First Example of Supported Microwave-Assisted Synthesis of New Chiral Bipyridines and a Terpyridine − Use in Asymmetric Cyclopropanation

Frédéric Pezet,[a] Isabelle Sasaki,*[a] Jean-Claude Daran,[a] Jérôme Hydrio,[a] Hassan Aït-Haddou,*[b] and Gilbert Balavoine[a]

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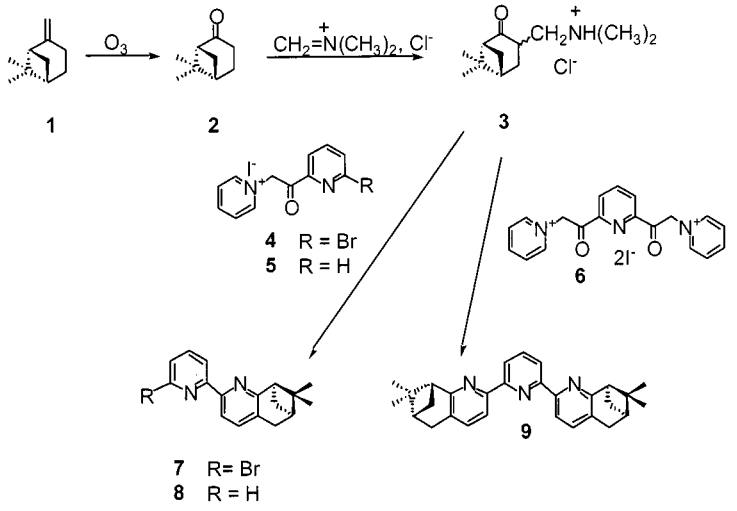
We present herein the first alumina-supported synthesis of chiral bipyridines and of a chiral C2-symmetric terpyridine conducted under microwave irradiation, and our preliminary results from copper-mediated enantioselective cyclopropanation with this terpyridine. Reaction yields were excellent and enantioselectivities of up to 87% were observed. Moreover, with *trans*-β-methylstyrene, a remarkable diastereoselectivity (ratio *trans*/*cis* = 7:93) was observed.

Introduction

Nitrogen-containing ligands for asymmetric homogeneous and heterogeneous catalysis have been highly developed.[1] Enantioselective reactions of olefins and diazoacetates catalyzed by a variety of metal complexes are also well known.[2,3] *N,N*-donor ligands led to remarkable *ee* values with copper complexes of bis-oxazolines[4,5] and semicorrins.[6] Chiral bipyridines were used for the first time by Katsuki[7,8] and very recently, Kwong and Lee[9] reported good enantioselective cyclopropanation with chiral C_2-symmetric terpyridine ligands.[10,11] Herein, we report a convenient synthesis of new chiral bi- and terpyridine ligands derived from the Kröhnke's method,[12] by using solvent-free microwave irradiation. Although microwave irradiation has been used for Suzuki coupling reactions of heterocycles,[13] to the best of our knowledge this is the first utilisation of microwave irradiation to form pyridyl rings. We also report the preparation and the characterisation of the corresponding Cu^{II} and Zn^{II} complexes, and the preliminary results of the catalytic activities of the terpyridine copper complex in asymmetric cyclopropanation.

Results and Discussion

Synthesis of polypyridine ligands usually requires a Stille coupling[14] or a Krönke reaction.[12] We used the latter, and carried out the preparation of the ligands in an expedient three-step synthesis: (−)-β-Pinene [(−)-**1**] was ozonolized to produce enantiomerically pure (+)-nopinone [(+)-**2**],[15,16] which was converted into the corresponding Mannich base **3** with the ratio 92:8 (determined by ^{1}H NMR) in favour of the (1*R*,3*R*,5*R*) diastereoisomer (Scheme 1). Condensation of the mixture of the two diastereoisomers of **3** with one equivalent of **4**[17] or **5**, or with half an equivalent of **6** under



Scheme 1. Synthesis of the polypyridyl ligands

[a] Laboratoire de Chimie de Coordination, CNRS, UPR 8241, 205, route de Narbonne, 31077 Toulouse, France
Fax: (internat.) + 33-5/6155-3003
E-mail: sasaki@lcc-toulouse.fr
[b] University of Texas at Austin, Department of Chemistry and Biochemistry,
Austin, Texas, USA

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the usual conditions (AcOH or formamide, NH_4OAc, 100 °C) led to **7**, **8**, or **9**, respectively, in very low yields (traces).

