# Equilibrium and solution structural study of the proton, copper(II), nickel(II) and zinc(II) complexes of 1-(2-aminoethylamino)-1-deoxy-D-galactitol

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Protonation and copper(II), nickel(II) and zinc(II) complex-formation equilibria of 1-(2-aminoethylamino)-1-deoxy-D-galactitol and the solution co-ordination structure of the complexes were investigated by potentiometric titrations, UV/VIS absorption, CD, EPR and $^{13}$C NMR spectroscopies in aqueous solution ($I = 0.1$ mol dm$^{-3}$, $NaClO_4$; $T = 298$ K). In acidic media the ethane-1,2-diamine (en) residue dominates the co-ordination for all the metal ions studied, but the spectroscopic results are consistent with weak co-ordination of alcoholic hydroxy group(s). In equimolar solution and at neutral pH, dialkoxide-bridged dimeric species were formed with nickel(II) and copper(II). In case of an excess of galactitol bis- and tris-complexes were also detected. In the latter system metal-promoted deprotonation occured above pH 9 and in this way the second ligand is successively displaced from the co-ordination sphere of copper(II). In the finally formed $MLH_{-2}$ species the ligand is co-ordinated by two amino and two deprotonated alcoholic hydroxy groups. Nickel(II) formed a $ML_2H_{-2}$ complex in the alkaline pH region. The deprotonation processes of the $ZnL_2$ complex leading also to $ML_2H_{-2}$ took place at almost the same pH as for $NiL_2$. Evidence of the deprotonation of the alcoholic hydroxy groups is available only above pH ≈ 11 in the zinc(II)-containing system.

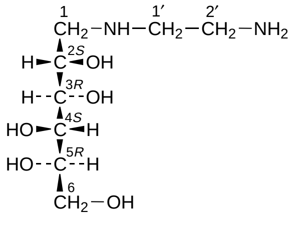
The complex formation of amino alcohols is of increasing interest from both chemical and biological aspects.[1–4] The presence of anchoring amino group(s) may promote the deprotonation of strongly basic donor groups, such as the amide group in peptides[5] or the alcoholic hydroxy group in aldosamines,[6] by the formation of a stable chelate ring. In the case of cyclic amino alcohols it was established that the conformation of the compound determines the number and quality of the co-ordinating donor groups.[7] Still several questions remained concerning the behaviour of open-chain-type carbohydrate derivatives such as: (*i*) the co-ordination of still protonated alcoholic hydroxy groups to the metal ions, (*ii*) the assignment of the deprotonated alcoholic hydroxy groups and (*iii*) the number of such groups.

To answer these questions we started a systematic study on the metal-ion complexation of polyalcohol type ligands obtained from simple sugars by varying the anchoring groups in the molecule.[8] The present compound is 1-(2-aminoethylamino)-1-deoxy-D-galactitol (aegaln), prepared from D-galactose and ethane-1,2-diamine. Potentiometric, UV/VIS, CD, EPR and NMR spectroscopic methods were utilised to obtain the stability constants and the solution co-ordination structure of its copper(II), nickel(II) and zinc(II) complexes formed in aqueous media.

## Experimental

### Materials

The galactitol was obtained as described previously.[2] Its purity was checked by elemental analysis, $^1$H and $^{13}$C NMR spectroscopy and by potentiometric titration. Copper(II), nickel(II) and zinc(II) perchlorate (Fluka) solutions were standardised complexometrically. pH-Metric titrations were performed using Titrisol standard NaOH solution (Merck). All other reagents were Reanal products of analytical grade.



aegaln

### pH-Metric measurements

The co-ordination equilibria were investigated by potentiometric titrations in aqueous solution ($I = 0.1$ mol dm$^{-3}$, made up using $NaClO_4$ and $T = 298 \pm 0.1$ K) in an automatic titration set including a Dosimat 665 (Metrohm) autoburette, a Radelkis OP-201/8 precision digital pH-meter and an IBM compatible personal computer. The Orion 9103BN type semi-micro combined pH electrode was calibrated[8] using the modified Nernst equation (1), where $J_H$ and $J_{OH}$ are fitting

$$E = E_0 + K\cdot\log[H^+] + J_H[H^+] + J_{OH}K_W[H^+]^{-1} \quad (1)$$

parameters in acidic and alkaline media for the correction of experimental errors, mainly due to the liquid junction and to the alkaline and acidic errors of the glass electrode; $K_W = 10^{-13.75}$ mol$^2$ dm$^{-6}$ is the autoprotolysis constant of water.[9] The parameters were calculated by a non-linear least-squares method.

