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Synthesis and studies of hydrolysis of *p*-nitrophenyl picolinate catalysed by Schiff base zinc (II) complexes with aza-crown ether or morpholino-pendants

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Four Schiff base zinc (II) complexes with either benzo-10-aza-crown ether pendants or morpholino-pendants have been synthesised and employed as models for hydrolase enzymes by studying the kinetics of their hydrolysis reactions with *p*-nitrophenyl picolinate (PNPP). A kinetic model of PNPP cleavage catalysed by these complexes is proposed. The effects of complex structures and reaction temperature on the rate of catalytic PNPP hydrolysis have been also examined. The rate increases with pH of the buffer solution; all four complexes exhibited high activity in the catalytic PNPP hydrolysis. Compared with their crown-free analogues, the crowned Schiff base complexes exhibit higher catalytic activity. The catalytic activity of a phenyl-bridged Schiff base complex is larger than that of an ethyl-bridged Schiff base complex under the same substitute groups and metal ion.

Keywords: synthesis, benzo-10-aza-crown ether, Schiff base zinc (II) complexes, mimic hydrolase, *p*-nitrophenyl picolinate

Research on the hydrolysis of carboxyl and phosphoric esters is particularly important for environment and biological applications.[1,2] Much research has been aimed to develop high efficiency and selectivity of catalysts in order to achieve environment-friendly and high-economy processes. Studies on mimic hydrolytic metalloenzymes have used metal ions cobalt(III),[3,4] cobalt(II),[5,6] copper(II),[7,8] nickel(II),[9] manganese (III),[10,11] and lanthanum(III),[12,13] *etc.* as the active centre of the mimic system, respectively; but use of zinc(II) complexes as the synthetic model of metalloenzymes has been infrequent.

Studies of hydrolase mimics is an important area in enzyme simulation research, such as studies of hydrolyses of carboxyl esters.[14-18] The artificial systems that have been used have similar catalytic function to natural enzymes, but they are structurally more simple and stable than enzymes, and they can provide information on mechanistic aspects of enzyme action. In recent years, various chemical systems have been used as models for natural enzymes.[19-21] Crown ethers are generally considered as first generation biomimetics due to their host–guest recognition properties. Therefore, crown ether complexes may provide useful models for hydrolase enzymes because the crown ether can offer a hydrophobic environment.

Previously, the catalytic performances of bis-Schiff base manganese(III) and cobalt(II) complexes with aza-crown ethers or morpholino-pendants in *p*-nitrophenyl picolinate (PNPP) hydrolysis have been reported.[22-26] However, zinc (II) Schiff base complexes containing crown ethers, which can offer the hydrophobicity of outer ethylene groups and hydrophilicity of inner oxygen atoms in an orderly arrangement, have been seldom reported as synthetic models of metalloenzymes. In this paper, the synthesis of four Schiff base zinc (II) complexes with either benzo-10-aza-crown ether pendants (ZnL^1, ZnL^2) or morpholino-pendants (ZnL^3, ZnL^4) have been synthesised and employed as models for hydrolase enzymes by studying the kinetics of their hydrolysis reactions with *p*-nitrophenyl picolinate (PNPP). Compared with the crown-free analogues ZnL^3 and ZnL^4, the effect on PNPP catalytic hydrolysis of ligand structure and the crown ether ring in the complexes has been also been examined. The proposed structures of the Schiff base–zinc (II) complexes are shown in Fig. 1.

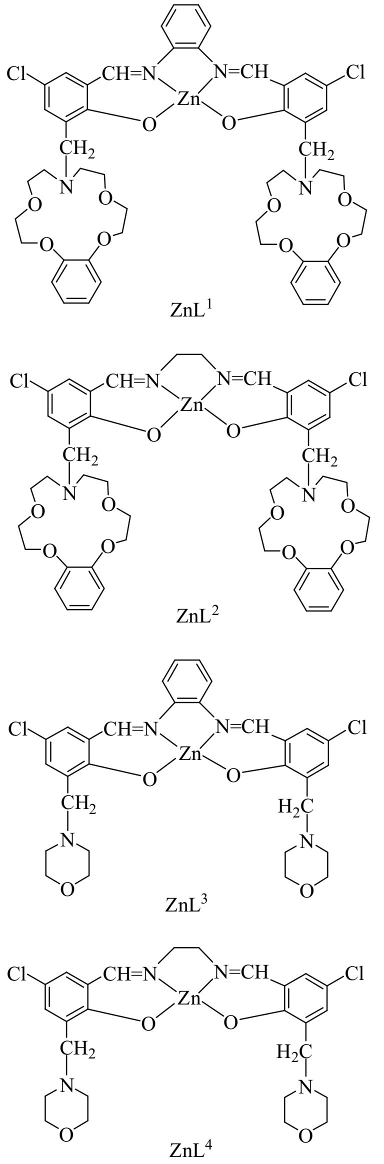

Fig.1 Structure of the Schiff base zinc complexes.

