

A Multinuclear (^1H , ^{13}C , ^{113}Cd) Nuclear Magnetic Resonance and Magnetic Circular Dichroism Spectroscopic Study of Thiolate Complexes of Cadmium

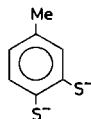
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Appropriate combinations of ^1H , ^{13}C and ^{113}Cd NMR have been used to study ca. 0.05 M solutions of a wide range of ^{113}Cd -enriched thiolatocadmates formed from the corresponding poorly soluble cadmium thiolates in the presence of excess thiolate. In addition, MCD spectra have been recorded for dilute, ca. 10^{-5} M, solutions of a representative set of thiolate complexes of cadmium.

Cadmium-113 chemical shifts are given for the complexes formed by 31 different thiolates individually in water at ambient probe temperature, and slow-exchange ^1H and/or ^{13}C and/or ^{113}Cd NMR spectra are reported for several typical complexes at reduced temperature in CD_3OD . In aqueous solution at ambient probe temperature, ligands with vicinal thiolate groups



and $^-\text{SCH}_2\text{CHRS}^-$ ($R = \text{H, Me, Et, CH}_2\text{OH, CH}_2\text{SO}_3^-$ or CH_2S^-) form bis(chelate) complexes which have $\delta_{\text{Cd}} \geq 778$ ppm, less shielded than the range for tetrahedral $\text{Cd}(\text{SR})_4^{2-}$ ($R = \text{Me, Et, Pr, Me}_2\text{CH, Bu, EtMeHC, Ph, PhCH}_2, \text{CH}_2\text{CH}_2\text{X}$ ($X = \text{OH, NH}_2, \text{ or CO}_2^-$), $\text{CH}_2\text{CH}(\text{OH})\text{Me, CH}_2\text{CH}(\text{OH})\text{CH}_2\text{OH, L-CH}_2\text{CH}(\text{NH}_2)\text{CO}_2^-$, or CH_2CO_2^- for which $\delta_{\text{Cd}} < 666$ ppm. Increasing alkyl substitution in the α -position causes increasing shielding of the cadmium resonance for both the chelate complexes and the complexes of monodentate thiolates.

Separate ^{113}Cd and, in some cases, ^1H resonances have been found for members of the series $[\text{Cd}(\text{SR})_n(\text{SR}')_{4-n}]^{2-}$ ($R = \text{Me, R}' = \text{CHMe}_2; R = \text{Ph, R}' = \text{CH}_2\text{Ph; } n = 0-4$) and $[\text{Cd}(\text{S}(\text{CH}_2)_2\text{S})_{n/2}(\text{SCHMe}_2)_{4-n}]^{2-}$ ($n = 0, 2, \text{ or } 4$) at low temperature: ^{113}Cd chemical shifts change additively or near-additively in these series.

The MCD data indicate that in most of the complexes formed at the ca. 10^{-5} M concentrations used for the optical studies, the local microsymmetry about the cadmium approaches tetrahedral. Specifically, the complexes $[\text{Cd}(\text{SR})_{2.5}]_n^{0.5n-}$ ($R = \text{Me, Et, or Pr}$) exhibited well-resolved, symmetric A terms under the $\text{S} \rightarrow \text{Cd}$ charge transfer band in the 250 nm region. Complexes of the dithiolates $^-\text{S}(\text{CH}_2)_n\text{S}^-$ ($n = 2, 3, \text{ or } 4$) and $^-\text{SCH}_2\text{CHMeS}^-$ gave MCD spectra which were much broader and less well-resolved. The spectra of the systems containing the vicinal dithiolates showed the formation of two complexes, as the band centre of the MCD signal blue-shifted when L/M was increased from 1 to 2; at $L/M = 2$, bis-(dithiolate) complexes are most likely formed. With the ligand $^-\text{SCH}_2\text{CHCH}_2\text{OH}$ (BAL), the corresponding spectra were similar at $L/M = 2$ but quite different at $L/M = 1$. A B term centred on the 250 nm charge transfer band was observed for the solution where $\text{BAL}/\text{Cd} = 1$, demonstrating loss of tetrahedral symmetry about cadmium, probably due to ligation by the ligand hydroxyl group.

These studies provide ^{113}Cd NMR and MCD 'fingerprint' data necessary for the interpretation of the corresponding spectra of related and more complicated, biologically important cadmium complexes.

Introduction

A very important part of the chemistry of divalent cadmium involves its interaction with the soft donor atom sulfur. An understanding of the coordination of cadmium by simple sulfur ligands is vital to an understanding of the way this toxic Group IIB element interacts with environmental and biological ligand systems. The extensive literature concerning complexes of cadmium, mercury and the methylmercuric ion with sulfur-containing amino-acids has been reviewed lately [1], and a companion review covers complexation of the mercuric and methylmercuric ions by certain thiolates and dithiolates [2]. Surprisingly, however, simple, soluble, mononuclear,

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binary thiolatocadmates have received little study, though they are essential models for complexes of cadmium with more complicated sulfhydryl-containing ligands. Schwarzenbach *et al.* [3] have suggested the formation of $\text{Cd}(\text{SCH}_2\text{CH}_2\text{OH})_4^{2-}$ in solutions of $\text{Cd}(\text{ClO}_4)_2$ and $\text{HSCH}_2\text{CH}_2\text{OH}$ at high L/M and pH, but have not studied this complex further; at intermediate $\text{SCH}_2\text{CH}_2\text{OH}/\text{Cd}^{2+}$ ratios, decanuclear species are formed, one of which, $\text{Cd}_{10}(\text{SCH}_2\text{CH}_2\text{OH})_{16}^{4+}$, has been characterized in the solid state by X-ray analysis [3], and scrutinized in solution by variable temperature ^{113}Cd NMR [4]. ^{113}Cd NMR was also used to study the complex $\text{Cd}(\text{SCH}_2\text{CH}_2\text{OH})_n(\text{DMSO})_x^{(n-2)-}$ ($n \geq 4$, $x \geq 0$), a product of the dissolution of polymeric [5] $\text{Cd}(\text{SCH}_2\text{CH}_2\text{OH})_2$ in DMSO, and the maleonitriledithiolato complex, $\text{Cd}(\text{mnt})_2^{2-}$, in the same solvent [4]. The structure of the $\text{Cd}(\text{mnt})_2^{2-}$ anion in the solid state has not been reported to our knowledge, and the structure of this complex in the DMSO solution could not be found with certainty: a mononuclear complex with tetrahedral coordination of cadmium was one of several possibilities considered.

We present here the results of a study of a range of thiolatocadmates in which the ligands are alkyl thiolates or dithiolates, propanetrithiolate, or other related simple thiolate-containing ligands. As investigative probes we have used multinuclear (^1H , ^{13}C , ^{113}Cd) NMR, UV and MCD spectroscopies. The ^{113}Cd NMR results usefully complement and extend the earlier ^{113}Cd data of Holm and coworkers [4] on cadmium sulfur complexes, as well as providing 'fingerprint' data of import to an understanding of the very complicated ^{113}Cd NMR spectra of the sulfur-rich metal binding protein metallothionein which have been observed by several groups [6–9]. Similarly, the MCD spectra of the simple thiolato complexes are useful for comparison with the MCD spectra of cadmium metallothionein that have been reported from one of our laboratories [10]. (Because of the broad and overlapping nature of the absorption bands of the cadmium-thiolate chromophore, MCD is more sensitive than absorption spectroscopy to the symmetry and electronic structure of the chromophore.) In addition, our results have been evaluated in the context of chelation therapy for cadmium-intoxicated rats [11].

Experimental

Materials

Cadmium nitrate of certified quality was purchased from Fisher Scientific Company. ^{113}CdO (96.3 atom% ^{113}Cd), from Merck Sharp and Dohme Canada Ltd., or Oak Ridge National Laboratory, was converted to the nitrate for the ^{113}Cd NMR studies.

1,2-Propanedithiol and 1,2- and 1,4-butanedithiols were obtained from Chemical Procurement Labs, and 1,2,3-propanetrithiol from the Parish Chemical Company. All other ligands were purchased from the Aldrich Chemical Company. All the thiols gave satisfactory NMR spectra (^1H and/or ^{13}C) and were used as received.

Deuterated solvents, with or without ^{13}C depletion, were from Merck Sharpe and Dohme Canada.

Physical Measurements

a) NMR Spectra

All the NMR spectra were measured using a Varian XL-100-12 Spectrometer System operating at 100.10, 25.16 and 22.19 MHz for ^1H , ^{13}C and ^{113}Cd , respectively. All the spectra are reported with increasing chemical shift corresponding to increasing frequency. Proton spectra were obtained using the CW mode, and ^{13}C (with and without ^1H decoupling) and ^{113}Cd spectra using the FT mode. (No proton decoupling was used for the ^{113}Cd spectra as a negative Overhauser effect is expected.) Typically, acceptable ^{13}C - $\{^1\text{H}\}$ spectra of samples with $[\text{L}] \approx 0.4$ M could be obtained in several hours using a 15° tip angle, 3.3 s acquisition time, a 5 kHz spectral window and a 3.5 s cycle time; for ^{113}Cd NMR of samples with $[\text{L}] = 0.05$ M, the corresponding settings were 18° , 1 s, 10 kHz and 3.6 s.

Assignments in the ^{13}C NMR spectra were made from the coupled spectra obtained by the usual gated decoupling technique. (We could find no literature spectra of thiolates.)

