefore assigned to *cis*-$Pt(NH_3)_2(impaH_3$-*N*$)(H_2O)^{2+}$ (XVII). This compound is probably an intermediate in the conversion of XV, the chelate complex with phosphonate coordinated, to XVI, the more stable chelate complex in acid solution with carboxylate coordinated.

When alkali was added to a solution of XVI to increase the pH to 11, deprotonation of the uncoordinated phosphonate group led to changes in the NMR spectra (Table II) corresponding to deprotonation of the uncoordinated phosphonate group to give XVIII. When this solution was allowed to stand several days, this carboxylate-bound complex was converted to the phosphonate-bound isomer XIX (that is deprotonated XV. The relationship between XV and XIX was established through several experiments where pH was changed and spectra run immediately). Direct reaction of *cis*-$Pt(NH_3)_2(OH)_2$ with $impa^{3-}$ gave, after 1 week, a mixture of the isomers of $Pt(NH_3)_2$(impa-*N*,*O*)$^-$ (XVIII and XIX), but, on further standing, the peaks due to XIX grew and eventually became the only peaks observed in the NMR spectra. No long-range P–C–N–Pt–N coupling was observed in the ^{15}N NMR spectrum of XIX.

Reactions of $PtCl_4^{2-}$ with the Ligands (Schemes III and IV). The ^{31}P NMR spectrum of a solution of K_2PtCl_4 and $idmpH_4$ (1:1) at pH 1.5 showed peaks assignable to a small amount of the chelate complex $PtCl_2(idmpH_3$-*N*,*O*$)^-$ (XX, Scheme III): a singlet with satellites at 47.11 ppm assigned to the phosphorus atom in the five-membered ring, and a singlet with satellites at 13.56 ppm assigned to the "free" phosphonic acid group. The large Pt–P coupling constants (124.5 and 200.2 Hz, respectively) are consistent with ligand nitrogen being bound. This complex is analogous to $PtCl_2(idaH$-*N*,*O*$)^-$ formed when $PtCl_4^{2-}$ was mixed with $idaH_2$ in aqueous solution.[3]

When the pH of the solution was increased to 6 immediately after the solutions of K_2PtCl_4 and $idmpH_4$ were mixed and the solution was allowed to stand for several hours, the ^{31}P NMR spectrum of the solution showed only one singlet with satellites at 41.24 ppm (J(Pt–P) = 102.5 Hz). This spectrum is consistent with both phosphonate groups being equivalent and contained in five-membered chelate rings, as in PtCl(idmp-*N*,*O*,*O*)$^{3-}$ (XXI) in which the ligand is bound meridionally, as a tridentate. This is analogous to PtCl(ida-*N*,*O*,*O*)$^-$.[3]

Under comparable conditions, the *N*-methyl analogue, $midmpH_4$, formed similar complexes XXII and XXIII. All midmp complexes showed significantly smaller Pt–P coupling constants than the corresponding idmp complexes (see Table II), indicating that this coupling is very sensitive to nitrogen substitution.

A number of unidentified minor peaks were also observed in the NMR spectra of these solutions. There was also some tendency for platinum metal to deposit at pH >5.

Reaction of *N*-(phosphonomethyl)glycine, $impaH_3$, with K_2PtCl_4 at pH 2 gave, in solution, the chelate complex *cis*-$PtCl_2$($impaH_2$-*N*,*O*$)^-$ (XXIV, Scheme IV) in which the ligand is bound through nitrogen and the carboxylate oxygen atom. The ^{31}P chemical shift, 12.11 ppm, was consistent with the phosphonate group being uncoordinated; the large value of J(Pt–P) indicated that the N-atom was coordinated. A ^{13}C NMR spectrum was obtained, which, although not of sufficient quality to allow platinum couplings to be determined, confirmed that carboxylate was coordinated, through the low shielding of this C atom.[26] (^{13}C NMR: P–CH_2, 53.54 ppm, doublet, ^1J(P–C) = 136.7 Hz; C–CH_2, 57.44 ppm, singlet; CO_2, 189.14 ppm.)