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Experimental

Methods and materials

Melting points were determined on a Yanaco MP-500 micro-melting point apparatus and were uncorrected. Infrared spectra were recorded on a Nicolet-1705X spectrometer (KBr, film). ^{1}H NMR spectra were determined on a Bruker AC-200 MHz spectrometer using Me_4Si as an internal standard. Mass spectra were obtained on a Finnigan MAT 4510 s and Finnigan LCQ-^{DECA} spectrometers. The zinc (II) content was measured by an IRIS-Advantage ICP emission spectrometer. The halogen analysis was measured using the mercury titration method.[27,28] Other elementary analyses were performed on a Carlo Erba 1106 elemental analyser. Molar conductance was obtained on a DDS-11A conductivitimeter. Kinetic studies were carried out by UV-vis methods with a GBC 916 UV-vis spectrophotometer equipped with a thermostatic cell holder.

All reagents, unless otherwise indicated, were of analytical grade and used without further purification. Tris[tris(hydroxymethyl) aminomethane] was purchased from Aldrich. Buffers were made from standardised nitric acid. The water used for kinetics was obtained by doubly distilling deionised water. The ionic strength of the buffers was maintained at 0.1 mol dm^{-3} KNO_3. The pH of the buffers was measured at 25 °C using a Radiometer PHM 26 pH meter fitted with G202C glass and K4122 calomel electrodes. The following compounds were prepared according to the literature: PNPP (*p*-nitrophenylpicolinate),[29] *N*-(2-hydroxy-3-formyl-5-chlorobenzyl)benzo-10-aza-15- crown-5 and *N*-(2-hydroxy-3-formyl-5-chlorobenzyl)morpholine.[30] PNPP stock solution was prepared in acetonitrile.

Synthesis of Schiff base ligands H_2L^1–H_2L^4

Schiff base ligand H_2L: A solution of 1, 2-phenylenediamine (1.08 g, 10 mmol) and *N*-(2-hydroxy-3-formyl-5-chlorobenzyl)benzo-10-aza-15-crown-5 (8.72 g, 20 mmol) in anhydrous EtOH (40 cm^3) was stirred for 4 h under an N_2 atmosphere at 80 °C, and then the mixture was cooled. The resulting yellow precipitate was filtered and washed with EtOH. After recrystallisation from EtOH, yellow crystals (8.20 g, yield 87%) were obtained. m.p. 94–96 °C. ^{1}H NMR(200 MHz, $CDCl_3$) δ: 9.90(s, 2H, OH, D_2O exchangeable), 8.33(s, 2H, N=CH), 7.76–6.80(m, 16H, ArH), 4.18–3.68(m, 28H, OCH_2, NCH_2Ar), 2.84 (t, J = 6.1 Hz, 8H, NCH_2); IR (KBr, cm^{-1})ν_{max}: 3412, 2949, 2868, 1631, 1596, 1502, 1256, 1128, 1050, 930; ESI-MS *m/z*: 944 (M^+ + 1); (Found C 61.49, H 6.14, N 5.78, Cl 7.71. $C_{50}H_{56}N_4O_{10}Cl_2$ requires C 61.63, H 5.94, N 5.94, Cl 7.53%).

Ligand H_2L^2 was prepared as described for H_2L^1 except starting with ethylenediamine instead of 1, 2-phenylenediamine to give a yellow solid, in yield 85%, m.p. 85–86 °C. ^{1}H NMR(200 MHz, $CDCl_3$) δ: 9.89 (s, 2H, OH, D_2O exchangeable), 8.27 (s, 2H, N=CH), 7.57–6.87(m, 12H, ArH), 4.16–3.76 (m, 32H, OCH_2, NCH_2Ar, $C{=}NCH_2$), 2.83 (t, J = 5.4 Hz, 8H, NCH_2); IR (KBr, cm^{-1})ν_{max}: 3448, 2949, 2864, 1635, 1600, 1500, 1256, 1128, 1050, 928; ESI-MS *m/z*: 896 (M^+ + 1); (Found C 61.45, H 6.15, N 6.41, Cl 7.78. $C_{46}H_{56}N_4O_{10}Cl_2$ requires C 61.68, H 6.26, N 6.26, Cl 7.93%).