Samples for ^1H NMR were contained and run in 5 mm od NMR tubes in the conventional manner, while both the ^{13}C and ^{113}Cd NMR samples were prepared in hand made 10 mm od tubes which were run mounted coaxially in a 12 mm od NMR tube as described earlier [12]. For the ^{113}Cd NMR spectra measured at ambient probe temperature, D_2O in the outer annulus was used as a lock substance, while $(\text{CD}_3)_2\text{CO}$ was used similarly for reduced temperature spectra.¹ At room temperature, the spectra were referenced by sample interchange with aqueous 4 M $\text{Cd}(\text{NO}_3)_2$ for which a resonance is observed with a single 90° pulse. ($\delta_{0.1\text{ M Cd}(\text{ClO}_4)_2} = \delta_{4\text{ M Cd}(\text{NO}_3)_2}$, -65 ppm [13].) No completely satisfactory reference for low temperature ^{113}Cd NMR was found, and in any case the shifts of the mixed complexes appeared to be somewhat sensitive to solution composition, so the data in Tables 3 and 4 are reported using the signal from a suitable complex as a primary internal reference. It is clear from the instrument settings that for a given complex the

¹ $(\text{CD}_3)_2\text{CO}$ was the preferred lock substance even for CD_3OD solutions because the methanol becomes viscous at the temperatures used but the $(\text{CD}_3)_2\text{CO}$ remains mobile.

^{113}Cd chemical shift is not greatly different at low temperature in CD_3OD from its value at 308 K. For the reduced temperature ^{13}C spectra, either the solvent residual signal, or the residual signal from $(\text{CD}_3)_2\text{CO}$ when used as an external lock substance, or, for MeS^- -containing samples, Me_2CO briefly inserted in the outer annulus, was used as a primary reference, as appropriate for the particular sample. (At 193 K, $\delta_{\text{c}}(\text{TMS}(\text{int})) = \delta_{\text{c}}(\text{CD}_3\text{OD}(\text{int})) + 48.9 \text{ ppm} = \delta_{\text{c}}(\text{CH}_3)_2\text{CO}(\text{ext}) + 31.3 \text{ ppm}$.)

b) Optical Spectra

Absorption spectra were recorded on either a Cary 118 or a Cary 219 Spectrometer. Magnetic circular dichroism spectra were recorded on a Jasco J5 spectrometer with a Sproul SS20 modification using an Oxford Instruments SM2 superconducting magnet operating at 5.5 T. The spectrometer was calibrated as described previously [14]. The MCD band of aqueous CoSO_4 at 510 nm had an intensity value, given as $[\theta]_{\text{M}}$, of $-62.6 \text{ deg cm}^2 \text{ dmol}^{-1} \text{ T}^{-1}$. Except where noted otherwise, cuvettes of 1 cm pathlength were used throughout.

Sample Preparation

All solvents used were deaerated with argon or nitrogen, and all manipulations carried out either in airless ware or in a glove bag flushed with argon or nitrogen, or, for MeSH transfers, using a vacuum line. All NMR samples were flame sealed. Samples for optical spectroscopy were stoppered tightly and showed no evidence of ligand oxidation during the time of the experiment.

a) NMR Samples

The ^1H NMR samples were prepared by mixing CD_3OD solutions of NaSR (itself produced *in situ* from solutions of RSH and a two fold excess of CD_3ONa in CD_3OD) and cadmium nitrate. The final concentration of thiolate groups was 0.1 M. TMS was added as internal reference.

Samples for reduced temperature ^{13}C or ^{113}Cd spectroscopy were prepared like the proton samples, except that for ^{13}C samples of alkylthiolates $^{12}\text{CD}_3\text{OD}$ was used as solvent. Cadmium-113 samples for ambient probe temperature measurements were prepared similarly, but using water as solvent and NaOH to produce the thiolate. All the ^{113}Cd samples had (total thiolate):Cd ratios of 12, to maintain an approximately constant ionic strength, except that 1,2,3-propanetrithiolate was used at a trithiolate:Cd ratio of 6 ((total thiolate):Cd = 18) with a correspondingly higher base concentration to ensure complete ionization.² The pH of the aqueous ^{113}Cd

² A D_2O solution made up with 1,2,3-propanetrithiol: $\text{OD}^- = 6$ showed no unionized $-\text{SH}$ by ^1H NMR. (Proton exchange between ionized and unionized $-\text{SH}$ groups is slow on the NMR timescale.)

samples was thus *ca.* 13 for most samples, slightly higher for the trithiolate-containing samples.

b) Samples for UV and MCD

Stock thiolate solutions were prepared in triply distilled water using thiol group: $\text{OH}^- = 2$. The solutions for spectroscopy were prepared by mixing appropriate volumes of the stock thiolate solution and a stock cadmium solution ($\sim 10^{-4} \text{ M}$); the spectra were recorded immediately. The pH was typically 10.0–10.5.

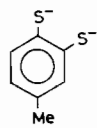
Preparation of Insoluble Cadmium Thiolates

Addition of 2 mol of thiolate groups, produced in an aqueous solution with $\text{OH}^-/\text{thiol group} = 2$, to 1 mol of $\text{Cd}(\text{NO}_3)_2$ in aqueous solution, resulted in immediate precipitation of the neutral thiolates.³ The insoluble products, which were white except for the complex of toluene-3,4-dithiolate, which was yellow, were filtered off, washed with water and dried *in vacuo*. Analytical data for the new compounds are given in Table 1. Satisfactory analytical data could not be obtained for the product which precipitated S^- from $\text{Cd}^{2+} - \text{SCH}_2\text{CHCH}_2\text{S}^-$ at L/M = 2/3.

Elemental Microanalyses

These were performed by Guelph Chemical Laboratories Ltd.

TABLE I. Analyses of Some Cadmium Thiolates, $\text{Cd}(\text{SR})_2$.

$(\text{RS}^-)_2$	Analysis Found (Calcd) %	
	C	H
$(n\text{-C}_3\text{H}_7\text{S}^-)_2$	26.89 (27.44)	5.70 (5.34)
$(n\text{-C}_4\text{H}_9\text{S}^-)_2$	32.88 (33.05)	6.31 (6.20)
$(n\text{-C}_5\text{H}_{11}\text{S}^-)_2$	36.91 (37.69)	6.85 (6.91)
$^-\text{SCH}_2\text{CH}_2\text{S}^-$	11.61 (11.74)	1.98 (1.96)
$^-\text{SCH}_2\text{CH}_2\text{CH}_2\text{S}^-$	15.91 (16.48)	2.99 (2.75)
	28.91 (31.53)	2.40 (2.25)

³ Precipitation of the neutral thiolates followed by decomposition with HNO_3 is a satisfactory way to recover ^{113}Cd -enriched cadmium.

Results and Discussion

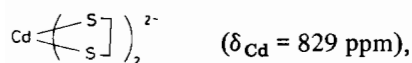
NMR Studies

The compounds $\text{Cd}(\text{SR})_2$ prepared here (e.g. Table I) and those prepared earlier by others ($\text{R} = \text{Et}$, and Bu^t [15]; $\text{R} = \text{Ph}$ [16]) have low solubility in H_2O or MeOH . However all except $\text{Cd}(\text{SBu}^t)_2$ are solubilized by addition of an approximately four molar excess of thiolate. The soluble thiolatocadmates, normally produced *in situ* from $\text{Cd}(\text{NO}_3)_2$ and excess thiolate, have been studied by ^{113}Cd , ^{13}C and ^1H NMR.

a) ^{113}Cd NMR

i) Chemical Shifts

The thiolatocadmates exhibit ^{113}Cd resonances greatly deshielded relative to the octahedral $\text{Cd}(\text{OH}_2)_6^{2+}$ cation, as shown by the data in Table II. The extensive deshielding caused by coordination of sulfur ligands to cadmium has been noted by several groups of workers [e.g. Refs 4, 17–20]. The least shielded resonance we observe, that of



has a chemical shift similar to that of the least shielded resonance observed by Holm and coworkers [4], that of $\text{Cd}(\text{mnt})_2^{2-}$ ($\delta_{\text{Cd}} = 813 \text{ ppm}$).

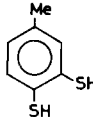
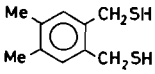
The complexes of aliphatic monothiolates give cadmium chemical shifts in the range $\delta_{\text{Cd}} = 662\text{--}663 \text{ ppm}$. The data in Table 2 demonstrate a substituent effect corresponding to a shielding of ca. 15–20 ppm per alkyl substituent in the α -position. Thus the complex of MeEtHCS^- has the most shielded resonance of the alkylthiolate complexes ($\delta_{\text{Cd}} = 622 \text{ ppm}$), and the MeS^- complex the least shielded resonance ($\delta_{\text{Cd}} = 663 \text{ ppm}$). The effect, if any of β alkyl substitution is much smaller. The ligands having a hydroxyl, amine, or carboxylate group (or both $-\text{NH}_2$ and $-\text{CO}_2$ for the cysteinate) in the β -position give complexes with chemical shifts a little larger than in the complexes of the unsubstituted aliphatic analogs, but clearly in the same range, suggesting very strongly that, at the pH used for our study, only the thiolate donor site is bound to cadmium. This is consistent with the preferential binding series demonstrated by Rabenstein and Fairhurst [21] for MeHg^+ as an acceptor. It is probable that the highly deshielded ^{113}Cd resonance ($\delta_{\text{Cd}} = 610 \text{ ppm}$ in a rapidly exchanging system) observed by Birgersson *et al.* [18] for a solution where glutathione/ $\text{Cd} = 4$, $\text{pD} = 7.90$, is from a mixture where the major species involves binding to cadmium *via* thiolate only. Similarly our results support the suggestion [22] that the 751 ppm ^{113}Cd resonance of ^{113}Cd -substituted horse-liver alcohol dehydrogenase is from a site involving coordinated thiolates (of cysteine residues) only.

