ChemComm

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2019, **55**, 13574

Received 16th September 2019,
Accepted 18th October 2019

DOI: 10.1039/c9cc07266g

rsc.li/chemcomm

Cu(I)–SNS complexes for outer-sphere hydroboration and hydrosilylation of carbonyls†

Matthew R. Elsby and R. Tom Baker *

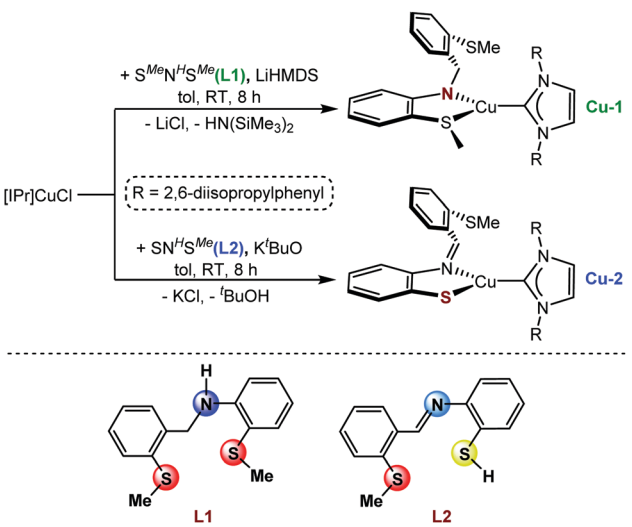
Two new NHC–Cu(I)-[κ²-SNS] complexes were synthesized to directly compare the bifunctional catalytic activity of a hard amido *vs.* a soft thiolate donor. The Cu thiolate complex catalyzed ketone hydroboration but not hydrosilylation, while the Cu amido complex is a high-performing outer-sphere carbonyl reduction catalyst using boranes and silanes.

Transition-metal complexes that include redox[1] or Lewis acid[2] /base[3] functionality in their ligands have extensive applications in homogeneous catalysis.[4] Bifunctional catalysts based on earth abundant first-row transition metals are especially sought after for their economy and low toxicity, and have been shown to facilitate difficult catalytic transformations.[5] Cooperativity between a ligand and metal centre to facilitate E–H bond activation is often a crucial aspect of bifunctional carbonyl reduction mechanisms,[6] such as the hydrosilylation of ketones and aldehydes.[7] A key strategy of this transformation is the use of a ligand that incorporates a Lewis basic donor site to form a reactive metal-hydride intermediate after activation of an E–H bond.[8] Comparing the bifunctional capacity of hard *vs.* soft donors in these ligand frameworks may aid in the design of future ligand frameworks for catalytic applications.

We have reported two easily prepared SNS ligands (Scheme 1) that have both demonstrated bifunctional catalytic activity in their first-row metal complexes.[9] Upon deprotonation, **L1** features a hard nitrogen donor in a thioether–amido–thioether framework, while **L2** incorporates a soft sulfur donor in a thiolate–imine–thioether framework. Previous work has shown that the coordination chemistry of **L1** and **L2** can differ greatly even under identical conditions. As part of our efforts to compare the properties and capabilities of these two ligands, we report herein the synthesis of NHC–Cu–[κ²-SNS] amido and thiolate complexes as catalysts for hydroboration and hydrosilylation of ketones and aldehydes.

There are many examples of Cu[NHC] complex-catalysed hydroboration and hydrosilylation, which have been the subject of review.[10] By combining the copper–NHC framework with **L1** and **L2**, we expected that the crowded and coordinatively saturated metal centre may force an outer-sphere bifunctional mechanism.[11] While most Cu-catalysed carbonyl reductions proceed *via* the *in situ* formation of a copper-butoxide base to generate the active copper-hydride species,[12] the use of either the thiolate or amido acting as an internal base may function in a similar capacity.[13]

The reaction of CuCl(IPr) with one equiv. of **L1** and LiHMDS in toluene afforded the 16e- Cu(κ²-S^{Me}NS^{Me})(IPr) (**Cu-1**) complex in 92% yield (Scheme 1) (IPr = 1,3-bis[2,6-diisopropylphenyl]-1,3-dihydro-2*H*-imidazol-2-ylidene; HMDS = hexamethyldisilazide, N[(SiMe$_3$)$_2$]$^-$). As shown in Fig. 1, the solid-state structure of **Cu-1** features a distorted trigonal planar geometry [N(1)–Cu(1)–S(1) = 85.14(8)°;



Scheme 1 Syntheses of **Cu-1** and **Cu-2**.

