129. Comparison of the Complexation of Open-Chain and Cyclic N_2S_2 Ligands with Cu^+ and Cu^{2+}

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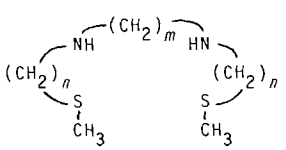
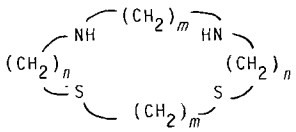
The complexation properties of the open-chain N_2S_2 ligands **1**–**4** are described and compared to those of analogous N_2S_2 macrocycles **5**–**7**. With Cu^{2+}, the open-chain ligands give complexes with the stoichiometry CuL^{2+} and $CuLOH^+$, the stabilities and absorption spectra of which have been determined. The ligand field exerted by these ligands is relatively constant and independent of the length of the chain. With Cu^+, the species $CuLH_2^{3+}$, $CuLH^{2+}$, and CuL^+ were identified and their stabilities measured. The redox potentials calculated from the equilibrium constants and measured by cyclic voltammetry agree and lie between 250 and 280 mV against *SHE*. The comparison between open-chain and cyclic ligands shows that *1)* a macrocyclic effect is found for Cu^{2+} but not for Cu^+, *2)* the ligand-field strength is very different for the two types of ligands, and *3)* the redox potentials span a larger interval for the macrocyclic than for the open-chain complexes.

Introduction. – Ligands with a N_2S_2-donor set have been widely used as models to study the complexes with Cu^{2+} [1] [2], since the active site of the 'blue' Cu proteins also has the same donor set, *i.e.* two N-atoms from two imidazoles and two S-atoms, one from a cysteine and the other from a methionine [3].

Most of these studies are related to mimicking the spectroscopic properties of the natural systems. So, the position and the high molar absorptivity of the 'blue' Cu band have been the subject of many theoretical [4] [5] and experimental [5] [6] studies. The nature of this band and the correlation between the spectral properties and the geometry of the Cu^{2+}-coordination sphere have been investigated [7]. Other studies have tried to understand the unusually low $A_\parallel$ values found in the EPR spectra of 'blue' Cu proteins [8]. In contrast to the amount of spectroscopic work, little is known about the stability of the Cu^+ and Cu^{2+} complexes and the nature of the species formed by such N_2S_2 ligands. Recently, we have reported on these properties for a series of N_2S_2 macrocycles with *cis*- and *trans*-arrangement of the hetero atoms [9]. We observed that these ligands are



1 $n = m = 2$
2 $n = 2, m = 3$
3 $n = 3, m = 2$
4 $n = m = 3$



5 $n = m = 2$
6 $n = 3, m = 2$
7 $n = m = 3$

equally well-suited to bind Cu^+ and Cu^{2+}. However, despite the identical N_2S_2-donor set, significant differences in stability were observed, which resulted in redox potentials $E_{Cu^+/Cu^{2+}}$ ranging from 80 to 420 mV against *SHE*. This large range is a direct consequence of the different stabilities of the Cu^{2+} complexes, which span five orders of magnitude, while all the Cu^+ species have rather similar stabilities. To see whether this is also true for other N_2S_2 systems, we have now investigated the complexation properties of the open-chain ligands **1–4**, which can be considered as analogs of the previously studied N_2S_2 macrocycles **5–7**, cleaved between the two *cis*-S-atoms.

Experimental. – *S*-Methylcysteamine [10] (b.p. 60–62°/40 Torr) and 3-(methylthio)propylamine [11] were prepared according to the indicated literature. All other compounds were synthesized following the general procedure.

General Procedure. 1,2-Dibromoethane or 1,3-dibromopropane (1 equiv.) were reacted with *S*-methylcysteamine or 3-(methylthio)propylamine (2 equiv.) in abs. EtOH under reflux for 4–6 d. The mixture was then cooled to −18°, whereby the dihydrobromide of the product crystallized. This was recrystallized from EtOH/H_2O with addition of a few drops of 47% HBr.

