ORGANIC LETTERS

2011
Vol. 13, No. 21
5808–5811

Rh(III)-Catalyzed Oxidative Olefination of *N*-(1-Naphthyl)sulfonamides Using Activated and Unactivated Alkenes

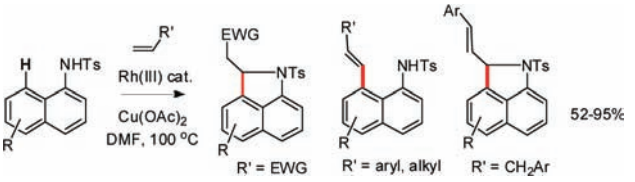
Xuting Li,[†,‡] Xue Gong,[†] Miao Zhao,[†] Guoyong Song,[†] Jian Deng,[‡] and Xingwei Li*[,†]

Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China, and School of Chemistry and Chemical Engineering, University of South China, Hengyang 421001, China

xwli@dicp.ac.cn

Received September 6, 2011

ABSTRACT



Rhodium(III)-catalyzed oxidative olefination of *N*-(1-naphthyl)sulfonamides has been achieved at the *peri* position. Three categories of olefins have been successfully applied. Activated olefins reacted to afford five-membered azacycles as a result of oxidative olefination−hydroamination. Unactivated olefins reacted to give the olefination product. 2-fold oxidative C−C and C−N coupling was achieved for allylbenzenes.

The oxidative coupling of unreactive C−H bonds with olefins (the Fujiwara-Moritani reaction)[1] represents an atom-economic strategy to directly functionalize arenes without prior activation and has received increasing attention since 1967. It has become an attractive alternative to the Heck reaction. Achieving oxidative C−C coupling in high catalytic efficiency using readily available starting materials should increase sustainability in synthesis.[2] A common strategy to achieve selective C−H oxidative olefination is the use of a neighboring directing group. Palladium,[2,3] ruthenium,[4] and rhodium[5] have been reported to effectively catalyze this transformation with the assistance of directing groups such as amide, oxime, pyridyl, ketone, carboxyl, and ester. In contrast to the well-studied palladium catalysts, rhodium(III) complexes have been recently explored and have been found to effect at low catalyst loading with high functional group tolerance.[6−10] Despite the success, nearly all oxidative olefination required somewhat activated alkenes such as

[†] Chinese Academy of Sciences.
[‡] University of South China.

(1) (a) Moritani, I.; Fujiwara, Y. *Tetrahedron Lett*. **1967**, 1119. (b) Jia, C.; Piao, D.; Oyamada, J.; Lu, W.; Kitamura, T.; Fujiwara, Y. *Science* **2000**, *287*, 1992. (c) Jia, C.; Kitamura, T.; Fujiwara, Y. *Acc. Chem. Res*. **2001**, *34*, 633.

(2) (a) Ackermann, L.; Vicenteand, R.; Kapdi, A. R. *Angew. Chem., Int. Ed*. **2009**, *48*, 9792. (b) Yeung, C. S.; Dong., V. M. *Chem. Rev*. **2011**, *111*, 1215. (c) Sun, C.-L.; Shi, Z.-J. *Chem. Commun*. **2010**, *46*, 677. (d) Liu, C.; Zhang, H.; Shi, W.; Lei, A. *Chem. Rev*. **2011**, *111*, 1780. (e) Bras, J. E.; Muzart, J. *Chem. Rev*. **2011**, *111*, 1170.

(3) For recent reviews, see: (a) Lyons, T. W.; Sanford, M. S. *Chem. Rev*. **2010**, *110*, 1147. (b) Chen, X.; Engle, K. M.; Wang, D. H.; Yu, J.-Q. *Angew. Chem., Int. Ed*. **2009**, *48*, 5094. (c) Xu, L.-M.; Yang, Z.; Shi, Z.-J. *Chem. Soc. Rev*. **2010**, *39*, 712.

(4) For ruthenium (II)-catalyzed C−H activation/functionalization, see ref 2a and the following: (a) Ackermann, L.; Lygin, A. V.; Hofmann, N. *Angew. Chem., Int. Ed*. **2011**, *50*, 6379. (b) Ackermann, L.; Novák, P.; Vicente, R.; Hofmann, N. *Angew. Chem., Int. Ed*. **2009**, *48*, 6045. (c) Weissman, H.; Song, X.; Milstein, D. *J. Am. Chem. Soc*. **2001**, *123*, 337. (d) Ueyama, T.; Mochida, S.; Fukutani, T.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett*. **2011**, *13*, 706 and references therein. For a pioneering example of Ru(II)-catalyzed C−H funcationalization of acetophenones, see. (e) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N. *Nature* **1993**, *366*, 529.

