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Allylcopper Intermediates with N-Heterocyclic Carbene Ligands: Synthesis, Structure, and Catalysis

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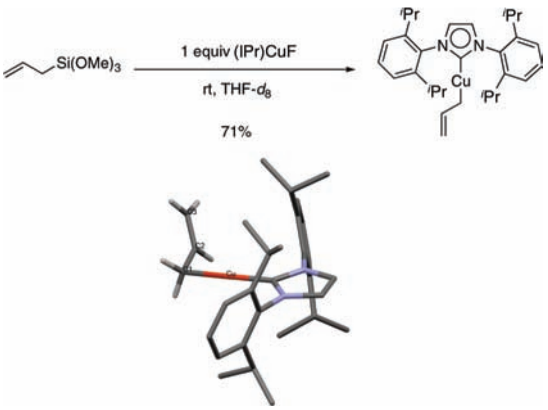
ABSTRACT



Allylcopper intermediates with N-heterocyclic carbene ligands are synthesized by transmetalation of allylsiloxane reagents, and the crystal structures of allylcopper compounds are reported. The allylcopper transmetalation is utilized for catalytic aldehyde allylation, which is found to be facilitated by a trifluorosilane co-catalyst.

Allylcopper organometallics have an extensive history as reactive intermediates in synthetic chemistry. Allylcopper species exhibit reactivity unique from that of alkyl or aryl organometallics, such as altered regioselectivity.[1] Allylcopper reagents have been employed in stoichiometric and catalytic transformations.[2] Understanding the chemistry of organocopper reagents, and of allylcopper reagents in particular, is challenging because typical organocuprate reagents exist as complex aggregates in solution.[3] The reactivity of allylcopper(I) reagents has been examined, but little structural information has been reported apart from limited NMR studies;[4] we are not aware of any published crystal structure of an allylcopper species.

As part of a program to develop synthetic methods that allow catalytic access to organocopper intermediates from organosilane reagents,[5] we here examine the use of allylsilanes as precursors to *N*-heterocyclic-carbene-ligated allylcopper intermediates.[6] We present the first crystal structure

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(1) (a) Lipshutz, B. H.; Hackmann, C. *J. Org. Chem.* **1994**, *59*, 7437–7444. (b) Hutchinson, D. K.; Fuchs, P. L. *Tetrahedron Lett.* **1986**, *27*, 1429–1432.

(2) (a) Wada, R.; Shibuguchi, T.; Makino, S.; Oisaki, K.; Kanai, M.; Shibasaki, M. *J. Am. Chem. Soc.* **2006**, *128*, 7687–7691. (b) Kondo, J.; Inoue, A.; Shinokubo, H.; Oshima, K. *Tetrahedron Lett.* **2002**, *43*, 2399–2402. (c) Hojo, M.; Harada, H.; Murakami, C.; Hosomi, A. *J. Chem. Soc., Chem. Commun.* **1994**, 2687–2688.

(3) (a) Hope, H.; Olmstead, M. M.; Power, P. P.; Sandell, J.; Xu, X. *J. Am. Chem. Soc.* **1985**, *107*, 4337–4338. (b) Lorenzen, N. P.; Weiss, E. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 300–302.

(4) (a) Merchan, M.; Gonzalez-Luque, R.; Nebot-Gil, I.; Tomas, F. *Chem. Phys. Lett.* **1985**, *114*, 516–519. (b) Lipshutz, B. H.; Ellsworth, E. L.; Dimock, S. H.; Smith, R. A. J. *J. Am. Chem. Soc.* **1990**, *112*, 4404–4410. (c) Karlström, A. S.; Bäckvall, J. E. *Chem.—Eur. J.* **2001**, *7*, 1981–1989. (d) Yamanaka, M.; Kato, S.; Nakamura, E. *J. Am. Chem. Soc.* **2004**, *126*, 6287–6293. (e) Bartholomew, E. R.; Bertz, S. H.; Cope, S.; Murphy, M.; Ogle, C. A. *J. Am. Chem. Soc.* **2008**, *130*, 11244–11245.

(5) (a) Herron, J. R.; Russo, V.; Valente, E. J.; Ball, Z. T. *Chem.—Eur. J.* **2009**, *15*, 8713–8716. (b) Herron, J. R.; Ball, Z. T. *J. Am. Chem. Soc.* **2008**, *130*, 16486–16487.