The species formed in the systems were characterised by the

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equilibrium process (2) or (3) while the formation constants for

$$pM + qL \xrightleftharpoons{\beta_{\mathbf{M}_p\mathbf{L}_q\mathbf{H}_{-r}}} M_pL_qH_{-r} + rH \qquad (2)$$

$$pM + qL + rOH \xrightleftharpoons{\beta_{\mathbf{M}_p\mathrm{L}_q(\mathrm{OH})_r}} M_pL_q(OH)_r \qquad (3)$$

these generalised species are given by equation (4) and were

$$\beta_{\mathbf{M}_p\mathrm{L}_q\mathrm{H}_{-r}} =$$

$$\frac{[M_pL_qH_{-r}][H]^r}{[M]^p[L]^q} = \frac{[M_pL_q(OH)_r](K_\mathbf{W})^r}{[M]^p[L]^q[OH]^r} = \beta_{\mathbf{M}_p\mathrm{L}_q(\mathrm{OH})_r}(K_\mathbf{W})^r \qquad (4)$$

calculated by the computer program PSEQUAD.[10] Here M denotes the metal ion and L the non-protonated ligand molecule. In the following, charges are omitted and the water molecules (necessary to ensure six-co-ordination) are not shown.

The protonation constants were determined from five titrations (80–110 data points per titration and the galactitol concentration was varied from $2 \times 10^{-3}$ to $2 \times 10^{-2}$ mol dm$^{-3}$). The complex stability constants were also determined from five independent titrations (80–110 data points per titration) for all metal-to-galactitol ratios in each system. The copper(II)-to-galactitol ratio was varied from 1 : 1 to 1 : 10, while the nickel(II)- and zinc(II)-to-galactitol ratio was varied from 1 : 2 to 1 : 10; in all systems studied the metal-ion concentration ranged from $2 \times 10^{-3}$ to $10^{-2}$ mol dm$^{-3}$.

### Electronic absorption and CD measurements

The UV/VIS spectra were recorded on a Hewlett-Packard 8452A diode-array spectrophotometer. The individual spectra of the copper(II) complexes formed were calculated by PSEQUAD. The CD spectra were recorded on a Jobin Yvon CD6 spectropolarimeter in the wavelength interval from 230 to 800 nm. The metal-ion concentration was $5 \times 10^{-3}$ mol dm$^{-3}$ in cells with 0.1 and 1 cm optical pathlengths in the UV and VIS spectral regions, respectively. The CD data are given as the differences in molar absorption coefficients between left and right circularly polarised light, normalised to the metal-ion concentration in dm$^3$ mol$^{-1}$ cm$^{-1}$ units.

### EPR measurements

The EPR spectra were recorded on a JEOL-JES-FE 3X spectrometer in the X band at 298 K with 100 KHz field modulation. Manganese(II)-doped MgO powder served as the field standard. The copper(II) concentration was $5 \times 10^{-3}$ mol dm$^{-3}$. The EPR parameters were calculated by a recently developed computer program[11] able to treat the spectra of several (but preferably two) coexisting species.

### NMR measurements

The $^{13}$C NMR measurements were performed on a Bruker AM-400 at 100.12 MHz operating at room temperature. The pH readings in a mixture of 10% $D_2O$–90% water were uncorrected for the isotopic effect. The chemical shifts are given as relative shifts from the sodium salt of 4,4-dimethyl-4-silapentane-1-sulfonate using 1,4-dioxane as internal reference (δ 67.4 from this sodium salt).

## Results and Discussion

The galactitol undergoes two deprotonation processes during the potentiometric titration (Table 1) from pH 2 to 11 which can be assigned to the two ammonium groups, on the basis of $^{13}$C NMR titrations,[2] the larger protonation constant to the primary, the smaller to the secondary ammonium group having two electron-attracting substituents. The protonation constants are in very good agreement with those reported previously[2] (see Table 1). Comparison with the protonation constants of en[12,13] and *N*-(2-hydroxyethyl)ethane-1,2-diamine (hen),[14] shown in Table 1, reflects the negative inductive effect of the polyhydroxyalkyl chain present in aegaln. The first alcoholic hydroxy group has the largest effect, while that of the further hydroxy groups is much smaller. The alcoholic hydroxy groups do not deprotonate in the pH interval studied.

**Table 1** Protonation constants of aegaln and related diamine compounds ($I = 0.1$ mol dm$^{-3}$, $NaClO_4$; $T = 298$ K)

| | aegaln | en | hen |
|---|---|---|---|
| $pK_d^{H_2L}$ | 6.43(1) | 7.10[a] | 6.60[b] |
| | 6.39[c] | 7.12[d] | |
| $pK_d^{HL}$ | 9.50(1) | 9.70[a] | 9.59[b] |
| | 9.48[c] | 9.96[d] | |

[a] From ref. 12 ($I = 0.1$ mol dm$^{-3}$, $NaClO_4$). [b] From ref. 14 ($I = 0.1$ mol dm$^{-3}$, $KNO_3$). [c] From ref. 2 ($I = 0.1$ mol dm$^{-3}$, NaCl). [d] From ref. 13 ($I = 0.1$ mol dm$^{-3}$, $KNO_3$).

