120. Stabilities and Redox Properties of Cu(I) and Cu(II) Complexes with Macrocyclic Ligands Containing the N_2S_2 Donor Set

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Summary

The complexation of Cu(I) and Cu(II) by a series of 12-, 14- and 16-membered macrocyclic ligands **1–6** containing the N_2S_2 donor set has been studied potentiometrically, spectrophotometrically and voltammetrically.

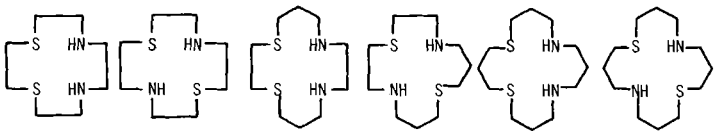
In the case of Cu(II), mononuclear complexes CuL^{2+} with stability constants of 10^{10}–10^{15} are formed. In addition, partially hydrolyzed species $Cu(L)OH^+$ are observed at pH > 10 for the 12-membered ligands. For Cu(I), beside the species CuL^+ with stabilities of 10^{12}–10^{14}, the unexpected formation of protonated species $CuLH^{2+}$ was detected. In contrast to the well-known general trends in coordination chemistry, the stability of these protonated species increases relative to that of the complexes with the neutral ligand when the ring size and concomitantly the distance between neighbouring donor atoms is decreased. From the stability constants of the Cu(I)- and Cu(II)-complexes the redox potentials have been calculated and are compared to the values of $E_{1/2}$ obtained by cyclic voltammetry. Despite the identical donor set the Cu(II)/Cu(I) redox potentials of the complexes are spanning a range of 340 mV or six orders of magnitude in relative stability, reflecting the importance of subtle differences in steric requirements.

Introduction. – Following the structural characterization of 'blue' or 'type 1' copper in plastocyanin [1], a great deal of interest has focussed on the study of copper complexes with sulfur-containing low-molecular ligands [2]. Chelators with up to five sulfur atoms as donors have been studied, but ligands with the N_2S_2 donor set would be of most direct relevance from the bioinorganic point of view. An actual copy of the active center in blue copper proteins with two imidazoles, one cysteine and one methionine would be difficult to obtain, however, since special precautions would be necessary to prevent the formation of cystine by oxidative dimerization. Nevertheless, thiolate coordination has been achieved in ternary Cu(II)-complexes with macrocyclic ligands [3]. Normally, however, thiaethers were exclusively used as the sulfur donors [2].

A large part of the effort in mimicking the natural systems has gone in the study of spectroscopic properties. Although generally not matching the enzymes, complexes with thiaethers have high-intensity visible absorption spectra, the molar absorptivities increasing with the number of sulfur atoms [4] [5]. The nature of this band and of additional transitions in the near UV region has been discussed in detail [4] [6]. Corre-

lation between spectral properties and structure, especially distortion from the square planar arrangement preferred by Cu(II) has been sought [7]. Also, EPR spectra have been widely studied in the hope of a better understanding of the unusually low $A_{\parallel}$-value observed in 'blue' copper proteins [8].

Relatively little is known, however, about the stability of Cu(II)- and especially Cu(I)-complexes with ligands containing the N_2S_2 donor set. We have recently synthesized a series of six macrocyclic ligands **1–6**, containing two secondary amino groups and two thiaether groups with *cis*- and *trans*-arrangement of the heteroatoms and ring sizes ranging from 12 to 16 [5].



The present study was undertaken in order to tackle the following questions: *i*) what are the absolute and relative stabilities of the Cu(I)- and Cu(II)-complexes with diazadithia macrocycles, is there any conspicuous influence of the ring size? *ii*) Are the expected complexes CuL^+ and CuL^{2+} with the neutral ligands the only species formed in aqueous solution? *iii*) How does Cu(I), which prefers linear arrangement of aliphatic amino groups, adjust to the steric restriction implied by the *cis*-ligands **1**, **3** and **5**? *iv*) How closely can we correlate thermodynamic redox potentials calculated from the stability constants of the Cu(I)- and Cu(II)-complexes with those obtained from cyclic voltammetry?

