Polymeric Thiolate Complexes in Solution. Stability Constants of the Cadmium(II) Complexes of 4-Mercapto-1-methylpiperidine

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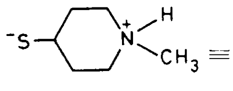
Polynuclear complex formation between Cd^{II} and 4-mercapto-1-methylpiperidine has been studied by e.m.f. measurements with glass and cadmium amalgam electrodes at 25 °C in a 3 mol dm^{-3} (sodium) perchlorate medium [+10% (v/v) CH_3OH]. Conclusions drawn from graphical methods agree well with results obtained from the numerical treatment. The best fit to the experimental data corresponds to the existence of two 'core + links' series, $Cd[Cd(HA)_3]_n^{(2n+2)+}$ and $(HA)_2[Cd(HA)_2]_n^{2n+}$, HA being the uncharged ligand, from which only the following species are present: $[Cd(HA)_4]^{2+}$ (log $\Psi_{1,4}$ = 23.06 ± 0.01), $[Cd_3(HA)_6]^{6+}$ (log $\Psi_{3,6}$ = 48.59 ± 0.02), $[Cd_3(HA)_8]^{6+}$ (log $\Psi_{3,8}$ = 61.85 ± 0.03), $[Cd_4(HA)_9]^{8+}$ (log $\Psi_{4,9}$ = 73.50 ± 0.02), and $[Cd_4(HA)_{10}]^{8+}$ (log $\Psi_{4,10}$ = 80.48 ± 0.01). A mechanism for the formation of these species and their possible geometries are suggested.

An understanding of the co-ordination of zinc, cadmium, and mercury by simple thiol ligands is vital in determining the way in which these Group 2B elements interact with environmental and biological ligands. Thus, while it is now clear that the thiol group of the cysteinyl residues in metallothioneins (low molecular weight sulphydryl-rich proteins containing up to seven cadmium and/or zinc ions) plays a central role in metal binding, co-ordination around the metal atom has been only partially elucidated.[1]

Cadmium thiolate complexes show a great variety of structures ranging from mononuclear species to polymeric chains.[2] However, investigations on the soluble species formed in solutions containing cadmium ions and simple mercaptans are scarce. The main reason for this lack of information is the insolubility of these ligands and the $[Cd(SR)_2]$ neutral complexes. In order to avoid this problem Schwarzenbach *et al.*[3] and De Brabander and Van Poucke [4] have used water-soluble thioglycol. Their results, reported separately, seem to differ essentially in the interpretation of the experimental data. Furthermore, the structure of a solid cadmium complex showed that the solubilizing alcohol function also acts as a co-ordinating group [5] and thus this can also occur in the soluble species.

Observed molecular structures of metal complexes of 4-mercapto-1-methylpiperidine indicate that this ligand behaves as a zwitterion,[6-9] $^{-}S\text{-}C_5H_9\overset{+}{N}(CH_3)H$, (I). The protonation of the nitrogen atom prevents its co-ordination to metal atoms



$\equiv$ HA

(I)

and at the same time makes the study of metal complex formation with thiol ligands in solution possible. Following this principle, the equilibrium constants for the complex species formed with zinc ions and the same ligand have already been reported.[10]

As an attempt to determine the nature of cadmium thiolate complexes existing in solution, a potentiometric study of the equilibria between this cation and the ligand 4-mercapto-1-methylpiperidine was undertaken. The crystal structure of a solid cadmium complex of this ligand is already known.[8]

Experimental

Reagents.—An acidified stock solution of cadmium perchlorate (Alfa) was standardized gravimetrically as anthranilate, $Cd(C_7H_6O_2N)_2$, and volumetrically with ethylenediaminetetra-acetate. Methanol (Merck, p.a.) was used after distillation over NaOH. The rest of the reagents and solutions were prepared according to published procedures.[10]

Apparatus.—The titrations were performed in an oil thermostat at 25.0 ± 0.1 °C and under a nitrogen atmosphere. The program POTTIT [11] (HP-85 microcomputer) was used to command automatically four microburettes (Hamilton, Microlab M) and two potentiometers (Crison, Digilab). The titration procedure has already been described.[10] A glass electrode (Ingold HA 201) and an electrolytically prepared cadmium amalgam electrode (0.05% in cadmium) were used to measure the concentrations of the free hydrogen and cadmium ions respectively. Both electrodes were standardized in concentration units and *in situ* before each titration.[12] A silver electrode [13] coated with AgCl (prepared by anodic oxidation of a HCl solution) in conjunction with a 'Wilhelm' glass apparatus was used as reference half-cell.