10.1021/ol902458v

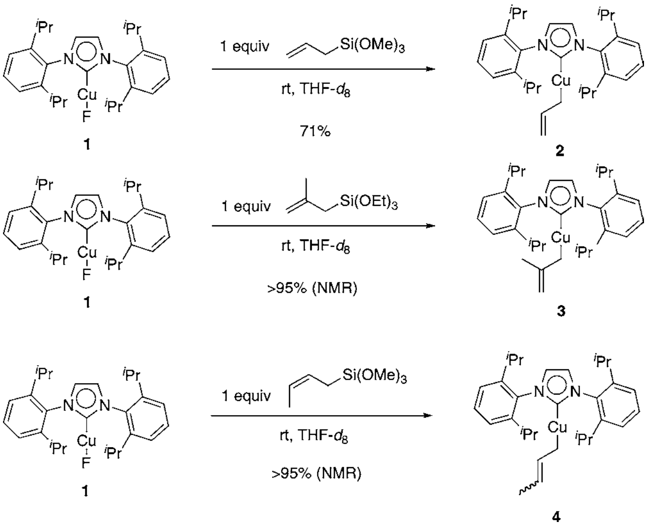
analysis of allylcopper compounds and develop a catalytic aldehyde allylation process based on these intermediates.

The allylation of aldehydes is an important reaction that allows the formation of homoallylic alcohols. Catalytic allylation utilizes allylmetalloids such as those of boron, silicon, and tin.[7] Mechanistically, most catalytic processes involve aldehyde activation.[8] Alternatively, Lewis base methods for allylsilane activation have been described.[9] A final mechanistic possibility, transmetalation to a new reactive organometallic, is also possible but has generally been less studied beyond stoichiometric examples.[10] Palladium complexes with pincer ligands have been shown to catalyze allylation of allylstannanes by a transmetalation mechanism.[11] Other selective allylation reactions have been reported, including those of copper and silver, for which there exists at least some evidence of transmetalation pathways.[12]

The fluoride complex, (IPr)CuF (IPr = 1,3-bis(2′,6′-diisopropylphenyl)imidazol-2-ylidene), is a stable complex that allows access to organocopper compounds upon treatment with organosiloxanes containing transferable groups, affording complexes that are challenging to access by alternative methods.

It is possible to employ this methodology in the synthesis of allylcopper species. When a stoichiometric amount of an allylsilane is added to (IPr)CuF in THF-d_8 (Scheme 1), the formation of an allylcopper species **2** can be observed in less than 5 min by ^{1}H NMR, where peaks at δ 6.43 (quint, 1H) and δ 3.09 (d, 4H) ppm correspond to an allyl unit in fast exchange between η^1 and η^3 coordination modes. In variable-temperature NMR experiments with complex **2**, significant line broadening occurred below −60 °C, but no static structure was observed upon cooling to −90 °C.

Scheme 1. Synthesis of Allylcopper Species



The NMR spectrum of the 2-methallylcopper complex **3** is also consistent with fast exchange between η^1 and η^3 coordination modes, exhibiting two singlet resonances at δ 2.14 (4H) and δ 1.09 (3H) ppm. On the basis of subsequent X-ray structural data (see below), it is likely that the η^1 structure is the lower-energy isomer in solution. A previous NMR study of allylic cuprates reported data consistent with an η^1 complex,[13] rather than the dynamic structures observed here with neutral allylcopper species. Finally, the crotylsilane reagent reacts with (IPr)CuF, affording an organocopper complex **4** with a ^{1}H NMR spectrum containing four peaks for an allylcopper complex at δ 5.39 (1H), 3.93 (1H), 0.99 (3H), and 0.59 (2H) ppm.

Although stable for hours in solution (THF) at room temperature, the substituted complexes **3** and **4** are significantly less stable than the parent allyl complex **2**, and we have been unable to isolate complexes **3** or **4** in reasonable yield. However, it is possible to grow single crystals of the complexes **2** and **3** suitable for X-ray diffraction by diffusional recrystallization in THF/pentane at −35 °C. The X-ray structures of compounds **2** and **3** (Figure 1) show that both complexes crystallize in the η^1 coordination mode, without significant interaction between the metal and the π system.

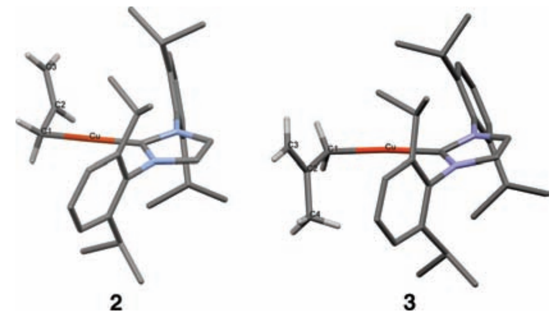


Figure 1. X-ray structure of complexes **2** and **3**.