Department of Chemistry and Biomolecular Sciences and Centre for Catalysis Research and Innovation, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada. E-mail: rbaker@uottawa.ca

† Electronic supplementary information (ESI) available: Experimental details including synthesis and characterization, ^{1}H and ^{13}C{^{1}H} NMR spectra for all complexes. CCDC 1952495 (**Cu-1**) and 1952496 (**Cu-2**). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c9cc07266g

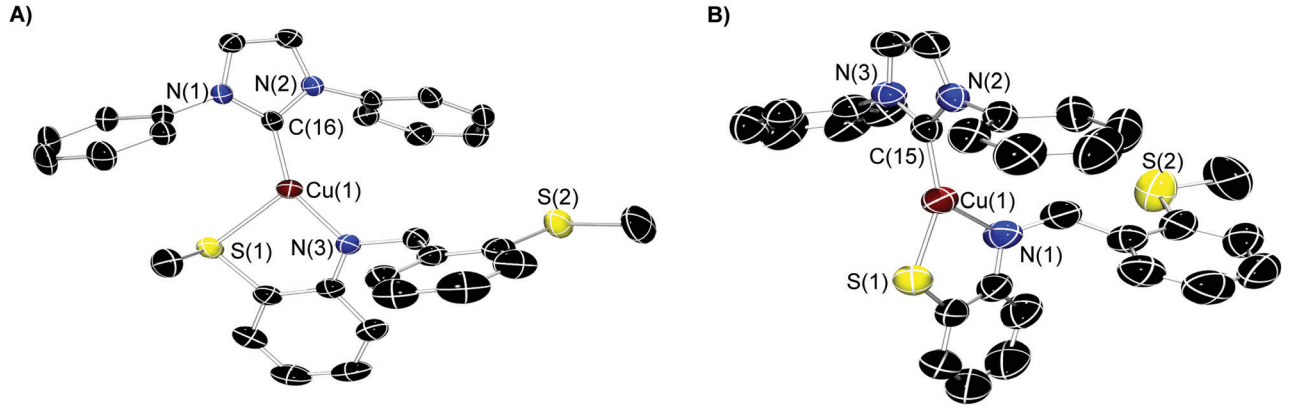
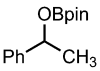
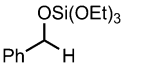
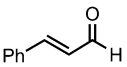
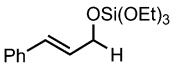
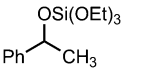
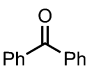
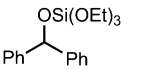
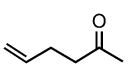
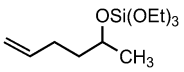
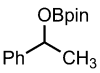


Fig. 1 ORTEP depiction of the solid-state molecular structures of (A) **Cu-1**: selected bond lengths (Å): Cu(1)–S(1) 2.4820(14), Cu(1)–N(3) 1.948(2), Cu(1)–C(16) 1.919(3); (B) **Cu-2**: selected bond lengths (Å): Cu(1)–S(1) 2.1802(8), Cu(1)–N(1) 2.130(2), Cu(1)–C(15) 1.889(2). Hydrogen atoms and NHC-isopropyl substituents are omitted for clarity.