Calculations and Results

Five titrations were carried out with total metal-ion concentrations, B, in the range $0.4 \leqslant B \leqslant 6.4$ mmol dm^{-3}. The total ligand concentration, L, was about four times that of B and both were kept constant in each titration. The symbols used throughout are the same as those used by Sillén [14,15] and are as follows: HA = ligand in its zwitterionic form, see structure (I); b = concentration of free metal; H = total concentration of hydrogen ion; h = concentration of free hydrogen ion; E = e.m.f. from the glass electrode; $\bar{r}$ = average number of protons bound to the ligand; K_2 = second acid-dissociation constant of the ligand; n = number of links in a 'core + links' complex; Z = average number of ligands bound per metal; p = number of metal atoms in a complex; q = number of HA in a complex; $\bar{p},\bar{q}$ = average stoicheiometric coefficients of the complexes; t = number of HA per metal in link; r = constant number of HA in core (if free from metal); and $\eta = \log (B/b)$.

Assuming complexes of general formula $Cd_pA_qH_r$, overall charges are omitted throughout for clarity, values for log h and $\bar{r}$ were calculated from the primary data according to equations (1) and (2). The calibration constant E_0 was deter-

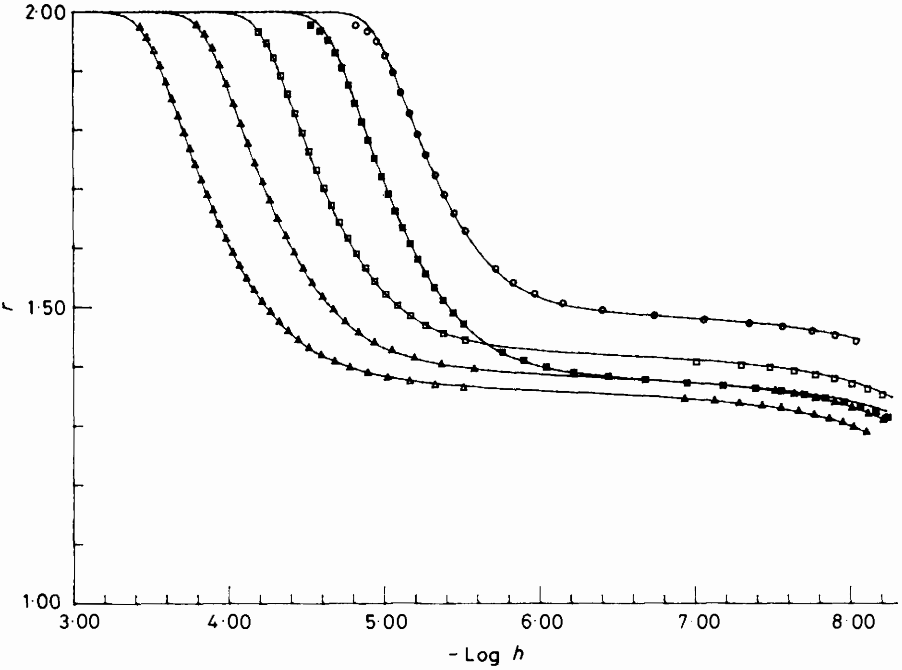


Figure 1. Average number of protons bound to the ligand, $\bar{r}$, as a function of log h at different ligand : metal ratios: $B = 0.423$, $L = 2.082$ (○); $B = 0.817$, $L = 3.316$ (■); $B = 1.627$, $L = 7.09$ (□); $B = 3.217$, $L = 13.17$ (▲); and $B = 6.400$, $L = 25.18$ mmol dm^{-3} (△). The lines drawn were calculated from the constants in the Table

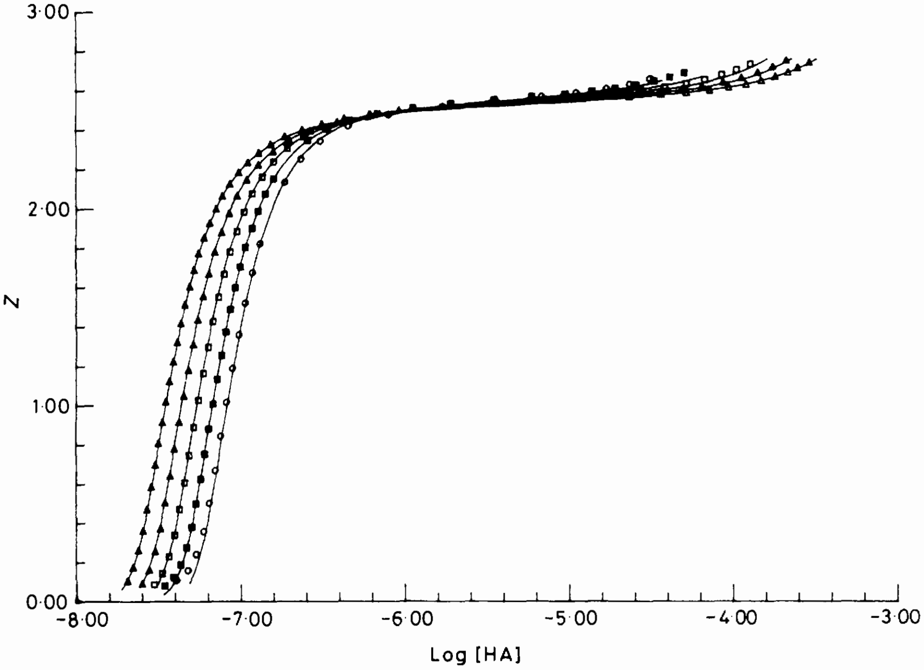


Figure 2. Formation curve for $Cd_p(HA)_q$ species at different ligand : metal ratios, from glass electrode experimental data; for key to symbols see Figure 1. The lines drawn were calculated from the constants in the Table