To study the above questions, the complexation of the ligands **1–6** with Cu(I) as well as with Cu(II) was investigated by pH- or spectrophotometric titrations and by cyclic voltammetry.

Experimental Part. – The six N_2S_2-macrocycles **1–6** and their Cu(II)-complexes were synthesized as described in [5]. $[Cu(CH_3CN)_4]BF_4$, prepared and purified as published in [9], was used as the source of cuprous ion. All other reagents were of analytical grade and used without further purification. The measurements were run at 20° and $I = 0.2$ (Na_2SO_4 or $NaClO_4$).

Potentiometric measurements were run using our fully automatic pH-titration unit, consisting of a combined glass electrode *(Metrohm, UX)*, a *Metrohm E600* digital pH-meter, a *Metrohm E655* digital burette, a *Dolphin* microprocessor and a tape recorder *(Microcorder ZE 601)* [10]. The pH-electrode was calibrated with two buffer solutions of pH 4 and 7 and checked daily by titrating a mixture of H_2SO_4 and CH_3COOH ($I = 0.2$, Na_2SO_4). The pK_H-values of the ligands were obtained from titrations of 3.2 mM ligand hydrochloride or hydrobromide in Na_2SO_4 ($I = 0.2$) solution containing 2% *v/v* CH_3CN with 0.4M NaOH.

Since some of the cuprous complexes of the macrocycles **1–6** are very sensitive to O_2 [11], great care was taken to exclude O_2 during the titration. In a typical experiment, the solution containing all components except Cu(I) was purged for 30–45 min with O_2-free N_2. Then a degassed CH_3CN-solution of $[Cu(CH_3CN)_4]BF_4$ was added by means of a syringe. These solutions were titrated with O_2-free 0.4M NaOH solution, which was added in 0.01-ml portions up to a total of 0.5 ml. The exact composition of the solutions is given in *Table 1*. The calculations of the pK_H-values of the ligands and of the stability of the Cu(I)-complexes were done on a *Hewlett Packard HP 9835* desk top computer using the program TITFIT [12].

Spectrophotometric titrations were used to determine the stability constants of the Cu(II)-complexes with the N_2S_2-macrocycles using the automatic titration setup for a *Cary 118C* described in [13]. 2.3 ml of the

Table 1. *Experimental Conditions of the Titrations of the Ligands* **1–6** *with* Cu^+

Soln.	c_L [mM]	c_{Cu} + [mM]	% *v/v* CH_3CN	tot. volume [ml]
1	3.20	2.56[a])	2	25
2	3.20	1.28[a])	2	25
3	1.60	1.28	2	50
4	1.60	1.28	1	50

[a]) For *cis*-[12]aneN_2S_2 also with 1% *v/v* CH_3CN.

Table 2. *Experimental Conditions of the Spectrophotometric Titrations of the Macrocycles* **1–6** *with* Cu^{2+}

Ligand	$c_{Cu}2+$ [mM]	c_L [mM]	Starting pH	ml NaOH (M)	Spectral range [nm]
1	1.08	1.28	1.4	0.3 (0.4)	540–740
2	1.66	1.90	2.8	0.3 (0.1)	500–700
3	1.78	2.00	0.8	[a])	460–660
4	1.78	2.00	2.8	0.3 (0.1)	480–680
5	1.78	2.00	4.4	0.2 (0.05)	500–700
6	1.78	2.00	4.3	0.2 (0.05)	500–740

[a]) Batch titration, *cf.* text.

ligand/metal solution adjusted to $I = 0.2$ with Na_2SO_4 and acidified to a starting pH low enough so that no complex was formed, were titrated by 0.01-ml additions of NaOH as to cover the pH-range where the complex is formed. The experimental details are given in *Table 2.*

