Solution *versus* Solid State Conformation of Group 12 Metal Complexes of Active Aldehyde Derivatives of Thiamine†

Maria Louloudi,[a,b] Nick Hadjiliadis*[,a,b] and Ian S. Butler[c]

[a] *University of Ioannina, Department of Chemistry, Laboratory of Inorganic and General Chemistry, Ioannina 45-110, Greece*

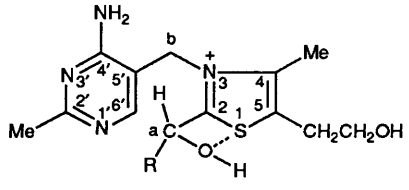
[b] *Technological Institution of Athens, Department of Chemistry, Physics and Materials Technology, Agiou Spyridonos and Pallikaridi, Egaleo, Athens, Greece*

[c] *McGill University, Department of Chemistry, 801 Sherbrooke Street West, Montreal, P.Q., H3A 2K6 Canada*

Molar conductances in water and dimethylformamide and ^{13}C NMR spectra in D_2O and $(CD_3)_2SO$ solutions and solid-state ^{13}C cross polarization magic angle spinning NMR spectra have been measured for the chloride salts of 2-(α-hydroxybenzyl)thiamine (hbt), 2-(α-hydroxycyclohexylmethyl)-thiamine (hcmt), their protonated forms [hbt]Cl·HCl and [hcmt]Cl·HCl and zwitterionic complexes of the type $[M(hbt)Cl_3]$ and $[M(hcmt)Cl_3]$ (M = Zn, Cd or Hg). The data affords good evidence for bonding of the metals to the N(1′) atom of the pyrimidine moieties in the ligands, as well as of the S conformation of the ligands in solution. The small chemical shifts observed for the carbon atoms situated adjacent to the N(1′) site [C(2′), C(6′) and 2′-CH_3] in the solid-state and solution ^{13}C NMR spectra of the complexes are attributed to the synergic interaction of metal complexation which causes a downfield shift and the accumulation of negative charge at the same position due to $[MCl_3]^-$ which leads to an opposing upfield shift. The ^{199}Hg NMR spectra of $[Hg(hbt)Cl_3]$ and $[Hg(hcmt)Cl_3]$ in $(CD_3)_2SO$ further substantiate these conclusions. Overall, the results strongly support earlier suggestions for the role of metal ions in the enzymatic action of thiamine.

The so-called 'active aldehyde' derivatives of thiamine pyrophosphate of general formula **1** are intermediates in the enzymatic action of the thiamine enzymes[1,2] carboxylase, pyruvic dehydrogenase, transketolase and phosphoketolase. These biochemical processes require Mg^{2+} ions to take place *in vivo* and other bivalent metals such as Co^{2+}, Zn^{2+}, Cd^{2+} and Ni^{2+} also *in vitro*.[2,3] Investigation of the role that the bivalent metals play in these enzymatic reactions has been hampered because thiamine itself and its phosphate derivatives do not readily form complexes containing direct metal–ligand (M–L) bonds, principally because of the net positive charge located on the thiazolium moiety which leads to the formation of ionic salts[4] of the type $[L]^{2+}[MX_4]^{2-}$, $[L]^{2+}2[MX_3]^-$ or $2[L]^+$-$[MX_4]^{2-}$. The 'active aldehyde' derivatives, on the other hand, do form complexes with a direct M–N(1′) bonding to the pyrimidine moiety.[5]

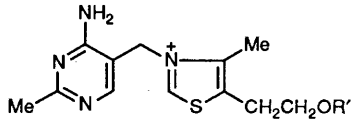
In the crystal structure of $[Hg(hbt)Cl_3]\cdot H_2O$[5] the hbt ligand adopts the S conformation.[6] The three possible conformations S, V and F of thiamine[6] are defined by the torsional angles φ_P = N(3)–C(b)–C(5′)–C(4′) and φ_T = C(5′)–C(b)–N(3)–C(2) (see structure **1**) as follows: for the S conformation $\varphi_T = \pm 100$, $\varphi_P = \pm 150$: for the V conformation, $\varphi_T = \pm 90$, $\varphi_P = \pm 90$; and for the F conformation, $\varphi_T = 0$, $\varphi_P = \pm 90°$. The S conformation of the ligand together with M–N(1′) bonding are also apparently present in the complexes of hbt with Zn^{2+}, Cd^{2+}, Co^{2+} and Ni^{2+} **2** from their identical, band-by-band, vibrational (IR, Raman) spectra compared to those of $[Hg(hbt)Cl_3]$, with the exception of the metal–ligand vibrations.[7,8] Furthermore, the formation of similar complexes of hcmt with the same metals and the similarity of their behaviour to that of the corresponding hbt complexes allowed us to conclude that these complexes should also have an M–N(1′) bonding and a S conformation of the ligand in the solid state.[5,7,8]