The polar solvents used for this reaction absorb microwaves very efficiently,[18] so we decided to carry out Kröhnke's synthesis under microwave irradiation. The yields increased to 10% (130 W, 5−15 min.), but the high temperatures decomposed most of the reactants or intermediates. In order to decrease the temperature dramatically, we tested solvent-free alumina-supported reaction conditions under microwave irradiation.[19] The alumina was mixed with ammonium acetate as an ammonia source. We expected that the strong affinity between alumina and salt reactants would provide a cleaner chemical conversion into the intermediate 1,5-diketone. Indeed, the microwave irradiation of this solvent-free mixture at 260 W for a few minutes led to the expected ligands **7**, **8**,[20] and **9** with good yields (45%, 50%, and 33%, respectively). Thus, the microwave irradiation eliminated the necessity of heating the reaction under reflux in the aggressive solvent (AcOH) that is required under the standard procedure, and the reaction time was reduced from approximately 4 hours to only a few minutes. Ligand **7** is particularly interesting for further study as it is a key product for the synthesis of polypyridines (by homocoupling to C2-symmetrical chiral quaterpyridines, or, after heterocoupling, to non-symmetrical chiral quaterpyridines).

Crystals suitable for X-ray crystallography were obtained by slow evaporation of a solution of **9** in chloroform. The molecular structure of **9**, as determined by X-ray analysis, is shown with its atom labelling scheme in Figure 1. Important bond lengths and bond angles are given in Table 1.

The main part of the molecule is roughly planar with the largest deviation being 0.211 Å at C(25). However, the external pyridine rings are slightly twisted with respect to the central one, resulting in dihedral angles of 10.95° and 6.32° for rings 2 and 3, respectively. Consequently, the C atoms of the pinene fragment are not symmetrically distributed with respect to the main plane of the terpyridine fragment, C(243) and C(343) being twisted away from it by 1.622 Å and −0.712 Å, whereas C(245) and C(345) are located −0.468 Å and 1.428 Å on each side of this plane. As observed in the related dipineno-[4,5:4′′,5′′]-fused 2,2′:6′,2′′-terpyridine[11] and in other terpyridine systems,[21] the nitrogen atoms are in the trans position with respect to each other in order to minimise the interactions between the nitrogen lone pairs.

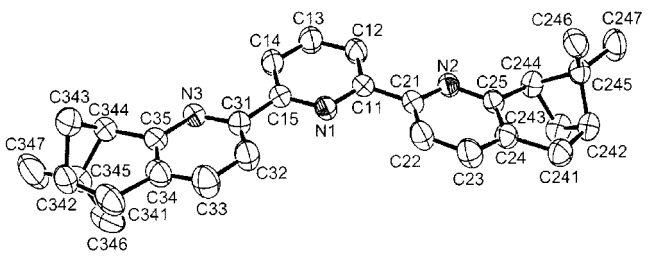
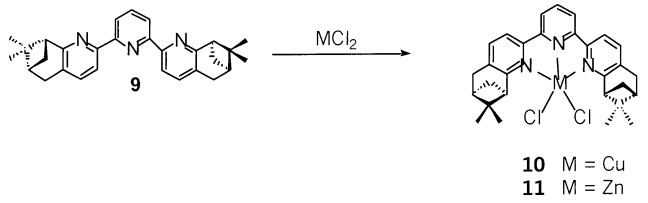


Figure 1. Molecular view of **9** with atom labelling scheme; ellipsoids represent 30% probability



Scheme 2. Synthesis of the complexes

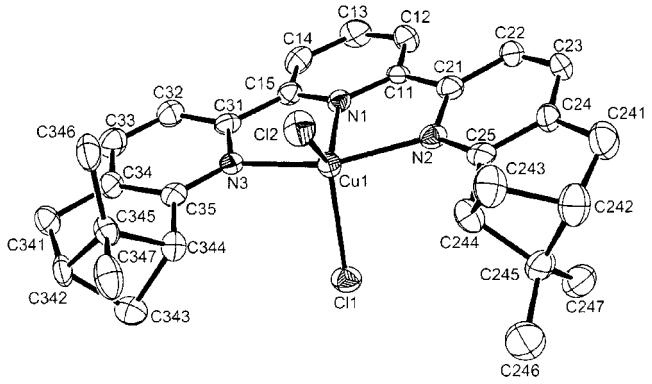


Figure 2. Molecular view of complex **10** with atom labelling scheme; ellipsoids are drawn at 30% probability

In order to investigate the coordination chemistry of this new terpyridine **9**, its copper complex was synthesised. Heating ligand **9** with $CuCl_2{\cdot}H_2O$ in EtOH for 3 hours under reflux resulted in the formation of **10** (Scheme 2). Crystals suitable for X-ray crystallography were obtained by recrystallization from dichloromethane/ether. The zinc complex **11** was also synthesised by reacting ligand **9** with $ZnCl_2$ in refluxing THF for 3 hours. Crystals suitable for X-ray crystallography were obtained by recrystallization from dichloromethane/ether. As the two complexes **10** and **11** are isostructural, only the copper one is shown, along with its atom labelling scheme, in Figure 2. Selected bond lengths and bond angles are given in Table 2.

