DOI: 10.1002/adsc.201200115

Conformationally Rigid Chiral Pyridine *N*-Oxides as Organocatalyst: Asymmetric Allylation of Aldehydes

Elumalai Gnanamani,[a] Nagamalla Someshwar,[a] and Chinnasamy Ramaraj Ramanathan[a,*]

[a] Department of Chemistry, Pondicherry University, Puducherry – 605 014, India
Fax: (+91)-413-265-6740; phone: (+91)-413-265-4416; e-mail: crrnath.che@pondiuni.edu.in

Received: February 12, 2012; Revised: April 30, 2012; Published online: ■■ ■■, 0000

Dedicated to Professor Mariappan Periasamy on the occasion of his 60th birthday.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201200115.

Abstract: A pyridine unit with a conformationally rigid chiral backbone has been designed and synthesized in an enantiomerically pure form to utilize in the Lewis base-catalyzed Sakurai–Hosomi–Denmark-type allylation reaction. The chiral pyridine *N*-oxide in 1:1 mixture of chloroform and 1,1,2,2-tetrachloroethane produced the homoallylic alcohols in up to 98% yield and up to 94% *ee*.

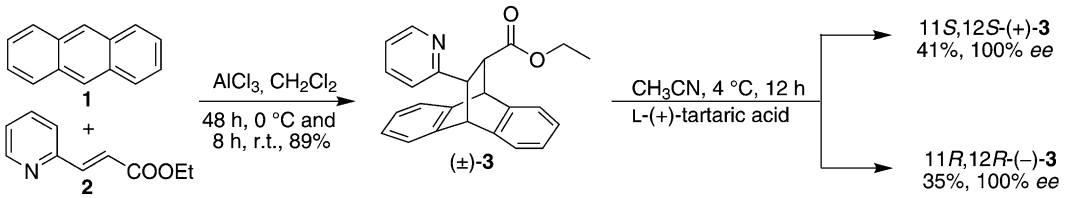
Keywords: activation of allylsilanes; catalyst design; chiral pyridine *N*-oxides; homoallylic alcohols.; organocatalysts

The design and synthesis of novel catalysts for the enantioselective activation of electrophiles/nucleophiles is one of the challenges in asymmetric organocatalysis.[1] Activation of a carbonyl group towards nucleophiles is generally achieved by Lewis acids or organocatalysts. Lewis base activation of nucleophiles is one of the promising complimentary technologies to establish new C–C bonds with carbonyl groups.[2] Organocatalytic enantioselective allylation reactions are considered to be one such tool to produce homoallylic alcohols which are, in turn, used to synthesize biologically active molecules as well as for the assemblage of complex natural products.[3]

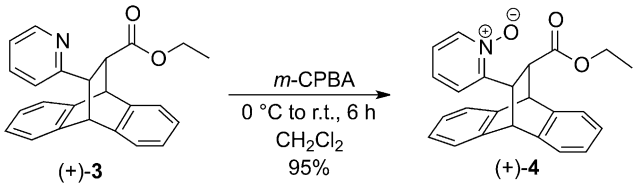
Due to the advantages associated with pyridine *N*-oxides over other Lewis base activators such as phosphoramides,[4] sulfoxides,[5] formamides,[6] etc., considerable attention has been paid to both the development of novel chiral pyridine *N*-oxides and examination of their efficacy in catalyzing the Sakurai–Hosomi–Denmark-type allylation reaction.[7–10] For example, Nakajima,[8] Hayashi,[9] Malkov,[7] and Kočovský[7] have introduced successful catalysts to effect the allylation reaction. Most of these chiral pyridine *N*-oxides are synthesized through difficult synthetic processes whilst some of them are from natural sources.[7b] The enantioselectivity of the allylation reaction often depends on the electronic property of the carbonyl compounds as well as the catalyst used. It has been documented that catalysts with an electron-rich aromatic ring attached at the position 6 of the pyridine *N*-oxide display increased enantioselectivity when reacting with electron-deficient benzaldehyde derivatives. This has been rationalized through arene-arene interactions.[7a] Later studies had shown that the electron-rich aldehydes also deliver homoallylic alcohols in high enantioselectivity.[7b]

We have initiated our effort to develop a conformationally rigid novel chiral pyridine *N*-oxide to catalyze the asymmetric allylation reaction, which resulted in two important observations: (i) with an electron-rich catalyst, the electron-rich benzaldehyde produced higher enantioselectivity; (ii) a mixture of solvents enhances the yield and enantioselectivity. Based on the steric requirements, the designer catalyst with a conformationally rigid chiral backbone possessing a pyridine unit was synthesized in racemic form from anthracene **1** and dienophile **2** in the presence of aluminum chloride. The racemic pyridine derivative **3** was resolved to obtain the corresponding antipodes in enantiomerically pure forms using L-(+)-tartaric acid (Scheme 1).[11]