When the reaction was carried out at pH 7, the ^{31}P NMR spectrum showed a singlet with satellites at 42.99 ppm (J(Pt–P) = 95.2 Hz), and the ^{13}C spectrum showed a peak due to the carboxyl C atom at 188.44 ppm ("satellites" were not resolved from the baseline). These data are consistent with the presence of PtCl(impa-*N*,*O*,*O*)$^{2-}$ (XXV), with the ligand coordinated meridional. The methylene region of the spectrum was complex, and no attempt was made to assign peaks in this region.

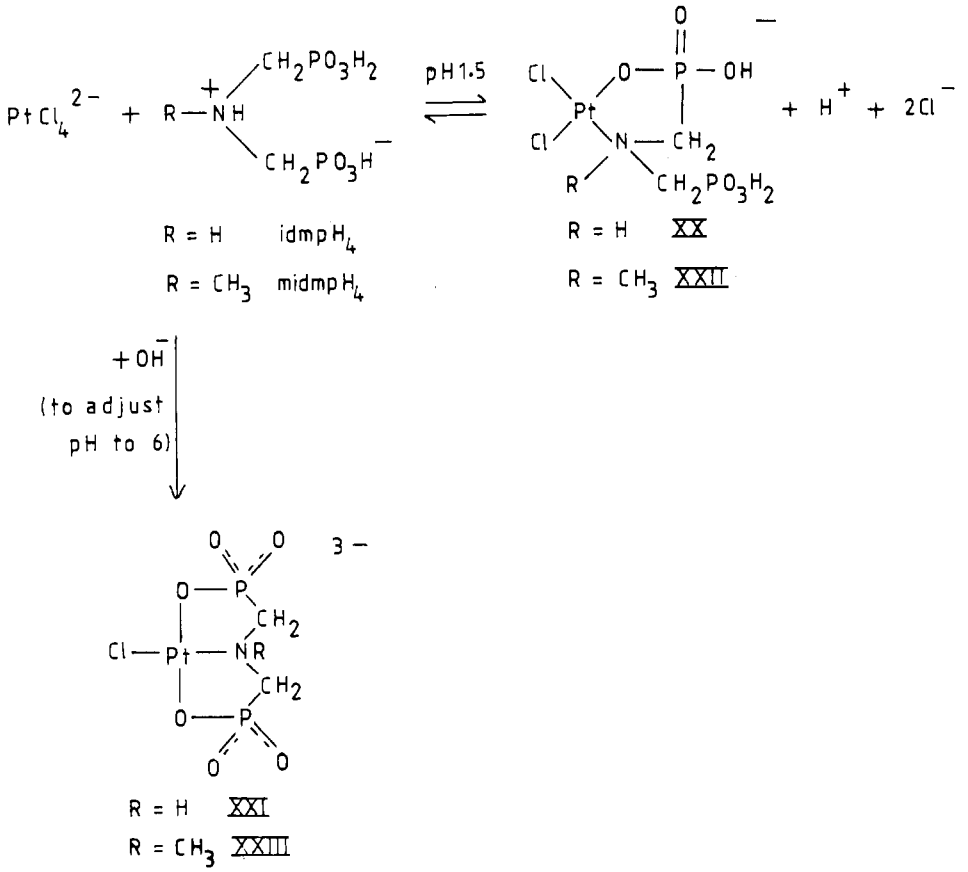
Addition of alkali to a solution of $PtCl_2(impaH_2$-*N*,*O*$)^-$ (XXIV) initially caused deprotonation to $PtCl_2$(impa-*N*,*O*$)^{3-}$ (XXVI), which, on standing at pH 7, converted to PtCl(impa-*N*,*O*,*O*$)^{2-}$ (XXV). Again, platinum metal deposited from some of these solutions at pH >6.

