Organic & Biomolecular Chemistry

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/c5ob02259b

Cyclopropenation of internal alkynylsilanes and diazoacetates catalyzed by copper(I) N-heterocyclic carbene complexes†

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Received 2nd November 2015,
Accepted 21st December 2015

DOI: 10.1039/c5ob02259b

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Copper(I) N-heterocyclic carbene (CuNHC) complexes are more catalytically active than traditional transition metal salts for the cyclopropenation of internal alkynylsilanes and diazoacetate compounds. A series of 1,2,3-trisubstituted and 1,2,3,3-tetrasubstituted cyclopropenylsilane compounds were isolated in good overall yields. An interesting regioselective and chemodivergent reaction pathway was also observed to furnish a tetra-substituted furan for an electron-rich donor/acceptor diazoacetate. Finally, a practical synthesis of a cyclopropenyl-containing starting material that is useful for bioorthogonal chemistry is also described.

Introduction

Cyclopropene compounds are a valuable class of highly strained (54.5 kcal mol^{-1})[1] three-membered carbocyclic molecules which possess a uniquely reactive π bond. Many useful synthetic activation modes are known for their conversion into a diverse array of complex cyclic and acyclic molecular building blocks.[2] To the contrary, the synthesis of cyclopropene compounds has received less attention. One promising approach is the transition metal-catalyzed cyclopropenation of alkynes and diazoacetates, which has several distinct synthetic advantages over traditional 1,2-elimination strategies.[3] However, only a few transition metal catalysts (*e.g.* Rh(II),[4] Cu(I),[5] Co(II),[6] and Ir(II)[7]) are reported for the cyclopropenation of *terminal alkynes* and diazoacetates; while, an entirely different set of catalysts (*e.g.* Cu(I),[8] Ag(I),[9] and chiral Ag(I)/Au(I),[10]) are reportedly known to be most effective for the cyclopropenation of *internal alkynes* with the exception of the copper(I)-homoscorpionate catalysts.[11] And yet, to a much lesser extent, a series of miscellaneous reactions have been reported for the cyclopropenation of *internal alkynylsilanes* with rather ineffective catalysts (e.g Rh(II)-,[4b,12] Cu(0)-,[13] Cu(I)-,[14] and Cu(II)-[8,15]). This is despite the fact that 1-silylcyclopropenes are useful starting materials for platinum-catalyzed rearrangements,[16] Sila Morita–Baylis–Hillman reactions,[17] indium-catalyzed cycloisomerizations,[18] Pauson-Khand transformations,[12a,19] gold-catalyzed isomerizations,[20] and rearrangements into complex Vaska-type iridium complexes.[13a] Furthermore, 1-silylcyclopropene compounds are also valuable starting materials for the synthesis of a new class of bioorthogonal chemical reporters that are used in cellular metabolic labeling experiments.[21]

There are two methods that are used for the synthesis of 1- and 2-silylcyclopropenes.[22] In the first method, cyclopropene starting materials are treated to strongly basic/nucleophilic reaction conditions that are incompatible with base-sensitive functional groups and are more susceptible to destructive ring-opening reactions.[22a] To circumvent this, an inverse-addition protocol,[22b] carboxylate dianion approach,[22c] and a more mild, Cu(I)-catalyzed silylation have been reported.[22d] Still, the transition metal-catalyzed [2 + 1] cycloaddition of alkynylsilanes and diazoacetates is the most direct and general approach for the synthesis of 1-silylcyclopropenes, but these strategies are often fraught with consistently low yields (< 41%) and use an excess of alkynylsilane (2.5–10 fold) (Scheme 1). Recently, we reported a CuI-catalyzed cyclopropenation of 1-TMS-2-(4-methoxyphenyl)acetylene **1** (1.00 mmol) in the presence of a donor–acceptor diazoacetate **2a** (3.00 mmol) that afforded the corresponding 1,2,3,3-tetrasubstituted cyclopropenylsilane **3a** in modest yield (Scheme 2).[23] Given that this new finding gave slightly higher yields than all other previous examples, in addition to the commercial availability of highly active copper(I) N-heterocyclic carbene complexes for catalytic carbene transfer reactions,[24] we set out to examine their overall effectiveness for this transformation.

