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New chiral bidentate ligands containing thiazolyl and pyridyl donors for copper-catalyzed asymmetric allylic oxidation of cyclohexene

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Abstract

Chiral bidentate ligands **1**–**3**, which contain a combination of thiazolyl and pyridyl donors units, were prepared. The syntheses are facile and being based on Kröhnke condensation of a pinene derivative to form the pyridine ring. Modification at the 8-position of the tetrahydroquinoline ring can be carried out by alkylation reaction with **2a** and **3a** but not **1a**. The structure of a copper(II) perchlorate complex of **1a** was characterized with X-ray crystallography, which reveals the binding of the pyridyl–thiazole as a *N*–*N* donors at the copper center. The copper(I) thiazolyl–pyridine complexes prepared in situ are active catalysts in the enantioselective allylic oxidation of cyclohexene using *tert*-butyl perbenzoate as the oxidant. The isolated yields of the allylic benzoate were up to 98%, and enantioselectivity was up to 62% e.e.

Keywords: Copper; Pyridyl; Thiazolyl; Asymmetric; Allylic; Oxidation

1. Introduction

The copper-catalyzed allylic oxidation (Kharash-Sosnovsky reaction) of olefins with peresters has been the subject of numerous synthetic and mechanistic investigations [1–10]. The allylic ester product of the reaction can easily be converted into allylic alcohol by saponification or reduction method. Besides, an organometallic allylic copper(I) benzoate complex was proposed as the intermediate [11]. The first asymmetric version of the Kharash-Sosnovsky reaction was reported in 1965 by Denney et al. [8], though the enantioselectivity was not very good. Better enantioselectivity control has started to appear recently [12–30]. Among them, some of them are of non C_2-symmetry [18,25,26]. Our group has been interested in pyridine-based chiral ligand design and exploration of their applications in the asymmetric allylic oxidation [26]. Thiazole which has different electron density and ring size compare to pyridine is of interest because of their different coordination chemistry compare to pyridine. Incorporation of it into a chiral bidentate ligand, like pyridyl–thiazole, should be of interest as it has the potential of being *N*–*S* or *N*–*N* ligand which could be useful for a variety of asymmetric reaction and provides a framework of ligand environment for further design and development. Herein, we report the synthesis of several series of new chiral C_1-pyridyl–thiazole ligands **1**–**3** and their application in the Cu(I)-catalyzed asymmetric allylic oxidation of cyclohexene using *tert*-butyl perbenzoate as oxidant. The *N*–*N* coordination mode was demonstrated by the X-ray structure of a copper(II) ion complex.

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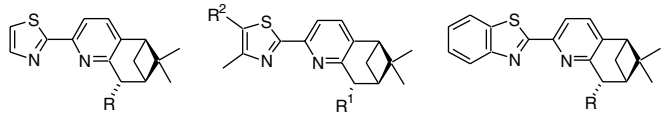


1a: R = H
1b: R = CH_3

2a: R^1 = H, R^2 = H
2b: R^1 = CH_3, R^2 = H
2c: R^1 = *i* Pr, R^2 = H
2d: R^1 = *n*Pr, R^2 = *n*Pr
2e: R^1 = *n*Bu, R^2 = *n*Bu
2f: R^1 = Benzyl, R^2 = Benzyl
2g: R^1 = CH_2SiMe_3, R^2 = CH_2SiMe_3

