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# Monodentate Non-$C_2$-symmetric Chiral *N*-Heterocyclic Carbene Complexes for Enantioselective Synthesis. Cu-Catalyzed Conjugate Additions of Aryl- and Alkenylsilylfluorides to Cyclic Enones

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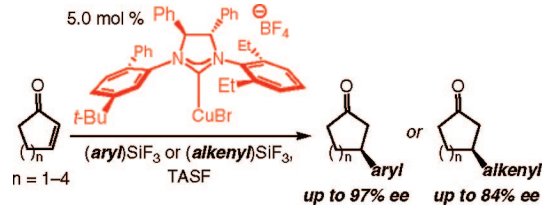


A new class of enantioselective conjugate addition (ECA) reactions that involve aryl- or alkenylsilyl fluoride reagents and are catalyzed by chiral non-$C_2$-symmetric Cu-based *N*-heterocyclic carbene (NHC) complexes are disclosed. Transformations have been designed based on the principle that a catalytically active chiral NHC−Cu−aryl or NHC−Cu−alkenyl complex can be accessed from reaction of a Cu−halide precursor with in situ-generated aryl- or alkenyltetrafluorosilicate. Reactions proceed in the presence of 1.5 equiv of the aryl- or alkenylsilane reagents and 1.5 equiv of tris(dimethylamino)sulfonium difluorotrimethylsilicate (TASF). Desired products are isolated in 63−97% yield and 73.5:26.5−98.5:1.5 enantiomeric ratio (47%−97% ee). A major focus of the present studies is the design, evaluation, and development of new chiral imidazolinium salts and their derived NHC−Cu complexes as catalysts that promote reactions of various carbosilanes to a range of electrophilic substrates. Toward this end, nearly 20 new chiral monodentate imidazolinium salts, most of which are non-$C_2$-symmetric, have been prepared and fully characterized and their ability to serve as catalysts in the ECA reactions has been investigated.

## Introduction

The emergence of *N*-heterocyclic carbenes (NHCs) has had a notable impact on the development of a variety of catalytic transformations.[1,2] Research in these laboratories has focused on the design and development of a number of chiral bidentate NHC-based Ru,[3] Cu,[4] and Mg[5] complexes. The derived Cu-based systems promote conjugate addition and allylic alkylation reactions in high enantioselectivity; in all such processes, metal-based nucleophiles, such as Grignard, dialkyl- or diarylzinc, or trialkyl- or dialkylarylaluminum reagents are used. We have more recently turned our attention toward identification and development of chiral NHC−Cu complexes that catalyze C−C bond-forming reactions with the more functional group tolerant and less moisture- and oxygen-sensitive organosilanes (vs the aforementioned alkylmetal reagents).

Herein, we detail the development of a Cu-catalyzed enantioselective conjugate addition (ECA) process[6] that involves easily accessible aryl- or vinyltrifluorosilanes (eq 1). Transformations can be performed with five-, six-, seven-, and eight-membered ring cyclic enones ($n = 1-4$, eq 1), furnishing the desired $\beta$-aryl- and $\beta$-alkenyl cyclic ketones in up to 98.5:1.5 and 96:4 enantiomeric ratio (er), respectively. The present

(1) For recent reviews on *N*-heterocyclic carbenes as catalysts in organic synthesis, see: (a) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606–5655. (b) Marion, N.; Díez-González, S.; Nolan, S. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 2988–3000.

(2) For representative reviews on *N*-heterocyclic carbenes as ligands in metal-catalyzed processes, see: (a) Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Angew. Chem., Int. Ed.* **2007**, *46*, 2768–2813. (b) Gade, L. H.; Bellemin-Laponnaz, S. *Top. Organomet. Chem.* **2007**, *21*, 117–157. (c) Tekavec, T. N.; Louie, J. *Top. Organomet. Chem.* **2007**, *21*, 159–192.

(3) (a) Van Veldhuizen, J. J.; Garber, S. B.; Kingsbury, J. S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2002**, *124*, 4954–4955. (b) Van Veldhuizen, J. J.; Gillingham, D. G.; Garber, S. B.; Kataoka, O.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2003**, *125*, 12502–12508. (c) Gillingham, D. G.; Kataoka, O.; Garber, S. B.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2004**, *126*, 12288–12290. (d) Van Veldhuizen, J. J.; Campbell, J. E.; Giudici, R. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2005**, *127*, 6877–6882. For an overview, see: (e) Hoveyda, A. H.; Gillingham, D. G.; Van Veldhuizen, J. J.; Kataoka, O.; Garber, S. B.; Kingsbury, J. S.; Harrity, J. P. A. *Org. Biomol. Chem.* **2004**, *2*, 8–23.

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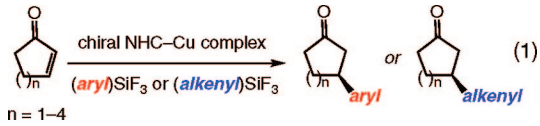
investigations have led us to design, prepare, and examine approximately 20 new non-$C_2$-symmetric chiral imidazolinium salts, utilized to access the derived monodentate NHC−Cu complexes. It should be noted that although Pd-[7,8] and Rh-catalyzed[9,10] conjugate additions of organosilanes, including the related enantioselective protocols, have been reported previously, this disclosure puts forward the first examples of Cu-catalyzed variants of this class of transformations.[11]

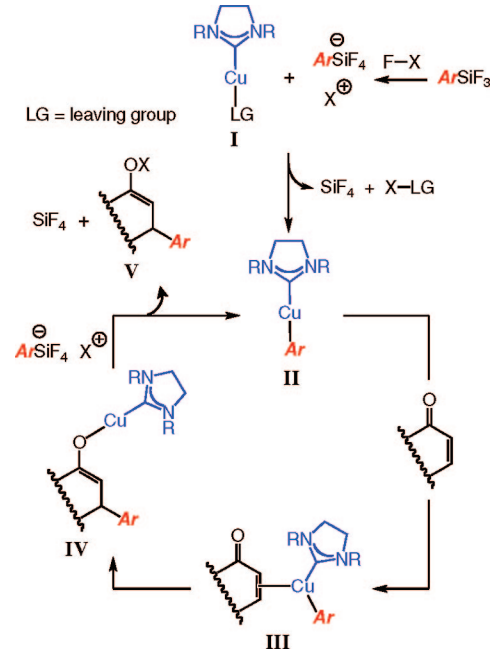



Design, synthesis, and examination of catalytic activity of easily accessible and readily modifiable chiral NHC complexes that can be used in enantioselective synthesis is a principal impetus for carrying out the investigations described in this report. Identification of an efficient set of protocols that allows for efficient activation of aryl- as well as alkenylsilanes by NHC-based catalysts serves as another main objective. We surmised that once the appropriate class of chiral catalysts and methods for use of the Si-based reagents are identified and established, a number of C−C bond-forming protocols involving several types of electrophiles (e.g., carbonyls or imines) would follow. Catalytic ECA reactions with cyclic enones were, therefore, selected to serve as a platform for exploring the utility of NHC-based catalysts to promote enantioselective C−C bond-forming reactions with organosilanes.

