Tetrahedron: *Asymmetry* 19 (2008) 1367–1371

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

journal homepage: www.elsevier.com/locate/tetasy

Synthesis of enantiopure triazolium salts from pyroglutamic acid and their evaluation in the benzoin condensation

Dieter Enders *, Jianwei Han

Institute of Organic Chemistry, RWTH Aachen University, Landoltweg 1, 52074 Aachen, Germany

ARTICLE INFO

Article history:
Received 22 April 2008
Accepted 16 May 2008
Available online 10 June 2008

ABSTRACT

A family of enantiopure 1,2,4-triazolium salts were prepared starting from the inexpensive (*S*)-pyroglutamic acid. After treatment with base, the corresponding *N*-heterocyclic carbenes were tested as organocatalysts in the asymmetric benzoin condensation and gave good yields and up to 95% ee.

1. Introduction

In the fast growing field of carbene organocatalysis,[1] *N*-heterocyclic carbenes (NHCs) as versatile carbon-centered Lewis bases[2] have received considerable attention especially due to their ability to reverse the polarity of certain functional groups. Many different NHCs have been developed as efficient nucleophilic catalysts in carbonyl umpolung (benzoin reaction, Stetter reaction),[1,3] a^3 to d^3 umpolung,[4] redox catalysis,[5] transesterification,[6] polymerization,[7] and ring-opening reactions.[8] In the earlier years, the catalyst core was usually thiazolium-derived and a number of chiral thiazolium salts were prepared and tested in the asymmetric benzoin reaction.[1] Unfortunately, the enantiomeric excesses observed with thiazolium salts as precatalysts only varied from negligible to moderate (up to 55% ee).[1,9]

In 1995, our group disclosed a stable storable carbene containing a triazole ring system derived from salt **1**.[10] Subsequent work resulted in the introduction of the first chiral triazol-derived carbene starting from 1,2,4-triazolium salt **2**. This enantiopure carbene was successfully applied in the asymmetric benzoin and intramolecular Stetter reaction.[11] In 1998, Leeper et al. introduced a bicyclic skeleton into a carbene catalyst by synthesizing the chiral triazolium salt **3**.[12] In 2002, a novel bicyclic triazolium salt **4** was developed by our group for the asymmetric benzoin condensation, which achieved 83% yield and 90% ee with benzaldehyde as the starting material.[13] Subsequently, the Rovis group contributed significantly to the asymmetric intramolecular Stetter reaction (up to 97% ee) by introducing the tetracyclic triazolium salts **5**.[14] Recently, we successfully employed the tetracyclic NHC-precatalyst **6** in the intramolecular crossed benzoin reaction[15] (Fig. 1).

Although a number of enantioselective variants of the benzoin condensation have been reported, this reaction remains as a good model to test newly developed *N*-heterocyclic carbene catalysts. A very recent report[16] on the use of the bicyclic triazolium salts **8a** and **8c** bearing a diphenyl(trialkylsilyloxy)-methyl substituent in the Staudinger reaction prompted us to disclose our own results in this field. Herein, we report the synthesis of chiral triazolium salts derived from (*S*)-pyroglutamic acid and their use in the benzoin condensation.

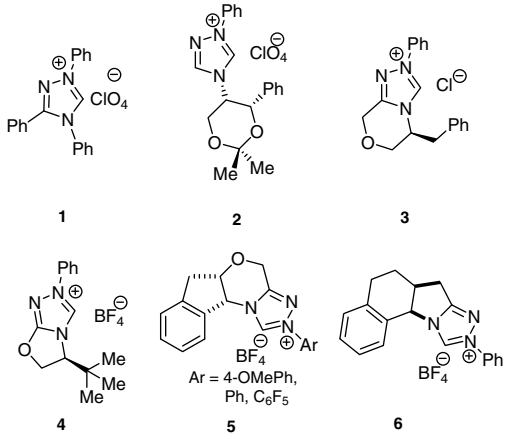


Figure 1. Various triazolium salts as NHC precatalysts.

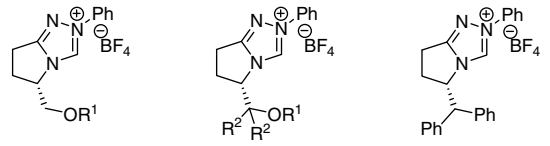
2. Results and discussion

Inspired by the successful application of catalyst **7** in the intramolecular benzoin condensation,[15] we continued to focus on the preparation of new pre-carbene salts bearing sterically demanding side chains. In 2005, we started to synthesize the new carbene catalysts **8a–c** and **9** on the basis of our previous work in the eighties with chiral auxiliaries such as SADP and RADP derived from proline.[17] All these catalysts could be prepared in a short and efficient

* Corresponding author. Tel.: +49 241 809 4676; fax: +49 241 809 2127.
E-mail address: enders@rwth-aachen.de (D. Enders).