2,11-Dithia-5,8-diazadodecane Dihydrobromide (**1**). Yield 21%. M.p. 232–233°. ^{1}H-NMR (D_2O): 2.16 (*s*, 2 CH_3S); 2.83 (*t*, 2 CH_2S); 3.40 (*t*, 2 CH_2N); 3.53 (*s*, 2 CH_2N). Anal. calc. for $C_8H_{22}Br_2N_2S_2$ (370.21): C 25.96, H 5.99, Br 43.17, N 7.57, S 17.32; found: C 26.17, H 5.89, Br 43.03, N 7.60, S 17.27.

2,12-Dithia-5,9-diazatridecane Dihydrobromide (**2**). Yield 23%. M.p. 268–270°. ^{1}H-NMR (D_2O): 1.95 (*m*, $CH_2-CH_2-CH_2$); 2.00 (*s*, 2 CH_3S); 2.55 (*t*, 2 CH_2S); 3.20 (*t*, 2 CH_2N); 3.45 (*s*, 2 CH_2N). Anal. calc. for $C_9H_{24}Br_2N_2S_2$ (384.23): C 28.14, H 6.30, Br 41.59, N 7.29, S 16.69; found: C 28.22, H 6.36, Br 41.01, N 7.28, S 16.39.

2,13-Dithia-6,9-diazatetradecane Dihydrobromide (**3**). Yield 34%. M.p. 233–234°. ^{1}H-NMR (D_2O): 2.00 (*m*, 2 $CH_2-CH_2-CH_2$); 2.10 (*s*, 2 CH_3S); 2.65 (*t*, 2 CH_2S); 3.30 (*t*, 2 CH_2N); 3.55 (*s*, CH_2N). Anal. calc. for $C_{10}H_{26}Br_2N_2S_2$ (398.26): C 30.16, H 6.58, Br 40.13, N 7.03, S 16.10; found: C 30.17, H 6.53, Br 39.90, N 7.12, S 15.91.

2,14-Dithia-6,10-diazapentadecane Dihydrobromide (**4**). Yield 31%. M.p. 241° (dec.). ^{1}H-NMR (D_2O): 1.95 (*m*, 3 $CH_2-CH_2-CH_2$); 2.05 (*s*, 2 CH_3S); 2.55 (*t*, 2 CH_2S); 3.05 (*t*, 4 CH_2N). Anal. calc. for $C_{11}H_{28}Br_2N_2S_2$ (412.29): C 32.05, H 6.85, Br 38.76, N 6.80, S 15.35; found: C 32.07, H 6.87, Br 38.69, N 6.81, S 15.47.

Alternative Procedure: N,N'-*Bis[3-(methylthio)propyl]malonamide.* A soln. of 3.0 ml (2.7 mmol) of malonate and 5.9 g (5.6 mmol) of 3-(methylthio)propylamine in 10 ml of abs. MeOH was refluxed for 2 h and left at r.t. overnight. Evaporation of the solvent gave 5.85 g of the product which was recrystallized from CH_2Cl_2/Et_2O: yield 75%. M.p. 103–104°. ^{1}H-NMR (CD_3OD): 1.80 (*quint.*, 2 $CH_2-CH_2-CH_2$); 2.05 (*s*, 2 CH_3S); 2.55 (*t*, 2 CH_2S); 3.30 (*t*, 2 CH_2N); 3.35 (*s*, $CO-CH_2-CO$). Anal. calc. for $C_{11}H_{22}N_2O_2S_2$ (278.43): C 47.45, H 7.97, N 10.06, S 23.03; found: C 47.39, H 7.89, N 10.13, S 22.81.

2,14-Dithia-6,10-diazapentadecane Dihydrobromide (**4**). To a soln. of 4.3 g (15.3 mmol) of *N,N*-bis[3-(methylthio)propyl]malonamide in 85 ml of abs. THF, 65 ml of 1M B_2H_6 in THF were added and refluxed for 4 h under N_2. After cooling, abs. MeOH was added to destroy the excess B_2H_6 and the solvent was evaporated. The residue was taken up in 85 ml of abs. MeOH, 2 ml of H_2O, and 8.5 ml of conc. HCl and refluxed for 1.5 h. Thereafter, the solvent was removed and the residue dissolved in 55 ml of 1.5M KOH. The aq. phase was extracted 4 times with CH_2Cl_2. The combined fractions were dried (Na_2SO_4) and evaporated. The residue (3.8 g) was transformed into the dihydrobromide by reacting it with aq. HBr and crystallized by adding abs. EtOH: yield 3.3 g (53%). The properties are identical to those described above (overall yield 40%).