(5) For reviews on rhodium(I)-catalyzed functionalization of C−H bond, see: (a) Colby, D. A.; Bergman, R. G.; Ellman, J. A. *Chem. Rev*. **2010**, *110*, 624. (b) Lewis, J. C.; Bergman, R. G.; Ellman, J. A. *Acc. Chem. Res*. **2008**, *41*, 1013.

(6) For a review on Rh(III)-catalyzed oxidative coupling, see: Satoh, T.; Miura, M. *Chem.—Eur. J*. **2010**, *16*, 11212.

(7) (a) Ueura, K.; Satoh, T.; Miura, M. *Org. Lett*. **2007**, *9*, 1407. (b) Mochida, S.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem*. **2009**, *74*, 6295. (c) Umeda, N.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem*. **2009**, *74*, 7094. (d) Mochida, S.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett*. **2010**, *12*, 5776.

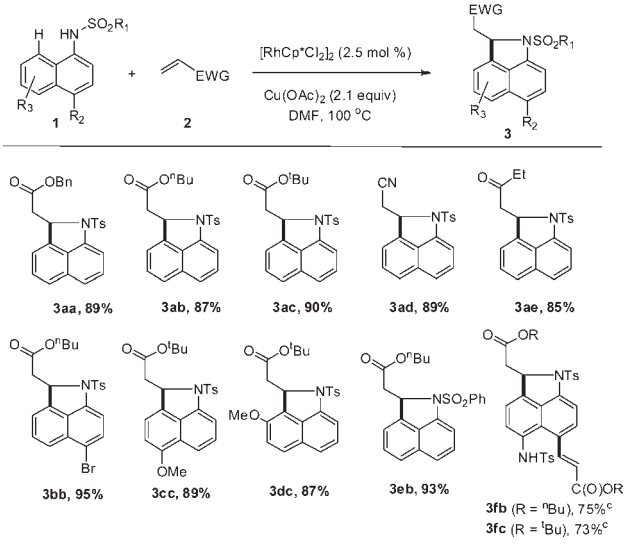
(8) (a) Patureau, F. W.; Glorius, F. *J. Am. Chem. Soc*. **2010**, *132*, 9982. (b) Rakshit, S.; Grohmann, C.; Besset, T.; Glorius, F. *J. Am. Chem. Soc*. **2011**, *133*, 2350. (c) Patureau, F. W.; Besset, T.; Glorius, F. *Angew. Chem., Int. Ed*. **2011**, *50*, 1064.

10.1021/ol2023856
Published on Web 10/11/2011

acrylates and styrenes. Glorius[8a] and Bergman and Ellman[11] reported the only two examples of Rh(III)-catalyzed olefination using unactivated olefins. In Bergman and Ellman's report,[11] various unactuvated alkenes such as 1-hexene are smoothly coupled with *O*-methyl oximines. We now report a general method of Rh(III)-catalyzed oxidative olefination of the sulfonamides of 1-naphthylamine at the peri position using activated and unactivated alkenes.

Although the sulfonamide group can act as a directing group in facilitating C−H activation, only very limited examples have been reported.[12] In this context, given that sulfonamide groups can be readily installed and removed, it is important to explore this type of substrate for selective C−H activation. We initiated our investigation on the oxidative olefination of *N*-(1-naphthyl)sulfonamide **1a** with benzyl acrylate. Our initial screening indicated that the coupled product **3aa** was isolated in 70% yield when a combination of $[RhCp^*Cl_2]_2$ (2.5 mol %) and $Cu(OAc)_2$ (2.1 equiv) was used in DCE (120 °C). Replacing the solvent with DMF resulted in significant decomposition under the same conditions. Gratifyingly, by lowering the temperature to 100 °C, a clean reaction was achieved and **3aa** was isolated in 89% yield (Scheme 1). Notably, no silver salt additive is necessary under these conditions. This product was characterized as a five-membered azacycle as a result of olefination followed by intramolecular hydroamination.[7a,10a,10b,13]

Scheme 1. Oxidative Olefination Using Activated Alkenes[a,b]