In terms of its substituent effect on δ_{Cd} , a phenyl group in the α -position (in the PhCH_2S^- complex) behaves like an alkyl substituent, but perhaps not unexpectedly, the $^-\text{SCH}_2\text{CO}_2^-$ complex has a chemical shift which is unique but still probably indicative of bonding by thiolates only (and not the CdS_2O_2 kernel suggested earlier for a thiolate-rich solution [17]). Similarly, and not unexpectedly, the PhS^- complex has a unique chemical shift. The complex of $\text{D}^-\text{SCMe}_2\text{CH}(\text{NH}_2)\text{CO}_2^-$ has a chemical shift which, by analogy with the L-cysteinate complex, is anomalously small, perhaps indicating that the steric crowding around the sulfur in the D-penicillaminato ligand prevents ligation by sulfur alone. In this context it should be noted again that we could not prepare thiolatocadmates of the sterically demanding Bu^tS^- .

The shift that we observe for the complex of $^-\text{SCH}_2\text{CH}_2\text{OH}$ is close to that measured for $\text{Cd}(\text{SCH}_2\text{CH}_2\text{OH})_n(\text{DMSO})_x^{(n-2)-}$ ($\delta_{\text{Cd}} = 655 \text{ ppm}$ [4]) and evidently the same species is being produced in this and the earlier work. On the other hand, the resonances observed earlier for the $\text{Cd}_{10}(\text{SCH}_2\text{CH}_2\text{OH})_{16}^{4+}$ cation ($\delta_{\text{Cd}} = 515$ and 382 ppm [4]) are extensively shielded from those we observed here for thiolatocadmates. Under the conditions of our experiment we do not expect thiolate bridging between metals to occur, whereas all the ligands of the decanuclear cation are involved in sulfur bridging [3]. Evidently, ligation of cadmium by the sulfur atoms of bridging thiolates does not cause such extensive deshielding as produced by coordination of terminal thiolates. It is important to note that even the least shielded cadmium resonance of $\text{Cd}_{10}(\text{SCH}_2\text{CH}_2\text{OH})_{16}^{4+}$ does not exemplify what is to be expected from a typical discrete CdS_4 moiety.

Complexes of ligands having vicinal thiolate groups give resonances in the region 778–829 ppm, deshielded significantly from the range observed for the other thiolate complexes. Within this range, the substituent effects on the resonances of the aliphatic dithiolates are qualitatively similar to those observed for the monothiolates (see above). Also it is again clear that, at the high pH of the solutions used, no other potential donor sites on the ligand compete with the thiolate site for coordination to cadmium. The toluenedithiolate is shown by ^{13}C NMR to behave as a chelate (see later), and similarly ^1H NMR, and ^{113}Cd NMR of the system $\text{Cd}^{2+}\text{--S}(\text{CH}_2)_2\text{S}^-\text{Me}_2\text{HCS}^-$, verify chelate behaviour by the ethanedithiolate (see below). Almost certainly the other vicinal dithiolates (including mnt^- studied earlier [4]) coordinate in a bidentate manner also. From the rather limited data available (see above and below) we tentatively suggest that the large chelate effect on ^{113}Cd chemical shifts is specific for complexes containing five-membered chelate rings (as is the deshielding of ^{13}P in five-membered rings, e.g. Refs.

TABLE II. ^{113}Cd NMR Data for Some Cadmium(II) Thiolate Complexes in Water at 308 K^{a,b}.

Parent Thiol	L/M in complex ^c	(ppm) ^d	Approximate natural $\nu_{\frac{1}{2}}(\text{Hz})$
<i>Monothiols</i>			
CH_3SH	4	663	4
$\text{C}_2\text{H}_5\text{SH}$	(4)	648	4
$n\text{-C}_3\text{H}_7\text{SH}$	(4)	647	7
$n\text{-C}_4\text{H}_9\text{SH}$	(4)	644	12
$(\text{CH}_3)_2\text{CHSH}$	4	625	10
$\text{C}_2\text{H}_5\text{CH}(\text{CH}_3)\text{SH}$	(4)	622	12
$\text{C}_6\text{H}_5\text{CH}_2\text{SH}$	4	646	10
$\text{HSCH}_2\text{CH}_2\text{OH}$	(4)	666, 655 ^e	4, -
$\text{HSCH}_2\text{CH}_2\text{NH}_2$	(4)	659	4
$\text{HSCH}_2\text{CH}_2\text{COOH}$	(4)	660	4
$\text{HSCH}_2\text{CH}(\text{OH})\text{CH}_3$	(4)	659	9
$\text{HSCH}_2\text{CH}(\text{OH})\text{CH}_2(\text{OH})$	(4)	658	9
$\text{HSCH}_2\text{CH}(\text{NH}_2)\text{CO}_2^-[\text{L}]$	(4)	623	10
$\text{HSC}(\text{CH}_3)_2\text{CH}(\text{NH}_2)\text{CO}_2^-[\text{D}]$? ^f	577	10
HSCH_2COOH	(4)	601, 620 ^g	15, -
$\text{C}_6\text{H}_5\text{SH}$	4	583	7
<i>Dithiols</i>			
a) <i>Vicinal dithiols</i>			
$\text{HSCH}_2\text{CH}_2\text{SH}$	2	829	9
$\text{HSCH}_2\text{CH}(\text{CH}_3)\text{SH}$	(2)	780	47
$\text{HSCH}_2\text{CH}(\text{C}_2\text{H}_5)\text{SH}$	(2)	780	9
$\text{HSCH}_2\text{CH}(\text{SH})\text{CH}_2\text{OH}$	(2)	782	15
$\text{HSCH}_2\text{CH}(\text{SH})\text{CH}_2\text{SO}_3^-$	(2)	786	12
	(2)	796	4
$\text{HSCH}_2\text{CH}(\text{SH})\text{CH}_2(\text{SH})$	(2)	778	27
$(\text{NC}_2\text{C}(\text{SH})_2)_2$	2	813 ^e	-
$\text{HSCH}_2\text{CH}(\text{SH})\text{CH}_2(\text{SH})$ $(\text{NC})_2\text{C}_2(\text{SH})_2$			
b) <i>Others</i>			
$\text{HSCH}_2\text{CH}_2\text{CH}_2\text{SH}$	(3?) ^f	663	9
$\text{HSCH}_2\text{CH}(\text{OH})\text{CH}_2\text{SH}$	(3?)	685	32
$\text{HSCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{SH}$?	648	37
$\text{HSCH}_2[\text{CH}(\text{OH})]_2\text{CH}_2\text{SH}$ [erythro]	?	674	17
$\text{HSCH}_2[\text{CH}(\text{OH})]_2\text{CH}_2\text{SH}$ [threo]	?	673	27
$\text{HS}(\text{CH}_2)_5\text{SH}$?	646	12
	?	631	22

^aThis work unless otherwise noted. ^bIn this work, $[^{113}\text{Cd}] = 0.05 \text{ M}$; $\text{RS}^-/\text{Cd} = 12$ except for 1,2,3-propanetrithiolate (see Experimental Section). ^cParenthesized stoichiometries derived by comparison of δ_{Cd} with complexes of known stoichiometry, except where noted. ^dRelative to external $0.1 \text{ M Cd}(\text{ClO}_4)_2$. Measured from external $4 \text{ M Cd}(\text{NO}_3)_2$ and converted using $\delta_{0.1 \text{ M Cd}(\text{ClO}_4)_2} = \delta_{4 \text{ M Cd}(\text{NO}_3)_2} - 65 \text{ ppm}$ [13]. Decreasing shielding corresponds to increasing chemical shift. ^eIn DMSO; from Ref. 4 (see text). ^fSee text for discussion of this species. ^gFrom Ref. 17 for a solution with $\text{Cd: HSCH}_2\text{CO}_2\text{H} = 1:5$, pH 10.6, but assigned to a CdS_2O_2 kernel.

23 and 24). However, the chemical shifts of the other α, ω -dithiolate complexes show that they contain the same CdS_4 kernel as the complexes of monothiolates, though the behaviour of the longer chain dithiolates may be complicated (see below). Nonetheless it is noteworthy that only those ligands which could form five membered rings gave resonances in a range quite distinct from the range observed for the monothiolate complexes. This observation may be useful as a screening device: of the ligands studied in this work, all those capable of mobilizing cadmium bound biologically as cadmium–thionein [11] gave resonances in the higher frequency group, *i.e.* were capable of behaving as chelates.

The ^{113}Cd resonances observed for cadmium–thioneins from various sources fall in the approximate range 580–670 ppm [6–9]. Comparison with our results for the model thiolatocadmates and the results of Holm and coworkers for the extensively bridged $\text{Cd}_{10}(\text{SCH}_2\text{CH}_2\text{OH})_{16}^{4+}$, suggests that in the metalloprotein bridging by the cysteinate sulfur atoms is not extensive. However ^{113}Cd – ^{113}Cd coupling between cadmium ions in some of the sites of the ^{113}Cd -enriched protein has been observed [6c], indicating that at least some of the metal ions must be in close proximity.

ii) Slow-Exchange Spectra of Some Thiolatocadmates with Mixed Thiolate Ligands

Four ternary systems of the general type Cd^{2+} – RS^- – $\text{R}'\text{S}^-$ were studied by reduced temperature ^{113}Cd NMR. The particular ligand combinations were chosen firstly to try and obtain information about the stoichiometry and structures of complexes with some of the simpler representative thiolates from Table II, in cases where this could not be obtained unambiguously by other means, and secondly, for practical reasons, using the results in Table II as a basis, to provide a reasonable spread of chemical shifts for the mixed complexes.