Measurements. – As source of Cu^+, a soln. of $[Cu(CH_3CN)_4](ClO_4)$ [12] in CH_3CN was used. All other reagents were of anal. grade and used without further purification. The measurements were run at 20.0° ± 0.1° and $I = 0.2$ (Na_2SO_4).

The potentiometric measurements were done using the automatic pH titration unit described in [13]. The pH electrode was calibrated with two buffers at pH 4 and 7 and checked daily by titrating a mixture of H_2SO_4 and AcOH at $I = 0.2$ (Na_2SO_4). The calibration was considered to be satisfactory if $\log K^H$ of AcOH and pK_W were in the range of 4.560–4.585 and 14.027–14.061, respectively. The $\log K^H$ values were obtained from titration of $1.6 \cdot 10^{-3}$M ligand hydrobromide in Na_2SO_4 ($I = 0.2$) soln. containing 2% (*v/v*) CH_3CN with 0.4M NaOH (*Titrisol, Merck*). In the case of **3** and **4**, titrations with 1% (*v/v*) and 4% (*v/v*) CH_3CN were also run to study the influence

of CH_3CN on $\log K^H$. The effect was small, the $\log K^H$ values differing by 0.02–0.04 log units. The stability constants of the Cu^{2+} complexes with **2–4** were obtained from titrations of $0.5–2.0 \cdot 10^{-3}$M ligand hydrobromide with 0.8 or 0.4 equiv. of Cu^{2+} in Na_2SO_4 ($I = 0.2$) using 0.4M NaOH. The stabilities of the Cu^+ complexes with **1–4** were determined from titrations of $0.8–1.6 \cdot 10^{-3}$M ligand hydrobromide with 0.8 or 0.4 equiv. Cu^+ in 2% and 4% (v/v) CH_3CN with 0.4M NaOH. To suppress the oxidation of the Cu^+ species, good care was taken to exclude O_2 during the titrations. The calculation of the $\log K^H$ values (mixed constants containing the proton activity) and stability constants was done on a *Hewlett-Packard HP9835* desk top computer using the program TITFIT [14].

Spectrophotometric titrations were used to study the complexation of Cu^{2+} with **1**, using the automatic titration setup for a *Cary 118C* described in [15], since this complex was too stable to be measured potentiometrically. 2.3 ml of $1.4 \cdot 10^{-3}$M ligand hydrobromide and $1.2 \cdot 10^{-3}$M or $0.7 \cdot 10^{-3}$M Cu^{2+} in Na_2SO_4 soln. were titrated with 0.1M NaOH starting from pH 1.8 where the complex is not yet formed. The calculations were done on a desk-top computer *Hewlett-Packard HP9835* using the program SPECFIT [16].

Since the stability constants $K^*_{Cu^{II}LH_2}$ could not be obtained from potentiometric titrations, they were indirectly determined from the kinetic measurements of the Cu(I) autoxidation in the presence of different amounts of LH_2^{2+} using a *Beckman* oxygen electrode coupled to a high-impedance millivolt recorder as described in [17]. Typical concentrations were: 10^{-4}M Cu^+, 1% (v/v) CH_3CN (for **3** also 2% v/v), 10^{-2}M chloroacetate buffer (pH 3.1), ligand $0–2 \cdot 10^{-3}$M and Na_2SO_4 to make $I = 0.2$. Pseudo-first-order rate constants were determined from the slope $\Delta[O_2]/\Delta t$ at $t = 0$: $k_{obs.}$ (s^{-1}) $= -\Delta[O_2]/([O_2]_{tot.} \cdot \Delta t)$.

The cyclic voltammetry was done using a *Metrohm* scanner *E612* and a *Metrohm* VA-detector *E611* equipped with a *Hewlett-Packard* Plotter *7005 B*. A three-electrode system consisting of a *Beckman* Pt disk as working electrode, surrounded by a Pt spiral as counter electrode and a NaCl-sat. Ag/AgCl reference electrode connected to the soln. through a 0.2M $NaClO_4$ salt bridge was used. The soln. contained $5 \cdot 10^{-4}$M ligand, $4 \cdot 10^{-4}$M Cu^{2+} in 0.05M borate buffer (pH = 9) and 0.2M $NaClO_4$. The cyclic voltammograms, run at scan rates of 5–30 mV s^{-1}, were graphically evaluated.