0957-4166/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2008.05.017

route from the commercially available and inexpensive (*S*)-pyroglutamic acid **10** (Fig. 2).



7a R^1=TBS
7b R^1=TIPS

8a R^1=TBS R^2=Ph
8b R^1=TMS R^2=Me
8c R^1=TMS R^2=Ph

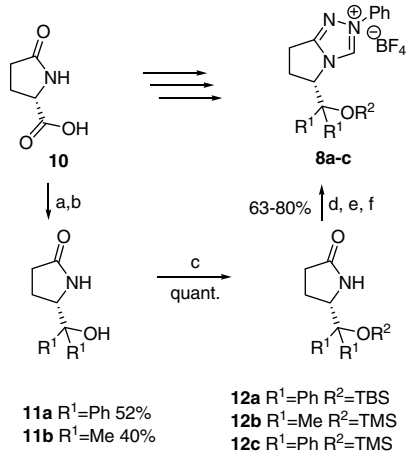
9

Figure 2. Chiral triazolium salts derived from (*S*)-pyroglutamic acid.

As is shown in Scheme 1, the pyroglutamic acid **10** was converted in two steps by esterification, followed by Grignard addition, into the corresponding substituted γ-butyro lactams **11a** and **11b** in an overall yield of 52% and 40%, respectively. Protection of the alcohol function of **11a** and **11b** proceeded smoothly with different silyl protecting groups leading to the corresponding silyl ethers **12a–c** in virtually quantitative yields. The bicyclic triazolium salts **8a–c** were then obtained in 68–80% yield following a modified three-step one pot procedure reported by Rovis et al.

The precatalyst **9** was prepared in a similar manner (Scheme 2). Reduction of the tertiary alcohol group of compound **11a** led to lactam **13**, which was then easily converted into the trazolium salt **9** in 85% yield. These two synthetic routes allow the efficient and flexible synthesis of the bicyclic triazolium core by simply using different Grignard substrates and different silyl protecting groups.

We then investigated the potential of the four new catalysts in the intermolecular benzoin condensation by using benzaldehyde as a substrate (Table 1). The first conditions utilizing precatalyst **8c** with KHMDS in toluene provided the best results for this transformation. Under the given conditions (entry 1), **8c** afforded the benzoin product in 66% yield and 95% ee. Under the same conditions, precatalyst **8a** showed a slightly lower selectivity (91% ee) and provided the product with a much lower yield (entry 2). Furthermore, the dimethylsilyl substituted triazolium salt **8b** delivered much lower enantiomeric excesses (42%) than the diphenyl carbene precursor **8c**, but accompanied with good yields (84%). Precatalyst **9** gave rise to the desired benzoin in good yields but only 5% enantiomeric excess at room temperature utilizing KHMDS as base and toluene as solvent. However, by changing the reaction conditions to DBU and THF, the yields could be increased, while the selectivity for the tested precatalysts dropped significantly. The enantioselectivity for **8c** as a precatalyst only gave the benzoin in 70% ee, and the product was obtained as a racemate when **8b** was used as precatalyst. In the cases of Et_3N and *i*-Pr_2NEt as base in THF as solvent, precatalyst **8c** did not afford the product (entries 7 and 8).



10 **8a-c**

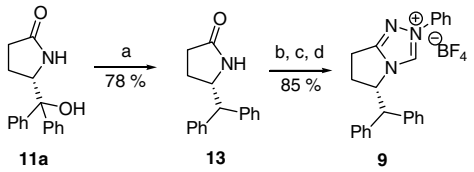
a,b — 63-80% d, e, f

c, quant.

11a R^1=Ph 52%
11b R^1=Me 40%

12a R^1=Ph R^2=TBS
12b R^1=Me R^2=TMS
12c R^1=Ph R^2=TMS

Scheme 1. Synthesis of precatalysts **8a–c**. Reagents and conditions: (a) $SOCl_2$, MeOH, 0–23 °C, 12 h; (b) R^1MgBr (3 equiv), THF, 0–23 °C, 12 h; (c) R^2OTf, DCM, 23 °C, 12 h; (d) Me_3OBF_4, DCM, 23 °C, 24 h; (e) $PhNHNH_2$, DCM, 23 °C, 24 h; (f) $HC(OMe)_3$, 80 °C, 12 h (steps d, e and f in one pot).

