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Asymmetric Alkylation

Chiral N-Heterocyclic Carbene Ligands Bearing a Pyridine Moiety for the Copper-Catalyzed Alkylation of *N*-Sulfonylimines with Dialkylzinc Reagents

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Abstract: Amino acid-derived chiral imidazolium salts, each bearing a pyridine ring, were developed as N-heterocyclic carbene ligands. The copper-catalyzed asymmetric alkylation of various *N*-sulfonylimines with dialkylzinc reagents in the presence of these chiral imidazolium salts afforded the corresponding alkylated products with high enantioselectivity (up to 99% *ee*). The addition of HMPA to the reaction mixture as a co-solvent is critical in terms of chemical yield and enantioselectivity. A wide range of *N*-sulfonylimines and dialkylzinc reagents were found to be applicable to this reaction.

Introduction

The application of N-heterocyclic carbenes (NHCs) in organic synthesis has dramatically increased since Bertrand, Arduengo and their co-workers reported the first stable nucleophilic carbene around 1990.[1] NHCs have become extremely popular ligands in organometallic chemistry[2] and many complexes incorporating NHCs have been used in synthetic methods, including cross coupling and metathesis reactions. In addition, applications of chiral NHCs to catalytic asymmetric reactions have been reported, with good to excellent stereoselectivity. In 2001, Woodward reported the first copper-catalyzed conjugate addition of diethylzinc,[3] and Alexakis expanded this method to allow asymmetric synthesis using chiral NHC precursors derived from C2-symmetric diamines.[4] Okamoto also reported a copper-catalyzed asymmetric allylic alkylation reaction using the same catalyst as Alexakis.[5] In 2004, Arnold reported the isolation of the first-ever chiral chelating copper(II) alkoxy-NHC complex and obtained moderate enantioselectivity from the copper-catalyzed conjugate addition of diethylzinc to cyclohexenone.[6] Mauduit also introduced an alcohol moiety to the NHC ligand to achieve higher enantioselectivity during catalytic asymmetric conjugate addition.[7] The efficient conjugate addition of Grignard reagents to β-substituted cyclic enones has also been developed through the utilization of Mauduit's ligand.[8] Furthermore, dramatic improvements have been reported by Hoveyda, who developed a chiral bidendate alkoxy-NHC precursor derived from axial-symmetric aminohydroxynaphthalene and was able to obtain high enantioselectivity in copper-catalyzed reactions.[9] As a result of these various breakthroughs, chiral multidentate NHC chemistry has attracted significant attention.[10] For example, Katsuki,[11] Sakaguchi,[12] Williams,[13] Hayashi,[14] and Tomioka[15] all independently developed chiral multidentate NHC precursors for copper-catalyzed asymmetric reactions and were each successful in achieving high enantioselectivity.

Herein, we report the synthesis of a series of chiral imidazolium salts, derived from commercially available L-amino acids and each bearing a pyridine moiety. In addition, we describe the application of these chiral imidazolium salts to the copper-catalyzed asymmetric alkylation of *N*-sulfonylimines with dialkylzinc reagents.[16] We have recently developed a family of chiral triazolium salts bearing a pyridine moiety, which have been shown to catalyze both the benzoin condensation reaction and the intramolecular Stetter reaction to give products with up to 99% *ee*.[17] However, to the best of our knowledge, the compounds described herein represent the first chiral imidazolium salts incorporating a pyridine ring to be reported in the literature.

Results and Discussion

Synthesis of chiral imidazolium salts

We initially designed and synthesized a range of chiral imidazolium salts, all bearing a pyridine ring (Figure 1), each of which was readily prepared from commercially available L-amino acids (Scheme 1). During the synthesis of these compounds, the aminoalkyl bromide hydrogenbromides **14a–d** were prepared by the reduction of L-amino acids with $LiAlH_4$ followed by neutralization and subsequent bromination of the alcohol group by treatment with PBr_3.[18] The pyridinoimidazole compounds **15a–c** were prepared from the reaction of imidazole and the corresponding aryl bromide derivatives in the

