Hydrophobic Interactions in Ternary Zinc(II) and Copper(II) Complexes containing 1,10-Phenanthroline or 2,2′-Bipyridyl and an Alkane Carboxylate or Sulphonate

By **Paul R. Mitchell**, Institute of Inorganic Chemistry, University of Basel, CH-4056 Basel, Switzerland

The methyl resonances of $[Me_3Si(CH_2)_3SO_3]^-$ and of $[Me_3Si(CH_2)_2CO_2]^-$ are shifted upfield by $[Zn(bipy)]^{2+}$ or by $[Zn(phen)]^{2+}$, whereas Zn^{2+} causes no shift at all; 2,2′-bipyridyl (bipy) or 1,10-phenanthroline (phen) alone cause only much smaller upfield shifts. This effect is attributed to a hydrophobic interaction between the trimethylsilyl group and the heterocyclic aromatic ring system. The stability constants of all four ternary complexes have been determined from the variation of the n.m.r. spectra with $[Zn(bipy)]^{2+}$ or $[Zn(phen)]^{2+}$ concentration. The stability constants of the binary Cu^{2+} and Zn^{2+} and the ternary $[Cu(bipy)]^{2+}$, $[Zn(bipy)]^{2+}$ $[Cu(phen)]^{2+}$ and $[Zn(phen)]^{2+}$ complexes of $[Me_3Si(CH_2)_2CO_2]^-$ have been determined by potentiometric titrations, and indicate small positive values of $\Delta \log K$. The methyl resonances of a range of medium-length straight- and branched-chain carboxylic acids are also shifted, showing that a hydrophobic interaction between an aromatic group and a methyl, isopropyl, or t-butyl group can also occur in a ternary complex.

INTERLIGAND interactions in ternary complexes often have a considerable effect on the stability, structure, and reactivity of such a complex;[1] an indirect interaction may be mediated by the metal,[2] for example through the involvement of metal *d* orbitals in transition-metal complexes, or a direct ligand–ligand interaction may occur. Even relatively weak non-covalent interactions [3] may have a striking effect not only on the stability but also on the detailed structure of ternary complexes.

Ternary metal-ion amino-acid complexes containing two oppositely charged side chains have been prepared, and the ionic interaction influences not only the spectroscopic properties [4,5] but may also be sufficiently stereoselective for resolution of one amino-acid to be possible.[6] Aromatic ring stacking between a nucleotide and a heterocyclic aromatic ligand, *e.g.* bipyridyl,[7,8] phenanthroline,[9] or tryptophan,[10] has been observed in ternary metal complexes, and may even cause considerable stability enhancement.[9]

Although it has been suggested [3] that a hydrophobic interaction between aliphatic groups, or between an aliphatic and an aromatic group, may be nearly as strong as that between two aromatic groups (*i.e.* aromatic ring stacking), an interligand hydrophobic interaction has not yet been observed in ternary complexes. However, it has been suggested [11] that e.s.r. measurements indicate that copper complexes of hydrophobic amino-acids, *e.g.* $[Cu(L\text{-valO})_2]$ or $[Cu(L\text{-leuO})_2]$ (valO = valinate, leuO = leucinate), form weak dimers linked by a hydrophobic interaction, whereas bis(glycinato)copper(II) does not.

In an investigation of the ^1H n.m.r. spectrum of metal complexes the resonance of 3-(trimethylsilyl)propanesulphonate used as reference was observed [12] to shift anomalously in the presence of $[Zn(bipy)]^{2+}$ or of $[Zn(phen)]^{2+}$ but not significantly in the presence of Zn^{2+}, of 2,2′-bipyridyl, or of 1,10-phenanthroline alone.[†] Since it seemed probable that this effect was due to a hydrophobic interaction in the ternary complex, the ternary systems were investigated in more detail by ^1H n.m.r. spectroscopy and by potentiometric titrations.

RESULTS AND DISCUSSION

Hydrogen-1 N.M.R. Study of the Ternary Zn^{2+}–(N–N)–A^- *Systems.*—Protonation, or co-ordination of a diamagnetic metal ion, usually causes a downfield shift of the resonances of nearby groups, whereas in aromatic systems the ring current causes those protons lying above an aromatic ring to shift upfield.[13]

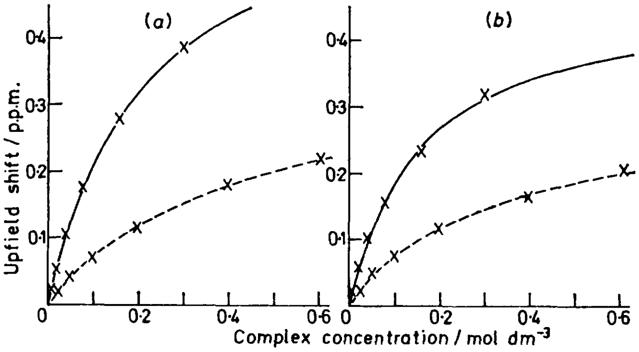

FIGURE 1 Upfield shifts of the trimethylsilyl resonance of $[Me_3Si(CH_2)_3SO_3]^-$ (*a*) and of $[Me_3Si(CH_2)_2CO_2]^-$ (*b*) in a ternary mixture containing in addition either Zn^{2+}–bipy (· · · ·) or Zn^{2+}–phen (——) compared with the resonance positions of the free trimethylsilyl ligands (60 MHz, 35 °C; $I \geqslant 0.1$ mol dm^{-3}, $Na[NO_3]$). The curves shown are the computer-calculated best fits of the experimental data with the stability constants and extrapolated upfield shifts given in Table 1