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(6) For examples of NHC−copper complexes and their use in catalysis, see: (a) Jurkauskas, V.; Sadighi, J. P.; Buchwald, S. L. *Org. Lett.* **2003**, *5*, 2417–2420. (b) Mankad, N. P.; Laitar, D. S.; Sadighi, J. P. *Organometallics* **2004**, *23*, 3369–3371. (c) Kaur, H.; Zinn, F. K.; Stevens, E. D.; Nolan, S. P. *Organometallics* **2004**, *23*, 1157–1160. (d) Laitar, D. S.; Tsui, E. Y.; Sadighi, J. P. *J. Am. Chem. Soc.* **2006**, *128*, 11036–11037. (e) Blue, E. D.; Davis, A.; Conner, D.; Gunnoe, T. B.; Boyle, P. D.; White, P. S. *J. Am. Chem. Soc.* **2003**, *125*, 9435–9441. (f) Goj, L. A.; Blue, E. D.; Delp, S. A.; Gunnoe, T. B.; Cundari, T. R.; Petersen, J. L. *Organometallics* **2006**, *25*, 4097–4104. (g) Delp, S. A.; Munro-Leighton, C.; Goj, L. A.; Ramirez, M. A.; Gunnoe, T. B.; Petersen, J. L.; Boyle, P. D. *Inorg. Chem.* **2007**, *46*, 2365–2367. (h) Lebel, H.; Davi, M.; Diez-Gonzalez, S.; Nolan, S. P. *J. Org. Chem.* **2006**, *72*, 144–149.

(7) Denmark, S. E.; Almstead, N. G. In *Modern Carbonyl Chemistry*; Otera, J., Ed.; Wiley-VCH: Weinheim, 2000.

(8) (a) Denmark, E. S.; Wilson, T.; Willson, T. M. *J. Am. Chem. Soc.* **1988**, *110*, 984–986. (b) Denmark, E. S.; Almstead, N. G. *J. Am. Chem. Soc.* **1993**, *115*, 3133–3139.

(9) (a) Denmark, S. E.; Coe, D. M.; Pratt, N. E.; Griedel, B. D. *J. Org. Chem.* **1994**, *59*, 6161–6163. (b) Denmark, S. E.; Fu, J. *J. Am. Chem. Soc.* **2000**, *122*, 12021–12022. (c) Denmark, S. E.; Wynn, T. *J. Am. Chem. Soc.* **2001**, *123*, 6199–6200. (d) Denmark, S. E.; Fu, J. *Chem. Rev.* **2003**, *103*, 2763–2793.

(10) Lipshutz, B. H.; Crow, R.; Dimock, S. H.; Ellsworth, E. L. *J. Am. Chem. Soc.* **1990**, *112*, 4063–4064.

(11) (a) Solin, N.; Kjellgren, J.; Szabó, K. J. *Angew. Chem., Int. Ed.* **2003**, *42*, 3656–3658. (b) Wallner, O. A.; Szabó, K. J. *Chem.—Eur. J.* **2006**, *12*, 6976–6983.

(12) (a) Wadamoto, M.; Yamamoto, H. *J. Am. Chem. Soc.* **2005**, *127*, 14556–14557. (b) Yamasaki, S.; Fujii, K.; Wada, R.; Kanai, M.; Shibasaki, M. *J. Am. Chem. Soc.* **2002**, *124*, 6536–6537.

(13) Lipshutz, B. H.; Ellsworth, E. L.; Dimock, S. H.; Smith, R. A. J. *J. Org. Chem.* **1989**, *54*, 4977–4979.

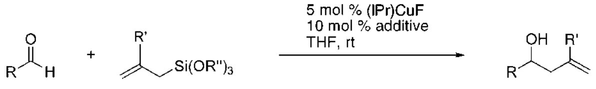
The crystal structures of **2** and **3** exhibit dihedral angles for the allyl ligand (Cu−C1−C2═C3) of 108.0° and 103.0°, respectively. These dihedral angles are consistent with hyperconjugative interactions previously discussed for (η^1-allyl)palladium complexes.[14] In addition, the allyl units have C2═C3 bond lengths of 1.306 and 1.278 Å, similar to that expected for a free double bond. The lack of intermolecular interactions in the solid state provides evidence that these allylcopper species are likely monomeric in solution as well, in contrast to many organocuprates.[3]