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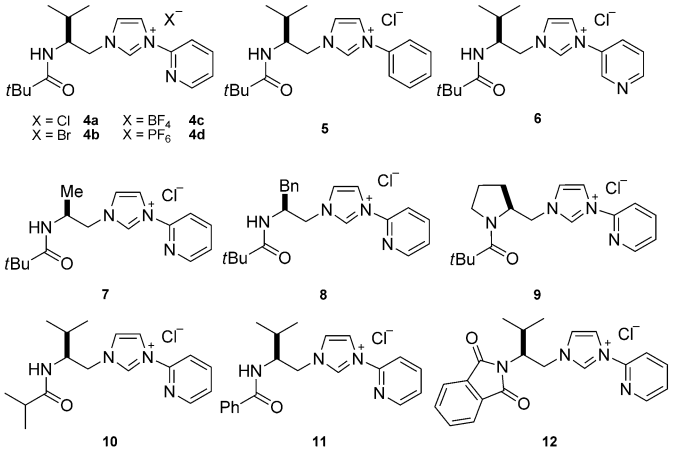
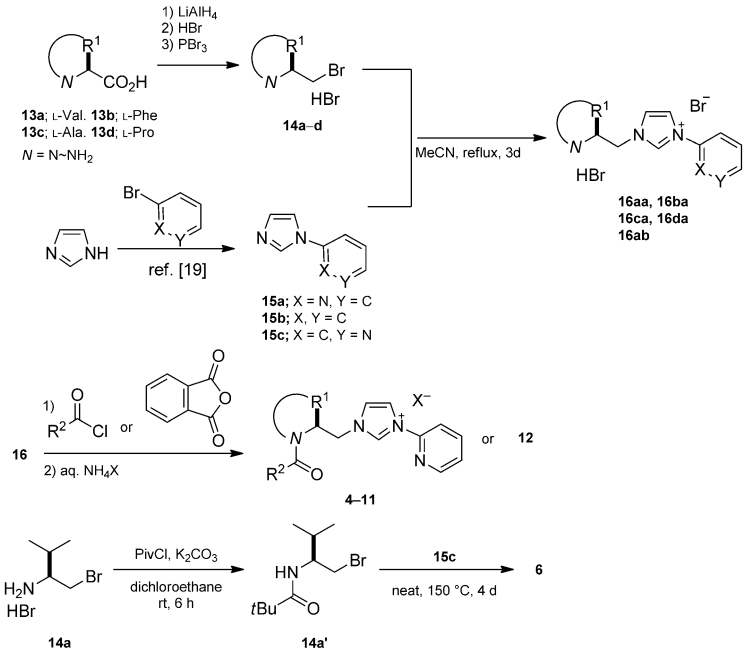


Figure 1. Amino acid-derived chiral imidazolium salts bearing a pyridine ring.



Scheme 1. General synthesis of the chiral imidazolium salts.

presence of copper salt.[19] The hydrobromide salts of the aminoalkyl bromides were coupled to **15a–c** in MeCN under reflux conditions to give the series of ammoniumalkyl imidazolium salt derivatives, **16**. Finally, modification of the amino group was accomplished by reaction with the corresponding acyl chloride in the presence of potassium carbonate followed by treatment with ammonium salt solutions to give the desired imidazolium salts. In the case of **12**, the ammonium alkyl imidazolium salt was treated with phthalic anhydride and potassium carbonate in toluene under reflux conditions. In the synthesis of the imidazolium salt **6**, the pivalamide **14a′**, which was derived from the reaction of **14a** with pivaloyl chloride, was coupled with 3-pyridinoimidazole **15c**.

