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Additive-Free Pd-Catalyzed α-Allylation of Imine-Containing Heterocycles

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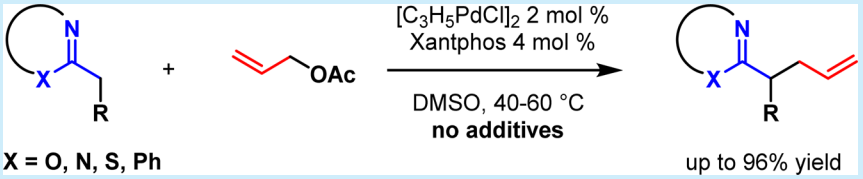
Supporting Information



ABSTRACT: An additive-free Pd-catalyzed α-allylation of different imino-group-ontaining heterocycles is reported. The activation of α-CH pronucleophiles (pK_a (DMSO) > 25) occurs without the addition of strong bases or Lewis acids using only the Pd/Xantphos catalyst system. The reaction scope has been studied for various 5- and 6-membered nitrogen-containing heterocycles (yields up to 96%). Mechanistic investigations suggest an initial allylation of the imine-*N* followed by a Pd-catalyzed formal aza-Claisen rearrangement.

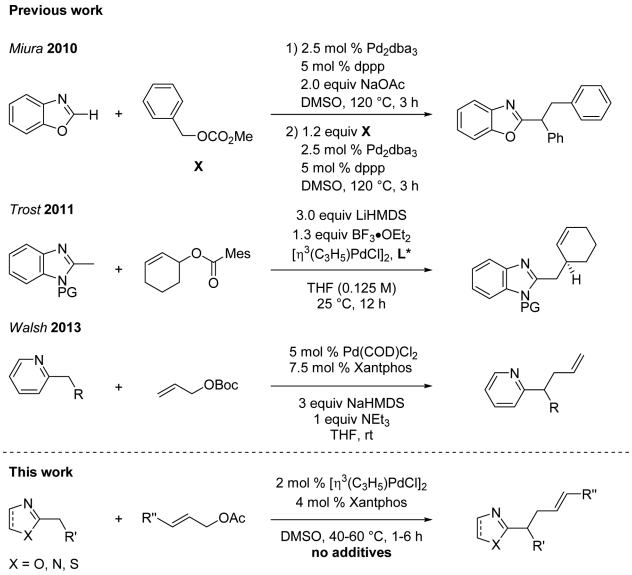
Over the past decade, the transition-metal-catalyzed CH functionalization of heterocycles has expanded the organic tool box with efficient means to form C−C bonds without apparent leaving groups on the heterocycle substrate.[1,2] Among these the allylation of heterocycles at the sp^2-hybridized carbon under CH-activation has been described by using various transition metals as catalysts.[3] Apart from CH-activated direct allylation of aromatic heterocycles, activation of C-sp^3 pronucleophiles for the formation of C−C bonds in classical allylic alkylations requires addition of bases or in situ generated bases or additives[4] and can only be circumvented in rare cases without additives.[5]

In this context, the activation of C(sp^3)−H bonds of nitrogen heterocycles with pK_a's (DMSO) > 25 requires overstoichiometric amounts of reagents as described in previous work by Trost, Walsh, and others (Scheme 1),[6] whereas the activation of α-acidic protons of aldehydes or ketones (pK_a's < 25 in DMSO) can be achieved with catalytic amounts of reagents.[7] We now report a new method for the additive-free α-allylation of several heterocycles with allyl acetate under mild conditions (Scheme 1), which complements the existing work on various nucleophiles.[8]

In our ongoing efforts to use the Tsuji−Trost allylation[9] for the synthesis of biologically active molecules,[10] we have observed that, when DBN is used as base additive, under certain circumstances the formation of allylated 1,8-diazabicyclonon-5-ene (**3**) could be observed. This reaction aroused our interest as it appeared to have proceeded under direct C−H allylation in an α-position to an amidine moiety[2] whereas comparable *N*-heterocycles could only be activated with strong bases and additives (Scheme 2).[6]

