[Cu(tren)OH]ClO4·2H2O. A solution of tren·3HCl (1.2 g, 4.7 mmol) in water (50 ml) was treated with a 33% NaOH solution (1.6 ml) under vigorous magnetic stirring. The NaCl which resulted upon addition to the solution of absolute ethanol (90 ml) was filtered off. To the free tetradentate ligand solution was then added $CuCl_2 \cdot 2H_2O$ (0.767 g, 4.5 mmol) and $LiClO_4$ (0.48 g, 4.5 mmol). The dark blue solution was evaporated to a volume of about 25 ml and slowly cooled in a dewar to room temperature. The blue crystals thus obtained were filtered, washed with methanol and ether, and vacuum-dried; yield 54%.

[Cu(tren)NCS]BPh. This complex was obtained by passing a solution of [Cu(tren)NCS]SCN (0.65 g, 2 mmol) in water (30 ml) through a column of an anionic resin (Dowex 1-X4, 50–100 mesh) in ClO_4^- form. The addition of $NaBPh_4$ (0.68 g, 2 mmol) to the resulting blue solution afforded a precipitate, which was washed with H_2O and vacuum-dried over P_2O_5.

[Cu(tren)NH3](BPh4)2. This compound was obtained by passing gaseous ammonia for 15 min through an acetone solution (30 ml) of the [Cu(tren)OH]BPh_4 derivative (1.09 g, 2 mmol). During this time a color change of the solution from deep green to dark blue was observed. The final product, obtained by adding an aqueous solution (100 ml) of $NaBPh_4$ (0.69 g, 2 mmol), was filtered, thoroughly washed with H_2O, and vacuum-dried; yield 85%.

Registry No. [Cu(tren)OH]BPh_4, 54750-19-5; [Cu(tren)OH]ClO_4, 54750-20-8; [Cu(tren)py]$(BPh_4)_2$, 54689-08-6; [Cu(tren)-NH_2Ph]$(BPh_4)_2$, 54689-10-0; [Cu(tren)-4-$CH_3O(NH_2Ph)$]$(BPh_4)_2$, 54689-12-2; [Cu(tren)NCS]BPh_4, 52665-52-8; [Cu(tren)NH_3]-$(BPh_4)_2$, 54689-14-4.

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Contribution from the Department of Chemistry, University of Alberta, Edmonton, Alberta, Canada

Nuclear Magnetic Resonance Studies of the Solution Chemistry of Metal Complexes. XII. Binding of Methylmercury by Methionine[1]

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The complexation of metal ions by the amino acid methionine has been the subject of considerable research, with much of the interest focusing on participation of the thioether group in the metal binding.[2-7] Li and Manning showed by a comparison of the formation constants of the glycine and methionine complexes of Zn(II) that binding of Zn(II) by methionine is through the amino and carboxylate dentates.[2] In a similar but more extensive study, Lenz and Martell concurred with the conclusions of Li and Manning and proposed that, of the metal ions Ag(I), Ca(II), Cd(II), Co(II), Cu(II), Hg(II), Mg(II), Mn(II), Ni(II), Pb(II), and Sr(II), only Ag(I) binds to the thioether group.[3] McAuliffe, Quagliano, and Vallarino[4] showed by infrared spectroscopy that, in the solid state at least, binding of several of these and other metal ions by anionic methionine is as proposed by Lenz and Martell.[3] More recently, however, Natusch and Porter have demonstrated by proton magnetic resonance (PMR) spectroscopy that, in acidic solution, a previously undetected complex forms in which Hg(II) is bonded solely to the thioether group.[7,8]

The observation that the thioether group can bind Hg(II) in acidic solution suggests that this group might be an important binding site for methylmercury, whose importance in mercury poisoning is well established. In this paper, we present PMR results which show that one-coordinate methylmercury binds to the thioether group of methionine in acidic solution. Formation constants have been determined for this interaction and for the binding of methylmercury by the amino group, the exclusive binding site in basic solution. From these and previously reported results, binding sequences are derived as a function of pH for the binding of methylmercury by the sulfhydryl, amino, carboxyl, and thioether ligands.