mined *in situ* before each titration using the Gran functions.[12]

$$\log h = (E - E_0)/59.16 \qquad (1)$$

$$\bar{r} = (H - h)/L \qquad (2)$$

Figure 1 shows a plot of $\bar{r}$ *vs.* $-\log h$. The presence of a plateau for values $1 \leqslant \bar{r} \leqslant 2$ when $-\log h \geqslant 4.5$ indicates that 4-mercapto-1-methylpiperidine acts as a 'monoprotonated' ligand analogously as with Zn^{II}.[10] Furthermore, *X*-ray diffraction studies on the complex $[Cd(HA)_2][ClO_4]_2 \cdot 2H_2O$ [5] showed that the ligand co-ordinates to the metal ion as the zwitterion, (I), suggesting that this is the form present in the soluble species.

For complexes of the type $Cd_p(HA)_q$ a formation constant $\Psi_{p,q}$ can be defined according to equation (3), where $\Psi_{p,q}$ is

$$\Psi_{p,q} = [Cd_p(HA)_q][Cd]^{-p}[HA]^{-q} \qquad (3)$$

related to the stoicheiometric overall stability constant by the relationship (4), K_2 being already known.[12]

$$\beta_{p,q,q} = \Psi_{p,q} \cdot K_2^{-q} \qquad (4)$$

In a two-component system, the experimental function, Z, and the free ligand concentration, [HA], can be calculated using known equations.[10]

The curves of Z *vs.* log [HA] for various values of B, Figure 2, are practically parallel up to $Z \simeq 2.0$. From $Z \simeq 2.0$ the curves start to converge until they finally intersect at $Z \simeq 2.55$ from where they diverge in the other direction.

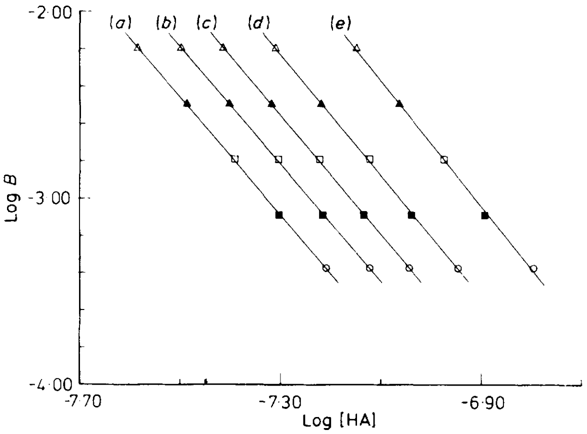


Figure 3. Variation of total concentration of Cd^{II} with that of the free ligand for several Z values, from glass electrode experimental data: Z = 0.4 (*a*), 0.8 (*b*), 1.2 (*c*), 1.6 (*d*), and 2.0 (*e*). The straight lines were calculated by linear regression (for key to symbols see Figure 1)

For Z values up to *ca.* 2.0 the 'core + links' hypothesis was used.[14,15] The value of t in $Cd[Cd(HA)_t]_n$ was determined by the usual method, Figure 3. From the glass electrode measurements the average value found, $\bar{t}$, was 3.20, $\sigma = 0.04$ being the standard deviation. Accepting that the true value for t should be in the range $\bar{t} \pm 3\sigma$, possible values were $3.08 \leqslant t \leqslant 3.32$. The same treatment using the plot of η *vs.* log [HA], Figure 4, gave a t value in the range $3.05 \leqslant t \leqslant 3.15$. These values were difficult to interpret.

By means of the MESAK integration method [14] the average values $\bar{p}$ and $\bar{q}$ for the complexes $Cd_p(HA)_q$ were calculated from the Z *vs.* log [HA] data. The results for B = 6.4 and 1.627 mmol dm^{-3} are shown in Figure 5. In range A and C the points fall on two straight lines (linear regression) indicating the existence of two different series of 'core + links' complexes, $Cd[Cd(HA)_3]_n$ and $(HA)_2[Cd(HA)_2]_n$, respectively. Range B is a transition from range A to range C and thus it is possible to assume that both series coexist here. From the shape of the curves it is possible to see that in range B the presence of $(HA)_2[Cd(HA)_2]_n$ is greater in the solution with lower B value.