Addition of Zn^{2+} (1.4 mol dm^{-3}) to $[Me_3Si(CH_2)_2CO_2]^-$ or to $[Me_3Si(CH_2)_3SO_3]^-$ causes no shift (<0.003 p.p.m.) owing to the length of the aliphatic chain between the donor group and the trimethylsilyl group observed. On addition of increasing amounts of $[Zn(bipy)]^{2+}$ or of $[Zn(phen)]^{2+}$ the trimethylsilyl resonance is shifted upfield by up to 0.4 p.p.m. From the variation of the upfield shift with concentration (Figure 1) it is possible to calculate the stability constants and the extrapolated shifts for the completely complexed silyl ligands (Table 1). The stability constant obtained using a 1 : 1 ratio of $[Zn^{2+}] : [phen]$ in which only 53% of the phenan-

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[†] Abbreviations: bipy = 2,2′-bipyridyl; phen = 1,10-phenanthroline; N–N = bipy or phen; A^- = 3-(trimethylsilyl)propionate, 3-(trimethylsilyl)propane-1-sulphonate, or an aliphatic carboxylate anion.

throline is present as $[Zn(phen)]^{2+}$ was the same as that obtained using a 5 : 1 ratio, in which 93% is present as $[Zn(phen)]^{2+}$.

The stability constants of the carboxylato-complexes are, as expected, higher than those of the sulphonato-complexes, and the stability constants with $[Zn(phen)]^{2+}$ are higher than those with $[Zn(bipy)]^{2+}$. The extrapolated upfield shift for complete complex formation is *ca.* 60% higher for the $[Zn(phen)]^{2+}$ than for the $[Zn(bipy)]^{2+}$ systems: this is also to be expected since the effects of the ring currents are to some extent additive.[13]

However, the presence of a hydrophobic interaction in these ternary complexes does not necessarily mean that the ' closed ' form predominates in the intramolecular equilibrium of the type:

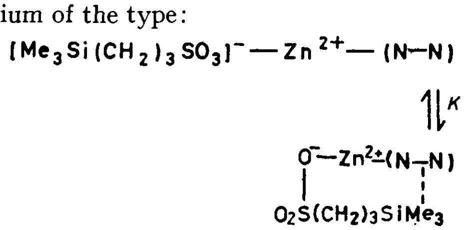

TABLE 1

Results obtained from an n.m.r. study of the ternary complexes of $[Me_3Si(CH_2)_3SO_3]^-$ or $[Me_3Si(CH_2)_2CO_2]^-$ with $[M(N–N)]^{2+}$ (35 °C, I = 0.1—1.2 mol dm^{-3}, $Na[NO_3]$) [a]

System	log K	$\Delta\delta$ [b]
$[Me_3Si(CH_2)_3SO_3]^-$–$[Zn(bipy)]^{2+}$	0.45 ± 0.06	0.38 ± 0.03
–$[Zn(phen)]^{2+}$	0.77 ± 0.04	0.66 ± 0.03
$[Me_3Si(CH_2)_2CO_2]^-$–$[Zn(bipy)]^{2+}$	0.59 ± 0.13	0.31 ± 0.05
–$[Zn(phen)]^{2+}$	0.90 ± 0.08	0.48 ± 0.05
	0.87 ± 0.12 [c]	
$[Me_3Si(CH_2)_3SO_3]^-$–$[Cu(phen)]^{2+}$	*ca.* 0.8 ± 0.3	0.16 ± 0.05

[a] The errors given are three times the standard error of the mean. [b] The difference between the chemical shift of the silyl ligand itself and that of the silyl ligand completely co-ordinated to $[Zn(bipy)]^{2+}$ or $[Zn(phen)]^{2+}$. [c] Determined using a 5 : 1 mixture of Zn^{2+}—phen: under these conditions 93% of the phenanthroline is present as $[Zn(phen)]^{2+}$ and only 7% as $[Zn(phen)_2]^{2+}$. With a 1 : 1 mixture, as used for the other experiments, 53% of the phenanthroline is present as $[Zn(phen)]^{2+}$, 41% as $[Zn(phen)_2]^{2+}$, and 6% as $[Zn(phen)_3]^{2+}$

Similar differences have been observed [9] for interactions between the two aromatic ring systems in the binary complexes $[(phen)(atp)]^{4-}$ and $[(bipy)(atp)]^{4-}$ and in the ternary complexes $[Zn(phen)(atp)]^{2-}$ and $[Zn(bipy)(atp)]^{2-}$ (H_4atp = adenosinetriphosphate); these interactions are at least in part hydrophobic. However, it is also noticeable that, especially for the $[Zn(phen)]^{2+}$ systems, the extrapolated upfield shift is much smaller for the carboxylate than for the sulphonate. This is probably due to the shorter aliphatic chain in the carboxylate, which cannot therefore interact fully with the homoaromatic ring of phenanthroline; this steric effect should not occur with the $[Zn(bipy)]^{2+}$ complexes, and indeed the small difference between the carboxylate and the sulphonate for $[Zn(bipy)]^{2+}$ may not be significant. Hence it is possible to draw a tentative structure for the $[Zn(phen)\{Me_3Si(CH_2)_3SO_3\}]^+$ complex (Figure 2).