Discussion

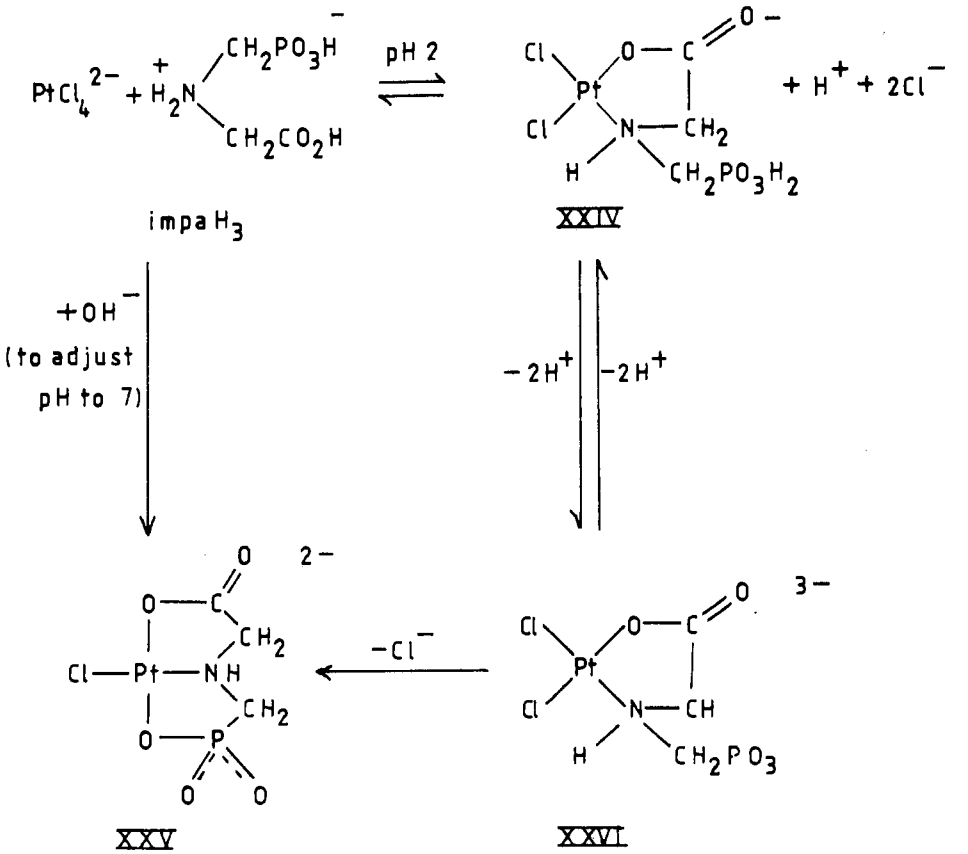
While the dinuclear complexes $[Pt(NH_3)_2]_2(\mu$-$O_3P(CH_2)_nNH_3)(\mu$-$OH)^{2+}$ play an important role in the reactions between *cis*-$Pt(NH_3)_2(H_2O)_2^{2+}$ and the simple (aminoalkyl)-phosphonic acids $NH_2(CH_2)_nPO_3H_2$ in moderately acidic solution, there is no evidence for formation of analogous complexes with the more complex ligands considered here. The initial phosphonate-bound complexes II–IV and XIII undergo ring closure

(26) Howarth, O. W.; Moore, P.; Winterton, N. *J. Chem. Soc., Dalton Trans.* **1974**, 2271.

Scheme III



Scheme IV



to form chelate complexes much more rapidly than the analogous *cis*-$Pt(NH_3)_2(O_3HP(CH_2)_nNH_3)(H_2O)^{2+}$.

There are close parallels with the behavior of iminodiacetic acid ($idaH_2$) and its *N*-methyl derivative ($midaH_2$), in the reactions with both *cis*-$Pt(NH_3)_2(H_2O)_2^{2+}$ [4] and $PtCl_4^{2-}$,[3] including the formation of complexes with the ligand meridional.