[a] Conditions: sulfonamide (0.5 mmol), alkene (0.75 mmol), $[RhCp^*Cl_2]_2$ (0.0125 mmol), $Cu(OAc)_2$ (1.05 mmol), DMF (3 mL), 100 °C, 16 h, under N_2, isolated yield. [b] **2a** = benzyl acrylate, **2b** = *n*-butyl acrylate, **2c** = *tert*-butyl acrylate, **2d** = acrylonitrile, **2e** = 1-penten-3-one. [c] Conditions: sulfonamide (0.5 mmol), alkene (1.5 mmol), $[RhCp^*Cl_2]_2$ (0.0125 mmol), $Cu(OAc)_2$ (2.1 mmol), DMF (3 mL), 100 °C, 18 h, under N_2, isolated yield.

With these optimized conditions in hand, we first examined the scope of activated olefins in their coupling with *N*-(1-naphthyl)sulfonamides (Scheme 1). Several acrylates readily coupled with **1a** to afford the cyclization products in high yields (87−90%). In addition, both electron-donating (**3cc** and **3dc**) and -withdrawing (**3bb**) groups in the naphthyl ring are well tolerated. Furthermore, no Heck-type product was generated for a halogen-functionalized substrate (see **3bb**). This specific feature highlights an advantage of Rh(III)-catalyzed C−C coupling reactions compared to many palladium-catalyzed ones in that the halogen is retained. In addition, other activated olefins such as acrylonitrile and enones are all efficient coupling partners. Thus, all the coupled products were isolated in comparably high yields (87−95%) for all monosulfonamides examined. In contrast, only unidentifiable products were isolated when PhNHTs was used as a substrate under the same conditions. C−H activation at both the *ortho* and *peri* position of 1-substituted naphthalenes has been noted using rhodium and palladium catalysts.[14] To better define the substrate scope, a centrosymmetric disulfonamide has been applied. Although two equivalents of olefin were oxidatively incorporated, NMR analyses indicated that monocyclization occurred. Thus, products **3fb** and **3fc** were isolated in good yields. In these reactions, failure of the second hydroamination is likely caused by the change of electronic effects induced by the first cyclization.

The scope of the olefin was successfully expanded. Simple styrene and 4-chlorostyrene readily coupled with **1a** to give products **4a** (93%) and **4b** (82%), respectively (Scheme 2). Significantly, unactivated simple olefins such as 1-hexene, vinylcyclohexane, and 4-methyl-1-pentene are also efficient coupling partners, and all the coupled products were isolated in high yield (72−93%). In line with the scope of sulfonamides in their coupling with acrylates, both electron-donating and halide substituents in the naphthyl ring can be tolerated, indicating the general applicability of the sulfonamide substrate. We noted that only two reports deals with rhodium-catalyzed oxidative olefination using unactivated alkenes.[8a,11]

(9) (a) Guimond, N.; Gorelsky, S. I.; Fagnou, K. *J. Am. Chem. Soc.* **2011**, *133*, 6449. (b) Tsai, A. S.; Tauchert, M. E.; Bergman, R. G.; Ellman, J. A. *J. Am. Chem. Soc.* **2011**, *133*, 1248. (c) Li, Y.; Li, B.-J.; Wang, W.-H.; Huang, W.-P.; Zhang, X.-S.; Chen, K.; Shi, Z.-J. *Angew. Chem., Int. Ed.* **2011**, *50*, 2115. (d) Gong, T.-J.; Xiao, B.; Liu, Z.-J.; Wan, J.; Xu, J.; Luo, D.-F.; Fu, Y.; Liu, L. *Org. Lett.* **2011**, *13*, 3235. (e) Park, S. H.; Kim, J. Y.; Chang, S. *Org. Lett.* **2011**, *13*, 2372.

(10) (a) Wang, F.; Song, G.; Li, X. *Org. Lett.* **2010**, *12*, 5430. (b) Wang, F.; Song, G.; Du, Z.; Li, X. *J. Org. Chem.* **2011**, *76*, 2926. (c) Chen, J.; Song, G.; Pan, C.-L.; Li, X. *Org. Lett.* **2010**, *12*, 5426.

