Allylic Alkylation

Enantioselective Synthesis of Allylsilanes Bearing Tertiary and Quaternary Si-Substituted Carbons through Cu-Catalyzed Allylic Alkylations with Alkylzinc and Arylzinc Reagents**

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Allylsilanes are widely used in stereoselective organic synthesis.^[1] Design and development of efficient catalytic asymmetric methods that furnish chiral allylsilanes in high enantiomeric purity would significantly expand the utility of these versatile nucleophiles. Herein, we report an efficient method for enantioselective synthesis of a range of allylsilanes by Cu-catalyzed asymmetric allylic alkylation (AAA)^[2] of Si-substituted unsaturated phosphates with dialkyl- and diarylzinc reagents [Eq. (1)]. Transformations are promoted

$$\begin{array}{c} \mathsf{R}^{1} \\ \mathsf{R}_{3}\mathsf{Si} \\ \mathsf{R}^{1} = \mathsf{H} \text{ or } \mathsf{Me} \end{array} \xrightarrow{1-2.5 \text{ mol } \% \text{ chiral catalyst}} (\mathsf{Alkyl})_{2}\mathsf{Zn} \text{ or } (\mathsf{Aryl})_{2}\mathsf{Zn} \text{ reagent} \xrightarrow{\mathsf{R}^{1} \\ \mathsf{SiR}_{3}} \operatorname{SiR}_{3}} \operatorname{Alkyl} \xrightarrow{\mathsf{OPO}(\mathsf{OEt})_{2}} \mathsf{OPO}(\mathsf{OEt})_{2} \\ \mathsf{R}^{1} = \mathsf{H} \text{ or } \mathsf{Me} \end{array}$$

by 1–2.5 mol% of chiral N-heterocyclic carbene based (NHCbased) catalysts and afford enantiomerically enriched allylsilanes in up to 98% *ee* and over 70% yield. Catalytic asymmetric reactions that afford tertiary as well as those that deliver quaternary Si-substituted carbon stereogenic centers are presented. To the best of our knowledge, this disclosure puts forth the first method for catalytic asymmetric synthesis of quaternary carbon stereogenic centers that bear a silyl group,^[3,4] as well as the first catalytic AAA that utilizes arylmetal reagents.^[5]

A number of protocols for catalytic enantioselective synthesis of allylsilanes have been developed. Such transformations include enantioselective couplings of 1-(silyl)-alkyl Grignard reagents with vinyl halides,^[6] hydrosilylations of 1,3-dienes,^[7] silylations of allylic chlorides,^[8] hydride additions to silyl-substituted allylic carbonates,^[9] and silaborations of allenes.^[10] These processes, all Pd-catalyzed, largely involve formation of C–Si or C–H bonds (with the exception of cross-coupling reactions)^[11] and deliver an array of synthetically useful allylsilanes in the non-racemic form. In

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many cases, however, products are obtained in less than optimal enantiomeric purity (< 90% ee). To address such complications and identify a more efficient method, we investigated the possibility of accessing allylsilanes of high enantiomeric purity through catalytic AAA of organozinc reagents to electrophilic Si-substituted alkenes [Eq. (1)]. Such transformations would be catalyzed by chiral Cu complexes generated in situ from amino acid based^[12] or bidentate NHC-based^[13,14] ligands developed in these labo-

(1)

ratories (see Scheme 1). Our interest was further fueled by the realization that, thus far, all catalytic AAA involving hard alkylmetals have been with substrates that carry a C-based substituent (i.e., versus a silyl group in this study).



Scheme 1. Chiral ligands and complexes used for in situ generation of chiral Cu-based catalysts.