1

R

Me	2-(α-Hydroxyethyl)thiamine (het)
Ph	2-(α-Hydroxybenzyl)thiamine (hbt)
C_6H_{11}	2-(α-Hydroxycyclohexylmethyl)thiamine (hcmt)



R′

H	Thiamine
PO_3^{2-}	Thiamine monophosphate
$P_2O_5^{2-}$	Thiamine pyrophosphate

These results emphasize the importance of the S conformation during the enzymatic reactions, as well as that of the N(1′) pyridimine site in complex formation.[5] The easier formation of metal complexes with the 'active aldehyde' derivatives of thiamine than with thiamine itself led us to the conclusion that complex formation follows the initial formation of these intermediates.[5]

Since all the thiamine enzymatic reactions take place in

† Thiamine = 3-(4-amino-2-methylpyrimidin-5-ylmethyl)-5-(2-hydroxyethyl)-4-methylthiazolium.

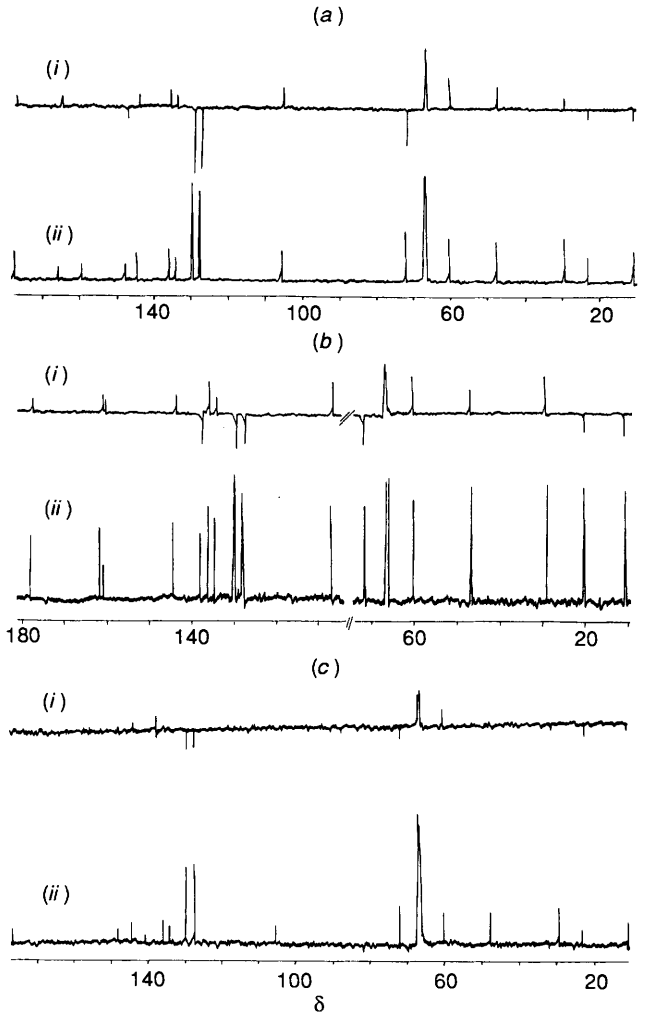
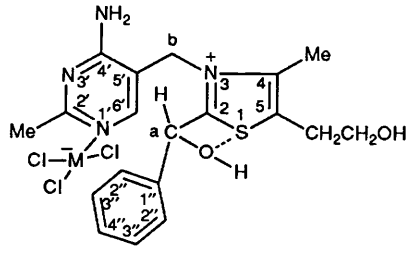


Fig. 1 Carbon-13 NMR spectra in D_2O of (*a*) [hbt]Cl, (*b*) [hbt]Cl·HCl and (*c*) [Cd(hbt)Cl_3]: (*i*) APT spectra; (*ii*) normal spectra



2 M = Zn^{2+}, Cd^{2+}, Hg^{2+}, Co^{2+}, Ni^{2+}

aqueous solutions, it is important to demonstrate whether or not the same type of complexes [M–N(1′) bonding and S ligand conformation] also exists in solution, thereby substantiating the above conclusion.[5,7,8] In this paper, we present ^{13}C NMR spectra of complexes of Zn^{2+}, Cd^{2+} and Hg^{2+} of hbt and hcmt in the solid state and in $(CD_3)_2SO$ and D_2O solutions. The similarity of the solid-state ^{13}C NMR spectra once again strongly supports the structural similarity of the complexes in the solid state, while the similarity of the solution and solid-state spectra shows that the same structures persist also in solution. The ^{199}Hg NMR spectra of [Hg(hbt)Cl_3] and [Hg(hcmt)Cl_3] in $(CD_3)_2SO$ provide additional support for this conclusion.

