Chiral Bifunctional N-Heterocyclic Carbenes: Synthesis and Application in the Aza-Morita–Baylis–Hillman Reaction

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Abstract: A series of chiral bifunctional N-heterocyclic carbene (NHC) precursors with a proximal hydroxy group were smoothly prepared from L-pyroglutamic acid. Promising enantiomeric excesses (up to 44% ee) were achieved for the bifunctional NHC-catalyzed enantioselective aza-Morita–Baylis–Hillman reaction of cyclopent-2-enone with *N*-tosylphenylmethanimine.

Key words: N-heterocyclic carbenes, bifunctional catalysts, enantioselective synthesis, aza-Morita–Baylis–Hillman reaction

N-Heterocyclic carbenes (NHCs), as Lewis basic organocatalysts, have been demonstrated to be very successful in recent years.[1] They have been found to be efficient catalysts for the umpolung reaction of aldehydes,[2] a^3 to d^3 umpolung reaction of enals,[3] transesterification,[4] acylation,[5] ring-opening polymerization,[6] activation of silylated nucleophiles,[7] and other reactions.[8] In the meantime, a number of chiral NHCs have been synthesized and applied for enantioselective organocatalytic reactions. After Sheehan and Hunneman's first report of chiral thiazolium salts as NHC precursors for organocatalytic reactions,[9] Leeper,[10] Enders,[11] Rovis,[12] Glorius,[13] Herrmann,[14] and others have synthesized series of novel chiral NHCs with monocyclic, bicyclic, or tricyclic backbones.[15] Representative examples are shown in Figure 1.

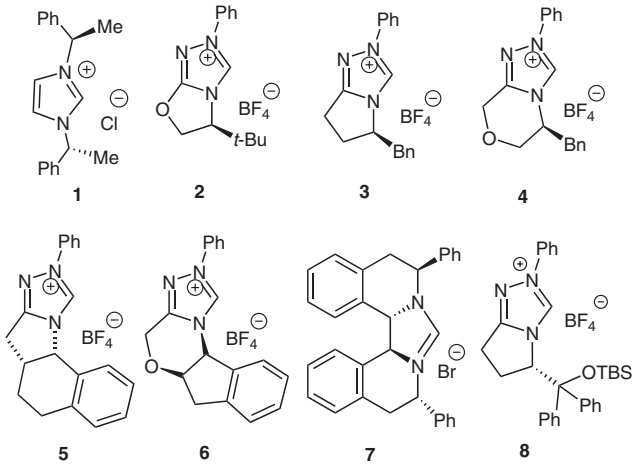

Figure 1 Selected chiral NHCs reported

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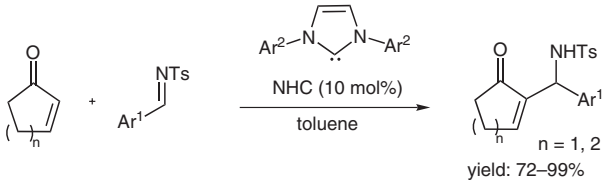
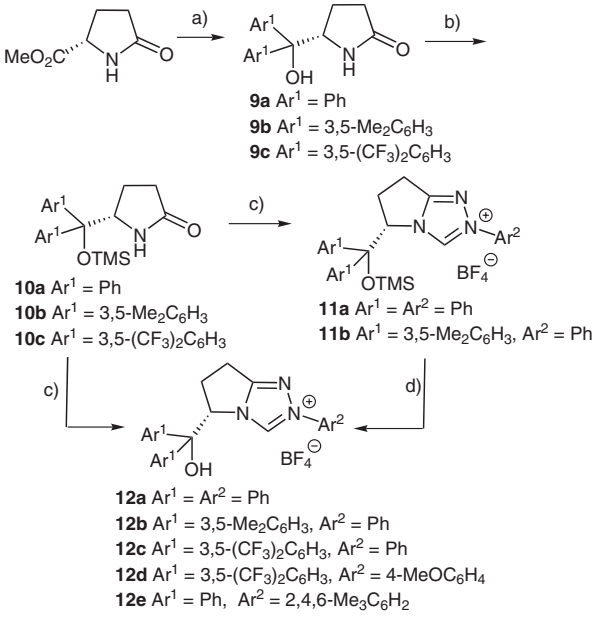
Recently, we documented that chiral NHC precursor **8** could be easily prepared from inexpensive L-pyroglutamic acid and it was shown to give products with very good enantioselectivities in the catalytic Staudinger reaction of ketenes with imines.[16] One possible feature of NHC precursor **8** is that its electronic and steric properties can be easily adjusted by variation of the substitution in the aryl groups. Furthermore, the silyl group in NHC precursor **8** may be removed to give a free hydroxy group that can function as hydrogen bond donor and thus resulting in bifunctional NHCs.