In order to prevent a possible self-deprotonation, which could be the case for bases like DBN, we used the readily available oxazoline **4** as a suitable test substrate to study the influence of ligand, solvent, leaving group, and temperature on the yield of the allylation reaction (Table 1 and Supporting Information). Among the tested 9 monodentate and 13 bidentate ligands (see the Supporting Information for full reaction optimization and results), only the bidentate ligands DPEPhos and Xantphos resulted in substantial product formation (77% and 99%, respectively), reflecting a strong influence of the bite angle.[11] As Xantphos has been identified as

Scheme 1. Related Work and Initial Plan on the Activation of Substrates with pK_a's Higher than 25 (DMSO)



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Scheme 2. Initial Observation of the Pd-Catalyzed α-Allylation

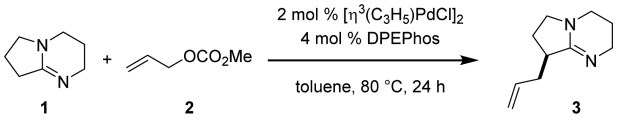
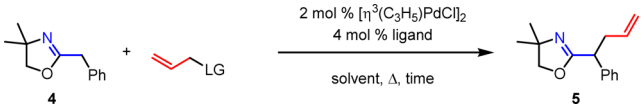


Table 1. Optimization of the Pd-Catalyzed Allylation[a]



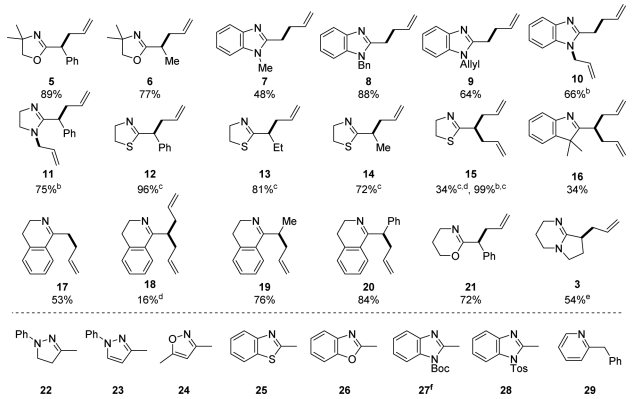
entry	LG	ligand	time (h)	t (°C)	solvent	**5** (%)[b,c]
1	OCO_2Me	DPEPhos	18	80	toluene	65
2	OH	DPEPhos	18	80	toluene	-
3	Br	DPEPhos	18	80	toluene	-
4	OAc	DPEPhos	18	80	toluene	77
5	OAc	DPEPhos	18	60	toluene	72
6	OAc	BINAP	18	60	toluene	3
7	OAc	(-)DIOP	18	60	toluene	-
8	OAc	DPPF	18	60	toluene	9
9	OAc	PHOX ligand	18	60	toluene	-
10	OAc	Trost ligand	18	60	toluene	-
11	OAc	XantPhos	18	60	toluene	99
12[d]	OAc	Xantphos	1	60	DMSO	99

[a]Reactions were performed with 2 mol % of $(C_3H_5PdCl)_2$, 4 mol % of ligand, 1.0 equiv (0.5 mmol) of allyl reagent, and 1.0 equiv (0.5 mmol) of **4** at 80 °C in solvent (0.2 M). Conversion was monitored via GC–MS with mesitylene (0.5 mmol) as internal standard. [b]Conversion to **5** was adjusted with the internal standard. [c]The racemic mixture of **5** could be observed with a chiral Feringa–phosphoamidite ligand (see the Supporting Information). [d]The reaction was performed in a 1.0 M solution at 60 °C, and complete conversion was observed after 1 h.

the best ligand in the initial screening, we used this ligand for subsequent reaction optimization studies.