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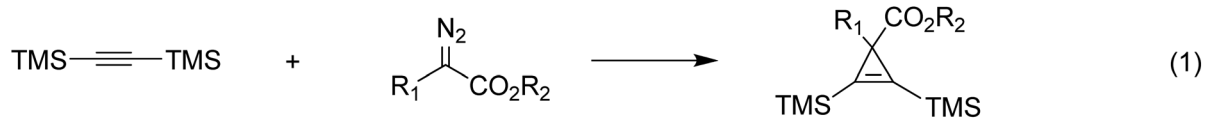
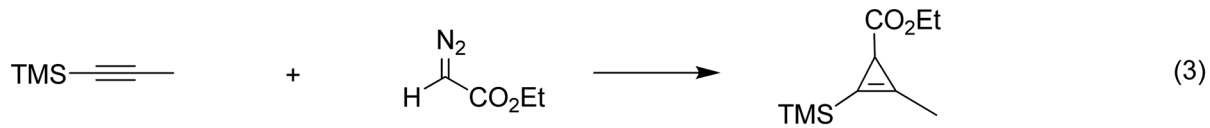
† Electronic supplementary information (ESI) available. CCDC 1434815. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5ob02259b



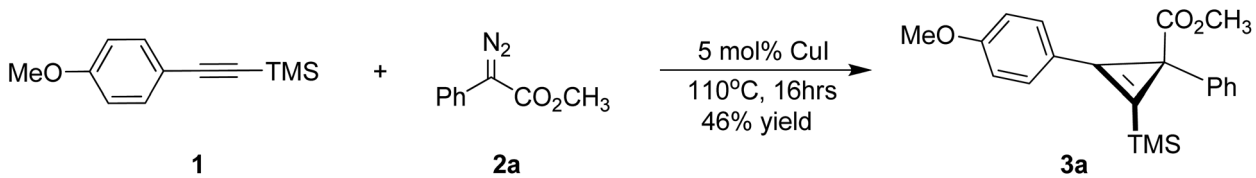
Maier (ref 14): R_1 = H, R_2 = Et *catalytic* CuBr, 18% yield
Kohn and Chen (ref 12b): R_1 = H, R_2 = Et (8.2 : 1 equivs) 2.5 mol% $Rh_2(OC_7H_{15})_4$, 60°C, 84h, 34% yield
Wheeler (ref 15e): R_1 = CO_2Me , R_2 = Me (5.1 : 1 equivs) 10^3 mol% $Cu(acac)_2$, 145°C, 36h, 33% yield

Wu (ref 13a): (2.83 : 1 equivs) 2 mol% Cu powder, 130°C, 16h, 30% yield
Neunhoeffer (ref 13b): (1 : 1 equivs) 23 mol% Cu powder, 135 - 145°C, 22% yield
Mueller and Granicher (ref 12c): (4.9 : 1 equivs) 1.7 mol% $Rh_2(OAc)_4$, 23°C, 11% yield



Shapiro (refs 15b-d): (3.0 : 1 equivs) *catalytic* $CuSO_4$, 110 - 120°C, 37% yield
Fox (ref 19): (2.0 : 1 equivs) 2 mol% $Rh_2(OAc)_4$ 25°C, 2.5h, 41% yield

Scheme 1 Collection of metal-catalyzed cyclopropenation of internal alkynylsilanes and diazoacetates.



1 **2a** **3a**

Scheme 2 Cu(I)-catalyzed synthesis of a tetra-substituted cyclopropene.

Results and discussion

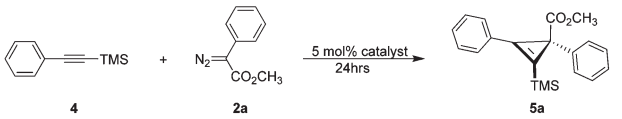
The study began by measuring the catalytic activities of various Cu(I)- and Rh(II)- salts for the cyclopropenation of 1-phenyl-2-trimethylsilylacetylene **4** and diazoacetate **2a** towards the synthesis of 1,2,3,3-tetrasubstituted cyclopropenylsilane **5a** (Table 1).

