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Copper-Catalyzed Diacetoxylation of Olefins using PhI(OAc)$_2$ as Oxidant

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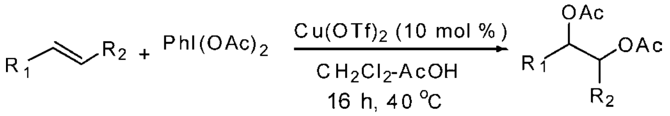
ABSTRACT



Copper(I) or -(II) salts with weakly coordinating anions catalyze the diacetoxylation of olefins efficiently in the presence of PhI(OAc)$_2$ as the oxidant under mild conditions. The reaction is effective for aryl, aryl alkyl, as well as aliphatic terminal and internal olefins forming the corresponding vicinal diacetoxy compounds in 70−85% yields and dr (syn/anti) of up to 5.2. Under these conditions, homoallylic alcohols formed the corresponding tetrahydrofuran derivatives in high yields.

Catalytic vicinal dioxygenation of olefins is an extremely important reaction in the synthesis of high value intermediates for pharmaceuticals and fine chemicals.[1] The OsO$_4$-catalyzed (or Upjohn) dihydroxylation[2] and its enantioselective version, the Sharpless dihydroxylation,[3] are among the most widely used dioxygenation reactions in organic synthesis. However, the use of expensive and highly toxic osmium catalysts has limited the use of this technology to merely synthesis in a small scale. In recent years, there has been substantial interest in the development of alternative catalysts for alkene dioxygenations.[4] Sudalai et al.[5] reported a metal-free catalytic version of the Woodward−Prevost[6] reaction using LiBr as the catalyst. In this reaction, syn and anti diols with excellent diastereoselectivities were obtained when NaIO$_4$ or PhI(OAc)$_2$ was used as the oxidant, respectively. Recently, Li et al.[7] and Jiang et al.[8] independently reported a Pd-catalyzed diacetoxylation of alkenes to the *syn*-1,2-diacetates using PhI(OAc)$_2$ or molecular oxygen as the oxidants, respectively. In the former case, a cationic palladium complex with electron-rich diphosphines as ligands was essential for the reaction, while in the latter case, Pd(OAc)$_2$ was sufficient to catalyze the transformation efficiently.

In recent years, the use of copper salts as catalysts has gained much prominence in organic synthesis due to their economic attractiveness, good functional group tolerance, and scalability in large-scale synthetic procedures.[9] The peroxydisulfate oxidation of aliphatic olefins[10] and α- and β-

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(1) Hudlicky, M. *Oxidations in Organic Chemistry*; ACS Monograph Series 186; American Chemical Society: Washington, DC, 1990; p 174. (b) Johnson, R. A.; Sharpless, K. B. In *Catalytic Asymmetric Synthesis*, 2nd ed.; Ojima, I., Ed.; Wiley-VCH: New York, 2000; p 357. (c) Haines, A. H. In *Comprehensive Organic Synthesis*, 1st ed.; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 7, p 437.

(2) (a) VanRheenen, V.; Kelly, R. C.; Cha, D. Y. *Tetrahedron Lett.* **1976**, 1973. (b) Eames, J.; Mitchell, H.; Nelson, A.; O'Brien, P.; Warren, S.; Wyatt, P. *J. Chem. Soc., Perkin. Trans. 1* **1999**, 1095.

(3) (a) Jacobsen, E. N.; Marko, I.; Mungall, W. S.; Schroeder, G.; Sharpless, K. B. *J. Am. Chem. Soc.* **1988**, *110*, 1968. (b) Kolb, H. C.; Van Nieuwenhze, M. S.; Sharpless, K. B. *Chem. Rev.* **1994**, *94*, 2483. (c) Gonzalez, J.; Aurigemma, C.; Truesdale, L. *Organic Syntheses*; Wiley: New York, 2004; Collect. Vol. 10, p 603; *Org. Synth.* **2002**, *79*, 93. (d) Johnson, R. A.; Sharpless, K. B. In *Catalytic Asymmetric Synthesis*, 2nd ed.; Ojima, I., Ed.; VCH: New York, 2000.