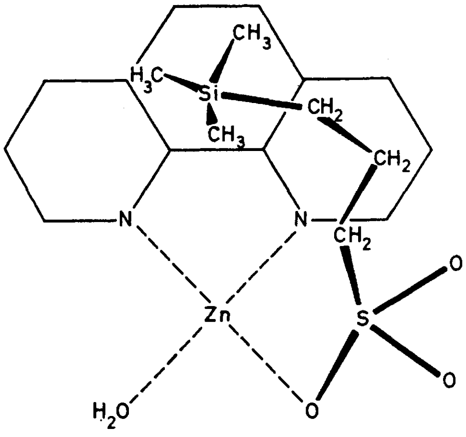

FIGURE 2 Tentative and simplified structure of the ternary stacked complex $[Zn(phen)\{Me_3Si(CH_2)_3SO_3\}]^+$

The intramolecular equilibrium constant K' is dimensionless, concentration independent, and is thus difficult to determine. Moreover, since it was not possible to determine the stability constants and the limiting shifts in any of the binary metal-free complexes such as $[(phen)\{Me_3Si(CH_2)_3SO_3\}]^-$, it was not possible to estimate K' by comparison of the upfield shifts for the binary and ternary systems, as has been done for the similar complexes between $[Zn(phen)]^{2+}$ or $[Zn(bipy)]^{2+}$ and nucleotides.[8,14] However, a comparison of the size of the limiting shifts with those of other ternary complexes containing $[Zn(bipy)]^{2+}$ or $[Zn(phen)]^{2+}$ strongly suggests that these ternary complexes are also predominantly (>60%) in the ' closed ' form.

Addition of Cu^{2+} (0.4 mol dm^{-3}) to a 0.1 mol dm^{-3} solution of $[Me_3Si(CH_2)_3SO_3]^-$ broadens the trimethylsilyl resonance from 0.5 to 19 Hz, whereas with the same concentration of $[Cu(bipy)]^{2+}$ the linewidth at half-height is 39 Hz and with $[Cu(phen)]^{2+}$ it is 55 Hz. Since the broadening was, within experimental error, proportional to the concentration of Cu^{II} no further conclusions could be drawn from the broadening. However, the trimethylsilyl resonance is shifted downfield (0.04 p.p.m.) by Cu^{2+} (0.4 mol dm^{-3}), no shift occurs with the same concentration of $[Cu(bipy)]^{2+}$, and $[Cu(phen)]^{2+}$ (0.4 mol dm^{-3}) shifts the resonance upfield (0.11 p.p.m.); moreover, the variation of the upfield shift in the presence of $[Cu(phen)]^{2+}$ suggests that log K = 0.8 ± 0.3, and that the extrapolated upfield shift is 0.16 ± 0.05 p.p.m., only a quarter of the upfield shift caused by $[Zn(phen)]^{2+}$, although the stability constants of the ternary complexes $[Zn(phen)\{Me_3Si(CH_2)_3SO_3\}]^+$ and $[Cu(phen)\{Me_3Si(CH_2)_3SO_3\}]^+$ are similar. The upfield shift of the trimethylsilyl resonance in [Cu(phen)-

$\{Me_3Si(CH_2)_3SO_3\}]^+$ and in $[Cu(bipy)\{Me_3Si(CH_2)_3SO_3\}]^+$ compared with that in $[Cu\{Me_3Si(CH_2)_3SO_3\}]^+$ indicates that a hydrophobic interaction also occurs in these ternary copper(II) complexes.

TABLE 2

Logarithms of the stability constants of the binary and ternary M^{2+}–(N–N)–$[Me_3Si(CH_2)_2CO_2]^-$ systems, determined by potentiometric titrations (35 °C, $I = 0.1$ mol dm^{-3}, $Na[NO_3]$) [a]

					log $\beta_{M(N-N)(O_2CR)}$ [c]		log $K_{M(N-N)(O_2CR)}$ [c]		
(N–N)	M^{2+}	log $K_{M(N-N)}$ [b]	log $K_{M(N-N)_2}$ [b]	log $K_{M(O_2CR)}$	(*i*)	(*ii*)	(*i*)	(*ii*)	Δ log K_M [d]
	Cd^{2+}			1.57 ± 0.04					
bipy	Cu^{2+}	7.57	5.40	1.80 ± 0.02	9.57 ± 0.03	9.53	2.00	1.96 ± 0.03	0.16
	Zn^{2+}	5.04	4.33	1.03 ± 0.02	6.21 ± 0.06	6.13	1.17	1.09 ± 0.04	0.06
phen	Cu^{2+}	8.83	6.51	1.80 ± 0.02	10.82 ± 0.02	10.79	1.99	1.96 ± 0.02	0.16
	Zn^{2+}	6.28	5.53	1.03 ± 0.02	7.33 ± 0.12	7.33	1.05	1.05 ± 0.05	0.02

[a] The errors given are three times the standard error of the mean, or the sum of the probable systematic errors, whichever is the larger. Acidity constants: 3-(trimethylsilyl)propionic acid, $pK_{RCO_2H} = 4.75 \pm 0.01$; bipy and phen, $pK_{H_2bipy} = -0.2$ and $pK_{H_2phen} = -1.6$;[20] $pK_{Hbipy} = 4.36$ and $pK_{Hphen} = 4.81$.[18,c] [b] Recalculated for a temperature of 35 °C from the results obtained by Anderegg.[18] [c] Calculated using procedures (*i*) and (*ii*) (see Experimental section). [d] Calculated [*cf.* equation (7)] from the results obtained with procedure (*ii*).

Hydrogen-1 *N.M.R. Study of the Binary* (N–N)–A^- *Systems.*—Although stability constants for a hydrophobic stacking interaction between two aromatic moieties are often fairly low, in particular cases stability constants of stacking between bipyridyl [7,9] or phenanthroline [9] and another aromatic moiety have been determined and lie in the range 6—30 dm^3 mol^{-1}; stability constants for stacking with phen are higher than with bipy. The stability constant for a hydrophobic interaction between bipy or phen and an aliphatic group is expected to be significantly lower.