(IPr)CuF (**1**) catalyzes the allylation of allyltrimethoxysilane with octanal. A preliminary screening of solvents was conducted, and tetrahydrofuran was found to provide the highest yields. Unfortunately, the efficiency of catalytic reactivity with this initial result was quite limited: extension of the reaction to other aldehydes or to the substituted allylsilanes was unproductive (Table 1, entries 3, 4). The lower reactivity of methallyl silanes is in contrast to the inherent nucleophilicity of more electron-rich methallyl species relative to unsubstituted allylmetals. We examined additives that might improve the efficiency and generality of the catalytic process. Because stoichiometric examinations had convinced us that transmetalation is a fast process with allylsiloxanes, we examined a variety of metal salts with the hope that Lewis acids might facilitate the C−C bond-forming step (Table 1). In a screen of Lewis acid additives, lithium salts provided no benefit, but some lanthanide triflate salts did allow low yields of allylation product (entries 8−10). In a search for Lewis acids that would be soluble in aprotic solvent and would not prevent turnover of the copper catalyst, we examined the use of trifluorosilanes.[15] Remarkably, a great improvement in reactivity is obtained when using octyltrifluorosilane as an additive. This result has proven general, allowing clean catalytic reactivity with substrates that are unproductive without the trifluorosilane.

The role of a trifluorosilane additive in the catalytic process remains unclear. After the discovery of this additive, an NMR experiment demonstrated that allylcopper complexes formed in situ do react smoothly with aldehydes within minutes at room temperature. Furthermore, additional allylsilane can be added after 1,2-addition, regenerating the allylcopper complex, all without the need for a trifluorosilane additive. Thus all steps on the catalytic cycle appear kinetically competent, but the catalytic system does not function in the absence of additive. This may point to a role of trifluorosilane additives in increasing turnover rate by increasing fluoride concentration, in thwarting catalyst-kill events, or in allowing an inactive catalyst form to be reintroduced in the catalytic cycle.

We have verified that trifluorooctylsilane alone does not catalyze the reactions. We have also considered the possibility that the trifluorooctylsilane might serve as a dehydrating agent or alternatively as a source of water, but rigorous exclusion of water or addition of small quantities of water both fail to produce a beneficial result.

Table 1. Allylations of Aldehydes with 5 mol % (IPr)CuF[a]



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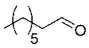
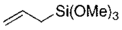
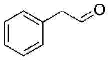
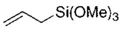
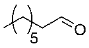
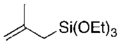
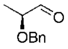
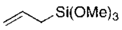
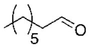
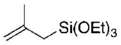
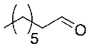
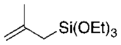
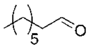
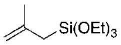
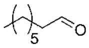
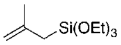
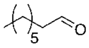
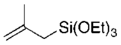
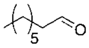
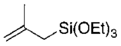
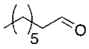
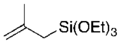
1			-	85
2			-	42
3			-	-
4			-	-
5			LiBF$_4$	-
6			LiPF$_6$	-
7			LiOTf	-
8			In(OTf)$_3$	17
9			La(OTf)$_3$	13
10			Eu(OTf)$_3$	9
11			(*n*-octyl)SiF$_3$	72

[a] The reaction time was 48 h. [b] Isolated yield after column chromatography. [c] Yields were determined by NMR spectroscopy, using 1,4-dimethoxybenzene as an internal standard (entries 5−9).

Using the silicon trifluoride additive to enhance the reactivity of the allylcopper species, we studied the reaction of five different aldehydes with allyltrimethoxysilane, (2-methylallyl)triethoxysilane, and (*Z*)-crotyltrimethoxysilane (Tables 2 and 3 and Scheme 2). The reaction succeeds even with the readily enolized substrate phenylacetaldehyde (Table 2, entries 3, 4; Table 3, entry 2). With a (*Z*)-crotylsilane, modest preference for products with the 1,2-*anti* stereochemistry is observed. This stereochemical outcome is consistent with an open transition state.[7] The terminal olefin products of S_E2' addition are observed exclusively, despite the conformational lability of the allylcopper intermediate.

Diastereoselectivity was unaltered when the (*E*)-crotyltrimethoxysilane was used, consistent with our observation that the allylcopper intermediate participates in fast $\eta^1-\eta^3$ interconversion.