3a: R = H
3b: R = *n*Pr
3c: R = Benzyl
3d: R = CH_2SiMe_3

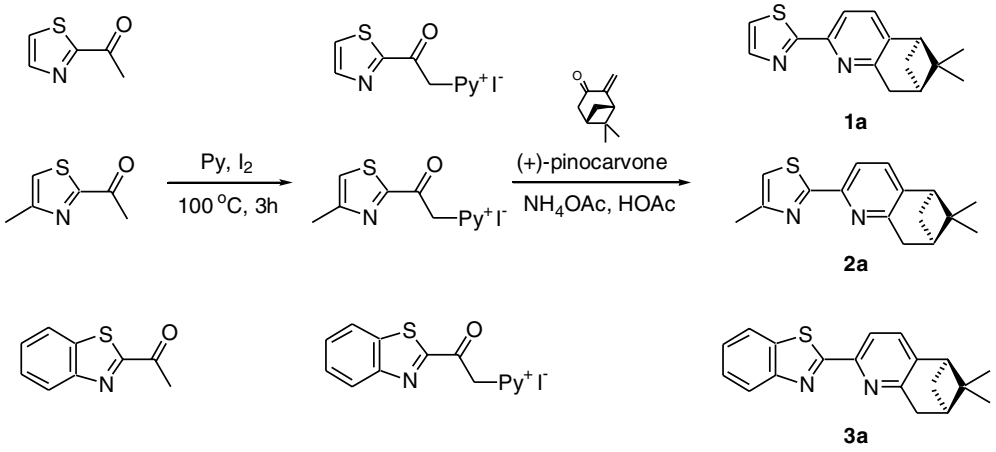
2. Results and discussion

2.1. Synthesis of C_1-symmetric pyridyl–thiazole ligands

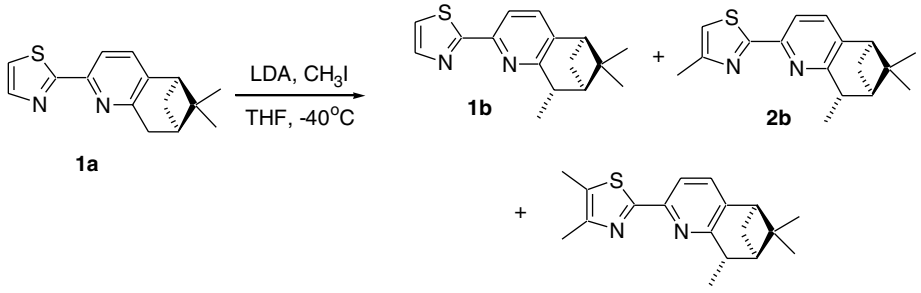
The key step in the synthesis of these ligands is the assembly of the pyridine unit from the reaction of an acetylthiazolyl–pyridinium salt with (+)-pinocarvone. Ligands **1a**, **2a** and **3a**, which have a chiral rigid substituent fused to the pyridine ring, were easily prepared by two steps syntheses using 2-acetylthiazole, 2-acetyl-4-methylthiazole and 2-acetyl-benzothiazole as the starting material, respectively (Scheme 1). The acetylthiazolyl–pyridinium salts were simply prepared by reaction of 2-acetylthiazoles with iodine in pyridine at 100 °C for 3 h to give yellow precipitates which were filtered and washed with cold absolute ethanol. After drying under vacuum, pale yellow powders were obtained as thiazoliacetyl–pyridinium iodide salts in quantitative yields. Cyclization of the pyridinium iodide salts with (+)-pinocarvone afforded 42%, 50% and 50% yields of **1a**, **2a** and **3a**, respectively, after purification with flash column chromatography.

In an attempt to introduce a methyl group at the 8-position of the tetrahydroquinoline ring of **1a**, **1a** was treated with lithium diisopropylamide (LDA) at −40 °C, followed by reaction with the methyl iodide [31–34]. Careful analysis using ^{1}H NMR and GC–MS identified the product as a mixture of the mono-, di- and trimethylsubstituted isomers (Scheme 2). Repeated column chromatography gave ligand **1b** and **2b** in 7% and 4% yield only. This observation indicates that the protons in the thiazolyl-ring could be detached by LDA during lithiation even at low temperature condition. Lithiation of pyridyl–thiazole ligands **2a** and **3a** which do not have a proton next to the nitrogen of the thiazole ring were attempted and had no problem.

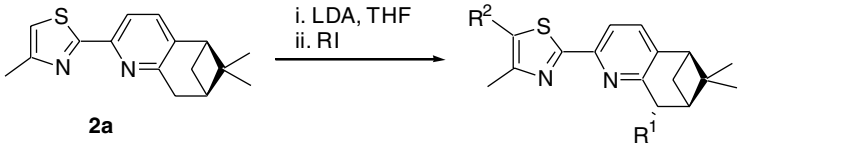
The 4-methylthiazolyl–pyridine derivatives **2c**–**2g** were prepared by one pot reaction using **2a** as the starting material (Scheme 3). In an example, compound **2a** in THF was added dropwise under nitrogen at −40 °C to a freshly prepared LDA solution. The reaction was kept at −40 °C for 2 h. The pale yellow LDA solution became deep blue. Then



Scheme 1.

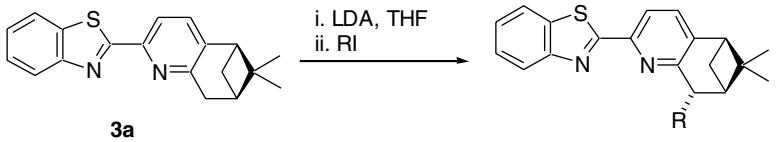


Scheme 2.



2c: R^1= *i*Pr, R^2= H
2d: R^1= *n*Pr, R^2= *n*Pr
2e: R^1= *n*Bu, R^2= *n*Bu
2f: R^1= Benzyl, R^2= Benzyl
2g: R^1= CH_2SiMe_3, R^2 = CH_2SiMe_3

Scheme 3.



3b: R = *n*Pr
3c: R = Benzyl
3d: R = CH_2SiMe_3

Scheme 4.

addition of 2-iodopropanes to the mixture gave mono-substituted compound **2c** in 50% yields. Interestingly, primary alkyl iodides such as 1-propyl iodide, 1-butyl iodide, benzyl iodide or (iodomethyl)trimethylsilane gave the di-substituted products **2d**–**2g** as the major product. The isolated yields were found slightly varied with different alkyl iodides.

