Effects of Structural Distortion on the Ligand Exchange Reactions of Copper(II)–Schiff Base Complexes

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Summary Structural distortion of copper(II)–Schiff base complexes $Cu(sal–N–R)_2$ from square planar towards tetrahedral geometry causes the rates of the ligand exchange reactions between $[Cu(sal–N–R)_2]$ and ethylenediamine to increase.

IT has recently been reported that the substitution reactions of the copper(II) complex of 2,2′,2″-triaminotriethylamine, which has a trigonal bipyramidal structure, are dramatically slower (by a factor of *ca.* 3000) than those of $[Cu(H_2O)_6]^{2+}$.[1] This decrease is attributed to the absence of the dynamic Jahn–Teller effect.[2] The importance of slow substitution reactions at the metal centres of copper–proteins is becoming increasingly apparent,[3] and a great deal of interest has recently focussed on attempts to relate the results of kinetic studies of ligand exchange reactions of copper(II) complexes to the biological transport of copper.[4,5] We here report the first direct correlation between structural distortion and kinetic reactivity of copper(II) complexes to be unambiguously demonstrated.

The ligand exchange reactions of various bis(salicylaldimine) copper(II) complexes $[Cu(sal–N–R)_2]$ with ethylenediaminetetra-acetate (edta) and ethylenediamine (en) in EtOH–H_2O (50% v/v) have been studied. *X*-Ray crystallographic studies have shown (Table 1) that a change of the substituent group, R, on the imine nitrogen of the ligand from a normal alkyl to an α-branched alkyl group causes a change in structure from square planar to nearly tetrahedral.[6] Spectroscopic studies have demonstrated the retention of these structural features in weakly co-ordinating solvents.[7] Thus, this series of complexes affords a system in which the ligand donor set remains constant while the structure varies.

TABLE 1. Bond distances Å

R	Cu–N	Cu–O	θ[a]
H	1·90	1·91	—
Me	1·99	1·90	—
Pr^n	1·99	1·86	—
Pr^i	1·98	1·88	59·7
Bu^t	Av. 1·98	Av. 1·90	53·6

[a] θ = The dihedral angle between the planes of the two ligands for distorted tetrahedral geometry.

Initial experiments utilizing edta demonstrated a lack of dependence on the edta concentration even though the product in every case is $[Cu(edta)]^{2-}$. The rates of these reactions are found to be identical to the rates of hydrolysis of the bound salicylaldimine ligands. In addition, the rate of the ligand exchange reaction of bis-salicylaldehydocopper(II) with edta is outside the range of the stopped-flow instrument. Thus, hydrolysis of bound Schiff base appears to be the rate-determining step with edta acting as a scavenger for the hydrolysed complexes.

With en as the exchanging ligand, a first-order dependence on added en is observed with the rates of these reactions at least 10 times greater than those with edta. Thus, we conclude that the process observed is the exchange of en for an intact Schiff base. The experimentally observed rate law is given in equation (1), where $k_2[en]_T = k_2^{en}[en] + k_2^{Hen}[Hen^+] + k_2^{H_2en}[H_2en^{2+}]$. We have determined the pK_a's of H_2en^{2+} and Hen^+ by potentiometric titration at 25·0 °C

$$-d[Cu(sal\text{–}N\text{–}R)_2]/dt = k_2[Cu(sal\text{–}N\text{–}R)_2][en]_T \quad (1)$$

[$\mu = 0{\cdot}10$ M ($NaClO_4$)] in 50% v/v EtOH–H_2O to be $6{\cdot}96 \pm 0{\cdot}03$ and $9{\cdot}64 \pm 0{\cdot}02$, respectively. Utilizing these values and kinetic data from pH 9 to 12, $k_2^{en} = 1{\cdot}9 \times 10^3$ l mol^{-1} s^{-1} and $k_2^{Hen} = 3{\cdot}0 \times 10^2$ l mol^{-1} s^{-1} for [Cu(sal–N–Bu^n)$_2$]. Comparison of the rate constants for the square planar species (R = Pr^n, Bu^n, and n-decyl) (Table 2) reveals

TABLE 2. Dependence of k_2 on R for the reaction of en with [Cu(sal–N–R)$_2$] at pH 10·3, $\mu = 0{\cdot}10$ ($NaClO_4$), 25·0 °C.