The Cu(II)-complex with **3** is so slowly formed that a batch titration was used. 6 ml 2 mM ligand, 1.78 mM Cu^{2+} and 0.067M H_2SO_4 were mixed with x ml (x = 0, 0.5, ...4) 0.067M H_2SO_4 or 0.2M NaOH and (4 – x) ml 0.067M Na_2SO_4. These solutions were left for 3 days in a thermostat at 20° to reach the equilibrium. Each determination was run in duplicate. The calculations were done using the program SPECFIT [14] on a desk-top computer *Hewlett Packard HP 9835.*

The cyclic voltammograms were run using a *Metrohm* scanner *E612* and a *Metrohm* VA-detector *E611* equipped with a *Hewlett Packard* plotter *7005B.* A three-electrode system was used: a *Beckman* Pt-disk as working electrode, surrounded by a Pt-spiral as counter electrode and a saturated calomel reference electrode connected through a 0.2M $NaClO_4$ salt bridge. The Cu(II)-complexes ($4 \cdot 10^{-4}$M) were dissolved in 0.2M $NaClO_4$. The cyclic voltammograms, run with scan rates of 5–30 mVs^{-1}, were evaluated graphically.

Results and Discussion. – *Ligand Protonation Constants.* The successive protonation constants $\log K^H_{HL}$ and $\log K^H_{H_2L}$ of the ligands **1–6** are summarized in *Table 3.* Quite in contrast to results with triaza-macrocycles [15], no extremely high (*i.e.* above 12) values are observed. Thus no specific stabilization by H-bond formation has to be invoked. In

Table 3. *Ligand Protonation Constants and Standard Deviations of the Macrocycles* **1–6** *in 2% v/v* CH_3CN *at 20° and* $I = 0.2$

Macrocycle	$\log K^H_{HL}$	$\log K^H_{H_2L}$
cis-[12]aneN_2S_2 (**1**)	9.11 (0.01)	5.20 (0.01)
trans-[12]aneN_2S_2 (**2**)	9.14 (0.01)	6.29 (0.01)
cis-[14]aneN_2S_2 (**3**)	9.75 (0.01)	6.01 (0.01)
trans-[14]aneN_2S_2 (**4**)	9.22 (0.01)	8.00 (0.01)
cis-[16]aneN_2S_2 (**5**)	10.45 (0.01)	7.86 (0.01)
trans-[16]aneN_2S_2 (**6**)	9.89 (0.02)	9.11 (0.03)

fact, the logarithms of the first protonation constants all are in the range of 9.1 to 10.5, which is typical for slightly acidified secondary aliphatic ammonium ions. The addition of the second proton also follows the trends expected from open-chain analogs. Thus $\Delta \log K = \log K^{H}_{LH} - \log K^{H}_{LH_2}$ is larger for the *cis*- than for the *trans*-derivatives by 1.1 to 2.7 log units for a given ring size and decreases with the ring size for both *cis*- and *trans*-derivatives. These observations are easily accounted for by electrostatic interaction. With *trans*-[16]aneN$_2$S$_2$ (**6**) the interaction is essentially zero, $\Delta \log K = 0.78$ as compared to 0.6 on a purely statistical basis. The only somewhat surprising result is found for *trans*-[12]aneN$_2$S$_2$ (**2**) with $\Delta \log K = 2.8$. This difference is larger than that for the 12-membered 1,4,7,10-tetraazacyclododecane ($\Delta \log K = 1.0$ [16]) and even than that for 1,3-diaminopropane ($\Delta \log K = 1.78$ [17]). Molecular models indicate that indeed the two nitrogen atoms of **2** are only about 5 Å apart in the most stable conformation.