**Table 2** Overall stability constants and the visible absorption properties of the complex species formed in the copper(II)–aegaln system, calculated by the PSEQUAD computer program ($I = 0.1$ mol dm$^{-3}$, $NaClO_4$; $T = 298$ K)

| Species | log β | $\lambda_{max}$/nm | $\varepsilon_{max}$/dm$^3$ mol$^{-1}$ cm$^{-1}$ |
|---|---|---|---|
| Cu(HL) | 13.63(2) | — | — |
| CuL | 10.08(1) | 671 | 48 |
| $Cu_2L_2H_{-2}$ | 10.67(1) | 597 | 128 |
| $Cu_2L_2H_{-3}$ | 0.77(2) | 647 | 133 |
| $CuLH_{-2}$ | −6.28(1) | 638 | 67 |
| CuL(HL) | 22.25(3) | — | — |
| $CuL_2$ | 17.21(1) | 580 | 92 |
| $CuL_2H_{-1}$ | 7.45(1) | 662 | 93 |

### Copper(II) complexes

In the course of the potentiometric titrations no precipitation of the metal hydroxide was observed at any metal to galactitol ratios and concentrations applied in the region pH 2–11.5. The stability constants for the set of complex species giving the best fit to the experimental data are presented in Table 2.

**Complexes between pH 2 and 5.** In the acidic pH region Cu(HL) and CuL species were formed at any metal-to-galactitol ratio studied (Fig. 1). The formation constants for these species on the basis of equation (5) are 4.13(2) and

$$M + H_rL \rightleftharpoons M(H_rL), \text{ where } r = 1 \text{ or } 0 \qquad (5)$$

10.08(1), respectively, reflecting an extra stabilisation in species CuL caused by the chelate ring formation.

The basicity-adjusted stability constants $\log K = \log \beta_{\mathbf{ML}} - \log \beta_{\mathbf{H}_2\mathrm{L}}$ relating to equation (6) for the CuL species of en, hen

$$M + H_2L \rightleftharpoons ML + 2H \qquad (6)$$

and aegaln [−6.57;[13] −6.10[14] and −5.85(1) in logarithmic units, respectively] reveal some extra stabilisation in complexes of hydroxyamines compared to en. The UV/VIS (Table 2) and EPR spectra of the CuL complex (Table 3, Fig. 2) are entirely compatible with a 2N,2O donor set in the equatorial plane of copper(II). The above-mentioned extra stabilisation and the existence of a relatively low intensity CD spectrum for this complex (Fig. 3) suggest the weak, additional co-ordination of at least one of the oxygen-donor atoms of the polyhydroxyalkyl chain located on carbon atom(s) having *S* configuration, taking into account the shape of the spectrum[6,8] because of the lack of any optical activity in the en part of the ligand.

**Complexes between pH 5 and 8.** The species distribution diagrams for the L : M = 1 : 1 and 3 : 1 systems at physiological pH (Fig. 1) show an equilibrium between two species depending on the metal-to-galactitol ratio. The species formed in equimolar solution could be characterised as $CuLH_{-1}$ or its oligomer $(CuLH_{-1})_n$. The process leading to this species can be explained in two ways: either by deprotonation (*i*) of an alcoholic hydroxy group from the polyhydroxyalkyl chain or (*ii*) of a co-ordinated water molecule. The $pK_d$ value for an alcoholic hydroxy group is higher even in the presence of copper(II) ions when only this type of donor group is present in the ligand molecule,[15] and copper(II) hydroxide precipitation is also expected. If an anchoring donor group is present in the molecule, and the ligand conformation allows the co-ordination of the alcoholic OH group, its deprotonation occurs in the region pH 5–7.[6,8] However, the co-ordinated water molecule deprotonates in the same pH region ($pK_d \approx 5$–6) in the aqueous copper(II) solutions.[16] Since pH-metric measurements alone cannot distinguish between these processes, spectroscopic