Although no product was observed at room temperature (Table 1, entries 1–2, 8), higher reaction temperatures (110 °C) resulted in modest isolated yields of the cyclopropenylsilane product **5a** (Table 1, entries 3–6) with cuprous salts. Comparatively, trifluorotoluene proved to be a more inert solvent than toluene and we did not observe any appreciable amount of cyclopropanation byproducts (Table 1, entry 4). (1,3-Bis-(diisopropyl-phenyl)imidazole-2-ylidene) copper(I) chloride, (^{i}PrCuCl), afforded **5a** in high isolated yield (84%, Table 1, entry 7). ^{i}PrCuCl is a N-heterocyclic carbene (NHC) copper (I) choride salt that is useful for the cyclopropanation and aziridination reactions of olefins.[24] Other Cu(I)–NHC salts were screened, but no significant improvement in the isolated yield was observed (Table 1, entries 9–11). Dirhodium(II) acetate, a benchmark catalyst for carbene transfer reactions, afforded cyclopropene **5a** in significantly lower isolated yield (24%, Table 1, entry 12). Finally, the thermally–induced cyclopropenation of **4** and **2a** afforded **5a** in comparable yield (24%).

With the optimized ^{i}PrCuCl-catalyzed reaction conditions in hand, we investigated the role of the silyl group's steric size on the reactivity of the cyclopropenation reaction (Table 2).

1-TBS-2-phenylacetylene **6** was easily converted to the corresponding cyclopropene **11a** in good yield (81%), while phenyl tripropylsilylacetylene **7** afforded cyclopropene **12a** in poor yield (8%). Increasing the steric bulk of the silane group

Table 1 Optimization of reaction conditions



4 2a 5a

Entry	Catalyst	Solvent	Temperature (°C)	Isolated yield (%)
1	CuI	CH_2Cl_2	23	—
2	CuI	CH_3Ph	23	—
3	CuI	CH_3Ph	110	26
4	CuI	CF_3Ph	110	34
5[a]	CuI	CF_3Ph	110	8
6	CuTC	CF_3Ph	110	15
7	^{i}PrCuCl	CF_3Ph	110	84
8	^{i}PrCuCl	CF_3Ph	23	—
9	MesCuCl	CF_3Ph	110	74
10	^{i}PrCuBF$_4$	CF_3Ph	110	65
11	(^{i}Pr)$_2$CuBF$_4$	CF_3Ph	110	64
12	$Rh_2(OAc)_4$	CF_3Ph	110	24
13	None	CF_3Ph	110	24

Reaction conditions: A solution of **4** and catalyst in CF_3Ph (2 mL) was added a solution of **2a** in CF_3Ph (20 mL) at 1.00 mL min^{-1} at 110 °C. The reaction was concentrated and purified by chromatography.

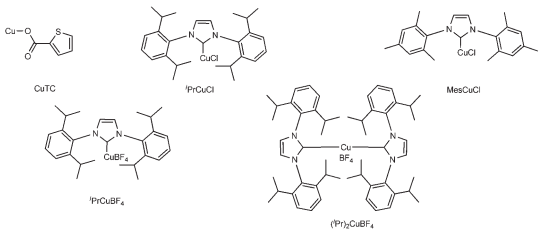
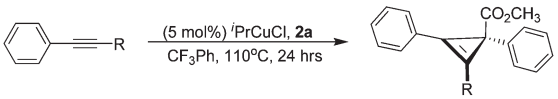


Table 2 Silane steric effects on the ^{i}PrCuCl-catalyzed cyclopropenation

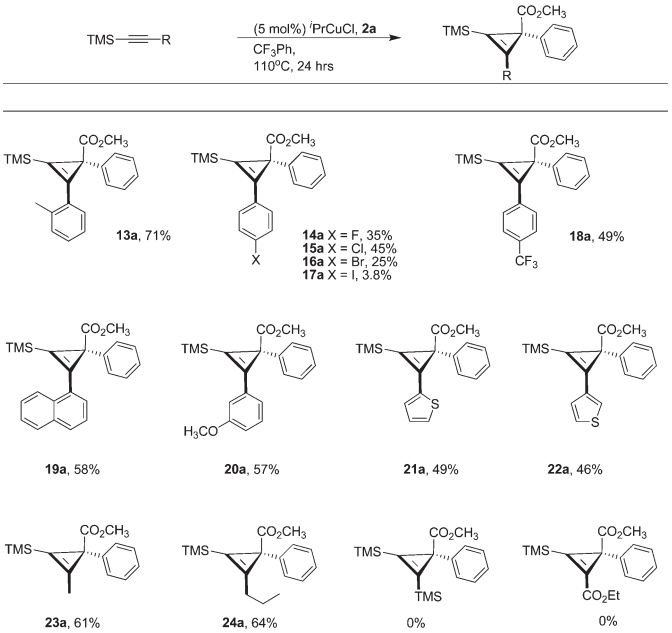


Entry	Alkyne	R	Product	Isolated yield (%)
1	6	$(CH_3)_2{}^{t}$BUSi	**11a**	81
2	7	(^{n}Pr)$_3$Si	**12a**	8
3	8	(^{i}Pr)$_3$Si		—
4	9	(Ph)$_2{}^{t}$BuSi		—
5	10	(Ph)$_3$Si		—