Experimental

The ligands [hbt]Cl and [hcmt]Cl were prepared according to the literature.[9] The preparation of their complexes with Zn^{2+}, Cd^{2+} and Hg^{2+} has also been described.[5]

The molar conductances were determined for 10^{-3} mol dm^{-3} solutions of the complexes in water and dimethylformamide (dmf), at 20 °C with a Conductoscope E365 (Metrohm, Herisau, Switzerland). The ^{13}C NMR spectra in solution were recorded with a Varian XL 300 spectrometer (H, 299.945; C, 75.429 MHz) with dioxane as an internal reference, calibrated in such a way that $SiMe_4$ corresponds to 0 ppm. The ^{199}Hg NMR spectra were recorded with the same instrument (53.652 MHz). The internal reference was $HgMe_2$ corresponding to 0 ppm. The solid-state ^{13}C cross polarization magic angle spinning (CP MAS) NMR spectra were obtained on a Chemagnetics CMX-300 spectrometer (H, 299.604; C, 75.34 MHz). Hexamethylbenzene was used as a reference with $\delta(CH_3)$ 17.4. The instrumental conditions employed were: proton decoupling field 65 KHz, spinning speed 4 kHz (in zirconia rotors, 7.5 mm diameter), acquisition time 34 ms, ^1H $\frac{\pi}{2}$ pulse width 4 μs, contact time 2 ms, recycle delay 2 s, and applied line broadening 15 Hz.

Owing to the different solubilities of the compounds and for the purposes of comparison, the following solution NMR spectra were recorded: [hbt]Cl, [hbt]Cl·HCl, [Zn(hbt)Cl_3] and [Cd(hbt)Cl_3] in D_2O, [hbt]Cl·HCl, [Cd(hbt)Cl_3] and [Hg(hbt)Cl_3] in $(CD_3)_2SO$; [hcmt]Cl, [hcmt]Cl·HCl, [Zn(hcmt)Cl_3] and [Cd(hcmt)Cl_3] in D_2O; and [hcmt]Cl, [hcmt]Cl·HCl, [Cd(hcmt)Cl_3] and Hg(hcmt)Cl_3 in $(CD_3)_2SO$.

Results and Discussion

The molar conductance values (Λ_M) of the complexes in dmf solutions[5] were in the range 41–51 Ω^{-1} cm^{-2} mol^{-1} and in aqueous solutions were 282–322 Ω^{-1} cm^{-2} mol^{-1}. The values in dmf are lower than those expected for 1:1 electrolytes[10] and increase with time. The values in water, on the other hand, correspond to 1:3 electrolytes[10] and do not change with time. These observations can be explained either by slow replacement of a Cl^- ion by a dmf molecule in the first case and the immediate replacement of all three Cl^- ions by H_2O molecules in the second, or by the concomitant rupture of the M–N(1′) and M–Cl bonds in both cases. The latter process is less likely and would result in decomposition of the complexes in solution. For this reason an examination of the NMR spectra of the complexes in solution and subsequent comparison with corresponding solid-state data would be expected to provide a more definitive answer as to the existence or not in solution of the complexes found in the solid state.[5,7,8]

^{13}C NMR Spectra in Solution.—The ^{13}C NMR chemical shifts of the compounds in D_2O and $(CD_3)_2SO$ are given in Table 1. The spectral assignments are based on those of [hbt]Cl[11] at pH 0.9 and 6.7, comparison with the spectra of [hcmt]Cl (containing a cyclohexyl instead of the phenyl group) and attached proton test (APT) experiments[12,13] in which the methyl and methine groups display negative resonances, while the methylene and tertiary carbons appear positive (Fig. 1).

Protonation of both ligands [hbt]Cl and [hcmt]Cl chiefly affects the C(2′), C(6′) and 2′-CH_3 carbons adjacent to N(1′),[11] which shift upfield in D_2O by 3.1, 9.0 and 1.9 ppm for the former ligand and 3.9, 8.9 and 2.3 ppm for the latter. In the case of hcmt the corresponding shifts in $(CD_3)_2SO$ are 4.5, 10.0 and 3.9 ppm respectively. The shifts of the remaining carbons are much smaller and insignificant on going from the ligands to the complexes (Table 1).