In the binary systems bipy–$[Me_3Si(CH_2)_2CO_2]^-$, phen–$[Me_3Si(CH_2)_2CO_2]^-$, bipy-$[Me_3Si(CH_2)_3SO_3]^-$, and phen-$[Me_3Si(CH_2)_3SO_3]^-$, upfield shifts of the trimethylsilyl group are small, but clearly observable. Since the maximum upfield shifts observable are only 0.017, 0.012, 0.018, and 0.024 p.p.m. respectively ([silyl] = 0.01 mol dm^{-3}; [bipy] = 0.04 or [phen] = 0.02 mol dm^{-3}) it was clear from preliminary measurements that, with the combination of low stability constants and small upfield shifts, the stability constants of the hydrophobic interaction could not be determined. However, by comparing these upfield shifts in these binary metal-free systems with the extrapolated upfield shifts for the completely formed ternary complexes in the ternary systems with Zn^{2+}, it is possible to estimate the stability constants; for the phen systems log $K \simeq 0.3$ and for the bipy systems log $K \simeq 0$.

Potentiometric Determination of the Stabilities of the Ternary M^{2+}–(N–N)–A^- *Complexes.*—The stability constants determined by potentiometric titrations for the ternary Cu^{2+} and Zn^{2+} complexes are given in Table 2. It is notable that the values of Δ log K are around zero, or slightly positive, *i.e.* significantly larger than the statistical value of −0.3 expected for Cu^{2+} and −0.2 expected for Zn^{2+} (see Experimental section).

The stability constant for the $[Me_3Si(CH_2)_2CO_2]^-$–$[Zn(phen)]^{2+}$ system determined by potentiometric titration agrees well with that determined from n.m.r. measurements in which two different ratios of $[Zn^{2+}]$: [phen] were used. However, the agreement is less satisfactory for the $[Me_3Si(CH_2)_2CO_2]^-$–$[Zn(bipy)]^{2+}$ system; the reason for this discrepancy is not clear.

Hydrogen-1 *N.M.R. Study of the Effect of* Zn^{2+}, $[Zn(bipy)]^{2+}$, *and* $[Zn(phen)]^{2+}$ *on Straight- and Branched-chain Carboxylates of Varying Chain Lengths.*—Since it appeared from the comparison of the extrapolated upfield shifts for the four systems studied in detail that the length of the aliphatic chain had an influence on the hydrophobic interaction, the upfield shifts in binary mixtures of a range of linear- and branched-chain carboxylate ions with Zn^{2+}, and in the ternary mixtures of these acids with $[Zn(bipy)]^{2+}$ and $[Zn(phen)]^{2+}$, were investigated.

Since the aim of the experiment was only to investigate the variation of upfield shift with increasing chain length, and as the stability constants of these carboxylic acids change very little with chain length, for each acid the n.m.r. spectra of the carboxylate anion, of the binary mixture containing an excess of Zn^{2+}, and of the ternary mixtures containing an excess of a 1 : 1 mixture of either Zn^{2+}–bipy or Zn^{2+}–phen were compared under standard conditions chosen such that the degree of complex formation was as high as could be easily obtained. Owing to the lower solubility of the zinc salts of the longer chain acids (C_6–C_7) it was necessary to use somewhat more dilute solutions: the degree of complex formation is however not affected significantly and is *ca.* 85, 80, and 60% for the systems containing Zn^{2+}, Zn^{2+}–bipy, and Zn^{2+}–phen, respectively. The results are in Table 3.

As expected, Zn^{2+} shifts the resonances downfield, but the effect is large only with acetate and falls off rapidly with increasing chain length, being very small for four-carbon chains (butyrate, 3-methylbutyrate, and 3,3-dimethylbutyrate) and negligible for longer chains. However, the upfield shift by Zn^{2+}–bipy, and by Zn^{2+}–phen, negligible with acetate, increases rapidly with increasing chain length (3—5 carbon atoms), and then changes relatively little as the chain length is increased further (5—7 carbon atoms). The insolubility of the zinc salts, and of the ternary complexes $[Zn(bipy)A]^+$ and $[Zn(phen)A]^+$, prevented the series being extended further. For pentanoate the methylene group adjacent to the methyl group is also shifted, although less than the

TABLE 3

Extrapolated shifts (p.p.m.) of the methyl groups in the binary complexes $[ZnA]^+$ and of ternary complexes $[Zn(bipy)A]^+$ and $[Zn(phen)A]^+$ for linear- and branched-chain carboxylates of varying chain length [a]

	$[MeCO_2]^-$			
Zn^{2+}	−0.12			
$[Zn(bipy)]^{2+}$	<0.005			
$[Zn(phen)]^{2+}$	<0.005			
	$[EtCO_2]^-$		$[Pr^iCO_2]^-$	$[Bu^tCO_2]^-$
Zn^{2+}	−0.03		−0.06	−0.06
$[Zn(bipy)]^{2+}$	0.06		0.06	0.06
$[Zn(phen)]^{2+}$	0.10		0.10	0.09
	$[PrCO_2]^-$		$[Pr^iCH_2CO_2]^-$	$[Bu^tCH_2CO_2]^-$
Zn^{2+}	−0.018		−0.022	−0.018
$[Zn(bipy)]^{2+}$	0.13		0.16	0.18
$[Zn(phen)]^{2+}$	0.20		0.24	0.29
	$[Me(CH_2)_3CO_2]^-$		$[Pr^i(CH_2)_2CO_2]^-$	$[Me_3Si(CH_2)_2CO_2]^-$
Zn^{2+}	−0.005	(−0.08) [b]	−0.005	0.003
$[Zn(bipy)]^{2+}$	0.18	(0.08) [b]	0.21	0.31
$[Zn(phen)]^{2+}$	0.31	(0.18) [b]	0.39	0.48
	$[Me(CH_2)_4CO_2]^-$			$[Me_3Si(CH_2)_3SO_3]^-$
Zn^{2+}	0.004	(−0.017) [b]		−0.003
$[Zn(bipy)]^{2+}$	0.23	(0.34) [b]		0.38
$[Zn(phen)]^{2+}$	0.43	(0.48) [b]		0.66
	$[Me(CH_2)_5CO_2]^-$			
Zn^{2+}	[c]			
$[Zn(bipy)]^{2+}$	[c]			
$[Zn(phen)]^{2+}$	0.37	(0.47) [b]		