Table 1. *Protonation Constants, Cu^{2+} Stability Constants, and Absorption Maxima of the N_2S_2 Ligands* **1–4** *in 2% (v/v) CH_3CN at 20° and I = 0.2 (Na_2SO_4).* For comparison, the values for **5–7** are also given [7]. Values in brackets are standard deviations.

Ligand	$\log K^H_{H2L}$	$\log K^H_{HL}$	$\log K_{Cu^{II}L}$	$\log K_{Cu^{II}LOH}$	λ_{max} [nm] (ε [M^{-1} cm^{-1}])
1	6.42(1)	9.09(2)	12.62(2)	9.72(2)	580 (378)
2	8.04(1)	9.77(1)	12.97(1)	11.40(3)	563 (355)
3	7.10(1)	9.74(1)	10.98(1)	10.22(2)	570 (395)
4	8.67(1)	10.34(1)	[a])	[a])	
5	5.20	9.11	13.95	11.08	620 (610)
6	6.01	9.75	15.85	[b])	533 (386)
7	7.86	10.45	10.15	[a])	607 (800)

[a]) Precipitation of $Cu(OH)_2$. [b]) Not observed.

Results and Discussion. – The ligand-protonation constants of **1–4** are given in *Table 1*. The log values for the first protonation, $\log K^H_{LH}$, are in the range of 9.1–10.3, which is typical for secondary aliphatic amines. The second protonation is strongly dependent on the chain length (m), which separates the two amino groups. So, **1** and **3** with an ethylene bridge ($m = 2$) have significantly lower $\log K^H_{LH_2}$ values than **2** and **4** with a propylene bridge ($m = 3$), in line with the different electrostatic repulsion between the two ammonium groups.

Cu^{2+} Complexes. With the ligands **1–4**, only the species CuL^{2+} *(Eqn. 1)* and $CuL(OH)^+$ *(Eqn. 2)* were observed and their stability constants are given in *Table 1*.

$$Cu^{2+} + L \rightleftharpoons CuL^{2+};\ K_{Cu^{II}L} \quad (1)$$

$$CuL(OH)^+ + H^+ \rightleftharpoons CuL^{2+};\ K_{Cu^{II}LOH} \quad (2)$$

First, we note that **4** does not form a stable Cu^{2+} complex; hydrolysis to $Cu(OH)_2$ occurs. The stabilities of CuL^{2+} are about the same for L = **1** and **2**, although the overall basicities of the ligands differ by orders of magnitude. This is probably due to two opposite effects. On one side, the chain length (m) between the two amino N-atoms is 2 and 3, on the other side, the chelate ring sequence is 5,5,5 and 5,6,5 for L = **1** and **2**, respectively. So, **1** with the structural element of a substituted ethylenediamine should give a stronger complex than **2**, but be less favourable than **2** in regard of the chelate ring sequence. The CuL^{2+} complex with **2** has the lowest tendency to hydrolyse to $CuL(OH)^+$, indicating that it is tailored for a square-planar geometry. The λ_{max} values *(Table 1)* also show that the ligand-field strength is largest for **2**. As expected for S-ligands, the molar absorptivities ε are somewhat higher than those of Cu^{2+} complexes with only N donors.

A comparison between the open-chain and the macrocyclic N_2S_2 ligands [9] seems appropriate *(Table 1)*. All macrocycles **5**–**7** form CuL^{2+}, including **7** with $m = n = 3$, in contrast to **4**. The tendency to hydrolyse and give $CuL(OH)^+$ was only observed with **5**, whereas the Cu^{2+} complex with **6** does not, and that with **7** gives $Cu(OH)_2$ at higher pH. In general, the stability constants are 1–2 log units higher for the macrocycles than for the corresponding open-chain ligands. Both observations can quantitatively be rationalized in terms of the macrocyclic effect [18], which, for N_2S_2 ligands, was specifically studied by measuring the enthalpy and entropy of formation [19]. The λ_{max} values of the Cu^{2+} complexes with the open-chain ligands are more homogeneous than those with the cyclic compounds. Probably, this is due to the fact that open-chain ligands adapt themselves to the geometrical requirements of the metal ion, whereas the macrocycles, being somewhat more rigid, impose their structure upon the metal ion. This last point is clearly found for **5** which, being to small to encompass the metal ion, gives square-pyramidal or trigonal-bipyramidal complexes, whereas **1** probably gives a tetragonal Cu^{2+} complex (compare λ_{max} values).