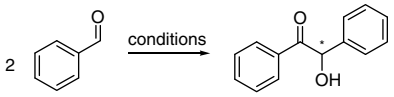


a, 78 % — b, c, d, 85 %

11a **13** **9**

Scheme 2. Synthesis of precatalyst **9**. Reagents and conditions: (a) *t*-BuLi, Et_3SiH, DCM, −20 to 23 °C, 66 h; (b) Me_3OBF_4, DCM, 23 °C, 24 h; (c) $PhNHNH_2$, DCM, 23 °C, 24 h; (d) $HC(OMe)_3$, 80 °C, 12 h (steps b, c and d in one pot).

Table 1
The benzoin condensation as a test model for the novel NHCs[a]

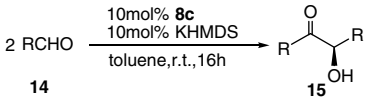


2 — conditions

Entry	Conditions	Yield[b] (%)	ee[c] (%)
1	**8c**, KHMDS, toluene	66	95
2	**8a**, KHMDS, toluene	38	91
3	**8b**, KHMDS, toluene	84	42
4	**9**, KHMDS, toluene	90	5
5	**8c**, DBU, THF	80	70
6	**8b**, DBU, THF	93	0
7	**8c**, Et_3N, THF	0	n.d.
8	**8c**, *i*-Pr_2NEt, THF	<5	n.d.

[a] All reactions were performed with 10 mol % of the precatalyst and 10 mol % base at room temperature for 16 h.
[b] Yields of isolated benzoin.
[c] The enantiomeric excess was determined by HPLC with a chiral stationary phase (Daicel Chiralpak AD).

Various aromatic or heteroaromatic aldehydes **14** were tested in the benzoin condensation with the optimized protocol to afford the α-hydroxy ketones (Scheme 3, Table 2), which were obtained in modest yield and acceptable enantiomeric excesses determined by HPLC. In general, electron-rich aromatic aldehydes were less active, but showed better asymmetric induction than electron-deifi-



2 RCHO — 10mol% **8c**, 10mol% KHMDS, toluene,r.t.,16h

14 **15**

Scheme 3. Intermolecular benzoin condensations with different aldehydes.

Table 2
Scope of the benzoin condensation[a]

14, **15**	R	Yield[b] (%)	ee[c] (%)
a	Ph	66	95
b	2-Naphthyl	71	50
c	4-ClPh	65	77
d	3-ClPh	50	84
e	4-MePh	8	95
f	4-MeOPh	<5	n.d.
g	2-Furyl	95	21
h	2-Thiophenyl	77	51

[a] All reactions were performed with 10 mol % of the precatalyst and 10 mol % base at room temperature for 16 h.
[b] Yields of isolated benzoins.
[c] The enantiomeric excess was determined by HPLC with a chiral stationary phase (Daicel Chiralpak AD).

cent aldehydes. Aldehydes bearing electron-withdrawing groups could be converted to acyloin products in moderate yields (50–65%); however, the enantioselectivity of the process decreased (50–84% ee). The heteroaromatic aldehydes **14g** and **14h** showed generally higher yields but the lowest enantioselectivity.

Notably, the absolute configuration of the benzoin product was determined to be *R* by correlation of the measured specific rotation value with the corresponding literature data,[13] which is in accordance with the postulated transition-state model.

3. Conclusion

In conclusion, four chiral triazolium salts bearing differently substituted side chains and silyl protection groups were prepared from the inexpensive (*S*)-pyroglutamic acid and tested in the intermolecular benzoin condensation. The best of them provided the (*R*)-configured benzoin products in good yields and enantiometric excesses of 21–95%.

4. Experimental

4.1. General

All solvents were dried by conventional methods. The aldehydes were either freshly distilled or recrystallized. Other starting materials and reagents were purchased from commercial suppliers and used without further purification. Toluene and THF were freshly distilled from Na/Pb alloy under argon. Preparative column chromatography: Merck Silica Gel 60, particle size 0.040–0.063 mm (230–240 mesh, flash). Analytical TLC: Silica Gel 60, F254 plates from Merck, Darmstadt. Optical rotation values were measured on a PerkinElmer P241 polarimeter. IR spectra were taken on a Perkin–Elmer FT/IR 1760 spectrophotometer. ^{1}H and ^{13}C NMR spectra were recorded on a Gemini 300 or a Varian Inova 400 and all measurements were performed with tetramethylsilane as an internal standard. Mass spectra were acquired on a Finnigan SSQ 7000 spectrometer (CI 100 eV; EI 70 eV). Microanalyses were obtained with a Vario EL element analyzer. Melting points were determined with a Tottoli melting point apparatus and are uncorrected. (*S*)-Pyroglutamic acid methyl ester was synthesized according to the literature.[15]