In our previous publication, we found an NHC-catalyzed aza-Morita–Baylis–Hillman (aza-MBH) reaction of cyclic enones with imines (Equation 1).[17] It was reported that bifunctional chiral phosphines or amines could catalyze aza-MBH reactions of linear enones to give the corresponding adducts with high enantioselectivities.[18] However, when cyclic enones were employed instead of linear enones, low enantiomeric excesses were obtained.[19] Thus, it became interesting for us to synthesize bifunctional NHCs and investigate chiral NHC-catalyzed aza-MBH reactions.



Equation 1 Aza-MBH reactions catalyzed by achiral NHCs

The addition of Grignard reagents to the methyl ester of L-pyroglutamic acid gave the diarylmethyl alcohols **9a–c** and subsequent protection of the hydroxy group with trimethylsilyl triflate gave the corresponding ethers **10a–c** (Scheme 1). Leeper's and Rovis's three-step synthesis of triazolium salts was then applied;[10,12] methylation with Meerwein's reagent, reaction with arylhydrazine, and cyclization with trimethyl orthoformate gave the NHC precursors **11a**,**b**. Desilylation of **11a**,**b** under acidic conditions gave the final NHC precursors **12a**,**b** with a free hydroxy group. It is important to note that the trimethylsilyl ether was deprotected in situ under the conditions of cyclization for triazolium salts **12c** and **12d**. As for the cyclization of the compound prepared from 2,4,6-trimethylphenylhydrazine, the reaction had to be carried



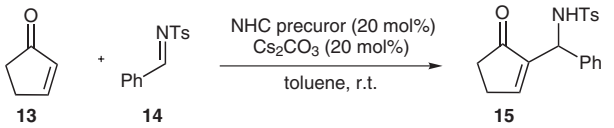
Scheme 1 Synthesis of bifunctional NHC precursors. *Reagents and conditions*: (a) RMgBr, THF; (b) TMSOTf, Et_3N; (c) (i) $MeO_3^+BF_4^-$; (ii) Ar^2NHNH_2; (iii) $HC(OEt)_3$, MeOH, (90 °C, 4 h for **11a**, **11b**, **12c**, **12d**; 120 °C, sealed tube, 4 d for **12e**); (d) HBF_4, THF, 60 °C.

out in a sealed tube at 120 °C for four days and the in situ desilylation was also observed, giving the desired compound **12e**.

The bifunctional NHCs and several other NHCs reported were then tested in the aza-MBH reaction of cyclopent-2-enone (**13**) with *N*-tosylphenylmethanimine (**14**). The results are summarized in Table 1.