[a] Except for the trimethylsilyl derivatives for which the stability constants were determined (Table 2), these extrapolated shifts are calculated assuming $\log K = 1.0$. [b] Shifts of the methylene group adjacent to the methyl group. [c] Not measurable owing to precipitation.

methyl group itself, for hexanoate the shifts of the methyl and of the adjacent methylene group are fairly similar (especially for the Zn^{2+}–phen system), and for heptanoate the methylene group is shifted significantly more than the methyl group. This suggests that the structure of these carboxylato-complexes closely resembles that of the silylpropanesulphonato-complex depicted in Figure 2 and also suggests that, of the linear carboxylates, the ' best fit ' occurs with pentanoate and hexanoate. Indeed the stability constants of the ternary complexes of pentanoate with $[Zn(phen)]^{2+}$ and with $[Cu(phen)]^{2+}$, determined potentiometrically, have been found to be somewhat higher than expected by comparison with shorter-chain carboxylates such as acetate or propionate.[15]

It is also interesting to note that the upfield shift of the branched-chain carboxylates is similar to, but somewhat higher than, that of the linear carboxylate of the same chain length. The reason for this is uncertain, but may be either that the stability constant is a little higher, or, more likely, that a higher proportion of the complex is in the ' closed ' form due to the increased hydrophobicity of the isopropyl or t-butyl groups.

EXPERIMENTAL

The metal(II) nitrates, sodium nitrate, sodium acetate, 1,10-phenanthroline hydrate, and 2,2′-bipyridyl were *pro analysi* from Merck AG, Darmstadt, Germany; the concentrations of stock solutions of the metal(II) nitrates were determined by titration with ethylenediamine-*NNN′N′*-tetra-acetate. Sodium 3-(trimethylsilyl)propane-1-sulphonate, sodium 3-(trimethylsilyl)propionate, and 10% tetramethylammonium hydroxide solution were also from Merck; tetramethylammonium nitrate was prepared by neutralizing the hydroxide with nitric acid (*p.a.*). The potentiometric titrations were carried out with a Metrohm E 536 potentiograph. Hydrogen-1 n.m.r. spectra were recorded using a Varian Anaspect EM-360 spectrometer (60 MHz) at 35 °C, usually with solutions in H_2O.

Observation of Upfield Shifts of Methyl Resonances in the Presence of Phenanthroline and Bipyridyl Zinc Complexes.— In the presence of 0.1 mol dm^{-3} sodium perchlorate, crystallization occurs even at 10^{-3} mol dm^{-3} $[Zn(phen)]^{2+}$ or at 5×10^{-4} mol dm^{-3} $[Cu(phen)]^{2+}$. Therefore, nitrate salts were used throughout; at 25 °C clear solutions were obtained with $[Zn(phen)]^{2+}$ (*ca.* 0.2), $[Zn(bipy)]^{2+}$ (>0.6), $[Cu(phen)]^{2+}$ (*ca.* 0.5), and $[Cu(bipy)]^{2+}$ (>0.6 mol dm^{-3}). For n.m.r. experiments at 35 °C even more concentrated solutions of $[Zn(phen)]^{2+}$ could be used (up to 0.3 mol dm^{-3}).

Variations in the magnetic susceptibility of the strong solutions needed prevent the use of an external reference, since precise susceptibility corrections would be complicated. Of the internal references commonly used in aqueous solution, Bu^tOH is known to be shifted in the presence of high concentrations of aromatic solutes owing to hydrophobic interactions.[16] Although acetonitrile or dioxan could give weak complexes with Zn^{2+}, the stability constants are expected to be very low. However, the spherically symmetric tetramethylammonium ion seemed the best choice as inert reference; in some experiments acetonitrile or dioxan was used as an additional reference as a check on the validity of this assumption. The results were usually the same, although at high concentrations of Zn^{2+} the resonance of acetonitrile shifted somewhat.* All the chemical shifts were therefore measured in p.p.m. *upfield* from the

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* The small variation of the shift of the acetonitrile resonance with $[Zn(phen)]^{2+}$ or $[Zn(bipy)]^{2+}$ concentration is consistent with weak complex formation $K_{Zn(phen)(MeCN)} \bumpeq 4$, $K_{Zn(bipy)(MeCN)} \bumpeq 3$. The maximum shift observed with 0.6 mol dm^{-3} $[Zn(bipy)]^{2+}$, 0.3 mol dm^{-3} $[Zn(phen)]^{2+}$, and 1.44 mol dm^{-3} Zn^{2+} is 0.048 and 0.060 p.p.m. upfield, and 0.044 p.p.m. downfield respectively. These results may be taken as an indication that a hydrophobic interaction also occurs in the weak ternary complexes $[Zn(bipy)(NCMe)]^{2+}$ and $[Zn(phen)(NCMe)]^{2+}$.

centre peak of the triplet resonance of the tetramethylammonium ion (usually 0.005—0.02 mol dm^{-3}).