In addition, the ligand series of benzothiazolyl–pyridines derivatives **3b**–**3d** were synthesized based on a similar synthetic approach with **3a** as the starting. In the lithiation reaction, alkyl groups were only introduced at the 8-position of the tetrahydroquinoline ring as the benzothiazolyl cyclic ring was inert for substitution. Pure compounds of **3b**–**3d** were obtained up to 53% yields (Scheme 4). All C_1-pyridyl–thiazole ligands were characterized unambiguously by ESI-MS, ^{1}H and ^{13}C NMR.

2.2. Synthesis of ligand *1a* copper(II) complex and X-ray crystal structure analysis of $[Cu(\mathbf{1a})_2(H_2O)](ClO_4)_2$

The coordination chemistry of these ligands was demonstrated with a copper(II) complex of ligand **1a**. When a solution of **1a** was refluxed with $Cu(ClO_4)_2 \cdot 6H_2O$ salt in a CH_2Cl_2/ethanol (1:3), a green solution was formed. Evaporation and addition of diethyl ether led to a green precipitate which was formulated to be $[Cu(\mathbf{1a})_2](ClO_4)_2$ with ESI-MS and CHN analysis. Recrystallization of the compound in an ethanol solution at room temperature led to single crystals which are suitable for X-ray analysis. Crystallographic data are summarized in Table 1. The perspective view and atomic numbering of the crystal structure are shown in Fig. 1. The compound

Table 1
Crystallographic data for $[Cu(\mathbf{1a})_2(OH_2)](ClO_4)_2$

Empirical formula	$C_{30}H_{34}C_{12}CuN_4O_9S_2$
Formula weight	793.17
Temperature (K)	273
Wavelength (Å)	0.71073
Crystal color	Green
Crystal system	Orthorhombic
Space group	$P2_12_12_1$
Unit cell dimensions	
a (Å)	9.3221(19)
b (Å)	18.895(4)
c (Å)	19.102(4)
α (°)	90
β (°)	90
γ (°)	90
Volume (Å^3)	3364.6(12)
Z value	4
Density (calcd.) (Mg/m^3)	1.566
Absorption coefficient (mm^{-1})	0.991
F_{000}	1636
Crystal size (mm^3)	$0.20 \times 0.15 \times 0.05$
Theta range for data collection (°)	1.52–28.48
Index ranges	$-12 \leqslant h \leqslant 12$, $-24 \leqslant k \leqslant 24$, $-14 \leqslant l \leqslant 25$
Reflections collected	24156
Independent reflections [R_{int}]	7976 [0.0903]
Completeness to theta = 28.48°	95.6%
Absorption correction	Semi-empirical from equivalents
Maximum and minimum transmission	1.00 and 0.67
Refinement method	Full-matrix least-squares on F^2
Data/restraints/parameters	7976/0/433
Goodness-of-fit on F^2	1.007
Final R indices [$I > 2\sigma(I)$]	$R_1 = 0.0567$, $wR_2 = 0.0987$
R indices (all data)	$R_1 = 0.1093$, $wR_2 = 0.1152$
Absolute structure parameter	−0.022(16)
Largest difference peak and hole (e Å^{-3})	0.953 and −0.625

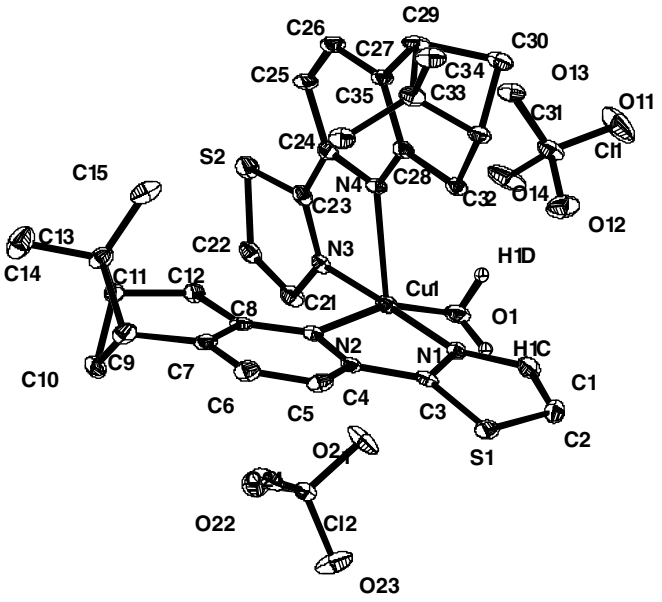


Fig. 1. X-ray crystal structure of $[Cu(\mathbf{1a})_2(H_2O)](ClO_4)_2$.