any further had a detrimental effect on the reactivity and alkynylsilanes **8–10** were recovered without significant decomposition. This feature may be especially useful when one or more acetylenic sites are reactive.[19]

With the optimum reaction conditions in hand, we surveyed various aliphatic and aromatic alkynylsilanes to measure the activity of ^{i}PrCuCl-catalyzed cyclopropenation in the presence of **2a** (Table 3). The relatively electron-rich and sterically-hindered *ortho*-tolyl(trimethylsilyl)acetylene was converted into the corresponding cyclopropene **13a** in good yield (71%).

Table 3 Cyclopropenation of electronically and structurally diverse alkynylsilanes



Electron-deficient *para*-halophenyl(trimethylsilyl)acetylenes furnished the corresponding cyclopropenes **14a–17a** in moderate overall yields, while 2-(4-iodophenyl)cyclopropene **17a** was isolated in low yield (3.8%). In a straightforward manner, trifluorotolyl, 1-naphthyl, and *meta*-methoxyphenyl alkynylsilanes furnished cyclopropenyl esters **18a–20a** in useful overall yields (>49%, Table 3). Interestingly, both 2- and 3-thiophene substituted alkynylsilanes were converted into cyclopropenes **21a** and **22a** in modest isolated yields. 2-Alkyl-1-trimethyl-

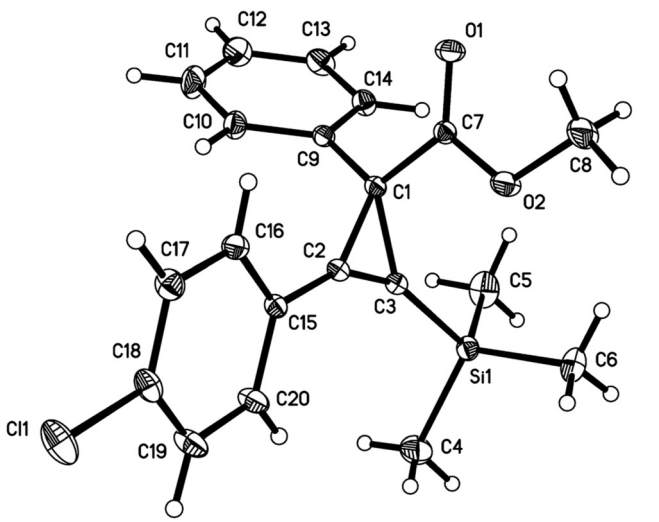


Fig. 1 OTREP diagram of **15a**.

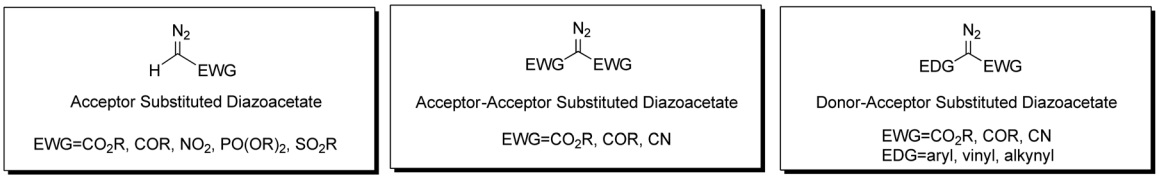


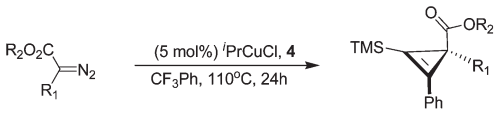
Fig. 2 Three classes of diazoacetate compounds used in carbene transfer reactions With this in mind, we tested the reactivity and selectivity of various diazoacetate compounds for the ^{i}PrCuCl-catalyzed cyclopropenation of internal alkynylsilane compounds (Table 4).