The enantiomerically pure *N*-oxide (11*S*,12*S*)-(+)-**4** was easily generated in 95% yield by treating (11*S*,12*S*)-(+)-**3** with *meta*-chloroperbenzoic acid (*m*-CPBA) in dichloromethane at room temperature for 6 h (Scheme 2). The catalyst (11*S*,12*S*)-(+)-**4** was then evaluated for the enantioselective allylation reaction with 4-methoxybenzaldehyde using allyltrichlorosilane, diisopropylethylamine (DIPEA) and tetrabutylammonium iodide (TBAI) in the presence of



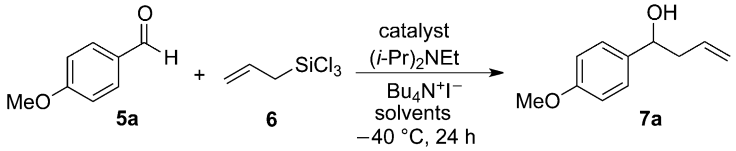
Scheme 1. Synthesis of chiral pyridine derivative **3**.



Scheme 2. Preparation of pyridine *N*-oxide (+)-**4**.

20 mol% of catalyst at −40 °C in various solvents. The homoallylic alcohol **7a** was produced in 33–54% *ee* and up to 89% yield (Table 1, entries 1–5). To increase the enantioselectivity of allylation reaction, the sterically crowded groups such as phenyl, 1-naphthyl and 9-anthracenyl groups were introduced at the position 6 of the pyridine ring of the catalyst (11*S*,12*S*)-

Table 1. Effect of catalyst/solvent on efficiency and enantioselectivity of allylation of 4-methoxybenzaldehyde **5a** with allyltrichlorosilane **6**.[a]



Entry	Catalyst[b]	Solvent	Yield [%][c]	*ee* [%][d]	Entry	Catalyst[b]	Solvent	Yield [%][c]	*ee* [%][d]
1	(+)-**4**	CH_3CN	60	33	22	(−)-**12e**	$Cl_2(CH)_2Cl_2$	6	28[f]
2	(+)-**4**	CH_2Cl_2	78	47	23	(−)-**12f**[e]	CH_3CN	5	56[f]
3	(+)-**4**	$CHCl_3$	89	54	24	(+)-**12g**	CH_3CN	20	60
4	(+)-**4**	$Cl(CH_2)_2Cl$	65	34	25	(+)-**12g**	CH_2Cl_2	17	76
5	(+)-**4**	$Cl_2(CH)_2Cl_2$	85	47	26	(+)-**12g**	$CHCl_3$	16	76
6	(+)-**12a**	CH_3CN	2	56	27	(+)-**12g**	$Cl(CH_2)_2Cl$	8	50
7	(+)-**12a**	CH_2Cl_2	4	42	28	(+)-**12g**	$Cl_2(CH)_2Cl_2$	48	78
8	(+)-**12a**	$CHCl_3$	5	40	29	(+)-**12h**	CH_3CN	64	72
9	(+)-**12a**	$Cl(CH_2)_2Cl$	nr	nd	30	(+)-**12h**	CH_2Cl_2	63	74
10	(+)-**12a**	$Cl_2(CH)_2Cl_2$	5	20	31	(+)-**12h**	$CHCl_3$	**84**	**76**
11	(−)-**12b**[e]	CH_3CN	nr	nd	32	(+)-**12h**	$Cl_2(CH)_2Cl_2$	**88**	**77**
12	(−)-**12c**[e]	CH_3CN	nr	nd	33	(+)-**12h**	$Cl(CH_2)_2Cl$	15	83
13	(−)-**12d**	CH_3CN	22	63[f]	34	(+)-**12h**	toluene	nr	nd
14	(−)-**12d**	CH_2Cl_2	6	67[f]	35	(+)-**12h**	THF	nr	nd
15	(−)-**12d**	$CHCl_3$	5	45[f]	36	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (1:1)	96	79
16	(−)-**12d**	$Cl(CH_2)_2Cl$	nr	nd	37[g]	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (1:1)	91	82
17	(−)-**12d**	$Cl_2(CH)_2Cl_2$	9	66[f]	38[h]	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (1:1)	**84**	**87**
18	(−)-**12e**	CH_3CN	trace	nd	39[h]	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (1:2)	76	86
19	(−)-**12e**	CH_2Cl_2	3	40[f]	40[h]	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (1:3)	39	86
20	(−)-**12e**	$CHCl_3$	2	35[f]	41[h]	(+)-**12h**	$CHCl_3$: $Cl_2(CH)_2Cl_2$ (2:1)	85	85
21	(−)-**12e**	$Cl(CH_2)_2Cl$	nr	nd	42[h]	(+)-**12h**	$CHCl_3$:$Cl_2(CH)_2Cl_2$ (3:1)	86	84