Surprisingly, complexation of both ligands at N(1′) causes much smaller upfield shifts of these carbons and the spectra closely resemble those of the free ligands. For example, the three more sensitive carbons [C(2′), C(6′) and 2′-CH_3] shift upfield in D_2O by only 1.0, 2.3 and 0.6 ppm for [Zn(hbt)Cl_3] compared to [hbt]Cl and downfield by 0.6, 1.8 and 0.5 ppm for [Zn(hcmt)Cl_3] compared to [hcmt]Cl. In $(CD_3)_2SO$ the shifts are even smaller (Table 1). This unusual behaviour of the metal

Table 1 Carbon-13 NMR chemical shifts of the compounds in solution

Compound	C(2)	C(2′)	C(4′)	C(4)	C(6′)	C(1″)	C(5)	C(4″)	C(3″)	C(2″)	C(5′)	C_a	CH_2OH	C_b	5-CH_2	2′-CH_3	4-CH_3
[hbt]Cl[a]	177.6	165.6	159.3	144.3	147.7	135.8	134.0	129.6	129.5	127.5	105.3	71.8	60.2	47.5	29.2	23.0	10.9
[hbt]Cl·HCl[a]	178.9	162.5	161.6	145.1	138.7	136.8	135.3	130.5	130.5	128.5	107.7	72.5	60.9	47.5	30.0	21.1	11.6
[Zn(hbt)Cl_3][a]	177.8	164.6		144.7	145.4	135.9	134.1	129.6	129.6	127.5	105.7	71.8	60.2	47.3	29.2	22.4	10.9
[Cd(hbt)Cl_3][a]	177.5			144.4	148.0	135.7	134.0	129.6	129.5	127.4	106.0	71.8	60.2	47.4	29.2	23.0	10.8
[hcmt]Cl[a]	178.0	166.6	160.2	143.6	148.1	43.1	134.4	29.1	25.8	25.2	107.5	72.7	60.0	47.2	29.2	23.1	10.9
[hcmt]Cl·HCl[a]	177.8	162.7	161.6	143.4	139.2	43.3	134.8	29.1	26.3	25.3	108.7	72.4	60.0	46.7	29.2	20.8	11.0
[Zn(hcmt)Cl_3][a]	178.0	167.2	160.0	143.7	149.9	43.1	134.2	29.2	25.7	25.3	107.4	72.7	60.1	47.4	29.2	23.6	11.0
[Cd(hcmt)Cl_3][a]	178.0	167.2	159.9	143.7	149.8	43.0	134.3	29.2	25.7	25.2	107.3	72.7	60.2	47.4	29.2	23.7	11.1
[hbt]Cl·HCl[b]	178.5	161.3	160.8	143.3	139.1	138.2	134.5	129.3	129.0	128.0	107.7	70.0	59.6	47.2	29.8	20.8	11.5
[Cd(hbt)Cl_3][b]	177.6	165.8	160.0	143.0		137.8	134.4	129.0	129.0	127.6	105.3	70.5	59.6	47.6	29.7	24.6	11.3
[Hg(hbt)Cl_3][b]	177.5	165.8	160.0	143.0	146.2	137.9	134.4	129.2	129.1	127.6	105.4	70.3	59.6	47.5	29.7		11.5
[hcmt]Cl[b]	179.5	166.3	160.4	142.5	150.8	43.0	134.1	29.0	25.9	25.7	106.8	71.7	59.7	47.6	29.7	25.0	11.6
[hcmt]Cl·HCl[b]	180.0	161.8	161.5	142.4	140.8	43.4	134.2	28.9	26.1	25.7	108.6	71.6	59.6	46.8	29.7	21.1	11.6
[Cd(hcmt)Cl_3][b]	179.0	166.6	160.3	142.5	150.9	43.0	134.1	29.0	25.7	25.5	106.6	72.0	59.7	47.3	29.7	25.2	11.6
[Hg(hcmt)Cl_3][b]	179.0	166.4	160.4	142.5		43.1	134.2	29.0	25.7	25.5	106.8	71.9	59.7	47.2	29.7	24.9	11.6

[a] In D_2O solution. [b] In $(CD_3)_2SO$ solution.

complexes can be explained in terms of two opposing effects: the metal complexation at N(1′) which should cause a downfield shift of the adjacent carbon atoms,[14] while localization of the net negative charge of the $[MCl_3]^-$ moiety at the same position should cause a deshielding effect on the carbons. The stacking interaction of the pyrimidine and benzene rings in [hbt]Cl·HCl[15] and [Hg(hbt)Cl_3],[5] being almost parallel with an average distance of 3.5 Å, probably also contributes to the very small shifts of the carbon atoms situated near N(1′). This latter suggestion is supported by the fact that for the hcmt ligand and its complexes,[9] which lack a similar stacking interaction, the corresponding carbons are shifted by 1–4 ppm downfield, compared to the hbt ligand and its complexes.