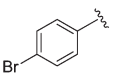
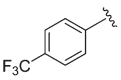
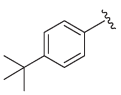
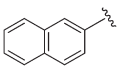
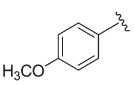
silylacetylenes were smoothly converted into **23a** and **24a** in good isolated yields (61% and 64%, respectively, Table 3). Unfortunately, both bistrimethylsilylacetylene and ethyl 3-(trimethylsilyl)propiolate were unreactive presumably due to their relatively higher electron deficient nature (Table 3). Compound **15a**, serving as a representative example of the 1,2,3,3-tetrasubstituted cyclopropenes synthesized in this study, was recrystallized from refluxing hexane to yield suitable crystals for X-ray crystallography (Fig. 1).

Several decades of transition metal carbenoid research suggests that the selectivity for carbene transfer reactions is largely dependent on the electronic nature of the diazoacetate.[25] As a result, three classes of diazoacetate compounds have been classified based primarily on their differing reactivity and/or selectivity observed for carbene transfer reactions (Fig. 2).

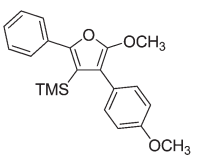
Both the CuI- and ^{i}PrCuCl-catalyzed cyclopropenation of alkynylsilane **4** in the presence of acceptor-substituted diazo-

Table 4 Survey of the reactivity of various diazoacetate compounds

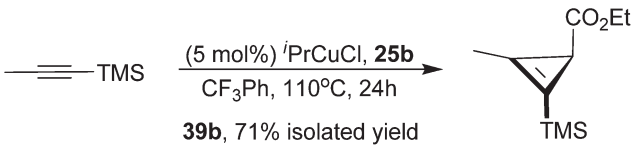


Entry	Diazoacetate	R_1	R_2	Product	Isolated yield (%)
1[a]	**25b**	H	CH_2CH_3	**32b**	41
2	**25b**	H	CH_2CH_3	**32b**	77
3[b]	**26c**	CO_2CH_3	CH_3	—	n.d.
4	**27d**		CH_3	**33d**	63
5	**28e**		CH_3	**34e**	54
6	**29f**		CH_3	**35f**	69
7	**30g**		CH_3	**36g**	61
8[c]	**31h**		CH_3	**37h**	69

[a] 5 mol% CuI. [b] n.d. = not determined. [c] Tetra-substituted furan **38h** was also isolated.



38h, 21% isolated yield



Scheme 3 Synthesis of a bioorthogonal chemical reporter precursor.

acetate **25b** cleanly furnished cyclopropene **32b** in substantially higher overall isolated yields than previous reports (Table 4, entries 1 and 2).[12c,13] The acceptor-acceptor substituted diazomalonate compound **26c** was completely unreactive in the presence of alkynylsilane **4** (Table 4, entry 3). Electron-deficient donor–acceptor diazoacetates **27d** and **28e** afforded cyclopropene compounds **33d** and **34e** in satisfactory isolated yields (63% and 54%, respectively) (Table 4, entries 4 and 5). Cyclopropenes **35f** and **36g** were also isolated in good yields from donor–acceptor diazoacetates **29f** and **30g** (69% and 61%, respectively) (Table 4, entries 6 and 7). Interestingly, electron-rich donor–acceptor diazoacetate **31h** afforded tetra-substituted cyclopropene **37h** and a tetra-substituted furan **38h** as a separable mixture by flash chromatography in good overall yields (Table 4, entry 9). To the best of our knowledge, this is the first example of a donor–acceptor diazoacetate compound undergoing a formal [3 + 2] cycloaddition to form a tetra-substituted furan. A two-dimensional [^{1}H, ^{1}H]-NOESY spectrum was recorded to corroborate the structure of **38h**. NOE crosspeaks were observed between the TMS group and both the (i) phenyl group and (ii) *para*-methoxy-substituted phenyl group (see ESI†). It is plausible that the β-silicon hyperconjugation in close proximity to the site of C–O bond formation is responsible for the high regioselectivity observed.

