Chiral zinc(II) bipyridine complex. Crystal structure and catalytic activity in asymmetric allylation reaction

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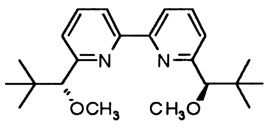
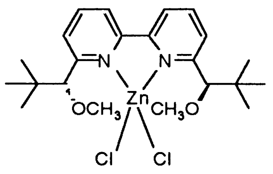
A chiral bipyridine zinc(II) complex, Zn(**L**)Cl_2 (L = chiral bipyridine), has been prepared and characterized by usual spectroscopic means and X-ray crystallography. Reaction of Zn(**L**)Cl_2 with $AgCF_3SO_3$ gave Zn(**L**)$(CF_3SO_3)_2$ *in situ*; this complex is an active catalyst for allylation of aldehydes with enantiomeric excesses up to 60%.

Catalytic asymmetric allylation of aldehydes is of great interest in organic syntheses because chiral homoallyl alcohols are useful intermediates for the synthesis of complex chiral molecules[1] but there are no metal catalysts supported by chiral bipyridines for this transformation. It is well documented that bipyridine ligands have useful applications in catalysis, photochemistry, electrochemistry and supramolecular chemistry.[2] However, the use of chiral bipyridine ligands, when compared with other chiral *N*,*N* bidentate ligands, in asymmetric catalysis is still in its infancy.[3] Chiral bis(oxazoline) metal complexes, for example, have enjoyed a much broader popularity than chiral bipyridine complexes.[4] Chiral Zn(II) bis(oxazoline) complexes have been shown to catalyse free radical carbon–carbon bond forming reactions,[5] allylation of cyclopropene acetals,[6] allylation of oximes[7] and more recently allylation of aldehydes,[8] while to the best of our knowledge there are no reports on the use of zinc bipyridine complexes for these reactions.

The facile synthesis of the chiral bipyridine ligand **L** was first reported by Bolm *et al.* These workers and others also reported that **L** is an active catalyst for diethyl zinc additions and nickel-catalysed conjugate additions.[9,10] We recently reported that chiral copper complexes of **L** are active catalysts for asymmetric cyclopropanation of alkenes.[11] These results suggest the potential of this type of ligand in asymmetric catalysis. In order to expand the scope of this class of ligands, herein we report the synthesis, spectroscopic characterization and X-ray crystal structure of Zn(**L**)Cl_2 and the use of zinc complexes of **L** as active catalysts for allyl addition reactions of aldehydes.



(*R*,*R*)-L



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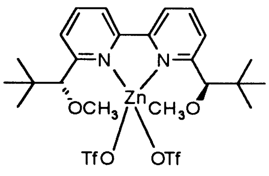

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Experimental

Dichloromethane was distilled under N_2 from calcium hydride. Ligand **L** was prepared according to the literature procedure.[9] Only (*R*,*R*)-**L** was used in this study. All other chemicals were of reagent grade quality and were used as commercially obtained. ^{1}H-NMR and ^{13}C-NMR spectra were recorded on a Jeol 270 FT-NMR spectrometer. IR spectra were recorded on a Perkin Elmer FTIR-1600 spectrometer. UV spectra were recorded on a Perkin Elmer UV spectrometer Lambda 19. Elemental analyses were performed by MEDAC Ltd. or on a Leco CHN-900 micro carbon hydrogen nitrogen determinator.

Preparation and characterization of zinc(II) chiral bipyridine complex 1

Ligand (*R*,*R*)-**L** (0.14 g, 0.4 mmol) was dissolved in THF. Zinc chloride (0.055 g, 0.4 mmol) was added to the mixture. The colourless solution was refluxed for 2 h under a nitrogen atmosphere. A white solid precipitated during the reaction. The solid was recrystallized from CH_2Cl_2–diethyl ether to give colourless crystals, which were isolated by filtration and dried *in vacuo*. The complex was characterized by X-ray crystallography, IR, UV and CHN analysis. Yield: 98%. Anal. calcd for $ZnN_2Cl_2C_{22}H_{32}O_2$: C, 53.62; H, 6.54; N, 5.68%. Found: 53.31; H, 6.50; N, 5.59%. IR(KBr): 3089.1 s, 2971.2 vs, 2848.8 vs, 2868.5 s, 2830.2 s, 1597.5 s, 1573.7 s, 1478.9 s, 1459.4 s, 1433.6 s, 1397.2 s, 1360.2 s, 1351.3 s, 1260.4 s, 1228.4 m, 1203.7 m, 1166.1 s, 1089.2 vs, 1021.7 s, 961.1 s, 819.7 s, 785.6 s, 671.6 m, 648.1 s cm^{-1}. UV (CH_2Cl_2), $\lambda_{max}(\varepsilon)$: 250 (8000), 308 nm (18600). MS (+FAB): 455 $(M - Cl)^+$.