(4) Shing, T. K. M.; Tai, V-W. F.; Tam, E. K. W. *Angew. Chem., Int. Ed.* **1994**, *33*, 2312. (b) Shing, T. K. M.; Tam, E. K. W.; Tai, V-W. F.; Chung, I. H. F.; Jiang, Q. *Chem.*—*Eur. J.* **1996**, *2*, 50. (c) Verboom, R. C.; Plietker, B. J.; Bäckvall, J. E. *J. Organomet. Chem.* **2003**, *687*, 508. (d) Yoshisaki, H.; Bäckvall, J. E. *J. Org. Chem.* **1998**, *63*, 9339. (e) Grennberg, H.; Bäckvall, J. E. *J. Chem. Soc., Chem. Commun.* **1993**, 1331. (f) Grennberg, H.; Fazon, S.; Bäckvall, J. E. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 263. (g) Bäckvall, J. E.; Nordberg, R. E. *J. Am. Chem. Soc.* **1981**, *103*, 4959.

(5) Emmanuvel, L.; Ali Shaikh, T. M.; Sudalai, A. *Org. Lett.* **2005**, *7*, 5071.

(6) (a) Woodward, R. B.; Brutcher, F. V. *J. Am. Chem. Soc.* **1958**, *80*, 209. (b) Prévost, C. *Compt. Rend.* **1933**, *196*, 1129.

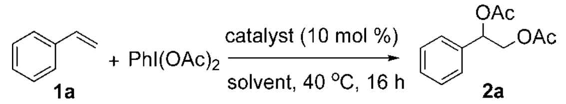
(7) Li, Y.; Song, D.; Dong, V. M. *J. Am. Chem. Soc.* **2008**, *130*, 2962.

(8) Wang, A.; Jiang, H.; Chen, H. *J. Am. Chem. Soc.* **2009**, *131*, 3846.

(9) (a) Hideki, Y.; Koichiro, O. *Angew. Chem., Int. Ed.* **2005**, *44*, 4435. (b) Ken-ichi, Y.; Kiyoshi, T. *Chem. Rev.* **2008**, *108*, 2874. (c) Punniyamurthy, T.; Rout, L. *Coord. Chem. Rev.* **2008**, *252*, 134. (d) Olafs, D.; Hien-Quang, D.; Dmitry, S. *Acc. Chem. Res.* **2009**, *42*, 1074.

10.1021/ol902813m

Table 1. Copper-Catalyzed Diacetoxylation of Styrene: Optimization Studies



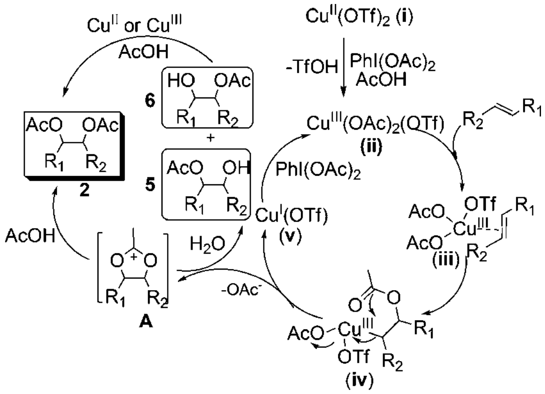
entry	catalyst	solvent	yield of **2a**^{a} (%)
1	Cu(OTf)$_2$	CH_2Cl_2	68^b
2	Cu(OTf)$_2$	AcOH	78^c
3	Cu(OTf)$_2$	AcOH-H_2O (1:1)	trace^d
4	Cu(OTf)$_2$	CH_2Cl_2−AcOH (3:1)	78^e
5	Cu(OTf)$_2$	CH_2Cl_2−AcOH (3:1)	85
6	Cu(OTf)$_2$	CH_2Cl_2	80^f
7	Cu(OTf)$_2$	CH_3CN-AcOH (3:1)	80
8	Cu(OTf)$_2$	CH_2Cl_2−AcOH (3:1)	81
9	Cu(CH_3CN)$_4$$BF_4$	CH_2Cl_2−AcOH (3:1)	77
10	Cu(OAc)$_2$	CH_2Cl_2−AcOH (31)	-
11	CuOAc	CH_2Cl_2−AcOH (3:1)	-
12	CuCl	CH_2Cl_2−AcOH (3:1)	-
13		CH_2Cl_2−AcOH (3:1)	-
14	Cu(OTf)$_2$	CH_2Cl_2−AcOH (3:1)	-^{g}