4.2. Synthesis of the triazolium salts

4.2.1. (*S*)-5-(Hydroxydiphenylmethyl)pyrrolidin-2-one 11a

Phenylmagnesium bromide (80 mL, 240 mmol, 3.0 M solution in Et_2O) was slowly added to a solution of methyl pyroglutamate (11.2 g, 78.5 mmol) in THF (100 mL) at −78 °C over 30 min. After warming to 0 °C and stirring for 30 min at 0 °C, then reflux for 1 h, the reaction mixture was quenched with 5% aqueous HCl solution. After extraction of the water layer (CH_2Cl_2, 3 × 50 mL), the combined organic layers were dried over Na_2SO_4 and concentrated in vacuo. The solid residue was recrystallized from Et_2O to give colorless crystals (14.0 g, 65%). $[\alpha]_D^{23} = -85.5$ (*c* 1.01, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): 1.87–1.96 (m, 1H, C(O)CH_2CHH), 2.01–2.2.18 (m, 1H, C(O)CH_2CHH), 2.20–2.40 (m, 2H, C(O)CH_2), 4.04 (br s, 1H, OH), 4.67–4.72 (dd, 1H, *J* = 8.2, 4.8 Hz, NCH), 4.90 (br s, 1H, NH), 7.08–7.34 (m, 6H, Ph), 7.43–7.49 (m, 4H, Ph). ^{13}C NMR (75 MHz, $CDCl_3$): 21.4, 30.1, 60.5, 78.6, 125.5, 125.7, 126.9, 127.3, 128.1, 128.7, 143.2, 145.2, 179.3.

4.2.2. (*S*)-5-(2-Hydroxypropan-2-yl)pyrrolidin-2-one 11b

According to the literature,[18] to a vigorously stirred solution of (*S*)-pyroglutamic acid methyl ester (11.2 g, 78 mmol) in 150 mL of THF under argon at room temperature was added a 3.0 M solution of MeMgBr in diethylether (65 mL, 0.19 mol). After 3 h at reflux, the reaction mixture was quenched with saturated aqueous $NaHCO_3$ solution and repeatedly extracted with THF. The organic phase was dried over $MgSO_4$, concentrated in vacuo, and the crude product was purified by chromatography with EtOAc/MeOH (40:1) to afford 5.4 g (48%) of **11b** as an oil. ^{1}H NMR (300 MHz, $CDCl_3$): 0.88 and 0.95 (s, 3H, C(CH_3)$_2$), 1.77–1.78 (m, 1H, C(O) CH_2CHH), 1.85–2.05 (m, 1H, C(O)CH_2CHH), 2.10–2.30 (m, 2H, C(O)CH_2), 2.90 (br s, 1H, OH), 3.83–3.87 (dd, *J* = 8.3, 5.8 Hz, 1H, NCH), 7.10 (br s, 1H, NH). ^{13}C NMR (75 MHz, $CDCl_3$): 21.8, 23.2 and 26.3, 30.5, 63.6, 71.6, 179.5.

4.2.3. (*S*)-5-[(*tert*-Butyldimethylsilyloxy)diphenylmethyl]-pyrrolidin-2-one 12a

tert-Butyldimethylsilyl triflate (1.78 mL, 7.5 mmol) and 2,6-lutidine (1.05 mL, 9.0 mmol) were slowly added to a solution of alcohol **11a** (0.80 g, 3 mmol) in CH_2Cl_2 (30 mL) at 0 °C. After being stirred overnight at room temperature, the reaction mixture was quenched with 5% aqueous HCl. After extraction of the water layer (CH_2Cl_2, 3 × 10 mL), the combined organic layers were dried over Na_2SO_4 and concentrated in vacuo. After flash chromatography (EtOAc/PE = 1:1) **12a** was obtained as a colorless solid (1.14 g, 3 mmol, 99%). $[\alpha]_D^{23} = -65.0$ (*c* 1.01, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): −0.39 (s, 3H, $SiCH_3$), −0.34 (s, 3H, $SiCH_3$), 0.94 (s, 9H, $SiC(CH_3)_3$), 0.99–1.02 (m, 1H, $COCH_2CHH$), 1.77–1.91 (m, 1H, C(O)CH_2CHH), 2.04–2.22 (m, 2H, C(O)CH_2), 4.62–4.60 (dd, *J* = 7.4, 5.2 Hz, 1H, NCH), 5.84 (br s, 1H, NH), 7.31–7.34 (m, 10H, Ph). ^{13}C NMR (75 MHz, $CDCl_3$): −3.4 and −3.3, 18.6, 22.2, 25.9, 28.7, 59.7, 82.2, 127.6, 127.6, 127.1, 128.5, 128.6, 142.1, 142.7, 178.5.