Ligand H_2L^3 was prepared as described for H_2L^1 except starting with *N*-(2-hydroxy-3-formyl- 5-chlorobenzyl)morpholine instead of *N*-(2-hydroxy-3-formyl-5-chlorobenzyl)benzo-10-aza-15-crown-5 to give a yellow solid, in yield 83%, m.p. 215–217 °C. ^{1}H NMR (200 MHz, $CDCl_3$) δ: 10.23 (s, 2H, OH, D_2O exchangeable), 8.64(s, 2H, N=CH), 7.46–7.20 (m, 8H, ArH), 3.79–3.67 (m, 12H, OCH_2, NCH_2Ar), 2.69 (t, J = 5.6 Hz, 8H, NCH_2); IR (KBr, cm^{-1})ν_{max}: 3448, 2959, 2842, 1632, 1599, 1504, 1229, 1118, 1036, 928; ESI-MS *m/z*: 584 (M^+ + 1); (Found C 61.55, H 5.65, N 9.41, Cl 12.18. $C_{30}H_{32}N_4O_4Cl_2$ requires C 61.75, H 5.49, N 9.61, Cl 12.19%).

Ligand H_2L^4 was prepared as described for H_2L^3 except starting with ethylenediamine instead of 1, 2-phenylenediamine to give a yellow solid, in yield 85%, m.p. 204–206 °C. ^{1}H NMR(200 MHz, $CDCl_3$) δ: 10.15 (s, 2H, OH, D_2O exchangeable), 8.56 (s, 2H, N=CH), 7.45–7.23 (m, 4H, ArH), 3.86–3.76 (m, 16H, OCH_2, NCH_2Ar, $C{=}NCH_2$), 2.76 (t, J = 5.5 Hz, 8H, NCH_2); IR (KBr, cm^{-1}) ν_{max}: 3442, 2959, 2842, 1632, 1597, 1501, 1230, 1129, 1036, 930; ESI-MS *m/z*: 536(M^+ + 1); (Found C 58.45, H 6.15, N 10.31, Cl 13.18. $C_{26}H_{32}N_4O_4Cl_2$ requires C 58.32, H 5.98, N 10.47, Cl 13.27%).

General methods for preparation of Schiff base–zinc(II) complexes

A solution of Schiff base ligand (1.0 mmol) and $ZnCl_2$ (1.1 mmol) in EtOH (15 cm^3) was stirred for 2 h under a N_2 atmosphere at 70 °C, then the mixture was cooled and filtered, washed with ethanol to give the complexes, and the pure product was obtained after recrystallisation from ethanol.

ZnL^1: Straw yellow, 81% yield, m.p. >300 °C.IR (KBr, cm^{-1})ν_{max}: 1615, 1226, 1124; ESI-MS *m/z*: 1007(M^+ + 1); (Found C 59.45, H 5.51, N 5.66, Cl 7.19, Zn 6.28. $ZnC_{50}H_{54}N_4O_{10}Cl_2$ requires C 59.64, H 5.37, N 5.57, Cl 7.06, Zn 6.46%); Λ_m(S.cm^2 mol^{-1}): 8.21.

ZnL^2: Straw yellow, 72% yield, m.p. >300 °C.IR (KBr, cm^{-1}) ν_{max}: 1618, 1225, 1126; ESI-MS *m/z*: 959(M^+ + 1). (Found C 57.53, H 5.82, N 5.99, Cl 7.24, Zn 6.59. $ZnC_{46}H_{54}N_4O_{10}Cl_2$ requires C 57.62, H 5.64, N 5.85, Cl 7.41, Zn 6.78%). Λ_m(S.cm^2 mol^{-1}): 9.51.

ZnL^3: Straw yellow, 63% yield, m.p. 235–237 °C. IR (KBr, cm^{-1}) ν_{max}: 1614, 1226, 1130; ESI-MS *m/z*: 647(M^+ + 1). (Found C 55.91, H 4.54, N 8.49, Cl 10.81, Zn 10.19. $ZnC_{30}H_{30}N_4O_4Cl_2$ requires C 55.72, H 4.64, N 8.67, Cl 10.99, Zn 10.06%). Λ_m(S.cm^2 mol^{-1}): 8.52.

ZnL^4: Straw yellow, 68% yield, m.p. 211–213 °C. IR (KBr, cm^{-1}) ν_{max}: 1616, 1235, 1125. ESI-MS *m/z*: 599(M^+ + 1). (Found C 52.33, H 5.21, N, 9.18, Cl 11.71, Zn 10.69. $ZnC_{26}H_{30}N_4O_4Cl_2$ Calcd C 52.17, H 5.02, N 9.36, Cl 11.87, Zn 10.87%). Λ_m (S.cm^2 mol^{-1}) 9.26.