C(16)–Cu(1)–S(1) = 123.90(7)°; C(16)–Cu(1)–N(1) = 150.89(9)°], due to the long Cu–$S_{thioether}$ bond length [2.4820(14) Å]. The other thioether moiety is directed away from the Cu-centre rather than bonding to form an 18e- complex, presumably due to the NHC steric bulk. The analogous reaction of CuCl(IPr) with one equiv. of **L2** and K^{t}BuO gave the Cu(κ^2-S^{Me}NS)(IPr) (**Cu-2**) product in 88% yield. The ^{1}H NMR spectrum showed two sets of resonances (one broad and one sharp), presumably due to *E*- and *Z*-isomers relative to the imine C–H; slow exchange was confirmed by a 2D ^{1}H-EXSY experiment. The solid-state structure of **Cu-2** (Fig. 1) shows a less distorted trigonal planar geometry than **Cu-1**, with a more crowded Cu-centre due to the short Cu–$S_{thiolate}$ bond distance [2.1802(8) Å]. Furthermore, while the NHC ligand in **Cu-1** is in the same coordination plane as the amido and thioether, in **Cu-2**, the N–C–N plane of the NHC is twisted 81.3° relative to the S–Cu–N plane.

To investigate and directly compare the bifunctional activity of the two ligand systems, a series of E–H bond activation studies were carried out (Table 1). The reaction of benzaldehyde and pinacolborane with 1 mol% **Cu-1** gave quantitative conversion to the hydroboration product after 5 min at room temperature. The analogous reaction with acetophenone provided the same results with no decrease in activity with this less reactive substrate. Similar reactions with triethoxysilane afforded quantitative hydrosilylation products in 5 min. Lowering the catalyst loading to 0.1 mol% still gave quantitative conversion in 15 min, demonstrating the high activity and stability of **Cu-1**. Although sterically hindered ketones commonly present problems for Cu-catalyzed hydrosilylations,[14] benzophenone was efficiently converted to the silyl ether product in 10 min at room temperature. Triethylsilane may also be used as the silane source, however the reaction requires gentle heating and longer reaction times to reach completion (5%, 40 °C, 30 min). In contrast, attempted reactions with 4-*tert*-butyl styrene were unsuccessful and resulted in catalyst decomposition. To confirm selectivity for carbonyls over alkenes, *trans*-cinnamaldehyde was treated with triethoxysilane and 1 mol% **Cu-1**, affording the silyl ether product with no indication of the alkene hydrosilylation product. Interestingly, after 24 h we observed significant *cis*–*trans* equilibration in solution (see ESI†). In addition, aliphatic 5-hexen-2-one gave exclusive and quantitative hydrosilylation product with no indication of isomerization, providing further evidence that alkenes cannot bind to the metal centre during catalysis.

Table 1 Substrate scope of hydroboration and hydrosilylation reactions of carbonyls with catalytic **Cu-1** and **Cu-2**

Catalyst	Substrate	Carbonyl	Product	Yield (%)
Cu-1	HBpin			>99
Cu-1	HBpin			>99
Cu-1	$HSi(OEt)_3$			>99
Cu-1	$HSi(OEt)_3$			92
Cu-1	$HSi(OEt)_3$			>99
Cu-1	$HSi(OEt)_3$			>99
Cu-1	$HSi(OEt)_3$			>99
Cu-2	HBpin			>99
Cu-2	HBpin			>99
Cu-2	HBpin			>99

Conditions: copper catalyst (1 mol%), room temperature, 5–15 min. Yields were determined from ^{1}H NMR relative to internal standard mesitylene.

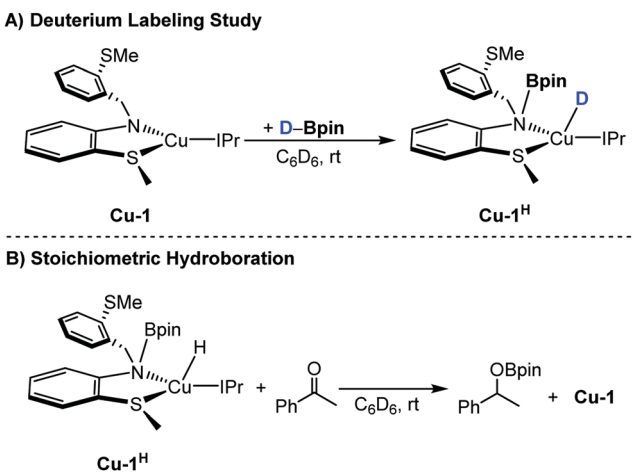
Since **Cu-1** was found to be an efficient catalyst for both hydroboration and hydrosilylation of carbonyls, the activity of **Cu-2** was also investigated. Reaction of benzaldehyde and pinacolborane with 1 mol% **Cu-2** afforded the hydroboration

product in near quantitative yield after 5 min. Analogous reactions with acetophenone, and even bulky benzophenone also resulted in complete conversion. However, **Cu-2** was not an active catalyst for hydrosilylations. Attempts to facilitate the hydrosilylation of either benzaldehyde or acetophenone were unsuccessful, even with higher catalyst loadings, longer reaction times, and elevated temperatures (see ESI†).