In both complexes, the metal atom is surrounded by the three nitrogens of the terpyridine ligand and the two chlorine atoms in a distorted trigonal bipyramidal geometry (Table 2). The axial positions are occupied by two nitrogen atoms N(2) and N(3) [N(2)−Cu−N(3) = 157.2(2)° and 150.9(1)° for the Cu and Zn complexes, respectively]. The equatorial plane is made up of the two chlorine atoms and the nitrogen N(1) of the terpyridine moiety. The two M−Cl bonds are identical within experimental errors [M−Cl(1)= 2.317(1), 2.250(1) Å and M−Cl(2) = 2.314(1), 2.258(1) Å for the Cu and Zn complexes, respectively]. Although such a geometry has been observed for related five-coordinate $ZnCl_2$ species,[22] it is unusual for five-coordinate $CuCl_2$ complexes, which normally prefer square pyramidal conformations.[23] However, a similar pseudo trigonal-bipyramidal geometry has been observed in [Cu(terpy)X_2] (X= Br, I, NCS) complexes.[24] The occurrence of a trigonal bipyramidal geometry might be related to the presence of the bulky pinene substituents.

Table 1. Selected bond lengths [Å] and angles [°] for **9**, **10**, **and 11**

9		**10**		**11**	
N(1)−C(11)	1.340(3)	Cu(1)−N(1)	1.974(4)	Zn(1)−N(1)	2.074(3)
N(1)−C(15)	1.344(2)	Cu(1)−N(2)	2.074(4)	Zn(1)−N(2)	2.217(3)
N(2)−C(25)	1.336(2)	Cu(1)−N(3)	2.081(4)	Zn(1)−N(3)	2.218(3)
N(2)−C(21)	1.353(3)	Cu(1)−Cl(1)	2.3169(12)	Zn(1)−Cl(1)	2.2505(9)
N(3)−C(35)	1.341(3)	Cu(1)−Cl(2)	2.3136(13)	Zn(1)−Cl(2)	2.2580(9)
N(3)−C(31)	1.346(3)	N(1)−C(11)	1.333(5)	N(1)−C(11)	1.337(4)
C(11)−C(12)	1.379(3)	N(1)−C(15)	1.334(6)	N(1)−C(15)	1.341(5)
C(11)−C(21)	1.482(3)	N(2)−C(25)	1.340(6)	N(2)−C(25)	1.337(4)
C(12)−C(13)	1.374(3)	N(2)−C(21)	1.367(6)	N(2)−C(21)	1.357(4)
C(13)−C(14)	1.371(3)	N(3)−C(35)	1.348(6)	N(3)−C(35)	1.327(5)
C(14)−C(15)	1.382(3)	N(3)−C(31)	1.364(5)	N(3)−C(31)	1.356(5)
C(15)−C(31)	1.480(3)	N(1)−Cu(1)−N(2)	78.50(16)	N(1)−Zn(1)−N(2)	75.25(10)
C(21)−C(22)	1.378(3)	N(1)−Cu(1)−N(3)	78.80(16)	N(1)−Zn(1)−N(3)	75.62(11)
C(22)−C(23)	1.376(3)	N(2)−Cu(1)−N(3)	157.24(15)	N(2)−Zn(1)−N(3)	150.86(11)
C(23)−C(24)	1.381(3)	N(1)−Cu(1)−Cl(1)	118.63(11)	N(1)−Zn(1)−Cl(1)	118.78(8)
C(24)−C(25)	1.392(3)	N(2)−Cu(1)−Cl(1)	97.57(11)	N(2)−Zn(1)−Cl(1)	98.19(8)
C(31)−C(32)	1.378(3)	N(3)−Cu(1)−Cl(1)	94.68(9)	N(3)−Zn(1)−Cl(1)	95.35(7)
C(32)−C(33)	1.386(3)	N(1)−Cu(1)−Cl(2)	122.68(11)	N(1)−Zn(1)−Cl(2)	117.41(8)
C(33)−C(34)	1.370(3)	N(2)−Cu(1)−Cl(2)	93.72(11)	N(2)−Zn(1)−Cl(2)	95.61(8)
C(34)−C(35)	1.390(3)	N(3)−Cu(1)−Cl(2)	97.11(10)	N(3)−Zn(1)−Cl(2)	98.06(7)
C(11)−N(1)−C(15)	118.6(2)	Cl(1)−Cu(1)−Cl(2)	118.68(5)	Cl(1)−Zn(1)−Cl(2)	123.81(4)
C(25)−N(2)−C(21)	117.8(2)	C(11)−N(1)−C(15)	121.1(4)	C(11)−N(1)−C(15)	120.8(3)
C(35)−N(3)−C(31)	117.3(2)	C(11)−N(1)−Cu(1)	119.5(3)	C(11)−N(1)−Zn(1)	119.3(2)
N(1)−C(11)−C(12)	122.4(2)	C(15)−N(1)−Cu(1)	119.1(3)	C(15)−N(1)−Zn(1)	119.5(2)
N(1)−C(11)−C(21)	116.0(2)	C(25)−N(2)−C(21)	118.1(4)	C(25)−N(2)−C(21)	118.5(3)
C(12)−C(11)−C(21)	121.6(2)	C(25)−N(2)−Cu(1)	127.4(3)	C(25)−N(2)−Zn(1)	126.8(2)
C(13)−C(12)−C(11)	118.6(2)	C(21)−N(2)−Cu(1)	113.7(3)	C(21)−N(2)−Zn(1)	114.5(2)
C(14)−C(13)−C(12)	119.7(3)	C(35)−N(3)−C(31)	118.0(4)	C(35)−N(3)−C(31)	119.2(3)
C(13)−C(14)−C(15)	119.1(2)	C(35)−N(3)−Cu(1)	128.0(3)	C(35)−N(3)−Zn(1)	125.7(2)
N(1)−C(15)−C(14)	121.7(2)	C(31)−N(3)−Cu(1)	113.9(3)	C(31)−N(3)−Zn(1)	113.6(2)
N(1)−C(15)−C(31)	116.1(2)				
C(14)−C(15)−C(31)	122.17(19)				
N(2)−C(21)−C(22)	122.0(2)				
N(2)−C(21)−C(11)	115.9(2)				
C(22)−C(21)−C(11)	122.11(19)				
C(23)−C(22)−C(21)	119.4(2)				
C(22)−C(23)−C(24)	119.6(2)				