has the formula of $[Cu(\mathbf{1a})(H_2O)](ClO_4)_2$. The copper metal center coordinates with two ligands of **1a**, which are both *N*,*N*-coordiated rather than *N*,*S*-coordinated, and a water molecule to form a 5-coordinated square pyramidal geometry. Selected bond distances and bond angles for the Cu-complex are listed in Table 2. The two thiazolyl ligands are found *cis* to each other with atom *N*(4) of the ligand occupied the axial site, while atoms *N*(1), *N*(2), *N*(3) and O(1) occupied the equatorial sites to form a distorted square plane. The angles around the equatorial plane for *N*(1)–Cu(1)–O(1), *N*(1)–Cu(1)–*N*(2), *N*(2)–Cu(1)–*N*(3) and *N*(3)–Cu(1)–O(3) are 97.4°, 81.4°, 102.3° and 83.7°, respectively. The water molecule is fashioned *trans* to atom *N*(2) of the pyridine ring, which has slightly shorter Cu(1)–*N*(2) (2.177 Å) bond distance than the Cu(1)–*N*(4) (2.294 Å) of the second pyridine ring. The bond distances of Cu(1)–*N*(1) and Cu(1)–*N*(3) of the thiazole are comparable with each other. The shorter bond distance of Cu(1)–*N*(1) than that of Cu(1)–*N*(2) may indicate the *N*-donor of the thiazole ring has a better σ character than that of the pyridine.

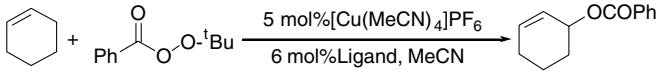
Table 2
Selected bond angles and bond distances for $[Cu(\mathbf{1a})_2(OH_2)](ClO_4)_2$ complex

Atoms	Bond angles (°)	Atoms	Bond distances (Å)
N(1)–Cu(1)–O(1)	97.41(15)	Cu(1)–N(1)	1.944(4)
N(2)–Cu(1)–O(1)	160.95(13)	Cu(1)–N(3)	1.952(4)
N(3)–Cu(1)–O(1)	83.76(15)	Cu(1)–O(1)	2.057(3)
N(1)–Cu(1)–N(2)	81.41(15)	Cu(1)–N(2)	2.177(4)
N(1)–Cu(1)–N(3)	174.35(18)	Cu(1)–N(4)	2.294(4)
N(1)–Cu(1)–N(4)	106.41(15)		
N(2)–Cu(1)–N(3)	102.28(14)		
N(2)–Cu(1)–N(4)	87.49(13)		
N(3)–Cu(1)–N(4)	78.20(15)		

2.3. Copper-catalyzed asymmetric allylic oxidation

In the first investigation of using C_1-pyridyl–thiazoles as ligands in asymmetric allylic oxidation of cyclohexene, the active Cu(I) catalysts of **1a** and **1b** were prepared in situ by reacting with $[Cu(CH_3CN)_4]^+PF_6^-$ salts in acetonitrile under nitrogen for 2 h. To the catalyst solution, cyclohexene (4 mmol) was added first, then followed by dropwise addition of *t*-butyl peroxybenzoate (1 mmol) over a period of 1 min. The reactions were monitored by TLC and carried on until complete conversion of oxidant or the turnover of the catalyst slowed down. The conversions of *t*-butyl peroxybenzoate oxidant were completed efficiently within 48 h. The allylic benzoates were isolated in 55–60% yields from the reactions with e.e. up to 25%. Obviously, with a rigid methyl group at the 8-position of the tetrahydroquinoline ring **1b** led to a better outcome in terms of e.e. for the allylic oxidation (Table 3, entries 1–2). These results prompted us to examine ligands with modification at the 8-position with different alkyl groups which have different steric hindrance and the effect of substitution on the thiazole ring further. Results are summarized in Table 3. The Cu(I) complexes of **2a**–**3d** are all active catalysts in the oxidation reaction. In most of the cases, conversions were completed within 48 h and allylic benzoates were isolated as product in excellent yields up to 98%. For ligands with a substituent at the 8-position of tetrahydroquinoline, they led to (*R*)-configured allylic benzoates, while C_1-ligands such as **1a**, **2a** and **3a** resulted in (*S*)-configured allylic benzoates with lower enantioselectivity. The presence of an alkyl group at 8-position of tetrahydroquinoline seems to be very important in the enantiocontrol but

Table 3
Asymmetric allylic oxidation of cyclohexene catalyzed by Cu(I) complexes of chiral thiazolyl–pyridines at room temperature



Entry	Ligand	Time (h)	Conversion (%)[a]	Yield (%)[b]	e.e. (%)[c]
1	**1a**	48	100	60	13 (*S*)
2	**1b**	48	100	55	25 (*R*)
3	**2a**	48	100	59	8 (*S*)
4	**2b**	48	100	58	36 (*R*)
5	**2c**	48	100	75	62 (*R*)
6	**2d**	60	100	95	61 (*R*)
7	**2e**	48	100	62	62 (*R*)
8	**2f**	48	98	63	55 (*R*)
9	**2g**	48	100	95	58 (*R*)
10	**3a**	60	93	96	10 (*S*)
11	**3b**	48	94	85	43 (*R*)
12	**3c**	60	95	98	48 (*R*)
13	**3d**	48	95	96	39 (*R*)

[a] Conversion was determined by GC based on the consumption of *tert*-butyl perbenzoate.
[b] Isolated yields based on conversion.
[c] Determined by HPLC analysis using a chiral OD column. The absolute configurations were assigned by comparing the order of elution with samples of known configuration [21].

the enantioselectivity is not very sensitive to the size of the bulk at the position when they are bigger than a methyl group (Table 3, entries 5–9 and 11–13).