## Results and Discussion

**1. Mechanistic Considerations.** We began by envisioning a plausible pathway through which an NHC−Cu complex might promote conjugate addition of an organosilane to an enone. We surmised that reaction of an NHC−Cu complex (**I**, Scheme 1), wherein the transition metal is bound to an effective leaving group (e.g., a halide), with an in situ-generated hypervalent[12] tetrafluoroaryl silicate, can give rise to the derived NHC−Cu−aryl complex **II** (Scheme 1).[13] As shown in Scheme 1, the requisite pentavalent aryl silicate would be obtained through reaction of a trifluoroaryl silane and an appropriate fluorinating agent. Association of the Lewis acidic NHC−Cu with the α,β-

**SCHEME 1. Plausible Pathway for Conjugate Addition of $ArSiF_3$ Catalyzed by an NHC−Cu Complex**




(4) For application of bidentate NHC−Cu complexes, developed in these laboratories, to catalytic enantioselective allylic alkylations and conjugate additions, see: (a) Larsen, A. O.; Leu, W.; Nieto-Oberhuber, C.; Campbell, J. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2004**, *126*, 11130–11131. (b) Lee, K-s.; Brown, M. K.; Hird, A. W.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2006**, *128*, 7182–7184. (c) Reference 3d. (d) Brown, M. K.; May, T. L.; Baxter, C. A.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2007**, *46*, 1097–1100. (e) Kacprzynski, M. A.; May, T. L.; Kazane, S. A.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2007**, *46*, 4554–4558. (f) Lee, Y.; Akiyama, K.; Gillingham, D. G.; Brown, M. K.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2008**, *130*, 446–447. (g) May, T. L.; Brown, M. K.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2008**, *47*, 7468–7472. (h) Brown, M. K.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2008**, *130*, 12904–12906. For related developments from other laboratories, see: (i) Arnold, P.; Rodden, M.; Davis, K. M.; Scarisbrick, A. C.; Blake, A. J.; Wilson, C. *Chem. Commun.* **2004**, 1612–1613. (j) Clavier, H.; Coutable, L.; Toupet, L.; Guillemin, J.-C.; Mauduit, M. *J. Organomet. Chem.* **2005**, *690*, 5237–5254. (k) Martin, D.; Kehrli, S.; d'Augustin, M.; Clavier, H.; Mauduit, M.; Alexakis, A. *J. Am. Chem. Soc.* **2006**, *128*, 8416–8417. For application of the same class of chiral bidentate NHC complexes to enantioselective hydroboration, see: (l) Lee, Y.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 3160–3161.

(5) Lee, Y.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2006**, *128*, 15604–15605.

(6) For recent reviews on enantioselective conjugate addition reactions involving organometallic nucleophilic reagents, see: (a) Krause, N.; Hoffmann-Röder, A. *Synthesis* **2001**, 171–196. (b) Feringa, B. L., Naaz, R.; Imbos, R.; Arnold, N. A, In *Modern Organocopper Chemistry*; Krause, N., Ed.; Wiley-VCH: Weinheim, 2002; pp 224−258. (c) López, F.; Minnaard, A. J.; Feringa, B. L. *Acc. Chem. Res.* **2007**, *40*, 179–188. (d) Harutyunyan, S. R.; den Hartog, T.; Geurts, K.; Minnaard, A. J.; Feringa, B. L. *Chem. Rev.* **2008**, *108*, 2824–2852. (e) Alexakis, A.; Bäckvall, J. E.; Krause, N.; Pàmies, O.; Diéguez, M. *Chem. Rev.* **2008**, *108*, 2796–2823. (f) von Zezschwitz, P. *Synthesis* **2008**, 1809–1831. (g) Gutnov, A. *Eur. J. Org. Chem.* **2008**, 4547–4554. (h) Yamamoto, Y.; Nishikata, T.; Miyaura, N. *Pure Appl. Chem.* **2008**, *80*, 807–817.

(7) For non-enantioselective Pd-catalyzed conjugate additions with arylsiloxanes, see: (a) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Chem. Lett.* **2003**, 752–753. (b) Denmark, S. E.; Amishiro, N. *J. Org. Chem.* **2003**, *68*, 6997–7003. (c) Gini, F.; Hessen, B.; Feringa, B. L.; Minnaard, A. J. *Chem. Commun.* **2007**, 710–712. (d) Lerebours, R.; Wolf, C. *Org. Lett.* **2007**, *9*, 2737–2740.

(8) For Pd-catalyzed ECA reactions involving aryl- or alkenylsilanes, see: Nishikata, T.; Yamamoto, Y.; Gridnev, I. D.; Miyuara, N. *Organometallics* **2005**, *24*, 5025–5032.

(9) For non-enantioselective Rh-catalyzed conjugate addition reactions with arylsiloxanes, see: (a) Mori, A.; Danda, Y.; Fujii, T.; Hirabayashi, K.; Osakada, K. *J. Am. Chem. Soc.* **2001**, *123*, 10774–10775. (b) Huang, T.-S.; Li, C.-J. *Chem. Commun.* **2001**, 2348–2349. (c) Oi, S.; Honma, Y.; Inoue, Y. *Org. Lett.* **2002**, *4*, 667–669. (d) Koike, T.; Du, X.; Mori, A.; Osakada, K. *Synlett* **2002**, 301–303. (e) Murata, M.; Shimazaki, R.; Ishikura, M.; Watanabe, S.; Masuda, Y. *Synthesis* **2002**, 717–719. For a review of Rh-catalyzed conjugate addition reactions, see: (f) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829–2844.

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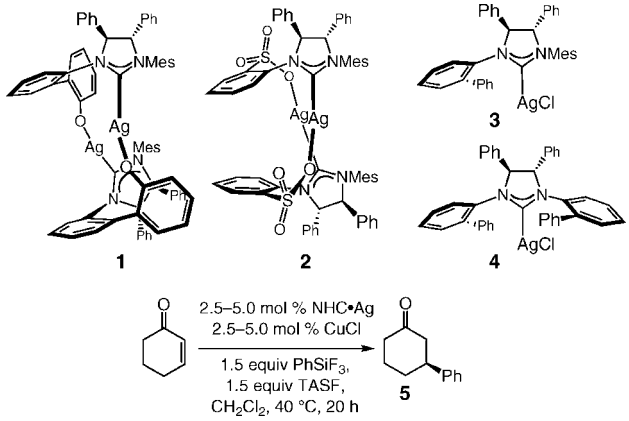
(11) For conjugate additions of alkylcopperpentafluorosilicates to α,β-unsaturated ketones promoted by stoichiometric amounts of $Cu(OAc)_2$, see: (a) Yoshida, J.; Tamao, K.; Kakui, T.; Kurita, A.; Murata, M.; Yamada, K.; Kumada, M. *Organometallics* **1982**, *1*, 369–380. For Cu-catalyzed cross-coupling reactions of alkynyl- and alkenylsilanes, respectively, see: (b) Nishihara, Y.; Ikegashira, K.; Mori, A.; Hiyama, T. *Tetrahedron Lett.* **1998**, *39*, 4075–4078. (c) Nishihara, Y.; Ikegashira, K.; Toriyama, F.; Mori, A.; Hiyama, T. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 985–990. For Cu-catalyzed reactions of allyltrimethoxysilane to carbonyl-containing compounds and imines, see: (d) Yamasaki, S.; Fujii, K.; Wada, R.; Kanai, M.; Shibasaki, M. *J. Am. Chem. Soc.* **2002**, *124*, 6536–6537. For Rh-catalyzed enantioselective conjugate addition reactions that involve vinylsilanes, see: (e) Shintani, R.; Ichikawa, Y.; Hayashi, T.; Chen, J.; Nakao, Y.; Hiyama, T. *Org. Lett.* **2007**, *9*, 4643–4645.

(12) For reviews regarding the chemistry of hypervalent silanes, see: (a) Kumada, M.; Tamao, K.; Yoshida, J.-i. *J. Organomet. Chem.* **1982**, *239*, 115–132. (b) Chuit, C.; Corriu, R. J. P.; Reye, C.; Young, J. C. *Chem. Rev.* **1993**, *93*, 1371–1448. (c) Rendler, S.; Oestreich, M. *Synthesis* **2005**, 1727–1747. (d) Orito, Y.; Nakajima, M. *Synthesis* **2006**, 1391–1401.