4.2.4. (*S*)-5-(2-(Trimethylsilyloxy)propan-2-yl)pyrrolidin-2-one 12b

Trimethylsilyl triflate (1.36 mL, 7.5 mmol) and 2,6-lutidine (1.05 mL, 9.0 mmol) were slowly added to a solution of alcohol **11b** (0.43 g, 3 mmol) in CH_2Cl_2 (30 mL) at 0 °C. After being stirred overnight at room temperature, the reaction mixture was quenched with 5% aqueous HCl. After extraction of the water layer (CH_2Cl_2, 3 × 10 mL), the combined organic layers were dried over Na_2SO_4 and concentrated in vacuo. After flash chromatography (EtOAc/petroleum ether = 1:1) **12b** was obtained as a oil (0.64 g, 99%). $[\alpha]_D^{23} = -5.3$ (*c* 1.01, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): 0.18 (s, 9H, $Si(CH_3)_3$), 1.08 and 1.13 (s, 3H, C(CH_3)$_2$), 1.75–1.87 (m, 1H, C(O)CH_2CHH), 1.89–2.02 (m, 1H, C(O)CH_2CHH), 2.10–2.32 (m, 2H, C(O)CH_2), 3.36–3.40 (dd, *J* = 8.4, 4.7 Hz, 1H, NCH), 7.26 (br s, 1H, NH). ^{13}C NMR (75 MHz, $CDCl_3$): 2.2, 21.6, 25.1, 25.7, 30.3, 64.0, 75.1, 179.0.

4.2.5. (*S*)-5-(Hydroxydiphenylmethyl)pyrrolidin-2-one 12c

Trimethylsilyl triflate (1.36 mL, 7.5 mmol) and 2,6-lutidine (1.05 mL, 9.0 mmol) were slowly added to a solution of alcohol **11a** (0.80 g, 3 mmol) in CH_2Cl_2 (30 mL) at 0 °C . After being stirred overnight at room temperature, the reaction mixture was quenched with 5% aqueous HCl. After extraction of the water layer (CH_2Cl_2, 3 × 10 mL), the combined organic layers were dried (Na_2SO_4) and concentrated in vacuo. After flash chromatography (EtOAc/PE = 1:1) **12c** was obtained as a colorless solid (1.06 g, 99%). $[\alpha]_D^{23} = -75.5$ (*c* 1.01, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): 0.00 (s, 9H, $Si(CH_3)_3$), 1.38–1.52 (m, 1H, C(O)CH_2CHH), 2.02–2.25 (m, 3H, C(O)CH_2CH), 4.73–4.77 (dd, 1H, *J* = 7.8, 5.0 Hz, NCH), 5.90 (br s, 1H, NH), 7.38–7.47 (m, 10H, Ph). ^{13}C NMR (75 MHz, $CDCl_3$): 1.71, 22.1, 28.9, 60.1, 82.5, 127.7, 127.8, 127.9, 128.0, 142.7, 142.7, 178.5.

4.2.6. (*S*)-5-Benzhydrylpyrrolidin-2-one 13

Trifluoroborane etherate (8.3 mL, 67.0 mmol) was added to a solution of Et_3SiH (17.9 mL, 112 mmol) and **11a** (6.0 g, 22.3 mmol) in CH_2Cl_2 (240 mL) at −20 °C over 5 min. The mixture was stirred

at rt for 66 h. During this time, additional Et_3SiH (28.5 mL, 178 mmol) and $BF_3{\cdot}OEt_2$ (22.0 mL, 178 mmol) were added to complete the reaction. The reaction mixture was washed with saturated aqueous $NaHCO_3$ solution, brine, and then dried over Na_2SO_4. Concentration and chromatography ($CHCl_3$/AcOEt = 2:1) gave **13** as a colorless solid (4.37 g, 78%). $[\alpha]_D^{23} = +25.5$ (*c* 1.01, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): 1.74–1.86 (m, 1H, C(O)CH_2CH*H*), 2.09–2.21 (m, 1H, C(O)CH_2C*H*H), 2.30–2.36 (m, 2H, C(O)CH_2), 3.76 (d, *J* = 10.4 Hz, 1H, $CHPh_2$), 4.37–4.45 (m, 1H, NCH), 5.44 (br s, 1H, NH), 7.22–7.30 (m, 10H, Ph). ^{13}C NMR (75 MHz, $CDCl_3$): 26.4, 30.1, 57.5, 58.4, 126.9, 127.1, 127.8, 128.7, 129.0, 140.6, 141.5, 177.2.