Cu^+ Complexes. Since Cu^+ is relatively soft and related in its complexing properties to Ag^+, the species $CuLH_2^{3+}$ with exclusive thioether coordination could be expected. To determine the stability of this species, we have measured the rate of autoxidation of Cu^+ in the presence of different amounts of ligand. The plots of log k_{obs} against log [L] *(Fig. 1)*

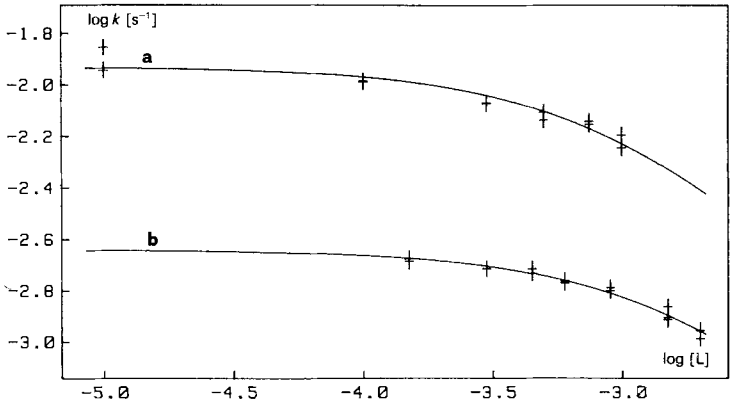


Fig. 1. *Dependence of the autoxidation rate on the ligand concentration for L* = **3**. $[Cu^+] = 1 \cdot 10^{-4}$ M, $[O_2] = 1 \cdot 10^{-4}$ M at pH = 3.1 in *a)* 1% (*v*/*v*) CH_3CN and *b)* 2% (*v*/*v*) CH_3CN.

can be explained by assuming that only Cu^+ reacts with O_2, but not $CuLH_2^{3+}$. (*Eqn. 3* and *4*)

$$CuLH_2^{3+} \underset{}{\overset{K^*_{Cu^ILH_2}}{\rightleftharpoons}} LH_2^{2+} + Cu^+ \tag{3}$$

$$Cu^+ + O_2 \xrightarrow{k^*} \text{Products} \tag{4}$$

For this scheme, one can write *Eqn. 5–8*, from which *Eqn. 9* can be derived, with $B = [L]_{tot} - [Cu]_{tot} + 1/K^*_{Cu^ILH_2}$.

$$[L]_{tot} = [CuLH_2^{3+}] + [LH_2^{2+}] \tag{5}$$

$$[Cu]_{tot} = [CuLH_2^{3+}] + [Cu^+] \tag{6}$$

$$K^*_{Cu^ILH_2} = [CuLH_2^{3+}]/[Cu^+][LH_2^{2+}] \tag{7}$$

$$k_{obs.} = k^*[Cu^+]\,[O_2] \tag{8}$$

$$k_{obs.} = k^*\left\{-B/2 + \sqrt{B^2/4 + [Cu]_{tot.}\,K^*_{Cu^ILH_2}}\right\}[O_2] \tag{9}$$

Since one has to work in solutions containing CH_3CN, Cu^+ is in fact a mixture of the aquo ion Cu^+_{aq} and the CH_3CN complexes $Cu(CH_3CN)^+$, $Cu(CH_3CN)_2^+$, and $Cu(CH_3CN)_3^+$. k^* and $K^*_{Cu^ILH_2}$, which can be obtained by non-linear curve fitting of *Eqn. 9*, thus, are conditional parameters depending on $[CH_3CN]$. Similarly, in the titrations with Cu^+ (2–4%, *v/v*) CH_3CN was used to stabilize Cu^+ and, therefore, all stability constants given

Table 2. *Conditional Stability Constants of the Cu^+ Complexes with* **1–4** *in Presence of 1–4% (v/v) CH_3CN at 20° and I = 0.2 (Na_2SO_4).* Standard deviations in brackets.