NHC–copper-catalyzed asymmetric alkylation of *N*-sulfonylimines with dialkylzinc reagents

We began our studies with the reaction of *N*-sulfonylimine **1a** with diethylzinc (**2E**) in the presence of 5.0 mol% of copper(II) triflate and 6.5 mol% of the chiral imidazolium salt in toluene at 0 °C. Although **1a** was consumed after 12 h and the desired ethylated product **3aE** was obtained in 90% yield, no enantioselectivity was achieved (Table 1, entry 1). As a small amount of insoluble material was observed in the post-reaction solution, we examined the use of varying amounts of hexamethylphosphoramide (HMPA) as a co-solvent, with the aim of obtaining a clear solution. The addition of 10 mol% HMPA to the solvent mixture had no effect on the insoluble material, and gave the same level of enantioselectivity as was observed without HMPA (entry 2). However, the addition of 10 equivalents of HMPA resulted in an almost clear solution with no insoluble material, as well as a dramatic improvement in the enantioselectivity, such that the product (*R*)-**3aE** was obtained with 99% *ee* (entry 3).[20] As it was evident that both the solvent and the copper source influenced the efficiency of the reaction, we subsequently examined the ethylation of *N*-sulfonylimine with diethylzinc by using different solvents and copper salts. When employing dichloromethane as the solvent, the reaction proceeded slowly to afford the product **3aE** in 54% yield with 8% *ee* (entry 4). Interestingly, coordinative solvents such as diethyl ether, THF, and MeCN were found to be applicable to this reaction, giving **3aE** in high enantioselectivities, and the addition of HMPA to the reaction mixture as a co-solvent is critical in terms of chemical yield and enantioselectivity (entries 5–10).

Other copper salts were also investigated in the asymmetric ethylation of *N*-sulfonylimine; copper(II) salts such as copper(II) triflate and $CuCl_2 \cdot 2H_2O$ exhibited the highest efficiency, generating the desired product **3aE** with *ee* values of 99% and 98%, respectively (entries 3 and 11). In addition, copper(I) salts were also effective in this reaction, affording the product with excellent enantioselectivities in high yields, with the exception of CuCl (entries 12–17). In all cases, none of the product generated by the direct reduction of diethylzinc was observed, even in trials in which lower catalytic performance was found, such as entry 16. Even at lower catalyst loadings (1.0 mol% of $Cu(OTf)_2$ and 1.3 mol% of **4a**), the reaction proceeded cleanly to afford the product **3aE** in good yield and with consistently high enantioselectivity (entry 18). Based on previous reports,[21] the oxidation state of the active copper catalyst in the addition reaction of dialkylzinc reagents might be copper(I). That is, in situ reduction of copper(II) takes place prior to the formation of the NHC–copper complex. Subsequent alkyl transfer from zinc to copper gives NHC–Cu^{I}–R and R–Zn–X species, which react with *N*-sulfonylimine.

We next turned our attention to the structures of the chiral imidazolium salts **4**–**12**. We determined that Cl^- (as in **4a**) was

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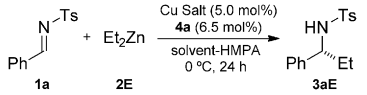
Table 1. Copper-catalyzed asymmetric ethylation of *N*-sulfonylimine with diethylzinc.[a]



1a 2E 3aE

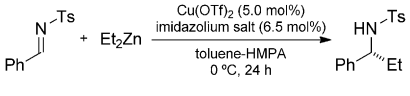
Entry	Solvent	Cu salt	Yield [%]	*ee* [%]
1[b]	toluene	$Cu(OTf)_2$	90	0
2[c]	toluene	$Cu(OTf)_2$	67	8
3	toluene	$Cu(OTf)_2$	85	99
4	CH_2Cl_2	$Cu(OTf)_2$	54	8
5	Et_2O	$Cu(OTf)_2$	85	93
6[b]	Et_2O	$Cu(OTf)_2$	16	26
7	THF	$Cu(OTf)_2$	88	89
8[b]	THF	$Cu(OTf)_2$	32	58
9	MeCN	$Cu(OTf)_2$	91	82
10[b]	MeCN	$Cu(OTf)_2$	50	0
11	toluene	$CuCl_2 \cdot 2H_2O$	98	98
12	toluene	CuTC[d]	95	96
13	toluene	$(CuOTf)_2$–PhH	97	93
14	toluene	$Cu(MeCN)_4BF_4$	99	95
15	toluene	CuCN	99	89
16	toluene	CuCl	39	95
17	toluene	CuI	90	96
18[e]	toluene	$Cu(OTf)_2$	92	91