Cu(II)-Complexes. The stability constants $K_{Cu^{II}L}$ *(Eqn. 1)* of the complexes calculated from the spectrophotometric titrations

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

and their standard deviations are given in *Table 4*. The standard deviations σ_E of the absorbances are also given to show the quality of the fit. The somewhat higher value of σ_E and of $\sigma_{\log K_{Cu^{II}L}}$ for **3** is due to the batch titrations, which are *per se* less precise than continuous titrations. While for the 12-membered ligands **1** and **2** an additional equilibrium *(Eqn. 2)* was observed at higher pH,

$$CuL^{2+} + OH^- \rightleftharpoons Cu(L)OH^+ \quad (2)$$

no such equilibria were found for the 14-membered ligands **3** and **4**, whereas for the 16-membered macrocycles **5** and **6** precipitation of $Cu(OH)_2$ occurs at pH > 7. The $\log K_{Cu^{II}L}$ values *(Table 4)* increase in the order: *cis*-[16]aneN$_2$S$_2$ (**5**) < *trans*-

Table 4. *Results from the Spectrophotometric Titrations and from Cyclic Voltammetry for the Cu^{2+}-Complexes with* **1**–**6** *at 20° and* I = *0.2*

Ligand	$\log K_{Cu^{II}L}$	$\sigma_E \times 10^3$	λ_{max} [nm]	$E_{1/2}$ [mV][a])	ΔE [mV][b])
1	13.94(3)	1.3	636	116	52
	13.96(3)	1.36	637		
2	11.70(6)	3.6	628	172	60
	11.68(7)	4.5	628	140[c])	70[c])
3	15.82(14)	6.3	531	84	70
	15.88(14)	6.4	531	76[d])	181[d])
4	12.91(5)	4.3	570	262	84
	12.85(5)	4.5	571		
5	10.13(4)	4.0	618	424	80
	10.17(2)	3.3	618		
6	10.25(2)	3.0	645	396	66
	10.29(3)	3.0	645		

[a]) Against SHE. [b]) Peak-to-peak separation. [c]) From [18]. [d]) From [19].

[16]aneN$_2$S$_2$ (**6**) < *trans*-[12]aneN$_2$S$_2$ (**2**) < *trans*-[14]aneN$_2$S$_2$ (**4**) < *cis*-[12]aneN$_2$S$_2$ (**1**) < *cis*-[14]aneN$_2$S$_2$ (**3**), and span more than 5 log units. That the weakest complexes are formed with the 16-membered macrocycles **5** and **6** is not surprising, since these rings are too large for Cu^{2+}, as discussed for the 16-membered N_4-macrocycle [20]. *cis*-[14]aneN$_2$S$_2$ (**3**) forms the strongest complex, since it has the ideal ring size and alternating 5- and 6-membered chelate rings, which are known to be optimal [21]. Interesting is that for the 12- and 14-membered ligands the *cis*-arrangement gives stronger complexes than the *trans* one, whereas for the 16-membered ligands no such effect is observed. The geometry and ligand field strength of the Cu(II)-complexes can be inferred from their absorption maxima *(Table 4)*. The strongest ligand field is observed for **3** whereas the weakest is found for **6**. However, for the 12-membered ligands **1** and **2** one does not expect square planar geometry since the rings are too small to encircle a metal ion [20]. Therefore the λ_{max}-values for **1** and **2** cannot be used for a direct comparison.

Cu(I)-Complexes. The stability constants of the complexes with Cu(I) are summarized in *Table 5*. Since $[Cu(CH_3CN)_4]BF_4$ in CH_3CN was used as the source of Cu(I), the presence of CH_3CN-complexes $Cu(CH_3CN)^+$ ($\log K_1 = 3.28$ [22]), $Cu(CH_3CN)_2^+$ ($\log \beta_2 = 4.35$ [23]), $Cu(CH_3CN)_3^+$ ($\log \beta_3 = 4.39$ [24]) and possibly of ternary Cu^+/macrocycle/CH_3CN complexes had to be considered. Therefore, complexation was studied in the presence of 1 and 2% *v/v* CH_3CN with each ligand.