Ligand	$\log K^*_{Cu^IL}$ [a]		$\log K^*_{Cu^ILH}$ [a]		$\log K^*_{Cu^ILH_2}$			N of CH_3CN in		
	2%	4%	2%	4%	1%	2%	4%	Cu^IL^+	Cu^ILH^{2+}	$Cu^ILH_2^{3+}$
1	10.64(1)	9.89(1)	5.29(1)	4.44(2)	2.61(5)[b]	2.32[c]	1.94[c]	0	0	1[d]
2	10.76(1)	10.05(1)	5.53(1)	5.06(2)	2.61(5)[b]	2.31[c]	1.94[c]	0	0, 1	1[d]
3	9.32(1)	8.59(1)	4.40(2)	3.99(1)	3.01(5)[b]	2.74(3)[b]	2.34[c]	0	0, 1	1
4	8.88(1)	8.13(1)	4.61(2)	3.83(7)	2.97(7)[b]	2.68[c]	2.30[c]	0	0	1[d]

[a]) Values determined from titration curves using a fixed $\log K^*_{Cu^ILH_2}$ given in this *Table*.
[b]) Values obtained from autoxidation kinetics.
[c]) Values calculated from those at 1% (*v/v*) CH_3CN assuming that 1 CH_3CN is coordinated in Cu^ILH_2.
[d]) Assumed in analogy to **3**.

in *Table 2* are conditional ones and depend on $[CH_3CN]$. They can be transformed into CH_3CN-independent constants taking into account the stability of the different Cu^+ complexes with CH_3CN and the number of CH_3CN molecules in ternary complexes Cu^+/ligand/CH_3CN. An indication of this is given by the dependence of $\log K^*$ on $[CH_3CN]$: for example a decrease of 0.6 or 0.3 log units will be found on going from solutions with 2 to 4% (*v/v*) of CH_3CN, if no or one molecule of CH_3CN is incorporated in the ternary complex, respectively. From *Table 2*, one can see that in the complexes CuL^+ no CH_3CN is bound, whereas in $CuLH_2^{3+}$ with L = **3** one CH_3CN is in the ternary complex. Once this is known, the stability constants according to *Eqn. 10–13* can be calculated.

$$Cu^{+}_{aq} + L \rightleftharpoons CuL^{+};\ K_{Cu^{I}L} \quad (10)$$

$$Cu^{+}_{aq} + LH^{+} \rightleftharpoons CuLH^{2+};\ K_{Cu^{I}LH} \quad (11)$$

$$Cu(CH_3CN)^{+} + LH_2^{2+} \rightleftharpoons Cu(CH_3CN)LH_2^{3+};\ K_{Cu^{I}(CH_3CN)LH_2} \quad (12)$$

$$Cu(CH_3CN)^{+} + LH^{+} \rightleftharpoons Cu(CH_3CN)LH^{2+};\ K_{Cu^{I}(CH_3CN)LH} \quad (13)$$

They are collected in *Table 3* together with the analogous constants for the macrocycles **5**–**7**.

The stability constants $K_{Cu^{I}L}$ of the open-chain ligands **1**–**4** run from 12.56 to 14.46 and cover the same range as the one spanned by the macrocycles. Contrary to the situation with Cu^{2+}, there is no sign of a 'macrocyclic effect'. This is understandable in view of the completely different coordination geometry of Cu^{+} compared to that of Cu^{2+}. Moreover, we find the opposite trend for the two classes of ligands. The open-chain ligands give the most stable Cu^{+} species for the short chains (**1** and **2**), whereas the macrocycle **7** with the largest ring forms the complex with the highest stability.

Table 3. *Stability Constants of the Cu^{+} Complexes and Redox Potentials* $E_0(CuL^{2+}/CuL^{+})$ *with Ligands* **1**–**4** *and the Macrocycles* **5**–**7** *at 20° and* I = *0.2 (Na_2SO_4).* Standard errors in brackets.