Kinetics studies

The pseudo-first-order rate constants (k_{obs}) were obtained based on the initial rate method, *i.e.* according to the equations: $(\text{rate})_0 = -(dC/dt)_0 = (dA/dt)_0/\varepsilon$ and $(\text{rate})_0 = k_{obs}[ML]_0$. $(\text{rate})_0$ was calculated initially, then the Fig. of $(\text{rate})_0$ versus $[ML]_0$ was plotted; the pseudo-first-order rate constants were obtained from the slope of the straight line in the Fig., where $(\text{rate})_0$ is the initial rate of PNPP hydrolysis and $[ML]_0$ is the initial concentration of the complex.

Each kinetic run was initiated by injecting an acetonitrile solution of PNPP at the desired concentration into a 1 cm cuvette containing 3 cm^3 of the desired concentration of the complex. The pseudo-first-order rate constants for PNPP hydrolysis were determined by monitoring the release of *p*-nitrophenol at 400 nm under the conditions of more than 10-fold excess of substrate over catalyst concentration, and each kinetic run was reproducible to within 3% error. The molar extinction coefficients (ε) of *p*-nitrophenol were examined by measuring absorption values of the desired concentration of *p*-nitrophenol at the various pH of the solutions. The ionic strength of all reaction systems was maintained at 0.1 mol dm^{-3} KNO_3.

Results and discussion

Synthesis

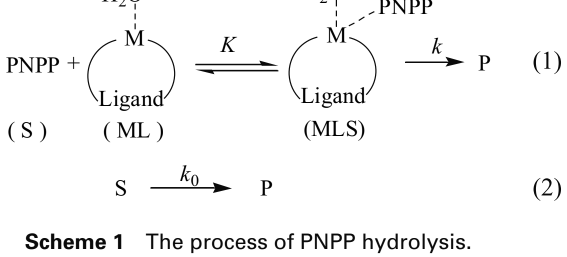
Compared with the IR spectra of the ligand, the IR spectra of complexes were almost at the same frequency, except for the C=N stretching vibration shifted 16–19 cm^{-1} to lower frequency and its intensity was greater than that of free ligand. This indicated the formation of a N–O…Zn coordination bond; the absence of an OH stretching vibration in the complexes indicated deprotonation of OH of the ligand after complex formation. The C–O–C stretching vibrations in the crown ether ring for the complexes were almost at the same frequency as those of the free ligand. The observed molar conductance of all complexes in DMF solution (1.0×10^{-3} mol L^{-1}) at 25 °C showed that they were non-electrolytes.[31] The ESI-MS Mass spectra and elemental analysis of the complexes indicated that Schiff base H_2L formed 1 : 1 (ligand/metal) complexes (ML). The facts above showed that Schiff base ligands can coordinate with zinc ion as in Fig. 1.

Pseudo-first-order rate constants of catalytic PNPP hydrolysis at 25 °C

The pseudo-first-order-rate constants obtained for catalytic PNPP hydrolysis are shown in Table 1. The pseudo-first-order-rate constant (k_0) for PNPP hydrolysis in the absence of catalyst is 7.8×10^{-6} s^{-1} at pH = 7.00, 25 °C, [S] = 2.0×10^{-4} mol dm^{-3}. The rate for the PNPP hydrolysis catalysed by the complexes (see Table 1) increases by a factor of *ca* 1.05×10^3 times for ZnL^1, 9.48×10^2 times for ZnL^2, 7.56×10^2 times for ZnL^3, and 6.79×10^2 times for ZnL^4 under the same experimental conditions. The catalytic activity followed the order $ZnL^1 > ZnL^2 > ZnL^3 > ZnL^4$.

Kinetic model of the catalytic PNPP hydrolysis

The catalytic hydrolysis of PNPP in aqueous solution of the complexes can be expressed as Scheme 1 involving equations (1) and (2):



Scheme 1 The process of PNPP hydrolysis.