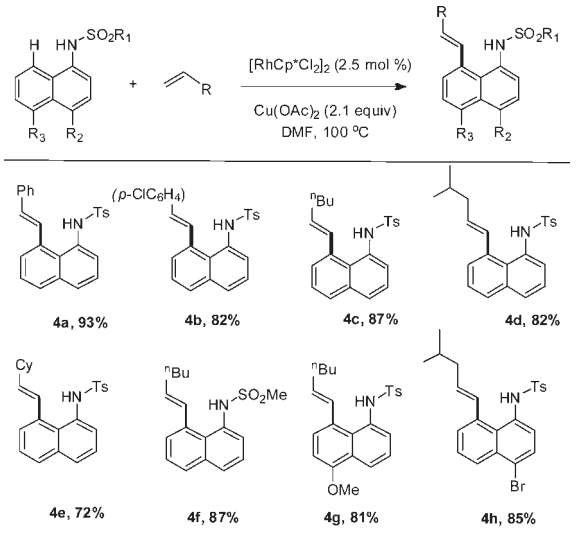
(11) Tsai, A. S.; Brasse, M.; Bergman, R. G.; Ellman, J. A. *Org. Lett.* **2011**, *13*, 540.

(12) (a) Dai, H.-X.; Stepan, A. F.; Plummer, M. S.; Zhang, Y.-H.; Yu, J.-Q. *J. Am. Chem. Soc.* **2011**, *133*, 7222. (b) Youn, S. W.; Bihn, J. H.; Kim, B. S. *Org. Lett.* **2011**, *13*, 3738. (c) Miura, M.; Tsuda, T.; Pivsa-Art, S.; Nomura, M. *J. Org. Chem.* **1998**, *63*, 5211.

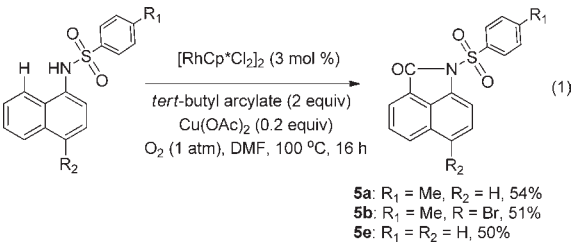
(13) (a) Zhu, C.; Falck, J. R. *Org. Lett.* **2011**, *13*, 1214. (b) Li, J.-J.; Mei, T.-S.; Yu, J.-Q. *Angew. Chem., Int. Ed.* **2008**, *47*, 6452. (c) Lu, Y.; Wang, D.-H.; Engle, K. M.; Yu, J.-Q. *J. Am. Chem. Soc.* **2010**, *132*, 5916. (d) Willwacher, J.; Rakshit, S.; Glorius, F. *Org. Biomol. Chem.* **2011**, *9*, 4736.

(14) (a) Kim, B. S.; Jang, C.; Lee, D. J.; Youn, S. W. *Chem. Asian J.* **2010**, *5*, 2336. (b) Mochida, S.; Shimizu, M.; Hirano, K.; Satoh, T.; Miura, M. *Chem. Asian J.* **2010**, *5*, 847. (c) Chen, X.; Li, J.-J.; Hao, X.-S.; Goodhue, C. E.; Yu, J.-Q. *J. Am. Chem. Soc.* **2006**, *128*, 78. (d) Kaïm, L. E.; Gamez-Montano, R.; Grimaud, L.; Ibarra-Riverab, T. *Chem. Commun.* **2008**, 1350. (e) Harayama, T.; Sato, T.; Hori, A.; Abeand, H.; Takeuchi, Y. *Synthesis* **2004**, *9*, 1446.

Scheme 2. Olefination Using Unactivated Alkenes[a]



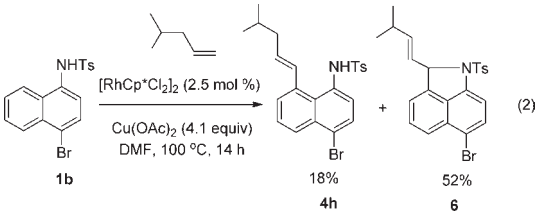
[a] Conditions: sulfonamide (0.5 mmol), alkene (0.75 mmol), [RhCp*-$Cl_2]_2$ (0.125 mmol), $Cu(OAc)_2$ (1.05 mmol), DMF (3 mL), 100 °C, 16 h, under N_2, isolated yield.