With these optimized conditions in hand (Table 1, entry 12), we sought to investigate the scope and limitations of this reaction and tested a series of heterocycles featuring an imine moiety as part of the ring structure (Scheme 3). We were pleased to see that the catalyst combination Pd/Xantphos enabled the allylation of several different nitrogen heterocycles,

Scheme 3. Substrate Scope of Different Imine-Containing Heterocycles for the Pd-Catalyzed Allylation[a]



[a]Reactions were performed with 2 mol % of $(C_3H_5PdCl)_2$, 4 mol % of Xantphos, 1.0 equiv (1.0 mmol) of allyl acetate, and 1.0 equiv (1.0 mmol) of substrate at 60 °C in DMSO (1.0 M) for 1 h. [b]Isolated yield when 2.0 equiv (2.0 mmol) of allyl acetate was used. [c]40 °C was used for this reaction. [d]Isolated yield when 1.0 equiv (1.0 mmol) of allyl acetate was used. [e]1.0 equiv (1.0 mmol) of allylmethylcarbonate was used instead of 1.0 equiv (1.0 mmol) of allyl acetate. [f]Deprotection and subsequent *N*-allylation were observed for this substrate.

like dihydroimidazoles, tetrahydropyrimidines, dihydroisoquinolines, thiazolines, and benzimidazoles. Thiazolines proved to be more reactive than other heterocycles and could be converted even at 40 °C. 2-Alkylbenzimidazoles were converted to **7**–**10** in moderate to good yields. Interestingly, some substrates which are less substituted have a tendency to preferentially generate the diallylated products **15** and **16**. In these cases, only diallylated products and starting material could be observed via GC–MS if the reactions were quenched before completion. Other diallylated products could only be monitored in traces and in only one case were produced in a significant amount when 1.0 equiv of allylating reagent was used (Scheme 3, **18**). Unfortunately, several heterocycles could not be allylated with the applied reaction conditions (Scheme 3, **22**–**29**). Interestingly, benzothiazole **25** and benzoxazole **26** could not be converted compared to the benzimidazole series **7**–**10**. Moreover, the electronic properties of the heterocycle seemed to have a great impact on the outcome of the reaction. Electron-deficient nitrogen heterocycles **23**, **24**, and **29** were not converted even with the optimized reaction conditions.

The failure of the reaction with substrates **27** and **28** suggested that electron-withdrawing protecting groups on the methyl benzimidazole ring adversely affected the reactivity of these substrates (Scheme 2). Therefore, we envisioned a suitable one-pot protection/allylation/deprotection protocol, in which the allyl group would serve as a temporary protecting group. We were pleased to see that *C*-allylation product **32** could be generated in 61% yield with slightly modified conditions to the known standard procedures using phenylsilane for the deprotection of the intermediately formed *N*-allyl group (Scheme 4).[12]

After having established the scope of the nucleophile substrates, we studied various alternative allyl electrophiles for their suitability in our reaction. We could use the monosubstituted allylacetates **35** and **37** as electrophiles. However, higher substituted electrophiles **39**–**41** were not converted. Moreover, longer reaction times were necessary for the active electrophiles to enable satisfying conversions (Table 2).

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Scheme 4. One-Pot Approach for the α-Allylation of Unprotected 2-Methylbenzimidazole

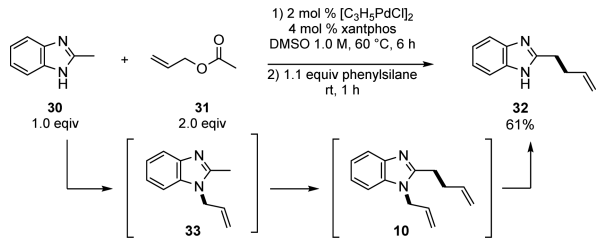
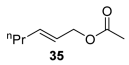
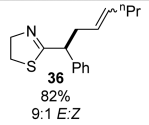
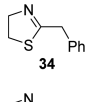
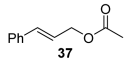
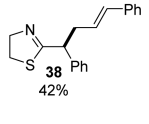
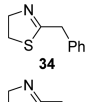
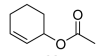
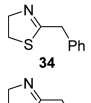
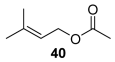
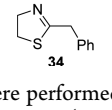