Table 1 The pseudo–first-order rate constants (k_{obs}) of catalytic PNPP hydrolysis in buffer solutions

Complex	10^4 [PNPP]/ mol dm^{-3}	$10^2 k_{obs}$(s^{-1})				
		pH 7.00	7.30	7.60	7.90	8.20
ZnL^1	2.00	0.82	1.63	3.49	8.55	22.94
	2.67	1.07	2.01	4.42	11.58	28.14
	3.33	1.34	2.67	5.72	13.72	35.54
	4.00	1.59	3.26	6.87	16.92	43.11
	4.67	1.89	3.58	7.67	18.99	49.28
ZnL^2	2.00	0.74	1.52	3.29	8.06	22.42
	2.67	0.98	1.98	4.32	10.51	25.64
	3.33	1.22	2.46	5.59	12.59	33.21
	4.00	1.45	2.99	6.37	14.68	39.32
	4.67	1.63	3.32	6.89	17.62	46.76
ZnL^3	2.00	0.59	1.33	2.73	7.33	20.47
	2.67	0.75	1.81	3.63	9.98	22.61
	3.33	0.92	2.27	4.46	10.65	29.89
	4.00	1.12	2.52	5.12	13.82	34.49
	4.67	1.33	2.84	5.83	14.99	38.31
ZnL^4	2.00	0.53	1.16	2.53	7.19	19.94
	2.67	0.67	1.59	3.35	9.41	21.34
	3.33	0.83	1.91	3.94	10.13	26.36
	4.00	0.98	2.18	4.65	12.98	32.11
	4.67	1.18	2.47	5.42	14.19	34.03

Condition: 25±0.1 °C, I = 0.1 mol dm^{-3} KNO$_3$, [complex] = 1.0×10^{-5} mol dm^{-3}

Where S is the substrate PNPP, ML is the hydrated complex, MLS represents the intermediate made from ML and S, P represents the product *p*-nitrophenol, *K* is the association constant between the substrate(S) and the hydrated complex (ML), and *k* is first-order-rate constant for the product formation, and is pH-dependent. k_0 is the pseudo-first-order-rate constant in absence of catalyst.

The rate of spontaneous hydrolysis is much lower than that of catalytic hydrolysis in buffered aqueous solution, so the products of PNPP spontaneous hydrolysis can be neglected in the kinetics calculations. From the previous report, [24] and Scheme 1, we have:

$$\frac{1}{k_{obs}} = \frac{1}{k} + \frac{1}{Kk[S]} \tag{3}$$

In the above equations, [ML] and $[ML]_T$ are the free and the total concentration of the hydrated complex, respectively; [S] is the concentration of free substrate and can be substituted by the initial concentration of the substrate based on the initial rate method; [MLS] is the concentration of the intermediate formed by the substrate and the hydrated complex in the buffered solution; k_{obs} is the pseudo-first-order-rate constant.

Based on the experimental data (see Table 1) and equation (3), the relationships between $1/k_{obsd}$ versus $1/[S]$ were plotted in Fig. 2, showing a good linear relationship between the variables, with $r^2 > 0.98$. The plots have a positive intercept that evaluates the first-order-rate constant *k* with relative standard deviation of less than 1%. The *k* of calculation has been listed in Table 2.

pH-rate profile and stoichiometry of the kinetic constants

From the results obtained, it was shown that the first-order-rate constant (*k*) was pH-dependent. In other words, *k* is related to the acid dissociation constant K_a of H_2O coordinated to the metal ion. The *k* increases along with the increase of the pH value from 7.00 to 8.20. This implies that the reaction process contains proton transfer in the rate-determining step in Scheme 1, which can be shown as Scheme 2.

K_a is the acidic dissociation constant of H_2O coordinated to the metal ion; k_1 is the first-order-rate constant, which is pH-independent. In this process, the intermediate MLS is first ionised or undergoes proton transfer, and then electronic transfer inside the intermediate MLS gives the products. The rate for PNPP catalytic hydrolysis depends on the stabilisation of the intermediate MLS$^-$. According to the principles of chemical equilibration, it is more favourable for the intermediate MLS to form the intermediate MLS$^-$ and generate the products in alkaline solution. Hence, the first-order-rate constants (*k*) increase with the increase of pH value in the reaction system.

Table 2 *k* (s^{-1}) of the catalytic hydrolysis of PNPP by Schiff base zinc complexes in buffer solution

pH	7.00	7.30	7.60	7.90	8.20
k(ZnL^1)	0.454	0.751	1.200	2.587	3.463
k(ZnL^2)	0.231	0.409	0.651	1.095	2.026
k(ZnL^3)	0.135	0.257	0.430	0.659	1.150
k (ZnL^4)	0.093	0.180	0.313	0.483	0.742