[a] All reactions were performed with **5a** (0.25 mmol, 1 equiv.), **6** (1.2 equiv.), catalyst **4** or **12a–h** (20 mol%) and $(i\text{-Pr})_2$NEt (5 equiv.) in solvents (0.76 mL) at −40 °C for 24 h.

[b] The catalysts (+)-**12**(**a**, **g** and **h**) were synthesized from (11*S*,12*S*)-(+)-**3** and the catalysts (−)-**12**(**b–f**) were synthesized from (11*R*,12*R*)-(−)-**3.**

[c] Isolated yield.

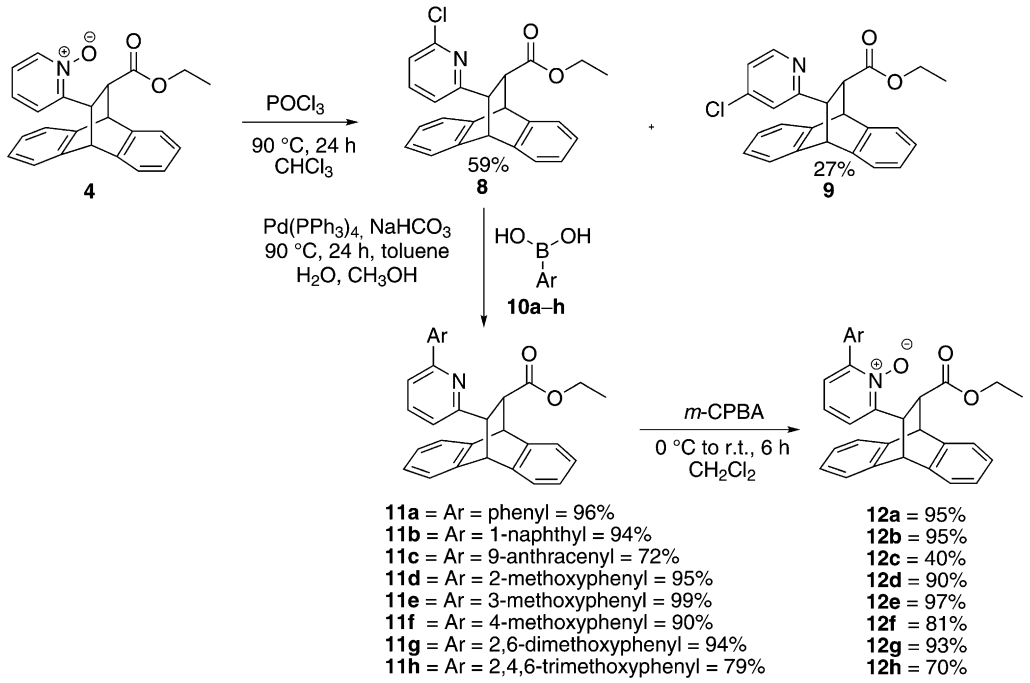
[d] The *ee* was determined by chiral HPLC analysis and the product **7a** produced in all experiments is of the (*S*)-(−)-configuration (unless otherwise stated), as revealed by the comparison of HPLC retention times,[14a] with the literature value.

[e] The catalysts were also studied in other solvents but they are ineffective.

[f] The products were of the (*R*)-(+)-configuration.[14a]

[g] Reaction was carried out at −55 °C for 24 h.

[h] Reactions were carried out at −78 °C for 24 h; nr = no reaction, nd = not determined.