The effect of substitution on the thiazole ring has also been examined. By comparing ligands **1**, **2** and **3**, the substitution is found to be important to the enantioselectivity. Benzothiazolyl–pyridines **3** with an aromatic ring fused in the thiazolyl-cycle do not induce a better enantiocontrol than 3-methyl substituted thiazolyl–pyridine **2** in all the cases (Table 3, entries 5–9 and 10–13), but the isolated yields of the allylic benzoates show improvement in general. Thiazole ring with no substitution gave the worst result in general (Table 3, entries 1–2 vs. 3–4).

In conclusion, we have successfully developed synthesis of new C_1-symmetric thiazolyl–pyridine ligands and their application in Cu(I)-catalyzed allylic oxidations of cyclohexene. Excellent isolated yields of cyclohexenyl benzoate up to 98% and enantioselectivities up to 62% e.e. were observed. Steric bulk on the tetrahydroquinoline ring and the thiazole ring are both important in term of enantioselectivity. The mechanism of the reactions is under investigation and efforts to extend the application of these ligands in asymmetric catalysis are underway.

3. Experimental

3.1. General methods

Acetonitrile was distilled under N_2 over calcium hydride. Chemicals were of reagent-grade quality and were obtained commercially. Pinocarvone was prepared using procedure reported previously [35]. 4-Methylthiazole, benzothiazole and 2-acetylthiazole were purchased from Aldrich and used as received. The pyridinium iodides were prepared according to reported procedures [36]. ^{1}H and ^{13}C NMR spectra were recorded with a Varian 300 MHz Mercury instrument. ESI-MS analysis was recorded using a PE SCIEX API 365 mass spectrometer. Reactions were monitored by GC using a Hewlett–Packard 5890II GC instrument with an Ultra 2-crosslinked 5% PhMesilcone (25 m × 0.2 mm × 0.33 μm) column. Electron ionization mass spectra were recorded on a Hewlett–Packard 5890II GC instrument coupled with a 5970 mass selective detector. Elemental analyses were performed on a Vario EL elemental analyzer. Diffraction intensity data of single crystals were collected on a Siemens SMART-CCD diffractometer at 273 K using graphite-monochromatised Mo Kα radiation. Crystallographic data for the structures have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 285470.

3.2. General procedure for formation of pyridine ring

2-Thiazoliacetyl–pyridinium iodide salts (1.5 mmol), (+)-pinocarvone (4.5 mmol, 0.675 g) and ammonium acetate were added to glacial acetic acid (2 mL). The mixture was refluxed at 120 °C overnight. The reaction mixture was quenched by saturated $NaHCO_3$ solution. The aqueous mixture was extracted with Et_2O (three times). The organic layers were combined and removed under reduced pressure. The resulting brown residue was purified by flash column chromatography.

3.3. Ligand *1a*

2-Thiazoliacetyl–pyridinium iodide salt was used: 0.16 g (42% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.68 (s, 3H), 1.30 (d, $J = 9.6$ Hz, 1H), 1.42 (s, 3H), 2.38–2.42 (m, 1H), 2.67–2.76 (m, 1H), 2.81 (t, $J = 6$ Hz, 1H), 3.17 (d, $J = 3$ Hz, 2H), 7.31 (d, $J = 7.8$ Hz, 1H), 7.38 (d, $J = 3.3$ Hz, 1H), 7.88–7.90 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 21.29, 25.97, 31.75, 36.40, 39.47, 40.08, 46.57, 116.48, 120.31, 133.72, 143.41, 143.63, 148.70, 157.05, 169.98; ESI-MS m/z: 257 ($M^+ + H$).

3.4. Ligand *2a*

4-Methyl-2-thiazoliacetyl–pyridinium iodide salts was used: 0.20 g (50% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.68 (s, 3H), 1.30 (d, $J = 9$ Hz, 1H), 1.42 (s, 3H), 2.36–2.41 (m, 1H), 2.52 (s, 3H), 2.67–2.74 (m, 1H), 2.78–2.82 (m, 1H), 3.17 (d, $J = 2.7$ Hz, 2H), 6.94 (s, 1H), 7.29 (d, $J = 7.8$ Hz, 1H), 7.88 (d, $J = 7.5$, 1H); ^{13}C NMR ($CDCl_3$): δ 17.21, 21.31, 26.00, 31.76, 36.42, 39.50, 40.10, 46.60, 115.15, 116.68, 133.72, 143.44, 148.47, 153.57, 157.10, 169.13; ESI-MS m/z: 271 ($M^+ + H$).