The values compiled in *Table 5* are dependent on $[CH_3CN]$, since the concentration of the free ion Cu(I) was taken as the sum of $[Cu^+]$ and the concentrations of Cu(I)/CH_3CN complexes. The number of CH_3CN-molecules bound to the macrocyclic cuprous complexes can be calculated from the dependence of the apparent stability constants on $[CH_3CN]$. It easily follows that a decrease by 0.6 or 0.3 log units will be observed by going from 1 to 2% *v/v* CH_3CN, if 0 or 1 molecule CH_3CN is bound to the macrocyclic complexes, respectively. Quite obviously, no CH_3CN is bound to any of the complexes CuL^+. There is evidence, however, for binding of CH_3CN to the monoprotonated complexes $CuLH^{2+}$ formed with the 12-membered ligands **1** and **2**. Once the

Table 5. *Stability Constants and Standard Deviations of the Cu(I)-Complexes with* **1–6** *in the Presence of 1% or 2% v/v CH_3CN at 20° and I = 0.2*

Ligand	$\log K_{Cu^IL}$		$\log K_{Cu^ILH}$		No of CH_3CN bound	
	1%	2%	1%	2%	CuL^+	$CuLH^{2+}$
1	10.02[b])	9.42(11)	6.45[c])	6.14(8)	0	1
2	9.17(11)	8.64(4)	6.05(9)	5.61(4)	0	1[d])
3	10.35[e])	9.57(5)	4.60[e])	4.01(3)	0	0
4	11.11[e])	10.44(8)	6.33[e])	5.78(8)	0	0
5	11.21[e])	10.63(4)	–[f])	–[f])	–	–
6	10.86[e])	10.17(4)	7.05[e])	6.44(2)	0	0

[a]) In this system an additional equilibrium $2CuLH^{2+} \rightleftharpoons Cu_2L_2^{2+} + 2H^+$ is observed with $\log K$ values of −8.64(5) and −8.81(4) at 1% and 2% CH_3CN, respectively. [b]) Calculated assuming no CH_3CN bound to CuL^+, *cf. Text.* [c]) Calculated from $\log K^H_{CuLH} = 5.55$ at 1% CH_3CN and $\log K^H_{CuLH} = 5.84$ at 2% CH_3CN, *cf. Text.* [d]) $\Delta \log K_{Cu^ILH} = 0.44$ may indicate mixture of $CuLH^{2+}$ and $Cu(CH_3CN)(LH)^{2+}$ which this ligand. [e]) Results from single titration curve; standard errors of 0.01 log units were considered unrealistic and are omitted. [f]) Species not observed.

number of bound CH_3CN-molecules is known, CH_3CN-independent stability constants can be obtained as defined by *Eqn. 3–5*. These are summarized in *Table 6*. Complexation with *cis*-[12]aneN_2S_2 (**1**) starts at very low pH-values and for 1% CH_3CN the complex with LH^+ is fully formed at the beginning of the titration. Only deprotonation to CuL^+ *(Eqn. 6)* and $Cu_2L_2^{2+}$ thus can be actually measured. From the dependence of $\log K^H_{CuLH}$ on $[CH_3CN]$, we can conclude that $CuLH^{2+}$ contains one molecule of CH_3CN in excess over CuL^+. Since no binding of CH_3CN to CuL^+ has been observed for the ligands **2–6**, the logical species are $Cu(CH_3CN)(LH)^{2+}$ and CuL^+ for **1**.

$$Cu^+ + L \rightleftharpoons CuL^+ \quad : K_{Cu^IL} \tag{3}$$

$$Cu^+ + LH^+ \rightleftharpoons CuLH^{2+} \quad : K_{Cu^ILH} \tag{4}$$

$$Cu(CH_3CN)^+ + LH^+ \rightleftharpoons Cu(CH_3CN)(LH)^{2+} : K_{Cu^I(an)(LH)} \tag{5}$$

$$CuL^+ + H^+ \rightleftharpoons CuLH^{2+} \quad : K^H_{CuLH} \tag{6}$$

Table 6. *Stability Constants of Cu^+ and Cu^{2+} Complexes with* **1–6** *and their $Cu^{II}L/Cu^IL$ Redox Potentials*