Surprisingly, when we attempted to carry out the reaction of **1a** and *tert*-butyl acrylate (2 equiv) under aerobic conditions (O_2 (1 atm) and $Cu(OAc)_2$ (20 mol %)) (eq 1), no olefination product such as **3ac** was detected. Instead, a formal oxidative carbonylation reaction occurred. On the basis of NMR, IR spectroscopy, and mass spectrometry, the product **5a** was determined as a lactam. In particular, the carbonyl carbon resonates characteristically at δ 165.1 in the ^{13}C NMR spectrum ($CDCl_3$), and a characteristic IR signal was also detected (1747 cm^{-1}). Thus products **5a**, **5b**, and **5e** were isolated in 50−54% yield under these unoptimized conditions. Our preliminary studies indicated that the $Cu(OAc)_2$ co-oxidant is necessary, and using a smaller amount of *tert*-butyl acrylate resulted in lower efficiency. Using *n*-butyl acrylate also resulted in lower yield. When DMA was used as a solvent for the reaction of **1a** under the same conditions (*tert*-butyl acrylate), **5a** was also isolated albeit at a lower yield. Although the carbonyl likely originates from DMF, no solid conclusion on the role of *tert*-butyl acrylate can be drawn at this stage.[15]

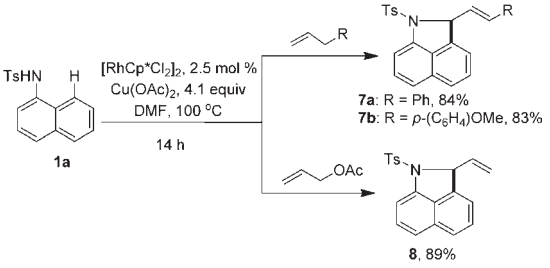
(15) Even though **5a** was also obtained using DMA as a solvent, no solid conclusion on the souce of carbonyl group of **5a** can be drawn. For example, Jiao recently reported that both DMF and DMA can be the souce of a cyanide group in the reaction with indole, where the CN group originates mainly from the NMe_2 group. See: (a) Ding, S.; Jiao, N. *J. Am. Chem. Soc.* **2011**, *133*, 12374. (b) Kim, J.; Chang, S. *J. Am. Chem. Soc.* **2010**, *132*, 10272. Labeling experiments are underway.

Given the proximity of the sulfonamide NH group and the olefin unit in products **4**, we reasoned that allylic olefin products could potentially undergo further intramolecular oxidative amidation via formal allylic C−H activation.[13a] In order to validate this possibility, an excess of $Cu(OAc)_2$ (4.1 equiv) was applied to the coupling of a 4-bromo substituted sulfonamide (**1b**) and 4-methyl-1-pentene. Indeed, the expected 2-fold oxidative coupling product (**6**) was isolated in 52% yield (eq 2), together with the direct olefination product **4h** (18%). Alternatively, **6** could also be obtained when **4h** was subjected to the standard reaction conditions, suggesting that **4h** is an intermediate in the formation of **6**.



The generality of this formal allylic C−H oxidation follows from the coupling of allylbenzenes and **1a**. The reaction of allylbenzenes and **1a** under the same conditions afforded **7a**,**b** in high yield, with no direct olefination product being isolable (Scheme 3). When allyl acetate was employed, product **8** was isolated in 89% yield. Formation of related terminal olefins starting from allyl acetate has been reported.[11,16]

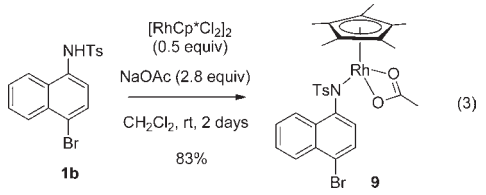
Scheme 3. Olefination Using Allylic Olefins



To explore the mechanism of this transformation, a stoichiometric reaction between **1b** and $[RhCp^*Cl_2]_2$ has been carried out in the presence of an access of NaOAc (25 °C). NMR analysis of the reaction product **9** indicated that the coordination sphere of the rhodium complex include a Cp* ring, a sulfonamidate, and an acetate (eq 3). Although the sixth coordination site and identity of **9** cannot be unambiguously established, IR spectroscopy suggested that the acetate likely adopts the η^2 binding mode in the sold state (no intense absorption in the range