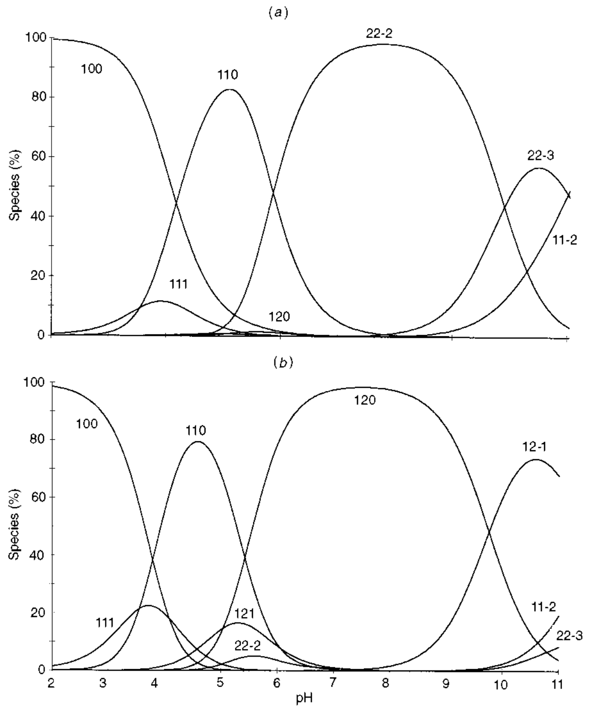


**Fig. 1** Species distribution curves for the copper(II)–aegaln 1 : 1 (*a*) and 1 : 3 (*b*) systems calculated on the basis of the copper(II) contents of the individual species ($[Cu^{2+}] = 0.01$ mol dm$^{-3}$)

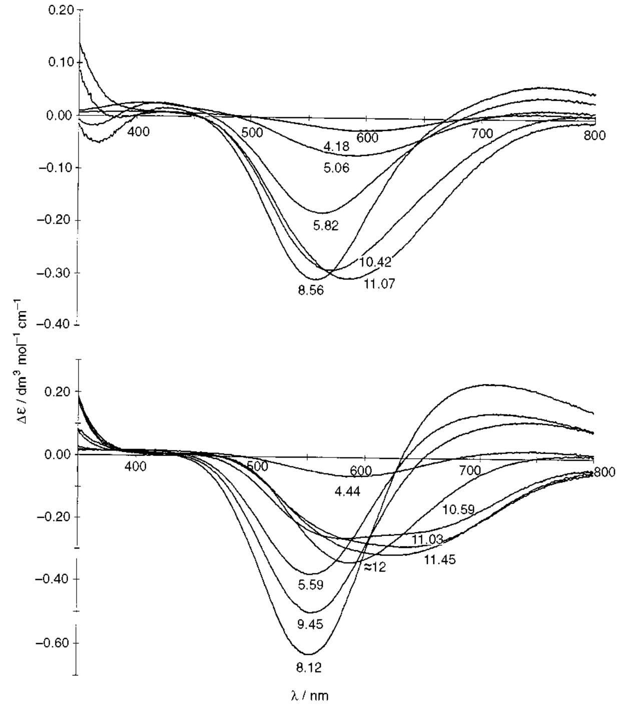


**Fig. 3** Circular dichroism curves detected in copper(II)–aegaln 1 : 1 (*a*) and 1 : 2 (*b*) systems as a function of pH: ($[Cu^{2+}] = 0.005$ mol dm$^{-3}$)

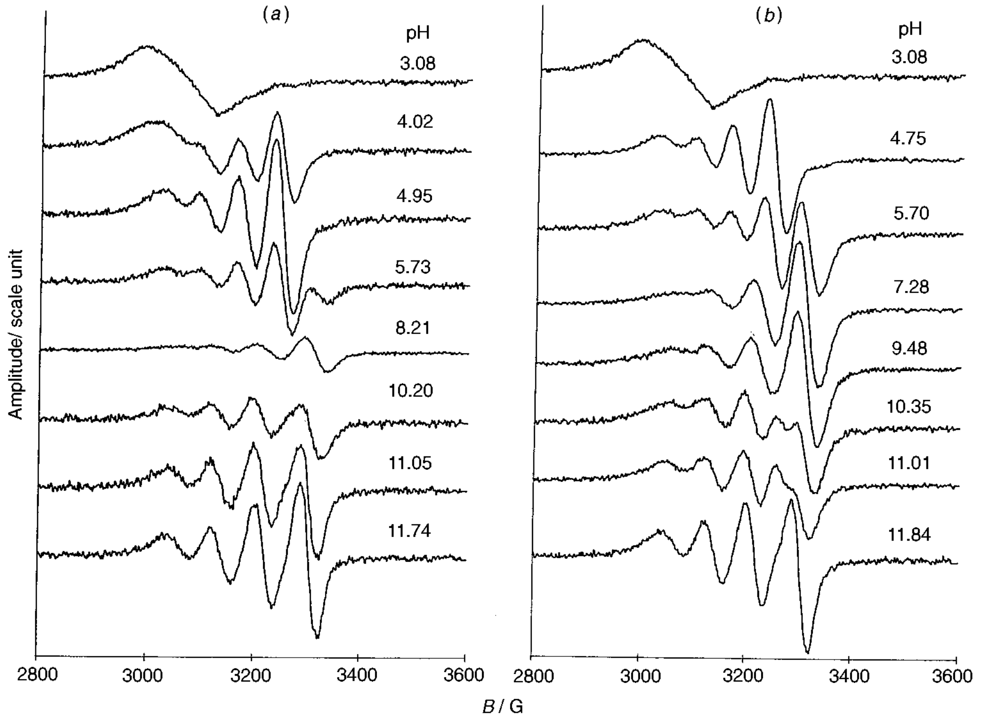
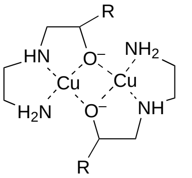