Normalised curves, y *vs.* x, were plotted from the glass electrode data up to $Z = 2.5$ for $t = 3$ in $Cd[Cd(HA)_t]_n$ and from $Z = 2.5$ to 2.75 for $t = 2$ and $r = 2$ in $(HA)_r[Cd(HA)_t]_n$, where $x = \log B + t \log [HA]$ and $y = Zt^{-1}$ and $x = \log B - r \log [HA]$ and $y = 1 + (t - Z)r^{-1}$ respectively, Figure 6. The points fell well on the curve for $y < 0.5$ in the first case and for practically all y values in the second, thus confirming the conclusions drawn from the MESAK method. Data from the cadmium amalgam electrode also fell satisfactorily on a normalised curve y *vs.* x for $y < 0.5$ where $y = \eta t^{-1}$ and $x = \log B + t \log [HA]$, Figure 7.

According to Sillén,[14] and assuming that the highest Z value for the $Cd[Cd(HA)_t]_n$ complexes and the lowest Z value for the $(HA)_r[Cd(HA)_t]_n$ complexes were in the range

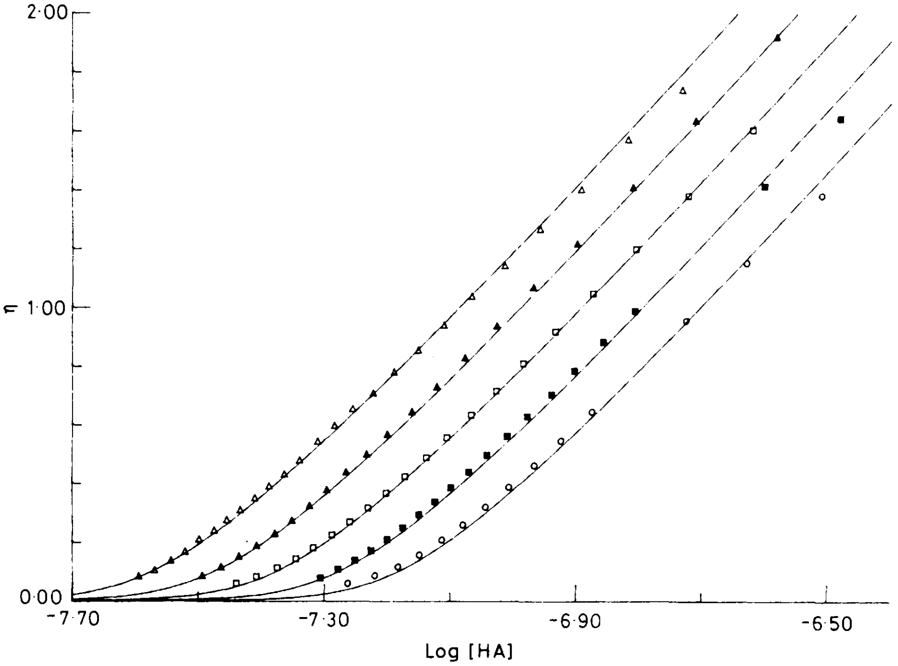


Figure 4. Set of curves η *vs.* concentration of free ligand, for $Cd_p(HA)_q$ species at different ligand: metal ratios, from the experimental data of the cadmium amalgam electrode. The lines drawn were calculated from the constants in the Table (for key to symbols see Figure 1)