(13) For a recent study regarding transmetalation of an NHC−Cu−F complex with triethoxyarylsilanes, see: Herron, J. R.; Ball, Z. T. *J. Am. Chem. Soc.* **2008**, *130*, 16486–16487.

**TABLE 1. Activity of NHC·Ag(I) Complexes for Enantioselective CA Reaction of Cyclohexenone with $PhSiF_3$[a]**




| entry | NHC·Ag; mol % | conv (%)[b] | er[c] |
|---|---|---|---|
| 1 | **1**; 2.5 | <2 | |
| 2 | **2**; 2.5 | <2 | |
| 3 | **3**; 5.0 | 52 | 85.5:14.5 |
| 4 | **4**; 5.0 | 17 | 67:33 |

[a] Reactions performed under $N_2$ atmosphere. [b] Conversion levels were determined by analysis of 400 MHz $^1$H NMR spectra of unpurified products. [c] Enantiomeric ratio (er) values were determined by GLC analysis; see the Supporting Information for details. TASF = $(Me_2N)_3SSi(Me_3)F_2$.

unsaturated ketone furnishes complex **III**; subsequent conjugate addition would generate the desired C−aryl bond. Reaction of the resulting NHC−Cu−enolate **IV** with another equivalent of the hypervalent arylsilicate is expected to deliver the conjugate addition product **V** along with tetrafluorosilane (Scheme 1).

**2. Identification of an Effective Class of Chiral NHC−Cu Complexes.** Our next objective became to identify which class of NHC−Cu complexes most efficiently promotes conjugate addition according to the general pathway depicted in Scheme 1. Key observations from this segment of our investigations are shown in Table 1; commercially available cyclohexenone and trifluorophenylsilane served as the representative substrate and organosilane, respectively, and tris(dimethylamino)sulfonium difluorotrimethylsilicate (TASF) was used for in situ formation of the hypervalent silicate.[14]

Bidentate NHC−Cu complexes (2.5 mol %) derived from the reaction of Ag-based carbenes **1** and **2** (entries 1−2, Table 1) are ineffective in promoting conjugate addition. In contrast, reaction with 5 mol % of monodentate Ag-based complexes **3**

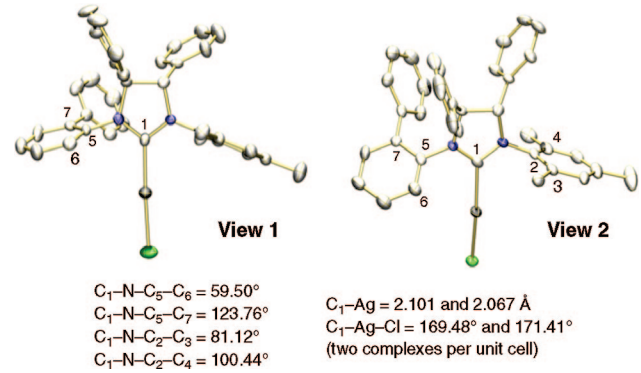



**FIGURE 1.** X-ray structure of NHC·Ag(I) complex **3** (two views shown).

(X-ray shown in Figure 1) or **4** in the presence of CuCl proceeds to 52% and 17% conversion, delivering enantiomerically enriched $\beta$-phenylcyclohexanone **5** in 85.5:14.5 and 67:33 er, respectively (entries 3 and 4, Table 1). The ECA in the presence of non-$C_2$-symmetric **3** is more efficient (52% vs 17% conversion) as well as more enantioselective (85.5:14.5 vs 67:33 er) than the $C_2$-symmetric complex **4**.[15,16]

We have demonstrated that bidentate NHC complexes such as **1** and **2** can be used to promote a number of enantioselective Cu-catalyzed processes involving Zn-, Mg-, or Al-based nucleophiles.[4,5] In all such cases, initial reaction of the nucleophilic organometallic reagent with the derived well-characterized dimeric NHC−Cu complex[3d,4a] likely results in the generation of monomeric bidentate Cu−carbenes, which are likely the catalytically active entities. It is plausible that the inactivity of the bidentate chiral NHCs, which exist in the dimeric form, is because the less nucleophilic phenyltetrafluorosilicate (vs the aforementioned metal-based reagents) is unable to promote effective dissociation of the corresponding dimeric Cu complexes.

Two different views of the X-ray structure of **3** and several noteworthy values are depicted (Figure 1). The dihedral angles listed in Figure 1 indicate that the dissymmetric aryl unit of **3** is significantly more tilted than the symmetric mesityl unit; such a conformational preference is likely to minimize unfavorable steric interaction with the phenyl group of the NHC backbone. As will be discussed below, the above structural attributes are relevant to the design of effective monodentate NHC-based catalysts.

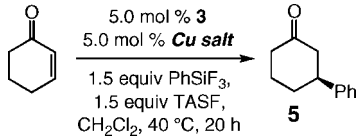
**3. Identification of an Optimal Cu Salt and Reaction with Isolated Chiral NHC−Cu Complexes.** Before initiating our studies regarding determination of the optimal chiral monodentate complex, we determined the identity of the most effective Cu salt. As the findings in Table 2 illustrate, in the presence of complex **3** nearly all salts examined deliver cyclohexanone **5** with similar enantioselectivity (84:16−86.5:13.5 er), with the highest conversion being observed when reaction is performed in the presence of CuBr (entry 2, Table 2). The lack of activity of the complex derived from CuCN

(14) For details regarding examination of various silylating agents in different solvents, leading to selection of TASF as the optimal choice, see the Supporting Information.

(15) For examples of $C_2$-symmetric chiral NHC−metal complexes used in enantioselective catalysis, see: (a) Herrmann, W. A.; Goossen, L. J.; Köcher, C.; Artus, G. R. J. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2805–2807. (b) Seiders, T. J.; Ward, D. W.; Grubbs, R. H. *Org. Lett.* **2001**, *3*, 3225–3228. (c) Guillen, F.; Winn, C. L.; Alexakis, A. *Tetrahedron: Asymmetry* **2001**, *12*, 2083–2086. (d) Pytkowicz, J.; Roland, S.; Mangeney, P. *Tetrahedron: Asymmetry* **2001**, *12*, 2087–2089. (e) Ma, Y.; Song, C.; Ma, C.; Sun, Z.; Chai, Q.; Andrus, M. B. *Angew. Chem., Int. Ed.* **2003**, *42*, 5871–5874. (f) Jensen, D. R.; Sigman, M. S. *Org. Lett.* **2003**, *5*, 63–65. (g) Tominaga, S.; Oi, Y.; Kato, T.; An, D. K.; Okamoto, S. *Tetrahedron Lett.* **2004**, *45*, 5585–5588. (h) Reference 4k. (i) Chaulagain, M. R.; Sormunen, G. J.; Montgomery, J. *J. Am. Chem. Soc.* **2007**, *129*, 9568–9569. (j) Sato, Y.; Hinata, Y.; Seki, R.; Oonishi, Y.; Saito, N. *Org. Lett.* **2007**, *9*, 5597–5599. (k) Baxter, R. D.; Montgomery, J. *J. Am. Chem. Soc.* **2008**, *130*, 9662–9663. (l) Xu, L.; Shi, Y. *J. Org. Chem.* **2008**, *73*, 749–751. (m) Matsumoto, Y.; Yamada, K.; Tomioka, K.-i. *J. Org. Chem.* **2008**, *73*, 4578–4581. (n) Lillo, V.; Prieto, A.; Bonet, A.; Díaz-Requejo, M. M.; Ramírez, J.; Pérez, P. J.; Fernández, E. *Organometallics* **2009**, *28*, 659–662. (o) Reference 4l.