R	$10^{-3}k_2$ l mol^{-1} s^{-1}
Pr^n	3·63
Pr^i	28·3
Bu^n	1·66
Bu^s	4·4
n-decyl	0·257

an inverse relationship between k_2 and chain length, the values of k_2 decreasing in the order Pr^n > Bu^n > n-decyl. This trend strongly implies that the rate-determining step involves opening of a Schiff base chelate ring.

There are two possible mechanisms which most reasonably explain the first order dependence on en which accompanies the rate-limiting ring-opening. Path 1 involves the formation, *via* a rapidly established pre-equilibrium, of an intermediate species in which one of the Schiff base donor groups is displaced by a solvent molecule (leaving one of the Schiff base ligands bound in a monodentate fashion). The intermediate and en then react to form products. Assuming a steady state concentration of the intermediate, the experimentally observed rate law is derived. However, the rate of the reaction of en with [Cu(sal–N–Bu^n)$_2$] (each at constant concentration) in the presence of successively greater concentrations of pyridine (0 to $2{\cdot}5 \times 10^{-3}$ M) is independent of the pyridine concentration. Thus, solvent intervention cannot be an important pathway in these reactions.

An alternative mechanistic path is given in equation (2). The intermediate (I) is a five-co-ordinate species with a monodentate en bound in an axial position. The rate-determining step is envisaged as a concerted process in which Schiff base ring opening is concurrent with ring closing by

$$[Cu(sal\text{–}N\text{–}R)_2] + en \overset{K}{\rightleftharpoons} (I) \overset{k'}{\rightarrow} \text{Products} \quad (2)$$

the free end of the axially bound en. Assuming a steady state concentration of (I), it can be shown that $k_2 = k'K$.

Comparison of the rate constants in Table 2 for the square planar species (R = Pr^n and Bu^n) with those for the isomeric tetrahedrally distorted species (R = Pr^i and Bu^s, respectively) reveals an increase in the rate of ligand exchange for the distorted *vs.* the square planar species. Implicit in the proposed mechanism (equation 2) is free access of the attacking ligand to the axial positions on the [Cu(sal–N–R)$_2$] complexes. Involvement of axial positions in ligand exchange reactions of copper(II) complexes (as well as other square planar complexes) has been previously proposed.[5,8] On the basis of electrostatics alone a six-fold decrease in K (equation 2) would be predicted for Cu^{2+} reacting with Hen^+ as compared to its reaction with en.[9] Comparison of k^{en} and k^{Hen} for [Cu(sal–N–Bu^n)$_2$] (1900 and 300 l mol^{-1} s^{-1}, respectively) yields a ratio very close to 6. In addition, there is a good deal of evidence which predicts that a decrease in the rate of ligand exchange will be seen when access to axial positions is sterically hindered.[5,8] The increase in rate exhibited by the distorted complexes relative to the square planar species as well as the fact that these complexes all obey a similar rate law requires accessibility to the axial sites in both cases. Thus, we have unambiguously shown that the effect of structural distortion is to increase the rate of ligand substitution reactions on copper(II) complexes.

In ref. 1 it was suggested that the relatively slow rates of substitution reactions at the metal centre in the catalytic mechanism of copper proteins may be due to the specific geometry of the copper centre. It was further suggested that one of the reasons for the relative slowness of these reactions is due to the absence of the dynamic Jahn–Teller effect as a direct consequence of this geometry. The results of the present work support the proposal that the specific geometry of the metal site affects the rate of substitution reactions at copper(II) centres. However, the faster rates of ligand exchange exhibited by the distorted complexes in which the influence of Jahn–Teller effects should be significantly reduced compared to the square planar complexes tend to cast doubt upon the importance of Jahn–Teller effects on the rate of substitution reactions at metal centres.

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