[a] GC yield, determined using dodecane as an internal standard. [b] Side products such as 2-phenylethane-1,1-diyl diacetate and styrene dimers were detected by GC−MS. [c] Small amount of benzaldehyde was detected by GC−MS. [d] Hydroxyacetates **5a** and **6a** (Scheme 1) and a major amount of benzaldehyde were detected by GC−MS. [e] At rt. [f] In the presence of 3 equiv of acetic acid with respect to styrene. [g] Reaction without PhI(OAc)$_2$.

alkenylbenzenes[11] to the corresponding allylic acetates and glycol diacetates, respectively, were known to be catalyzed by cupric acetate in acetic acid under reflux conditions. It was also reported that cupric nitrate, triflate,[12] and binuclear Cu(II) complexes can catalyze the oxidation of olefins to epoxides in the presence of iodosylbenzene as the oxidant.[13] To our knowledge, a general and efficient copper-catalyzed methodology for the dioxygenation of olefins to the corresponding diols or derivatives has not been developed to date. We report herein a mild and efficient copper-catalyzed vicinal diacetoxylation of olefins using PhI(OAc)$_2$[14] as the oxidant.

In our initial experiments, we found that Cu(II) triflate catalyzes the vicinal diacetoxylation of styrene in the presence of PhI(OAc)$_2$ as the oxidant to form 1-phenylethane-1,2-diyl diacetate efficiently. Traces of geminal diacetoxylation product were also detected by GC−MS. Small amounts of benzaldehyde[15] were formed when the reaction was carried out in acetic acid as solvent or in the presence of acetic acid/water mixture (entries 2 and 3, Table 1). This byproduct formation was minimized by adjusting the solvent system and optimizing the reaction conditions. Thus, the best yields of the 1,2-diacetoxylated product was obtained at an optimum CH_2Cl_2−AcOH ratio of 3:1 at 40 °C using 1.3 equiv of PhI(OAc)$_2$ (entry 5, Table 1). Alternatively, a 3:1 mixture of acetonitrile−AcOH could also be used as solvent without compromising the reaction yields. It is noted from entry 4 in Table 1 that this reaction can also be carried out at rt without significant variation in the yield of the desired product **2a**. Screening of other copper precursors showed that both copper(I) and copper(II) salts with weakly coordinating anions such as $^-$OTf (entries 1−8, Table 1) and $^-BF_4$ (entry 9, Table 1) were effective in the catalysis, while those with strongly coordinating $^-$OAc (entries 10 and 11, Table 1) and Cl^- (entry 12, Table 1) ions were totally inactive under these conditions. In control reactions without any copper catalyst, but with the oxidant and vice versa, no conversion of styrene was observed (entries 13 and 14, Table 1).