(16) Although non-$C_2$-symmetric chiral monodentate NHCs are commonly employed as catalysts (see ref 1), application of the corresponding metal-based complexes is relatively uncommon in enantioselective catalysis. See: (a) Enders, D.; Gielen, H.; Runsink, J.; Breuer, K.; Brode, S.; Boehn, K. *Eur. J. Inorg. Chem.* **1998**, 913–919. (b) Duan, W.-L.; Shi, M.; Rong, G.-B. *Chem. Commun.* **2003**, 2916–2917. (c) Focken, T.; Rudolph, J.; Bolm, C. *Synthesis* **2005**, 429–436. (d) Li, S.-J.; Zhong, J.-H.; Wang, Y.-G. *Tetrahedron: Asymmetry* **2006**, *17*, 1650–1654. (e) Fournier, P.-A.; Collins, S. K. *Organometallics* **2007**, *26*, 2945–2949. (f) Vehlow, K.; Wang, D.; Buchmeiser, M. R.; Blechert, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 2615–2618. (g) Reference 15n.

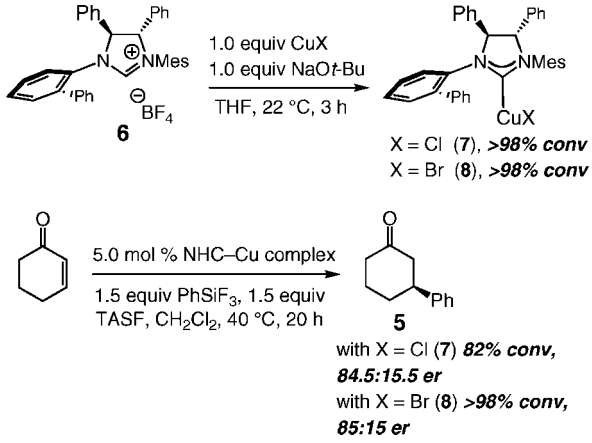
**TABLE 2. Screening of Cu Salts for ECA Reaction of Cyclohexenone with $PhSiF_3$ with NHC·Ag Complex 3**[a]




| entry | Cu salt | conv (%)[b] | er[c] |
|---|---|---|---|
| 1 | CuCl | 52 | 85.5:14.5 |
| 2 | CuBr | *79* | *86.5:13.5* |
| 3 | $CuBr_2 \cdot Me_2S$ | 30 | 85:15 |
| 4 | CuI | 26 | 84.5:15.5 |
| 5 | CuOAc | 38 | 84:16 |
| 6 | CuCN | <2 | |
| 7 | $(CuOTf)_2 \cdot C_6H_6$[d] | 53 | 84:16 |
| 8 | $(MeCN)_4CuPF_6$ | 35 | 84:16 |

[a–c] See Table 1. [d] 5.0 mol % of **3** and 2.5 mol % of Cu salt used.

**SCHEME 2. Synthesis and Examination of Catalytic Activity of NHC−Cu Complexes 7 and 8a**



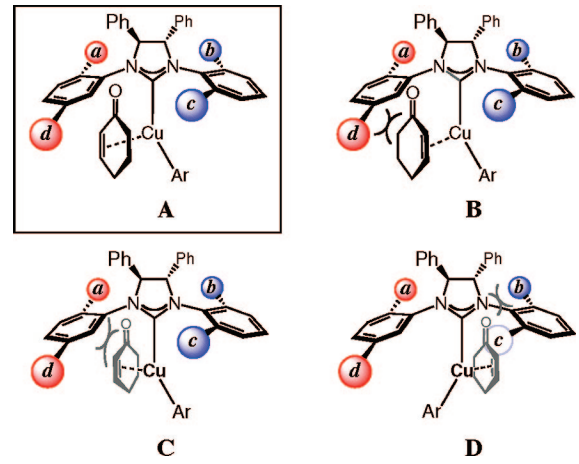

[a] See the Supporting Information for detailed procedures.

(entry 6, Table 2) likely reflects the strong Cu−CN bond [i.e., the derived NHC−Cu−Ar (**II** in Scheme 1) is not generated]. It might be for a similar reason that dimeric Cu complexes derived from **1** and **2** do not promote reaction: the Si-based nucleophile may not readily react with, and displace, the corresponding Cu−O bond.

We prepared chiral complexes **7** and **8**, as illustrated in Scheme 2, and investigated their ability to initiate the model ECA process versus the related transformations promoted by in situ-prepared catalysts. Although similar enantioselectivities are observed, use of carbenes **7** and **8** gives rise to more efficient conjugate additions. Thus, with **7**, reaction proceeds to 82% conversion (vs 52% when prepared in situ); when bromide **8** is utilized, >98% conversion is achieved under identical conditions (Scheme 2; see below for a discussion regarding the higher activity with NHC−CuBr complexes).

**4. Theoretical Basis for Catalyst Development; Structural Features of an Effective Chiral NHC−Cu Catalyst.** To base the design and development of chiral NHC catalysts on a mechanistic framework, we made the assumption that catalyst−substrate association is the critical stereochemistry-determining step of the catalytic cycle (see Scheme 1) and evaluated various modes of interaction, some of which are depicted in Scheme 3. We reasoned that the unsaturated carbonyl coordinates to the chiral NHC−CuAr complex in a manner that permits maximum overlap between the Cu−aryl bond and the $\pi^*$ of the electrophilic alkene. Accordingly, the substrate can approach the chiral catalyst through four quadrants, represented by **A**−**D** (Scheme 3); the orientation of the *N*-Ar substituents of the NHC are based on X-ray crystal structures such as those shown in Figure 1.