The results for the systems Cd^{2+} – MeS^- – Me_2HCS^- and Cd^{2+} – $^-\text{S}(\text{CH}_2)_2\text{S}^-$ – Me_2HCS^- are given in Table III, and those for the system Cd^{2+} – PhS^- – PhCH_2S^- in Table IV. These mixed-ligand systems give very broad, sometimes unobservable signals at ambient probe temperature, but at reduced temperature the two systems containing only monothiolates give signals from a total of five species as the $\text{RS}^-/\text{R}'\text{S}^-$ ratio is changed⁴: the parent complexes plus three mixed ligand complexes. These results are consistent with the formation of the four-coordinate, presum-

⁴ Qualitatively, no strong preference for coordination of one ligand or the other was noted in the systems Cd^{2+} – MeS^- – Me_2HCS^- or Cd^{2+} – $^-\text{S}(\text{CH}_2)_3\text{S}^-$ – Me_2HCS^- , but there was a strong preference for PhCH_2S^- in Cd^{2+} – PhS^- – PhCH_2S^- and for $^-\text{S}(\text{CH}_2)_2\text{S}^-$ in Cd^{2+} – $^-\text{S}(\text{CH}_2)_2\text{S}^-$ – Me_2HCS^- .

TABLE III. ^{113}Cd NMR Spectra of the Complexes $[\text{Cd}(\text{SMe})_n(\text{SCHMe}_2)_{4-n}]^{2-}$ and $[\text{Cd}(\text{S}(\text{CH}_2)_2\text{S})_{n/2}(\text{SCHMe}_1)_{4-n}]^{2-}$ in CD_3OD at 193 K^a.

Complex	$\delta_{^{113}\text{Cd}}$ (ppm) ^b
$[\text{Cd}(\text{SCHMe}_2)_4]^{2-}$	0 ^b
$[\text{Cd}(\text{SMe})(\text{SCHMe}_2)_3]^{2-}$	7.4
$[\text{Cd}(\text{SMe})_2(\text{SCHMe}_2)_2]^{2-}$	14.8
$[\text{Cd}(\text{SMe})_3(\text{SCHMe}_2)]^{2-}$	22.1
$[\text{Cd}(\text{SMe})_4]^{2-}$	28.8
$[\text{Cd}(\text{S}(\text{CH}_2)_2\text{S})(\text{SCHMe}_2)_2]^{2-}$	67.3
$[\text{Cd}(\text{S}(\text{CH}_2)_2\text{S})_2]^{2-}$	140.2

^a In mixtures with $[\text{Cd}]_{\text{total}} = 0.05 \text{ M}$ prepared with $\text{CD}_3\text{ONa}:\text{total thiol}:\text{Cd} = 24:12:1$. ^b Relative to $[\text{Cd}(\text{SCHMe}_2)_4]^{2-}$ in CD_3OD at 193 K, which has a shift of *ca.* 654 ppm from 0.1 M $\text{Cd}(\text{ClO}_4)_2(\text{aq})$ at ambient probe temperature.

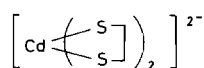
TABLE IV. ^{113}Cd NMR Spectra of the Complexes $[\text{Cd}(\text{SPh})_n(\text{SCH}_2\text{Ph})_{4-n}]^{2-}$ in CD_3OD at 193 K^a.

Complex	$\delta_{^{113}\text{Cd}}$ (ppm) ^b
$[\text{Cd}(\text{SPh})_4]^{2-}$	0 ^b
$[\text{Cd}(\text{SPh})_3(\text{SCH}_2\text{Ph})]^{2-}$	20.2
$[\text{Cd}(\text{SPh})_2(\text{SCH}_2\text{Ph})_2]^{2-}$	39.2
$[\text{Cd}(\text{SPh})(\text{SCH}_2\text{Ph})_3]^{2-}$	57.4
$[\text{Cd}(\text{SCH}_2\text{Ph})_4]^{2-}$	76.6

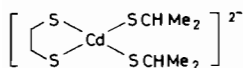
^a See footnote (a) Table III. ^b Relative to $[\text{Cd}(\text{SPh})_4]^{2-}$ in CD_3OD at 193 K which has a shift of *ca.* 595 ppm from 0.1 M $\text{Cd}(\text{ClO}_4)_2(\text{aq})$ at ambient probe temperature.

ably tetrahedral $\text{Cd}(\text{SMe})_n(\text{SCHMe}_2)_{4-n}^{2-}$ and $\text{Cd}(\text{SPh})_n(\text{SCH}_2\text{Ph})_{4-n}^{2-}$ in the two systems. This interpretation is strongly supported by the fact that both sets of shifts show near-additivity of substituent effects, a result not unexpected for sets of closely related complexes but surprising otherwise. Though such additivity has not, apparently, been reported for tetrahedral cadmium complexes previously (see however, Ref. 20), it is an example of a well-known phenomenon. In particular, the tin(IV) analogs of the tetrathiolatocadmates, $\text{Sn}(\text{SR})_n(\text{SR}')_{4-n}$, exhibit ^{119}Sn chemical shifts which change linearly with n [25]. (Also, insofar as overlap of data occurs, the shielding pattern for the tin and cadmium complexes is the same, *i.e.* $\text{MeS} > \text{EtS} > \text{PhCH}_2\text{S} > \text{Pr}^i\text{S} > \text{SPh}$ [25]).

In the system Cd^{2+} – $^-\text{S}(\text{CH}_2)_2\text{S}^-$ – Me_2HCS^- a single new complex is formed, as expected if the dithiolate acts as a chelate in both

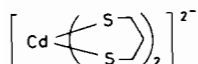


and the mixed ligand species, which must be

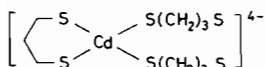


with the same tetrahedral CdS_4 core as the two parent complexes. It is interesting that even in this mixed ligand system the chemical shifts are close to additive, suggesting that the ^{113}Cd chemical shift chelate effect of the five membered ring is cumulative, as is also the case with ^{31}P chemical shifts [24].

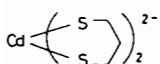
At reduced temperature the behaviour of even the binary system $\text{Cd}^{2+}-\text{S}(\text{CH}_2)_3\text{S}^-$ is complicated: three ^{113}Cd NMR signals were observed when L/M was varied. At L/M ≈ 3 , and 193 K, the major signal was deshielded by 37.0 ppm from $\text{Cd}(\text{SCHMe}_2)_4^{2-}$ and two minor signals occurred with shifts of 29.5 and 20.6 ppm from $\text{Cd}(\text{SCHMe}_2)_4^{2-}$. At L/M ≈ 6 , the signal at 37.0 ppm was not observed and the 29.5 ppm resonance was the major feature, the 20.6 ppm resonance being a minor feature. The ^1H NMR spectrum shows that a complex with L/M ≈ 2 is formed at low L/M and therefore we tentatively ascribe the 37.0 ppm resonance to a bis(chelate) complex



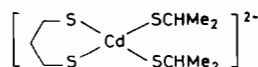
(A result suggesting that the ^{113}Cd NMR chelate effect of a six membered ring, though much smaller than that for a five-membered ring, is still noticeable.) It seems unlikely that the other two species occurring at higher L/M will have higher coordination numbers about cadmium, for there is no evidence of this in any other system studied. They must, however, have higher (complexed L)/Cd and could, perhaps, be



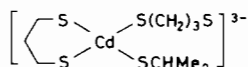
(the 29.5 ppm resonance) and $\text{Cd}(\text{S}(\text{CH}_2)_3\text{S})_4^{4-}$ (the 20.6 ppm resonance) both with CdS_4 kernels, as the three species have the additive ^{113}Cd shifts expected for the suggested formulation. In the mixed ligand system $\text{Cd}^{2+}-\text{S}(\text{CH}_2)_3\text{S}^- - \text{Me}_2\text{HCS}^-$, when (total thiolate): Cd = 12, two new mixed ligand species are formed. At high $\text{Me}_2\text{HCS}^-/\text{S}(\text{CH}_2)_3\text{S}^-$ ratios the signal of the parent $\text{Cd}(\text{SCHMe}_2)_4^{2-}$ is observed together with a new resonance deshielded by 18.0 ppm from it. The shift of this new resonance, near the midpoint between the resonances of $\text{Cd}(\text{SCHMe}_2)_4^{2-}$ and



is probably due to



At smaller $\text{Me}_2\text{HCS}^-/\text{S}(\text{CH}_2)_3\text{S}^-$ ratios, a second new species is formed, with a signal deshielded by 23.8 ppm from $\text{Cd}(\text{SCHMe}_2)_4^{2-}$. The exact nature of this species could not be ascertained, but its shift is close to that expected for



assuming our analysis of the system $\text{Cd}^{2+}-\text{S}(\text{CH}_2)_3\text{S}^-$ is correct (*i.e.* ≈ 24 ppm).

b) ^1H NMR

Complexes of several of the simpler thiolates and some mixed ligand complexes have been studied by ^1H NMR. In line with the variable temperature ^{113}Cd NMR results (see above) partially or completely exchange-averaged spectra are observed at ambient probe temperature, but at lower temperatures separate signals from free and complexed ligand are observed as shown by the data in Table V.