Although good yields were obtained, no enantioselectivities were observed for the reactions catalyzed by chiral NHCs generated in situ from mono- or bicyclic NHC precursors **1**, **3**, or **4** (entries 1–3). The reaction catalyzed by benzotricyclic NHC **5** gave the aza-MBH adduct **15** in 74% yield with 9% ee (entry 4). The C_2-symmetric imidazolylidene NHC **7**, prepared from (*S*)-3-phenyl-3,4-dihydroisoquinoline, works well but with no enantioselectivity was observed (entry 5). The *tert*-butyldimethylsilyl- or trimethylsilyl-protected NHC precursors **8** and **11a**, prepared from L-pyroglutamic acid, lead to reactions in good yields with 10% ee and 2% ee, respectively (entries 6 and 7). Removal the trimethylsilyl group gives the NHC **12a** with a free hydroxy group, which improves the enantioselectivity from 2% ee to 8% ee (entries 7 and 8). Bulkier substituents in NHCs **12b** and **12c** benefits the enantioselectivities of the catalytic reactions, and **12c** with electron-withdrawing group (CF_3) is better than **12b**, which contains an electron-donating group (CH_3) (44% ee vs 34% ee, entries 9 and 10). The strongly electron-withdrawing group are thought to increase the acidity of the free hydroxy group in NHC **12c** and makes it a better hydrogen bond donor. Thus the stronger hydrogen bond between NHC **12c** and imine **14** may result in improved enantioselectivity for the reaction. The reaction catalyzed by NHC

Table 1 Chiral NHC-Catalyzed Aza-MBH Reaction



13 (0.3 mmol) + 14 (0.45 mmol) → 15

Entry	NHC precursor	Yield[a] (%)	ee[b] (%)
1	**1**[c]	75	0
2	**3**	76	0
3	**4**	40	0
4	**5**[c]	74	9
5	**7**	82	0
6	**8**[c]	75	10
7	**11a**[c]	63	2
8	**12a**	56	8
9	**12b**	65	26
10	**12c**	54	44
11	**12d**	30	34
12	**12e**	30	–2

[a] Isolated yields.
[b] Determined by chiral HPLC.
[c] 10 mol% NHC precursor and Cs_2CO_3 were employed.

12d (Ar^2 = 4-$MeOC_6H_4$) gave products with a little worse enantioselectivity (entry 11 vs 10). The NHC **12e** (Ar^1 = Ph, Ar^2 = 2,4,6-$Me_3C_6H_2$) showed reversed enantioselectivity, but only with –2% ee.

In conclusion, a series of bifunctional NHC precursors with a proximal hydroxy group were smoothly prepared from L-pyroglutamic acid. The free hydroxy group in these NHCs showed some positive impact on the catalytic aza-MBH reaction of cyclopent-2-enone with an imine and afforded the product with promising enantioselectivities (up to 44% ee). Further investigation of the synthesis of bifunctional NHCs and their potential applications in organocatalysis are underway in our laboratory.

Unless otherwise indicated, all starting materials were obtained from commercial supplies and used as received. Anhyd toluene, THF, and Et_2O were distilled from Na/benzophenone. CH_2Cl_2 was distilled from CaH_2. *N*-Tosylphenylmethanimine,[20] imidazolium **1**,[14a] **7**,[14b] and triazolium salts **3**,[12c] **4**,[10b] **5**,[11b] **8**,[16] **11a**,[16] and **11b**[16] were prepared according to the literature. All reactions were carried out in an oven-dried flask under N_2. Column chromatograph was performed with silica gel 200–300 mesh. All ^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were recorded on a Bruker DMX 300 spectrometer in $CDCl_3$ with TMS as internal standard. IR spectra were recorded on a Jasco FT/IR-480 spectrophotometer.

5-[Diaryl(hydroxy)methyl]pyrrolidin-2-ones 9a–c
These were synthesized according to the literature procedure.[16]

(*S*)-5-[Bis(3,5-dimethylphenyl)(hydroxy)methyl]pyrrolidin-2-one (9b)
White solid; yield: 40%; mp 79–80 °C.

$[\alpha]_D^{25}$ –82.3 (*c* 1, $CHCl_3$).

IR (KBr): 3414, 2916, 1684, 1602, 1453, 1278, 1172, 848, 747 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.07 (s, 2 H), 7.04 (s, 2 H), 6.81 (s, 2 H), 5.78 (s, 1 H), 4.67 (dd, *J* = 5.1, 8.4 Hz, 1 H), 3.74 (s, 1 H), 2.26 (s, 6 H), 2.25 (s, 6 H), 2.36–2.19 (m, 2 H), 2.04 (m, 1 H), 1.89 (m, 1 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 179.4, 145.5, 143.5, 138.1, 137.6, 128.9, 128.6, 123.5, 123.4, 78.5, 60.8, 30.3, 21.6, 21.5.