**SCHEME 3. Models for Chiral NHC−Cu−Substrate Association**

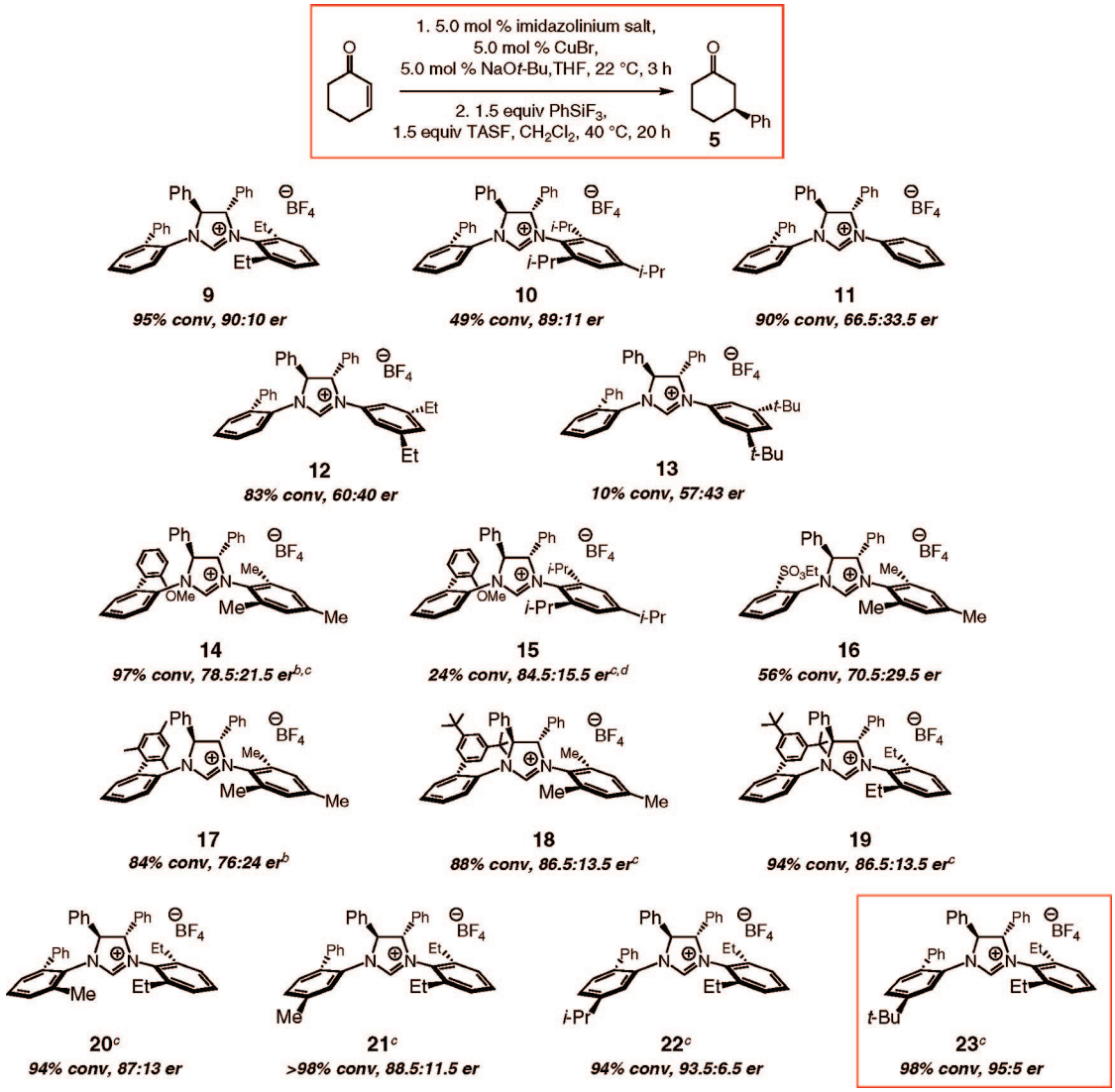



The quadrant labeled as **A** represents the most accessible mode of association for a substrate molecule (Scheme 3). In contrast, complex **B**, expected to deliver the opposite product enantiomer, should be less favored as a result of steric interactions with the dissymmetrically substituted *N*-Ar unit. Examination of molecular models indicates that the presence of a *meta* substituent, such as ***d*** in **B**, might lead to enhancement of enantioselectivity by discouraging **B** versus **A**. Positioning of a group *ortho* to ***d*** would be detrimental to **A** as well as **B**; it is such interactions that we expect to render reaction through **C** and **D** as energetically unfavorable. In a $C_2$-symmetric chiral NHC, one that lacks substituents ***b*** and ***d***, similar arguments hold except that **A** and **D** would represent equally favorable pathways. In light of the above considerations, our initial finding regarding the higher effectiveness of the non-$C_2$-symmetric complex **3** derived from imidazolinium salt **6** versus that obtained from the $C_2$-symmetric **4** (Table 1) emerged as noteworthy. We continued to focus on the development of non-$C_2$-symmetric variants; this decision was not only based on our preliminary findings but also because dissymmetric NHC-metal complexes—particularly the monodentate variants—have not been widely developed and utilized in enantioselective catalysis.[16]

**5. Preparation and Examination of Catalytic Activity of Various Chiral Monodentate Non-$C_2$-symmetric NHC Complexes.** We investigated the ability of a number of chiral monodentate non-$C_2$-symmetric NHC−Cu complexes to promote the ECA to cyclohexenone with $PhSiF_3$. The chiral imidazolinium salts used to synthesize the derived Cu complexes and the results obtained from each corresponding ECA process are summarized in Scheme 4.

**a. Variations at the Symmetric *N*-Aryl Moiety.** We began by investigating the effect of the alteration of the size of the substituents of the symmetrically substituted *N*-Ar unit of the carbene on efficiency and enantioselectivity. Examination of the models presented in Scheme 3 suggests that the substituents represented by ***b*** and ***c*** might influence selectivity by discouraging substrate approach proximal to the symmetrically substituted *N*-aryl group. Such variations can change the orientation of the phenyl units of the carbene backbone, in

**SCHEME 4. Screening of Non-$C_2$-symmetric Imidazolinium Salts Used To Prepare Monodentate NHC−CuBr Complexes for ECA Reaction of Cyclohexenone with $PhSiF_3$[a]**



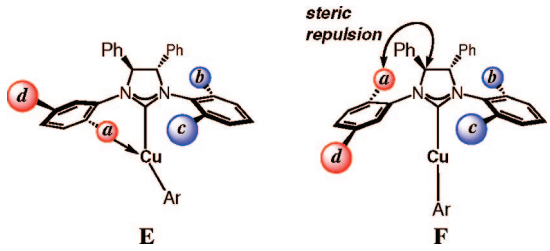

[a] Reactions performed under $N_2$ atmosphere; see the Supporting Information for detailed experimental procedures. [b] CuCl used and reaction performed at 60 °C. [c] The derived Cu-based complexes are formed as 2:1 (**14**), 1:1 (**15**), 17:1 (**20**), 9:1 (**22**), and 19:1 (**23**) mixtures of atropisomers; all other complexes, including that derived from **21**, are formed as a single isomer (>98:<2). The major diastereomer and/or that used, after separation and purification, in the ECA process is illustrated. All stereoisomer ratios were determined by analysis of the 400 MHz $^1$H NMR spectra of the unpurified mixtures. [d] Reaction performed at 60 °C.

turn altering the conformational preferences of the dissymmetrically substituted *N*-Ar moiety. The observed differences in the activity and selectivity of chiral complex **3** and the $C_2$-symmetric **4** (see Table 1) might, therefore, be partly due to conformational preferences of one *N*-Ar group, which depends on whether *the other N*-aryl unit is symmetrically (as in **4**) or nonsymmetrically (e.g., **3**) substituted. As will be discussed below in more detail, the larger steric presence provided by the 2,6-disubstituted *N*-aryl unit, an attribute that may not be available in a $C_2$-symmetric complex, gives rise to higher reactivity.

We first prepared and examined the activity of the CuBr complexes derived from imidazolinium salts **9**−**11** (Scheme 4). We established that changing the Me groups of the mesityl unit in **6** to the larger Et units results in higher enantioselectivity (90:10 er vs 85:15 er for **6**) without a significant diminution in efficiency. When alterations of this type are extended to the *i*-Pr substituents (cf. **10**, Scheme 4), however, ECA efficiency suffers (49% conversion vs 95% conversion with **9** or >98% conversion with **6**), but **5** is still generated with similar enantiomeric purity (89:11 er vs 90:10 er with **9**; see Scheme 4). The significance of the NHC's *N*-Ar substituents to enantioselectivity is exhibited by the low er values obtained in the reactions performed with the CuBr complex derived from imidazolinium salts **11**−**13** (66.5:33.5 er, 60:40 er and 57:43 er, respectively). These findings illustrate that with NHC−Cu complexes that bear sterically demanding substituents (e.g., Cu−carbenes derived from **10** and **13**), the rate of formation of the requisite NHC−Cu−aryl (i.e., **I** → **II**, Scheme 1) as well as coordination with the enone substrate (i.e., **II** → **III**, Scheme 1) is adversely affected.

**b. Variations at the Dissymmetric *N*-Aryl Moiety.** Next, we examined the effect of the substituents represented by ***a*** in the models shown in Scheme 3. We hypothesized that in complexes derived from **14**−**16**, association of the Lewis basic heteroatom-containing substituent, as represented by complex **E**, might further discourage substrate chelation through mode

**C** (Scheme 3). As the data in Scheme 4 illustrate, however, ECA with Cu salts derived from **14**−**16** deliver **5** with slightly lower or similar enantioselectivity [78.5:21.5 er, 84.5:15.5 er, and 70.5:29.5 er, respectively, vs NHC derived from **6**, affording 98% conversion and 85:15 er]. The data obtained for reactions promoted by chiral carbenes corresponding to **14**−**16** thus illustrate that, although association of the substituent ***a*** with the Cu center, as depicted in **E**, might disfavor **C** (Scheme 3), the resulting conformational tilt of the *N*-aryl moiety can reduce selectivity by rendering the front left quadrant of the complex accessible and coordination through mode **B** more favorable.