Experimental Section

Methylmercuric hydroxide (Alfa Inorganics) was purified and a stock solution was prepared as described previously.[9] The stock solution was standardized by titration of aliquots with a standard sodium chloride solution in an acidified ethanolic medium; the end point was located potentiometrically by means of an Ag–AgCl indicating electrode.[1] Methionine (British Drug Houses) was used as received. Tetramethylammonium (TMA) nitrate was prepared by titration of a 25% aqueous solution of tetramethylammonium hydroxide (Eastman Organic Chemicals) with HNO_3 to a neutral pH.

pH measurements and PMR measurements were made as described previously.[1,9] Chemical shifts were measured relative to the central resonance of the TMA triplet or the *tert*-butyl resonance of *tert*-butyl alcohol but are reported relative to the methyl resonance of sodium 2,2-dimethyl-2-silapentane-5-sulfonate (DSS). Positive shifts correspond to resonances of protons less shielded than those of DSS.

Solutions were prepared by the procedures described previously.[1,9] The pH was adjusted with HNO_3 or KOH. The nitrate anion forms a complex with methylmercury,[10] but the interaction is so weak[11] that it does not compete with hydroxide or methionine for the methylmercury cation.

Results and Discussion

The chemical shifts of the methyl and methine protons of methionine, which give rise to a singlet and a triplet, are shown as a function of pH in Figure 1 for a solution containing 0.150 *M* methionine and for a solution containing 0.160 *M* methionine and 0.160 *M* methylmercury. At pH <2, the chemical shift of the methine proton is not affected by the presence of methylmercury, whereas the methyl protons are deshielded, indicating that, in this pH range, the thioether group is the binding site. As the pH is increased from pH 2, the two chemical shift curves for the methine proton become increasingly different, while those for the methyl protons approach each other, indicating that the methylmercury is shifting from the thioether group to the other end of the molecule. At pH ~8–9, coordination is exclusively to the amino end. As the pH is increased above pH 8–9, the complex begins to dissociate, as indicated by the shift of the methine resonance of the methylmercury-containing solution toward that of free methionine. The overlap of the two curves at pH >13.5 indicates complete dissociation at this pH.

The chemical shift and the mercury–proton spin–spin coupling constant of the methyl protons of methylmercury also indicate complexation of methylmercury by methionine. In Figure 2, the coupling constant is shown as a function of pH for a solution containing 0.190 *M* methylmercury and for a solution containing 0.160 *M* methionine and 0.160 *M* methylmercury. The pH dependence of the coupling constant of the 0.190 *M* methylmercury solution is due to the formation of $(CH_3Hg)_2OH^+$, a very small amount of $(CH_3Hg)_3O^+$, and

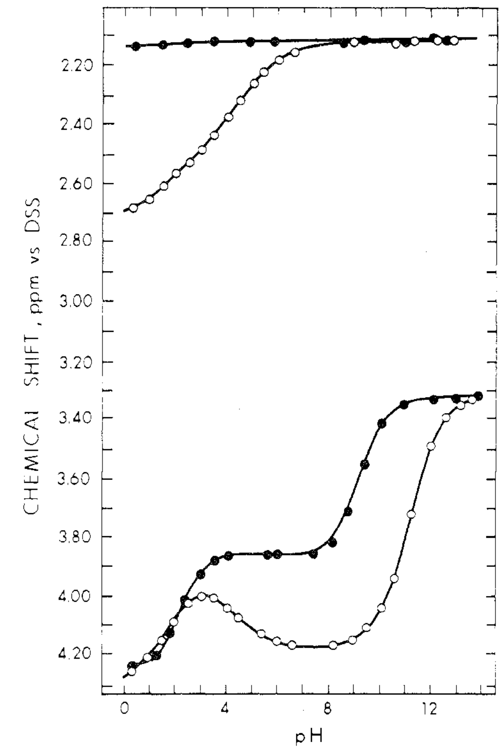

Figure 1. pH dependence of the chemical shift of the methyl (upper curves) and methine (lower curves) protons of methionine in aqueous solutions containing 0.150 *M* methionine (closed points) and 0.160 *M* methionine and 0.160 *M* methylmercury (open points).