The results in Table V show that the proton complexation shifts are largest for CH_2 groups adjacent to the coordinated thiolate sulfur atom and decrease monotonically with distance from the donor site in an aliphatic chain. The largest complexation shift observed here is only 0.3 ppm, and consequently integral analysis of some of the spectra was complicated considerably by overlap of the bound and free ligand signals. Not unexpectedly, the ^{113}Cd spectra are more sensitive to complexation than the ^1H spectra in most instances.

In several cases, $^{111}/^{113}\text{Cd}$ satellites were observed about the α -methylene signal for a complexed ligand (see Table V). (Both 113- and 111-cadmium have spin $I = \frac{1}{2}$; their similar nuclear magnetic moments, -0.6195 and -0.5922 nuclear magnetons, respectively, lead to satellite overlap at the small splittings observed here.) The reduced coupling constant, $J/\mu_M\mu_H$, is *ca.* ± 11 Hz for the $\text{Cd}(\text{SMe})_4^{2-}$ ion, less than the *ca.* ± 24 Hz which can be deduced from $^3\text{J}(\text{Sn}-\text{H})$ in $\text{Sn}(\text{SMe})_4$ [25], and a similar situation holds for the analogous species $\text{M}(\text{SCH}_2\text{Ph})_4$. If, as seems likely, the reduced couplings have the same sign, the difference probably reflects the greater 's' electron density at the tin nucleus.

The complex of $\text{S}(\text{CH}_2)_2\text{S}^-$ was found to have L/M ≈ 2 . In the low temperature spectrum of this species two approximately equally intense lines are observed for the complexed ligand. These we attribute to the presence of chelate rings in which conformational equilibration is slow so that axial-equatorial signal averaging does not occur.

Those mixed ligand species studied by ^{113}Cd NMR (see Tables III and IV and text) were investigated by

TABLE V ^1H NMR Chemical Shifts and (parenthesized) Complexation Shifts of Some Four-Coordinate Tetrathiolatocadmates in CD_3OD

L	T(K)	$\delta_{\text{H}}^{\text{a}}$ ($\Delta\delta_{\text{H}}^{\text{b}}$)		
		H_{α}	H_{β}	H
CH_3S^-	193	2 09(0 11) ^c		
$\text{C}_2\text{H}_5\text{S}^-$	193	2 68(0 20)	1 30(0 05)	
$n\text{-C}_3\text{H}_7\text{S}^-$	193	2 61(0 18)	1 61(0 10)	0 97(0 04)
$\text{C}_6\text{H}_5\text{CH}_2\text{S}^-$	203	3 83(0 24) ^d		
$^-\text{S}(\text{CH}_2)_2\text{S}^-$	193	2 69(0 07) ^e , 2 66(0 04) ^e		
$^-\text{S}(\text{CH}_2)_3\text{S}^-$	223	2 81(0 29) ^f	1 85(0 03)	

^a Relative to internal TMS ^b $\Delta\delta_{\text{H}} = \delta_{\text{H, complex}} - \delta_{\text{H, free ligand}}$ ^c $^3\text{J}_{(^{111}/^{113}\text{Cd}-\text{H})} = 18 \text{ Hz}$ ^d $^3\text{J}_{(^{111}/^{113}\text{Cd}-\text{H})} \approx 13 \text{ Hz}$
^e See text, $^3\text{J}_{(^{111}/^{113}\text{Cd}-\text{H})_{\text{ave}}} \approx 20 \text{ Hz}$ ^f This system is complicated, see text

^1H NMR also In many cases, the separate spectra of the different mixed ligand species which were known to be present were not observed For example, only a single resonance for complexed MeS^- was observed for mixtures of the species $\text{Cd}(\text{SMe})_n(\text{SCHMe})_{4-n}^{2-}$ and only a single signal from $\alpha\text{-CH}_2$ groups in the ternary system $\text{Cd}^{2+}\text{-Me}_2\text{HCS}^- \text{-}^-\text{S}(\text{CH}_2)_3\text{S}^-$ (Also only a single $\alpha\text{-CH}_2$ resonance is observed in $\text{Cd}^{2+}\text{-}^-\text{S}(\text{CH}_2)_3\text{S}^-$ as L/M is varied though several species occur (see above)) In the mixed ligand system most amenable to study, that containing $\text{Cd}(\text{SPh})_n\text{-}(\text{SCH}_2\text{Ph})_{4-n}$, the methylene resonances of the four PhCH_2S^- -containing complexes had a total spread of 0 28 ppm at 223 K, the shifts from the free ligand being 0 23 ppm ($n = 0$), 0 16 ppm ($n = 1$), 0 06 ppm ($n = 2$), and $-0 05$ ppm ($n = 3$) ($^3\text{J}_{(^{111}/^{113}\text{Cd}-^1\text{H})}$ does not change significantly over this series) Again it is clear that, in most instances, ^{113}Cd NMR is superior to ^1H NMR as a probe for the thiolatocadmates

c) ^{13}C NMR

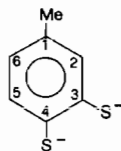
Carbon-13 NMR was used to study several complexes with representative ligands The number of alkylthiolates scrutinized was limited by the expense of using ^{13}C -depleted $^{12}\text{CD}_3\text{OD}$ as solvent At ambient probe temperature, all the systems studied gave exchange-averaged spectra from which useful information could sometimes be obtained by way of the (averaged) complexation shifts $\Delta\delta_{\text{c}} (= \delta_{\text{c, bound}} - \delta_{\text{c, free}})$ At reduced temperature in some instances slow exchange spectra were observed

At 193 K, in CD_3OD with excess PhS^- present, the system $\text{Cd}^{2+}\text{-PhS}^-$ showed separate resonances from the free ligand and $[\text{Cd}(\text{SPh})_4]^{2-}$ $\text{C}_1, \text{C}_2, \text{C}_6, \text{C}_{3,5}$ and C_4 and $\delta_{\text{c}} = 146 8, 134 0, 128 5$ and $122 2$, and $143 8, 134 0, 128 6$, and $123 1$ ppm for the free⁵

⁵ Conflicting assignments have been given for the ^{13}C NMR spectrum of PhSH [26–28] We prefer the assignments of Refs 26 and 27

and bound ligands, respectively The upfield shift of C_1 on complexation is analogous to that observed when PhS^- is protonated to the thiol,⁵ while the downfield shift of C_4 suggests net electron withdrawal on coordination of the ligand (A similar effect has been noted on coordination of PPh_3 to 'hard' acceptors [29])

At 308 K in CD_3OD ,



(tdt^{2-}) gives ^{13}C resonances at 19 1, 122 9, 130 6, 134 6, 135 6, 145 3 and 148 8 ppm, assigned to $\text{CH}_3, \text{C}_6, \text{C}_1, \text{C}_5, \text{C}_2, \text{C}_4$ and C_3 , respectively In a mixture with L/M = 5 3, the corresponding exchange-averaged resonances occur at 19 1, 123 7, 131 6, 134 3, 135 2, 143 7 and 147 4 ppm, respectively Of particular note are the upfield complexation shifts of C_3 and C_4 which are analogous to the shielding of C_1 of PhS^- on complexation Neither the free ligand nor the complex have high solubility in CD_3OD at reduced temperature. Nevertheless, what is apparently a poor (in terms of \bar{S}/\bar{N}) slow-exchange spectrum of the mixture can be obtained by lowering the temperature, and particularly conspicuous are resonances from C_3 and C_4 of the free and bound ligand For example, in the 193 K spectrum δ_{c_3} is 149 3 and 145 5 ppm and $\delta_{\text{c}_4} = 145 5$ and 141 7 ppm for the free and complexed ligand, respectively For both donor sites, $\Delta\delta_{\text{c}}$ is comparable to that observed for the PhS^- complex, showing both sulfur atoms to be coordinated, suggesting chelate behaviour Comparison of the exchange-averaged values of $\Delta\delta_{\text{c}}$ with those computed for various stoichiometries from the observed slow-exchange values, shows that tdt^{2-} gives, with cadmium, the bis(chelate) complex $\text{Cd}(\text{tdt})_2^{2-}$, having, presumably, a tetrahedral CdS_4 core

At 193 K, CD_3OD solutions of Cd^{2+} with excess MeS^- give well resolved spectra showing separate lines at $\delta_c = 7.1$ and 9.2 ppm for free MeS^- and $\text{Cd}(\text{SMe})_4^{2-}$, respectively. The $^{111}/^{113}\text{Cd}$ satellites could not be observed with certainty about the resonance for the complex, but shoulders suggest $^2J(^{111}/^{113}\text{Cd}-^{13}\text{C}) \approx 10$ Hz. The corresponding EtS^- -containing system gave broad lines at reduced temperature and separate free and bound resonances could not be seen. However, the 308 K spectra show that $\Delta\delta_{\text{CH}_2}$ is again positive, while δ_{CH_3} is negative: in the free ligand $\delta_{\text{CH}_2} = 20.0$ and $\delta_{\text{CH}_3} = 23.1$ ppm while in a solution wherein $\text{EtS}^-/\text{Cd}^{2+} = 6$, the corresponding values are 21.9 and 22.7 ppm respectively. Opposing shifts of α - and β -carbons may account from the absence of any cadmium-induced shift of $^-S(\text{CH}_2)_2\text{S}^-$ ($\delta_c = 23.8$ ppm at 308 K) on complexation, but this same rationalization cannot be applied to the system Cd^{2+} - PhCH_2S^- in which only the substituted aryl carbon shows a significant complexation shift: at 308 K the free ligand resonances at 30.9(CH_2), 126.3(C_4), 129.2 and 129.5 (C_2 and C_3 or vice-versa) and 149.6(C_1) ppm become 30.9, 126.4, 129.1, 129.4 and 148.3 ppm in a mixture where $\text{PhCH}_2\text{S}^-/\text{Cd}^{2+} = 6.8$. (Free and bound C_1 resonances are incompletely resolved at 193 K).