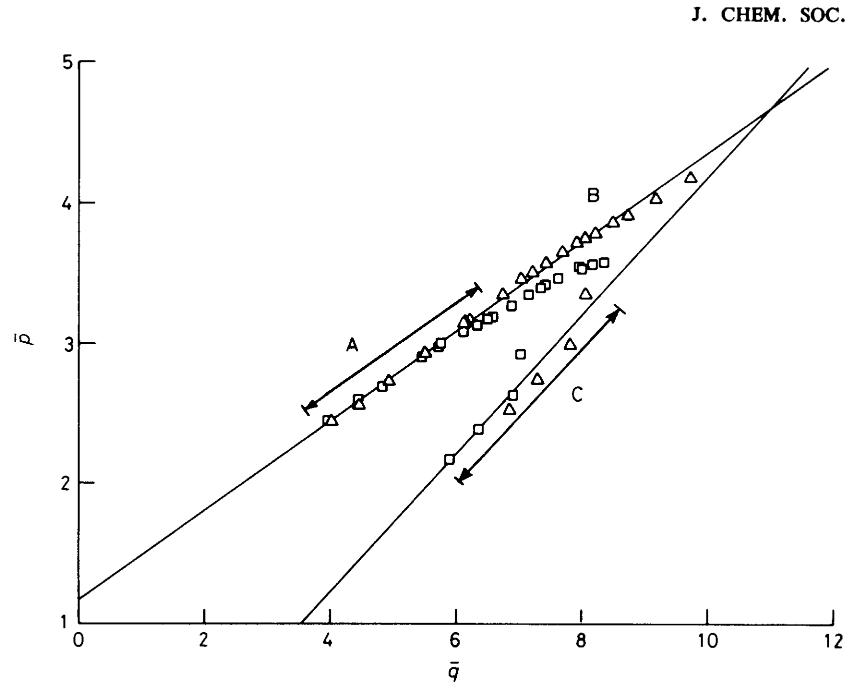


Figure 5. Average composition ($\bar{p},\bar{q}$) for $Cd_p(HA)_q$ species calculated from the glass electrode experimental data by the MESAK method. The straight lines were calculated by linear regression using 16 points (range A) and eight points (range C), respectively. Range B constitutes the remainder of the points (for key to symbols see Figure 1)

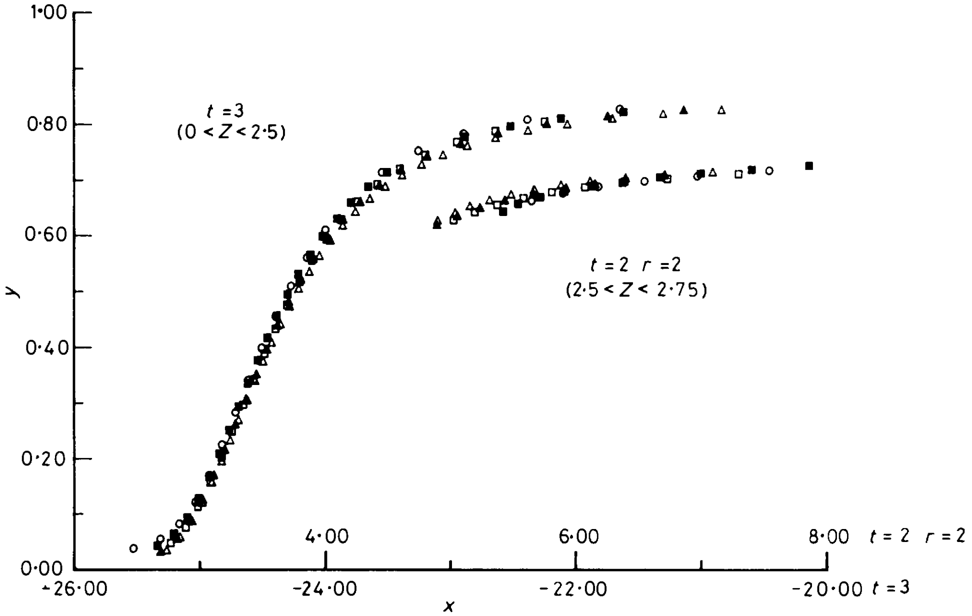


Figure 6. Normalised curves (x vs. y) for $Cd[Cd(HA)_t]_n$ complexes, taking $t = 3$; and for $(HA)_r[Cd(HA)_t]_n$ complexes, taking $t = 2$ and $r = 2$ at different ligand: metal ratios, from glass electrode experimental data (for key to symbols see Figure 1)

$2.45 \leqslant Z \leqslant 2.55$, it was found that the maximum value for p in $Cd_p(HA)_q$ should be either 4, 5, or 6.

In order to determine the set of $Cd_p(HA)_q$ species and equilibrium constants [equation (3)] for reaction (5) that best

$$pCd + qHA \rightleftharpoons Cd_p(HA)_q \qquad (5)$$

fit the experimental data, the program MINIQUAD 75 [16] was used in conjunction with a VAX/CMS computer.

First, only experimental data from the glass electrode measurements were taken into account. Complexes of formula $Cd[Cd(HA)_3]_n$ and $(HA)_2[Cd(HA)_2]_n$ for all positive integral values for n up to 5 were introduced in the first run together with the corresponding appropriate formation constants. These were estimated by assuming that they can be expressed as $\Psi_n = K_0K^n$.[15] The formation constants $\Psi_{2,3}$, $\Psi_{3,6}$, and $\Psi_{4,10}$ were calculated by assuming that at $Z = q/p$ the only existing species is $Cd_p(HA)_q$, then $[Cd_p(HA)_q] = ZB/q$. Free cadmium ion concentration was an experimental datum. By using $\Psi_{2,3} = K_0K^1$ and $\Psi_{3,6} = K_0K^2$ the constants K_0 and K can be calculated. Thus, $\Psi_{4,9}$, $\Psi_{5,12}$, and $\Psi_{6,15}$ can be determined. Analogously, using $\Psi_{4,10}$ and $\Psi_{5,12}$, the formation constants for the species belonging to the other 'core + links' series, $\Psi_{3,8}$, $\Psi_{2,6}$, and $\Psi_{1,4}$, can be estimated.