Ligand	$\log K_{Cu^ILH}$	$\log K_{Cu^IL}$	$\log K_{Cu^{II}L}$	$E_{1/2}$ [mV][d]	
				calc.[c])	exp.
1	7.00[a])	13.14	13.95	112	116
2	6.49[a])	12.33	11.69	198	172
3	7.73	13.39	15.85	15	84
4	9.46	14.20	12.89	237	262
5	[b])	14.35	10.15	409	424
6	10.17	13.95	10.27	377	396

[a]) $\log K(Cu(CH_3CN)^+ + LH^+ \rightleftharpoons Cu(CH_3CN)(LH)^{2+})$. [b]) Species not observed. [c]) Calculated with *Eqn. 7*. [d]) Against SHE.

The complexation with Cu(I) differs in two main points from that with Cu(II). First, the ring size has a much weaker effect on the stability constants with Cu(I) than with Cu(II). Whereas $K_{Cu^{II}L}$ varies almost by six orders of magnitude, the constants K_{Cu^IL} only encompass 2 orders of magnitude. No significant trend can be observed. The ligands with *cis*-configuration give the more stable complexes for the 12- and 16-membered rings, but the reverse is true for the 14-membered rings. Interestingly, *cis*-[16]aneN_2S_2 (**5**) forms the strongest complex of the whole series with Cu(I), but in turn the least stable species with Cu(II). As is easily verified by inspection of molecular models, the 16-membered macrocycles **5** and **6** can form practically unstrained tetrahedral complexes. The very different requirements of Cu(I) and Cu(II) are also clearly exemplified by *cis*-[14]aneN_2S_2 (**3**). This compound forms the by far most stable cupric complex of the whole series, but it forms the weakest Cu(I)-species of all 14- and 16-membered ligands.

The second point of difference between the complexation with Cu(II) and with Cu(I) concerns the formation of additional species beside the 1:1 complexes. With

Cu(II) and **1** or **2** a hydroxylated species $Cu(L)OH^+$ is formed, but with Cu(I) no deprotonation of CuL^+ is observed in any case up to pH 11.5. However, protonated complexes $CuLH^{2+}$ are formed and some of them show surprisingly high stabilities. The effect is most prominent with the smallest rings **1** and **2** where complexation of LH^+ starts around pH 2. With these two ligands the formation of $CuLH^{2+}$ is essentially complete around pH 4 and as shown in *Fig. 1* for *cis*-[12]aneN_2S_2, deprotonation to CuL^+ occurs in a separate buffer region. With the ligands **3**, **4** and **6** [$CuLH^{2+}$] reaches maximum values of 20–60%, so that no separate buffer regions can be observed, as indicated in *Fig. 1* for *cis*-[14]aneN_2S_2. No protonated species could be detected with **5**.

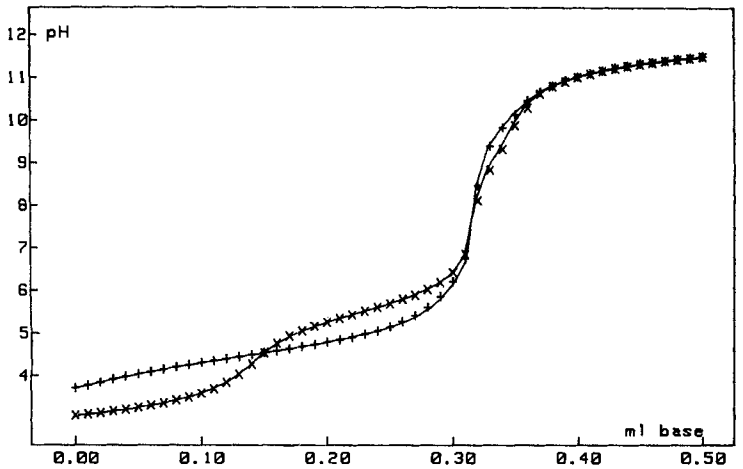


Fig. 1. *Potentiometric titration curves of* cis-*[12]aneN_2S_2* (**1**) (×) *and* cis-*[14]aneN_2S_2* (**3**) (+) *in the presence of Cu(I).* c_L = 3.2 mM, c_M = 2.56 mM, 2% *v/v* CH_3CN. —— *Calculated curves.*