Scheme 3. Synthesis of chiral pyridine *N*-oxides **12a–h.**

(+)-**4** *via* chlorination of pyridine *N*-oxide **4** followed by Suzuki coupling of isomer **8** with the respective boronic acids **10a–c** (Scheme 3). As an encouragement, when the catalyst **12a** was examined for the allylation reaction at −40 °C, the homoallylic alcohol **7a** was produced with improved enantioselectivity (56% *ee*) but disappointingly very low yield (Table 1, entries 6–10). The enhancement of enantioselectivity may be due to the involvement of an arene-arene interaction as claimed by earlier reports.[7a] Unfortunately, the 1-naphthyl-substituted **12b** and 9-anthracenyl-substituted **12c** chiral pyridine *N*-oxides even failed to catalyze the reaction (Table 1, entries 11 and 12), which may be due to the combined electronic and steric effects infulencing negatively on the allylation reaction. This has been supported by the fact that the introduction of either alkyl or aryl groups at the positions 2 and/or 6 of the pyridine ring reduces the nucleophilicity/basicity of the pyridine and consequently reduces the nucleophilicity of the corresponding *N*-oxide.[12] Hence the electron-rich aryl rings (methoxy-substituted benzene group) have been introduced at the 6 position of the pyridine ring in (11*S*,12*S*)-(+)-**4** to afford the chiral biaryls **11d–11h**, which may enhance both reactivity and selectivity. A single crystal X-ray crystallographic analysis exposed the presence of a cavity-like structure after the introduction of an aryl moiety at the position 6 of the pyridine ring in **4** (Figure 1).[13] Oxidation of **11d–11h**

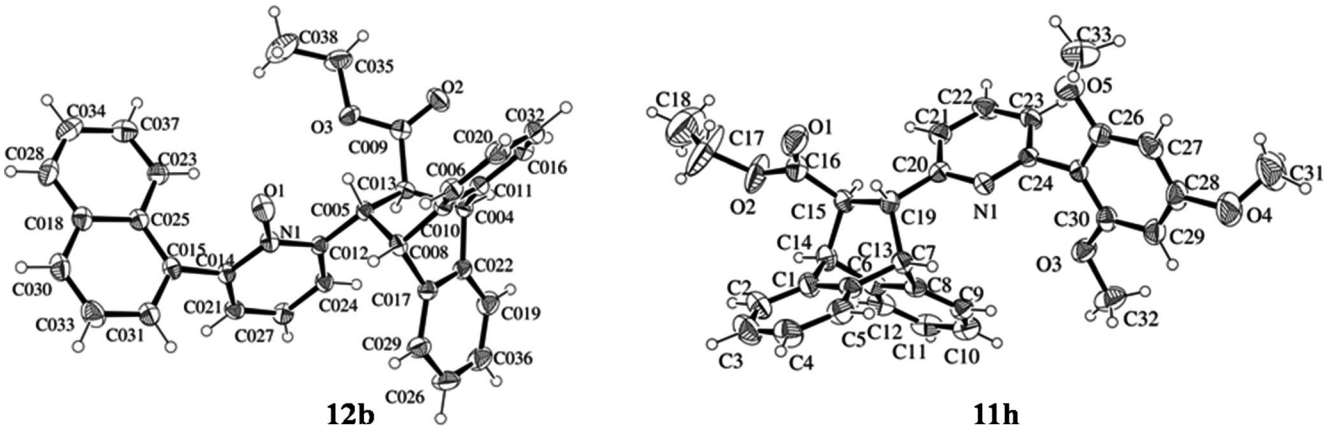
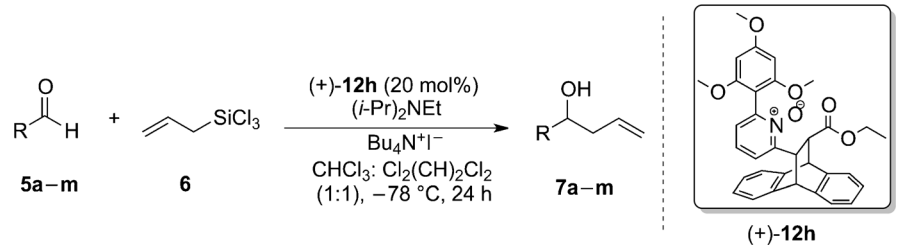


Figure 1. ORTEP representations of the X-ray crystal structures of **12b** and **11h**.

Table 2. Asymmetric allylation of aldehydes with allyltrichlorosilane catalyzed by (+)-**12h**.[a]



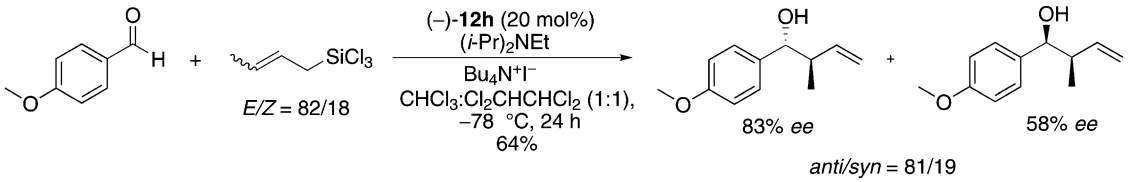
Entry	Aldehyde	R	Yield [%][b]	*ee* [%][c]	Configuration[d]
1	**5a**	4-MeO-C_6H_4	84	87	*S*
2	**5b**	2-MeO-C_6H_4	95	80	*S*
3	**5c**	C_6H_5	87	83	*S*
4	**5d**	9-anthryl	62	92	*S*
5	**5e**	piperonyl	58	81	*S*
6	**5f**	3,4-dimethoxy	81	94	*S*
7	**5g**	4-NO_2-C_6H_4	47	25	*S*
8	**5h**	4-Cl-C_6H_4	98	76	*S*
9	**5i**	2-thienyl	71	92	*R*
10	**5j**	3-thienyl	67	89	*S*
11	**5k**	2-furyl	52	93	*R*
12	**5l**	(*E*)-C_6H_5CH=CH	37	71	*S*
13	**5m**	cyclohexyl	64	33	*S*