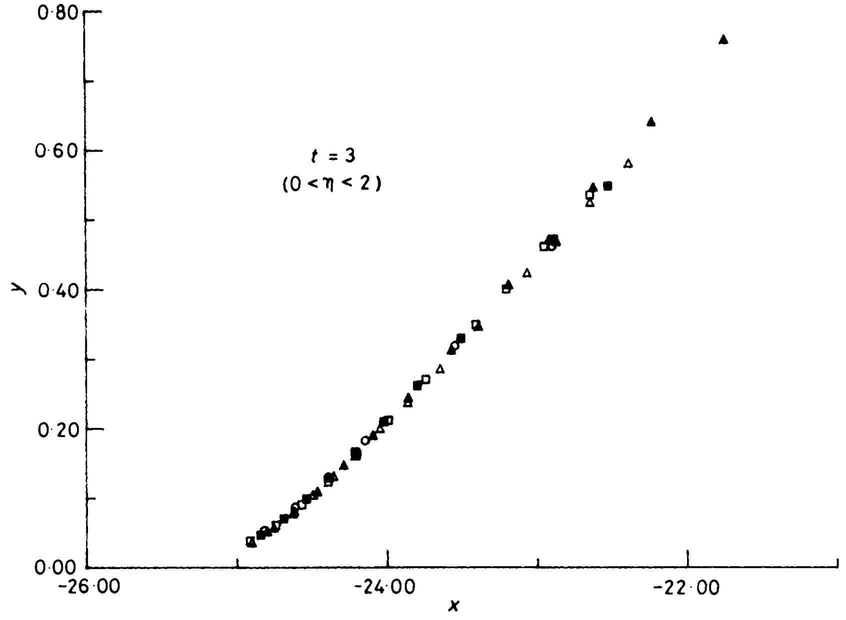


Figure 7. Normalised curve (x *vs.* y) for $Cd[Cd(HA)_t]_n$ complexes, taking $t = 3$ at different ligand: metal ratios, from experimental data of the cadmium amalgam electrode (for key to symbols see Figure 1)

Table. Cadmium complex formation constants from MINIQUAD-75, with standard deviations

	Glass electrode	Glass electrode + cadmium amalgam electrode
$[Cd_3(HA)_6]^{6+}$	$\log \psi_{3,6} = 48.59 \pm 0.02$	48.72 ± 0.04
$[Cd_4(HA)_9]^{8+}$	$\log \psi_{4,9} = 73.50 \pm 0.02$	73.51 ± 0.04
$[Cd_4(HA)_{10}]^{8+}$	$\log \psi_{4,10} = 80.48 \pm 0.01$	79.99 ± 0.09
$[Cd_3(HA)_8]^{6+}$	$\log \psi_{3,8} = 61.85 \pm 0.03$	—
$[Cd(HA)_4]^{2+}$	$\log \psi_{1,4} = 23.06 \pm 0.01$	—
Number of points	177	113
U^a	6.05×10^{-8}	2.39×10^{-6}
σ^b	1.07×10^{-5}	8.39×10^{-5}
R^c	0.001	0.008

[a] $U = \sum_{i=1}^{N} \sum_{j=1}^{M} [T_{ij}(\text{calc.}) - T_{ij}(\text{expt.})]$, where T_{ij} = analytical concentration of the jth component at the ith point, M = number of components, N = number of points. [b] σ = standard deviation of difference T_{ij}(calc.) − T_{ij}(expt.), with respect to the median value. [c] Crystallographic R factor.

About 40 different models of 'core + links' complexes, some of them including species that did not belong to the previously mentioned 'core + links' series, were tried. None of these models gave better results than those of the first run. The set of species and constants that gave the lowest values for U, σ, and R [16] are given in the Table. Results obtained using experimental data from the cadmium amalgam electrode are also given in the Table, although, in this case only points in which b is not negligible could be considered owing to the sensitivity of this electrode. The corresponding values found for U, σ, and R also reflect its lower accuracy.