We began by examining the reaction of vinylsilane **5** with Et_2Zn in the presence of amino acid based ligand **1**, shown to be highly effective in promoting Cu-catalyzed AAA of alkylzinc reagents to di- and trisubstituted alkenes.^[12c] As shown in entry 1 of Table 1, with 10 mol % **1** and 5 mol % (CuOTf)₂·C₆H₆ (-15°C, 24 h) there is only 50% conversion

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Table 1: Initial catalyst screening.^[a]

Dh		1–10 mol % chiral li	gand E	t	
ETII	5	1–5 mol % Cu salt, I THF, –15 °C, 24	Et ₂ Zn, · h	SiMe ₂ Ph	6a
Entry	Ligand; mol%	Cu salt; mol%	Conv. [%] ^[b]	$S_{N}2'/S_{N}2^{[b]}$	ee [%] ^[c]
1	1 ; 10	(CuOTf) ₂ ·C ₆ H ₆ ; 5	50	>98:2	69
2	2 ; 1	(CuOTf) ₂ ·C ₆ H ₆ ; 1	>98	>98:2	98
3	3 ; 1	(CuOTf)₂·C ₆ H ₆ ; 1	>98	>98:2	94
4	4;1	(CuOTf)₂·C ₆ H ₆ ; 1	98	>98:2	92
5	2 ; 1	(CuOTf) ₂ ·toluene; 1	>98	>98:2	98
6	2 ; 1	CuOAc; 2	70	>98:2	98
7	2 ; 1	CuCl; 2	80	>98:2	98
8	2 ; 1	Cu(OTf) ₂ ; 2	12	>98:2	70
9	2 ; 1	Cu(OAc) ₂ ; 2	20	>98:2	95
10	2 ; 1	CuCl ₂ ·2H ₂ O; 2	25	>98:2	95

[a] Reactions performed under N₂ atmosphere. [b] Conversions and S_N2'/S_N2 ratios determined by analysis of 400-MHz ¹H NMR spectra. [c] Enantioselectivities determined by chiral GLC and HPLC analysis; see the Supporting Information for details.

to the desired allylsilane; although over 98% S_N2'/S_N2 selectivity is observed, **6a** is generated in 69% *ee*. In contrast, with 1 mol% NHC·Ag^I complex $2^{[13a]}$ and 1 mol% (CuOTf)₂·C₆H₆ (entry 2, Table 1), the reaction proceeds to over 98% conversion, affording **6a**

in 98% ee (>98% S_N2'/S_N2). As illustrated in entries 3 and 4 of Table 1, complexes $\mathbf{3}^{[13b]}$ and $\mathbf{4}^{[14]}$ furnish similar reactivity and regioselectivity levels but enantioselectivities are slightly diminished (94% ee and 92% ee, respectively). Commercially available (CuOTf)₂·toluene can also be used under otherwise identical conditions to afford the desired allylsilane 6 in over 98% conversion and 98% ee (entry 5, Table 1,). Although high activity is provided by $(CuOTf)_2 \cdot C_6 H_6$, as the data in entries 6 and 7 of Table 1 indicate, air-stable CuOAc and CuCl (commercial samples, not purified) can be used to promote the catalytic AAA in 98% ee; the latter transformations, however, proceed to 70% and 80% conversion, respectively, under the same reaction conditions [vs. > 98%conv. with $(CuOTf)_2 \cdot C_6H_6$]. Finally, as the data in entries 8-10 in Table 1 show, Cu^{II} salts provide significantly activity, lower although in two instances, 6a is isolated in 95% ee.

As illustrated by the data summarized in Table 2, a range of tertiary allylsilanes (6a-e) may be

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obtained in 92–98% *ee*, with greater than 98% site-selectivity (S_N2'/S_N2) and in over 70% yields with 1–2 mol% catalyst loading. A variety of alkylmetals, including the less reactive Me₂Zn (entry 4, Table 2), heteroatom-containing (entry 5) as well as secondary (entries 7 and 8) dialkylzinc reagents may be used with high efficiency. Catalytic alkylations can be readily performed with easy-to-handle and air-stable Cu salts (entries 2, 3, and 8, Table 2); higher catalyst loadings (2 mol% 2 and 4 mol% Cu salt) are required, however, to attain complete conversion. Moreover, Cu-catalyzed AAA can be carried out in undistilled THF and on the bench top: the Cu-catalyzed AAA in entry 2 of Table 2 proceeds to afford **6a** in 98% *ee* and 79% yield under such user-friendly conditions (0.8-mmol scale).