Due to chemical balance principle, we have:

$$K_a = [H^+]\,[MLS^-]/[MLS] \tag{4}$$

According to the material balance, we have:

$$[MLS] = [MLS]_t + [MLS^-] \tag{5}$$

Combination of equations (4) and (5) leads to:

$$[MLS^-] = \frac{K_a[MLS]}{[H^+] + K_a} \tag{6}$$

The rate equation in Scheme 2 can be expressed as:

$$k[MLS] = k_1\,[MLS^-] \tag{7}$$

Combination of equations (6) and (7) leads to:

$$k = \frac{K_a k_1}{[H^+] + K_a} \tag{8}$$

Rearrangement of equation (8) gives:

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_1 K_a}[H^+] \tag{9}$$

$[MLS^-]$ is the dissociated concentration of the intermediate (MLS), $[MLS]_t$ is the undissociated concentration of the intermediate (MLS). On the basis of equation (9), the k_1 and K_a values can be afforded from the slope and intercept of the plot of $1/k$ versus $[H^+]$ (Fig. 3) The results give k_1 and pK_a values of 4.66 s^{-1} and 7.98 for ZnL^1, 2.51 s^{-1} and 8.00 for ZnL^2, and 1.83 s^{-1} and 8.09 for ZnL^3, 1.41 s^{-1} and 8.15 for ZnL^4, respectively.

Effects of the complex structures on catalytic PNPP hydrolysis

The mimic hydrolase used in this paper exhibits similar structural features to those of the natural hydrolase in PNPP catalytic hydrolysis. Tables 1 and 2 show that: (1) the catalytic activity of the crown Schiff complexes is higher than that of the crown-free analogous. On the one hand, this can be attributed the crown ether ring in the Schiff base

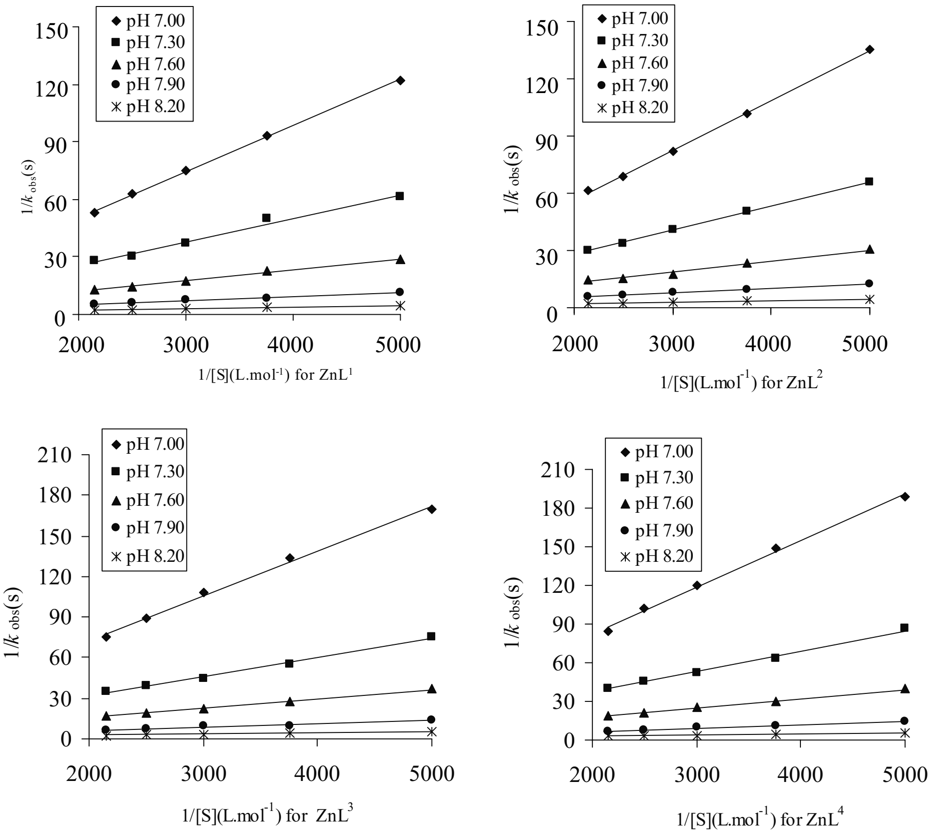


Fig. 2 Effect of substrate concentration on first-order rate constants for catalytic PNPP hydrolysis by the complexes ZnL^1, ZnL^2, ZnL^3, ZnL^4 in buffer solutions at 25 °C in the buffer solution ◆ pH7.00 ■ pH7.30 ▲ pH7.60 ● pH7.90 *pH8.20.