CH_3HgOH from $CH_3HgOH_2^+$ by addition of base.[12,13]

Of the two coordination sites at the amino end, the amino dentate binds methylmercury most strongly at pH >7.[9,14] Also, the data at pH >7 in Figure 2 are very similar to those observed for methylmercury in solutions containing an equimolar concentration of amine,[14] indicating that the complex formed in basic solution is I. At intermediate pH values, a complex

$$CH_3SCH_2CH_2CHCO_2^- \quad (\text{CH bonded to } H_2\overset{+}{N}HgCH_3)$$

I

may form in which methylmercury is bonded to the carboxylate group while the amino group is protonated, although it was not possible to identify such a complex in the present work.

The formation constant for binding of methylmercury by the thioether group, defined by eq 1, was determined from the

$$CH_3SCH_2CH_2CH(^+NH_3)CO_2H + CH_3Hg^{II} \rightleftarrows CH_3\overset{+}{S}(HgCH_3)CH_2CH_2CH(^+NH_3)CO_2H \quad (1)$$

chemical shift of the methyl protons of methionine in solutions having a range of methionine to methylmercury ratios at pH 0.5 (Table I). The data in Figures 1 and 2 indicate that, at this pH, the amino and carboxylate dentates of methionine are protonated and the free methylmercury exists predominantly as the aquated cation. In all cases, a single, averaged set of resonances was observed, indicating exchange between the free and complexed forms to be fast on the NMR time scale. The observed chemical shift for the methionine methyl protons, δ_{obsd}, is the sum of their chemical shifts in the free and complexed forms of methionine, δ_{free} and δ_{comp}, weighted according to the relative concentrations of the two forms, i.e.

$$\delta_{obsd} = P_{free}\delta_{free} + P_{comp}\delta_{comp} \quad (2)$$

where $P_{free} + P_{comp} = 1$. Substitution of the relation between

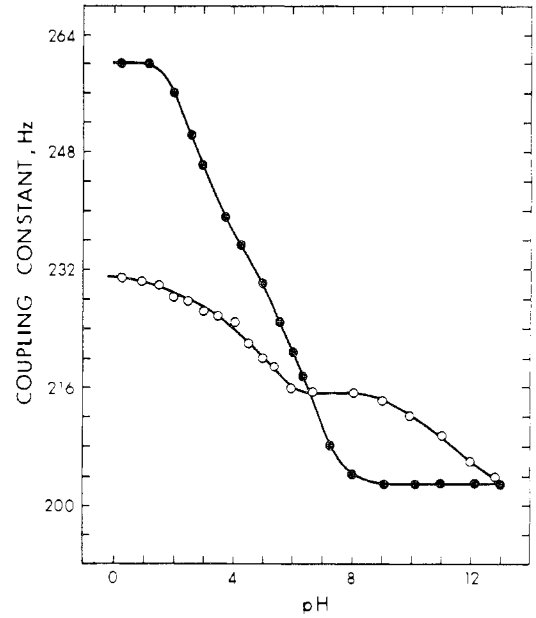

Figure 2. pH dependence of the methylmercury mercury–proton spin-spin coupling constant in aqueous solutions containing 0.190 *M* methylmercury (closed points) and 0.160 *M* methylmercury and 0.160 *M* methionine (open points).