Synthesis and examination of the catalytic activity of complexes derived from chiral salts **17**−**19** (Scheme 4) demonstrates that increasing the size of substituent ***a*** engenders diminution of enantioselectivity as well. As illustrated in **F**, conformational adjustment to minimize steric repulsion between the *ortho N*-aryl substituent and the NHC backbone likely leads to a similar conformational preference.

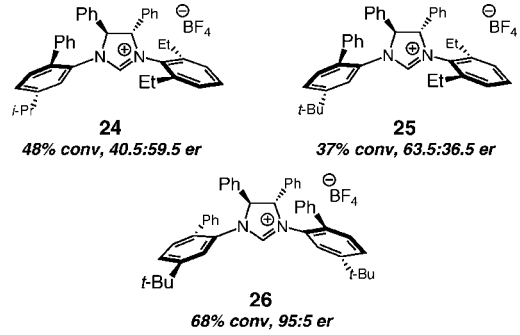
The above studies led us to probe the catalytic activity of chiral NHCs that would disfavor mode of complexation **B** (Scheme 3). Accordingly, imidazolinium salts **20** and **21** (Scheme 4) were synthesized and examined. Positioning of a methyl substituent at the *ortho* (**20**, Scheme 4) or *meta* (**21**) site of the dissymmetric *N*-aryl group of the NHC gives rise to a reaction that proceeds with slightly lower selectivity compared to the parent **9** (87:13 and 88.5:11.5 er, respectively, vs 90:10 er; see Scheme 4). We hypothesized that the positive effect of the *o*-methyl of **20** in discouraging reaction through **B** is likely offset by also disfavoring complex **A**, and the *m*-methyl of **21** is not sufficiently sizable to make its presence felt by the approaching substrate. That the NHC derived from **22**, bearing an *i*-Pr unit at the *meta* site of the *N*-aryl group delivers an improved 93.5:6.5 er and that enantioselectivity is further improved when *tert*-butyl-bearing **23** is used (95:5 er) lends credence to the proposed model.

**c. Reaction Promoted by Minor Atropisomers and a $C_2$-Symmetric NHC.** Synthesis of chiral imidazolinium salts **20**−**23**, wherein the dissymmetric *N*-aryl groups contain an *ortho* as well as a *meta* substituent, also yields some of the alternative atropisomer as the minor diastereomer (see Scheme 4 for isomer ratios); two examples (**24** and **25**) are depicted in Scheme 5. As the representative data indicate (Scheme 5), these minor diastereomers, separated from the major isomers by silica gel chromatography,[17] serve to generate substantially less effective chiral catalysts. The diminished reactivity and enantioselectivity observed with **24** and **25** are likely because mode of association **A** is rendered less energetically preferred due to unfavorable interaction between the protruding *o*-phenyl substituent and the bound enone substrate.

**d. Rationale for Lower Efficiency of the $C_2$-Symmetric NHC Complexes.** It is noteworthy that the Cu complex derived

(17) See the Supporting Information for experimental details.

**SCHEME 5. Cu-Catalyzed Enantioselective CA Reactions of Cyclohexenone and $PhSiF_3$ with Minor NHC Rotamers and the $C_2$-Symmetric Variant of 23**




from $C_2$-symmetric **26** (Scheme 5), corresponding to optimal imidazolinium salt **23** (Scheme 4), although equally discriminating (95:5 er), is a less active catalyst (68% vs 98% conversion). Such a difference in reactivity might be the result of stronger tendency of the relatively less hindered $C_2$-symmetric Cu-based complex to transform into less active bridged structures. This proposal is supported by the stronger tendency of Cl-based complexes (vs Br-based) to form structures with interconnecting halogen ligands,[18] and the larger difference in the efficiency of ECA reactions performed in the presence of NHC−Cu−chlorides derived from **3** and **4** (Table 1, 52% vs 17% conversion). It might be suggested that for similar reasons, when $C_2$-symmetric **26** is utilized in the presence of CuCl, there is only 16% conversion under identical conditions (vs 68% conversion with CuBr; see Scheme 5). Thus, by discouraging the formation of less active Cu-based systems, the larger size of the substituents of the symmetric *N*-aryl moiety promotes higher activity without engendering diminution of enantioselectivity.

**6. Catalytic ECA Reactions of Cyclic Enones and Arylsilyltrifluorides Catalyzed by Chiral Monodentate Non-$C_2$-symmetric NHC−Cu Complexes.** The generality of the Cu-catalyzed protocol to promote the enantioselective CA reactions of various cycloalkenones with a range of arylsilyltrifluorides[19] has been evaluated; the results of these studies are illustrated in Table 3. With cyclohexenone (entries 1−5), reactions are efficient, affording products in 90−93% yield. Silyl reagents bearing a sterically hindered (entry 2, Table 3), an electron-donating (entry 3), or an electron-withdrawing (entry 4) aryl group undergo reaction efficiently (90−93% yield after purification) and in high enantioselectivity (94:6−96.5:3.5 er).

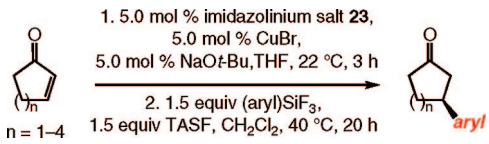
As illustrated in entry 5 of Table 3, with diphenylsilyldifluoride, use of 0.75 equiv of the reagent leads to >98% conversion; the desired product is isolated in 92% yield and 94:6 er. The latter finding indicates that both aryl units of $Ph_2SiF_2$ are transferred in the course of the catalytic process.

The transformations shown in entries 6−11 of Table 3 involve medium ring substrates cycloheptenone and cyclooctenone; products are obtained in 63−92% yield and 92.5:7.5 to 98.5:1.5 er. Reactions with the seven-membered ring enone proceed slightly less efficiently than those of cyclohexenone: with the sterically hindered *o*-$MeC_6H_4SiF_3$ (entry 7, Table 3), ECA

(18) (a) Carvajal, A.; Liu, X.-Y.; Alemany, P.; Novoa, J. J.; Alvarez, S. *Int. J. Quantum Chem.* **2002**, *86*, 100–105. (b) Samant, R. A.; Ijeri, V. S.; Srivastava, A. K. *J. Electroanal. Chem.* **2002**, *534*, 115–121.

(19) The arylsilyltrifluoride reagents used in this study are based on previously reported procedures: (a) Brook, M. A.; Neuy, A. *J. Org. Chem.* **1990**, *55*, 3609–3616. (b) Powell, D. A.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 7788–7789. The aryl-based reagents are typically obtained in 40−65% yield after distillation.