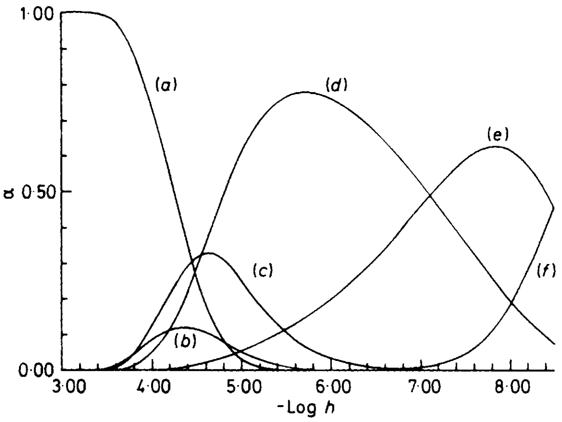


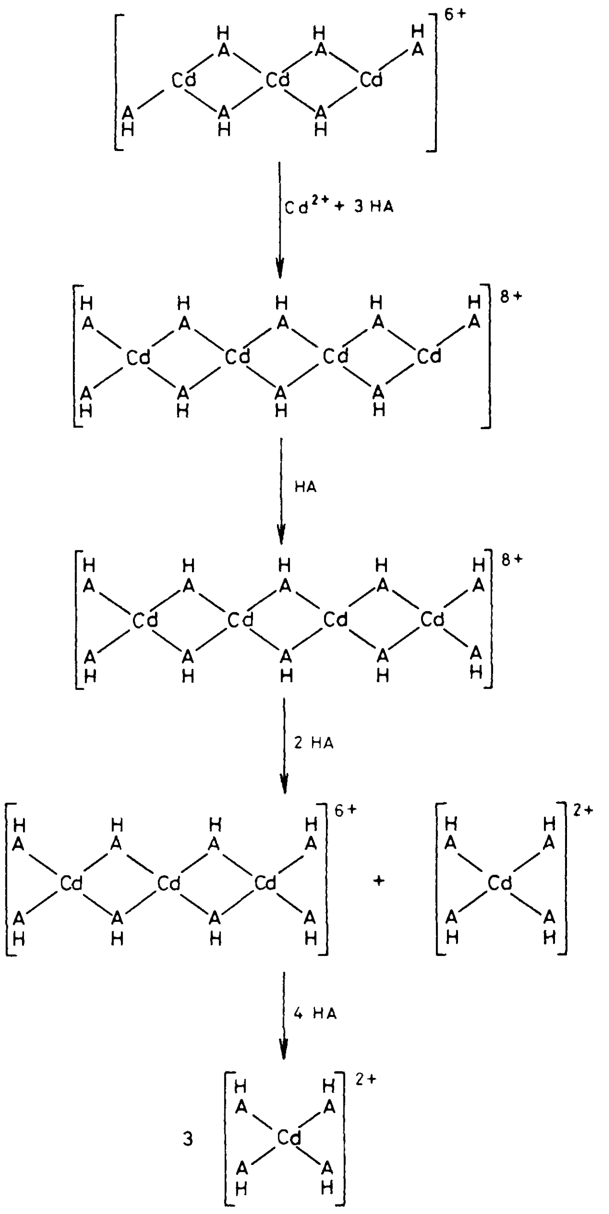
Figure 8. Concentration distribution of the complexes $[Cd_p(HA)_q]^{2p+}$ formed in the Cd^{II}–4-mercapto-1-methylpiperidine system. B = 6.4 mmol dm^{-3}, L = 25.18 mmol dm^{-3}: (a) $p = 1, q = 0$; (b) $p = 3$, $q = 6$; (c) $p = 4$, $q = 9$; (d) $p = 4$, $q = 10$; (e) $p = 3$, $q = 8$; and (f) $p = 1$, $q = 4$

Discussion

From the experimental data from both electrodes, 4-mercapto-1-methylpiperidine forms polynuclear complexes with Cd^{II} of the following formulae: $[Cd_3(HA)_6]^{6+}$, $[Cd_4(HA)_9]^{8+}$, $[Cd_4(HA)_{10}]^{8+}$, $[Cd_3(HA)_8]^{6+}$, and $[Cd(HA)_4]^{2+}$, the first two species belonging to a $Cd[Cd(HA)_3]_n$ 'core + links' series and the remainder to a $(HA)_2[Cd(HA)_2]_n$ series.

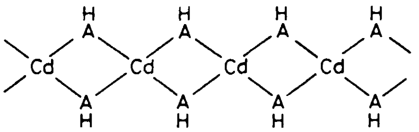
The final results agree well with deduction obtained from the graphical treatment of the experimental data and in particular explain the value found for t in $Cd[Cd(HA)_t]_n$ for $0 \leqslant Z \leqslant 2.4$. Owing to the fact that both series of complexes coexist in solution the theoretical value for t should be in the range $3.0 \leqslant t \leqslant 3.33$, the actual value depending on the amount of $[Cd_4(HA)_{10}]^{8+}$ present in solutions where the free cadmium ion concentration is not negligible. That is, the lower limit for t corresponds to its value in the series $Cd[Cd(HA)_3]_n$ and the upper one to its value in the series $[Cd_4(HA)_{10}]^{8+}$, which can be written as $Cd[Cd(HA)_{3.33}]_3$.

The fraction of Cd^{II} complexed in the various species $Cd_p(HA)_q$, $\alpha_{p,q}$, is shown as a function of log h in Figure 8 (for



Scheme.

$B = 6.4$ mmol dm^{-3} and $L = 25.18$ mmol dm^{-3}). From these distribution curves predominance of the species $[Cd_4(HA)_{10}]^{8+}$ in a wide pH range is clear. Noting that it was not possible to avoid solid formation if $B > 6.5$ mmol dm^{-3} and that the structure of the complex $[Cd(HA)_2][ClO_4]_2{\cdot}2H_2O$ consists of polymeric chains [8] as indicated below, it seems reasonable to



consider that $[Cd_4(HA)_{10}]^{8+}$ is a finite polymeric chain with four metal atoms.