[a] Using 2.0 equiv of **2E** and 10 equiv of HMPA unless otherwise noted. [b] In the absence of HMPA. [c] Using 10 mol% of HMPA. [d] CuTC = copper(I) thiophene-2-carboxylate. [e] Using 1.0 mol% of $Cu(OTf)_2$ and 1.3 mol% of **4a**.

suitable for use as the counter anion to the imidazolium salt in this reaction, whereas the reactions employing chiral imidazolium salts bearing Br^- (**4b**), BF_4^- (**4c**) and PF_6^- (**4d**) all resulted in lower enantioselectivities (Table 2, entries 1–4). The role of counter anions of the imidazolium salts on the enantioselectivity was not clear; however, the counter anion might effect to the solubility and/or stability of the NHC–copper complex. To examine the effect of the pyridine ring portion of the imidazolium salt, we conducted the asymmetric alkylation of *N*-sulfonylimine **1a** with the imidazolium salt **5**, which contained a phenyl ring rather than the 2-pyridine ring. The reaction proceeded smoothly, giving the product **3aE** in 86% yield but with only 63% *ee* (entry 5). This result clearly indicates that the pyridinyl group played an important role in achieving the high stereoselectivity observed in the prior reactions. The position of the nitrogen atom on the pyridine moiety was also critical to obtaining the ethylated product **3aE** with high enantioselectivity. Thus, the introduction of a nitrogen atom at the C3-position of the aromatic ring (as in **6**) lowered the enantioselectivity still further (entry 6). The use of the chiral imidazolium salts derived from L-alanine, **7**, L-phenylalanine, **8**, and L-proline, **9**, also resulted in relatively low enantioselectivities (entries 7–9). The effect of the amidocarbonyl moiety was also investigated. Imidazolium salt **4a**, which contained the bulkier pivaloyl group, was found to function as the best ligand for the copper-catalyzed reaction, and gave **3aE** with 99% *ee*, whereas NHC precursors bearing isobutylamide or benzamide groups showed lower enantioselectivity (entries 10 and 11). Finally, we determined that the hydrogen atom of the amidocarbonyl group may be a vital factor in terms of achieving high stereoselectivity. Thus, when a phthalimide group was introduced to form imidazolium salt **12** and this compound was used in the catalytic ethylation of **1a**, the enantioselectivity was reduced significantly to 35% *ee* (entry 12).

Applying the optimized reaction conditions, the scope of the catalytic asymmetric alkylation was subsequently demonstrated by experimenting with various *N*-sulfonylimines and dialkylzinc compounds (Table 3). It was gratifying to observe that

Table 2. Effects of various chiral imidazolium salts on the copper-catalyzed asymmetric ethylation of *N*-tosylimines.[a]

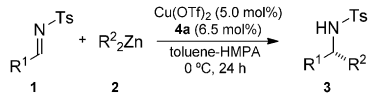


1a 2E 3aE

Entry	Imidazolium salt	Yield[%]	*ee* [%]
1	**4a**	85	99
2	**4b**	88	82
3	**4c**	89	90
4	**4d**	94	64
5	**5**	86	63
6	**6**	80	15
7	**7**	87	30
8	**8**	92	43
9	**9**	77	4
10	**10**	90	87
11	**11**	90	86
12	**12**	86	35

[a] Using 2.0 equiv of **2E** and 10 equiv of HMPA.

Table 3. Catalytic asymmetric alkylation of *N*-tosylimines with various dialkylzinc compounds.[a]