On the other hand, comparison of the protonated ligand [hbt]Cl·HCl with the [Zn(hbt)Cl_3] complex reveals downfield shifts of 2.1, 6.7 and 1.3 ppm respectively of the C(2′), C(6′) and 2′-CH_3 carbons, in D_2O. The analogous values for [hcmt]Cl·HCl and [Zn(hcmt)Cl_3] in D_2O are 4.5, 10.7 and 2.8 ppm respectively. In $(CD_3)_2SO$ comparisons of [hbt]Cl·HCl and [Hg(hbt)Cl_3] and [hcmt]Cl·HCl and [Hg(hcmt)Cl_3], for example, give the following downfield shifts of these three carbon atoms: 4.5, 7.1 and 3.7 ppm for the former pair and 4.6, 10.0 and 3.8 ppm for the latter pair. Similar comparisons and behaviour of thiamine chloride hydrochloride = [thm]Cl·HCl and its zwitterionic complexes with Pt^{2+}, Pd^{2+}, Cd^{2+} [17] and Hg^{2+},[18] of the type M(thm)Cl_3 (M is the metal) led to the conclusion of direct M–N(1′) bonding in solution. Such bonding was supported by crystal structure data for [Pt(thm)Cl_3][19] and [Cd(thm)Cl_3].[20]

It is therefore reasonable for us to conclude that the M–N(1′) bonding and S ligand conformation found in the solid complexes should also persist in D_2O and $(CD_3)_2SO$ solutions, as in the structure for [Hg(hbt)Cl_3]·H_2O.[5] Further support for this comes from the isostructural complexes [Co(hbt)Cl_3], [Co(hcmt)Cl_3] and [Ni(hcmt)Cl_3],[8] which apparently have the same pseudo-tetrahedral structure in the solid state (by diffuse reflectance) and in dmf solutions, as revealed by their UV/VIS spectra.

^{13}C *CP MAS NMR Spectra.*—More evidence for the existence of M–N(1′) bonding and the S conformation of the ligands in solution comes from a comparison of the solid state, high-resolution ^{13}C NMR spectra with the corresponding ^{13}C NMR solution data. Such a comparative NMR technique, which has only been exploited quite recently, is an important complement to X-ray crystallography.[21] The chemical shifts of the various carbon atoms are included in Table 2.

The proposed assignments for the solid-state NMR spectra are based on comparisons with the related solution spectra, internal comparisons of the spectra of the compounds containing the hbt and hcmt ligands and cross-polarization interrupted-decoupling experiments, in which the methine and methylene carbons do not appear.[22] High-quality spectra are obtained (Fig. 2).

Although the chemical shifts of the corresponding spectra in D_2O and $(CD_3)_2SO$ solutions and the solid state do differ somewhat irregularly, each solution peak does have a counterpart in the solid-state spectrum. The differences are presumably attributable to intermolecular solid-state packing effects. These effects should influence most those carbons situated at the molecular periphery,[23] *e.g.* the CH_2OH, C_b, 5-CH_2, 4-CH_3 and C(2) and C(4) carbons to which the peripheral functional groups are attached (Table 2).

The carbons located near to the N(1′) site, however, undergo similar shifts for the ligands and the complexes, to those in solution. Thus, the C(2′), C(6) and 2′-CH_3 carbons shift upfield by 4.0, 7.9 and 0.6 ppm on passing from [hbt]Cl to [hbt]Cl·HCl and by 3.2, 4.2 and 4.8 from [hcmt]Cl to [hcmt]Cl·HCl. In the case of [Hg(hbt)Cl_3] these carbons shift downfield by 0.6, 0.5 and 4.1 ppm, respectively, compared to free [hbt]Cl. For [Hg(hcmt)Cl_3], however, these downfield shifts are 3.1, 1.8 and 2.1 ppm respectively. The explanation for this behaviour must be related to that given earlier for the solution ^{13}C NMR results. With the exception of 2′-CH_3 carbon, for which packing effects should also be important, the downfield shifts are again larger for the hcmt complexes, possibly reflecting the lack of the additional pyrimidine-benzene stacking effect which exists for the hbt complexes.[5,9,15]