The real-time labelling of a biomolecule which contains a reactive non-natural functional group with a molecular imaging agent – often referred to as bioorthogonal chemistry – is among the most essential tools used for imaging cellular processes under physiological conditions.[26] In recent years, cyclopropenyl-containing compounds have emerged as an important class of bioorthogonal moieties that are effectively incorporated in biomolecules and subsequently labeled *via* an inverse-demand Diels–Alder cycloaddition reaction with a tetrazine fluorescent tag.[21] We applied our methodology towards the synthesis of a frequently utilized cyclopropene starting material **39b** and observed the highest isolated yield (71%) reported to date from 1-TMS-propyne and ethyl diazoacetate (Scheme 3). In comparison to other previously reported transition metal-catalyzed processes (Scheme 1, eqn (3)),[15b–d,19] this strategy is a more sustainable alternative for the synthesis 1-silylcyclopropenyl-containing bioorthogonal ligands.

Conclusions

Cu(I)–NHC salts are efficient catalysts for the direct transition metal-catalyzed cyclopropenation of a wide range of internal alkynylsilanes and diazoacetate towards the synthesis of polysubstituted 1-silylcyclopropene compounds in good overall yields. In particular, diazoacetate compounds displayed a wide range of reactivity ranging from unreactive to facilitating an unexpected regioselective tetra-substituted furan product by means of a chemodivergent pathway. Finally, the ^{i}PrCuCl-catalyzed cyclopropenation of 1-TMS-2-propyne and ethyl diazoacetate is a highly effective method for the synthesis of a bioorthogonal chemical reporter that is useful for imaging cellular processes.

Acknowledgements

This work was supported in part by the Rochester Institute of Technology (RIT) FEAD grant and the RIT Office of the Vice President of Research. B. A. M thanks the RIT Honor's program for summer financial support. T. N. thanks RIT SCMS for the Daniel J. Pasto Undergraduate Cooperative Fellowship award. Thank you to Dr William W. Brennessel and the X-ray Crystallographic Facility in the Department of Chemistry at the University of Rochester for structural analysis. Special thanks to Dr Sandip Sur and the Nuclear Magnetic Resonance Spectrometer Facility in the Department of Chemistry at the University of Rochester for NMR spectral analysis.

References

1 P. v. R. Schleyer, J. E. Williams and K. R. Blanchard, *J. Am. Chem. Soc.*, 1970, **92**, 2377.
2 (*a*) C. Song, J. Wang and Z. Xu, *Org. Biomol. Chem.*, 2014, **12**, 5802; (*b*) L. H. Phun, J. Aponte-Guzman and S. France, *Synlett*, 2012, 2723; (*c*) M. Rubin and P. G. Ryabchuk, *Chem. Heterocycl. Compd.*, 2012, **48**, 126; (*d*) Z.-B. Zhu, Y. Wei and M. Shi, *Chem. Soc. Rev.*, 2011, **40**, 5534; (*e*) F. Miege, C. Meyer and J. Cossy, *Beilstein J. Org. Chem.*, 2011, **7**, 717; (*f*) M. Rubin, M. Rubina and V. Gevorgyan, *Chem. Rev.*, 2007, **107**, 3117; (*g*) M. Rubin, M. Rubina and V. Gevorgyan, *Synthesis*, 2006, 1221.
3 (*a*) A. R. A. Dulayymi, J. R. A. Dulayymi, M. S. Baird and G. Koza, *Russ. J. Org. Chem.*, 1997, **33**, 798; (*b*) K. B. Baucom and G. B. Butler, *J. Org. Chem.*, 1972, **37**, 1730; (*c*) M. S. Baird, H. H. Hussain and W. Nethercott, *J. Chem. Soc., Perkin Trans. 1*, 1986, 1845; (*d*) W. M. Sherrill, R. Kim and M. Rubin, *Synthesis*, 2009, 1477.
4 (*a*) N. Petiniot, A. J. Anciaux, A. F. Noels, A. J. Hubert and P. Teyssie, *Tetrahedron Lett.*, 1978, 1239; (*b*) M. N. Protopopova, M. P. Doyle, P. Mueller and D. Ene, *J. Am. Chem. Soc.*, 1992, **114**, 2755; (*c*) M. P. Doyle, M. Protopopova, P. Muller, D. Ene and E. A. Shapiro, *J. Am. Chem. Soc.*, 1994, **116**, 8492; (*d*) P. Muller and H. Imogai, *Tetrahedron: Asymmetry*, 1998, **9**, 4419; (*e*) H. M. L. Davies and G. H. Lee, *Org. Lett.*, 2004, **6**, 1233; (*f*) L.-a. Liao, F. Zhang, N. Yan, J. A. Golen and J. M. Fox, *Tetrahedron*, 2004, **60**, 1803; (*g*) Y. Lou, M. Horikawa, R. A. Kloster,