Table 2. Crystallographic data

	9	**10**	**11**
Formula	$C_{29}H_{31}N_3$	$C_{29}H_{31}Cl_2N_3Cu$	$C_{29}H_{31}Cl_2N_3Zn$
Fw (g)	421.6	556.01	557.84
Temperature, K	293 (2)	180 (2)	180 (2)
Crystal system	Monoclinic	Trigonal	Trigonal
Space group	$P2_1$	$P6_1$	$P6_1$
a, Å	13.0610 (11)	10.3549 (8)	10.4288 (4)
b, Å	6.3367 (8)	10.3549 (8)	10.4288 (4)
c, Å	15.5512 (14)	42.080 (4)	42.213 (2)
α, °	90.0	90.0	90.0
β, °	113.64 (9)	90.0	90.0
γ, °	90.0	120.0	120.0
U/Å^3	1179.1 (2)	3907.5 (6)	3976.0 (3)
Z	2	6	6
ρ (calcd.), g,cm^{-3}	1.187	1.418	1.398
μ (Mo-K_α), cm^{-1}	0.698	10.67	11.51
θ range, °	$2.68 < \theta < 26.13$	$2.27 < \theta < 20.95$	$2.25 < 2\theta < 20.96$
Reflections measured	11778	11611	14569
Independent reflections (R_{int})	4509 (0.0586)	2680 (0.0565)	2805 (0.0468)
Data/restraints/parameters	4509/1/293	2680/1/320	2805/1/320
*R*1, w*R*2 [$I > 2\sigma(I)$]	0.0372, 0.0693	0.0274, 0.0405	0.0256, 0.0536
*R*1, w*R*2 (all data)	0.0921, 0.0848	0.0398, 0.0429	0.0293, 0.0552
$(\Delta/\sigma)_{max}$	0.001	0.001	0.001
$\Delta\rho_{min}/\Delta\rho_{max}$	−0.13/0.11	−0.21/0.22	−0.16/0.16
GOF	0.881	0.922	1.023

Owing to some hydrogen interactions occurring between the H attached to carbon C(12) and Cl(1)[20] [C−H···Cl: C−H = 0.95 Å, C···Cl = 3.501(5) Å, H···Cl = 2.568(1) Å, C−H···Cl= 167.6(1)°] the packing in the cell displays a right-handed helix arrangement of the complexes around the 6_1 axes (Figure 3). Such an arrangement explains the long *c* axes relative to *a* and *b*. The crystallisation in this space group is certainly induced by the shape and the (*R*,*R*) configuration of the terpyridine ligand.