Ligand	$\log K_{Cu^{I}L}$	$\log K_{Cu^{I}LH}$	$\log K_{Cu^{I}(CH_3CN)LH_2}$	E_0 [mV] *vs. SHE*	
				Calc.[a])	Exp.(ΔE)[b])
1	14.33(3)	8.92(8)	3.16(5)	260	277 (63)
2	14.46(2)	9.35(10)[c])	3.17(5)	247	230 (95)
3	13.02(2)	8.25(10)[c])	3.57(5)	279	258 (63)
4	12.56(3)	8.28(5)	3.48(7)	[d])	[d])
5	13.14	7.00[c])		112	116 (52)
6	13.39	7.73		15	84 (70)
7	14.35			409	424 (80)

[a]) Calculated using *Eqn. 15.* [b]) Peak separation in mV. [c]) Probably a mixture of $Cu(CH_3CN)LH^{2+}$ and $CuLH^{2+}$. [d]) Cu^{2+} complex not stable.

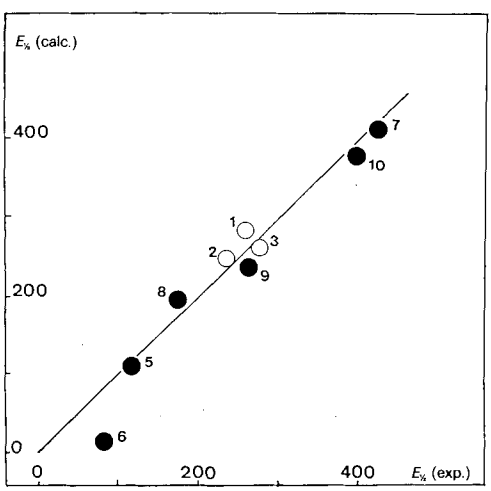


Fig. 2. *Correlation between the calculated* (according to *Eqn. 15*) *and experimentally determined Cu^{2+}/Cu^{+} potentials for open-chain* (○) *and cyclic* (●) *N_2S_2 ligands*

Redox Potentials. The potentials were measured by cyclic voltammetry of the Cu^{2+} complexes. With the exception of **4**, all measurements were *quasi*-reversible as indicated by ΔE (60–90 mV), by $i_a/i_c \approx 1$ and by the fact that the peak separation remains constant for different scan rates. The corresponding calculated values were obtained from *Eqn. 15* by inserting the stability constants for Cu^{2+} ($K_{Cu^{II}L}$), those for

$$E_0(CuL^{2+}/CuL^{+}) = E_0(Cu^{2+}/Cu^{+}) - 0.059 \log(K_{Cu^{II}L}/K_{Cu^{I}L}) \quad (15)$$

Cu^{+} ($K_{Cu^{I}L}$), and the redox potential $E_0(Cu^{2+}/Cu^{+}) = 158.6$ mV [20]. Calculated and experimental values differ by ± 20 mV, which could be due to differences in the reversibility of the complexes measured. The values $E_0(CuL^{2+}/CuL^{+})$ are relatively insensitive to the length of the chains connecting the donor atoms. In contrast, the redox potentials for the macrocyclic complexes vary by about 360 mV *(Fig. 2)*.

Conclusions. – The results of this report clearly show the differences between open-chain and macrocyclic N_2S_2 ligands. For Cu^{2+}, the well-known 'macrocyclic effect' is observed, whereas for Cu^{+} this is not the case. Specifically, the stability constants for the complexation with Cu^{+} are high with short open-chain ligands, and low with the small macrocycles **5** and **6** *(Fig. 3)*. The open-chain ligands, despite of their different chain

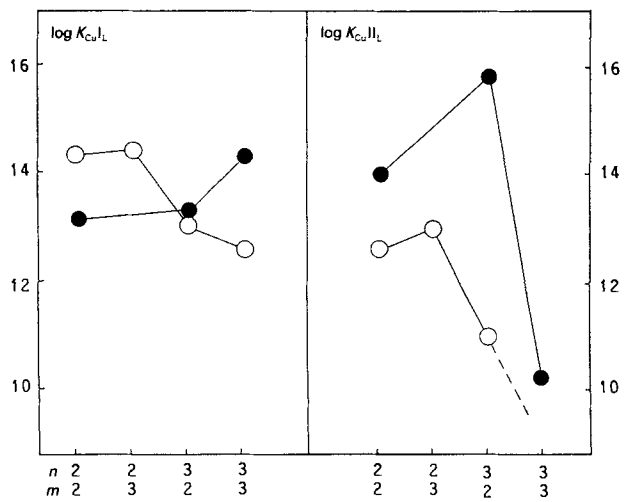


Fig. 3. *Comparison of the stability constants for* Cu^{+} (left) *and* Cu^{2+} (right) *with open-chain* (○) *and cyclic* (●) N_2S_2 *ligands*