[a] All reactions were performed with **5** (0.25 mmol, 1 equiv.), **6** (1.2 equiv.), catalyst (+)-**12h**, (*i*-Pr)$_2$NEt (5 equiv.) and TBAI (1 equiv.) in 1:1 mixture of chloroform:1,1,2,2-tetrachloroethane (0.76 mL) at −78 °C for 24 h.
[b] Isolated yield.
[c] The *ee* was determined by chiral HPLC analysis.
[d] Absolute configurations were assigned by comparing the HPLC retention time with the literature data.[14,8a]

using *m*-CPBA produced the chiral pyridine *N*-oxides **12d–12h** (Scheme 3).

Promisingly, the catalysts **12d** and **12e** gave the homoallylic alcohol in increased enantiomeric excess, up to 67% *ee* with poor yield when the reactions were carried out in various solvents, whereas the catalyst **12f** failed to catalyze the reaction (Table 1, entries 13–23). The low yield may probably be due to the insufficient nucleophilicity of the Lewis bases **12d**–**12f**. Hence the additional methoxy group containing molecules **12g** and **12h** were screened for allylation of 4-methoxybenzaldehyde under the established conditions using allyltrichlorosilane, DIPEA and TBAI in various electrophilic, nucleophilic and neutral solvents (Table 1, entries 24–35). Between these two catalysts, the catalyst **12h** enhanced the enantioselectivity of the reaction and increased the yield of the homoallylic alcohol (Table 1, entries 29–33). Reactions in solvents such as chloroform and 1,1,2,2-tetrachloroethane furnished the homoallylic alcohol in higher enantiomeric purity with good yield. On the other hand 1,2-dichloroethane produced the homoallylic alcohol in 83% *ee* with poor yield (15%) (Table 1, entry 33). Hence the solvents chloroform and 1,1,2,2-tetrachloroethane were selected for further optimization of the reaction conditions to enhance the enantioselectivity without diminishing the yield.

Lowering the reaction temperature generally enhances the enantioselectivity of the reaction (*vide infra*). But the freezing points of chloroform and 1,1,2,2-tetrachloroethane, respectively, are −63.5 °C and −44 °C and this hindered the use of these solvents at −78 °C. Mixing of two solvents is known to reduce the freezing point of the mixture thus enabling the experiment to be conducted at −78 °C.[15] Therefore the preliminary experiments were carried out with 1:1 mixtures of chloroform and 1,1,2,2-tetrachloroethane at −40 °C, −55 °C and −78 °C in the presence of the catalyst (+)-**12h** (Table 1, entries 36–38). The homoallylic alcohol was produced in 84% yield with 87% *ee* when the experiment was carried out at −78 °C (Table 1, entry 38). Increasing the concentration of 1,1,2,2-tetrachloroethane reduces the yield of the product (Table 1, entries 39 and 40), while retaining the enantiomeric purity of the homoallylic alcohol. Increasing the percentage of chloroform marginally increases the yield, but reduces the enantiomeric purity of the homoallylic alcohol (Table 1, entries 41 and 42). This study, without compromising the yield, showed better enantioselectivity in a 1:1 mixture of chloroform and 1,1,2,2-tetrachloroethane (Table 1, entry 38).



Scheme 4. Crotylation of 4-methoxybenzaldehyde.

Having identified the appropriate solvent combination, we tried to identify the appropriate base, additives and the amount of catalyst required for better yield and enantioselectivity.[16] After extensive experimentation based on the above variables, the best conditions were found to be 20 mol% catalyst loading, with TBAI (1 equiv.) as additive and DIPEA (5 equiv.) as base in a 1:1 mixture of chloroform and 1,1,2,2-tetrachloroethane at −78 °C (Table 1, entry 38).