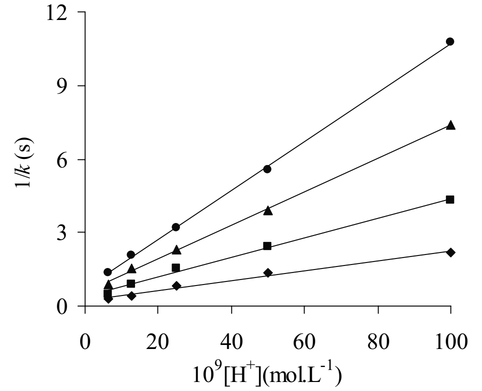


Fig. 3 pH-rate profile for the catalytic hydrolysis of PNPP by the Schiff base zinc complexes in the buffer solution at 25 °C (◆ ZnL^1 ■ ZnL^2 ▲ ZnL^3 ● ZnL^4).

complexes which offers a hydrophobic environment owing to its outer ethylene groups, so the hydrophobic PNPP molecule interacts more favourably with these complexes; on the other hand, as hydrogen bonds may be formed between the oxygen atoms of the crown ether ring and H_2O in the intermediate MLS, H_2O coordinated to the metal can be activated synergistically by both the metal ion and crown, the rate of formation of the intermediate MLS^- may be faster in crown Schiff base complexes than that in crown-free Schiff base complexes; (2) it can be seen that the catalytic activity of phenyl-bridged Schiff base complex is larger than that of ethyl-bridged Schiff base complex under the same substitute groups and metal ion. In other words, the catalytic activity follows the order $ZnL^1 > ZnL^2$, and $ZnL^3 > ZnL^4$, respectively. This perhaps can be attributed to rigidity, since phenyl-bridged Schiff bases possess more rigidity than that of ethyl-bridged Schiff bases due to the different bridge chain.

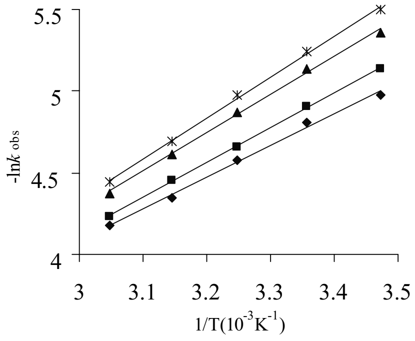


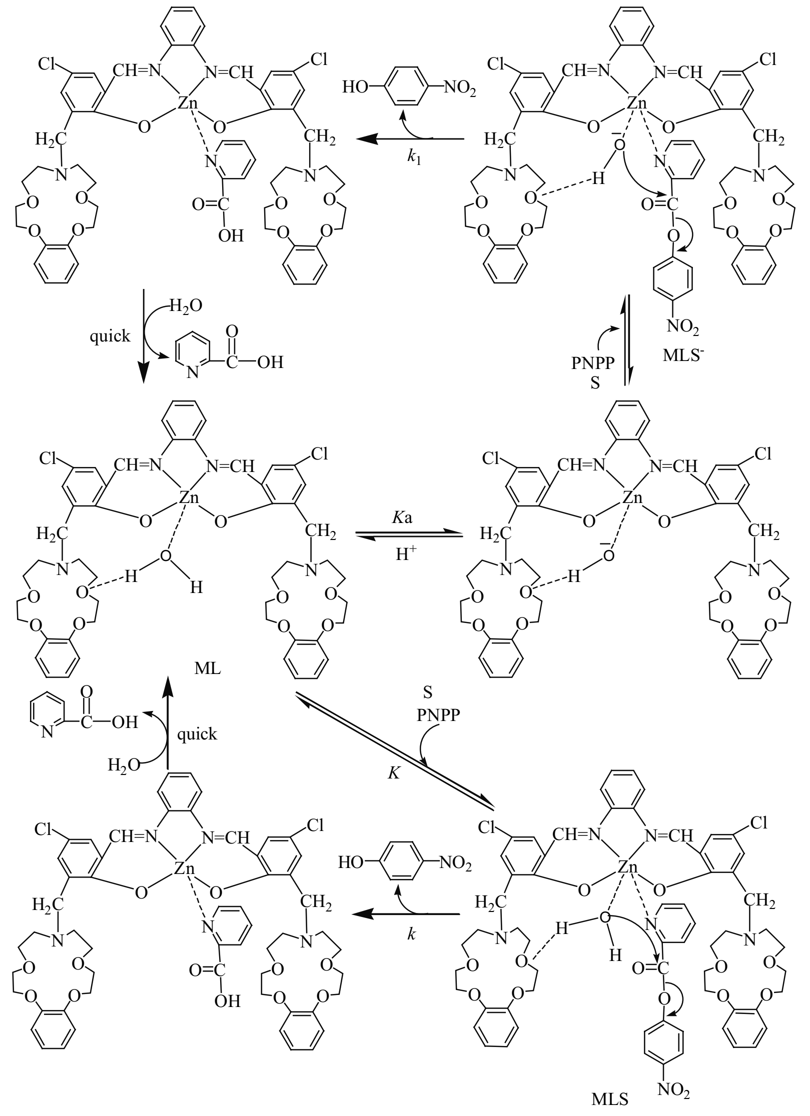
Fig. 4 The plot of $-\ln k_{obs}$ *versus* 1/T at pH = 7.00 [S]=2.0 × 10^{-4} mol dm^{-3}, [complex] = 1.0 × 10^{-5} mol dm^{-3}. (◆ ZnL^1 ■ ZnL^2 ▲ ZnL^3 * ZnL^4).