Scheme 1. Proposed Mechanism of Copper-Catalyzed Diacetoxylation of Olefins



The proposed mechanism for the copper-catalyzed diacetoxylation reaction is outlined in Scheme 1. When the Cu(OTf)$_2$-catalyzed diacetoxylation of styrene (**1a**) was monitored by GC−MS, small amounts of hydroxyacetates (**5a** and **6a** in Scheme 1, R_1, R_2 = Ph, H) along with the 1,2-diacetate **2a** were observed as intermediates. These hydroxyacetates **5a** and **6a** were completely converted to the diacetate **2a** after 16 h. The detection of **5a** and **6a** in the reaction suggests the formation of an acetoxonium ion **A** as the intermediate.[7,11b] This in turn could be formed via a Cu(III)−Cu(I) catalytic cycle[12,13,16] as shown in Scheme 1.[17] The Cu(II)(OTf)$_2$ is oxidized to the active Cu(III)(OAc)$_2$-(OTf) by the oxidant PhI(OAc)$_2$ which then coordinates and inserts olefin forming the intermediate species **iii** and **iv**. Release of **A** from **iv** by a S_N2-type reductive elimination leads to Cu(I)OTf, which is oxidized back to the active Cu(III) species **ii** by PhI(OAc)$_2$. The reaction of the intermediate **A** with acetic acid will then lead to the

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(10) Arnodi, C.; Citterio, A.; Minisci, F. *J. Chem. Soc., Perkin Trans. 2* **1983**, 531.

(11) (a) Citterio, A.; Arnodi, C. *J. Chem. Soc., Perkin Trans. 1* **1983**, 891. (b) Dobson, P.; Norman, J. A.; Thomas, C. B. *J. Chem. Soc., Perkin Trans. 1* **1986**, 1209.

(12) (a) Franklin, C. C.; VanAtta, R. B.; Tai, A. F.; Valentine, J. S. *J. Am. Chem. Soc.* **1984**, *106*, 814. (b) VanAtta, R. B.; Franklin, C. C.; Valentine, J. S. *Inorg. Chem.* **1984**, *23*, 4121.

(13) Tai, A. F.; Margerum, L. D.; Valentine, J. S. *J. Am. Chem. Soc.* **1986**, *108*, 5006.

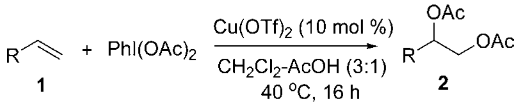
(14) Stang, P. J.; Zhdankin, V. V. *Chem. Rev.* **1996**, *96*, *3*, 1123.

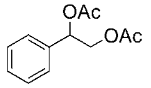
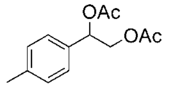
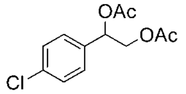
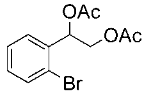
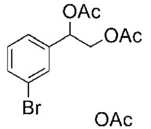
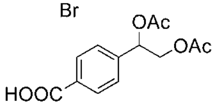
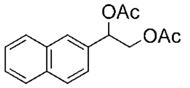
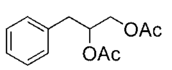
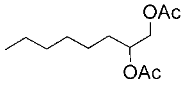
(15) Benzaldehyde could be formed by the oxidative cleavage of the hydroxyacetate intermediates **5a** and **6a** (see ref 11b).

(16) (a) Chemler, S. R.; Fuller, P. H. *Chem. Soc. Rev* **2007**, *36*, 1153, and references cited therein. (b) Zabawa, T. P.; Kasi, D.; Chemler, S. R. *J. Am. Chem. Soc.* **2005**, *127*, 11250.

formation of the diacetoxylated product **2a** while trace amounts of extrinsic water that may be present in the solvent give rise to the hydroxyacetates **5a** and **6a** which are subsequently acylated in the presence of Cu(III) or any Cu(II) species present in the reaction mixture, leading to **2a**. The acylation of alcohols by $Cu(OTf)_2$ in acetic acid has been reported previously.[18]