X-Ray crystallographic analysis and data collection. Suitable crystals for X-ray structure analysis were grown by dissolving **1** in CH_2Cl_2 with diffusion of diethyl ether into the solution. These colourless crystals were air stable. Diffraction data were obtained on a Rigaku AFC7R diffractometer at ambient temperature. Intensity data were corrected for Lorentz and polarization effects. Absorption corrections based on the χ-scan technique were also applied. The structure was solved by direct methods (SIR 92) and refined on *F* by least-squares analysis. The absolute structure of the molecule was determined by analysis of both configurations including the anom-

Table 1 Crystallographic data for **1**

Formula	$ZnN_2Cl_2C_{22}H_{32}O_2$
Formula weight	492.79
Crystal system	Monoclinic
Lattice type	C-centred
Lattice parameters	$a = 14.646(2)$ Å
	$b = 8.597(2)$ Å
	$c = 10.128(2)$ Å
	$\beta = 105.45(1)°$
	$U = 1229.2(4)$ Å
Space group	$C2$ (#5)
Z	2
Temperature	25.0 °C
μ(MoKα)	12.4 cm^{-1}
Reflections measured	1822
Independent reflections	870 [R(int) = 0.038]
R, R_w [$I > 3I(\sigma)$]	0.046, 0.047

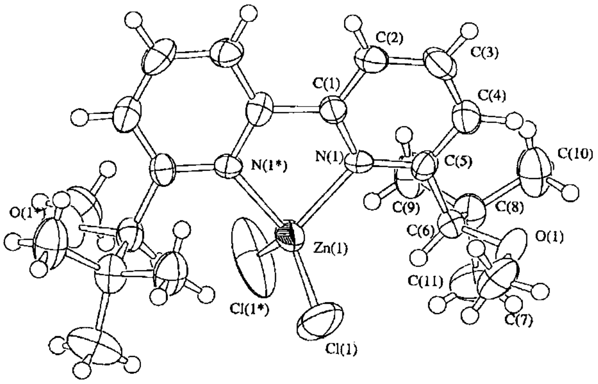


Fig. 1 X-Ray structure of zinc(II) bipyridine chloride complex **1**.

alous scattering effect. The Flack parameter was refined to give a value of 0.008(1). Hydrogen atoms were placed in their ideal positions (C–H, 0.95 Å) and included in the structure factor calculations but were not refined. All calculations were performed on a Silicon Graphic workstation using the TeXsan package. Crystal data and details of the measurements are summarized in Table 1.

CCDC reference number 440/110. See http://www.rsc.org/suppdata/nj/1999/629/ for crystallographic files in .cif format.

Procedures for allylation of aldehydes using Zn(II) chiral bipyridine complexes

Complex **1** (0.024 g, 0.05 mmol) and a silver(I) salt AgX (0.1 mmol, $X^- = OTf^-$, SbF_6^-, PF_6^-, ClO_4^-, BF_4^- or tosylate) were dissolved in CH_2Cl_2 (5 ml). The solution was stirred for 2.5 h at room temperature and filtered. Aldehyde (0.5 mmol) and allyltributyltin (0.166 g, 0.5 mmol) were added to this mixture, which was stirred at room temperature. The reaction was quenched by adding a saturated solution of $NaHCO_3$. The mixture was extracted with diethyl ether and evaporated. The product was purified by column chromatography. The purified product was characterized by ^1H- and ^{13}C-NMR, IR, and GC-MS. The enantiomeric excesses were determined by HPLC using a chiral column.

Procedures for allylation of aldehydes using Cu(II) and Ag(I) chiral bipyridine complexes

Following a similar procedure as above, the copper catalyst was generated by stirring Cu(**L**)Cl_2 (0.024 g, 0.05 mmol) with AgOTf (0.026 g, 0.1 mmol) in CH_2Cl_2 (5 ml) for 2.5 h at room temperature and filtered. The silver catalyst was generated by refluxing AgOTf (0.013 g, 0.05 mmol) with **L** (0.0175 g, 0.05 mmol) in CH_2Cl_2 for 2.5 h.