Based on these conditions, the versatility of catalyst (+)-**12h** was examined for the enantioselective allylation reaction with various aromatic, heterocyclic and aliphatic aldehydes (Table 2). Interestingly the aromatic aldehydes with electron-releasing functional groups or benzaldehyde produced better yields and higher levels of asymmetric induction (Table 2, entries 1–3), even though the aldehydes and catalysts are not electronically complementary to each other. To further exemplify this observation, the reaction was carried out with an electron-withdrawing group-containing benzaldehyde such as 4-nitrobenzaldehyde, which generated the corresponding homoallylic alcohol in poor yield and low optical purity (Table 2, entry 7). Condensed polycyclic aromatic aldehyde, for example, anthracene-9-carboxaldehyde, generated the corresponding homoallylic alcohol in 62% yield with good enantioselectivity (92% *ee*), which strongly suggests the involvement of steric factors in the enantioselectivity.

All the aldehydes, except 2-thiophenecarbaldehyde **5i** and 2-furancarbaldehyde **5k**, produced homoallylic alcohols with the *S* configuration in the presence of (+)-**12h**. This showed the involvement of a six-membered chair-like cyclic transition state which, in turn, facilitated the transfer of the allyl nucleophile to the *si*-face of the prochiral aldehydes (Table 2, entries 1–8, 10, 12, and 13). Furthermore, this conclusion was corroborated by treating the 4-methoxybenzaldehyde with crotyltrichlorosilane ($E/Z = 82:18$)[17] in the presence of catalyst (−)-**12h**, which produced the *anti*/*syn* alcohols in an 81:19 ratio (Scheme 4).

Electron-rich heterocyclic carboxaldehydes such as furan- and thiophenecarbaldehydes **5i**–**5k** successfully furnished the homoallylic alcohols **7i**–**7k** in excellent enantioselectivity (Table 2, entries 9–11). As a surprise, the thiophene-2-carbaldehyde and 2-furfural produced the corresponding homoallylic alcohols in the opposite configuration in contrast to the reported stereochemical outcome (Table 2, entries 9 and 11).[10e,7e] This stereochemical outcome may be explained by the involvement of an axial orientation of the heterocycles in such a way that the lone pair of electrons on either O/S is stabilizing the positive charge of the β-carbon of allyl reagent as well as ensuring exposure of the *re*-face of the aldehyde to the γ-carbon of allyl reagent, which then facilitates the transfer of the allyl group from a hypervalent silicon complex to the *re*-face of the carbonyl group.[18]

In summary, we have designed and synthesized a series of enantiomerically pure pyridine *N*-oxides and evaluated their ability to promote the Sakurai–Hosomi–Denmark-type allylation of aldehydes with allyltrichlorosilane. An electron-rich pyridine *N*-oxide is a prerequisite for high enantioselectivity and good yield. The notable observation of the present article contemplates the beneficial effect of a mixture of solvents on the enantioselectivity. The stabilizing effect of a partial positive charge on the β-carbon by the lone pair electrons of the S/O atoms of the heterocyles in 2-thiophenecarbaldehyde and 2-furancarbaldehyde, respectively, accounts for the excellent enantioselectivity and opposite configuration of the homoallylic alcohol produced. Further studies on modification of the catalyst structure to enhance the enantioselectivity of all class of aldehydes are in progress in this laboratory.

Experimental Section

General Experimental Procedure for the Asymmetric Allylation of Aldehydes

Allyltrichorosilane (44 μL, 0.3 mmol) was added dropwise to the solution of catalyst (+)-**12h** (26.8 mg, 0.05 mmol), diisopropylethylamine (0.21 mL, 1.25 mmol), *tetra*-*n*-butylammonium iodide (92.3 mg, 0.25 mmol) and aldehyde (0.25 mmol) in chloroform:1,1,2,2-tetrachloroethane (1:1, 0.76 mL) under nitrogen atmosphere at −78 °C with stirring. After 24 h the reaction mixture was quenched with aqueous saturated $NaHCO_3$ (2 mL). The organic layer was separated and then the aqueous layer was extracted with diethyl ether (3× 5 mL). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4, filtered and the solvent was evaporated on a rotary evaporator under reduced pressure.

The residue was purified through silica gel column chromatography to afford the homoallylic alcohols.

Acknowledgements

We thank DST, New Delhi for financial support. E. G. and N. S. thank CSIR, New Delhi for SRF and JRF respectively. We gratefully acknowledge Prof. M. L. N. Rao, IITK, Kanpur, Prof. K. R. Prasad, IISc, Bengaluru, and Department of Chemistry, IITM, Chennai for HR-MS analyses; CIF, Pondicherry University for NMR/IR data; and the single crystal XRD facility (DST-FIST), Department of Chemistry, Pondicherry University for XRD data.