Determination of the Stability Constants of Ternary Complexes of Aliphatic Carboxylates with $[Zn(phen)]^{2+}$ *and* $[Zn(bipy)]^{2+}$ *by* ^1H *N.M.R.*—Since the stability constants are rather low it was not possible to keep the ionic strength constant throughout a series of measurements. Instead, in the weaker solutions of $[Zn(phen)]^{2+}$ and $[Zn(bipy)]^{2+}$, sodium nitrate was added to bring the ionic strength to 0.1 mol dm^{-3}, whereas in the stronger solutions, in which the ionic strength was >0.1 mol dm^{-3}, no sodium nitrate was added. In a series, the ionic strength typically varied from 0.1 to 1.0, and occasionally even to 2.0 mol dm^{-3}. However, variations in the ionic strength in the range 0.1—1.0 mol dm^{-3} have little effect on the stability constant.[17]

In a binary M^{2+}–bipy or M^{2+}–phen system the equilibria [18] (1)—(3) must be considered. In a 1 : 1 Zn^{2+}–bipy

$$M^{2+} + N\text{–}N \rightleftharpoons [M(N\text{–}N)]^{2+} \qquad (1)$$

$$[M(N\text{–}N)]^{2+} + N\text{–}N \rightleftharpoons [M(N\text{–}N)_2]^{2+} \qquad (2)$$

$$[M(N\text{–}N)_2]^{2+} + N\text{–}N \rightleftharpoons [M(N\text{–}N)_3]^{2+} \qquad (3)$$

mixture the proportions of Zn^{2+}, $[Zn(bipy)]^{2+}$, $[Zn(bipy)_2]^{2+}$, and $[Zn(bipy)_3]^{2+}$ are 23.5, 54, 21, and 1.5%; in a 1 : 1 Cu^{2+}–bipy mixture the analogous proportions are 5.5, 89, 5.5, and 2×10^{-5}%. Owing to the stability of the complexes, these proportions remain essentially unchanged for concentrations $>10^{-4}$ mol dm^{-3}; the proportions in the Cu^{2+}–phen and Zn^{2+}–phen systems are almost identical to those of the analogous bipy systems.

The stability constants of the binary metal carboxylate or metal sulphonate complexes are much lower so that $[MA_2]$ is

$$M^{2+} + A^- \rightleftharpoons [MA]^+$$
$$K_{MA} = [MA^+]/[M^{2+}][A^-] \qquad (4)$$

negligible under the conditions used. Equations (5) and (6) define the stability constants of the ternary systems.

$$[M(N\text{–}N)]^{2+} + A^- \rightleftharpoons [M(N\text{–}N)A]^+$$
$$K_{M(N\text{–}N)A} = [M(N\text{–}N)A^+]/[M(N\text{–}N)^{2+}][A^-] \qquad (5)$$

$$[M(N\text{–}N)_2]^{2+} + A^- \rightleftharpoons [M(N\text{–}N)_2(A)]^+$$
$$K_{M(N\text{–}N)_2A} = [M(N\text{–}N)_2A^+]/[M(N\text{–}N)_2{}^{2+}][A^-] \qquad (6)$$

The appropriate way of quantifying the increase or decrease in stability of these mixed-ligand complexes is by comparison of the co-ordination of the anionic ligand to free M^{2+} and to $[M(N\text{–}N)]^{2+}$ [equation (7)]. Owing to the

$$\Delta \log K_M = \log K_{M(N\text{–}N)A} - \log K_{MA} \qquad (7)$$

presence of considerable amounts of $[Zn(N\text{–}N)_2]^{2+}$ under most conditions amenable to experimental measurement for systems containing Zn^{2+}, the increase or decrease in the stability of $[M(N\text{–}N)_2A]^+$ must also be considered [equation (8)]. For octahedral complexes $\Delta \log K_M$ and $\Delta \log K_{M(N\text{–}N)}$

$$\Delta \log K_{M(N\text{–}N)A} = \log K_{M(N\text{–}N)_2A} - \log K_{M(N\text{–}N)A} \qquad (8)$$

can be calculated from statistical considerations [1] to be −0.2 and −0.3 respectively. For mixed-ligand complexes, especially those of first-row transition metals with an aromatic heterocyclic ligand, and an oxygen-donor ligand, $\Delta \log K$ is usually somewhat larger than calculated statistically.[1] Indeed *in the present case* values around zero are to be expected, *i.e.* expression (9) is applicable.

$$K_{MA} \simeq K_{M(N\text{–}N)A} \simeq K_{M(N\text{–}N)_2A} \qquad (9)$$

The upfield shift ($\Delta\delta$) of the resonance of A^- in the ternary mixture compared with that of A^- alone is given by (10)

$$\Delta\delta = \{\Delta\delta_{MA}[MA^+] + \Delta\delta_{M(N\text{–}N)A}[M(N\text{–}N)A^+] + \Delta\delta_{M(N\text{–}N)_2A}[M(N\text{–}N)_2A^+]\}/[A]_T \qquad (10)$$

where $\Delta\delta_{MA}$, $\Delta\delta_{M(N\text{–}N)A}$, and $\Delta\delta_{M(N\text{–}N)_2A}$ are the upfield shifts of A in $[MA]^+$, $[M(N\text{–}N)A]^+$, and $[M(N\text{–}N)_2A]^+$ respectively. Since M^{2+} alone was found to have no influence on the shift of A^-, $\Delta\delta_{MA} = 0$.