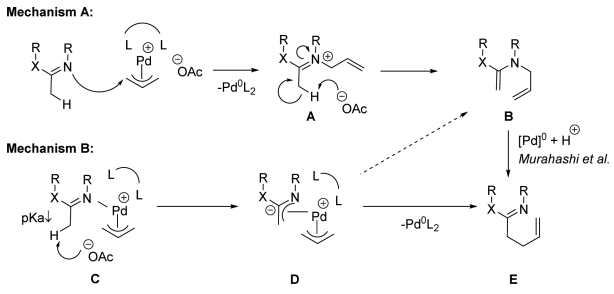
Table 2. Scope of the Allylating Reagents[a]

entry	substrate	allyl reagent	product (yield) %
1	 34	 35	 36 82% 9:1 *E*:*Z*
2	 34	 37	 38 42%
3[b]	 34	 39	-
4[b]	 34	 40	-
5[b]	 34	 41	-

[a]Reactions were performed with 2 mol % of $(C_3H_5PdCl)_2$, 4 mol % of Xantphos, 1.0 equiv (1.0 mmol) of allyl reagent, and 1.0 equiv (1.0 mmol) of substrate at 60 °C in DMSO (1.0 M) for 6 h. [b]No conversion could be detected at 60 and 100 °C after 24 h.

The observation that a rather electron-rich imine moiety was necessary for the reaction should also give a hint about the underlying mechanism for this reaction. Due to the rather high pK_a of the α-proton of the imine functionality, we excluded a direct deprotonation by the acetate anion released after formation of the η^3-Pd−allyl complex. We hypothesized that the CH bond could be acidified either by an initial allylation of the imine-*N* leading to an iminium ion **A** (Scheme 5,

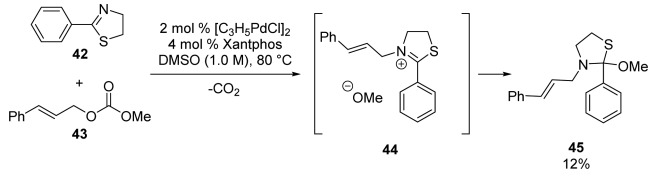
Scheme 5. Proposed Reaction Mechanism



mechanism A) or by complexation of the cationic Pd-complex as a Lewis acid **C** (Scheme 5, mechanism B). According to mechanism A, an *N*-vinyl allylamine intermediate **B** would form from **A**, which can undergo a Pd-catalyzed aza-Claisen rearrangement.[13]

In order to test these mechanistic hypotheses, we performed an experiment in which we used thiazoline **42** as a substrate without enolizable α-hydrogen. According to mechanism A, a nucleophilic base should be able to attack the cationic intermediate **43** at the electrophilic iminium. In the experiment, we could trap the proposed intermediate **44** and isolated adduct **45** in 12% yield after 5 h at 80 °C when allylmethylcarbonate was used as electrophile (Scheme 6),

Scheme 6. Trapping Experiment for the Elucidation of the Reaction Mechanism



which gives support to mechanism A. This mechanism also explains why less nucleophilic heterocylces and less electrophilic allyldonors are not turned over in this reaction (see Scheme 2 and Table 2).

In conclusion, we have shown that the α-allylation of imine-containing heterocycles can be mediated by a Pd/Xantphos catalyst system, which operates without the addition of any additive resulting in mild reaction conditions. It is suggested that in contrast to other established allylation reactions this transformation is initiated by an initial *N*-allylation event, which enables deprotonation leading to an *N*-vinylallylamine suitable for an aza-Claisen rearrangement. This reaction complements established Pd-catalyzed allylation reactions using pronucleophiles activated by strong bases and broadens the scope of allylic substitution toward late-stage functionalization of pharmaceutically relevant heterocycles.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b03407.