HRMS (P-SIMS): *m*/*z* $[M + H]^+$ calcd for $C_{21}H_{26}NO_2$: 324.1957; found: 324.1963.

(*S*)-5-{Bis[3,5-bis(trifluoromethyl)phenyl](hydroxy)methyl}pyrrolidin-2-one (9c)
White solid; yield: 59%; mp 157–158 °C.

$[\alpha]_D^{25}$ –57.2 (*c* 0.5, CH_2Cl_2).

IR (KBr): 3450, 1684, 1374, 1279, 1171, 1135, 682 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 8.01 (s, 2 H), 7.88 (s, 2 H), 7.84 (s, 1 H), 7.76 (s, 1 H), 7.10 (s, 1 H), 5.37 (s, 1 H), 4.80 (m, 1 H), 2.2–2.1 (m, 1 H), 1.80–1.70 (m, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.98, 147.10, 144.95, 132.70 (q, $^2J_{C,F}$ = 33.2 Hz), 132.30 (q, $^2J_{C,F}$ = 33.2 Hz), 125.99 (m, $^3J_{C,F}$), 125.36 (m, $^3J_{C,F}$), 130.10 (q, $^1J_{C,F}$ = 271.1 Hz), 122.29 (m, $^3J_{C,F}$), 121.82 (m, $^3J_{C,F}$), 77.77, 60.15, 29.90, 21.29.

HRMS (P-SIMS): *m*/*z* $[M + H]^+$ calcd for $C_{21}H_{14}F_{12}NO_2$: 540.0827; found: 540.0805.

5-[Diaryl(trimethylsiloxy)methyl]pyrrolidin-2-ones 10a–c
These were synthesized according to the literature procedure.[16]

(*S*)-5-[Bis(3,5-dimethylphenyl)(trimethylsiloxy)methyl]pyrrolidin-2-one (10b)
Yellow solid; yield: 77%; mp 82–83 °C.

$[\alpha]_D^{25}$ –78.0 (*c* 1, $CHCl_3$).

IR (KBr): 3437, 2953, 2919, 1699, 1604, 1456, 1253, 1095, 840 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.00 (m, 6 H), 6.05 (s, 1 H), 4.67 (m, 1 H), 2.37 (s, 6 H), 2.36 (s, 6 H), 2.11 (m, 3 H), 1.63 (m, 1 H), 0.00 (s, 9 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 176.8, 141.6, 141.4, 135.4, 135.2, 127.1, 127.0, 123.8, 123.6, 80.6, 58.4, 27.5, 20.3, 19.5, 17.2, –0.01.

HRMS (P-SIMS): *m*/*z* $[M + H]^+$ calcd for $C_{24}H_{34}NO_2Si$: 396.2353; found: 396.2352.

(*S*)-5-{Bis[3,5-bis(trifluoromethyl)phenyl](trimethylsiloxy)methyl}pyrrolidin-2-one (10c)
Yellow solid; yield: 94%; mp 129–130 °C.

IR (KBr): 3438, 1706, 1370, 1282, 1175, 1140, 906, 838, 678 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.98 (s, 1 H), 7.95 (s, 1 H), 7.84 (s, 2 H), 7.75 (s, 2 H), 6.38 (br s, 1 H), 4.79 (m, 1 H), 2.07–2.27 (m, 2 H), 1.89–2.07 (m, 1 H), 1.47–1.58 (m, 1 H), –0.05 (s, 9 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 179.8, 145.6, 144.6, 132.0 (q, $^2J_{C,F}$ = 34.0 Hz), 131.68 (q, $^2J_{C,F}$ = 34.0 Hz), 128.1 (m, $^3J_{C,F}$), 123.1 (q, $^1J_{C,F}$ = 273.9 Hz), 122.4 (m, $^3J_{C,F}$), 82.0, 59.8, 29.90, 29.2, 1.4.