**Fig. 2** The EPR curves for copper(II)–aegaln 1 : 1.25 (*a*) and 1 : 2.5 systems (*b*) ($[Cu^{2+}] = 0.005$ mol dm$^{-3}$) systems as a function of pH

**Table 3** The EPR parameters[a] calculated for the individual complex species in the copper(II)–aegaln systems

| Species | $g_0$ | $A_0$/mT | $A_0$(N)/mT | $n_N$ | $\sigma_M$/mT $-\frac{3}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{3}{2}$ |
|---|---|---|---|---|---|---|---|---|
| CuL | 2.141 | 6.59 | 1.0 | 2 | 4.9 | 3.4 | 2.4 | 1.6 |
| $CuLH_{-2}$ | 2.119 | 7.94 | 0.9 | 2 | 4.1 | 2.8 | 1.9 | 1.3 |
| $CuL_2$ | 2.112 | 7.88 | 1.0 | 4 | 8.9 | 4.8 | 2.8 | 1.5 |
| $CuL_2H_{-1}$ | 2.123 | 6.32 | 1.0 | 3 | 4.2 | 2.9 | 2.0 | 1.4 |
| $CuLH_{-2}$[b] | 2.119 | 7.93 | 0.8 | 2 | 4.4 | 3.0 | 2.1 | 1.5 |

[a] The $g_0$ values are assumed to be accurate to 0.001, $A_0$ values for copper(II) to 0.01 mT, $A_0$ values for nitrogens to 0.05 mT, and the linewidth values to a maximum of 0.3 mT in the low magnetic field region; 1G = $10^{-4}$ T. [b] Determined from the spectra of the solutions containing an excess of galactitol.



**Scheme 1** Structure proposed for the dimeric complex $M_2L_2H_{-2}$

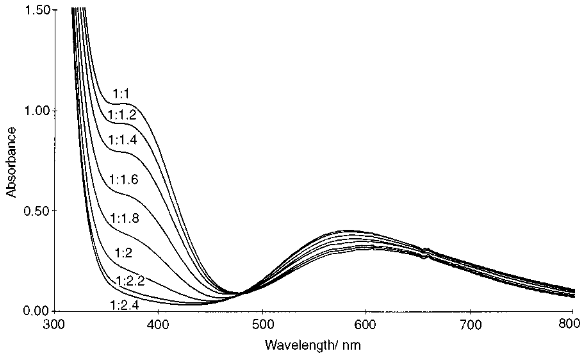


**Fig. 4** Visible absorption spectra of the copper(II)–aegaln system as a function of the galactitol excess ($[Cu^{2+}] = 0.01$ mol dm$^{-3}$)

measurements are required to obtain additional information on the structure of the above complex.

The dramatic decrease in the intensity of EPR spectra [Fig. 2(*a*)] between pH 5 and 7 indicates the formation of oligomeric copper(II) complex(es) having strong antiferromagnetic interactions between the adjacent copper(II) centres. The strong coupling suggests the formation of a dihydroxide- (or dialkoxide)-bridged dimer complex.

The increase in the CD intensity associated with the d–d transition [see Fig. 3(*a*)] between pH 5 and 9 in equimolar solution is evidence in support of the deprotonation of alcoholic hydroxy group(s) in the oligomeric species. Thus the anchoring en residue effectively promotes deprotonation of an alcoholic OH group. In this complex the vicinal dissymmetry of the C(2) carbon atom determines the sign and the intensity of the Cotton effect observed.

The presence of a charge-transfer (c.t.) absorption band at about 380 nm (Fig. 4), strongly indicates a dibridged dimeric structure in $(CuLH_{-1})_n$. This c.t. band disappears when the galactitol excess is increased to L : M = 2.4 : 1. It is characteristic for dibridged copper(II) complexes, when alkoxide, phenoxide, carboxylate or hydroxide oxygen-donor atoms serve as bridges,[1,17–19] and was assigned to a copper(II)–oxygen–copper(II) charge-transfer transition.[18,19] It is associated with CD bands of low intensity[18] when an optically active ligand coordinates [Fig. 3(*a*)]. Experimental results showed[20] that the intensity of the above-mentioned charge transfer band is affected by the Cu–O–Cu angle, which also depends on the number of the chelate ring atoms containing the bridging oxygen. From literature data,[20] we suggest the deprotonated C(2)–OH groups to be the bridges, in accord with the CD spectroscopic results (see Scheme 1).