Because of the inconsistency with which cadmium complexation affects the free ligand spectra, overall ^{13}C NMR is not as satisfactory as ^{113}Cd NMR for scrutiny of the thiolatocadmates.

d) Absorption and Magnetic Circular Dichroism Spectra

Absorption and MCD spectra were recorded for a similar series of thiolate complexes using monothiolates, dithiolates and trithiolates as ligands in order to determine the effects of different coordination geometries on the optical data. We should point out at this stage that the typical concentration of Cd^{2+} in these solutions was of the order 5×10^{-5} M whereas for the NMR studies the solutions were near-saturated, with Cd^{2+} concentrations of 5×10^{-2} M. While this large reduction in concentration will affect the degree of aggregation, the complexes in solutions with these lower concentrations are more appropriate for consideration as models for the Cd^{2+} - and Zn^{2+} -binding protein metallothionein. In particular, as there is no natural circular dichroism from the synthetic compounds, and the absorption spectra are generally poorly resolved, the additional assignment criteria afforded by the MCD spectra will allow comparison between the binding sites of Cd^{2+} in the protein and the thiolate models, at concentrations at which NMR studies are difficult.

The data presented in Figs. 1–5 are the spectra recorded for a series of thiolatocadmium complexes that are representative of the set described in NMR studies above.

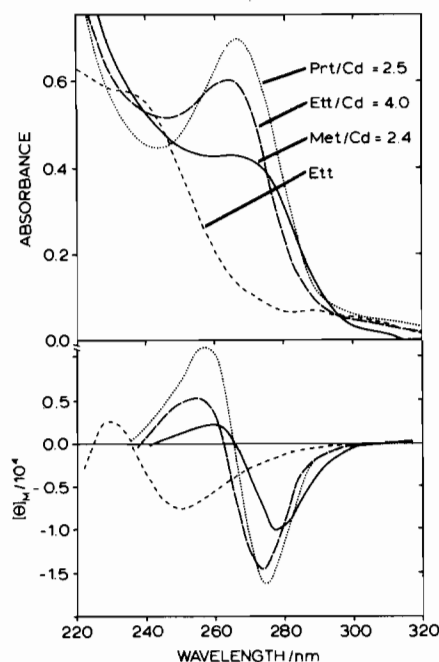


Fig. 1. Absorption (top) and MCD (bottom) spectra of complexes of monothiolates with Cd^{2+} . Propanethiolate (Prt): with $[\text{Prt}] = 0.00011$ M and $[\text{Cd}^{2+}] = 0.000044$ M, $L/M = 4.0$, dotted line. Ethanethiolate (Ett): with $[\text{Ett}] = 0.000192$ M and $[\text{Cd}^{2+}] = 0.000048$ M, $L/M = 4.0$, heavy dashed line; with $[\text{Ett}] = 0.00024$ M, light dashed line. Methanethiolate: with $[\text{Met}] = 0.00011$ M and $[\text{Cd}^{2+}] = 0.000046$ M, $L/M = 2.4$, solid line.

In Fig. 1 the thiolates are the monodentate ligands methane-, ethane- and propane-thiolates. All the RS^- complexes of cadmium studied exhibited a broad absorption shoulder, with an extinction coefficient in the 30 – 40000 $\text{L mol}^{-1} \text{cm}^{-1}$ range, that lies on the low energy side of an intense UV band. When the absorption due to the complex formation was reasonably well resolved, as is the case for the monothiolates in Fig. 1, Job's plots could be used to obtain the stoichiometric ratios of the ligand to the metal. For the monothiolates a value of 2.5:1 was obtained. This corresponds closely to the composition of the cluster reported by Dance [30] which suggests that some bridging sulfurs are involved. Therefore the absorption and MCD spectra were measured for solutions in which $L/M \approx 2.5$.

Of all the complexes studied, the spectra of these monothiolatocadmium species show the greatest resolution of the new absorption band in the 240 nm to 290 nm region that is observed following complexation. The MCD spectra are similarly well resolved, with peak and trough wavelengths lying approximately symmetrically about the absorption band centre. For each complex the new absorption is red-shifted from the spectrum of the uncomplexed ligand; in Fig. 1 this is illustrated by the absorption

TABLE VI. Absorption and MCD Spectral Parameters of Cadmium Thiolate Complexes.

Ligand ^a	L/M	ϵ^b (λ^c)	$[\theta]_m(\lambda_{\text{peak}})^d$	$[\theta]_m(\lambda_{\text{through}})$	$\Delta\epsilon/\epsilon^e$
MeS ⁻	2.4	9300 (265.5)	2.6×10^3 (255)	-10.2×10^3 (278)	4.2×10^{-4}
EtS ⁻	4.0	12430 (262.5)	5.3×10^3 (225)	-14.7×10^3 (273.5)	4.9×10^{-4}
PrS ⁻	2.5	13950 (265.5)	11.2×10^3 (258)	-18.5×10^3 (275)	6.5×10^{-4}
EdT	2.0	13540 (249)	1.36×10^3 (240)	-4.5×10^3 (262.5)	
BAL	2.0	16660 (248.5)	4.90×10^3 (240)	-9.50×10^3 (258)	
1,2 Pdt	2.0	19330 (249)	6.20×10^3 (241.5)	-9.80×10^3 (259)	
Edt	1.0	5000 (254)	0.70×10^3 (244)	-1.4×10^3 (278.5)	
BAL	1.0	8700 (252.5)	—	-2.94×10^3 (271)	
1,2 Pdt	1.0	11800 (253)	2.48×10^3 (245)	-2.98×10^3 (265)	
1,3 Pdt	2.0	9440 (257.5)	1.8×10^3 (249)	-6.2×10^3 (278.5)	
1,4 Bdt	3.0	17810 (245)	2.1×10^3 (235.5)	-6.9×10^3 (267)	
Ptt	3.0	44250 (233)	4.2×10^3 (228)	-22.2×10^3 (255)	

^a Abbreviations used are given in the text. ^b ϵ is calculated by assuming complete complex formation and that $[\text{complex}] = [\text{Cd}^{2+}]$. ^c λ is taken from the cross-over wavelength of the MCD band. ^d $[\theta]_m$ has units $\text{deg cm}^2 \text{dmol}^{-1} \text{T}^{-1}$. ^e $\Delta\epsilon/\epsilon = [\theta]_m/3300$, with units $\text{L mol}^{-1} \text{cm}^{-1} \text{T}^{-1}$.

and MCD spectra of ethanethiolate, in the absence of added cadmium.

Following the example of the analyses of the well known spectra of the transition-metal oxyanions [31, 32], and the tetrahedral halomercurates [33], we attribute the new absorption in this region to ligand-to-metal charge transfer arising from a combination of $3p(\text{S}) \rightarrow 5s$ and $5p(\text{Cd})$ transitions. In their analysis of the MCD spectra of a series of $[\text{HgX}_4]^{2-}$ halo complexes, Schreiner *et al.* [33] used the positive sign (*i.e.* a positive high energy lobe of the derivative signal) of the MCD band observed at 232 nm for $\text{X} = \text{Cl}^-$, 250 nm for $\text{X} = \text{Br}^-$, and 323 nm for $\text{X} = \text{I}^-$, to assign the band to an $np(\text{X}^-) \rightarrow 6p(\text{Hg})$ degenerate transition. This assignment assumes that the symmetry is tetrahedral and that the band is a Faraday A term, not two oppositely-signed and overlapping B terms. As our system appears quite similar to the $[\text{HgX}_4]^{2-}$ chromophore a comparison of the two sets of MCD spectra is useful.

Clearly, the MCD bands observed for the three monothiolate complexes shown in Fig. 1 have the same derivative shape, with the same positive lobe to high energy of the band centre, that was reported for the $[\text{HgX}_4]^{2-}$ complexes [33]. If the cadmium species in solution are predominantly clusters of $\text{Cd}(\text{RS})_{2.5}$ units [3] then we anticipate a near tetrahedral symmetry about the Cd^{2+} . This will result in degeneracy in the excited states and the presence of A terms in the MCD spectrum. Thus the bands near 265 nm in Fig. 1 may be characterized as A terms arising from a charge transfer transition, $\text{RS}^- \rightarrow \text{Cd}^{2+}$. Further analysis requires either a moments calculation or band shape fitting, but neither of these methods would be reliable here in view of the extensive overlap of the bands. However, comparison between the magnitudes of the derivative signals

observed for the Cd^{2+} and the $[\text{HgX}_4]^{2-}$ species does allow an estimate of the symmetry around the Cd^{2+} . It would be expected that the $\Delta\epsilon/\epsilon$ ratio for the bands would increase with a decrease in the distortion from a pure tetrahedral symmetry. $\Delta\epsilon/\epsilon$ values (when $\Delta\epsilon$ has units $\text{L mol}^{-1} \text{cm}^{-1} \text{T}^{-1}$) were calculated from the data of Schreiner *et al.* [33] for $[\text{HgX}_4]^{2-}$: with $\text{X} = \text{Cl}^-$, $\Delta\epsilon/\epsilon_{232} = 4.16 \times 10^{-4}$ (A/D reported as +0.53), with $\text{X} = \text{Br}^-$, $\Delta\epsilon/\epsilon_{250} = 4.0 \times 10^{-4}$ (A/D = +0.26), and with $\text{X} = \text{I}^-$, $\Delta\epsilon/\epsilon_{323} = 8.3 \times 10^{-4}$ (A/D = +0.72). Thus the $\Delta\epsilon/\epsilon$ values do follow the A/D values reasonably well. From our data, Table VI, we find $\Delta\epsilon/\epsilon$ values for the monothiolates, Fig. 1, that range from 4.2×10^{-4} for methanethiolate to 6.5×10^{-4} for the propanethiolate complex.