HRMS (P-SIMS): *m*/*z* $[M + H]^+$ calcd for $C_{24}H_{22}NF_{12}O_2Si$: 612.1222; found: 612.1210.

2-Aryl-5-[diaryl(trimethylsiloxy)methyl]-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates 11a,b
These were synthesized according to the literature procedure.[16]

(*S*)-5-[Bis(3,5-dimethylphenyl)(trimethylsiloxy)methyl]-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborate (11b)
Yellow solid; yield: 82%; mp 98–99 °C.

$[\alpha]_D^{25}$ –96.5 (*c* 1, $CHCl_3$).

IR (KBr): 3424, 2949, 1680, 1595, 1249, 1080, 845, 764 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 8.66 (s, 1 H), 7.66 (m, 2 H), 7.56 (m, 3 H), 7.06 (s, 1 H), 6.99 (s, 1 H), 6.88 (s, 2 H), 6.81 (s, 2 H), 5.94 (d, *J* = 9.0 Hz, 1 H), 3.25 (m, 1 H), 2.82 (m, 2 H), 2.30 (s, 6 H), 2.24 (s, 6 H), 2.06 (m, 1 H), –0.11 (s, 9 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.5, 138.9, 138.3, 136.8, 136.5, 133.9, 129.3, 128.9, 128.8, 128.7, 124.6, 124.4, 119.5, 81.0, 66.7, 28.4, 19.8, 19.7, 19.6, –0.01.

MS (ESI): *m*/*z* (%) = 496.4 (100).

HRMS (P-SIMS): *m*/*z* $[M]^+$ calcd for $C_{31}H_{38}N_3OSi$: 496.2778; found: 496.2785.

2-Aryl-5-[diaryl(hydroxy)methyl]-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates 12a,b
To the soln of **11a**,**b** (0.2 mmol) in THF (1 mL), 48% (w/w) HBF_4 (0.132 μL, 1.0 mmol) was added and the mixture was stirred at 60 °C for 6 h. The mixture was extracted with EtOAc. The collected organic soln was concentrated and the residue was purified by column chromatography to afford **12a**,**b**.

(*S*)-5-[Hydroxy(diphenyl)methyl]-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates (12a)
White solid; yield: 74%; R_f = 0.21 (CH_2Cl_2–acetone, 4:1).

$[\alpha]_D^{25}$ –58.6 (*c* 0.5, MeCN).

IR (KBr film): 3485, 3218, 1590, 1449, 1198, 1063, 763, 701 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 8.76 (s, 1 H), 7.65–7.55 (m, 2 H), 7.55–7.40 (m, 5 H), 7.40–7.20 (m, 8 H), 5.99 (dd, *J* = 8.6, 2.4 Hz, 1 H), 4.32 (s, 1 H), 3.10–2.95 (m, 1 H), 2.95–2.80 (m, 1 H), 2.80–2.60 (m, 1 H), 2.60–2.40 (m, 1 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 163.44, 142.65, 141.39, 136.72, 135.43, 130.70, 129.97, 129.00, 128.55, 128.41, 128.03, 126.48, 126.06, 121.36, 78.83, 67.69, 29.79, 21.39.

HRMS (P-SIMS): *m*/*z* $[M]^+$ calcd for $C_{24}H_{22}N_3O$: 368.1757; found: 368.1760.

Anal. Calcd for $C_{24}H_{22}BF_4N_3O$: C, 63.32; H, 4.87; N, 9.23. Found: C, 63.14; H, 4.88; N, 9.21.

(*S*)-5-[Bis(3,5-dimethylphenyl)(hydroxy)methyl]-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborate (12b)
Yellow solid; yield: 70%; mp 82–83 °C.

$[\alpha]_D^{25}$ –110.4 (*c* 1, $CHCl_3$).