A number of di- and oligo-meric copper(II) complexes with similar ligands (short-chain diamines and mono- and di-amino-alcohols) were prepared and characterised by X-ray diffraction,[3,17] revealing copper(II) dimers with either hydroxide or alcoholic hydroxy oxygen bridging atoms. The formation of dimeric species has also been suggested with some related ligands in solution.[1,18] Replacement of the monomeric species with dimeric $Cu_2L_2H_{-2}$ complexes in the computation of the pH-metric titration curves significantly improved the fit of the experimental data. The stability constant $\log K_0 = \log \beta_{M_2L_2(OH)_2} - 2\log \beta_{ML} - 2\log K_W = 18.01(1)$ for the olation reaction (7) is higher than analogous constants for complexes

$$2ML + 2OH \rightleftharpoons M_2L_2(OH)_2 \qquad (7)$$

of *N*-alkyl-substituted en derivatives ($\log K_0 \approx 15$), where hydroxo-bridged dimers definitely exist.[21] This also suggests that the bridging donor groups are the alcoholic hydroxy groups rather than hydroxide ions (Scheme 1).

In the systems containing an excess of galactitol a monomeric bis complex is formed instead of the dimer in the same pH region. If we compare the basicity-adjusted stability constant $\log K = \log K_{ML_2} - \log \beta_{H_2L}$ [−8.80(2)] for reaction (8)

$$ML + H_2L \rightleftharpoons ML_2 + 2H \qquad (8)$$

with that for the en complex (−8.04),[12] in contrast to the CuL species, the $CuL_2$ complex of aegaln is less stable, due to the steric effect of the large polyhydroxyalkyl side chains. Such a steric effect has also been found in copper(II) complexes of *N*-alkyl-substituted en derivatives.[13]

The wavelength of the absorption maximum for the $CuL_2$ complex formed in the presence of an excess of galactitol between pH 5 and 9 (580 nm, Table 2) is similar to that of the en bis complex (560 nm[22]), indicating the presence of four amino nitrogen-donor groups in the equatorial positions of the copper(II) ions. The small red shift suggests weak axial co-ordination of alcoholic hydroxy groups, but the large CD intensity [Fig. 3(*b*)], compared to that of the CuL complex, requires us to take into account the conformational contribution of the chelate rings, enforced by the steric interaction of the two ligands.[23]

The EPR parameters determined from the spectra recorded the presence of an excess of galactitol in solution at physiological pH are similar to those for copper(II) complexes with four amino nitrogen-donor atoms in equatorial co-ordination sites.[24,25] The increased linewidths (Table 3), especially at lower magnetic fields, reflect the increased radius of the complex molecule compared to that formed in solutions with equimolar metal : ligand composition.

**Complexes above pH 8.** In equimolar solution, first the $Cu_2L_2H_{-3}$ complex forms (Fig. 1) at increasing pH, still with antiferromagnetic coupling between the two metal ions. However, the charge-transfer band discussed above disappears, while an important red shift of the d–d transition can be observed (see Table 2), indicating that this further deprotonation process changes the geometrical arrangement around the copper(II) chromophores in the $Cu_2L_2H_{-3}$ complex.

In case of an excess of galactitol deprotonation of the bis complex $CuL_2$ give the $CuL_2H_{-1}$ species was detected with a p$K_d$ value of 9.76(2). Increase of pH up to 10 causes a large red shift, approximately 90 nm, of the absorption maximum (Table 2) for this complex, which cannot be explained[22] only by axial co-ordination of a deprotonated alcoholic hydroxy group.

Rather it suggests a rearrangement of donor groups around copper(II) as seen later.

The best fit to the experimental EPR spectrum recorded at pH 10.35 [Fig. 2(*b*)] was obtained by taking into account two coexisting major species. One is dominant at pH 7 and was assigned as the $CuL_2$ species. The second can therefore be attributed to the $CuL_2H_{-1}$ complex. The EPR parameters of the latter species (Table 3) indicated three nitrogen donor atoms in the equatorial plane of the copper(II) ion and a strong tetragonal distortion of the co-ordination sphere, which could also explain the red shift of the visible absorption maximum. Thus, in agreement with previous results, we suggest the rearrangement of the co-ordination sphere as follows: one of the ligands is co-ordinated by two amino and one deprotonated alcoholic hydroxy groups in equatorial positions, while one of the amino groups of the second ligand is displaced from an equatorial to axial position. The CD intensity at pH ≈ 10.3 is decreased in comparison with that of the $CuL_2$ complex [Fig. 3(*b*)], suggesting that the vicinal dissymmetric effect through a deprotonated alcoholic hydroxy group became again the main contribution to the optical activity.