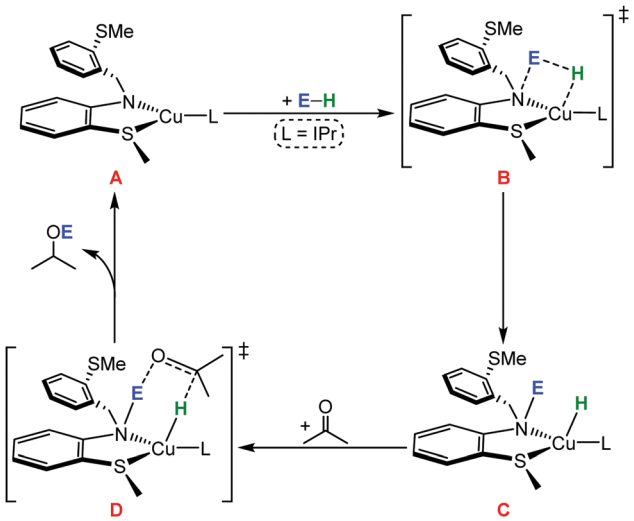
Several experiments were performed to gain insight into a plausible reaction pathway. By NMR spectroscopy, neither **Cu-1** nor **Cu-2** showed any reaction with stoichiometric benzaldehyde or with triethoxysilane at short reaction times; longer reaction times with the latter led to decomposition. In contrast, both complexes reacted with pinacolborane which has been shown previously to undergo B–H bond activation at metal amido[15] and thiolate[16] centres. Upon addition of 1 equiv. of pinacolborane to a C_6D_6 solution of **Cu-1**, an immediate colour change from pale yellow to dark yellow was observed. The ^{1}H NMR spectrum showed a new broad singlet at δ 2.5 assigned as a Cu–H species, as confirmed by the DBpin reaction with **Cu-1** (Scheme 2A). Further monitoring showed decomposition after approximately 1 h at room temperature, as evidenced by formation of a black precipitate and free **L1**.

The instability of monomeric NHC Cu–H species has been reported previously.[17] To establish the Cu–H species as an intermediate in the hydroboration reaction, a solution of **Cu-1^H** was prepared by reacting stoichiometric **Cu-1** and pinacolborane. The solution was then charged with stoichiometric acetophenone, resulting in the conversion to the hydroboration product, and reforming of **Cu-1** (Scheme 2B). It should be noted that the stoichiometric reaction of **Cu-2** with pinacolborane resulted in complete consumption of **Cu-2** into a new complex with multiple isomers that were not characterized further (see ESI†).

Based on the above experiments, a plausible reaction pathway for the hydroboration/hydrosilylation of carbonyls using **Cu-1** is shown in Scheme 3. The reaction begins with E–H bond activation through the proposed transition state, B, with the amido acting as a Lewis base. This results in the formation of a Cu–H species C, which then reacts with the carbonyl substrate



Scheme 2 Mechanistic studies performed with **Cu-1**.



Scheme 3 Proposed mechanism for E–H bond activation and reaction with carbonyls.

via outer-sphere transition state D, to furnish the final reduced carbonyl and regenerate A. The carbonyl substrate does not bind to the metal centre at any step throughout the catalytic cycle, explaining the selectivity for carbonyls over alkenes and lack of isomerization of the latter. It should be noted that for **Cu-2** catalyzed hydroboration, the thiolate donor serves as the Lewis base to promote B–H bond activation, as previously established by Wang.[18]