Table 2. Copper-Catalyzed Diacetoxylaton of Terminal Olefins

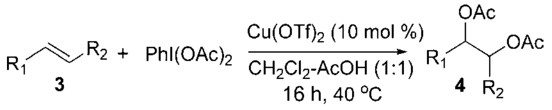


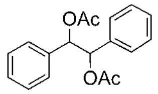
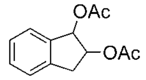
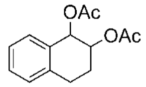
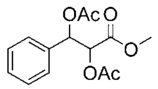
entry	product		yield, %[a]
1.		(**2a**)	80
2.		(**2b**)	75
3.		(**2c**)	82
4.		(**2d**)	75
5.		(**2e**)	79
6.		(**2f**)	70
7.		(**2g**)	72
8.		(**2h**)	82[b]
9.		(**2i**)	85[b]

[a] Isolated yield. [b] At 80 °C in AcOH as solvent.

After achieving an optimized catalyst system, we studied the generality of this method with other olefins. As shown in the Table 2, this methodology can be extended to a number of aryl (**1a**−**g**), aryl alkyl (**1 h**), and alkyl (**1i**) terminal olefins to yield the corresponding 1,2-diacetates (**2a**−**i**) in good to excellent yields. While the aryl olefins reacted efficiently at 40 °C, aryl alkyl and alkyl olefins required a slightly higher temperature (80 °C) for the reaction to proceed. In the case of 4-substituted styrene derivatives, i.e., 4-methylstyrene (**1b**), 4-chlorostyrene (**1c**), and 4-vinylbenzoic acid (**1f**), the yields were 75%, 82%, and 70%, respectively. 2- and 3-bromostyrenes (**1d** and **1e**) and 2-vinylnaphthalene (**1g**) were also reactive substrates giving rise to 75%, 79%, and 72% yields of the desired products, respectively. It is noteworthy that, under our conditions, allyl benzene (**1h**) and 1-octene (**1i**) yielded the corresponding 1,2-diacetate products (**2h** and **2i**) in excellent yields (82% and 85% at 80 °C in acetic acid as the solvent). This is in contrast to reports of the peroxydisulfate oxidation which gave the corresponding allylic acetates or 1,2,3-triacetates as the major products.[10]

Table 3. Copper-Catalyzed Diacetoxylation of Internal Olefins



entry	product		dr[a] (syn:anti)	yield, %[b]
1.		(**4a**)	5.2	71
2.		(**4b**)	3	78
3.		(**4c**)	1	75
4.		(**4d**)	1.8	70[c]

[a] Diastereomeric ratio detemined by ^1H NMR spectroscopy. [b] Isolated yield. [c] At 80 °C with AcOH as solvent.

The diacetoxylation of internal olefins was also investigated, and to our delight, the reaction proceeded in good yields albeit with moderate diastereoselectivities (Table 3). The "best" conditions for these reactions were found to use CH_2Cl_2−AcOH (1:1) as solvent at 40 °C. In the case of *trans*-stilbene (**3a**), a yield of 71% and a syn/anti ratio of 5.2 were observed under these conditions. Indene (**3b**) and 1,2-dihydronaphthalene (**3c**) gave the corresponding 1,2-diacetates **4b** and **4c** in 78% and 75% yields and a dr of 3 and 1, respectively. Methyl cinnamate (**3d**) only yielded trace amounts of the diacetoxylation product at 40 °C; however, at 80 °C in acetic acid as solvent the 1,2-diacetate product (**4d**) was obtained in 70% yield with a dr of 1.8.