On increasing the pH to 11.5 further deprotonation processes were detected and the spectroscopic results suggest the formation of the same $CuLH_{-2}$ species at any metal-to-ligand ratio studied. In this way, the displacement of the second ligand from the co-ordination sphere of copper(II), starting with the formation of $CuL_2H_{-1}$, was found to be complete at this pH. The absorption maximum for the complex $CuLH_{-2}$ (638 nm, Table 2), formed either from $Cu_2L_2H_{-3}$ or $CuL_2H_{-1}$, is consistent with values for copper(II) complexes with two amino and two deprotonated hydroxy groups in the equatorial plane ($\lambda_{max,calc} = 629$ nm[22]). The EPR parameters of the $CuLH_{-2}$ species suggest a ligand-field energy increase, $g_0$ is decreased and $A_0$ is increased, compared to that of CuL. The formation of mixed hydroxo complexes results in a significant decrease in hyperfine coupling constants[25b] ($A_0$). Therefore our results suggest a metal-promoted deprotonation and co-ordination of the second alcoholic hydroxy group too, in the equatorial positions of the copper(II) in $CuLH_{-2}$. The patterns of the CD spectra further indicate deprotonation of the second alcoholic hydroxy group, which could be the C(4)–OH for steric reasons.

## Nickel(II) and zinc(II) complexes

The potentiometric titration curves of the nickel(II)–aegaln 1:1 system can be fitted with the same set of species as that for the copper(II)-containing system, though there is no independent evidence for the presence of dinuclear species. Zinc(II) forms a hydroxide precipitate in equimolar solution. Apart from the shift of the complex-formation processes toward higher pH as compared to the copper(II) complexes, one can only observe differences in the behaviour of these metal ions when an excess of galactitol is applied: (*i*) nickel(II) and zinc(II) formed $ML_3$ besides the mono and bis complexes, while this complex was not detected with copper(II) even at a ten-fold galactitol excess; (*ii*) in alkaline solutions $ML_2H_{-2}$ species were also detected, in contrast to the copper(II)-containing systems. The stability constants calculated for the complexes formed with nickel(II) and zinc(II) are given in Table 4. The stability of the parent complexes follows the Irving–Williams order for the transition-metal complexes. The $\log(K_{ML}/K_{ML_2})$ values, however, are significantly lower than the same value for the copper(II) complexes due to the relatively strong, supplementary axial co-ordination of the alcoholic hydroxy groups in $ML_2$ species too, which is not favoured in the case of copper(II). The stability increase for both ML and $ML_2$ compared to the complexes of diamine ligands containing no polyhydroxyalkyl chain is also shown by the basicity-adjusted stability constants. According to equations (6) and (8) these are −10.26, −9.37, −9.12(1) and −11.14, −10.57, −10.17(2) for the nickel(II) complexes of en,[14] hen[14] and aegaln, respectively. The same values for the zinc(II) complexes are −11.99,[14] −10.91,[26] −10.80(1) from equation (6) and −12.98,[14] −11.40,[26] −11.15(2) from equation (8). The existence of CD spectra provides evidence for alcoholic hydroxy group co-ordination in the nickel(II) complexes. The wavelengths of the absorption maxima are very similar to those predicted by Jörgensen's rule of average environment.[27] Both the UV/VIS and the CD spectra of the equimolar and the galactitol excess systems are different above pH 6 and they remain different until the end of the titration (pH 11.5) as a consequence of the formation of $NiL_2H_{-2}$ species. Circular dichroism spectra of similar shape and intensity were observed by Yano and co-workers[28] for the ternary nickel(II) complexes with en and glycosylamine ligands (the latter derived from ketoses and ethanediamines), and crystal structure determination demonstrated the co-ordination of two alcoholic hydroxy groups.

Carbon-13 NMR titration have been performed for the zinc(II)–aegaln system as a function of pH at 3:1 galactitol to metal ratio. The results are shown in Fig. 5 together with the $^{13}C$ NMR chemical shifts of the galactitol itself as a function of pH. In the presence of zinc(II) ions one set of eight signals was observed over the whole pH region, indicating that the com-

**Table 4** Overall stability constants of the complex species formed in the nickel(II)– and zinc(II)–aegaln systems ($I = 0.1$ mol dm$^{-3}$, $NaClO_4$; $T = 298$ K)

| | log β | |
|---|---|---|
| Species | $M^{2+} = Ni^{2+}$ | $Zn^{2+}$ |
| MHL | 11.79(1) | 11.01(2) |
| ML | 6.81(1) | 5.13(1) |
| $M_2L_2H_{-2}$ | −1.37(1) | −2.72(1) |
| $M_2L_2H_{-3}$ | −11.03(2) | −11.91(2) |
| $MLH_{-2}$ | −12.31(1) | −12.06(1) |
| $ML_2$ | 12.57(1) | 9.91(1) |
| $ML_3$ | 14.77(2) | 12.14(3) |
| $ML_2H_{-1}$ | 2.97(1) | 0.86(1) |
| $ML_2H_{-2}$ | −8.40(2) | −10.25(3) |