1 2 3

Entry	R^1	R^2	Yield [%]	*ee* [%][e]
1	C_6H_5 (**1a**)	Et (**2E**)	85 (**3aE**)	99
2	1-naphthyl (**1b**)	Et (**2E**)	94 (**3bE**)	89
3	2-naphthyl (**1c**)	Et (**2E**)	91 (**3cE**)	91
4	2-MeC_6H_4 (**1d**)	Et (**2E**)	88 (**3dE**)	90
5	3-MeC_6H_4 (**1e**)	Et (**2E**)	95 (**3eE**)	94
6	4-MeC_6H_4 (**1f**)	Et (**2E**)	97 (**3fE**)	96
7	4-$MeOC_6H_4$ (**1g**)	Et (**2E**)	88 (**3gE**)	93
8	4-$CF_3C_6H_4$ (**1h**)	Et (**2E**)	93 (**3hE**)	90
9	4-BrC_6H_4 (**1i**)	Et (**2E**)	93 (**3iE**)	93
10	2-furyl (**1j**)	Et (**2E**)	99 (**3jE**)	91
11	*c*-C_6H_{11} (**1k**)	Et (**2E**)	76 (**3kE**)	75
12	C_6H_5 (**1a**)	*i*Pr (**2I**)	86 (**3aI**)	84
13[b]	C_6H_5 (**1a**)	Me (**2M**)	41 (**3aM**)	87
14[c]	C_6H_5 (**1a**)	Me (**2M**)	63 (**3aM**)	84
15[d]	C_6H_5 (**1a**)	Me (**2M**)	84 (**3aM**)	85

[a] Using 2.0 equiv of **2** and 10 equiv of HMPA unless otherwise noted. [b] The reaction was quenched after 72 h. [c] The reaction was carried out at room temperature for 48 h. [d] Using 10 equiv of **2M** at room temperature for 24 h. [e] The absolute configurations of **3**, except for **3aE**, **3aI**, and **3aM**, were assigned based on the analogous reactions in Scheme 1. Also see refs. [20] and [21].

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our catalytic system was applicable to a wide range of *N*-tosylimines when the reactions were performed with 5 mol% $Cu(OTf)_2$ and 6.5 mol% imidazolium salt **4a** in toluene at 0 °C. The *N*-tosylimines **1b** and **1c**, derived from 1-naphthaldehyde and 2-naphthaldehyde, respectively, were found to act as good substrates, generating the corresponding products **3bE** and **3cE** with 89% *ee* and 91% *ee* (entries 2 and 3). The reactions of **1d**, **1e**, and **1f**, having 2-, 3- and 4-methylphenyl groups, gave **3dE**, **3eE** and **3fE** with 90% *ee*, 94% *ee*, and 96% *ee*, respectively (entries 4–6). Even the relatively deactivated *N*-tosylimine **1g**, derived from 4-methoxybenzaldehyde, was applicable to this reaction, giving the product **3gE** in 88% yield with 93% *ee* (entry 7). We also investigated substituted *N*-tosylimines bearing an electron-withdrawing group at the *para*-position of the phenyl group; the reactions of *N*-tosylimines **1h** and **1i**, derived from 4-(trifluoromethyl)benzaldehyde and 4-bromobenzaldehyde, with diethylzinc (**2E**) gave the corresponding ethylated products **3hE** and **3iE** with 90% *ee* and 93% *ee* (entries 8 and 9). The reaction of **1j**, having a heterocyclic 2-furyl group, gave **3jE** in 99% yield with 91% *ee* (entry 10). It is noteworthy that the enolizable imine **1k** was efficiently ethylated without undergoing enolization, giving the corresponding product **3kE** in reasonable yield and enantioselectivity (entry 11). An isopropyl group was also introduced into **1a** by using the diisopropylzinc (**2I**), to afford (*R*)-**3aI**[21] with 84% *ee* in 86% yield (entry 12).

In contrast, the methylation of **1a** with dimethylzinc (**2M**) was very slow at 0 °C and generated (*R*)-**3aM**[22] with 87% *ee* in 41% yield after 72 h (entry 13). The conversion was improved when this reaction was conducted at room temperature, affording **3aM** with 84% *ee* in 63% yield (entry 14). Finally, we were able to obtain **3aM** in 84% yield without any loss of enantioselectivity when the reaction was carried out at room temperature using 10 equivalents of **2M** (entry 15).

Conclusion

We have successfully synthesized a series of amino acid-derived chiral imidazolium salts, each bearing a pyridine ring, and applied these compounds to the copper-catalyzed asymmetric alkylation of *N*-tosylimines, achieving satisfactory yields and enantioselectivities. Furthermore, the addition of HMPA to the reaction mixture as a co-solvent is critical in terms of chemical yield and enantioselectivity. A wide range of *N*-tosylimines and dialkylzinc reagents were found to be applicable to this reaction. As the tosyl group of the substrate is easily removed without any loss of enantioselectivity,[23] this method would also be applicable to the synthesis of chiral amines.