Full experimental procedures and spectroscopic characterizations (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For recent C−H activation reviews, see: (a) Ritleng, V.; Sirlin, C.; Pfeffer, M. *Chem. Rev.* **2002**, *102*, 1731−1769. (b) Lewis, J. C.; Bergman, R. G.; Ellman, J. A. *Acc. Chem. Res.* **2008**, *41*, 1013−1025. (c) Barker, T. J.; Jarvo, E. R. *Synthesis* **2011**, 3954−3964. (d) Li, H.; Li,

DOI: 10.1021/acs.orglett.6b03407
Org. Lett. 2017, 19, 126−129

B.-J.; Shi, Z.-J. *Catal. Sci. Technol.* **2011**, *1*, 191−206. (e) Neufeldt, S. R.; Sanford, M. S. *Acc. Chem. Res.* **2012**, *45*, 936−946. (f) Ramirez, T. A.; Zhao, B.; Shi, Y. *Chem. Soc. Rev.* **2012**, *41*, 931−942. (g) Kuhl, N.; Schröder, N.; Glorius, F. *Adv. Synth. Catal.* **2014**, *356*, 1443−1460. (h) Dastbaravardeh, N.; Christakakou, M.; Haider, M.; Schnürch, M. *Synthesis* **2014**, *46*, 1421−1439.

(2) For related C−H activations using imines or nitrogen heterocycles as directing groups, see: (a) Kakiuchi, F.; Sato, T.; Yamauchi, M.; Chatani, N.; Murai, S. *Chem. Lett.* **1999**, *28*, 19−20. (b) Thalji, R. K.; Ellman, J. A.; Bergman, R. G. *J. Am. Chem. Soc.* **2004**, *126*, 7192−7193. (c) Thalji, R. K.; Ahrendt, K. A.; Bergman, R. G.; Ellman, J. A. *J. Org. Chem.* **2005**, *70*, 6775−6781. (d) Harada, H.; Thalji, R. K.; Bergman, R. G.; Ellman, J. A. *J. Org. Chem.* **2008**, *73*, 6772−6779. (e) Yoshikai, N.; Matsumoto, A.; Norinder, J.; Nakamura, E. *Angew. Chem., Int. Ed.* **2009**, *48*, 2925−2928. (f) Gao, K.; Lee, P.-S.; Fujita, T.; Yoshikai, N. *J. Am. Chem. Soc.* **2010**, *132*, 12249−12251. (g) Patureau, F. W.; Glorius, F. *Angew. Chem., Int. Ed.* **2011**, *50*, 1977−1979. (h) Tredwell, M. J.; Gulias, M.; Gaunt Bremeyer, N.; Johansson, C. C. C.; Collins, B. S. L.; Gaunt, M. J. *Angew. Chem., Int. Ed.* **2011**, *50*, 1076−1079. (i) Ackermann, L.; Barfüsser, S.; Kornhaass, C.; Kapdi, A. R. *Org. Lett.* **2011**, *13*, 3082−3085. (j) Wang, C.; Chen, H.; Wang, Z.; Chen, J.; Huang, Y. *Angew. Chem., Int. Ed.* **2012**, *51*, 7242−7245. (k) Sirois, J. J.; Davis, R.; DeBoef, B. *Org. Lett.* **2014**, *16*, 868−871. (l) Li, J.; John, M.; Ackermann, L. *Chem. - Eur. J.* **2014**, *20*, 5403−5408. (m) McNally, A.; Haffemayer, B.; Collins, B. S. L.; Gaunt, M. J. *Nature* **2014**, *510*, 129−133. (n) Manikandan, R.; Madasamy, P.; Jeganmohan, M. *Chem. - Eur. J.* **2015**, *21*, 13934−13938. (o) Van Steijvoort, B. F.; Kaval, N.; Kulago, A. A.; Maes, B. U. W. *ACS Catal.* **2016**, *6*, 4486−4490. (p) Gao, K.; Yorimitsu, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2016**, *55*, 4573−4576.