A unique attribute of the chiral catalysts developed in these programs is the ability to promote additions to sterically congested trisubstituted olefins, furnishing quaternary carbon stereogenic centers efficiently and in high $ee^{[12a,c,d,13a-c]}$ We thus sought to determine whether chiral NHC·Cu complexes initiate efficient AAA of trisubstituted allylic phosphate **7** in spite of the increased steric hindrance projected by the Sibased substituent, an attribute that might be offset by a longer C–Si bond (vs. a C–C bond). The results of these studies, summarized in Table 3, illustrate that different dialkylzinc reagents, including the sterically demanding iPr_2Zn can be

Table 2: Cu-catalyzed enantioselective synthesis of tertiary alkyl-substituted allylsilanes.^[a]

			1–2 mol % 2	Alkyl			
	5 Frivie ₂ 5	1–2 mc T	l % Cu salt, (Alkyl)₂Zn, HF, −15 °C, 24 h	Sil	Ne ₂ Ph 6		
Entry	(Alkyl)2Zn; equiv	Cu salt	2 [mol%]; Cu salt [mol%]	Prod.	$S_N 2' / S_N 2^{[b]}$	Yield [%] ^[c]	ee [%] ^[d]
1	Et ₂ Zn; 3	(CuOTf)₂·C ₆ H ₆	1; 1	6a	>98:2	72	98
2	Et ₂ Zn; 3	CuOAc	2;4	6a	>98:2	84	95
3	Et ₂ Zn; 3	CuCl	2;4	6a	>98:2	80	92
4	Me₂Zn; 6	(CuOTf)₂·C ₆ H ₆	1; 1	6 b	>98:2	94	96
5	[AcO(CH ₂) ₄] ₂ Zn; 2	(CuOTf) ₂ ·C ₆ H ₆	1; 1	6c	>98:2	76	92
6	[Me ₂ CH(CH ₂) ₃] ₂ Zn; 2	(CuOTf)₂·C ₆ H ₆	1; 1	6 d	>98:2	74	98
7	<i>i</i> Pr ₂ Zn; 3	(CuOTf) ₂ ·C ₆ H ₆	1; 1	6e	>98:2	75	96
8	<i>i</i> Pr ₂ Zn; 3	CuOAc	2;4	6e	>98:2	75	97

[a] Reactions performed under N₂ atmosphere; > 98% conversion in all cases. [b] Conversions and S_N2'/ S_N2 ratios determined by analysis of 400-MHz ¹H NMR spectra. [c] Yields of isolated purified products. [d] Enantioselectivities determined by chiral GLC and HPLC analysis; see the Supporting Information for details.

Table 3: Cu-Catalyzed enantioselective synthesis of quaternary alkyl-substituted allylsilanes.^[a]

5	Me PhMe ₂ Si	OPO(OEt) ₂ 2.5–10	2.5–5 mol % 2 mol % Cu salt, (Alkyl) ₂ THF, –15 °C, 48 h	Alkyl Zn, Me` 8	SiMe ₂ Ph		
Entry	(Alkyl) ₂ Zn; equiv	Cu salt	2 [mol%]; Cu salt [mol%]	Prod.	$S_N 2' / S_N 2^{[b]}$	Yield [%] ^[c]	ee [%] ^[d]
1	Et ₂ Zn; 3	(CuOTf)₂·C ₆ H ₆	2.5; 2.5	8 a	>98:2	75	91
2	Et ₂ Zn; 3	CuOAc	5; 10	8 a	>98:2	87	91
3	[Me ₂ CH(CH ₂) ₃] ₂ Zn; 2	(CuOTf)₂·C ₆ H ₆	2.5; 2.5	8 d	>98:2	78	91
4	iPr ₂ Zn; 3	(CuOTf)₂·C ₆ H ₆	2.5; 2.5	8e	>98:2	81	92

[a] Reactions performed under N₂ atmosphere; > 98% conversion in all cases. [b] Conversions and S_N2′/S_N2 ratios determined by analysis of 400-MHz ¹H NMR spectra. [c] Yields of isolated purified products. [d] Enantioselectivities determined by chiral GLC and HPLC analysis; see the Supporting Information for details.