The original design of these Cu complexes was meant to crowd the Cu-centre with sufficient steric bulk to force an outer-sphere bifunctional mechanism. The fact that aldehydes and ketones readily react while olefins are inactive supports the envisioned outer-sphere mechanism, as the latter requires binding to the metal centre prior to activation. Complexes **Cu-1** and **Cu-2** also allowed a direct comparison for the bifunctional catalytic activity of the hard amido *vs.* the soft thiolate donor in the ligands **L1** and **L2**. While thiolate complex **Cu-2** is an efficient catalyst for hydroboration of carbonyls using pinacolborane, it was unable to effect the hydrosilylation. Amido complex **Cu-1** was shown to be superior for carbonyl reductions using either pinacolborane or triethoxysilane, giving full conversion at room temperature in less than 15 min, even with catalyst loadings of 0.1%. Mechanistic studies support the proposed reaction pathway in which the amido/thiolate serves as a Lewis base to facilitate E–H bond activation, generating a Cu–H intermediate that reacts with carbonyl substrates *via* an outer-sphere mechanism. There are few instances of copper being utilized in metal–ligand bifunctional catalysis, and most examples employ dinuclear-copper complexes.[19] Furthermore, nearly all examples of Cu–NHC catalyzed hydroboration and hydrosilylation reactions require either excess substrate, elevated temperatures, longer reaction times, or the use of base to generate the active Cu–H species (see Table S1 in ESI†).[10a,b] This work presents an extremely efficient carbonyl reduction pathway *via* a metal–ligand bifunctional outer-sphere mechanism that is unique for copper. Furthermore, installation of a chiral auxiliary in lieu of

the uncoordinated aryl-thioether may offer an opportunity for stereospecific catalysis. Future work will further explore potential reduction catalysis with other base metals.

We thank the NSERC and Canada Research Chairs program for generous financial support and the University of Ottawa, Canada Foundation for Innovation, and Ontario Ministry of Economic Development and Innovation for essential infrastructure. We also acknowledge Dr Jeff Ovens and Peter Pallister for XRD and NMR assistance.

Conflicts of interest

There are no conflicts to declare.

Notes and references

1 (*a*) B. de Bruin, P. Gualco and N. D. Paul, *Ligand Design in Metal Chemistry: Reactivity and Catalysis*, M. Stradiotto and R. J. Lundgren, 2016, p. 176; (*b*) V. Lyaskovskyy and B. de Bruin, *ACS Catal.*, 2012, **2**, 270–279; (*c*) H. Takeda, K. Koike, H. Inoue and O. Ishitani, *J. Am. Chem. Soc.*, 2008, **130**, 2023–2031.

2 (*a*) W. H. Harman and J. C. Peters, *J. Am. Chem. Soc.*, 2012, **134**, 5080–5082; (*b*) M. Devillard, G. Bouhadir and D. Bourissou, *Angew. Chem., Int. Ed.*, 2015, **54**, 730–732.

3 (*a*) D. Sellmann, R. Prakash, F. W. Heinemann, M. Moll and M. Klimowicz, *Angew. Chem., Int. Ed.*, 2004, **43**, 1877–1880; (*b*) M. L. Helm, M. P. Stewart, R. M. Bullock, M. R. DuBois and D. L. DuBois, *Science*, 2011, **333**, 863–866.

4 (*a*) J. R. Khusnutdinova and D. Milstein, *Angew. Chem., Int. Ed.*, 2015, **54**, 12236–12273; (*b*) T. Ikariya and A. J. Blacker, *Acc. Chem. Res.*, 2007, **40**, 1300–1308.

5 (*a*) J. I. van der Vlugt, *Eur. J. Inorg. Chem.*, 2012, 363–375; (*b*) R. H. Morris, *Acc. Chem. Res.*, 2015, **48**, 1494–1502; (*c*) L. Alig, M. Fritz and S. Schneider, *Chem. Rev.*, 2018, **119**, 2681–2751; (*d*) P. J. Chirik, *Acc. Chem. Res.*, 2015, **48**, 1687–1695; (*e*) W. Zuo, A. J. Lough, Y. F. Li and R. H. Morris, *Science*, 2013, **342**, 1080–1083; (*f*) C. P. Casey and H. Guan, *J. Am. Chem. Soc.*, 2007, **129**, 5816–5817.