N. A. Hawryluk and E. J. Corey, *J. Am. Chem. Soc.*, 2004, **126**, 8916; (*h*) M. Rubin and V. Gevorgyan, *Synthesis*, 2004, 796; (*i*) D. T. Nowlan III and D. A. Singleton, *J. Am. Chem. Soc.*, 2005, **127**, 6190; (*j*) Y. Lou, T. P. Remarchuk and E. J. Corey, *J. Am. Chem. Soc.*, 2005, **127**, 14223; (*k*) S. Chuprakov and V. Gevorgyan, *Org. Lett.*, 2007, **9**, 4463; (*l*) J. F. Briones, J. Hansen, K. I. Hardcastle, J. Autschbach and H. M. L. Davies, *J. Am. Chem. Soc.*, 2010, **132**, 17211; (*m*) J. F. Briones, J. Hansen, K. I. Hardcastle, J. Autschbach and H. M. L. Davies, *J. Am. Chem. Soc.*, 2010, **132**, 17211; (*n*) A. DeAngelis, O. Dmitrenko and J. M. Fox, *J. Am. Chem. Soc.*, 2012, **134**, 11035.

5 (*a*) P. J. Perez, M. Brookhart and J. L. Templeton, *Organometallics*, 1993, **12**, 261; (*b*) D.-J. Cho, S.-J. Jeon, H.-S. Kim, C.-S. Cho, S.-C. Shim and T.-J. Kim, *Tetrahedron: Asymmetry*, 1999, **10**, 3833; (*c*) M. Mar Diaz-Requejo and P. J. Perez, *J. Organomet. Chem.*, 2001, **617–618**, 110; (*d*) H. Martinez-Garcia, D. Morales, J. Perez, M. Puerto and D. Miguel, *Inorg. Chem.*, 2010, **49**, 6974; (*e*) C. Martin, M. Sierra, E. Alvarez, T. R. Belderrain and P. J. Perez, *Dalton Trans.*, 2012, **41**, 5319.

6 (*a*) X. Cui, X. Xu, H. Lu, S. Zhu, L. Wojtas and X. P. Zhang, *J. Am. Chem. Soc.*, 2011, **133**, 3304; (*b*) X. Cui, X. Xu, L. Wojtas, M. M. Kim and X. P. Zhang, *J. Am. Chem. Soc.*, 2012, **134**, 19981.

7 M. Uehara, H. Suematsu, Y. Yasutomi and T. Katsuki, *J. Am. Chem. Soc.*, 2011, **133**, 170.

8 N. P. a. E. A. S. Marina, *Russ. Chem. Rev.*, 1989, **58**, 667.

9 J. F. Briones and H. M. L. Davies, *Org. Lett.*, 2011, **13**, 3984.

10 J. F. Briones and H. M. L. Davies, *J. Am. Chem. Soc.*, 2012, **134**, 11916.

11 M. M. Diaz-Requejo, M. A. Mairena, T. R. Belderrain, M. C. Nicasio, S. Trofimenko and P. J. Perez, *Chem. Commun.*, 2001, 1804.

12 (*a*) M. K. Pallerla and J. M. Fox, *Org. Lett.*, 2005, **7**, 3593; (*b*) D. W. Kohn and P. Chen, *J. Am. Chem. Soc.*, 1993, **115**, 2844; (*c*) P. Mueller and C. Graenicher, *Helv. Chim. Acta*, 1993, **76**, 521.

13 (*a*) H.-P. Wu, D. H. Ess, S. Lanza, T. J. R. Weakley, K. N. Houk, K. K. Baldridge and M. M. Haley, *Organometallics*, 2007, **26**, 3957; (*b*) H. Neunhoeffer, R. Bopp and W. Diehl, *Liebigs Ann. Chem.*, 1993, 367.