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used in the enantioselective synthesis of allylsilanes **8a**, **8d**, and **8e** in 91–92% *ee* and 75–87% yields. The corresponding achiral S_N2 product remains undetected (> 98% S_N2' by 400-MHz ¹H NMR analysis).

Next, we focused our attention on catalytic AAA involving diarylzinc reagents. Initial studies, summarized in Equation (2) indicated that, in contrast to reactions with dialkylzinc reagents, chiral NHC complex 3 is significantly more

 $\begin{array}{c} \mbox{PhMe}_2\mbox{Si} & \mbox{OPO(OEt)}_2 & \mbox{1 mol \% chiral NHC•Ag} & \mbox{Ph}_2\mbox{e}_6\mbox{H}_6, \\ \mbox{2 equiv. Ph}_2\mbox{Zn, THF, -15 °C, 24 h} & \mbox{Ph}_2\mbox{P$

9a and **11a** in 90–92% *ee* and over 80% yield as a single regioisomer (>98% S_N2'). Cu-catalyzed AAA with ($pOMeC_6H_4$)₂Zn is equally efficient and selective (entry 4, Table 4). When ($pCF_3C_6H_4$)₂Zn is employed as the alkylating agent, although the reaction remains highly efficient (1 mol% **3**, >98% conversion, 77% yield), **9c** is obtained in 57% *ee* and, for the first (and only) time, we can detect the undesired S_N2 addition product (11:1 S_N2'/S_N2).

that is optimal (>98% conversion, 67% ee). As the data in

entry 1 of Table 5 indicate, when the reaction is performed at -78 °C [vs. -15 °C in Eq. (3)], in the presence of 1 mol % 4,

12a is isolated in 72% yield and 85% ee (>98% S_N2');

The advantages that arise from availability of a range of sterically and electronically distinct chiral NHC complexes are further highlighted by the initial studies in connection with AAA of trisubstituted alkene **7** by Ph₂Zn. As shown in Equation (3), it is now chiral complex **4** (Scheme 1), recently shown to be optimal in asymmetric conjugate additions of organozinc reagents to cyclic γ -ketoesters,^[14]

effective in promoting the reaction of **5** with commercially available Ph_2Zn . Thus, in the presence of $1 \mod \%$ **3**, AAA proceeds to over 98% conversion to afford **9a** in 90% *ee* and with greater than 98% S_N2' selectivity. With NHC complex **2**,

there is only 50 % conversion, affording 9a in 65 % *ee*, and with the typically more reactive carbene complex **4**, although greater than 98 % conversion is obtained, the desired product is formed in 77 % *ee*. As illustrated in entries 1–3 of Table 4, reactions with Ph₂Zn proceed readily with 1 mol % **3** to afford the desired allylsilanes

Table 4: Cu-catalyzed AAA of diarylzinc reagents to disubstituted vinylsilanes.^[a]

		RMe ₂ Si 5 1	$POPO(OEt)_2 = \frac{1}{1-2}$ $R = Ph$ $R = Me$	1 mol % 3 2 mol % Cu salt, (Aryl) ₂ Zn, THF, –15 °C, 24 h	Aryl SiMe ₂ R 9 F 11	R = Ph R = Me		
Entry	Substrate	(Aryl) ₂ Zn; equiv	Cu salt	3 [mol%]; Cu salt [mol%]	Product	$S_N 2^\prime/S_N 2^{[b]}$	Yield [%] ^[c]	ee [%] ^[d]
1	5	Ph ₂ Zn; 2	(CuOTf)₂·C ₆ H ₆	1; 1	9a	> 98:2	82	90
2	10	Ph ₂ Zn; 2	(CuOTf) ₂ ·C ₆ H ₆	1; 1	11a	>98:2	91	92
3	10	Ph ₂ Zn; 2	CuOAc	1; 2	11a	>98:2	86	91
4	5	<i>p</i> OMeC ₆ H ₄ ; 2	(CuOTf) ₂ ·C ₆ H ₆	1; 1	9 b	>98:2	88	91
5	5	$pCF_{3}C_{6}H_{4}; 2$	(CuOTf) ₂ ·C ₆ H ₆	1; 1	9c	11:1	77	57

[a] Reactions performed under N₂ atmosphere; >98% conversion in all cases. [b] Conversions and S_N2'/S_N2 ratios determined by analysis of 400-MHz ¹H NMR spectra. [c] Yields of isolated purified products. [d] Enantioselectivities determined by chiral GLC and HPLC analysis; see the Supporting Information for details.