3.5. Ligand *3a*

Benzothiazolioacetyl–pyridinium iodide was used: 0.23 g (50% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.70 (s, 3H), 1.32 (d, $J = 9.6$ Hz, 1H), 1.43 (s, 3H), 2.38–2.44 (m, 1H), 2.68–2.75 (m, 1H), 2.83 (t, $J = 5.7$ Hz, 1H), 3.20 (d, $J = 2.7$ Hz, 2H), 7.32–7.39 (m, 2H), 7.46 (t, $J = 8.1$ Hz, 1H), 7.92 (d, $J = 7.2$ Hz, 1H), 8.02–8.06 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 21.35, 25.99, 31.71, 36.41, 39.50, 40.08, 46.68, 117.52, 121.65, 123.08, 124.95, 125.83, 133.41, 144.21, 145.75, 148.46, 154.15, 157.11, 169.93; Anal. Calc. for $C_{19}H_{18}N_2S$: C, 74.47; H, 5.92; N, 9.14. Found: C, 74.24; H, 5.98; N, 9.09%. ESI-MS m/z: 307 ($M^+ + H$).

3.6. Methylation of ligand *1a*

To a 100 ml two-neck flask dry THF (5 mL) was added and cooled to −40 °C. The diisopropylamine (3.15 mmol, 0.45 mL) and *n*-butyllithium (1.6 M solution in hexane, 3.15 mmol, 1.97 mL) were added slowly with stirring. The LDA solution was then cooled at 0 °C for 30 min. A solution of **1a** (0.7 mmol, 0.19 g) in dry THF (5 mL) was added dropwise at −40 °C. The resulting deep blue solution was kept for 2 h at that temperature. The iodomethane (6 mmol) was added slowly to the mixture. The

temperature was then raised to room temperature over a period of 2 h. After stirred for overnight, the reaction was quenched with water (20 mL) and extracted CH_2Cl_2 (three times). The combined organic layer was dried with Na_2SO_4. After removal of solvent under reduced pressure and purification by repeated flash column chromatography with petroleum-ether:EtOAc (20:1), 13 mg (7% yields) of **1b** and 7 mg (4% yields) of **2b** were obtained. Ligand **1b**:^{1}H NMR (300 MHz, $CDCl_3$): δ 0.68 (s, 3H), 1.31 (d, $J = 9.9$ Hz, 1H), 1.43 (s, 3H), 1.44 (d, $J = 6.9$ Hz, 3H), 2.15–2.20 (m, 1H), 2.55–2.62 (m, 1H), 2.81 (t, $J = 5.7$ Hz, 1H), 3.22–3.26 (m, 1H), 7.29 (d, $J = 7.8$ Hz, 1H), 7.37 (d, $J = 3.3$, 1H), 7.86 (d, $J = 7.8$ Hz, 1H), 7.87 (d, $J = 3.3$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 18.16, 20.97, 26.31, 28.53, 38.71, 41.49, 46.64, 47.326, 116.58, 120.44, 133.54, 143.28, 148.39, 152.21, 161.00, 170.64; ESI-MS m/z: 271 ($M^+ + H$). Ligand **2b**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.67 (s, 3H), 1.31 (d, $J = 9.9$ Hz, 1H), 1.43 (s, 3H), 1.44 (s, 3H), 2.14–2.21 (m, 1H), 2.54 (s, 3H), 2.56–2.61 (m, 1H), 2.80 (t, $J = 5.4$ Hz, 1H), 3.21–3.25 (m, 1H), 6.95 (d, $J = 0.9$ Hz, 1H), 7.27 (s, 1H), 7.95 (d, $J = 7.5$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 17.30, 18.11, 20.91, 26.28, 28.50, 38.66, 41.42, 46.61, 47.24, 115.12, 116.26, 133.33, 143.08, 148.60, 153.62, 160.80, 169.64; mass spectrum m/z: 284 ($M^+ + H$).

3.7. General procedure for preparation of ligands *2c–2g* and *3b–3d*

A 100 mL flask was filled with dry THF (5 mL) and cooled to −40 °C. Diisopropylamine (3.15 mmol, 0.45 mL) and *n*-butyllithium (1.6 M solution in hexane, 3.15 mmol, 1.97 mL) were added slowly with stirring. The temperature was then raised to 0 °C and stirred for 30 min. The mixture was cooled to −40 °C again and **2a** or **3a** (0.7 mmol, 0.19 g) in dry THF (5 mL) was added slowly. A deep blue solution for **2a** or red-brown solution for **3a** was obtained and the resulting mixture was kept at −40 °C for 2 h. The appropriate iodoalkane (3–6 mmol) was added slowly to the mixture. The temperature was raised to room temperature over a period of 2 h and the solution was kept stirred overnight. The reaction was quenched with water (20 mL) and extracted with CH_2Cl_2 (three times). The combined organic layer was dried with Na_2SO_4. After removal of solvent under reduced pressure, the crude product was purified by flash column chromatography.