It also seems reasonable to propose that in those solutions where the free Cd^{II} concentration is not negligible the species present also have a linear polymeric structure in which some co-ordination sites of the cadmium are not occupied by sulphur atoms. When the free Cd^{II} concentration decreases these positions become occupied by ligand molecules, thus forming the species $[Cd_4(HA)_{10}]^{8+}$, which, when the free ligand concentration increases, starts to split to give finally the mononuclear species $[Cd(HA)_4]^{2+}$. In the range of concentrations studied the species $[Cd_5(HA)_{12}]^{10+}$ has not been detected despite the fact that it should be the bridge between both 'core + links' sets and that it is present for the Zn^{II} species.[10] When compared with the Zn^{II} complex species, the insolubility of the infinite polymeric chain, $[Cd(HA)_2]_n^{2n+}$, may account for the absence of $[Cd_5(HA)_{12}]^{10+}$.

The mechanism of formation and geometry of the species may be as suggested in the Scheme.

The results obtained with the same ligand and Zn^{II}[10] compare well with those of Cd^{II}. The solubility of Zn^{II} complexes allows the formation of the species $[Zn_5(HA)_{12}]^{10+}$ which is the one found with highest nuclearity in the 'core + links' series. This fact supports the assumptions made about the structure of the soluble Cd^{II} and Zn^{II} complexes, since a nuclearity greater than that of $[Zn_5(HA)_{12}]^{10+}$ would not be compatible with linear polymeric species similar to that found in $[Cd(HA)_2][ClO_4]_2{\cdot}2H_2O$.[8] The same type of structure has been found in the complex $[Cd\{SCH_2C(O)OEt\}_2]$ very recently.[2] However, cluster type structures have also been reported for Zn^{II}[17] and Cd^{II}[5] thiolate complexes.

In view of these results with 4-mercapto-1-methylpiperidine it seems much easier to intepret the behaviour of thiol ligands in solutions containing Cd^{II} or Zn^{II} than with thioalcohols.[3,4]

Acknowledgements

This work was supported by the Comisión Asesora Científica y Técnica (Spain).

References

1 J. H. R. Kägi, Y. Kojima, M. M. Kissling, and K. Lerch, 'Metallothionein,' eds. J. H. R. Kägi and M. Nordberg, Birkhäuser, Basel, 1980, p. 223.
2 I. G. Dance, M. L. Scudder, and R. Secomb, *Inorg. Chem.*, 1983, **22**, 1794.
3 G. Schwarzenbach, K. Gautschi, J. Peter, and K. Tunaboylu, *Trans. R. Inst. Technol., Stockholm*, 1972, 295.
4 H. F. De Brabander and L. V. Van Poucke, *J. Coord. Chem.*, 1974, **3**, 301.
5 S. Lacelle, W. C. Stevens, D. M. Kurtz, jun., J. W. Richardson, jun., and R. A. Jacobson, *Inorg. Chem.*, 1984, **23**, 930.
6 W. Gaete, J. Ros, X. Solans, M. Font-Altaba, and J. L. Briansó, *Inorg. Chem.*, 1984, **23**, 39.
7 M. C. Briansó, J. L. Briansó, W. Gaete, J. Ros, and C. Suñer, *J. Chem. Soc., Dalton Trans.*, 1981, 852.
8 J. C. Bayón, M. C. Briansó, J. L. Briansó, and P. González-Duarte, *Inorg. Chem.*, 1979, **18**, 3478.
9 H. Barrera, J. C. Bayón, P. González-Duarte, J. Sola, J. M. Viñas, M. C. Briansó, J. L. Briansó, and X. Solans, *Polyhedron*, 1982, **1**, 647.
10 J. C. Bayón and P. González-Duarte, *J. Chem. Soc., Dalton Trans.*, 1982, 487.
11 J. C. Bayón, E. Forrellad, and J. Vives, International MINIQUAD users' meeting, Pontignano, Italy, June 1983.
12 H. Barrera, J. C. Bayón, P. González-Duarte, J. Sola, and J. Vives, *Talanta*, 1983, **30**, 537.
13 A. S. Brown, *J. Am. Chem. Soc.*, 1934, **56**, 646.
14 L. G. Sillén, *Acta Chem. Scand.*, 1954, **8**, 299.
15 L. G. Sillén, *Acta Chem. Scand.*, 1954, **8**, 318.
16 P. Gans, A. Sabatini, and A. Vacca, *Inorg. Chim. Acta*, 1976, **18**, 237.
17 J. L. Hencher, M. Khan, F. F. Said, and D. G. Tuck, *Inorg. Nucl. Chem. Lett.*, 1981, **27**, 287.

Received 29*th December* 1983; *Paper* 3/2277