4.2.7. General procedure for the synthesis of the precatalysts

A 10 mL round-bottomed flask was charged with the lactam (1 mmol) and CH_2Cl_2 (10 mL). Trimethyloxonium tetrafluoroborate (0.16 g, 1.1 mmol) was added and the reaction mixture was stirred overnight at room temperature. Phenylhydrazine (0.11 mL, 1.1 mmol) was added to the solution and stirred overnight. The solvent was removed in vacuo and the product was used without further purification. Trimethyl orthoformate (10 mL) was added and the reaction mixture was heated to 80 °C and stirred at this temperature overnight. The solvent was removed in vacuo and the product was precipitated from ethyl acetate to give an off white/yellow powder. Recrystallization from hot MeOH afforded **8a–c** and **9** as a colorless crystalline solid.

4.2.8. (*S*)-5-((*tert*-Butyldimethylsilyloxy)diphenylmethyl)-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*][1,2,4]triazol-2-ium tetrafluoroborate 8a

Yield (0.45 g, 80%). Mp: 186 °C. $[\alpha]_D^{23} = -137.5$ (*c* 1.01, $CHCl_3$); IR (KBr): *v* = 3415, 3105, 2953, 2930, 2889, 2854, 1593, 1516, 1493, 1468, 1445, 1385, 1064, 873, 836, 779, 706. ^1H NMR (300 MHz, $CDCl_3$): −0.35 (s, 3H, $SiCH_3$), −0.32 (s, 3H, $SiCH_3$), 0.94 (s, 9H, $SiC(CH_3)_3$), 1.60–1.71 (m, 1H, C(O)CH_2CH*H*), 2.72–2.93 (m, 2H, C(O)C*H*$_2$CH), 3.12–3.27 (m, 1H, C(O)CH_2CH*H*), 6.10 (d, *J* = 7.7 Hz, 1H, NCH), 7.13–7.15 (m, 2H, Ph), 7.31–7.36 (m, 2H, Ph), 7.37–7.47 (m, 4H, Ph), 7.50–7.55 (m, 5H, Ph), 7.65–7.71 (m, 2H, Ph), 9.06 (s, 1H, NCHN). ^{13}C NMR (75 MHz, $CDCl_3$): −3.6 and −3.5, 18.6, 20.7, 26.0, 29.5, 66.3, 82.1, 121.4, 127.9, 128.4, 128.9, 129.0, 130.1, 130.9, 135.3, 136.9, 139.0, 140.0, 163.4. MS (ESI): *m*/*z* = 482.2 (100, M^+), 350.4 (5), 87.3 (100, BF_4^-); Anal. Calcd for $C_{27}H_{30}N_3OSi^+BF_4^-$: C, 63.27; H, 6.37; N, 7.38. Found: C, 63.75; H, 6.325; N, 7.40.

4.2.9. (*S*)-2-Phenyl-5-(2-(trimethylsilyloxy)propan-2-yl)-6,7-dihydro-5*H*-pyrrolo[2,1-*c*][1,2,4]triazol-2-ium tetrafluoroborate 8b

Yield (0.25 g, 63%). Mp: 110 °C. $[\alpha]_D^{23} = -46.3$ (*c* 1.01, $CHCl_3$); IR (KBr): *v* = 3424, 3193, 2977, 2898, 1592, 1532, 1470, 1438, 1400, 1249, 1187, 1144, 1060, 976, 882, 847, 765, 685, 520. ^1H NMR (300 MHz, $CDCl_3$): 0.0 (s, 9H, $Si(CH_3)_3$), 1.24 and 1.40 (s, 3H, $C(CH_3)_2$), 2.62–2.68 (m, 1H, C(O)CH_2CH*H*), 2.83–2.96 (m, 1H, C(O)CH_2C*H*H), 3.05–3.12 (m, 2H, C(O)CH_2), 4.79 (dd, *J* = 8.0, 0.9 Hz, 1H, NCH), 7.48–7.50 (m, 3H, Ph), 7.76–7.80 (m, 2H, Ph), 9.89 (s, 1H, NCHN). ^{13}C NMR (75 MHz, $CDCl_3$): 2.0, 22.0, 26.0 and 26.9, 29.3, 70.2, 74.7, 120.8, 130.2, 130.8, 137.2, 163.5. MS (ESI): *m*/*z* = 316.1 (100, M^+), 226.2 (15), 87.3 (100, BF_4^-); Anal. Calcd for $C_{27}H_{30}N_3OSi^+BF_4^-$: C, 50.63; H, 6.50; N, 10.42. Found: C, 50.88; H, 6.890; N, 10.47.