References

[1] a) A. Berkessel, H. Gröger, *Asymmetric Organocatalysis*, Wiley-VCH, Weinheim, **2005**; b) K. Mikami, M. Lautens, *New Frontiers in Asymmetric Catalysis*, John Wiley & Sons, Hoboken, New Jersey, **2007**.

[2] a) S. E. Denmark, G. L. Beutner, *Angew. Chem.* **2008**, *120*, 1584–1663; *Angew. Chem. Int. Ed.* **2008**, *47*, 1560–1638; b) S. E. Denmark, J. Fu, *Chem. Rev.* **2003**, *103*, 2763–2793.

[3] a) R. P. Murelli, A. K. Cheung, M. L. Snapper, *J. Org. Chem.* **2007**, *72*, 1545–1552; b) F. X. Felpin, M. J. Bertrand, J. Lebreton, *Tetrahedron* **2002**, *58*, 7381–7389.

[4] a) S. E. Denmark, J. Fu, M. J. Lawler, *J. Org. Chem.* **2006**, *71*, 1523–1536; b) T. Oyama, H. Yoshioka, M. Tomoi, *Chem. Commun.* **2005**, 1857–1859; c) S. E. Denmark, J. Fu, D. M. Coe, X. Su, N. E. Pratt, B. D. Griedel, *J. Org. Chem.* **2006**, *71*, 1513–1522; d) K. Iseki, Y. Kuroki, M. Takahashi, Y. Kobayashi, *Tetrahedron Lett.* **1996**, *37*, 5149–5150; e) K. Iseki, Y. Kuroki, M. Takahashi, S. Kishimoto, Y. Kobayashi, *Tetrahedron* **1997**, *53*, 3513–3526.

[5] a) A. Massa, M. R. Acocella, V. D. Sio, R. Villano, A. Scettri, *Tetrahedron: Asymmetry* **2009**, *20*, 202–204; b) V. D. Sio, A. Massa, A. Scettri, *Org. Biomol. Chem.* **2010**, *8*, 3055–3059; c) G. J. Rowlands, W. Kentish Barnes, *Chem. Commun.* **2003**, 2712–2713.

[6] K. Iseki, S. Mizuno, Y. Kuroki, Y. Kobayashi, *Tetrahedron* **1999**, *55*, 977–988.

[7] a) A. V. Malkov, L. Dufková, L. Farrugia, P. Kočovský, *Angew. Chem.* **2003**, *115*, 3802–3805; *Angew. Chem. Int. Ed.* **2003**, *42*, 3674–3677; b) A. V. Malkov, M. Bell, F. Castelluzzo, P. Kočovský, *Org. Lett.* **2005**, *7*, 3219–3222; c) A. V. Malkov, M. Barłóg, Y. Jewkes, J. Mikušek, P. Kočovský, *J. Org. Chem.* **2011**, *76*, 4800–4804; d) A. V. Malkov, P. Ramirez-López, L. Biedermannová, L. Rulíšek, L. Dufková, M. Kotora, F. Zhu, P. Kočovský, *J. Am. Chem. Soc.* **2008**, *130*, 5341–5348; e) A. V. Malkov, M. Bell, M. Orsini, D. Pernazza, A. Massa, P. Herrmann, P. Meghani, P. Kočovský, *J. Org. Chem.* **2003**, *68*, 9659–9668.

[8] a) M. Nakajima, M. Saito, M. Shiro, S. Hashimoto, *J. Am. Chem. Soc.* **1998**, *120*, 6419–6420; b) M. Nakajima, M. Saito, S. Hashimoto, *Chem. Pharm. Bull.* **2000**, *48*, 306–307.

[9] a) A. Kina, T. Shimada, T. Hayashi, *Adv. Synth. Catal.* **2004**, *346*, 1169–1174; b) T. Shimada, A. Kina, S. Ikeda, T. Hayashi, *Org. Lett.* **2002**, *4*, 2799–2801; c) T. Shimada, A. Kina, T. Hayashi, *J. Org. Chem.* **2003**, *68*, 6329–6337.