The reaction of homoallylic alcohol derivatives **7a**−**d** with $PhI(OAc)_2$ in AcOH in the presence of $Cu(OTf)_2$ at 80 °C gave the corresponding tetrahydrofuran derivatives **9a**−**d** (Table 4), plausibly via the 5-*exo*-*tet*-cyclization of the

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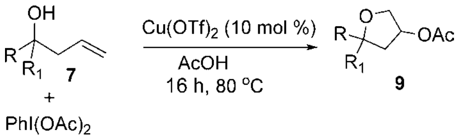
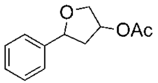
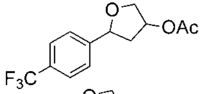
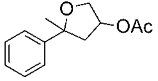
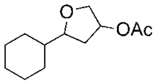
(17) The ESI-TOF-MS(+) analysis of a stoichiometric reaction of $Cu(OTf)_2$, $PhI(OAc)_2$, and styrene in AcOH indicated the formation of the species (**iv-a** + Na, $m/z = 457$) and (**iii-a** + Na-HOTf, $m/z = 307$). along with (**2a** + Na, $m/z = 245$) (R_1, R_2 = Ph, H) (see the Supporting Information).

(18) Chandra, K. L.; Saravanan, P.; Singh, R. K.; Singh, V. K. *Tetrahedron* **2002**, *58*, 1369.

Table 4. Formation of Tetrahydrofuran Derivatives by Copper-Catalyzed Oxidation of Homoallylic Alcohols using PhI(OAc)$_2$

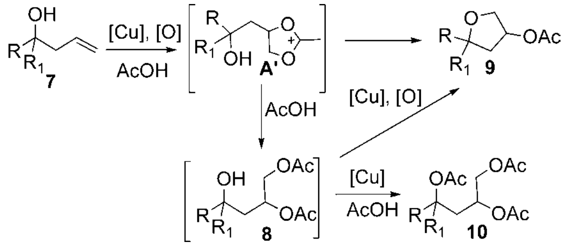


entry	product	dr[a]	yield of **9**, %[b]
1.	 (**9a**)	1.3	80
2.	 (**9b**)	1	82
3.	 (**9c**)	1.4	78
4.	 (**9d**)	1	76

[a] Diastereomeric ratio determined by GC analysis and ^{1}H NMR spectroscopy. [b] Isolated yield.

intermediate **A′** or **8** as shown in Scheme 2.[19] Thus, aryl and alkyl secondary alcohols **7a** (R, R_1 = Ph, H), **7b** (R, R_1 = 4-CF$_3$Ph, H), and **7d** (R, R_1 = Cy, H) gave the tetrahydrofuran derivatives **9a**, **9b**, and **9d** in 78−82% yield and a dr of 1−1.3 (Table 4). The tertiary alcohol 2-phenylpent-4-en-2-ol (**7c**) also reacted in a similar manner to form **9c** in 78% yields (dr 1.4). Small amounts of 4-phenylbutane-1,2,4-triyl triacetate (**10a**, R, R_1 = Ph, H) were also isolated from the reaction with 1-phenylbut-3-en-1-ol (**7a**). This could arise from the copper-catalyzed acylation of the intermediate **8a** (R, R_1 = Ph, H) as shown in Scheme 2.

Scheme 2. Proposed Formation of Tetrahydrofuran Derivatives from Homoallylic Alcohols



In conclusion, we have developed a simple and efficient copper-catalyzed diacetoxylation of olefins to the corresponding vicinal diacetoxy compounds under mild conditions. This methodology is applicable to aryl and aliphatic olefins as well as terminal and internal olefins and provides good yields and moderate diastereoselectivities. Under these conditions, homoallylic alcohols formed the corresponding tetrahydrofuran derivatives efficiently. Further studies directed toward an enantioselective variant are underway.

Acknowledgment. This work is funded by the Institute of Chemical and Engineering Sciences (Science and Engineering Research Council, Agency for Science, Technology and Research, Singapore).

Supporting Information Available: Experimental procedures and compound characterization data; NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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(19) Experiments using *O*-benzylated **8a** (R = Ph, R_1 = H; compound **S-2** in the Supporting Information) indicate the possibility of a copper-catalyzed cyclization to form **9a** under oxidative conditions (see the Supporting Information).