lengths, give a relatively homogeneous ligand field, as can be seen from the absorption maxima of the Cu^{2+} complexes and the redox potentials. This strongly contrasts with the macrocycles. We think that this is a consequence of the more rigid structure of the macrocycles, which do not adapt themselves to the geometrical requirements of the metal ions, but impose their geometry onto the coordinated metal ion.

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REFERENCES

[1] See for example 'Copper Coordination Chemistry: Biochemical and Inorganic Perspectives', Eds. K.D. Karlin and J. Zubieta, Academic Press, New York, 1983.

[2] 'Biological and Inorganic Copper Chemistry', Eds. K.D. Karlin and J. Zubieta, Adenine Press, New York, 1986, Vol. I and II.

[3] P.J. Colman, H.C. Freeman, J.M. Guss. M. Murata, V.A. Norris, J.A.M. Ramshaw, M.P. Venkatappa, *Nature (London)* **1978,** *272,* 319.

[4] A.R. Amundsen, J. Whelan, B. Bosnich, *J. Am. Chem. Soc.* **1970,** *99,* 6730; V.M. Miskowski, J.A. Tich, R. Solomon, H.J. Schugar, *J. Am. Chem. Soc.* **1976,** *98,* 8344.

[5] D.E. Nikles, M.J. Powers, F.L. Urbach, *Inorg. Chem.* **1983,** *22,* 3210.

[6] L. Siegfried, Th.A. Kaden, *Helv. Chim. Acta* **1984,** *67,* 29.

[7] J.R. Dorfman, R.D. Bereman, M.H. Whangbo in [1], p. 75.

[8] A.W. Addison in [1], p. 109; H. Yokoi, A.W. Addison, *Inorg. Chem.* **1977,** *16,* 1341; J. Peisach, W.E. Blumberg, *Arch. Biochem. Biophys.* **1974,** *165,* 691.

[9] K.P. Balakrishnan, Th.A. Kaden, L. Siegfried, A.D. Zuberbühler, *Helv. Chim. Acta* **1984,** *67,* 1060.

[10] C.C. Ou, V.M. Miskowski, R.A. Lalancette, J.A. Potenza, H.J. Schugar, *Inorg. Chem.* **1967,** *15,* 3157.

[11] P. Karrer, E. Scheitlin, H. Siegrist, *Helv. Chim. Acta* **1950,** *33,* 1239.

[12] A. Günter, A.D. Zuberbühler, *Chimia* **1970,** *24,* 340; P. Hemmerich, C. Sigwart, *Experientia* **1963,** *19,* 488; A.D. Zuberbühler, *Helv. Chim. Acta* **1970,** *53,* 473.

[13] H. Gampp, M. Maeder, A.D. Zuberbühler, Th.A. Kaden, *Talanta* **1980,** *27,* 513.

[14] A.D. Zuberbühler, Th.A. Kaden, *Talanta* **1982,** *29,* 201.

[15] G. Hänisch, Th.A. Kaden, A.D. Zuberbühler, *Talanta* **1979,** *26,* 563.

[16] H. Gampp, M. Maeder, C.J. Meyer, A.D. Zuberbühler, *Talanta* **1985,** *32,* 95 and 257.

[17] M. Güntensberger, A.D. Zuberbühler, *Helv. Chim. Acta* **1977,** *60,* 2584.

[18] D.K. Cabbiness, D.W. Margerum, *J. Am. Chem. Soc.* **1969,** *91,* 6540.

[19] M. Micheloni, P. Paoletti, L. Siegfried, Th.A. Kaden, *J. Chem. Soc., Dalton Trans.* **1985,** 1169.

[20] C. Berecki-Biedermann, G. Biedermann, L.G. Sillen, Report to Analytical Section, IUPAC (1953).