Hence from (5), (6), and (10) we obtain (11), and from (8) and (11) we can write (12).

$$\Delta\delta = \{\Delta\delta_{M(N\text{–}N)A}K_{M(N\text{–}N)A}[M(N\text{–}N)^{2+}][A^-] + \Delta\delta_{M(N\text{–}N)_2A}K_{M(N\text{–}N)_2A}[M(N\text{–}N)_2{}^{2+}][A^-]\}/[A]_T \qquad (11)$$

$$\Delta\delta = [A^-]K_{M(N\text{–}N)A}\{\Delta\delta_{M(N\text{–}N)A}[M(N\text{–}N)^{2+}] + \Delta\delta_{M(N\text{–}N)_2A}[M(N\text{–}N)_2{}^{2+}] \times 10^{\Delta \log K_{M(N\text{–}N)}}\}/[A]_T \qquad (12)$$

However, in an experiment in which the ratio of $[Zn^{2+}]$: [phen] was varied from 0.33 to 1.11 : 1, with a constant concentration of $Me_3Si(CH_2)_2CO_2{}^-$, it was found that the upfield shift in $[Zn(phen)_2\{Me_3Si(CH_2)_2CO_2\}]^+$ is probably not very much larger than that in $[Zn(phen)\{Me_3Si(CH_2)_2CO_2\}]^+$. The results of this experiment also clearly indicate that at very low, and very high, $[Zn^{2+}]$: [phen] ratios two other complexes which involve hydrophobic interactions are formed: $[\{Zn(phen)_3\}\{Me_3Si(CH_2)_2CO_2\}]^+$, an outer-sphere complex involving ion-pair formation and a hydrophobic interaction, which has $\log K_{Zn(phen)_3A} \sim 1$; and $[\{Zn(phen)\}\{Me_3Si(CH_2)_2CO_2Zn\}]^{3+}$, in which only a hydrophobic interaction is possible, which has $\log K_{Zn(phen)Zn(A)} \sim 0$.

If equilibria other than (13) are ignored, the value of log

$$[Zn(N\text{–}N)]^{2+} + A^- \rightleftharpoons [Zn(N\text{–}N)A]^+ \qquad (13)$$

$K_{M(N\text{–}N)A}$ obtained will be lower than the correct value by *ca.* 0.1 (if $\Delta \log K_{M(N\text{–}N)}$ is ∼0), estimated using equation (12).

The stability constants were therefore calculated from the variation of the upfield shift of the trimethylsilyl resonance as the concentration of $[Zn(bipy)]^{2+}$ or of $[Zn(phen)]^{2+}$ was increased, taking into account both $[Zn(phen)\{Me_3Si(CH_2)_2CO_2\}]^+$ and $[Zn(phen)_2\{Me_3Si(CH_2)_2CO_2\}]^+$, using a curve-fitting program on a Hewlett-Packard model 9821 connected to a model 9862 A plotter. An experiment carried out using a four-fold excess of Zn^{2+}, to ensure that almost all of the phenanthroline used was present as $[Zn(phen)]^{2+}$, considering only equilibrium (13), gave a very similar stability constant to that obtained using a 1 : 1 Zn^{2+} : phen mixture.

Determination of Equilibrium Constants by Potentiometric Titrations.—The acidity constant K_{HL} of 3-(trimethylsilyl)propionic acid was determined from automatic titrations under N_2 of aqueous solutions (50 cm^3) containing 1.8×10^{-3} mol dm^{-3} HNO_3 and $Na[NO_3]$ ($I = 0.1$ or 0.2 mol dm^{-3}) in the presence and absence of 1.2×10^{-3} mol dm^{-3} 3-(trimethylsilyl)propionate ($[RCO_2]^-$) with 0.1 mol dm^{-3} Na[OH] (35 °C). The differences between such pairs of titrations were measured, and the constant was calculated from the pH range which corresponded to a degree of neutralization from 0.1 to 0.9. There was no significant difference between the results obtained at $I = 0.1$ or 0.2 mol dm^{-3}.

The conditions of measurements for the determination of the stability constants, $K_{M(O_2CR)}$, were the same as for the acidity constant, but $Na[NO_3]$ was partly replaced by

$M[NO_3]_2$ to give the ratios $Cu^{2+} : [RCO_2]^- = 14 : 1$, $Zn^{2+} : [RCO_2]^- = 27.5 : 1$ ($I = 0.1$) and $55 : 1$ ($I = 0.2$ mol dm^{-3}), and $Cd^{2+} : [RCO_2]^- = 27.5 : 1$. Titrations of solutions without ligand were used as a basis for the evaluation. $K_{M(O_2CR)}$ was calculated [19] taking into account the species H^+, RCO_2H, $[RCO_2]^-$, M^{2+}, and $[M(O_2CR)]^+$.

The conditions used for the titrations of the mixed-ligand systems were the same as for the binary ones (and for the determination of the acidity constant) but the solutions contained in addition the aromatic heterocyclic ligands bipy or phen. The ratios were $Cu^{2+} : N{-}N : [RCO_2]^- = 14 : 14 : 1$ and $27.5 : 27.5 : 1$, and $Zn^{2+} : N{-}N : [RCO_2]^- = 27.5 : 27.5 : 1$ ($I = 0.1$) and $55 : 55 : 1$ ($I = 0.2$ mol dm^{-3}).

At least four independent titration curves were measured in all cases. There were no significant differences between the results obtained for the Zn^{2+} systems at $I = 0.1$ and 0.2 mol dm^{-3}. The mixed-ligand systems of Cd^{2+} could not be studied since a precipitate formed.

Calculation of Stability Constants from the Potentiometric Data on the Mixed-ligand Systems.—The acidity constants $K_{H_2(N-N)}$ were from the work of Linnell and Kaczmarczyk,[20] and the acidity constants $K_{H(N-N)}$ and the stability constants of the binary complexes with bipy or phen from the work of Anderegg;[18] the latter values were recalculated for a temperature of 35 °C.

Procedure (*i*). The overall stability constant $\beta_{M(N-N)(O_2CR)}$ was computed [19] by taking into account the species H^+, $[H_2(N{-}N)]^{2+}$, $[H(N{-}N)]^+$, N–N, $[M(N{-}N)]^{2+}$, $[M(N{-}N)_2]^{2+}$, RCO_2H, $[RCO_2]^-$, $[M(O_2CR)]^+$, M^{2+}, and $[M(N{-}N)(O_2CR)]^+$. The difference between the Na[OH] consumed in a titration of a solution containing only HNO_3 and one containing in addition the ternary system was used in the calculations.