Finally, a comparison of the data for the protonated ligands with those for metal complexes such as [Hg(hbt)Cl_3] and [Hg(hcmt)Cl_3] reveals that once again the C(2′), C(6′) and 2′-CH_3 carbon atoms shift respectively downfield by 4.6, 8.4 and 4.7 ppm with hbt and by 7.3, 6.1 and 6.7 ppm with hcmt. A similar conclusion concerning the existence of the M–N(1′) bonding in the solid state[5,7] may therefore also be made here, as in the case of the solutions.[16–18] Unfortunately, the presence of several peaks in the regions associated with the C(2′) and C(6′) carbon atoms obscured the observation of any $^2J(^{13}C–^{199}Hg)$ coupling. Such coupling would be quite small, but might have been detected otherwise,[24] as is the case for the solution spectra.

Consequently, the general similarity of the ^{13}C NMR spectra of the various compounds in the solid state, where any possible rapid metal–ligand exchange that might take in solution is frozen,[25] to those in solution not only confirms the isostructural nature of the complexes of the three metals with each ligand in the solid state,[5,7,8] but also confirms retention of both the M–N(1′) bonding and the S conformation of the ligands in the complexes in solution.

^{199}Hg *NMR Spectra.*—Additional convincing evidence for retention of the Hg–N(1′) bonding in $(CD_3)_2SO$ was provided

Table 2 Carbon-13 NMR chemical shifts of the compounds in the solid state

Compound	C(2)	C(2′)	C(4′)	C(4)	C(6′)	C(1″)	C(5)	C(4″)	C(3″)	C(2″)	C(5)	C_a	CH_2OH	C_b	5-CH_2	2′-CH_3	4-CH_3
[hbt]Cl	181.2	166.8	161.2	146.6	146.6	140.5	135.5	129.3	129.3	129.3	106.5	72.8		50.5		24.4	11.6
[hbt]Cl·HCl	176.0	162.8	162.8	145.2	138.7	138.7	133.3	128.6	128.6	128.6	105.3	72.9	60.2	48.1	30.7	23.8	12.7
[Cd(hbt)Cl_3]	180.9	167.2	159.8	145.4	145.4	137.2	134.1	133.3	130.2	126.3	105.4	71.2	62.8	50.1	32.5	28.1	14.0
[Hg(hbt)Cl_3]	185.1	167.4	159.4	147.1	147.1	137.5	133.5	133.5	129.9	127.2	107.0	71.5	63.8	50.7	32.2	28.5	13.7
[hcmt]Cl	184.1	166.6	162.1	146.7	147.9	43.9	135.8	26.8	26.8	25.7	106.1	74.3	64.5	51.1	31.1	26.8	13.3
[hcmt]Cl·HCl	181.9	163.4	163.4	143.7	143.7	43.8	133.3	27.4	27.4	27.4	108.1	73.1	60.0	46.9	31.7	22.0	12.1
[Cd(hcmt)Cl_3]	185.0	170.8	160.0	145.6	149.8	44.1	135.6	28.7	26.5	25.6	109.4	76.1	62.1	50.2	31.5	28.7	15.0
[Hg(hcmt)Cl_3]	185.1	170.7	159.8	145.8	149.8	44.3	136.2	28.7	26.9	25.9	109.7	76.3	62.7	50.4	31.8	28.7	15.1