4.2.10. (*S*)-5-(Diphenyl(trimethylsilyloxy)methyl)-2-phenyl-6,7-dihydro-5*H*-pyrrolo[2,1-*c*][1,2,4]triazol-2-ium tetrafluoroborate 8c

Yield (0.3 g, 68%). Mp: 215 °C. $[\alpha]_D^{23} = -130.2$ (*c* 1.01, $CHCl_3$); IR (KBr): *v* = 3171, 3065, 2958, 1594, 1520, 1444, 1394, 1254, 1193, 1052, 849, 763, 708, 633, 582, 525. ^1H NMR (300 MHz, $CDCl_3$): ^1H NMR (300 MHz, $CDCl_3$): 0.00 (s, 9H, $Si(CH_3)_3$), 2.08–2.20 (m, 1H, C(O)CH_2CH*H*), 2.82–3.01 (m, 2H, C(O)C*H*$_2$CH), 3.31–3.42 (m, 1H, C(O)CH_2CH*H*), 6.20 (d, *J* = 8.5 Hz, 1H, NCH), 7.34–7.36 (m, 2H, Ph), 7.40–7.45 (m, 5H, Ph), 7.51–7.54 (m, 3H, Ph), 7.64–7.67 (m, 3H, Ph), 7.76–7.79 (m, 2H, Ph), 8.95 (s, 1H, NCHN). ^{13}C NMR (75 MHz, $CDCl_3$): 1.4, 21.1, 29.8, 68.1, 121.2, 128.0, 128.5, 128.6, 128.8, 129.0, 129.2, 130.2, 135.4, 136.6, 139.7, 140.1, 162.5. MS (ESI): *m*/*z* = 440.1 (100, M^+), 350.5 (15), 87.3 (100, BF_4^-). Anal. Calcd for $C_{27}H_{30}N_3OSi^+BF_4^-$: C, 61.48; H, 5.73; N, 7.97. Found: C, 61.52; H, 5.581; N, 7.95.

4.2.11. (*S*)-5-Benzhydryl-2-phenyl-6,7-dihydro-5*H*-pyrrolo-[2,1-*c*][1,2,4]triazol-2-ium tetrafluoroborate 9

Yield (0.37 g, 85%). Mp: 180 °C. $[\alpha]_D^{23} = +14.5$ (*c* 1.01, $CHCl_3$); IR (KBr): *v* = 3440, 3166, 3061, 3030, 2960, 1814, 1592, 1522, 1495, 1450, 1387, 1291, 1202, 1069, 977, 921, 832, 764, 703, 630, 607, 588, 520, 493. ^1H NMR (300 MHz, $CDCl_3$): 2.49–2.60 (m, 1H, C(O)CH_2CH*H*), 2.84–2.97 (m, 1H, C(O)CH_2C*H*H), 3.11–3.16 (m, 2H, C(O)CH_2), 4.28/4.31 (d, *J* = 10.9 Hz, 1H, $CHPh_2$), 5.83–5.91 (m, 1H, NCH), 7.24–7.50 (m, 15H, Ph), 7.95 (s, 1H, NCHN). ^{13}C NMR (75 MHz, $CDCl_3$): 21.1, 32.4, 55.4, 64.0, 121.4, 127.7, 127.8, 128.2, 128.3, 129.2, 129.7, 129.9, 130.7, 135.3, 135.7, 138.8, 139.6, 162.5. MS (ESI): *m*/*z* = 352.2 (100, M^+), 274.4 (5), 87.3 (100, BF_4^-); Anal. Calcd for $C_{27}H_{30}N_3OSi^+BF_4^-$: C, 65.62; H, 5.05; N, 9.57. Found: C, 65.47; H, 5.21; N, 9.55.

4.3. Benzoin reaction

A dry flask was charged with the precatalyst (0.1 mmol, 10 mol %), absolute toluene (1 mL), KHMDS in toluene (0.5 M, 0.2 mL), and then the aromatic aldehyde (1 mmol) was added dropwise at room temperature under argon. The reaction mixture was stirred for 8 h, then the reaction mixture was directly purified by chromatography (silica gel, ether/pentane; 1:4) to give the desired benzoins as colorless solids or pale yellow oils. The ^1H NMR spectra were in accordance with those reported in the literature.[13]

Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft (Priority Programme 1179 Organocatalysis) and the Fonds der Chemischen Industrie. We thank Degussa AG, BASF AG, Bayer AG and Wacker Chemie for the donation of chemicals. We thank Alexander Henseler and Dr. Arun Narine for their help in the preparation of the manuscript.