Effect of temperature and apparent activation energy on catalytic PNPP hydrolysis

In order to investigate the effect of temperature on catalytic hydrolysis, the pseudo-first-order-rate constants (k_{obs}) of PNPP hydrolysis were obtained at five different temperatures from 15 to 55 °C at pH = 7.00, [S] = 2.0 × 10^{-4}mol dm^{-3}. According to the Arrhenius equation, straight lines for $-\ln k_{obs}$ *versus* $1/T$ were obtained (see Fig. 4). The apparent activation energy (E_a) values were determined from the slopes of the straight lines. The E_a values are 16.05 kJ mol^{-1} for ZnL^1, 17.76 kJ mol^{-1} for ZnL^2, 19.53 kJ mol^{-1} for ZnL^3, and 20.92 kJ mol^{-1} for ZnL.[4] Since the formation rate of the intermediate, MLS and MLS^-, should increase with rising reaction temperature, the rate of PNPP catalytic hydrolysis is enhanced.

Proposed mechanism for hydrolysis of PNPP catalysed by base complexes with azacrown ether pendant

The proposed mechanism of the catalytic hydrolysis of PNPP by ZnL^1, which is used as an example of PNPP catalytic hydrolysis by Schiff base complexes, is outlined in Scheme 2 on the basis of previous report[32,33] and pK_a values of complexes above. According



Scheme 2 Proposed mechanism for hydrolysis of PNPP catalysed by Schiff base zinc II) complex with benzo-10-aza-crown ether pendant.

to the complex structure, H_2O could be coordinated to the zinc (II) ion, which would result in the formation of the hydrated complex in aqueous solution. This hydrated complex may be the real active species for the PNPP catalytic hydrolysis.[34] Therefore, we assume that the mechanism of PNPP catalytic hydrolysis is similar to the hydrolytic reaction catalysed by hydrolytic metalloenzymes.

Scheme 2 shows that: (1) the H_2O coordinated to the zinc(II) ion is activated synergistically by the zinc(II) ion and crown ring, and then the intramolecular hydroxide is generated; (2) the N atom of the pyridine ring in a PNPP molecule is coordinated to the zinc(II) ion in the complex, forming the intermediate MLS; (3) the coordinated hydroxide OH^- in the intramolecular zinc(II) attacks the positive C atom of the ester carbonyl group in the PNPP molecule to promote the departure of the forming *p*-nitrophenol with a first-order-rate constant (k), which is the rate-determining step of the total reaction; and (4) H_2O is bonded to zinc(II) ion quickly again and the picolinic acid molecule coordinated to the zinc(II) ion is released.

Conclusion

In this report, we have investigated the catalytic hydrolysis of a carboxylic ester by Schiff base zinc(II) complexes with either benzo-10-aza-crown ether pendants (ZnL^1, ZnL^2), or morpholino-pendants (ZnL^3, ZnL^4). The rate of catalytic PNPP hydrolysis increases with increasing of pH of the buffer solution compared with the crown-free analogues ZnL^3 and ZnL^4. The crown Schiff base complexes (ZnL^1, ZnL^2) exhibit higher catalytic activity; the catalytic activity of phenyl-bridged Schiff base complex is larger than that of ethyl-bridged Schiff base complex under the same substitute groups and metal ion. The pseudo-first-order-rate for PNPP hydrolysis catalysed by ZnL^1 containing a benzo-10-aza-crown ether ligand is 1.05×10^3 times than that of spontaneous hydrolysis of PNPP at pH = 7.00, [S] = 2.0×10^{-4} mol dm^{-3}. The studies also indicate that the Schiff base complexes are stable in the range of temperature investigated and the apparent activation energy (E_a) values follow the order $ZnL^1 < ZnL^2 < ZnL^3 < ZnL^4$.

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