As indicated in *Table 5*, the protonated species with the two smallest macrocycles **1** and **2** are ternary complexes $Cu(CH_3CN)(LH)^{2+}$, whereas the other ones are binary species $CuLH^{2+}$. The stoichiometry $Cu(CH_3CN)(LH)^{2+}$ must reflect the general preference of Cu(I) for tetrahedral or trigonal planar rather than square pyramidal or square planar geometry. Assuming a S_2N donor set in $CuLH^{2+}$, inspection of molecular models indicates a rather wide opening in the coordination sphere with the 12-membered ligands, so that an additional ligand such as CH_3CN can coordinate. This opening is gradually reduced by increasing the ring size, and with *trans*-[16]aneN_2S_2 an unstrained trigonal planar arrangement with effective shielding of both perpendicular sites by the macrocycle can be obtained. Therefore, no binding of CH_3CN to $CuLH^{2+}$ is observed for the larger rings. Finally, *cis*-[12]aneN_2S_2 is unique in forming a dimeric species $Cu_2L_2^{2+}$. A mixture of $Cu_2L_2^{2+}$ and monomeric CuL^+ is necessary to explain the buffer region between pH 5 and 6. The potentiometric results are in favour of a ternary species $Cu_2L_2(CH_3CN)_2^{2+}$ (since the difference between the apparent constants measured in 1% and 2% *v/v* CH_3CN is 0.09 per Cu^+), but the present data are not sufficient to unambiguously establish the composition.

Redox Properties. The cyclic voltammograms of the Cu^{2+}-complexes in 0.2M $NaClO_4$ are reversible or quasi-reversible, as indicated by peak separations ΔE = 52–84 mV, by $i_a/i_c \simeq 1$ and by the observation, that the peak separation ΔE remains constant for scan rates between 5 and 30 mVs^{-1}. Although all ligands have the same N_2S_2 donor set, the potentials $E_{1/2}$ range from 84 mV to 424 mV against standard hydrogen electrode (SHE), indicating that the size of the macrocyclic ring plays an important role. Of course the differences in $E_{1/2}$ reflect differences in the relative stability towards Cu(II) and Cu(I). The quantitative relationship *(7)* between the redox potential of a Cu(II)/Cu(I) system and the stability constants of both ions allows to calculate the $E_{1/2}$ values from the stability data *(Table 6)*.

$$E_{1/2}(CuL^{2+}/CuL^{+}) = E_{1/2}(Cu^{2+}/Cu^{+}) - 0.059 \log \frac{K_{Cu^{II}L}}{K_{Cu^{I}L}} \qquad (7)$$

Taking 160 mV for the redox potential $E_{1/2}(Cu^{2+}/Cu^{+})$ of the free ions [25], the values of $E_{1/2}(CuL^{2+},CuL^{+})$ have been calculated and are included in *Table 6*. The correlation between the experimental $E_{1/2}$ from cyclic voltammetry and the calculated ones from the stability constants is shown in *Fig. 2*. Since most voltammograms are only

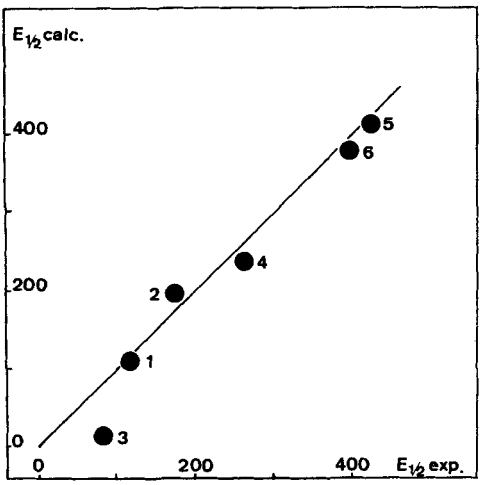


Fig. 2. *Comparison of redox potentials* (in mV *vs.* SHE) *calculated from potentiometric titrations with* Eqn. 7 *with results from cyclic voltammetry*