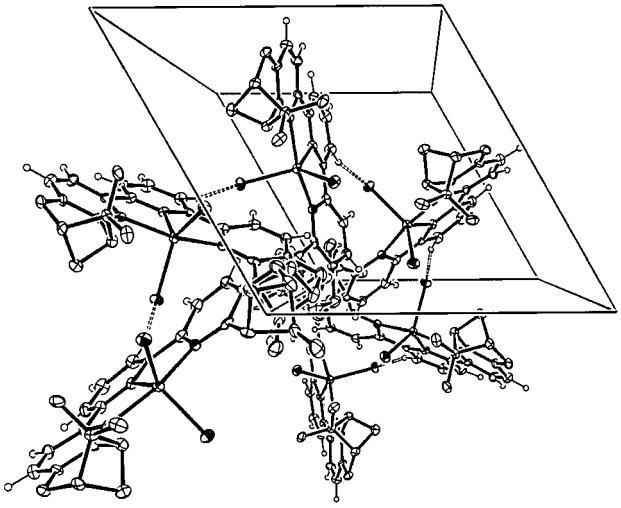
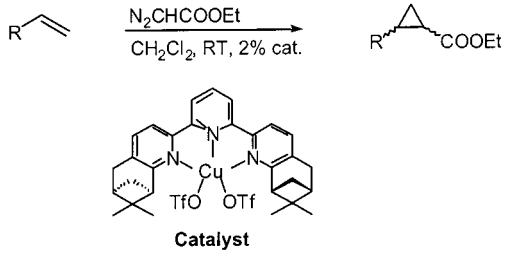


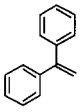
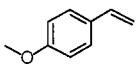
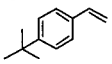
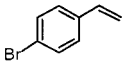
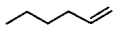
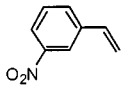
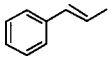
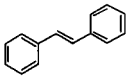
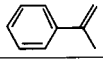
Figure 3. View along the 0 0 1 axis showing the right handed helix packing of the complexes around the 6_1 axes

To explore the catalytic potential of the copper terpyridine we examined the well-investigated cyclopropanation of various olefins with ethyl diazoacetate (Scheme 3). This commercially available diazoester, which is neither chiral nor a bulky reactant, has a very poor effect on the asymmetric induction, and allows one to evaluate the inherent capacity of the terpyridine to be a chiral controller. The reactions were carried out in the presence of 2mol % copper(II)triflate (2 mol % chiral ligand) in dichloromethane at ambient temperature. The use of other solvents such as toluene or THF led to much lower catalytic efficiency. The complex was found to be an efficient catalyst, converting alkenes and ethyldiazoacetate to optically active cyclopropanes (Table 3). Reaction of the mono-substituted olefins showed excellent yields of chiral cyclopropanes with good *trans*-selectivity, but moderate levels of enantioselectivity (6−66% *ee*) were observed. When ethyl diazoacetate was changed for the bulkier commercially available trimethylsilyldiazomethane, the diastereoselectivity increased slightly to a *trans*/*cis* ratio of 90:10, which has been observed with other copper catalysts.[7,8,25] Styrene derivatives bearing electron-donating groups showed lower enantioselectivity than those with electron-withdrawing groups, but higher reactivity (shorter reaction time). This result indicates that the active catalyst species is a strong electrophilic carbene copper complex.



Scheme 3. Cyclopropanation of olefins

Table 3. Catalytic asymmetric cyclopropanation with ethyl diazoacetate and chiral copper (II)terpyridine complex

Alkene	Time [h]	Ligand	Yield (%)	*trans*/*cis* ratio	e.e. *trans*	e.e. *cis*
	16	4	95	83/17 [a]	24 [b] (1*S*/2*S*)	54 [b] (1*S*/2*R*)
	16	4	91	–	74 [c] (*S*)	
	8	4	99	69/31 [a]	25 [b] N.D.	29 [b] N.D.
	16	4	96	66/34 [a]	40 [f] N.D.	6 [f] N.D.
	24	4	86	77/23 [a]	52 [f] N.D.	41 [f] N.D.
	16	4	82	78/22 [e]	41 [f] N.D.	66 [f] N.D.
	36	4	74	64/36 [g]	23 [h] N.D.	12 [h] N.D.
	16	4	98	7/93 [a,d]	9 [h] (1*S*/2*S*/3*S*)	65 [h] (1*S*/2*R*/3*R*)
	24	4	90		87 [c] N.D.	
	16	4	87	88/12	64 [h] N.D.	72 [h] N.D.

[a] GC. − [b] HPLC chiral column Pharmachir 7C (hexane/2-propanol 99:1 flow: 0.7 mL/min). − [c] Determined by ^{1}H NMR spectroscopy with Eu (hfc)$_3$. − [d] Major diastereoisomer: ethyl *trans*-3-methyl-*cis*-2-phenyl cyclopropanecarboxylate; minor diastereoisomer: ethyl *trans*-3-methyl-*trans*-2-phenylcyclopropanecarboxylate. − [e] Determined by ^{1}H NMR integration of methylene ($COOCH_2CH_3$). − [f] GC analytic chiral column Supelco-120 (oven temperature 120 °C to 200 °C **0.5** °C/min). − [g] Determined by ^{1}H NMR integration of the cyclopropyl protons. − [h] Determined by chiral GC after transesterification with (−)-menthol (99% *ee*). N.D.: absolute configuration not determined