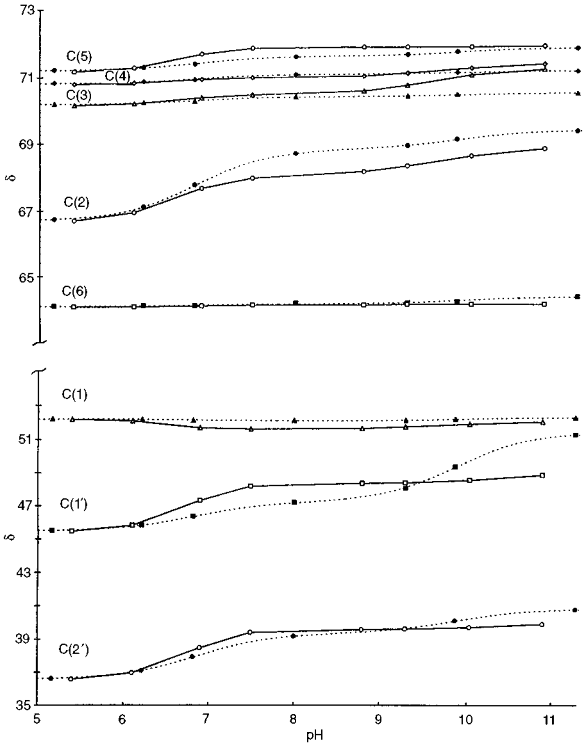


**Fig. 5** The $^{13}C$ NMR chemical shifts of the aegaln carbon atoms in the absence (dotted line) and in the presence (full line) of zinc(II) ions as a function of pH ($[Zn^{2+}] = 0.1$ mol dm$^{-3}$, [aegaln] = 0.3 mol dm$^{-3}$)

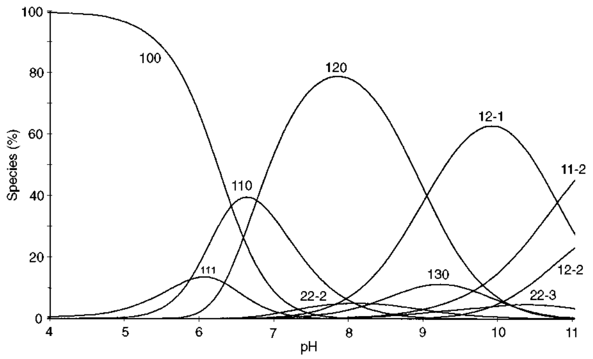


**Fig. 6** Species distribution curves for the zinc(II)–aegaln 1:3 system calculated on the basis of the zinc(II) contents of the individual species ($[Zn^{2+}] = 0.01$ mol dm$^{-3}$)

plexes formed are in fast exchange with each other on the $^{13}C$ NMR time-scale. The first significant shifts occurred in the region pH 6–8. The signals of C(1′), C(2′) and C(2) are most affected by the complex-formation processes (Fig. 5). According to the β effect,[29] co-ordination of the primary and secondary amino groups is suggested in this pH region for the ZnL and $ZnL_2$ parent complexes. This is in good agreement with the species distribution in this system (Fig. 6). Further increase of pH did not result in changes of the chemical shifts of the carbon signals of the en residue. Above pH 9 small but significant shifts can be observed in the C(2) and C(3) signals due to deprotonation processes (Fig. 5). This shows that one of the alcoholic hydroxy groups takes part in co-ordination either directly or through hydrogen bonding with a co-ordinated hydroxide ion. While the signals are sharp in this spectrum, above pH 11 severe broadening of the $^{13}C$ NMR lines occurs which affects mostly the C(2) carbon. Owing to this the chemical shift cannot be determined with accuracy, but it suggests that deprotonation of the alcoholic hydroxy groups takes place only at strongly alkaline pH.

## Conclusion

The compound aegaln proved to be an effective complex-forming agent for copper(II) ions. The en-type chelate ring serves as an anchor for metal-promoted deprotonation of the alcoholic hydroxy groups in aegaln which results in the formation of a dialkoxide-bridged dimeric species in the equimolar systems. In the presence of an excess of galactitol, the bis-en type of co-ordination is favoured near pH 7. With increasing pH, however, metal-promoted deprotonation of alcoholic hydroxy group(s) also occurs in this system near pH 9. During this process the second ligand is successively displaced from the co-ordination sphere of copper(II). The formation of $CuL_2H_{-1}$ and $CuLH_{-2}$ species in the alkaline pH region reflects that the polyhydroxyalkyl side chain effectively competes with the en-type co-ordination even in the presence of an excess of galactitol. In nickel(II)- and zinc(II)-containing systems complexes of composition $ML_3$ and $ML_2H_{-2}$ have also been observed. The CD spectra showed that the nickel(II) complexes are optically active, indicating participation of the alcoholic hydroxy groups in the co-ordination; NMR spectroscopy revealed that these groups take part in co-ordination at $pH \approx 9$ for the zinc(II) complexes but their deprotonation occurs only above pH 11.

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