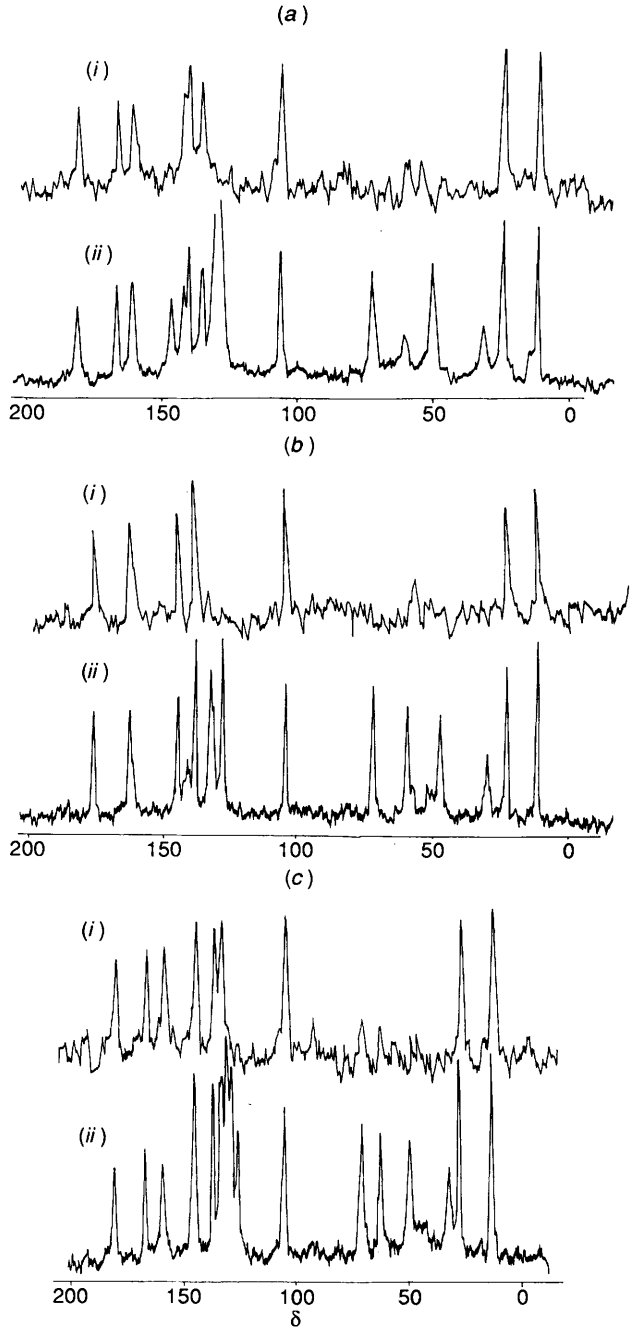


Fig. 2 Carbon-13 CP MAS NMR spectra of (*a*) [hbt]Cl, (*b*) [hbt]Cl·HCl and (*c*) [Cd(hbt)Cl_3]: (*i*) cross polarization interrupted-decoupling spectra; (*ii*) normal spectra

by the ^{199}Hg NMR spectra of [Hg(hbt)Cl_3] and [Hg(hcmt)Cl_3]. Both spectra show only one resonance for the Hg^{2+}, at δ −1200 and −1210 respectively, thus confirming the existence of only one complex species in solution in each case. The chemical shifts of the ^{199}Hg resonances range between δ −900 and −1000 for complexes of $HgMe^+$ with nucleic acid derivatives and these shifts are more negative when the ligand bears a net positive charge as in our case.[26] For complexes of triazines with Hg^{2+} of formula [HgX{$N_3(C_6H_4X\text{-}2)_2$}] (X = F, Cl, Br, I or Me) on the other hand, the ^{199}Hg resonance[27] appears at about δ −1400. Also $[HgCl_4]^{2-}$ with a similar environment to that in $HgCl_3$–L[N(1′)] shows its ^{199}Hg band at δ −1141.[28]

The breaking of the Hg–N(1′) bond in $(CD_3)_2SO$ can be excluded, at least in freshly prepared solutions, because the resulting [$HgCl_3${$(CD_3)_2SO$}] species should exhibit ^{199}Hg resonances at much less negative values[26,29] (δ > −800). We therefore conclude that Hg–N(1′) bonding exists in $(CD_3)_2SO$ solutions as well.

Conclusion

The results of the present study (similar complexes in solution as in the solid state) provide further evidence in favour of the conclusions drawn for the enzymatic action of thiamine enzymes,[5,7,8] *i.e.*, (1) the bonding site of bivalent metals with thiamine derivatives is the N(1′) atom of the pyrimidine moiety, (2) the S conformation of the ligands in the complexes is important for the deprotonation of the O(2β)–H proton in complexes **2**, resulting from the intramolecular S(1)···O(2β) electrostatic interaction[30] and (3) complex formation with metals should occur following formation of the 'active aldehyde' intermediates of thiamine.[5,7,8]

Acknowledgements

This work was financially supported in part by the Greek Ministry of Research and Technology and in part by a NATO grant awarded to N. H. and I. S. B. We thank Dr. F. Morin for his assistance in recording the ^{13}C CP MAS NMR spectra.