Table 5: Cu-catalyzed AAA of trisubstituted vinylsilanes by diarylzinc reagents.^[a]

	PhMe ₂ Si 7 OPO(OEt) ₂ 1-2.5 mol % 4 1-2.5 mol % Cu salt, (Aryl) ₂ Zn, THF Me ³ SiMe ₂ Ph 12									
Entry	(Aryl) ₂ Zn; equiv	Cu salt	4 [mol%]; Cu salt [mol%]	7 [°C];	Product	$S_{\rm N}2^\prime/S_{\rm N}2^{[b]}$	Conv. [%] ^[b] ; Yield [%] ^[c]	ee [%] ^[d]		
1	Ph₂Zn; 2	(CuOTf)₂·C ₆ H ₆	1; 1	-78; 24	12 a	>98:2	> 98 ; 72	85		
2	Ph ₂ Zn; 2	CuOAc	1; 2	-78; 24	12 a	>98:2	> 98 ; 77	84		
3	<i>p</i> OMeC ₆ H₄; 2	(CuOTf)₂·C ₆ H ₆	2.5; 2.5	-78;48	12b	>98:2	30; 25	90		
4	pOMeC ₆ H ₄ ; 2	$(CuOTf)_2 \cdot C_6H_6$	2.5; 2.5	-15; 24	12 b	>98:2	>98; 80	76		

[a] Reactions performed under N₂ atmosphere; >98% conversion in all cases. [b] Conversions and S_N2'/S_N2 ratios determined by analysis of 400-MHz ¹H NMR spectra. [c] Yields of isolated purified products. [d] Enantioselectivities determined by chiral GLC and HPLC analysis; see the Supporting Information for details.

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similar results are obtained with the more robust CuOAc (entry 2, Table 5). Catalytic AAA reactions involving ($pOMeC_6H_4$)₂Zn (entries 3 and 4, Table 5) are less efficient. Thus, at -78 °C, high enantioselectivity (90% *ee*, entry 3) is at the cost of low conversion (30% conversion, 25% yield); to achieve complete reaction, the temperature must be raised to -15 °C, an adjustment that causes diminution of selectivity (76% *ee*, entry 4 in Table 5). It is possible that the lower efficiency of the above process is partly due to stabilization of the intermediate Cu^{III} complex by the electron-donating *p*-OMe substituent (leading to a slower rate of reductive elimination)^[15] as well as the more sterically demanding olefinic site (vs. disubstituted alkenes in Table 4).

As mentioned previously, the utility of allylsilanes as chiral reagents for Lewis acid catalyzed additions to carbonyland imine-based electrophiles, is well appreciated.^[1,2] Nonetheless, additional examples are presented below. As exemplified by the reaction shown in Equation (4), tertiary allylsilanes, such as **6a** (98% *ee*), undergo catalytic cross-





metathesis in the presence of Ru catalyst 13^[16] to afford functionalized allylsilanes in high yields to afford y-substituted α,β -unsaturated carbonyls 14 [Eq. (4)] and 15. Two additional points are worthy of note: 1) Cross-metathesis reactions^[17] with PCy₃-bearing second-generation Grubbs catalyst^[18] are significantly less efficient (<40% conversion, under identical conditions). 2) Attempts to promote crossmetathesis with substrates bearing a quaternary Si-substituted carbon center proved unsuccessful (< 5% conversion, under identical conditions), a finding that points to the need for significantly more effective olefin metathesis catalysts. Another representative functionalization, involving an allylsilane with a quaternary carbon stereogenic center, is illustrated in Equation (5). Hydroboration (with 9borabicyclo[3.3.1]nonane, 9-BBN) of the terminal alkene in 8a (91% ee) proceeds smoothly to afford the corresponding enantiomerically enriched primary carbinol 16 in 80% yield. Subsequent oxidation (with N-methyl-2-pyrollidone, NMP)^[19]

Et

Mè

.OH

SiMe₂Ph

16 80% yield (91% ee)

cumene•H₂O_{2,} KH,

NMP, *n*Bu₄NF, 2 h

furnishes tertiary alcohol **17** with greater than 98% retention of stereochemistry and in 80% yield.