3.8. Ligand *2c*

2-Iodopropane and **2a** were used: 0.11 g (50% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.64 (s, 3H), 0.87 (d, $J = 6.9$ Hz, 3H), 1.24 (d, $J = 6.9$ Hz, 3H), 1.39 (d, $J = 9.6$ Hz, 1H), 1.42 (s, 3H), 2.35–2.41 (m, 1H), 2.51 (s, 3H), 2.55–2.62 (m, 1H), 2.68–2.77 (m, 2H), 2.91–2.94 (m, 1H), 6.92 (s, 1H), 7.26 (d, $J = 7.8$ Hz, 1H), 7.84 (d, $J = 7.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 17.38, 20.37, 21.04, 22.27, 26.36, 29.16, 30.48, 41.71, 41.88, 46.92, 48.96, 115.09, 115.51, 116.02, 133.34, 143.45, 148.43, 153.75, 159.55; ESI-MS m/z: 313 ($M^+ + H$).

3.9. Ligand *2d*

1-Iodopropane and **2a** were used: 0.11 g (43% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.64 (s, 3H), 1.00 (q, $J = 6.9$ Hz, 6H), 1.29 (d, $J = 9.9$ Hz, 1H), 1.42 (s, 3H), 1.48–1.57 (m, 3H), 1.64–1.73 (m, 2H), 2.20–2.32 (m, 2H), 2.39 (s, 3H), 2.50–2.55 (m, 2H), 2.71–2.79 (m, 2H), 3.00–3.04 (m, 1H), 7.23 (d, $J = 7.8$ Hz, 1H), 7.75 (d, $J = 7.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 13.65, 14.37, 15.10, 20.89, 24.92, 26.40, 28.37, 28.64, 34.70, 34.77, 43.49, 43.56, 43.70, 46.99, 114.92, 115.38, 115.89, 133.01, 142.19, 148.76, 160.09, 165.31; ESI-MS m/z: 355 ($M^+ + H$).

3.10. Ligand *2e*

1-Iodobutane and **2a** were used: 0.12 g (45% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.6–1.78 (19H), 0.64 (s, 3H), 1.42 (s, 3H), 2.29–2.32 (m, 1H), 2.39 (s, 3H), 2.50–2.59 (m, 1H), 2.76 (t, $J = 6.9$ Hz, 1H), 2.94–3.02 (m, 1H), 7.22 (d, $J = 7.8$ Hz, 1H), 7.78 (d, $J = 7.5$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 13.74, 14.11, 15.00, 20.89, 22.13, 22.92, 26.32, 26.38, 28.36, 30.04, 32.19, 33.75, 41.08, 43.56, 43.89, 47.03, 115.57, 119.49, 133.18, 133.50, 134.35, 142.38, 148.92, 160.32; ESI-MS m/z: 383 ($M^+ + H$).

3.11. Ligand *2f*

Benzyl iodide and **2a** were used: 0.16 g (52% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.59 (s, 3H), 1.32 (s, 3H), 1.37 (d, $J = 9.9$ Hz, 1H), 2.05–2.10 (m, 1H), 2.46 (s, 3H), 2.50–2.69 (m, 2H), 2.77 (t, $J = 5.7$ Hz, 1H), 3.28–3.32 (m, 1H), 3.72 (dd, $J = 13.8$, 3.6 Hz, 1H), 4.12 (s, 2H), 7.18–7.33 (m, 11H), 7.83 (d, $J = 7.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 15.25, 20.84, 26.24, 28.19, 32.59, 38.55, 41.14, 42.48, 45.92, 46.99, 116.00, 125.80, 126.56, 128.25, 128.31, 128.65, 129.29, 132.66, 133.47, 139.82, 140.98, 142.84, 148.92, 149.53, 159.12, 166.48; ESI-MS m/z: 451 ($M^+ + H$).

3.12. Ligand *2g*

(Iodomethyl)trimethylsilane and **2a** were used: 0.15 g (47% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.09 (s, 9H), 0.12 (s, 9H), 0.64 (s, 3H), 1.34 (d, $J = 9.9$ Hz, 1H), 1.40 (s, 3H), 1.51–1.57 (m, 2H), 2.16–2.20 (m, 2H), 2.33 (s, 3H), 2.48–2.55 (m, 2H), 2.72–2.77 (m, 1H), 3.14–3.19 (m, 1H), 7.18 (d, $J = 8.1$ Hz, 1H), 7.72 (d, $J = 7.5$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ −1.47, −0.36, 15.35, 17.28, 20.99, 26.59, 28.33, 28.48, 40.20, 41.49, 46.82, 47.05, 115.32, 116.11, 131.69, 133.03, 141.49, 146.97, 149.13, 161.72; ESI-MS m/z: 443 ($M^+ + H$).

3.13. Ligand **3b**

1-Iodopropane and **3a** were used: 90 mg (35% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.67 (s, 3H), 1.04 (t, $J = 7.2$ Hz, 3H), 1.32 (d, $J = 9.9$ Hz, 1H), 1.43 (s, 3H), 1.46–1.65 (m, 3H), 2.22–2.34 (m, 2H), 2.52–2.59 (m, 1H), 2.80 (t, $J = 5.4$ Hz, 1H), 3.05–3.10 (m, 1H), 7.29 (d, $J = 7.8$ Hz, 1H), 7.35 (t, $J = 8.1$ Hz, 1H), 7.45 (t, $J = 8.1$ Hz, 1H), 7.90 (d, $J = 8.1$ Hz, 1H), 7.99–8.05 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 14.38, 20.95, 20.98, 26.37, 28.35, 34.82, 41.12, 43.59, 43.65, 47.12, 117.22, 121.59, 123.02, 124.85, 125.72, 133.08, 135.92, 143.99, 148.21, 154.23, 160.58, 170.51; ESI-MS m/z: 349 ($M^+ + H$).