Procedure (*ii*). The results were evaluated assuming that the complex $[M(N{-}N)]^{2+}$ is completely formed in the binary systems. The stability constant, $K_{M(N-N)(O_2CR)}$, for the ternary complexes can be calculated by the same method [19] as for the binary complexes, considering only the species H^+, RCO_2H, $[RCO_2]^-$, $[M(N{-}N)]^{2+}$, and $[M(N{-}N)(O_2CR)]^+$. Here the difference between a pair of titrations of solutions with, and without, $[RCO_2]^-$ (the ternary system and the binary system, respectively), was used in the calculations.

Although more species are considered in procedure (*i*), more equilibrium constants have to be taken into account and this may lead to systematic errors. This danger is especially high in the present case since a large excess of M^{2+} and N–N, compared with $[RCO_2]^-$, had to be used in the experiments to gurantee a significant degree of formation of the ternary complex. Moreover, one complex which is present to a significant extent in the Zn^{2+} systems, $[Zn(N{-}N)_2(O_2CR)]^+$, cannot be considered since its formation constant is neither known nor determinable without considerable difficulty. These problems are eliminated by procedure (*ii*), where only the minimum number of species are considered, and since only one acidity constant $K_{H(O_2CR)}$ must be used in the calculations extraneous errors are reduced. This procedure is also preferable from the experimental point of view: errors resulting from acidic or basic impurity in the metal salt or in the heterocyclic aromatic ligand are eliminated, since the difference between the titration curves obtained in the presence and in the absence of $[RCO_2]^-$ is evaluated.* Thus a smaller standard error is obtained using procedure (*ii*). The agreement between the results obtained with the two procedures is however excellent for all the mixed-ligand systems studied.

I thank Dr. H. Sigel for his continuous encouragement, Mrs. E. Plattner and Miss R. Baumbusch for skilful assistance with the potentiometric titrations and their evaluation, and the Swiss National Science Foundation for the award of a research grant (project of Dr. H. Sigel). The computers used for the calculation of stability constants from the potentiometric titrations were made available by the Rechenzentrum der Universität Basel.

[8/1134 *Received, 19th June, 1978*]

REFERENCES

[1] H. Sigel, *Angew. Chem. Internat. Edn.*, 1975, **14**, 394; *Angew. Chem.*, 1975, **87**, 391.

[2] H. Sigel, B. E. Fischer, and B. Prijs, *J. Amer. Chem. Soc.*, 1977, **99**, 4489; H. Sigel, ' Structural Aspects of Mixed-Ligand Complex Formation in Solution,' in ' Metal Ions in Biological Systems,' Marcel Dekker, New York, 1973, vol. 2, pp. 63—125.

[3] E. Frieden, *J. Chem. Educ.*, 1975, **52**, 754.

[4] O. Yamauchi, Y. Nakao, and A. Nakahara, *Bull. Chem. Soc. Japan*, 1975, **48**, 2572.

[5] T. Sakurai, O. Yamauchi, and A. Nakahara, *Bull. Chem. Soc. Japan*, 1976, **48**, 169, 1579.

[6] T. Sakurai, O. Yamauchi, and A. Nakahara, *J.C.S. Chem. Comm.*, 1976, 553.

[7] C. F. Naumann and H. Sigel, *J. Amer. Chem. Soc.*, 1974, **96**, 2750; P. Chaudhuri and H. Sigel, *ibid.*, 1977, **99**, 3142.

[8] Y. Fukuda, P. R. Mitchell, and H. Sigel, *Helv. Chim. Acta*, 1978, **61**, 638.

[9] P. R. Mitchell and H. Sigel, *J. Amer. Chem. Soc.*, 1978, **100**, 1564.

[10] H. Sigel and C. F. Naumann, *J. Amer. Chem. Soc.*, 1976, **98**, 730.

[11] A. S. Grigorêva, E. E. Kriss, and K. B. Yatsimirskii, *Zhur. neorg. Khim.*, 1976, **21**, 1066; *Russ. J. Inorg. Chem.*, 1976, **21**, 581.

[12] P. R. Mitchell and H. Sigel, *Angew. Chem. Internat. Edn.*, 1976, **15**, 548; *Angew. Chem.*, 1976, **88**, 585.

[13] L. M. Jackmann and S. Sternhill, ' Applications of Nuclear Magnetic Resonance in Organic Chemistry,' 2nd edn., Pergamon, Oxford, 1969, p. 94.

[14] P. R. Mitchell and H. Sigel, unpublished work.

[15] K. H. Scheller and H. Sigel, unpublished work.

[16] R. A. Y. Jones, A. R. Katritzky, J. N. Murrell, and N. Sheppard, *J. Chem. Soc.*, 1962, 2576.

[17] ' Stability Constants of Metal-Ion Complexes,' eds. L. G. Sillén and A. E. Martell, *Special Publ.*, The Chemical Society, London, 1964.

[18] G. Anderegg, *Helv. Chim. Acta*, 1963, **46**, 2397, 2813.

[19] R. Griesser and H. Sigel, *Inorg. Chem.*, 1970, **9**, 1238; 1971, **10**, 2229.

[20] R. H. Linnell and A. Kaczmarczyk, *J. Phys. Chem.*, 1961, **65**, 1196.

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* If the effect of the presence of $[M(N{-}N)_2]^{2+}$ on the potentiometric titrations is considered in a similar manner to that used for the n.m.r. study, it is found that, if $\Delta \log K_M$ and $\Delta \log K_{M(N-N)}$ are approximately zero, reliable results for these systems are best obtained from the potentiometric titrations by using procedure (*ii*): indeed the titrations show that $\Delta \log K_M$ is in fact approximately zero (Table 2).