Based on the results and the sense of asymmetric induction, the metal carbenoid attack could be compared to the model previously reported by Pfaltz for *N,N*-bidentate ligands,[6] and by Kwong for *N,N,N*-tridentate ligands.[9] Using 1,1′- or 1,2-disubstituted olefins led to better results, showing that the steric interaction between the ligand and these olefins increased with respect to monosubstituted ones. For instance, a good *ee* of up to 87% was observed

with *trans*-stilbene. In contrast to the other substrates, *trans*-β-methylstyrene showed a remarkable reversed *cis*-selectivity, as already observed by Katsuki[8] with chiral bipyridine. The ratio *cis*/*trans* = 93:7 is of the same order as the results described by Nishiyama[26] with hydroxymethyl derivative of pybox and (+)-menthyl diazoacetate.

Conclusion

We have successfully synthesised new chiral ligands by microwave irradiation. The copper complex of the terpyridine derivative is an active catalyst for cyclopropanation and *ee*s up to 87% were observed. Cyclopropanation of *trans*-β-methylstyrene showed a very high *cis*-selectivity with ethyl diazoacetate. Further studies on other disubstituted olefins are under investigation.

Experimental Section

General: All reactions were carried out under an inert argon atmosphere. Chemicals were of reagent-grade quality and were obtained commercially. NMR spectra were recorded with a Bruker AM-250 (250 MHz) or AMX-400 (400 MHz) spectrometer for ^1H and ^{13}C and chemical shifts are reported in ppm downfield from Me_4Si in $CDCl_3$ or in CD_2Cl_2. All melting points are uncorrected and were measured on a SMP1 Stuart Scientific melting point apparatus. CI mass spectra and FAB mass spectra (*m*-nitrobenzyl alcohol matrix) were recorded with a quadrupolar Nermag R10−10H instrument. Optical rotations were measured on a Perkin−Elmer 241 polarimeter. Elemental analyses were performed by LCC (Laboratoire de Chimie de Coordination) Microanalytical Service. Column chromatography purifications were performed with Merck aluminum oxide (70−230 mesh ASTM), deactivated with 8% water. (+)-Nopinone was obtained from ozonolysis of (−)-β-pinene.[15]

Mannich Base of the Nopinone 3: *N*,*N*-dimethylmethyleneiminium chloride (6.8 g) was added to nopinone (**2**; 9 g) in 135 mL of dry acetonitrile. After stirring at room temperature for four days the white precipitate was filtered off and rinsed with acetonitrile. The filtrate was concentrated and more of the product was recovered (9.1 g, 60% yield). − M.p. 188 °C − ^1H NMR ($CDCl_3$): δ = 12.12 (m, 1 H), 3.5 (dd, ^2J = 12.8, ^3J = 3.6 Hz, 1 H), 3.23 (dd, ^2J = 12.8, ^3J = 10.0 Hz, 1 H), 2.92 (s, 6 H), 2.87 (m, 1 H), 2.66 (m, 2 H), 2.54 (m, ^2J = 14.0, ^3J = 2.4 Hz, 1 H), 2.34 (m sept, ^3J = 2.8 Hz, 1 H), 2.23 (ddd, ^2J = 14.0, ^3J = 3.6, ^3J = 3.6 Hz, 1 H), 1.34 (s, 3 H), 1.29 (d, ^2J = 10.8 Hz, 1 H), 0.94 (s, 3 H). − ^{13}CNMR ($CDCl_3$): δ = 211.9, 64.0, 58.4, 41.0, 40.7, 40.4, 29.7, 27.1, 26.2, 22.9. − MS (DCI, NH_3): *m*/*z* (%) = 196 (100), 197 (15). − $C_{12}H_{24}ClNO_2$·0.25H_2O: calcd. C 61.01, H 10.16, N 5.93; found C 60.92, H 9.23, N 6.01.

General Procedure for the Synthesis of Ligands 7 to 9 Under Microwave Irradiation: The aluminium oxide was prepared by mixing 10 g of aluminium oxide 90, 5 g of ammonium acetate, and 1 mL of AcOH in a mortar.