IR (KBr): 3471, 2919, 1594, 1469, 1080, 850, 760, 751 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 9.07 (s, 1 H), 7.69 (m, 2 H), 7.56 (m, 3 H), 7.03 (s, 2 H), 7.01 (s, 1 H), 6.59 (s, 1 H), 6.76 (s, 2 H), 5.98 (d, *J* = 6.9 Hz, 1 H), 3.45 (s, 1 H), 3.20 (m, 1 H), 2.93 (m, 1 H), 2.77 (m, 1 H), 2.35 (m, 1 H), 2.32 (s, 6 H), 2.24 (s, 6 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 162.1, 141.2, 140.2, 137.2, 136.6, 135.0, 133.9, 129.1, 128.3, 127.9, 122.3, 122.0, 119.9, 77.4, 66.5, 28.1, 19.9, 19.7, 19.6.

MS (ESI): *m*/*z* (%) = 424.4 (100).

HRMS (P-SIMS): *m*/*z* [M]$^+$ calcd for $C_{28}H_{30}N_3O$: 424.2383; found: 424.2397.

2-Aryl-5-[diaryl(hydroxy)methyl]-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates 12c–e

These were synthesized according to the literature procedure.[16]

(*S*)-5-{Bis[3,5-bis(trifluoromethyl)phenyl](hydroxy)methyl]-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates (12c)

Synthesized according to the literature procedure,[16] except that the ring closure was carried out in a flask under 90 °C for 15 h; white solid; yield: 65%; mp 166–167 °C.

$[\alpha]_D^{25}$ –24.5 (*c* 1, acetone).

IR (KBr): 3437, 1590, 1374, 1282, 1182, 1133, 1085, 908, 845, 764, 712, 682 cm^{-1}.

^{1}H NMR (300 MHz, DMSO-d_6): δ = 9.92 (s, 1 H), 8.51 (s, 2 H), 8.41 (s, 2 H), 8.12 (s, 1 H), 8.07 (s, 1 H), 7.65–7.87 (m, 5 H), 7.55 (s, 1 H), 6.76 (d, *J* = 6.3 Hz, 1 H), 3.28 (m, 2 H), 3.06 (m, 1 H), 2.63 (m, 1 H).

^{13}C NMR (75 MHz, DMSO-d_6): δ = 163.7, 145.9, 144.9, 137.8, 135.4, 131.33 (q, $^2J_{C,F}$ = 33.0 Hz), 130.87 (q, $^2J_{C,F}$ = 33.0 Hz), 129.8, 126.8, 123.08 (q, $^1J_{C,F}$ = 272.8 Hz), 122.5 (br s, $^3J_{C,F}$), 121.9, 121.6 (br s, $^3J_{C,F}$), 78.8, 66.2, 29.8, 21.1.

HRMS (P-SIMS): *m*/*z* [M]$^+$ calcd for $C_{28}H_{18}F_{12}N_3O$: 640.1252; found: 640.1239.

(*S*)-5-{Bis[3,5-bis(trifluoromethyl)phenyl](hydroxy)methyl]-2-(4-methoxyphenyl)-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates (12d)

Synthesized according to the literature procedure,[16] except that the ring closure was carried out in a flask under 110 °C for 15 h; yellow solid; yield: 82%; mp 130–131 °C.

$[\alpha]_D^{25}$ –23.9 (*c* 1, MeCN).

IR (KBr): 3437, 1590, 1527, 1378, 1280, 1182, 1138, 1080, 900, 840, 710, 678 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.34 (s, 1 H), 8.19 (s, 2 H), 7.99 (s, 2 H), 7.88 (s, 1 H), 7.85 (s, 1 H), 7.46 (d, *J* = 9.3 Hz, 2 H), 6.89 (d, *J* = 9.3 Hz, 2 H), 6.25 (m, 1 H), 5.34 (br s, 1 H), 3.80 (s, 3 H), 3.08 (m, 2 H), 2.93 (m, 1 H), 2.70 (m, 1 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 163.5, 161.5, 144.2, 143.9, 135.9, 132.8 (q, $^2J_{C,F}$ = 34.0 Hz), 132.5 (q, $^2J_{C,F}$ = 34.0 Hz), 128.4, 122.8 (q, $^1J_{C,F}$ = 274.4 Hz), 126.6, 125.9, 123.6, 123.2 (br, $^3J_{C,F}$), 122.6 (br, $^3J_{C,F}$), 114.8, 78.0, 66.6, 55.5, 29.6, 21.4.