References

1. Reviews: (a) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5506; (b) Marion, N.; Diez-Gonzalez, S.; Nolan, S. P. *Angew. Chem.* **2007**, *119*, 3046; Marion, N.; Diez-Gonzalez, S.; Nolan, S. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 2988; (c) Zeitler, K. *Angew. Chem.* **2005**, *117*, 7674; Zeitler, K. *Angew. Chem., Int. Ed.* **2005**, *44*, 7506; (d) Christmann, M. *Angew. Chem.* **2005**, *117*, 2688; (e) Christmann, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 2632; (f) Enders, D.; Balensiefer, T. *Acc. Chem. Res.* **2004**, *37*, 534.
2. Seayad, J.; List, B. *Org. Biomol. Chem.* **2005**, *3*, 719.
3. Seebach, D. *Angew. Chem.* **1979**, *91*, 259; Seebach, D. *Angew. Chem., Int. Ed.* **1979**, *18*, 239.
4. (a) Sohn, S. S.; Rosen, E. L.; Bode, J. W. *J. Am. Chem. Soc.* **2004**, *126*, 14370; (b) Burstein, C.; Glorius, F. *Angew. Chem.* **2004**, *116*, 6331; (c) Burstein, C.; Glorius, F. *Angew. Chem., Int. Ed.* **2004**, *43*, 6205.
5. (a) Reynolds, N. T.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2004**, *126*, 9518; (b) Chow, K. Y.-K.; Bode, J. W. *J. Am. Chem. Soc.* **2004**, *126*, 8126.
6. (a) Bakhtiar, C.; Smith, E. H. *J. Chem. Soc., Perkin Trans. 1* **1994**, 239; (b) Grasa, G. A.; Kissling, R. M.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 3583.
7. Eric, F.; Nyce, G.; Myers, M.; Mock, A.; Hedrick, J. *J. Am. Chem. Soc.* **2002**, *124*, 914.
8. (a) Zhou, H. Y.; Campbell, E. J.; Nguyen, S. T. *Org. Lett.* **2001**, *3*, 2229; (b) Wu, J.; Sun, X. Y.; Ye, S. Q.; Sun, W. *Tetrahedron Lett.* **2006**, *47*, 4813.
9. Pesch, J.; Harms, K.; Bach, T. *Eur. J. Org. Chem.* **2004**, 2025.

10. Enders, D.; Breuer, K.; Raabe, G.; Runsink, J.; Teles, J. H.; Melder, J.-P.; Ebel, K.; Brode, S. *Angew. Chem.* **1995**, *107*, 1119; Enders, D.; Breuer, K.; Raabe, G.; Runsink, J.; Teles, J. H.; Melder, J.-P.; Ebel, K.; Brode, S. *Angew. Chem., Int. Ed.* **1995**, *34*, 1021.
11. (a) Enders, D.; Breuer, K.; Teles, J. H. *Helv. Chim. Acta* **1996**, *79*, 1217; (b) Enders, D.; Breuer, K.; Runsink, J.; Teles, J. H. *Helv. Chim. Acta* **1996**, *79*, 1899.
12. Knight, R. L.; Leeper, F. J. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1891.
13. Enders, D.; Kallfass, U. *Angew. Chem.* **2002**, *114*, 1822; Enders, D.; Kallfass, U. *Angew. Chem., Int. Ed.* **2002**, *41*, 1743.
14. (a) Kerr, M. S.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2002**, *124*, 10298; Review: (b) Rovis, T. *Chem. Lett.* **2008**, 2.
15. Enders, D.; Niemeier, O.; Balensiefer, T. *Angew. Chem.* **2006**, *118*, 1351; Enders, D.; Niemeier, O.; Balensiefer, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 1463.
16. Zhang, Y.-R.; He, L.; Wu, X.; Shao, P.-L.; Ye, S. *Org. Lett.* **2008**, *10*, 277.
17. Enders, D.; Kipphardt, H.; Gerdes, P.; Brena-Valle, L.; Bhushan, V. *Bull. Soc. Chim. Belg.* **1988**, *97*, 691.
18. Leutenegger, U.; Umbricht, G.; Fahrni, C.; Matt, P.; Pfaltz, A. *Tetrahedron* **1992**, *48*, 2143.