3.14. Ligand **3c**

(2-Iodoethyl)benzene and **3a** were used: 0.15 g (53% yields); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.67 (s, 3H), 1.36 (d, $J = 9.9$ Hz, 1H), 1.45 (s, 3H), 1.73–1.89 (m, 1H), 2.35–2.40 (m, 1H), 2.54–2.66 (m, 2H), 2.83 (t, $J = 5.7$ Hz, 1H), 2.92–3.10 (m, 2H), 3.12–3.17 (m, 1H), 7.13–7.28 (m, 2H), 7.30–7.38 (m, 5H), 7.43–7.48 (m, 1H), 7.91 (d, $J = 7.8$ Hz, 1H), 8.03 (d, $J = 7.2$ Hz, 2H); ^{13}C NMR ($CDCl_3$): δ 20.99, 26.33, 28.54, 34.20, 34.72, 41.35, 43.36, 44.20, 47.12, 117.35, 121.65, 123.03, 124.90, 125.49, 125.76, 128.14, 128.34, 133.21, 135.90, 142.54, 143.97, 148.24, 154.23, 160.25, 170.43; ESI-MS m/z: 411 ($M^+ + H$).

3.15. Ligand **3d**

(Iodomethyl)trimethylsilane and **3a** were used: 90 mg (32%); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.15 (s, 9H), 0.68 (s, 3H), 1.38 (d, $J = 9.9$ Hz, 1H), 1.43 (s, 3H), 1.58–1.67 (m, 2H), 2.20–2.25 (m, 1H), 2.53–2.60 (m, 1H), 2.81 (t, $J = 6.0$ Hz, 1H), 3.21–3.25 (m, 1H), 7.29 (d, $J = 7.8$ Hz, 1H), 7.33–7.38 (m, 1H), 7.43–7.48 (m, 1H), 7.91 (d, $J = 7.8$ Hz, 1H), 8.02 (t, $J = 7.8$ Hz, 2H); ^{13}C NMR ($CDCl_3$): δ −0.41, 20.98, 21.06, 26.59, 28.43, 40.24, 41.53, 46.56, 47.22, 117.32, 121.73, 123.13, 124.97, 125.84, 133.16, 136.07, 143.62, 148.56, 154.32, 162.39, 170.63; ESI-MS m/z: 393 ($M^+ + H$).

3.16. Synthesis of $[Cu(\mathbf{1a})_2](ClO_4)_2$ complex

A solution of **1a** (0.22 mmol, 57 mg) in CH_2Cl_2 (2 mL) was added to an absolute ethanol solution (3 mL) of the hydrated $Cu(ClO_4)_2 \cdot 6H_2O$ salt (0.11 mmol, 40 mg). The green solution was refluxed for 2 h. The resulting solution was concentrated (1 mL) under reduce pressure. Diethyl ether (10 mL) was added and green precipitates formed immediately. The precipitates were collected and dry under vacuum to afford 80 mg (94% yields) of $[Cu(\mathbf{1a})_2](ClO_4)_2$ complex: IR (KBr): 3442, 3109, 2934, 1506, 1455, 1424, 1096, 623; ESI-MS m/z: 674 ($M^+ - ClO_4$); Anal. Calc. for $C_{30}H_{32}Cl_2CuN_4O_8S_2$: C, 46.48; H, 4.17; N, 7.23. Found: C, 46.27; H, 4.43; N, 7.47%.

3.17. General procedures for Cu(I)-catalyzed asymmetric allylic oxidation

To a two-neck round bottom flask were added $Cu(CH_3CN)_4]PF_6$ (0.05 mmol, 19 mg) and chiral ligands (0.06 mmol) with 3 mL CH_3CN and then stirred for 2 h at room temperature under nitrogen. After addition of cyclohexene (4 mmol, 100 μL), *tert*-butyl peroxybenzoate (1 mmol, 90 μL) was added slowly over a period of 1 min. The reaction was monitored by TLC and quenched with a saturated solution of $NaHCO_3$ when completed. The mixture was extracted CH_2Cl_2 (three times). After dried over $MgSO_4$ and removal of solvents, crude products of allylic benzoate were purified by flash column chromatography with petroleum-ether:EtOAc (40:1). The e.e. of the product was determined by HPLC with a Daicel Chiralcel OD column; eluent: hexane/isopropyl alcohol (1000:1 v/v); flow rate 0.5 mL min^{-1}; t_R: 22.7 min, t_S: 24.9 min; UV detector monitored at 254 nm. The absolute configurations of allylic benzoate were assigned by comparing the order of elution with samples of known configuration [20].

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