HRMS (P-SIMS): *m*/*z* [M]$^+$ calcd for $C_{29}H_{20}F_{12}N_3O_2$: 670.1358; found: 670.1347.

(*S*)-5-[Hydroxy(diphenyl)methyl]-2-mesityl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*]-1,2,4-triazol-2-ium Tetrafluoroborates (12e)

Synthesized according to the literature procedure,[16] except that the ring closure was carried out in a sealed tube under 120 °C for 4 d; white solid; yield: 59%; R_f = 0.25 (CH_2Cl_2–acetone, 4:1); mp 201–202 °C.

$[\alpha]_D^{25}$ –26.3 (*c* 0.9, MeCN).

IR (KBr film): 3486, 3143, 3062, 1587, 1450, 1191, 1056, 702 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.07 (s, 1 H), 7.51 (d, *J* = 7.3 Hz, 2 H), 7.33–7.20 (m, 8 H), 6.94 (s, 2 H), 6.13 (d, *J* = 8.3 Hz, 1 H), 4.39 (s, 1 H), 3.17–3.10 (m, 1 H), 2.97–2.85 (m, 1 H), 2.85–2.75 (m, 2 H), 2.30 (s, 3 H), 1.99 (s, 6 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 163.63, 142.61, 141.88, 141.35, 140.06, 134.99, 131.46, 129.44, 128.83, 128.56, 128.31, 128.10, 126.38, 126.11, 79.02, 77.20, 67.75, 29.82, 21.61, 20.98, 17.00.

HRMS (P-SIMS): *m*/*z* [M]$^+$ calcd for $C_{27}H_{28}N_3O$: 410.2226; found: 410.2217.

2-[Phenyl(tosylamino)methyl]cyclopent-2-enone (15) by NHC-Catalyzed Reaction of Cyclopent-2-enone (13) with *N*-Tosylphenylmethanimine (14)

To a soln of *N*-tosylphenylmethanimine (**14**, 116.6 mg, 0.45 mmol) in toluene (2.0 mL) was added cyclopent-2-enone (25 μL, 0.30 mmol) via a syringe, followed by addition of triazolium salt **12c** (44 mg, 0.06 mmol) and Cs_2CO_3 (20 mg, 0.06 mmol). The resulting mixture was stirred at r.t. for 36 h and TLC indicated complete consumption of cyclopent-2-enone. The solvent was removed under reduced pressure and the residue was purified by flash chromatography (silica gel, EtOAc–petroleum ether, 1:2) to give the desired product **15**[17,21] (55 mg, 54%) as a white solid.

HPLC analysis: 44.8% ee [Daicel CHIRALPAK OJ-H column; 20 °C; 0.8 mL/min; solvent system: *i*-PrOH–hexanes, 20:80; t_R = 31.7 min (minor), 41.6 min (major)].

$[\alpha]_D^{25}$ +3.9 (*c* 1, $CHCl_3$).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.60 (d, *J* = 8.3 Hz, 2 H), 7.34 (t, *J* = 2.7 Hz, 1 H), 7.21–7.15 (m, 7 H), 6.17 (d, *J* = 8.4 Hz, 1 H), 5.28 (d, *J* = 8.4 Hz, 1 H), 2.52–2.05 (m, 4 H), 2.37 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 208.3, 160.5, 143.5, 143.2, 138.6, 137.4, 129.3, 128.6, 127.8, 127.3, 126.7, 55.2, 34.9, 26.7, 21.4.

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