Freshly prepared aluminium oxide (3 g) was then added to a solution of **3** (1 mmol) and the pyridinium salt (1 mmol) in MeOH (30 mL). The solvent was evaporated and the resulting mixture was irradiated in the microwave oven for 4 min. at 260 W. After cooling, the ligand was extracted with CH_2Cl_2 and purified by column chromatography on aluminium oxide (eluent: 3% AcOEt in pentane)

Ligand 7: Following the above procedure with **4**, and the usual workup, gave **7** (0.142 g, 43%). − $[\alpha]_D^{20}$ = + 23.0 (*c* = 1, CH_2Cl_2). − M.p. 122 °C. − ^1H NMR ($CDCl_3$): δ = 8.33 (dd, ^3J = 7.5, ^4J = 1.0 Hz, 1 H), 8.15 (d, ^3J = 7.5 Hz, 1 H), 7. 60 (t, ^3J = 7.5 Hz, 1 H), 7.51 (d, ^3J = 7.5 Hz, 1 H), 7.41 (dd, ^3J = 7.5, ^4J = 1.0 Hz, 1 H), 3.04 (t, ^3J = 5.5 Hz, 1 H), 2.97 (d, ^3J = 2.5 Hz, 2 H,), 2.73 (td, ^2J = 9.5, ^3J = 5.5 Hz, 1 H), 2.33 (m sept, ^3J = 2.8 Hz, 1 H), 1.43 (s, 3 H), 1.32 (d, ^2J = 9.5 Hz, 1 H), 0.67 (s, 3 H). − ^{13}C NMR ($CDCl_3$): δ = 165.9, 158.0, 150.3, 141.3, 139.0, 135.9, 131.4, 127.2, 119.5, 119.2, 50.5, 40.0, 39.2, 31.3, 30.8, 26.0, 21.2. − MS (DCI, NH_3): *m*/*z* (%) = 317 (98), 319 (100) $[MH^+]$. − $C_{17}H_{17}BrN_2$ (329.24): calcd. C 62.02, H 5.20, N 8.51; found C 62.12, H 4.99, N 8.34.

Ligand 8: Following the above procedure with **5**, and the usual workup, gave **8** (0.125 g, 50%). − $[\alpha]_D^{20}$ = + 17.6 (*c* = 1, CH_2Cl_2). − M.p. 84 °C. − ^1H NMR ($CDCl_3$): δ = 8.61 (ddd, ^3J = 4.8, ^4J = 1.4 Hz, ^5J = 0.7 Hz, 1 H), 8.34 (d, ^3J = 8.0 Hz, 1 H), 8.12 (d, ^3J = 7.8 Hz, 1 H), 7.76 (dt, ^3J = 7.8, ^4J = 1.8 Hz, 1 H), 7.53 (d, ^3J = 7.8 Hz, 1 H), 7.19 (ddd, ^3J = 8.5, ^3J = 4.8 Hz, ^4J = 1.1 Hz, 1 H), 3.08 (dd, ^3J = 5.6, ^3J = 5.6 Hz, 1 H), 2.98 (d, ^3J = 2.5 Hz, 2 H), 2.74 (td, ^2J = 9.7, ^3J = 5.9 Hz, 1 H), 2.34 (m sept, ^3J = 2.8 Hz, 1 H), 1.43 (s, 3 H), 1.34 (d, ^2J = 9.7 Hz, 1 H), 0.69 (s, 3 H). − ^{13}C NMR ($CDCl_3$): δ = 165.9, 156.7,152.0, 149.1, 136.7, 135.9, 130.6, 123.0, 120.9, 118.7, 50.5, 40.0, 39.2, 31.3, 30.8, 26.0, 21.2. − MS (DCI, NH_3): *m*/*z* (%) = 251 $[MH]^+$. − $C_{17}H_{18}N_2$ (250.34): calcd. C 81.56, H 7.15, N 11.19; found C 81.59, H 7.13, N 11.15.

Ligand 9: Following the above procedure with half an equivalent of **6**, and the usual workup, gave **9** (0.080 g, 38%) − $[\alpha]_D^{20}$ = − 8.4 (*c* = 1, CH_2Cl_2). − M.p. 255 °C. − ^1H NMR ($CDCl_3$): δ = 8.38 (d, ^3J = 3.8 Hz, 2 H), 8.35 (d, ^3J = 3.8 Hz, 2 H), 7.86 (t, ^3J = 7.8 Hz, 1 H), 7.56 (d, ^3J = 7.8 Hz, 2 H), 3.09 (dd, ^3J = 5.6, ^3J = 5.6 Hz, 2 H), 2.99 (d, ^3J = 2.5 Hz, 4 H), 2.74 (td, ^2J = 9.7, ^3J = 5.9 Hz, 2 H), 2.35 (m sept, ^3J = 2.8 Hz, 2 H), 1.44 (s, 6 H), 1.35 (d, ^2J = 9.7 Hz, 2 H), 0.70 (s, 6 H). − ^{13}C NMR ($CDCl_3$): δ = 165.7, 155.7, 152.3, 137.6, 135.9, 130.5, 120.2, 118.8, 50.5, 40.1, 39.2, 31.3, 30.9, 26.0, 21.3. − MS (DCI, NH_3): *m*/*z* (%) = 422 $[MH]^+$. − $C_{29}H_{31}N_3$ (421.58): calcd. C 82.11, H 7.63, N 10.26; found C 82.51, H 7.28, N 9.55.