(3) For recent publications, see: (a) Wencel-Delord, J.; Dröge, T.; Liu, F.; Glorius, F. *Chem. Soc. Rev.* **2011**, *40*, 4740−4761. (b) Yu, D.-G.; Gensch, T.; de Azambuja, F.; Vásquez-Céspedes, S.; Glorius, F. *J. Am. Chem. Soc.* **2014**, *136*, 17722−17725. (c) Girard, S. A.; Knauber, T.; Li, C.-J. *Angew. Chem., Int. Ed.* **2014**, *53*, 74−100. (d) Sharma, S.; Shin, Y.; Mishra, N. K.; Park, J.; Han, S.; Jeong, T.; Oh, Y.; Lee, Y.; Choi, M.; Kim, I. S. *Tetrahedron* **2015**, *71*, 2435−2441. (e) Park, J.; Mishra, N. K.; Sharma, S.; Han, S.; Shin, Y.; Jeong, T.; Oh, J. S.; Kwak, J. H.; Jung, Y. H.; Kim, I. S. *J. Org. Chem.* **2015**, *80*, 1818−1827. (f) Moselage, M.; Sauermann, N.; Koeller, J.; Liu, W.; Gelman, D.; Ackermann, L. *Synlett* **2015**, *26*, 1596−1600. (g) Gensch, T.; Vásquez-Céspedes, S.; Yu, D.-G.; Glorius, F. *Org. Lett.* **2015**, *17*, 3714−3717. (h) Zell, D.; Bu, Q.; Feldt, M.; Ackermann, L. *Angew. Chem., Int. Ed.* **2016**, *55*, 7408−7412. (i) Ohmiya, H.; Zhang, H.; Shibata, S.; Harada, A.; Sawamura, M. *Angew. Chem., Int. Ed.* **2016**, *55*, 4777−4780. (j) Qi, Z.; Kong, L.; Li, X. *Org. Lett.* **2016**, *18*, 4392−4395. (k) Kalsi, D.; Laskar, R. A.; Barsu, N.; Premkumar, J. R.; Sundararaju, B. *Org. Lett.* **2016**, *18*, 4198−4201. (l) Manoharan, R.; Sivakumar, G.; Jeganmohan, M. *Chem. Commun.* **2016**, *52*, 10533−10536. (m) Yamaguchi, T.; Kommagalla, Y.; Aihara, Y.; Chatani, N. *Chem. Commun.* **2016**, *52*, 10129−10132. (n) Dai, H.; Yu, C.; Wang, Z.; Yan, H.; Lu, C. *Org. Lett.* **2016**, *18*, 3410−3413. (o) Takahama, Y.; Shibata, Y.; Tanaka, K. *Org. Lett.* **2016**, *18*, 2934−2937. (p) Liu, W.; Ackermann, L. *ACS Catal.* **2016**, *6*, 3743−3752. (q) Manikandan, R.; Jeganmohan, M. *Org. Biomol. Chem.* **2016**, *14*, 7691−7701. (r) Kumar, G. S.; Kapur, M. *Org. Lett.* **2016**, *18*, 1112−1115. (s) Bunno, Y.; Murakami, N.; Suzuki, Y.; Kanai, M.; Yoshino, T.; Matsunaga, S. *Org. Lett.* **2016**, *18*, 2216−2219. (t) Gensch, T.; Hopkinson, M. N.; Glorius, F.; Wencel-Delord, J. *Chem. Soc. Rev.* **2016**, *45*, 2900−2936.