Despite the uncertainties in obtaining good ϵ_{max} values for each of the RS^- species shown in Fig. 1, the propanethiolate spectra are well resolved and the derived $\Delta\epsilon/\epsilon$ value can be used with some confidence. Comparison with the $[\text{HgX}_4]^{2-}$ data suggests that the high $\Delta\epsilon/\epsilon$ value is evidence that these thiolate complexes are little distorted from the expected tetrahedral symmetry of the CdS_4 units.

The spectra recorded for the dithiolates, Fig. 2, are not nearly as well resolved as those obtained for the monothiolates, Fig. 1. It is clear that the two major causes are the broadness of the new charge bands and the reduced red-shifts of these bands away from the rising background absorption at 240 nm. The appearance of a reasonably strong derivative signal in each MCD spectrum indicates that complexation has occurred, however. The much greater band widths, and the considerably reduced intensities (about three times less than the monothiolates), suggests that more than one species is present in these solutions.

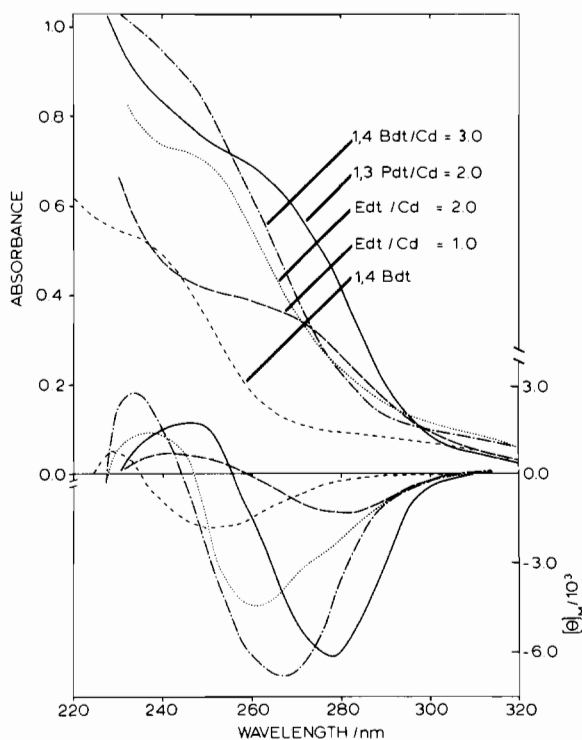


Fig. 2. Absorption (top) and MCD (bottom) spectra of complexes of dithiolates with Cd^{2+} . 1,4 Butanedithiolate (Bdt): $[\text{Bdt}] = 0.000144 \text{ M}$, and $[\text{Cd}^{2+}] = 0.000048 \text{ M}$, $L/M = 3$, -.-.-; $[\text{Bdt}] = 0.00008 \text{ M}$, dashed line. 1,3 Propanedithiolate (Pdt): $[\text{Pdt}] = 0.000144 \text{ M}$ and $[\text{Cd}^{2+}] = 0.000072 \text{ M}$, $L/M = 2$, solid line. Ethanedithiolate (Edt), $[\text{Edt}] = 0.000096 \text{ M}$ and $[\text{Cd}^{2+}] = 0.000048 \text{ M}$, $L/M = 2$, dotted line; $[\text{Edt}] = 0.00008 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00008 \text{ M}$, $L/M = 1$, dashed line.

It is to be expected that the chelating effect of the two thiol groups will be dependent on their spacing along the alkyl chain. Thus the thiols are adjacent in ethanedithiolate (Edt) and both monodentate and bidentate complexes can form. As the $\text{Edt}/\text{Cd}^{2+}$ ratio is increased from 1 to 2 we observe a blue-shift of the absorption maximum. The MCD spectrum of the 2:1 (L/M) solution (the dotted line in Fig. 2) indicates that a new species is formed which as a derivative-shaped band centred on *ca.* 248 nm, the spectrum of this species overlaps, to the red, a shoulder that is most likely the spectrum due to the 1:1 species (the dashed line in Fig. 2). The NMR data does indicate that, with L/M ratios higher than 2, bidentate chelation takes place. A Job's plot using absorption and MCD data for Edt-Cd complex formation gave maxima at L/M ratios of 0.6 and 1.5, which again suggests that the two types of complex are in equilibrium.

The spectra of the 1,3-propanedithiolate (1,3 Pdt) and 1,4-butanedithiolate (1,4 Bdt) complexes, shown in Fig. 2, have the same characteristics as the Edt set. We observe a poorly resolved absorption band and a

distinctive derivative-shaped MCD signal. Unlike the monothiolates, Edt and BAL (see below) ligands, the Job's plots for 1,3 Pdt and 1,4 Bdt showed only one maximum close to $L/M = 1.5$ for complex formation and the MCD cross-over points did not shift as the L/M ratio was changed. This strongly suggests that only a single complex is formed that is probably polymeric in nature. The MCD spectra of the Cd^{2+} complexes of 1,3 Pdt and 1,4 Bdt do in fact exhibit the greatest $[\theta]_M$ values of the dithiols shown in Fig. 2 which suggests that overlap with the spectra of another species at a different wavelength is less than is the case for the Edt spectra. The MCD bands are, however, considerably distorted with much greater intensity in the negative trough than in the positive peak. This suggests that there is a considerable B term component in addition to any A term component that arises from degeneracy. Because it is rather unrealistic to attempt to separate the contributions of each of the overlapping B terms and A terms in order to obtain $\Delta\epsilon/\epsilon$ values, we can only infer that the effect of the symmetry about the cadmium in these dithiolate complexes results in a much lower MCD signal amplitude than was observed for the monothiolates. This reduction in $\Delta\epsilon/\epsilon$ can be associated with a considerable distortion away from the tetrahedral symmetry found for the monothiolates.

In Figs. 3 and 4 we show the data measured for two related bis(dithiolato)cadmates, the 2,3 dimer-

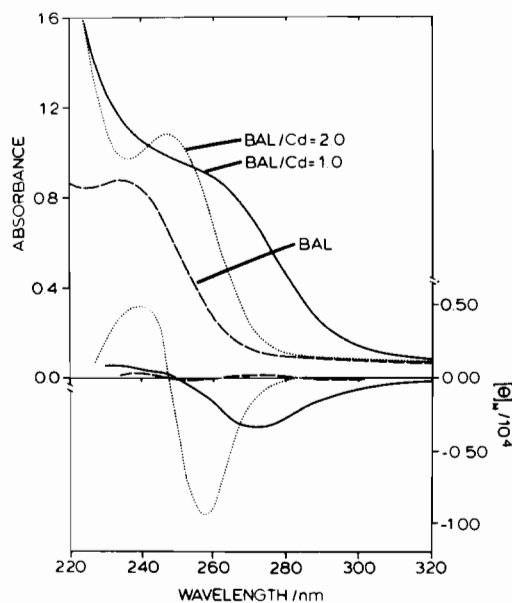


Fig. 3. Absorption (top) and MCD (bottom) spectra of 2,3 dimercaptopropanol (BAL) complexes of Cd^{2+} . $[\text{BAL}] = 0.000024 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00012 \text{ M}$, $L/M = 2$, dashed line; $[\text{BAL}] = 0.00020 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00020 \text{ M}$, $L/M = 1$, full line; $[\text{BAL}] = 0.00024 \text{ M}$, dotted line. A 0.5 cm path-length cell was used for both absorption and MCD measurements.

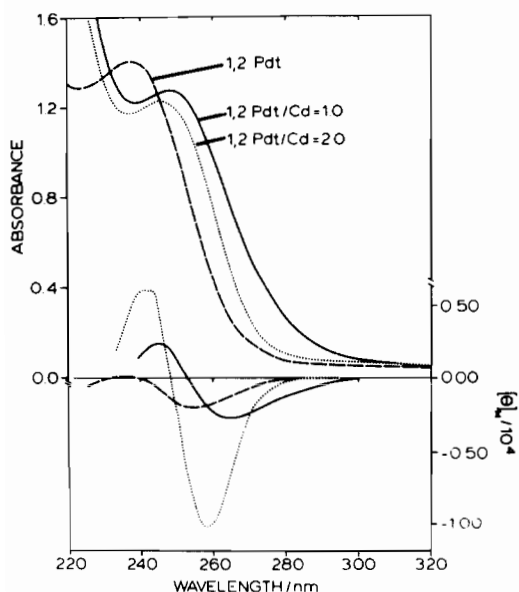


Fig. 4. Absorption (top) and MCD (bottom) spectra of 1,2 propanedithiolate (1,2 Pdt) complexes of Cd^{2+} . $[1,2 \text{ Pdt}] = 0.00024 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00012 \text{ M}$, $L/M = 2$, dashed line; $[1,2 \text{ Pdt}] = 0.00020 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00020 \text{ M}$, dotted line. A 0.5 cm pathlength cell was used for the absorption and MCD measurements.

captopropanol (or BAL) complex and the 1,2 propanedithiol (1,2 Pdt) complexes.