Synthesis of Copper Complex 10: Complex **10** was synthesized by mixing ligand **9** (0.1 mmol) and copper(II) chloride dihydrate (0.05 mmol) in absolute EtOH (6 mL). The mixture was heated under reflux for 3 hours and the precipitate then collected. The green-yellow complex crystallised by slow diffusion of ether into a solution of **10** in dichloromethane (16 mg, 58% yield). − Positive ion FAB-MS: *m*/*z* = 519 $[M - Cl]^+$, 484 $[M - 2Cl]^+$.

Synthesis of Zinc Complex 11: Complex **11** was synthesised by adding ligand **9** (0.1 mmol) in THF (20 mL) to a stirred solution of zinc(II) chloride (0.1 mmol) in THF (10 mL). The mixture was then heated under reflux for 3 hours. After cooling, the solvent was evaporated and the white solid was recrystallized from a mixture of dichloromethane and ether (38 mg, 70% yield). − ^1H NMR (CD_2Cl_2): δ = 8.16 (m, 3 H), 7.98 (d, ^3J = 7.9 Hz, 2 H), 7.73 (d, ^3J = 7.9 Hz, 2 H), 4.25 (dd, ^3J = 5.5, ^3J = 5.5 Hz, 2 H), 3.10 (d, ^3J = 2.5 Hz, 4 H), 2.89 (m, 2 H), 2.39 (m sept, ^3J = 2.8 Hz, 2 H), 1.55 (s, 6 H), 1.41 (d, ^2J = 10.1 Hz, 2 H), 0.76 (s, 6 H). − ^{13}C NMR (CD_2Cl_2): δ = 169.1, 151.5, 144.1, 142.4, 138.4, 136.6, 121.4, 119.5, 49.6, 40.2, 39.9, 32.5, 30.8, 26.3, 21.8. − Positive ion FAB-MS: *m*/*z* = 520 $[M - Cl]^+$, 484 $[M - 2Cl]^+$.

X-ray Crystallographic Study: Suitable crystals of ligand **9** were grown by slow evaporation of a chloroform solution. Suitable crystals of complexes **10** and **11** were grown by dissolving each of them in dichloromethane and allowing diethyl ether to diffuse into the solution. Data for **9**, **10**, and **11** were collected on a Stoe IPDS diffractometer. The final unit cell parameters were obtained by the least-squares refinement of 8000 reflections. Only statistical fluctuations were observed in the intensity monitors over the course of the data collections.

All the structures were solved by direct methods (SIR97[27]) and refined by least-squares procedures on F^2. All H atoms were introduced in calculated idealised positions [d(CH) = 0.96 Å] and treated as riding models with isotropic thermal parameters related to the carbon to which they are attached. Least-squares refinements were carried out by minimising the function $\Sigma w(F_o^2 - F_c^2)^2$, where F_o and F_c are the observed and calculated structure factors. The absolute structure for **10** and absolute configuration for **11** were determined by refining the Flack enantiopole parameter.[28] The weighting scheme used in the last refinement cycles was $w = 1/[\sigma^2(F_o^2) + (aP)^2 + bP]$, where $P = (F_o^2 + 2F_c^2)/3$ Models reached convergence with $R = \Sigma (||F_o| - |F_c||)/\Sigma(|F_o|)$ and $wR2 = \{\Sigma w(F_o^2 - F_c^2)^2/\Sigma w (F_o^2)^2\}^{1/2}$ with the values listed in Table 2. The calculations were carried out using the SHELXL-97 program[29] running on a PC. Molecular views were realised with the help of ORTEP32.[30] Crystallographic data (excluding structure factors) for the structure(s) included in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-158858 (**9**), -158859 (**10**) and -158860 (**11**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: (internat.) + 44-1223/336-033; E-mail: deposit@ccdc.cam.ac.uk].

Procedure for Copper-Catalysed Cyclopropanation: A solution of 0.2 mmol of ligand and 0.2 mmol of $Cu(OTf)_2$ in dichloromethane (2 mL) under argon was stirred for 2 hours at room temperature. The alkene (4 mmol) and the ethyl diazoacetate (0.2 mmol) were then added and the mixture was stirred for 30 min. The reduction of Cu^{II} to Cu^{I} could also be activated by gentle heating of the solution (the colour of the solution changing from green to reddish). Slow addition of 2 mL of a 0.5 mM solution of the diazo compound in CH_2Cl_2 was carried out over a period of 3 hours, using a syringe pump. The mixture was allowed to stir overnight at room temperature then worked up by removing the solvent and purifying the crude product by column chromatography (pentane/ethyl acetate). All isolated cyclopropanes were known compounds and were characterised by ^1H and ^{13}C NMR spectroscopy, and mass spectrometry.

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