[10] a) R. Hrdina, F. Opekar, J. Roithova, M. Kotora, *Chem. Commun.* **2009**, 2314–2316; b) R. Hrdina, M. Dracinsky, I. Valterova, J. Hodacova, I. Cisarova, M. Kotora, *Adv. Synth. Catal.* **2008**, *350*, 1449–1456; c) J. R. Fulton, J. E. Glover, L. Kamara, G. J. Rowlands, *Chem. Commun.* **2011**, *47*, 433–435; d) K. Vlašaná, R. Hrdina, I. Valterová, M. Kotora, *Eur. J. Org. Chem.* **2010**, 7040–7044; e) G. Chelucci, N. Belmonte, M. Benaglia, L. Pignataro, *Tetrahedron Lett.* **2007**, *48*, 4037–4041; f) R. Hrdina, I. Valterová, J. Hodačová, I. Cisařová, M. Kotora, *Adv. Synth. Catal.* **2007**, *349*, 822–826; g) L. Pignataro, M. Benaglia, R. Annunziata, M. Cinquini, F. Cozzi, *J. Org. Chem.* **2006**, *71*, 1458–1463; h) A. Kadlčiková, R. Hrdina, I. Valterová, M. Kotora, *Adv. Synth. Catal.* **2009**, *351*, 1279–1283; i) L. Pignataro, M. Benaglia, M. Cinquini, F. Cozzi, G. Celentano, *Chirality* **2005**, *17*, 396–403.

[11] E. Gnanamani, C. R. Ramanathan, *Tetrahedron: Asymmetry* **2009**, *20*, 2211–2215.

[12] R. P. Wurz, *Chem. Rev.* **2007**, *107*, 5570–5595.

[13] CCDC 862192, CCDC 862193, CCDC 862194, CCDC 862195, CCDC 862196, CCDC 862197 and CCDC 862198 contain the supplementary crystallographic data for this paper (compounds **8**, **11f**, **11a**, **11h**, **12b**, **11c** and **9**, respectively). These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

[14] a) P. Wang, J. Chen, L. Cun, J. Deng, J. Zhu, J. Liao, *Org. Biomol. Chem.* **2009**, *7*, 3741–3747; b) J. Y. Lee, J. J. Miller, S. S. Hamilton, M. S. Sigman, *Org. Lett.* **2005**, *7*, 1837–1839; c) P. Jain, J. C. Antilla, *J. Am. Chem. Soc.* **2010**, *132*, 11884–11886; d) I. S. Kim, M. Y. Ngai, M. J. Krische, *J. Am. Chem. Soc.* **2008**, *130*, 6340–6341; e) J. F. Traverse, Y. Zhao, A. H. Hoveyda, M. L. Snapper, *Org. Lett.* **2005**, *7*, 3151–3154; f) K. Takeuchi, T. Takeda, T. Fujimoto, I. Yamamoto, *Tetrahedron* **2007**, *63*, 5319–5322; g) G. Chelucci, S. Baldino, G. A. Pinna, M. Benaglia, L. Buffa, S. Guizzetti, *Tetrahedron* **2008**, *64*, 7574–7582; h) B. Bechem, R. L. Patman, A. S. K. Hashmi, M. J. Krische, *J. Org. Chem.* **2010**, *75*, 1795–1798; i) T. R. Wu, L. Shen, J. M. Chong, *Org. Lett.* **2004**, *6*, 2701–2704; j) X. Gao, I. A. Townsend, M. J. Krische, *J. Org. Chem.* **2011**, *76*, 2350–2354.

[15] C. Reichardt, T. Welton, *Solvents and Solvent Effects in Organic Chemistry*, Wiley-VCH, Weinheim, **2011**, pp 44.

[16] See the Supporting Information for details.

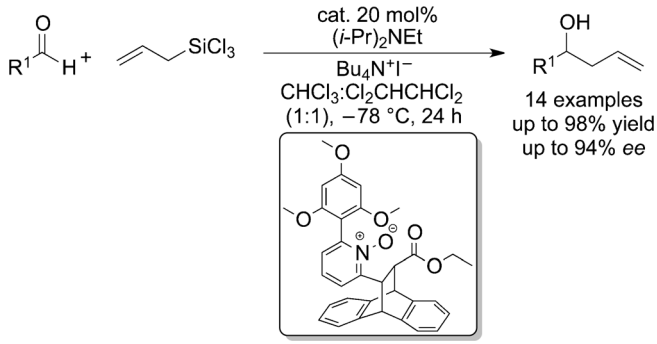
[17] Prepared as an 82/18 *trans/cis* mixture *via* the CuCl-catalyzed reaction of crotyl bromide with $HSiCl_3$.[4e]

[18] Also we may not rule out the possible coordination of the lone pair of electrons on S/O to the silicon atom of allylsilanes. Theoretical studies are in progress to ascertain this hypothesis.

Conformationally Rigid Chiral Pyridine *N*-Oxides as Organocatalyst: Asymmetric Allylation of Aldehydes

Adv. Synth. Catal. **2012**, *354*, 1 – 7

Elumalai Gnanamani, Nagamalla Someshwar, Chinnasamy Ramaraj Ramanathan*



7