Table I. PMR Data for Methionine and Methylmercury at pH 0.5[a]

[Methylmercury]$_{total}$, *M*	[Methionine]$_{total}$, *M*	δ_{CH_3S}[b]	δ_{CH_3Hg}[b]	J_{H-Hg}[c]
0.198	0.199	2.705	1.110	230
0.199	0.219	2.678	1.110	231
0.197	0.236	2.652	1.120	229
0.197	0.256	2.628	1.120	228
0.198	0.276	2.599	1.120	227
0.195	0.285	2.587	1.120	228
0.203	0.0302	2.818	1.100	
0.202	0.0595	2.808	1.100	
0.201	0.0991	2.796	1.100	237
0.202	0.148	2.768	1.110	

[a] At 25°. [b] Ppm vs. DSS. [c] Hz.

relative concentrations into eq 2 leads to

$$P_{comp} = \frac{\delta_{obsd} - \delta_{free}}{\delta_{comp} - \delta_{free}} \quad (3)$$

The fraction of methionine complexed at a given methionine to methylmercury ratio was calculated using eq 3, from which the concentrations of complexed ($=P_{comp}$[methionine]$_{total}$) and free methionine were obtained. The concentration of CH_3Hg^{II} is then given by the difference between the total methylmercury concentration and the concentration of the complex. Since δ_{comp} cannot be obtained directly, the procedure described previously for the evaluation of the formation constant of the methylmercury complex of formic acid[9] was used. The values determined for the formation constant and δ_{comp}, which are obtained simultaneously by this procedure, are 87 ± 4 and 2.863 ppm. From the chemical shift data for the methyl protons of methylmercury and the mercury–proton coupling constant data in Table I, the chemical shift of the methyl protons of methylmercury bonded to the thioether group is calculated to be 1.120 ppm while the mercury–proton coupling constant is found to be 223 Hz.

The formation constant for the amino complex, defined by eq 4, was determined from chemical shift data for the methine

$$CH_3SCH_2CH_2CH(H_2N)CO_2^- + CH_3Hg^{II} \rightleftarrows CH_3SCH_2CH_2CH(H_2\overset{+}{N}HgCH_3)CO_2^- \quad (4)$$

Table II. Order of Conditional Stability of Methylmercury Complexes of Ligands in Aqueous Solution

pH 1: sulfhydryl > thioether > H_2O > carboxylic acid > amine
pH 3: sulfhydryl > thioether ~ carboxylic acid > H_2O > amine
pH 5: sulfhydryl > carboxylic acid > thioether > amine ~ H_2O, OH^-
pH 7: sulfhydryl > amine > OH^- > carboxylic acid > thioether
pH 9: sulfhydryl > amine > OH^- > carboxylic acid > thioether
pH 11: sulfhydryl > OH^- > amine > carboxylic acid > thioether

proton of methionine and the methyl protons of methylmercury for the solution containing equimolar concentrations of methylmercuric hydroxide and methionine. The procedure has been described previously.[9,14] Only data at pH values greater than 8 were used to ensure that the only complex formed was the amino complex. From the chemical shift data for the methine proton, log $K_f = 7.5 \pm 0.1$ and the chemical shift of the methine proton in the complexed form is 4.21 ppm. The chemical shift data for the methyl protons of methylmercury yielded a log K_f of 7.40 ± 0.01 and a chemical shift of 0.91 ppm for these protons when CH_3Hg^{II} is bonded to the amino group. For comparison, log K_f for the nitrogen-bonded complex of valine is 7.41 while that of the nitrogen-bonded complex of β-alanine is 7.56.[14]

The extent of complexation of methylmercury by methionine and similar molecules is strongly pH dependent due to protonation of the ligand and reaction of methylmercury with hydroxide ion. Thus the conditional formation constant, defined by eq 5, is more informative than formation constants

$$\text{methylmercury (free)} + \text{ligand (free)} \rightleftarrows \text{complex} \qquad (5)$$

of the type defined by eq 1 and 4 since the conditional formation constant indicates directly the extent of complexation for the particular set of solution conditions for which it was derived. The conditional formation constant equals $\alpha\beta K_f$, where α is the fraction of the free ligand in the form which complexes and β the fraction of free methylmercury as the aquated cation for these solution conditions. From the results reported above and elsewhere,[1,9,14] the orders of conditional stability of methylmercury complexes of sulfhydryl, amine, carboxyl, and thioether ligands have been derived as a function of pH and are given in Table II. H_2O and OH^- are included to indicate those conditions where the conditional stability constants are so small that little or no complex forms.