14 G. Maier, M. Hoppe, H. P. Reisenauer and C. Krueger, *Angew. Chem., Int. Ed. Engl.*, 1982, **94**, 445.

15 (*a*) E. A. Shapiro, A. V. Kalinin, D. N. Platonov and O. M. Nefedov, *Izv. Akad. Nauk. Ser. Khim.*, 1993, 1248; (*b*) E. A. Shapiro, G. V. Lun'kova, I. E. Dolgii and O. M. Nefedov, *Izv. Akad. Nauk. SSSR, Ser. Khim.*, 1984, 2529; (*c*) E. A. Shapiro, G. V. Lun'kova, I. E. Dolgii and O. M. Nefedov, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1981, 1316; (*d*) E. A. Shapiro, G. V. Lun'kova, A. O. Nefedov, I. E. Dolgii and O. M. Nefedov, *Izv. Akad. Nauk. SSSR, Ser. Khim.*, 1981, 2535; (*e*) T. N. Wheeler and J. Ray, *J. Org. Chem.*, 1987, **52**, 4875.

16 J. Li, C. Sun, S. Demerzhan and D. Lee, *J. Am. Chem. Soc.*, 2011, **133**, 12964.

17 S. Chuprakov, D. A. Malyshev, A. Trofimov and V. Gevorgyan, *J. Am. Chem. Soc.*, 2007, **129**, 14868.

18 L. H. Phun, J. Aponte-Guzman and S. France, *Angew. Chem., Int. Ed.*, 2012, **51**, 3198.

19 M. K. Pallerla and J. M. Fox, *Org. Lett.*, 2007, **9**, 5625.

20 J. T. Bauer, M. S. Hadfield and A.-L. Lee, *Chem. Commun.*, 2008, 6405.

21 (*a*) D. M. Patterson and J. A. Prescher, *Curr. Opin. Chem. Biol.*, 2015, **28**, 141; (*b*) D. M. Patterson, L. A. Nazarova and J. A. Prescher, *ACS Chem. Biol.*, 2014, **9**, 592; (*c*) D. M. Patterson, K. A. Jones and J. A. Prescher, *Mol. BioSyst.*, 2014, **10**, 1693; (*d*) D. N. Kamber, L. A. Nazarova, Y. Liang, S. A. Lopez, D. M. Patterson, H.-W. Shih, K. N. Houk and J. A. Prescher, *J. Am. Chem. Soc.*, 2013, **135**, 13680; (*e*) D. M. Patterson, L. A. Nazarova, B. Xie, D. N. Kamber and J. A. Prescher, *J. Am. Chem. Soc.*, 2012, **134**, 18638.

22 (*a*) I. Zrinski and M. Eckert-Maksic, *Synth. Commun.*, 2003, **33**, 4071; (*b*) I. Zrinski, G. Gadanji and M. Eckert-Maksic, *New J. Chem.*, 2003, **27**, 1270; (*c*) L.-a. Liao, N. Yan and J. M. Fox, *Org. Lett.*, 2004, **6**, 4937; (*d*) E. A. F. Fordyce, Y. Wang, T. Luebbers and H. W. Lam, *Chem. Commun.*, 2008, 1124.

23 A. K. Swenson, K. E. Higgins, M. G. Brewer, W. W. Brennessel and M. G. Coleman, *Org. Biomol. Chem.*, 2012, **10**, 7483.

24 (*a*) B. M. Trost and G. Dong, *J. Am. Chem. Soc.*, 2006, **128**, 6054; (*b*) R. E. Gawley and S. Narayan, *Chem. Commun.*, 2005, 5109; (*c*) M. R. Fructos, T. R. Belderrain, M. C. Nicasio, S. P. Nolan, H. Kaur, M. M. Diaz-Requejo and P. J. Perez, *J. Am. Chem. Soc.*, 2004, **126**, 10846.

25 (*a*) M. P. Doyle, *Chem. Rev.*, 1986, **86**, 919; (*b*) M. P. Doyle, M. A. McKervey and T. Ye, *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds: From Cyclopropanes to Ylides*, 1998, 652 pp.

26 (*a*) C. P. Ramil and Q. Lin, *Chem. Commun.*, 2013, **49**, 11007; (*b*) M. F. Debets, J. C. M. van Hest and F. P. J. T. Rutjes, *Org. Biomol. Chem.*, 2013, **11**, 6439; (*c*) K. Lang and J. W. Chin, *ACS Chem. Biol.*, 2014, **9**, 16; (*d*) K. Lang and J. W. Chin, *Chem. Rev.*, 2014, **114**, 4764; (*e*) P. Shieh and C. R. Bertozzi, *Org. Biomol. Chem.*, 2014, **12**, 9307; (*f*) M. Zheng, L. Zheng, P. Zhang, J. Li and Y. Zhang, *Molecules*, 2015, **20**, 3190.