**TABLE 3. Catalytic Enantioselective CA Reactions of Cyclic Enones and Aryltrifluorosilanes with NHC−Cu Complexes Derived from Imidazolinium Salt 23[a]**



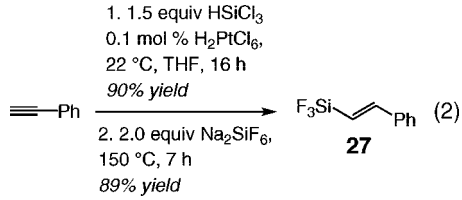

| entry | *n* | (aryl)$SiF_3$ | conv (%)[b] | yield (%)[c] | er[d] |
|---|---|---|---|---|---|
| 1 | 2 | $C_6H_5SiF_3$ | 98 | 91 | 95:5 |
| 2 | 2 | *o*-$MeC_6H_4SiF_3$ | >98[e] | 90 | 96.5:3.5 |
| 3 | 2 | *p*-$OMeC_6H_4SiF_3$ | >98 | 93 | 94:6 |
| 4 | 2 | *p*-$FC_6H_4SiF_3$ | 95[e,f] | 92 | 94:6 |
| 5 | 2 | $Ph_2SiF_2$ | >98[g] | 92 | 94:6 |
| 6 | 3 | $C_6H_5SiF_3$ | 97 | 92 | 95:5 |
| 7 | 3 | *o*-$MeC_6H_4SiF_3$ | 68[e,h] | 63 | 98.5:1.5 |
| 8 | 3 | *p*-$OMeC_6H_4SiF_3$ | 77[e] | 68 | 92.5:7.5 |
| 9 | 3 | *p*-$FC_6H_4SiF_3$ | 76[f] | 65 | 93:7 |
| 10 | 3 | $Ph_2SiF_2$ | 90[g] | 85 | 94:6 |
| 11 | 4 | $C_6H_5SiF_3$ | 86[e] | 80 | 92.5:7.5 |
| 12 | 1 | $C_6H_5SiF_3$ | 92 | 85 | 81.5:18.5 |
| 13 | 1 | *o*-$MeC_6H_4SiF_3$ | >98[i] | 92 | 90:10 |

[a] Reactions performed under $N_2$ atmosphere. [b] Conversion values (consumption of substrate) determined by analysis of 400 MHz $^1H$ NMR spectra of the unpurified mixtures. [c] Yields of isolated products after purification. [d] Enantiomer ratio values determined by GLC or HPLC analysis; see the Supporting Information for complete details. [e] Reaction time = 40 h. [f] 3 equiv of TASF used. [g] 0.75 equiv of $Ph_2SiF_2$ used. [h] 20 mol % catalyst loading utilized. [i] Reaction temperature = 60 °C.

proceeds to 68% conversion with 20 mol % catalyst and after an extended reaction time of 40 h. It should be noted, however, that catalytic ECA with the sterically demanding reagent affords the highest level of enantioselectivity (98.5:1.5 er in entry 7). As was the case in reaction with cyclohexenone, substoichiometric amounts of $Ph_2SiF_2$ are sufficient for achieving 90% conversion (85% yield, 94:6 er; see entry 10, Table 3).

Cu-catalyzed ECA reactions with cyclopentenone (entries 12−13, Table 3) are equally efficient, compared to the related transformations with the larger ring enones (85−92% yield); the desired products are, nonetheless, generated with markedly lower levels of enantiomeric purity (81.5:18.5 to 90:10 er). It is possible that mode of catalyst-substrate association **B** and **C** (Scheme 3) become more competitive with the smaller and sterically less demanding cyclic enones.

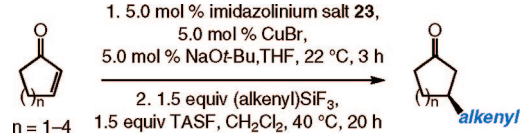
**7. Cu-Catalyzed ECA Reactions with Alkenylsilyltrifluorides.** The corresponding transformations involving alkenylsilyltrifluorides were investigated next. As illustrated by the example in eq 2, the requisite reagents can be readily accessed by a two-step procedure starting with a highly efficient and site-selective Pt-catalyzed hydrosilylation of a terminal alkyne with trichlorosilyl hydride, followed by treatment with $Na_2SiF_6$ to obtain the derived silyltrifluoride.

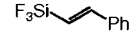
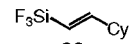
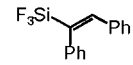


(2)

The results of our studies regarding Cu-catalyzed ECA reactions of alkenylsilyltrifluorides[20] are summarized in Table 4. Transformations with phenyl-substituted alkenylsilane **27** efficiently afford the desired products in 80−93% yield and 73.5:26.5−96:4 er. In contrast to processes with arylsilyltrifluorides (Table 3), reactions involving medium-ring enones (entries 3−4, Table 4) proceed with higher enantioselectivity than those with cyclohexenone (entry 2); the lower selectivity obtained with cyclopentenone (entry 1) is consistent with catalytic additions of aryl groups (see above). As indicated by the data summarized in entries 5−8 of Table 4, similar efficiencies and enantioselectivities are observed in reactions with cyclohexyl-substituted **28** and trisubstituted alkenylsilane **29**. Unlike transformations with arylsilylfluorides, however, increasing the size of the alkenyl group does not result in higher enantioselectivity (compare entries 1 and 2 or 6 and 7 in Table 3 with 2 and 8 in Table 4). The reason for such variations in selectivity, as well as the rationale for the lower levels of enantiomeric purity of products from alkenyl addition reactions, requires a better appreciation of the mechanistic nuances and kinetic differences between these two classes of ECA reactions.

**TABLE 4. Catalytic ECA Reactions of Cyclic Enones and Alkenyltrifluorosilanes with NHC−Cu Complexes Derived from 23[a]**




| entry | n | (alkenyl)$SiF_3$ | conv (%)[b] | yield (%)[c] | er[d] |
|---|---|---|---|---|---|
| 1 | 1 | | >98 | 81 | 73.5:26.5 |
| 2 | 2 |  | >98 | 93 | 87:13 |
| 3 | 3 | **27** | 97 | 91 | 96:4 |
| 4 | 4 | | 85 | 80 | 92:8 |
| 5 | 2 | | >98 | 97 | 83.5:16.5 |
| 6 | 3 |  | >98 | 88 | 88.5:11.5 |
| 7 | 4 | **28** | 92 | 83 | 86:14 |
| 8 | 2 |  **29** | 92 | 86 | 83.5:16.5 |

[a−d] See Table 1.

## Conclusions

We have developed a Cu-catalyzed method for enantioselective conjugate additions of aryl and alkenyl groups to cyclic enones. Reactions are promoted by chiral monodentate non-$C_2$-symmetric NHC−Cu complexes and afford the desired $\beta$-aryl- or $\beta$-vinylcycloalkanones in up to 98.5:1.5 er and 96:4 er, respectively. The present class of catalytic ECA reactions can be carried out in the presence of easily accessible aryl- or alkenylsilane reagents and thus do not require use of the corresponding air and moisture sensitive organometallics (e.g., organomagnesium halides, organozinc or organoaluminum reagents). Synthesis of the NHC complexes is relatively straightforward: parent imidazolinium salts are accessed in three simple steps, which are easily amenable to large scale preparations, in up to 76% overall yield from commercially available enantiomerically pure diphenylethylenediamine.[17]

(20) Alkenylsilyltrifluorides were prepared based on the same previously reported procedures used to access the corresponding aryl-based reagents (see ref 19), but in somewhat lower yields (27−81%).

The investigations described above illustrate the validity of the catalytic cycle shown in Scheme 1, demonstrating that with an appropriate NHC−Cu−halide complex, aryl- and vinylsilanes can be effectively activated and used in enantioselective C−C bond-forming processes. These studies pave the way for development of additional catalytic methods that are of substantial potential utility and involve chiral NHC catalysts, organosilanes, and other important classes of electrophiles (e.g., carbonyls and imines).

We have outlined the development and evaluation of the catalytic activity of new NHC-metal complexes that can serve as catalysts for a range of enantioselective processes. Our investigations shed light on the differences, at times subtle, regarding the chiral pockets presented by different NHC complexes for association with various cyclic enones. The resulting assortment of chiral monodentate non-$C_2$-symmetric imidazolinium salts that served as precursors to chiral NHC−Cu catalysts in the investigations detailed here, should be readily applicable to future research directed toward additions to other classes of substrates.