Results and discussion

Although zinc bipyridine complexes are common in the literature,[12] no crystallographically characterized zinc(II) complex containing a chiral bipyridine ligand has been reported. In this work, the reaction of ligand (*R*,*R*)-**L** with $ZnCl_2$ in dichloromethane, readily gave Zn(**L**)Cl_2 (complex **1**), which was isolated as a white solid in good yield. As with Zn(bipy)Cl_2 (bipy = bipyridine) and Zn(phen)Cl_2 (phen = phenanthroline), complex **1** is tetrahedral as depicted in Fig. 1.[13] Table 2 summarizes the structural parameters of **1**. The neutral complex has a C_2 symmetry axis passing through the zinc ion and the midpoint of the bipyridine ligand. The Zn–N bond distances of 2.07 Å are comparable to the related bond distances found for the achiral Zn(bipy)Cl_2 and Zn(phen)Cl_2 complexes.[13] The bite angle of 82.2° made by the chiral bipyridine and zinc is also comparable to a value of 80.3° cited in the literature for the zinc 2,2′-bipyridine dichloride complex.[13] The zinc–chlorine bond distances are 2.19 Å and the dihedral angles of Cl(1)–Zn(1)–N(1)–C(1) and Cl(1*)–Zn(1)–N(1)–C(1) are −115.4° and 110.4°. The bulkiness of this ligand can be illustrated by the fact that formation of a 2 : 1 ligand-to-zinc complex is not possible even with excess ligand and prolonged heating, whereas other bipyridines form 2 : 1 ligand-to-zinc complexes fairly easily.

The chloride complex **1** is not an active catalyst for allylation of aldehydes (see Table 3). However, Zn(**L**) triflate complex **2**, which was generated *in situ* by reacting **1** with silver triflate, served as an active catalyst. Positive FAB-MS spectral analysis provides evidence for **2** with a peak at *m*/*z* 569 $(M - OTf)^+$. The allylation of benzaldehyde by allyltributyltin in the presence of 10 mol% of zinc catalyst gave homoallylic alcohol as the only product in 92% isolated yield. The enantioselectivity was found to be 39% e.e. Employing ligand (*R*,*R*)-**L** with Zn(II) ion, the absolute configurations of homoallylic alcohol products formed from benzaldehyde were determined to be (*R*). With the result that ligand **L** can only form a 1 : 1 complex with Zn(II) ion, we believe that the catalytically active complex in the allylation is the four-coordinated Zn(**L**)$(OTf)_2$ complex.

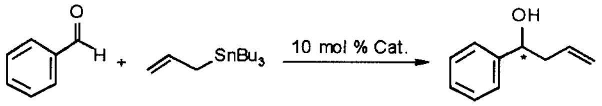
The effect of temperature on the enantioselective allylation of benzaldehyde was investigated. Lowering the temperature from room temperature to 0 °C hampered the reaction slightly in terms of yield but increased the enantioselectivity slightly. When the reaction temperature was decreased to −40 °C, the isolated yield decreased further but the enantioselectivity increased to 46%.

The effects of counter ions with the zinc complex were also investigated. A large counter ion effect was observed in these reactions (Table 3, entries 2 and 5–9). With triflate as anion, the allylation required 21 h for complete conversion and gave a 39% e.e. (entry 2). All other counter ions gave a lower e.e. and all counter ions except SbF_6^- gave a slower reaction when compared with triflate. This comparison reveals that the

Table 2 Selected structural parameters for **1**

Zn(1)–Cl(1)	2.188(4)	Zn(1)–N(1)	2.071(7)
Zn(1)–Cl(1*)	2.188(4)	Zn(1)–N(1*)	2.071(7)
Cl(1)–Zn(1)–Cl(1*)	114.6(3)	Cl(1*)–Zn(1)–N(1)	108.5(2)
Cl(1)–Zn(1)–N(1)	119.8(2)	N(1)–Zn(1)–N(1*)	82.2(4)
Cl(1)–Zn(1)–N(1)–C(1)	−115.4(5)	Cl(1*)–Zn(1)–N(1)–C(1)	110.4(5)

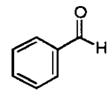
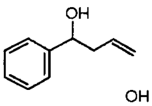
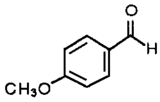
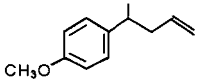
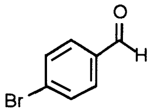
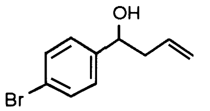
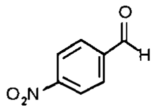
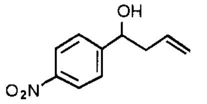
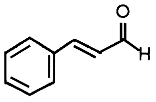
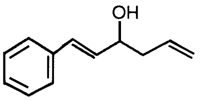
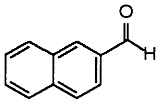
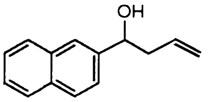
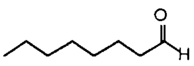
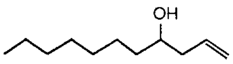
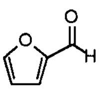
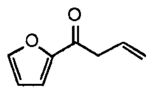
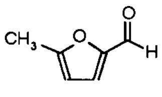
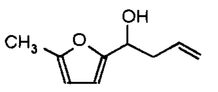
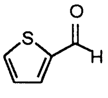
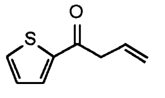
Table 3 Enantioselective allylation of benzaldehyde promoted by chiral bipyridine metal complexes[a]