Experimental Section

General

^{1}H NMR was recorded on a JEOL ECS 400 (400 MHz) NMR spectrometer. Chemical shifts δ are reported in ppm using TMS as an internal standard. Data are reported as follows: Chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, sept=septet, m = multiplet), coupling constant (*J*) and integration. ^{13}C NMR spectra were recorded on JEOL ECS 400 (100 MHz) NMR spectrometer. The chemical shifts were determined in the δ-scale relative to $CDCl_3$ ($\delta = 77.0$ ppm). The IR spectra were measured on JASCO FT/IR-230 spectrometers. The MS spectrum was recorded with a JEOL SX-102 A mass spectrometer, JMS-T100TD, and Bruker microtof II. All of the melting points were measured with YANAGIMOTO micro melting point apparatus. Dehydrated solvents were purchased for the reactions and used without further desiccation. Flash column chromatography was performed by using Cica silica gel 60N, spherical neutral (37563–84).

General procedure for the alkylation of *N*-sulfonylimines with dialkylzinc reagentes catalyzed by NHC–copper complexes

Under Ar atmosphere, the solution of imidazolium salt **4** (11.4 mg, 0.033 mmol) in 0.8 mL of HMPA and 2.0 mL of toluene was added to $Cu(OTf)_2$ (9.07 mg, 0.025 mmol). The mixture was diluted with toluene (10.1 mL) and the whole was cooled to 0 °C. After 15 min, a hexane solution of dialkylzinc (1.0 mL, 1.0 mmol) was added dropwise over 3 min at 0 °C and stirred for 30 min. A solution of imine **1a** (130 mg, 0.5 mmol) in 3.0 mL of toluene was added dropwise over 6 min at 0 °C. After 24 h, the reaction was quenched with 10% HCl and stirred at room temperature for another 30 min. The organic layer was separated and the water layer was extracted with ethyl acetate. The combined organic layers were washed with sat. $NaHCO_3$ and brine, and then dried over Na_2SO_4. The sample was concentrated and purified by silica gel column chromatography.

In the case of the asymmetric methylation, dimethylzinc (1.0 M in toluene) was used.

(*R*)-4-Methyl-*N*-(1-phenylpropyl)benzenesulfonamide (3aE): Silica gel column chromatography (hexane/acetone = 10:1 to 5:1) gave **3aE** (123 mg, 85% yield) as a white solid. The *ee* was determined to be 99% by HPLC (Daicel Chiralcel OD-H, hexane/*i*PrOH = 15:1, 0.6 mL min^{-1}, 254 nm, major 19.0 min and minor 25.3 min). M.p. = 102.0–102.6 °C; $[\alpha]_D^{25} = 47.5$ ($c = 0.53$ in EtOH); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 0.71$ (t, $J = 7.2$ Hz, 3H), 1.64 (m, 1H), 1.75 (m, 1H), 2.29 (s, 3H), 4.18 (m, 1H), 4.62 (d, $J = 7.2$ Hz, 1H), 6.92 (m, 2H), 7.04–7.10 (m, 5H), 7.46 ppm (d, $J = 6.8$ Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 10.4$, 21.3, 30.5, 59.8, 126.5, 126.9, 127.0, 128.1, 129.1, 137.6, 140.8, 142.7 ppm; IR (KBr): $\nu = 3270$, 2960, 1600, 1500, 1460, 1320, 1160, 1000 cm^{-1}; HRMS (DART): (*m/z*) calcd for $C_{16}H_{20}NO_2S$: 290.1215 $[M+H]^+$; found: 290.1223.

General procedure for the synthesis of ammoniumalkyl imidazolium salt (16)

Aminoalkyl bromide hydrogenbromide (1.0 equiv) and pyridinoimidazole (1.0 equiv) in MeCN (1.0 M) were heated at reflux for 3 days. After removing the solvent under reduced pressure, the resulting solid was recrystallized from EtOH to afford the desired products.