Because of the high degree of specificity in the binding of methylmercury by the thioether group in acidic solution, it may be possible to identify methionine resonances in the PMR spectra of methionine-containing peptides and proteins by observing changes in the spectrum as the peptide or protein is titrated with methylmercury at pH 0.5.

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Registry No. $CH_3S(HgCH_3)CH_2CH_2CH(NH_3)CO_2H$, 54517-53-2; I, 54517-54-3; methionine, 63-68-3; methylmercury$^+$, 22967-92-6.

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Contribution from the Department of Petroleum Chemistry, Faculty of Engineering, Osaka University, Suita, Japan 565

Synthesis of Novel Cationic Organonickel(II) Complexes, $[C_6Cl_5Ni(P)_{3-n}(3,5\text{-lut})_n]^+ClO_4^-$ (P = $PPhMe_2$, PPh_2Me; n = 1, 2, 3)

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In recent years the preparation, reactivity, and spectroscopic properties of a wide variety of cationic organoplatinum(II) complexes of the type $[RPt(Q)_2L]^+X^-$, where Q = tertiary phosphine or arsine and L = neutral ligand, have been investigated.[1-3] Similar studies, however, have been limited for nickel(II).[4,5] In connection with our current research program concerning the syntheses and reactions of cationic organonickel complexes, we have recently succeeded in the synthesis of the title complexes. We believe they are the first examples of cationic organonickel(II) complexes isolated with a square-planar configuration, except for the isocyanide complex reported by Cherwinski et al.[5] A cationic hydride complex has recently been reported.[6]

Results and Discussion

The chloride ligand in *trans*-$C_6Cl_5Ni(P)_2Cl$ (**1a**, P = $PPhMe_2$; **1b**, P = PPh_2Me) is labile and the complexes react readily with silver perchlorate even in a nonpolar solvent such as benzene resulting in the precipitation of silver chloride. Addition of a slight excess of 3,5-lutidine (3,5-lut) to the filtrate causes precipitation of a cationic pentachlorophenylnickel(II) complex, *trans*-$[C_6Cl_5Ni(P)_2(3,5\text{-lut})]^+ClO_4^-$, as its benzene solvate (**2'a** or **2'b**), which can be converted to the unsolvated complex (**2a** or **2b**) by recrystallization from ethanol. These complexes, **2a** and **2b**, further react with neat 3,5-lutidine giving the second type of cationic complex, *cis*-$[C_6Cl_5Ni(PPhMe_2)(3,5\text{-lut})_2]^+ClO_4^-$ (**3**), and the third type, $[C_6Cl_5Ni(3,5\text{-lut})_3]^+ClO_4^-$ (**4**), respectively (see Scheme I). In the complex **4** the pentachlorophenyl–nickel bond is still stable in the absence of tertiary phosphine ligand, which has long been known to stabilize a nickel–carbon bond.[7]

All the cationic pentachlorophenylnickel complexes thus obtained are thermally stable and each has a high melting point. They show in the ir spectra absorption bands near 1080 (vs) and 625 (s) cm^{-1}, which are characteristic of the anionic (Td) ClO_4 group.[8] In fact the complexes **2a** and **2b** are strong electrolytes even in dichloromethane.

The PMR spectra of **2a** and **2b** (Table I) are consistent with diamagnetic, trans-planar structures in solution. A symmetrical 1:2:1 triplet resonance in the vicinity of τ 8–9 is assigned to the phosphine methyl protons, indicative of "virtually" coupled trans phosphines.[9] The 3,5-lutidine ligand coordinated to nickel gives singlet resonances for the 3,5-methyl and 2,6-ring protons in the spectra both of **2a** and of **2b**. Complex **3** gives a doublet resonance for the phosphine methyl protons, in accordance with