Comparison of ^1J(Pt–N) trans to oxygen in $Pt(NH_3)_2$-$(idmpH_3$-*N*,*O*$)^+$ (VII), 376.5 Hz, and $Pt(NH_3)_2$(idmp-*N*,*O*)[2] (X),

353.5 Hz, indicates that the trans influence of the phosphonate group increases significantly when it is fully deprotonated. The smaller reduction in ^1J(Pt–N) trans to nitrogen, from 303.7 to 293.0 Hz, indicates that the trans influence of ligand nitrogen also increases slightly when its substituents are deprotonated. J(Pt–N) trans to carboxylate O remains constant at 345 Hz when Pt$(NH_3)_2$(impaH_2-N,O)$^+$ (XVI) is deprotonated to Pt$(NH_3)_2$(impa-N,O)$^-$ (XVIII), but J(Pt–N) trans to N decreases slightly (from 303.2 to 296.0 Hz) as expected. Comparison with the coupling constants for the phosphonate-bound isomer of Pt$(NH_3)_2$(impa-N,O)$^-$ (XIX), 349.6 Hz trans to O and 296.9 Hz trans to N, suggests that the trans influence of carboxylate is slightly greater than that of fully deprotonated phosphonate. Therefore, the trans influence order for these three O-donor groups is $-OPO_2H^-$, $<-OPO_2^- \leq -O-$ CO–, which presumably is also the order of increasing Pt–O bond strength.

From the reactions summarized in Schemes II and IV, there is, in acid solution, clearly a thermodynamic preference for the chelate complex with impa carboxylate bound. This may be ascribed to the higher Pt–O bond strength in the carboxylate complex XVI relative to the protonated phosphonate complex XV. In alkaline solution, there is a preference for the phosphonate-bound isomer XIX over the carboxylate-bound isomer XVIII. This does not correspond with the trans influence order. In the absence of a large trans influence difference between the two O-donor groups, the direction of the equilibrium will be determined by more subtle factors (e.g. the solvation of the $-PO_3^{2-}$ group compared with $-CO_2^-$).

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Registry No. I, 20115-64-4; II, 100019-82-7; III, 100019-83-8; IV, 100019-84-9; VII, 100019-85-0; VIII, 100019-86-1; IX, 100019-87-2; X, 100019-88-3; XI, 100019-89-4; XIII, 100019-90-7; XV, 100019-91-8; XVI, 100019-92-9; XVII, 100019-93-0; XVIII, 100019-94-1; XIX, 100019-95-2; XX, 100019-96-3; XXI, 100019-97-4; XXII, 100019-98-5; XXIII, 100019-99-6; XXIV, 100044-33-5; XXV, 100044-42-6; XXVI, 100044-43-7; idmph$_4$, 17261-34-6; midmpH_4, 5995-25-5; ntmpH_6, 6419-19-8; impaH_3, 1071-83-6; $PtCl_4^{2-}$, 13965-91-8; ^{195}Pt, 14191-88-9; ^{15}N, 14390-96-6.

Contribution from the Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore 560 012, India, and Division of Biological Sciences, National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada

Ternary Metal Complexes of Anionic and Neutral Pyridoxine (Vitamin B_6) with 2,2′-Bipyridine. Syntheses and X-ray Structures of (Pyridoxinato)bis(2,2′-bipyridyl)cobalt(III) Perchlorate and Chloro(2,2′-bipyridyl)(pyridoxine)copper(II) Perchlorate Hydrate