Entry	Catalyst[b]	Time/h	Isolated yield[c]/%	e.e.[d]/%
1	Zn(L)Cl_2	236	0	—
2	Zn(L)$(OTf)_2$	21	92	39
3[e]	Zn(L)$(OTf)_2$	24	73	43
4[f]	Zn(L)$(OTf)_2$	240	42	46
5	Zn(L)$(ClO_4)_2$	21	25	35
6	Zn(L)$(PF_6)_2$	21	56	26
7	Zn(L)$(BF_4)_2$	21	44	5
8	Zn(L)(*p*-tosylate)$_2$	21	37	33
9	Zn(L)$(SbF_6)_2$	21	94	23
10	Ag(L)OTf	66	69	0
11	Cu(L)$(OTf)_2$	125	21	3

[a] All the reactions were carried out in CH_2Cl_2 at room temperature unless otherwise stated. [b] Only (*R*,*R*)-**L** was used. [c] The product alcohol configuration is *R* in all cases. [d] Mean value of at least two experiments. E.e.s were determined by chiral HPLC analysis using a Daicel CHIRALCEL OD column with isopropanol–hexane mobile phase and reproducible within 2%. [e] Reaction was carried out at 0 °C. [f] Reaction was carried out at −40 °C.

Table 4 Enantioselective allylation by allyltributyltin of aldehydes catalysed by **2**[a]

Entry	Aldehyde	Product	Time/h	Isolated yields/%	e.e.[b]/%	Configuration
1			21	92	39	*R*[c]
2			22	90	38	*R*[c]
3			15	82	40	*R*[d]
4			70	82	40	*R*[c]
5			16	98	36	*R*[c]
6			25	83	38	ND[e]
7			30	82	56	*R*[c]
8			46	85	53	*R*[d]
9			46	91	59	ND[e]
10			29	92	41	ND[e]

[a] All the reactions were carried out in CH_2Cl_2 at room temperature, 10 mol% **2**. [b] Determined by chiral HPLC analysis using a Daicel CHIRALCEL OD column with isopropanol–hexane mobile phase. [c] Assignment by comparison of the sign of optical rotation with reported value.[16] [d] By analogy to the other case that is known unambiguously.[17] [e] Not determined.

counter ions differ in their degree of interaction with the Zn(II) centre and dramatically affect catalyst efficiency.

Other metal salt chiral bipyridine ligand combinations have also been screened (Table 3, entries 10, 11). The combination of $Zn(OTf)_2$ and **L** appears to smoothly and enantioselectively promote the allylation reaction while analogous silver and copper complexes failed to afford a significant enantiocontrol and gave lower yields. This is particularly surprising in the case of $Cu(OTf)_2$ as it is the metal of choice in the best catalytic systems for Diels–Alder[14] and Mukaiyama reactions.[15] However, a similar observation has been reported previously on allylation reactions catalysed by zinc bis(oxazoline) complexes.[8]

The potential of this zinc complex as a catalyst for asymmetric allylation is illustrated by the catalysis effect in the reaction of various aldehydes with allyltributyltin (Table 4). All reactions gave excellent yields and moderate enantioselectivities for aromatic, aliphatic and heterocyclic aldehydes. The enantioselectivities were found to be independent of the electronic properties of the substituents (electron withdrawing and donating) in aromatic aldehydes. Better enantioselectivities were found with straight chain and heterocyclic aldehydes.

Although the structure of the active intermediate that carries out the reaction is still elusive, the strong counter ion effect, which is similar to that in previously reported Lewis acid catalysed Diels–Alder reactions based on copper(II) bis(oxazoline) complexes,[10] strongly suggests that the chiral zinc bipyridine complex functions as a Lewis acid in this allylation reaction. Since the less nucleophilic triflate counter ion is unlikely to bind covalently to zinc even in a non-polar solvent, the higher catalytic activity of **2** probably comes from the formation of a cationic, strongly ion-paired complex. In fact, conductivity measurements in CH_2Cl_2 on $Zn(\mathbf{L})X_2$ with different counter ions indicate that **1** is a non-electrolyte while complexes with other ions show different degrees of ion dissociation.

Conclusion

Allylation of aldehydes with allyltributyl tin using catalytic amounts of $Zn(\mathbf{L})(OTf)_2$ complex is presented. Comparing the results using a zinc(II) triflate bis(oxazoline) complex as catalyst,[3] chiral bipyridine ligand **L** is more efficient than the chiral bis(oxazoline) ligand. Further work is now in progress to improve the reactivity and enantioselectivity.

Acknowledgements

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