References

1 R. Breslow, *J. Am. Chem. Soc.*, 1958, **80**, 3719; R. Breslow and E. McNelis, *J. Am. Chem. Soc.*, 1959, **81**, 3080; *J. Am. Chem. Soc.*, 1962, **82**, 2394.
2 N. Hadjiliadis and J. Markopoulos, *Chim. Chron (New Ser.)*, 1981, **10**, 1.
3 M. C. Scrutton, *Inorg. Biochem.*, 1973, **1**, 381.
4 See, for example, N. Hadjiliadis, A. Yannopoulos and R. Bau, *Inorg. Chim. Acta*, 1983, **69**, 109; A. Marzotto, G. Bandoli, D. E. Clemente, F. Benetollo and L. Galzigna, *J. Inorg. Nucl. Chem.*, 1973, **35**, 2769; M. F. Richardson, K. Franklin and D. M. Thomson, *J. Am. Chem. Soc.*, 1975, **97**, 3204.
5 M. Louloudi, N. Hadjiliadis, J. A. Feng, S. Sukumar and R. Bau, *J. Am. Chem. Soc.*, 1990, **112**, 7233.
6 J. Pletcher and M. Sax, *J. Am. Chem. Soc.*, 1972, **94**, 3998.
7 N. Hadjiliadis, M. Louloudi and I. S. Butler, *Spectrochim. Acta, Part A*, 1991, **47**, 445.
8 M. Louloudi and N. Hadjiliadis, *J. Chem. Soc., Dalton Trans.*, 1991, 1635.
9 J. Mieyal, G. Bantle, R. Votaw, I. Rosner and H. Sable, *J. Biol. Chem.*, 1971, **246**, 5213.

10 W. K. Geary, *Coord. Chem. Rev.*, 1971, **7**, 81.
11 A. Gallo and H. Sable, *J. Biol. Chem.*, 1976, **251**, 2564.
12 C. LeCocq and J. Y. Lallemand, *J. Chem. Soc., Chem. Commun.*, 1981, 150.
13 S. L. Patt and J. N. Shoolery, *J. Magn. Reson.*, 1982, **46**, 535.
14 G. C. Levy, R. L. Lichter and G. L. Nelson, *Carbon-13 nmr Spectroscopy*, 2nd edn., Wiley, New York, 1980.
15 J. Pletcher, M. Sax, G. Blank and M. Wood, *J. Am. Chem. Soc.*, 1977, **99**, 1396.
16 N. Hadjiliadis, J. Markopoulos, G. Pneumatikakis, D. Katakis and T. Theophanides, *Inorg. Chim. Acta*, 1977, **25**, 21.
17 A. Adeyemo, A. Shamin and A. Turner, *Inorg. Chim. Acta*, 1984, **91**, L23.
18 A. Adeyemo, *Inorg. Chim. Acta*, 1989, **160**, 253.
19 R. E. Cramer, R. E. Kirkup and M. J. Carrie, *Inorg. Chem.*, 1989, **156**, 77.
20 R. E. Cramer, R. B. Maynard and J. A. Ibers, *J. Am. Chem. Soc.*, 1981, **103**, 76.
21 C. J. Croombridge, R. K. Harris, K. J. Packer, M. B. Hursthouse and N. P. C. Walker, *J. Solid State Chem.*, 1985, **59**, 306.
22 G. R. Hays, *Analyst (London)*, 1982, **107**, 241; W. Xiaoling, Z. Shanmin and W. Xaewen, *J. Magn. Reson.*, 1988, **77**, 343.
23 P. A. Hunt, B. P. Straughan, A. A. M. Ali, R. K. Harris and B. J. Say, *J. Chem. Soc., Dalton Trans.*, 1990, 2131.
24 P. F. Barron, *J. Organomet. Chem.*, 1982, **236**, 157.
25 A. Yamazaki, *Coord. Chem. Rev.*, 1991, **109**, 107.
26 A. R. Norris and R. Kumar, *Inorg. Chim. Acta*, 1984, **93**, L63.
27 P. Peringer, *Inorg. Nucl. Chem. Lett.*, 1980, **16**, 461.
28 R. Colton and D. Dakternieks, *Aust. J. Chem.*, 1980, **33**, 2405; P. L. Goggin, R. L. Goodfellow, D. M. McEwan and K. Kessler, *Inorg. Chim. Acta*, 1980, **44**, L111.
29 M. J. Natan, C. F. Millikan, J. G. Wright and T. V. O'Halloran, *J. Am. Chem. Soc.*, 1990, **112**, 3255.
30 M. Sax, P. Pulsinelli and J. Pletcher, *J. Am. Chem. Soc.*, 1974, **96**, 155.

Received 14*th October* 1991; *Paper* 1/05203I