We thus introduce an efficient catalytic method for enantioselective synthesis of allylsilanes, including those that contain a quaternary Si-substituted carbon stereogenic center. The present study further underlines the rapidly emerging and significant utility of chiral bidentate NHC complexes in asymmetric catalysis and enantioselective synthesis. These investigations illustrate the significance of the availability of a diverse set of chiral NHCs to the development of catalytic asymmetric alkylations that can be effected on a range of substrates and with alkyl- as well as arylmetal nucleophiles.^[20]

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- [1] For utility of allylsilanes in organic synthesis, see:
 a) C. E. Masse, J. S. Panek, *Chem. Rev.* 1995, 95, 1293–1316; b) I. Fleming, A. Barbero, D. Walter, *Chem. Rev.* 1997, 97, 2063–2192; c) A. Barbero, F. J. Pulido, *Acc. Chem. Res.* 2004, 37, 817–825; For a recent diastereoselective method for synthesis of enantiomerically enriched allylsilanes, see: d) E. S. Schmidtmann, M. Oestrich, *Chem. Commun.* 2006, 3643–3645; For recent applications of a chiral enantiomerically pure allylsilane in organic synthesis, see: e) P. Va, W. R. Roush, *J. Am. Chem. Soc.* 2006, *128*, 15960–15961; f) A. K. Franz, P. D. Dreyfuss, S. L. Schreiber, *J. Am. Chem. Soc.* 2007, *129*, 1020–1021.
- [2] For an overview of recent advances in catalytic asymmetric allylic alkylation reactions, see: H. Yorimitsu, K. Oshima, *Angew. Chem.* 2005, 117, 4509– 4513; *Angew. Chem. Int. Ed.* 2005, 44, 4435–4439.
- [3] Quaternary Stereocenters: Challenges and Solutions for Organic Synthesis (Eds: J. Christophers, A. Baro),
 Wiley-VCH, Weinheim, 2006.
- [4] For diastereoselective synthesis of quaternary carbon centers bearing a Si substituent, see: a) J.-N. Heo, G. C. Micalizio, W. R. Roush, Org. Lett. 2003, 5, 1693–1696; b) B. M. Trost, Z. T. Ball, E.-J. Kang, Org. Lett. 2005, 7, 4911–4913.
- [5] In one case, Cu-catalyzed AAA of mixed alkyl–arylzinc reagents (Ph₂Zn + Me₂Zn or Et₂Zn) to a *meso*-bis(diethyl phosphate) was reported (\leq 78% *ee*). See: U. Piarulli, P. Daubos, C. Claverie, C. Monti, C. Gennari, *Eur. J. Org. Chem.* **2005**, 895–906.
- [6] a) T. Hayashi, M. Konishi, H. Ito, M. Kumada, J. Am. Chem. Soc.
 1982, 104, 4962–4963; b) T. Hayashi, M. Konishi, Y. Okamoto,
 K. Kabeta, M. Kumada, J. Org. Chem. 1986, 51, 3772–3781.
- [7] a) T. Hayashi, K. Kabeta, T. Yamamoto, K. Tamao, M. Kumada, *Tetrahedron Lett.* 1983, 24, 5661–5664; b) T. Hayashi, J. W. Han, A. Takeda, J. Tang, K. Nohmi, K. Mukaide, H. Tsuji, Y. Uozumi, *Adv. Synth. Catal.* 2001, 343, 279–283.
- [8] T. Hayashi, A. Ohno, S. Lu, Y. Matsumoto, E. Fukuyo, K. Yanagi, J. Am. Chem. Soc. 1994, 116, 4221–4226.
 - [9] a) T. Hayashi, H. Iwamura, Y. Uozumi, *Tetrahedron Lett.* **1994**, *35*, 4813–4816; For an overview, see: b) T. Hayashi, *Acc. Chem. Res.* **2000**, *33*, 354–362.
 - [10] T. Ohmura, H. Taniguchi, M. Suginome, J. Am. Chem. Soc. 2006, 128, 13682–13683.