(4) (a) Tsuji, J.; Shimizu, I.; Minami, Y.; Ohashi, T.; Sugiura, K.; Takahashi. *J. Org. Chem.* **1985**, *50*, 1523−1529. (b) Usui, I.; Schmidt, S.; Breit, B. *Org. Lett.* **2009**, *11*, 1453−1456. (c) Shang, R.; Yang, Z.-W.; Wang, Y.; Zhang, S.-L.; Liu, L. *J. Am. Chem. Soc.* **2010**, *132*, 14391−14393. (d) Jiang, G.; List, B. *Angew. Chem., Int. Ed.* **2011**, *50*, 9471−9474. (e) Hyodo, K.; Nakamura, S.; Tsuji, K.; Ogawa, T.; Funahashi, Y.; Shibata, N. *Adv. Synth. Catal.* **2011**, *353*, 3385−3390. (f) Komai, H.; Yoshino, T.; Matsunaga, S.; Kanai, M. *Synthesis* **2012**, *44*, 2185−2194. (g) Best, D.; Kujawa, S.; Lam, H. W. *J. Am. Chem. Soc.* **2012**, *134*, 18193−18196. (h) Zhang, J.; Bellomo, A.; Creamer, A. D.; Dreher, S. D.; Walsh, P. J. *J. Am. Chem. Soc.* **2012**, *134*, 13765−13772. (i) Cattopadhyay, K.; Recio, A., III; Tunge, J. A. *Org. Biomol. Chem.* **2012**, *10*, 6826−6829. (j) Fallan, C.; Lam, H. W. *Chem. - Eur. J.* **2012**, *18*, 11214−11218. (k) Yoshida, M.; Terumine, T.; Masaki, E.; Hara, S. *J. Org. Chem.* **2013**, *78*, 10853−10859. (l) Tang, S.; Wu, X.; Liao, W.; Liu, K.; Liu, C.; Luo, S.; Lei, A. *Org. Lett.* **2014**, *16*, 3584−3587. (m) Meazza, M.; Ceban, V.; Pitak, M. B.; Coles, S. J.; Rios, R. *Chem. - Eur. J.* **2014**, *20*, 16853−16857. (n) Huo, X.; Quan, M.; Yang, G.; Zhao, X.; Liu, D.; Liu, Y.; Zhang, W. *Org. Lett.* **2014**, *16*, 1570−1573.

(5) (a) Yuan, F.-Q.; Gao, L.-X.; Han, F.-S. *Chem. Commun.* **2011**, *47*, 5289−5291. (b) Das, D.; Roy, S. *Adv. Synth. Catal.* **2013**, *355*, 1308−1314.

(6) (a) Trost, B. M.; Thaisrivongs, D. A. *J. Am. Chem. Soc.* **2008**, *130*, 14092−14093. (b) Trost, B. M.; Thaisrivongs, D. A. *J. Am. Chem. Soc.* **2009**, *131*, 12056−12057. (c) Matsubara, R.; Masuda, K.; Nakano, J.; Kobayashi, S. *Chem. Commun.* **2010**, *46*, 8662−8664. (d) Mukai, T.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2010**, *12*, 1360−1363. (e) Trost, B. M.; Thaisrivongs, D. A.; Hartwig, J. *J. Am. Chem. Soc.* **2011**, *133*, 12439−12441. (f) Zhang, J.; Stanciu, C.; Wang, B.; Hussain, M. M.; Da, C.-S.; Carroll, P. J.; Walsh, P. J. *J. Am. Chem. Soc.* **2011**, *133*, 20552−20560. (g) Sha, S.-C.; Zhang, J.; Carroll, P. J.; Walsh, P. J. *J. Am. Chem. Soc.* **2013**, *135*, 17602−17609. (h) Mao, J.; Zhang, J.; Jiang, H.; Bellomo, A.; Zhang, M.; Gao, Z.; Dreher, S. D.; Walsh, P. J. *Angew. Chem.* **2016**, *128*, 2572−2576. (i) Schwarz, K. J.; Amos, J. L.; Klein, J. C.; Do, D. T.; Snaddon, T. N. *J. Am. Chem. Soc.* **2016**, *138*, 5214−5217.