A chiral aldehyde, 2-benzyloxypropionaldehyde, was also examined (Scheme 2). Efficient allylation does occur

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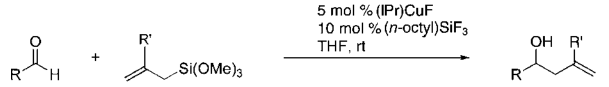
(14) Szabó, K. J. *Chem.—Eur. J.* **2000**, *6*, 4413–4421.

(15) For a recent example of trifluorosilanes as reagents in organocopper chemistry, see: Lee, K.; Hoveyda, A. H. *J. Org. Chem.* **2009**, *74*, 4455–4462.

Table 2. Allylations of Aldehydes with a Trifluorosilance Additive



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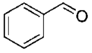
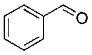
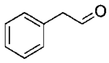
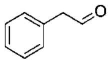
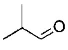
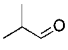
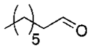
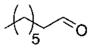
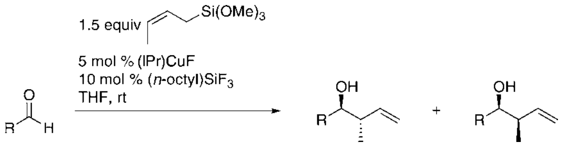
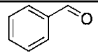
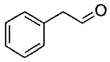
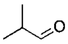
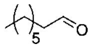
1		H	81
2		Me	75
3		H	73
4		Me	72
5		H	56
6		Me	65
7		H	88
8		Me	72

[a] When R′ = Me, the silane is -Si(OEt)$_3$. [b] Isolated yield after column chromatography and/or Kügelrohr distillation.

with this substrate, and consistent with the low Lewis acidity of the organocopper intermediate, the major isomer is that of nonchelate, Felkin−Ahn selectivity.[16] However, poor selectivities are observed with all three allylic nucleophiles. The reaction between 2-benzyloxypropanal and crotyltrimethoxysilane generates a mixture of four diastereomers, of which only three were observed in appreciable yield (Scheme 2).

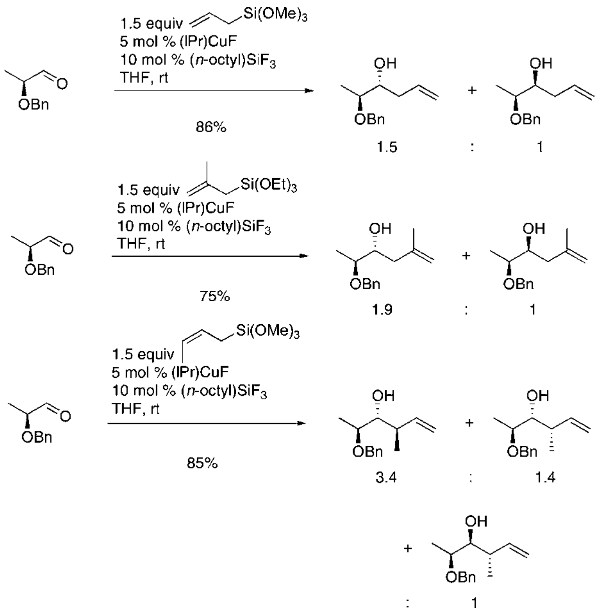
Table 3. Diastereoselective Allylation of Aldehydes with Crotyltrimethoxysilane



entry	aldehyde	yield (%)[a]	anti/syn[b]
1		78	2:1
2		66	2.5:1
3		61	4:1
4		79	3:1

[a] Isolated yields of pure compounds. [b] The syn/anti ratio was determined by ^{1}H and ^{13}C NMR spectroscopy.

Scheme 2. Catalytic Allylation of a Chiral Aldehyde[a]



[a] Isolated yield, syn/anti ratio determined by NMR spectroscopy and/or GC/MS.

We have demonstrated a synthetic approach to NHC−allylcopper complexes and report the first crystal structures of allylcopper species. The complex (IPr)CuF can be employed for the catalytic allylation of aldehydes with allylsilanes by a transmetalation mechanism, and a trifluorosilane additive was discovered to significantly facilitate this process. We intend to use this study as a launching pad for the development of other catalytic reactions of allylcopper intermediates and to extend this study to enantioselective allylation reactions using chiral ligands.

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Supporting Information Available: Experimental details and spectroscopic and analytical data for all compounds studied. This material is available free of charge via the Internet at http://pubs.acs.org.

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(16) Anh, N. T.; Eisenstein, O. *Nouv. J. Chim.* **1977**, *1*, 61–70.