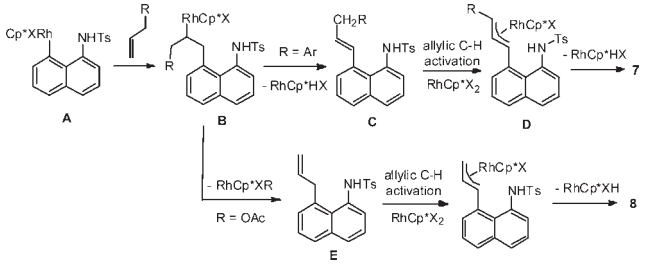
(16) (a) Lautens, M.; Tayama, E.; Herse, C. *J. Am. Chem. Soc.* **2005**, *127*, 72. (b) Steinig, A. G.; de Meijere, A. *Eur. J. Org. Chem.* **1999**, 1333. (c) Menard, F.; Perez, D.; Roman, D. S.; Chapman, T. M.; Lautens, M. *J. Org. Chem.* **2010**, *75*, 4056. (d) Mariampillai, B.; Herse, C.; Lautens, M. *Org. Lett.* **2005**, *7*, 4745.

of 1600−2100 cm^{-1}). Subjection of **9** (4 mol %) to the coupling of **1a** and *tert*-butyl acrylate under the standard conditions afforded product **3ac** in comparably high yield (86%), suggesting that **9** could be an active intermediate in this catalytic process. In addition, migratory insertion of Rh-bound amido groups to olefins has been reported.[17]

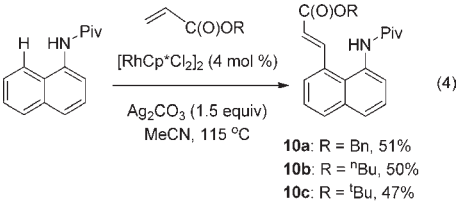


A plausible pathway for the formation of **7** is given in Scheme 4. Rhodation at the *peri* position (**A**) followed by insertion of the olefin affords a rhodium(III) alkyl species (**B**). Subsequent β-hydrogen elimination generates the direct olefination intermediate (**C**). This intermediate is proposed to undergo allylic C−H activation, leading to anη^3-allyl species (**D**) followed by nucleophilic C−N bond formation.[18] Formation of **8** starting from **1a** and ally acetate may likely follow the β-oxygen elimination of **B** that is generated after allyl acetate insertion, and olefin **E** is thus a likely intermediate.[11,16]

Scheme 4. Possible Mechanisms of the Formation of **7** and **8**



The scope of amide substrates was successfully extended to a pivalamide (eq 4). Although unactivated olefins are not appliable, acrylates did couple with this pivalamide under modified conditions in MeCN ($[RhCp^*Cl_2]_2$ (4 mol %) and Ag_2CO_3 (2.1 equiv). Thus, olefination products **10a**−**c** were isolated in moderate yields. Despite the lower catalytic efficiency, these products are complementary to those obtained from sulfonamides. The absence of any further aza-Michael reaction might be ascribed to both electronic and steric effects. Electronically, the NH proton is less acidic in products **10a**−**c**, and previous reports seem to indicate that acidic OH and NH groupstend to add to activated olefins.[7a,b,10a] Sterically, the bulky ^{t}Bu group in the amide renders the NH group less accessible.



In summary, we have successfully achieved the rhodium(III)-catalyzed oxidative olefination of *N*-(1-naphthyl)-sulfonamides at the *peri* position. This coupling process proceeded under simple conditions in high selectivity and high efficiency. Three categories of olefins have been successfully applied. Activated olefins reacted to afford new five-membered azacycles as a result of oxidative olefination-hydroamination sequence. Unactivated olefins coupled smoothly with *N*-(1-naphthyl)sulfonamides to afford the direct olefination product, which could undergo further intramolecular oxidative allylicamidation. 2-fold oxidation was successfully achieved for allylic olefins such as allylbenzene and allyl acetate. In contrast, although *N*-(1-naphthyl)-pivalamide also coupled with acrylate esters, only the direct olefination products were isolated. Thus, by introducing an appropriate directing group, C−H activation and oxidative functionalization using unactivated as well as activated terminal olefins can be achieved in high yield and high selectivity. Given the wide scope of substrates and cleavability of sulfonamide N−S and carboxamide N−C bonds in the coupled products, the current reactions are likely to find important synthetic utility. Studies on the mechanistic details of the C−H activation and of the oxidative carbonylation are currently underway in our laboratory.

Acknowledgment. This work was supported by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences.

Supporting Information Available. Synthetic procedures, characterization data, and NMR spectra of all coupled products. This material is available free of charge via the Internet at http://pubs.acs.org.

(17) Zhao, P.; Krug, C.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 12066.

(18) An alternative mechanism of Wacker-type amidation followed by β-hydrogen elimination is also possible (see ref 10b).