((*S*)-1-(2-Ammonio-3-methylbutyl)-3-(pyridin-2-yl)-1*H*-imidazol-3-ium) dibromide (16aa): Recrystallization from EtOH gave **16aa** (790 mg, 59%, 3.7 mmol scale) as a white solid. M.p. = 237.9–238.8 °C; $[\alpha]_D^{25} = 14.8$ ($c = 1.09$ in MeOH); ^{1}H NMR (400 MHz, $[D_4]$MeOH): $\delta = 1.20$ (d, $J = 6.8$ Hz, 6H), 2.21 (m, 1H), 3.93 (m, 1H), 4.73 (m, 1H), 4.77 (m, 1H), 7.65 (m, 1H), 8.02–8.07 (m, 2H), 8.18 (m, 1H), 8.54 (m, 1H), 8.66 (m, 1H), 10.2 ppm (br s, 1H) NH_2 proton was not observed cleanly; ^{13}C NMR (100 MHz, $[D_4]$MeOH): $\delta = 18.3$, 18.4, 30.8, 50.7, 57.8, 115.6, 121.5, 125.5, 126.8, 137.3, 141.8, 148.0, 150.6 ppm; IR (KBr): $\nu = 3430$, 2880, 2000, 1740, 1600, 1550, 1510,

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1480, 1440, 1340, 1250, 1220, 1080, 1070 cm^{-1}; HRMS (ESI): (*m/z*) calcd for $C_{13}H_{19}N_4$: 231.1604 $[M-(HBr+Br^-)]^+$; found: 231.1605.

General procedure for the synthesis of chiral imidazolium salt (4–12)

Acyl chloride (1.5 equiv) was added slowly to a suspension of **16** and K_2CO_3 (3.0 equiv) in MeCN (0.76 M) at 0 °C. The whole was warmed to room temperature and stirred for 24 h. The reaction mixture was filtered through Celite and the solvent was removed under reduced pressure. The resulting material was dissolved in $CHCl_3$ and the solution was washed ten times with sat. NH_4Cl (for **4a**), sat. NH_4Br (for **4b**), sat. NH_4BF_4 (for **4c**), or sat. NH_4PF_6 (for **4d**). The solvent was removed under reduced pressure and the residue was purified by silica-gel column chromatography.

(*S*)-1-(3-Methyl-2-pivalamidobutyl)-3-(pyridin-2-yl)-1*H*-imidazol-3-ium chloride (4a): Silica-gel column chromatography ($CHCl_3$/MeOH = 10:1 to 3:1) gave **4a** (191 mg, 36% yield, 1.5 mmol scale) as an amorphous. $[\alpha]_D^{25} = -131.3$ ($c = 0.50$ in $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.04$ (d, $J = 6.8$ Hz, 3H), 1.06 (d, $J = 6.8$ Hz, 3H), 1.07 (s, 9H), 2.05 (sept, $J = 6.8$ Hz, 1H), 4.26 (m, 1H), 4.35 (m, 1H), 5.23 (dd, $J = 12.4$, 6.2 Hz, 1H), 7.38 (br s, 1H), 7.45 (m, 1H), 7.70 (d, $J = 9.6$ Hz, 1H), 8.01 (m, 1H), 8.12 (m, 1H), 8.14 (m, 1H), 8.53 (m, 1H), 11.9 ppm (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta =$ 18.7, 19.5, 27.4, 31.2, 38.7, 51.2, 53.8, 113.7, 117.9, 123.5, 124.9, 136.0, 140.2, 145.7, 149.1, 179.5 ppm; IR (KBr): $\nu = 3440$, 2960, 1650, 1600, 1540, 1480, 1450, 1370, 1210, 1080, 1000 cm^{-1}; HRMS (ESI): (*m/z*) calcd for $C_{18}H_{27}N_4O$: 315.2179 $[M-Cl]^+$; found: 315.2187.

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Keywords: asymmetric alkylation · copper catalysis · enantioselectivity · N-heterocyclic carbenes · *N*-sulfonylimines

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