(7) (a) Mukherjee, S.; List, B. *J. Am. Chem. Soc.* **2007**, *129*, 11336−11337. (b) Bihelovic, F.; Matovic, R.; Vulovic, B.; Saicic, R. N. *Org. Lett.* **2007**, *9*, 5063−5066. (c) Usui, I.; Schmidt, S.; Breit, B. *Org. Lett.* **2009**, *11*, 1453−1456. (d) Krautwald, S.; Schafroth, M. A.; Sarlah, D.; Carreira, E. M. *J. Am. Chem. Soc.* **2014**, *136*, 3020−3023. (e) Huo, X.; Quan, M.; Yang, G.; Zhao, X.; Liu, D.; Liu, Y.; Zhang, W. *Org. Lett.* **2014**, *16*, 1570−1573. (f) Tang, S.; Wu, X.; Liao, W.; Liu, K.; Liu, C.; Luo, S.; Lei, A. *Org. Lett.* **2014**, *16*, 3584−3587. (g) Yang, C.; Zhang, K.; Wu, Z.; Yao, H.; Lin, A. *Org. Lett.* **2016**, *18*, 5332−5335.

(8) (a) Burger, E. C.; Tunge, J. A. *Org. Lett.* **2004**, *6*, 4113−4115. (b) Breit, B.; Breuninger, D. *Synthesis* **2005**, 147−157. (c) Zhang, P.; Brozek, L. A.; Morken, J. P. *J. Am. Chem. Soc.* **2010**, *132*, 10686−10688. (d) Zhang, P.; Le, H.; Kyne, R. E.; Morken, J. P. *J. Am. Chem. Soc.* **2011**, *133*, 9716−9719. (e) Niyomchon, S.; Audisio, D.; Luparia, M.; Maulide, N. *Org. Lett.* **2013**, *15*, 2318−2321. (f) Audisio, D.; Gopakumar, G.; Xie, L.-G.; Alves, L. G.; Wirtz, C.; Martins, A. M.; Thiel, W.; Fares, C.; Maulide, N. *Angew. Chem.* **2013**, *125*, 6434−64438. (g) Ardolino, M. J.; Morken, J. P. *J. Am. Chem. Soc.* **2014**, *136*, 7092−7100. (h) Misale, A.; Niyomchon, S.; Luparia, M.; Maulide, N. *Angew. Chem., Int. Ed.* **2014**, *53*, 7068−7073; *Angew. Chem.* **2014**, *126*, 7188−7193. (i) Xie, L.-G.; Bagutski, V.; Audisio, D.; Wolf, L. M.; Schmidts, V.; Hofmann, K.; Wirtz, C.; Thiel, W.; Thiele, C. M.; Maulide, N. *Chem. Sci.* **2015**, *6*, 5734−5739.

(9) (a) Tsuji, J.; Takahashi, H.; Morikawa, M. *Tetrahedron Lett.* **1965**, *6*, 4387−4388. (b) Trost, B. M.; Fullerton, T. J. *J. Am. Chem. Soc.* **1973**, *95*, 292−294. (c) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921−2943. (d) Trost, B. M. *J. Org. Chem.* **2004**, *69*, 5813−5837. (e) Lu, Z.; Ma, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 258−297.

(10) Brehm, E.; Breinbauer, R. *Org. Biomol. Chem.* **2013**, *11*, 4750−4756.

(11) Kamer, P.; Van Leeuwen, P.; Reek, J. *Acc. Chem. Res.* **2001**, *34*, 895−904.

(12) Wuts, P. G. M.; Greene, T. W. *Greene's Protective Groups in Organic Synthesis*, 4th ed.; Wiley: New York, 2007.

(13) (a) Murahashi, S.-I.; Makabe, Y. *Tetrahedron Lett.* **1985**, *26*, 5563−5566. (b) Murahashi, S.-I.; Makabe, Y.; Kunita, K. *J. Org. Chem.* **1988**, *53*, 4489−4495.

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