Addition of 1 mol eq. Cd^{2+} to the BAL ligand results in a 20 nm red-shift in the absorption, the full line in Fig. 3. The MCD spectrum of the ligand has negligible intensity on the scale used in Fig. 3 and essentially follows the baseline, unlike the ligand spectra for the other thiols used. The 1:1 complex has an MCD spectrum that is quite different when compared with the other thiolatocadmata spectra. In place of a derivative signal, we observe a negative B term roughly centred on the absorption maximum. There is no indication of derivative character and the signal intensity is close to the baseline zero at *ca.* 250 nm, a wavelength that can be quite reasonably associated with the end of the absorption band that results in the shoulder at 262 nm. Thus the 1:1 complex apparently does not exhibit the same tetrahedral geometry of coordinated sulfurs around the Cd^{2+} . With an L/M ratio of 2, the dashed line in Fig. 3, we observe a derivative-shaped band, quite similar in intensity to the monothiolatocadmata spectra, and unlike the spectrum of the 1:1 BAL complex. Because the negative lobe of the $L/M = 2$ spectrum occurs at a wavelength near the zero intensity point of the 1:1 MCD spectrum, it appears that there is very little of the 2:1 species mixed in with the 1:1 complexes in the 1:1 ratio solution.

We can test the effect on the OH group in BAL on the form of the complex by carrying out the same

experiments with 1,2 Pdt. Figure 4 shows the absorption and MCD spectra measured for $L/M = 1$ and $L/M = 2$ complexes. In these spectra we see that there is only a slight blue-shift of the charge transfer band at 246 nm as the L/M ratio increases from 1 to 2, quite unlike the BAL system, and the MCD signals of the 1:1 and 2:1 complexes are clearly both derivative-shaped bands which are approximately centred on their respective absorption maxima. Although the $L/M = 2$ MCD spectra of BAL and 1,2 Pdt are almost exactly the same, the 1:1 spectra are quite different. The 1,2 Pdt spectra follow the trend established by the other bis(dithiolato)cadmates, Fig. 2, in which the derivative-shaped signal for the 1:1 complex intensifies and blue-shifts at $L/M = 2$. This quite unusual spectral behaviour of the 1:1 BAL complex is rather difficult to account for. Because we do not observe similar effects with either the Edt or the 1,2 Pdt complexes it is probable that the terminal hydroxyl group is involved in the coordination sphere of the Cd^{2+} , perhaps in the same manner as the oxygens in the Cd^{2+} cluster compounds of $\text{HS}(\text{CH}_2)_2\text{-OH}$ reported by Schwarzenbach *et al.* [3]. In these compounds several different arrangements of sulfurs and oxygens are found coordinating to the Cd^{2+} cations. The low symmetry indicated by the B term in the MCD spectrum of the 1:1 complex suggests

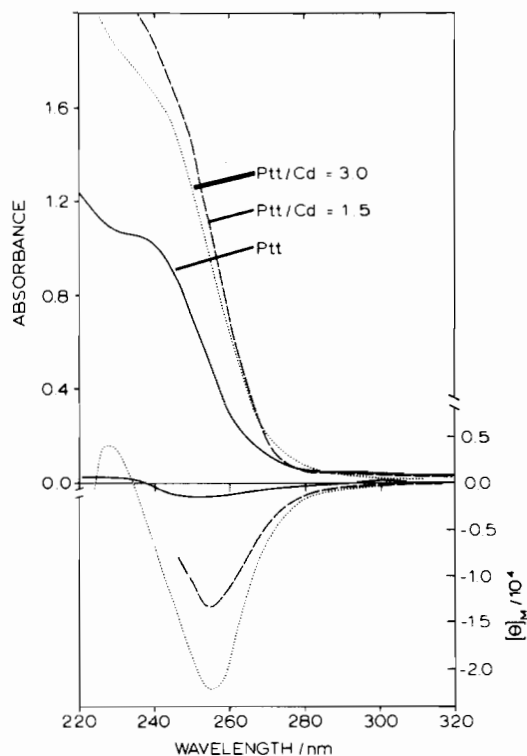


Fig. 5. Absorption (top) and MCD (bottom) spectra of propanetrithiolate (Ptt) complexes of Cd^{2+} . $[\text{Ptt}] = 0.00012 \text{ M}$ and $[\text{Cd}^{2+}] = 0.00004 \text{ M}$, $L/M = 3$, dotted line; $[\text{Ptt}] = 0.00012 \text{ M}$ and $[\text{Cd}^{2+}] = 0.0008 \text{ M}$, $L/M = 1.5$, dashed line; $[\text{Ptt}] = 0.00012 \text{ M}$, full line.

that there are not just four sulfurs around the Cd^{2+} but a mixture of sulfurs and oxygens.

Finally, in Fig. 5, we see that with the three adjacent sulfurs in propane trithiolate there is very little change in either the absorption or MCD spectrum as the L/M ratio is changed from 1:5 to 3:0. The distorted derivative MCD band in the L/M = 3:0 system suggests that the symmetry around the Cd^{2+} may not be as close to tetrahedral as in the mono-thiolates but there is little further information in these data.

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References

- 1 A. J. Carty, *A.C.S. Symp. Ser.*, **82**, 339 (1978).
- 2 A. J. Carty, *A.C.S. Symp. Ser.*, **82**, 327 (1978).
- 3 G. Schwarzenbach, K. Gautschi, J. Peter and K. Tunaboylu, *Trans. Roy. Inst. Technol., Stockholm*, No. 271, 295 (1972).
- 4 R. A. Haberkorn, L. Que, Jr., W. O. Gillum, R. H. Holm, C. S. Lui and R. C. Lord, *Inorg. Chem.*, **15**, 2408 (1976).
- 5 H.-B. Bürgi, *Helv. Chim. Acta*, **57**, 513 (1974).
- 6 a) J. D. Otvos and I. M. Armitage, *Abstr. Symp. on Metallothioneins and Other Low Molecular Weight Metal-Binding Proteins*, Zurich, Switzerland, July, 1978; b) I. M. Armitage, J. D. Otvos, J. F. Chlebowski and J. E. Coleman, *Abstr. 20th Exptl. NMR Conf.*, Asilomar, California, Feb. 1979; c) J. D. Otvos and I. M. Armitage, *J. Am. Chem. Soc.*, **101**, 7734 (1979).
- 7 P. J. Sadler, A. Bakka and P. J. Beynon, *FEBS Lett.*, **94**, 315 (1978).
- 8 K. T. Suzuki and T. Mattani, *Experientia*, **34**, 1449 (1978).
- 9 R. Olafson and J. D. Otvos, private communication.
- 10 A. Y. C. Law and M. J. Stillman, unpublished data.
- 11 G. M. Cherian, private communication.
- 12 P. A. W. Dean, D. G. Ibbott and J. B. Stothers, *Can. J. Chem.*, **54**, 166, 1493 (1976); L. C. Damude and P. A. W. Dean, *J. Organometal. Chem.*, **168**, 123 (1979).
- 13 R. J. Kostelnik and A. A. Bothner-By, *J. Mag. Reson.*, **14**, 141 (1974).
- 14 W. R. Browett and M. J. Stillman, *Biochim. Biophys. Acta*, **623**, 21–31 (1980).
- 15 A. J. Canty, R. Kishimoto, G. B. Deacon and G. J. Farquharson, *Inorg. Chim. Acta*, **20**, 161 (1976).
- 16 M. E. Peach, *J. Inorg. Nuclear Chem.*, **41**, 1390 (1979).
- 17 T. Maitani and K. T. Suzuki, *Inorg. Nuclear Chem. Lett.*, **15**, 213 (1979).
- 18 B. Birgersson, R. E. Carter and T. Drakenberg, *J. Magn. Reson.*, **28**, 299 (1977).
- 19 J. D. Kennedy and W. McFarlane, *J. Chem. Soc. Perkin Trans. II*, 1187 (1977).
- 20 P. A. W. Dean, to be published.
- 21 D. L. Rabenstein and M. T. Fairhurst, *J. Am. Chem. Soc.*, **97**, 2086 (1975).
- 22 B. R. Bobsein and R. J. Myers, *J. Am. Chem. Soc.*, **102**, 2454 (1980).
- 23 P. E. Garrou, *Inorg. Chem.*, **14**, 1435 (1975), and references therein.
- 24 R. Mason and D. W. Meek, *Angew. Chem. Int. Ed. Engl.*, **17**, 183 (1978), and references therein.
- 25 J. D. Kennedy, W. McFarlane, G. S. Pyne, P. L. Clarke and J. D. Wardell, *J. Chem. Soc. Perkin II*, 1234 (1975).
- 26 L. F. Johnson and W. C. Jankowski, "Carbon-13 NMR Spectra", Wiley-Interscience, New York, 1972, p. 164.
- 27 C. V. Senoff and J. E. H. Ward, *Inorg. Chem.*, **14**, 278 (1975).
- 28 C. Nagata, J. Saito and S. Tanaka, *Bunseki Kagaku*, **26**, 64 (1977).
- 29 D. G. Ibbott, Ph. D. Thesis, University of Western Ontario, 1976, p. 66, P. A. W. Dean and D. G. Ibbott, *Can. J. Chem.*, **54**, 177 (1976).
- 30 I. Dance, *Abstr. 179th ACS Natl. Meeting*, Houston, Texas, March 1980. Abstr. INOR 42.
- 31 R. H. Petit, B. Briat, A. Müller and E. Diemann, *Chem. Phys. Letters*, **20**, 540 (1973).
- 32 A. B. P. Lever in "Inorganic Electronic Spectroscopy" (M. F. Lappert, ed.), Elsevier, New York, 1968, pp. 224–248.
- 33 J. D. Gunter, A. F. Schreiner and R. S. Evans, *Inorg. Chem.*, **14**, 1589 (1975).