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9-BBN, THF, 1 h:

H₂O₂, NaOH, 0.5 h

Et

Mè

SiMe₂Ph

8a (91% ee)

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17 80% yield (91% ee)

(5)

Et

Mề ÔH

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- [11] Enantiomerically enriched cyclic allylsilanes can be synthesized through asymmetric ring-closing metathesis. See: A. F. Kiely, J. A. Jernelius, R. R. Schrock, A. H. Hoveyda, *J. Am. Chem. Soc.* 2002, 124, 2868–2869.
- [12] a) C. A. Luchaco-Cullis, H. Mizutani, K. E. Murphy, A. H. Hoveyda, *Angew. Chem.* 2001, *113*, 1504–1507; *Angew. Chem. Int. Ed.* 2001, *40*, 1456–1460; b) K. E. Murphy, A. H. Hoveyda, *J. Am. Chem. Soc.* 2003, *125*, 4690–4691; c) M. A. Kacprzynski, A. H. Hoveyda, *J. Am. Chem. Soc.* 2004, *126*, 10676–10681; d) K. E. Murphy, A. H. Hoveyda, *Org. Lett.* 2005, *7*, 1255–1258; For a related catalytic AAA involving an amino acid based chiral catalyst, see: e) U. Piarulli, P. Daubos, C. Claverie, M. Roux, C. Gennari, *Angew. Chem.* 2003, *115*, 244–246; *Angew. Chem. Int. Ed.* 2003, *42*, 234–236.
- [13] a) A. O. Larsen, W. Leu, C. Nieto-Oberhuber, J. E. Campbell, A. H. Hoveyda, J. Am. Chem. Soc. 2004, 126, 11130-11131;
 b) J. J. Van Veldhuizen, J. E. Campbell, R. E. Giudici, A. H. Hoveyda, J. Am. Chem. Soc. 2005, 127, 6877-6882; c) Y. Lee, A. H. Hoveyda, J. Am. Chem. Soc. 2006, 128, 15604-15605;
 d) D. G. Gillingham, A. H. Hoveyda, Angew. Chem. 2007, DOI: 10.1002/ange.200700501; Angew. Chem. Int. Ed. 2007, DOI: 10.1002/anie.200700501, in press; For other NHC-catalyzed

AAA reactions, see: e) S. Tominaga, Y. Oi, T. Kato, D. K. An, S. Okamoto, *Tetrahedron Lett.* **2004**, *45*, 5585–5588; f) S. Okamoto, S. Tominaga, N. Saino, K. Kase, K. Shimoda, *J. Organomet. Chem.* **2005**, *690*, 6001–6007.

- [14] M. K. Brown, T. L. May, C. A. Baxter, A. H. Hoveyda, Angew. Chem. 2007, 119, 1115–1118; Angew. Chem. Int. Ed. 2007, 46, 1097–1100.
- [15] J.-E. Bäckvall, M. Sellén, B. Grant, J. Am. Chem. Soc. 1990, 112, 6615–6621.
- [16] S. B. Garber, J. S. Kingsbury, B. L. Gray, A. H. Hoveyda, J. Am. Chem. Soc. 2000, 122, 8168–8179.
- [17] For a review of catalytic cross-metathesis reactions, see: S. J. Connon, S. Blechert, Angew. Chem. 2003, 115, 1944–1968; Angew. Chem. Int. Ed. 2003, 42, 1900–1923.
- [18] M. Scholl, S. Ding, C. W. Lee, R. H. Grubbs, Org. Lett. 1999, 1, 953–956.
- [19] Z.-H. Peng, K. A. Woerpel, Org. Lett. 2002, 4, 2845-2948.
- [20] For a discussion regarding the significance of catalyst diversity, see: A. H. Hoveyda, *Handbook of Combinatorial Chemistry* (Eds: K. C. Nicolaou, R. Hanko, W. Hartwig), Wiley-VCH, Weinheim, **2002**, pp. 991–1016.