S. P. Sudhakara Rao,[†] K. I. Varughese,[‡] and H. Manohar*[†]

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Ternary metal complexes involving vitamin B_6 with formulas $[Co^{III}(bpy)_2(PN\text{-}H)](ClO_4)_2$ and $[Cu^{II}(bpy)(PN)Cl]ClO_4\cdot H_2O$ (bpy = 2,2′-bipyridine, PN = neutral pyridoxine, PN-H = anionic pyridoxine) have been prepared for the first time and characterized by means of magnetic and spectroscopic measurements. The crystal structures of the compounds have also been determined. $[Co(bpy)_2(PN\text{-}H)](ClO_4)_2$ crystallizes in the space group $P2_1/c$ with a = 18.900 (3) Å, b = 8.764 (1) Å, c = 20.041 (2) Å, β = 116.05 (1)°, and Z = 4 and $[Cu(bpy)(PN)Cl]ClO_4\cdot H_2O$ in the space group $P\bar{1}$ with a = 12.136 (5) Å, b = 13.283 (4) Å, c = 7.195 (2) Å, α = 96.91 (2)°, β = 91.25 (3)°, γ = 71.63 (3)°, and Z = 2. The structures were solved by the heavy-atom method and refined by least-squares techniques to R values of 0.080 and 0.042 for 3401 and 2094 independent reflections, respectively. Both structures consist of monomeric units. The geometry around Co(III) is octahedral and around Cu(II) is distorted square pyramidal. In $[Co(bpy)_2(PN\text{-}H)](ClO_4)_2$, two oxygens from phenolic and 4-(hydroxymethyl) groups of PN-H and two nitrogens from each of two bpy's form the coordination sphere. In $[Cu(bpy)(PN)Cl]ClO_4\cdot H_2O$ one PN and one bpy, with the same donor sites, act as bidentate chelates in the basal plane, with a chloride ion occupying the apical position. In both structures PN and PN-H exist in the tautomeric form wherein pyridine N is protonated and phenolic O is deprotonated. However, a novel feature of the cobalt compound is that PN-H is anionic due to the deprotonation of the 4-(hydroxymethyl) group. The packing in both structures is governed by hydrogen bonds, and in the copper compound partial stacking of bpy's at a distance of ~3.55 Å also adds to the stability of the system. Infrared, NMR, and ligand field spectroscopic results and magnetic measurements are interpreted in light of the structures.

Introduction

Metal complexes of the B_6 vitamins and of the Schiff bases derived from them have been an interesting area of study in recent years.[1,2] Particularly, since the discovery of the enhanced catalytic role of metal ions in nonenzymatic reactions[3] (e.g. transamination of pyridoxamine with α-ketoglutarate) attention has been focused on complexes of Schiff bases derived from amino acids and pyridoxal (PL) [or pyridoxal phosphate (PLP)] with the aim of elucidating the mechanism of action of vitamin B_6 containing enzymes.[4–7] Considerable research has also been concerned with the ligating sites in these compounds. Many of the solution studies[7–15] and a few X-ray structural investigations[15–17] reveal that in vitamin B_6 complexes chelation occurs through phenolic oxygen and the 4-(aminomethyl) or 4-(hydroxymethyl) groups of pyridoxamine (PM) or pyridoxine (PN).[18] In Schiff base complexes also, chelation has been observed[6,19–30] through phenolic

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[‡] National Research Council of Canada.

(1) Holm, R. H. In "Inorganic Biochemistry"; Eichhorn, G. L., Ed.; Elsevier: New York, 1973; Vol. 2, pp 1137–1167.
(2) Martell, A. E. *Adv. Enzymol. Relat. Areas Mol. Biol.* **1982**, *53*, 163.
(3) (a) Metzler, D. E.; Snell, E. E. *J. Am. Chem. Soc.* **1952**, *74*, 979. (b) Longenecker, J. B.; Snell, E. E. *J. Am. Chem. Soc.* **1957**, *79*, 142.
(4) Metzler, D. E. *Adv. Enzymol. Relat. Areas Mol. Biol.* **1979**, *50*, 1.
(5) Vederas, J. C.; Floss, H. G. *Acc. Chem. Res.* **1980**, *13*, 455 and references cited therein.
(6) Rao, S. P. S.; Manohar, H.; Bau, R. *J. Chem. Soc., Dalton Trans.* **1985**, 2051.
(7) Martell, A. E.; Taylor, P. *Inorg. Chem.* **1984**, *23*, 2734.
(8) Gustafson, R. L.; Martell, A. E. *Arch. Biochem. Biophys.* **1957**, *68*, 485.
(9) Farago, M. E.; McMillan, M. M.; Sabir, S. S. *Inorg. Chim. Acta* **1975**, *14*, 207.
(10) Hartman, J. S.; Kelusky, E. C. *Can. J. Chem.* **1979**, *57*, 2118.
(11) Vishwanathan, T. S.; Swift, T. J. *Can. J. Chem.* **1979**, *57*, 1050.
(12) El-Ezaby, M. S.; Rashad, M.; Moussa, N. M. *J. Inorg. Nucl. Chem.* **1977**, *39*, 175.

0020-1669/86/1325-0734$01.50/0