6 P. A. Dub and J. C. Gordon, *ACS Catal.*, 2017, **7**, 6635–6655.

7 (*a*) S. N. MacMillan, W. H. Harman and J. C. Peters, *Chem. Sci.*, 2014, **5**, 590–597; (*b*) M. A. Nesbit, D. L. Suess and J. C. Peters, *Organometallics*, 2015, **34**, 4741–4752; (*c*) R. H. Morris, *Chem. Soc. Rev.*, 2009, **38**, 2282–2291.

8 M. Kanai, N. Kato, E. Ichikawa and M. Shibasaki, *Synlett*, 2005, 1491–1508.

9 (*a*) U. K. Das, S. L. Daifuku, S. I. Gorelsky, I. Korobkov, M. L. Neidig, J. J. Le Roy, M. Murugesu and R. T. Baker, *Inorg. Chem.*, 2016, **55**, 987–997; (*b*) U. K. Das, S. L. Daifuku, T. E. Iannuzzi, S. I. Gorelsky, I. Korobkov, B. Gabidullin, M. L. Neidig and R. T. Baker, *Inorg. Chem.*, 2017, **56**, 13766–13776; (*c*) U. K. Das, C. S. Higman, B. Gabidullin, J. E. Hein and R. T. Baker, *ACS Catal.*, 2018, **8**, 1076–1081.

10 (*a*) J. D. Egbert, C. S. Cazin and S. P. Nolan, *Catal. Sci. Technol.*, 2013, **3**, 912–926; (*b*) F. Lazreg, F. Nahra and C. S. Cazin, *Coord. Chem. Rev.*, 2015, **293**, 48–79; (*c*) Y. Tsuji and T. Fujihara, *Chem. Rec.*, 2016, **16**, 2294–2313.

11 O. Eisenstein and R. H. Crabtree, *New J. Chem.*, 2013, **37**, 21–27.

12 L. Dong, S. Qin, H. Yang, Z. Su and C. Hu, *Catal. Sci. Technol.*, 2012, **2**, 564–569.

13 (*a*) T. He, N. P. Tsvetkov, J. G. Andino, X. Gao, B. C. Fullmer and K. G. Caulton, *J. Am. Chem. Soc.*, 2009, **132**, 910–911; (*b*) M. Rakowski Dubois and D. L. Dubois, *Acc. Chem. Res.*, 2009, **42**, 1974–1982.

14 S. Díez-González, H. Kaur, F. K. Zinn, E. D. Stevens and S. P. Nolan, *J. Org. Chem.*, 2005, **70**, 4784–4796.

15 M. Pang, C. Wu, X. Zhuang, F. Zhang, M. Su, Q. Tong, C.-H. Tung and W. Wang, *Organometallics*, 2018, **37**, 1462–1467.

16 (*a*) L. Omann, C. D. F. Königs, H. F. Klare and M. Oestreich, *Acc. Chem. Res.*, 2017, **50**, 1258–1269; (*b*) K. D. Hesp, R. McDonald, M. J. Ferguson and M. Stradiotto, *J. Am. Chem. Soc.*, 2008, **130**, 16394–16406.

17 (*a*) N. P. Mankad, D. S. Laitar and J. P. Sadighi, *Organometallics*, 2004, **23**, 3369–3371; (*b*) S. C. Schmid, R. Van Hoveln, J. W. Rigoli and J. M. Schomaker, *Organometallics*, 2015, **34**, 4164–4173.

18 H. Song, K. Ye, P. Geng, X. Han, R. Liao, C.-H. Tung and W. Wang, *ACS Catal.*, 2017, **7**, 7709–7717.

19 (*a*) J. C. Deaton, S. C. Switalski, D. Y. Kondakov, R. H. Young, T. D. Pawlik, D. J. Giesen, S. B. Harkins, A. J. Miller, S. F. Mickenberg and J. C. Peters, *J. Am. Chem. Soc.*, 2010, **132**, 9499–9508; (*b*) R. Angamuthu, P. Byers, M. Lutz, A. L. Spek and E. Bouwman, *Science*, 2010, **327**, 313–315.