Application of the chiral monodentate NHC catalysts to development of efficient catalytic enantioselective additions of trifluoroorganosilanes to additional classes of electrophilic substrates, exploration of the mechanistic details of such processes, and applications to the synthesis of biologically active target molecules[21] are the subject of ongoing research in these laboratories.

## Experimental Section

General protocols, including chiral ligand and catalyst preparation, and details of X-ray crystallographic studies are provided in the Supporting Information.

**Imidazolinium Salt 23.** A mixture of 19:1 atropisomers was obtained. The $^1$H NMR spectrum (400 MHz) includes only major atropisomer, which was separated by silica gel column chromatography from minor atropisomer: IR (neat) 3064 (m), 2966 (s), 2875 (m), 1610 (s), 1585 (s), 1478 (s) cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 8.80 (1H, s), 7.69−7.63 (4H, m), 7.52−7.49 (2H, m), 7.42−7.32 (6H, m), 7.29−7.19 (4H, m), 7.11 (2H, t, $J$ = 8.0 Hz), 6.93 (1H, dd, $J$ = 7.4, 1.4 Hz), 6.46 (2H, d, $J$ = 7.2 Hz), 5.43 (1H, d, $J$ = 9.6 Hz), 5.31 (1H, d, $J$ = 9.2 Hz), 3.14 (1H, dq, $J$ = 14.8, 7.6 Hz), 2.79 (1H, dq, $J$ = 15.2, 7.6 Hz), 2.32 (1H, dq, $J$ = 15.2, 7.6 Hz), 1.90 (1H, dq, $J$ = 14.8, 7.6 Hz), 1.46 (3H, t, $J$ = 7.6 Hz), 1.24 (9H, s), 0.89 (3H, t, $J$ = 7.6 Hz); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 157.6, 153.5, 141.5, 141.2, 138.9, 135.4, 134.9, 131.9, 131.0, 130.7, 130.6, 130.3, 130.3, 129.8, 129.8, 129.7, 129.5, 129.1, 128.8, 128.6, 128.1, 127.7, 127.2, 127.1, 126.7, 75.5, 73.2, 35.0, 31.0, 24.3, 23.6, 14.7, 14.3; HRMS calcd for $C_{41}H_{43}N_2$ [M − $BF_4$](ES$^+$) 563.3426, found 563.3412; optical rotation $[\alpha]^{20}_D$ −337.8 (*c* 1.00, $CHCl_3$).

**(*S*)-3-(Phenyl)cyclohexanone (5).** An oven-dried vial equipped with a stir bar was charged with $PhSiF_3$ (79 mg, 0.49 mmol), tris(dimethylamino)sulfonium difluorotrimethylsilicate (TASF, 135 mg, 0.49 mmol), and $CH_2Cl_2$ (1 mL) under a dry $N_2$ atmosphere in a glovebox. The mixture was allowed to stir for 5 min, after which 2-cyclohexenone (32 mg, 0.33 mmol) and NHC−CuBr complex derived from imidazolinium salt **23** (11 mg, 0.016 mmol) were added. The vial was sealed with a cap before removal from the glovebox. After 20 h at 40 °C, the homogeneous light yellow solution was diluted with $CH_2Cl_2$ (3 mL), and the reaction was quenched by the addition of a 3.0 M solution of HCl (1 mL). The organic layer was separated, and the aqueous layer was washed with $CH_2Cl_2$ (2 × 2 mL). The combined organic layers were washed with a saturated aqueous $NaHCO_3$ solution (2 mL), brine (2 mL), and water (2 × 2 mL) and dried over $MgSO_4$. The volatiles were removed in vacuo, and the resulting light yellow oil was purified by silica gel column chromatography (hexanes/$Et_2O$:10/1) to afford 52 mg (0.30 mmol, 91% yield) of (*S*)-3-phenylcyclohexanone (**5**) as a colorless oil: $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 7.35−7.31 (2H, m), 7.26−7.22 (3H, m), 3.05−2.97 (1H, m), 2.63−2.34 (4H, m), 2.18−2.07 (2H, m), 1.91−1.72 (2H, m); optical rotation $[\alpha]^{20}_D$ −39.1 (*c* 0.975, $CHCl_3$) for an 95:5 er sample.[22]

**3-Phenylcyclooctanone:** IR (neat) 2925 (s), 2854 (s), 1702 (s), 1464 (m) cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 7.33−7.19 (5H, m), 3.19 (1H, tt, $J$ = 12.4, 3.2 Hz), 2.95 (1H, t, $J$ = 12.4 Hz), 2.58−2.41 (3H, m), 2.18−2.06 (1H, m), 1.96−1.84 (2H, m), 1.79−1.50 (4H, m), 1.46−1.36 (1H, m); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 216.2, 146.5, 128.7, 126.8, 126.5, 48.4, 44.8, 43.2, 35.3, 27.8, 24.6, 24.3; HRMS calcd for $C_{14}H_{19}O$ [M + H] (EI$^+$) 203.1436, found 203.1440; optical rotation $[\alpha]^{20}_D$ +3.4 (*c* 0.50, $CHCl_3$) for an 90:10 er sample.

**3-Styrylcyclooctanone:** IR (neat) 2926 (s), 2855 (s), 1697 (s), 1446 (m) cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 7.36−7.28 (4H, m), 7.23−7.19 (1H, m), 6.42 (1H, d, $J$ = 16.0 Hz), 6.18 (1H, dd, $J$ = 16.0, 7.2 Hz), 2.87−2.80 (1H, m), 2.64 (1H, t, $J$ = 12.0 Hz), 2.53−2.37 (3H, m), 2.08−1.96 (1H, m), 1.93−1.80 (2H, m), 1.74−1.67 (1H, m), 1.58−1.36 (4H, m); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 216.2, 137.5, 134.7, 128.7, 128.5, 127.4, 126.2, 46.8, 43.3, 41.6, 33.4, 27.9, 24.6, 23.8; HRMS calcd for $C_{16}H_{21}O$ [M + H] (ESI$^+$) 229.1592, found 229.1600.

**3-(2-Cyclohexylvinyl)cycloheptanone:** IR (neat) 2920 (s), 2849 (s), 1699 (s), 1447 (m) cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 5.36 (1H, dd, $J$ = 15.6, 5.6 Hz), 5.30 (1H, dd, $J$ = 15.6, 6.0 Hz), 2.57−2.42 (3H, m), 2.35−2.27 (1H, m), 1.96−1.83 (4H, m), 1.72−1.56 (6H, m), 1.48−1.35 (2H, m), 1.33−0.97 (6H, m); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 214.3, 135.3, 131.8, 50.1, 44.2, 40.7, 39.2, 37.7, 33.3, 33.3, 28.6, 26.3, 26.2, 26.2, 24.2; HRMS calcd for $C_{15}H_{25}O$ [M + H] (ESI$^+$) 221.1905, found 221.1902; optical rotation $[\alpha]^{20}_D$ −10.3 (*c* 0.50, $CHCl_3$) for an 89.5:11.5 er sample.

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**Supporting Information Available:** Experimental procedures and spectral data for substrates and products. This material is available free of charge via the Internet at http://pubs.acs.org.

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(21) For applications of chiral NHC−Cu and NHC−Ru complexes developed in these laboratories to target-oriented synthesis, see: (a) Gillingham, D. G.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2007**, *46*, 3860–3864. (b) Brown, M. K.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2008**, *130*, 12904–12906.

(22) All spectroscopic data match those reported previously; see: Takaya, Y.; Ogasawara, M.; Hayashi, T. *J. Am. Chem. Soc.* **1998**, *120*, 5579–5580.