quasi-reversible, care must be taken in setting $E_{1/2}$ equal to the standard redox potential. Our values differ by 15–20 mV which could stem from junction potentials that are difficult to control. *cis*-[14]aneN_2S_2, however, makes an exception with a deviation of 69 mV or more than one order of magnitude in relative stability. The reason for this discrepancy is presently unknown, but may be related to the very slow complex formation of this ligand with Cu^{2+}. So, inspite of these problems, $E_{1/2}$ from cyclic voltammetry appears to be a good way to obtain a guess for the redox potential, even though some

of the electrode reactions are not reversible. *Gisselbrecht & Gross* [18] have used the $E_{1/2}$ of *trans*-[12]aneN_2S_2 and the stability constant of CuL^{2+} ($\log K_{Cu^{II}L} = 9.44$ [26]) to calculate the stability of CuL^+. However, since the reported value for $K_{Cu^{II}L}$ is wrong, the calculated $K_{Cu^{I}L}$ value is also. In addition, this route, the use of $E_{1/2}$ and of one stability constant, to deduce the stability of the other form has the disadvantage that it does not indicate whether other species beside ML are also present in solution.

Conclusions. – In saturated tetradentate macrocyclic ligands the N_2S_2 set of donor atoms is equally well suited for the complexation of Cu(I) or of Cu(II). This is not unexpected considering the results for the tetraazamacrocycles which very strongly favour the cupric state [27] and for the corresponding tetrathia analogs which form only weak Cu(II) complexes and greatly stabilize the cuprous state [19] [28]. Nevertheless, despite the identical set of donor atoms employed in the present study, rather significant differences in relative stability are observed. As indicated in *Table 6*, the range of $K_{Cu^{II}L}/K_{Cu^{I}L}$ spans almost seven orders of magnitude and cyclic voltammetry gives an analogous picture. Steric factors related to the rather different geometric requirements of Cu^{2+} and Cu^+ must be responsible and our results can be rationalized on this basis. Thus 14-membered rings are ideally suited to form square planar complexes [20]. The ideal 5,6,5,6 sequence of chelate rings in the complex with ligand **3** leads to the strongest Cu(II)-complex of the series and also to the lowest redox potential. 16-membered ring systems are too large for square planar complexes [20], but can form essentially strain-free tetrahedral structures as indicated by molecular models. Consequently, ligands **5** and **6** are forming the weakest Cu(II)-complexes and give rise to the highest CuL^{2+}/CuL^+ redox potentials. Twelve-membered ring systems finally neither can form square planar nor tetrahedral structures and pentacoordination with trigonal bipyramidal or square pyramidal geometry would be logical. Relatively low redox potentials are again observed, indicating that Cu^{2+} can somewhat better adapt to these requirements.

In the present study considerable effort was put on the direct determination of the stability constants of the Cu(I)-complexes by potentiometric titrations. The number of such studies is relatively limited and routinely the Cu(I) stability constants are calculated from redox potentials and the stability constants of the cupric complexes. Our own results lead to three main conclusions in this respect: *i*) In 5 out of 6 systems a reasonable correlation between the results from cyclic voltammetry and from equilibrium measurements (15 to 20 mV or roughly 0.3 log units in relative stability) is obtained. *ii*) Relatively high discrepancies between the two methods are however possible even in cases where the cyclic voltammograms show quasi-reversible behaviour. This was the case with ligand **3** with a difference of 69 mV or 1.2 orders of magnitude in relative stability. *iii*) Cyclic voltammetry would not have revealed the formation of additional complexes, specifically the protonated species $CuLH^{2+}$ and $Cu(CH_3CN)(LH)^{2+}$ with Cu(I).

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