J|A|C|S
COMMUNICATIONS

Published on Web 06/15/2006

Rhodium(I)-Catalyzed Carboxylation of Aryl- and Alkenylboronic Esters with CO_2

Kazutoshi Ukai, Masao Aoki, Jun Takaya, and Nobuharu Iwasawa*

Department of Chemistry, Tokyo Institute of Technology, O-Okayama, Meguro-ku, Tokyo 152-8551, Japan

Received February 21, 2006; E-mail: niwasawa@chem.titech.ac.jp

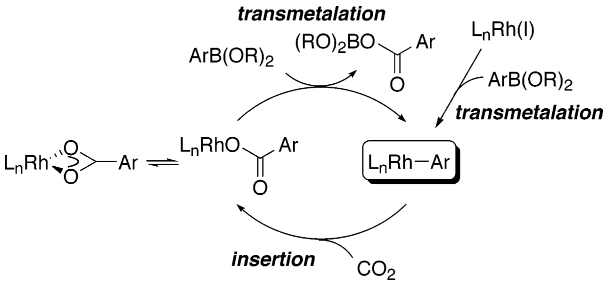
Development of a new method for the carboxylation of carbon nucleophiles using carbon dioxide as an electrophile is highly valuable, and, in particular, development of a catalytic method for this transformation is of paramount importance not only from a standpoint of a synthetic methodology but also from that of C1 chemistry.[1] However, CO_2 is a less-reactive electrophile, and organometallic reagents with high nucleophilicity such as organolithiums and Grignard reagents are usually required for this transformation.

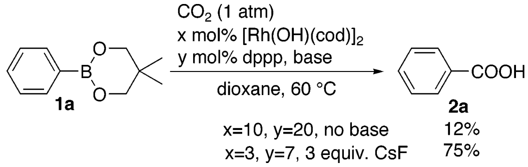
In the 1970s and 1980s, it was reported by Vol'pin, Aresta, and Darensbourg that phenylrhodium species readily reacted with CO_2 under high pressure (10∼20 atm) to give rhodium benzoate complexes.[2] However, a stoichiometric amount of rhodium species was employed, and no catalytic version of this reaction has been reported so far. To perform this reaction catalytically, it is necessary to regenerate the active catalyst from the rhodium carboxylates. Recent reports on rhodium(I)-catalyzed addition reactions of arylboronic reagents to various electrophiles such as carbonyl compounds,[3] electron-deficient alkenes,[4] and so on,[5] have prompted us to examine the reaction with CO_2, with the expectation that the high oxophilicity of boron compounds would make it possible to regenerate the active rhodium catalyst by promoting the exchange of rhodium carboxylates to boron carboxylates (Scheme 1). Recent progress on the facile preparation of various aryl- and alkenylboronic esters containing functional groups through the Pd-catalyzed coupling reaction of the corresponding halides with diboron reagents[6] or through the Rh or Ir-catalyzed borylation with the direct sp^2 C−H bond activation[7] would make this reaction highly useful for the synthesis of functionalized carboxylic acid derivatives.

At first we examined the reaction of several phenylboronic acid derivatives with CO_2 using $[Rh(OH)(cod)]_2$, which is known to be an efficient catalyst for transmetalation with arylboronic acid derivatives,[8] and it was found that when 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane (ester of phenylboronic acid with 2,2-dimethylpropan-1,3-diol) was treated with 10 mol % of the rhodium catalyst under an atmospheric pressure of CO_2 in the presence of 1,3-bis(diphenylphosphino)propane (dppp) in dioxane at 60 °C, the desired benzoic acid was obtained in 12% yield (eq 1). Other phenylboronic esters such as propan-1,3-diolate, ethylene glycolate, pinacolate, and catecholate gave almost no product.

We then examined various bases and ligands for the purpose of accelerating the transmetalation of the rhodium benzoate with the phenylboronic ester and enhancing the nucleophilicity of the phenylrhodium species. While use of several typical bases such as sodium alkoxide, potassium hydroxide, potassium carbonate, which were known to accelerate transmetalation of arylboronic acids or esters to arylrhodium species,[9] did not promote the carboxylation efficiently, use of cesium bases gave better results.[10] In particular, cesium fluoride was found to be the most efficient for this reaction.[11] Concerning the ligand, use of monodentate phosphine ligands did not promote the carboxylation reaction efficiently. However, use of bidentate ligands gave much better results. Among the ligands examined, dppp was found to be the best ligand for this reaction. Thus, benzoic acid was obtained in 75% yield using 3 mol % of rhodium catalyst and 3 equiv of CsF by heating the reaction mixture at 60 °C in the presence of 7 mol % dppp in dioxane under an atmospheric pressure of CO_2 (eq 1).

Scheme 1





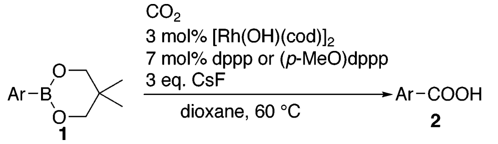
(1)

We next examined the generality of this reaction using several functionalized arylboronic esters. At this point, it was found that the reactive catalytic species were rather air-sensitive, and yield reproducibility was not always achieved well. Finally, good reproducibility of the reaction has been achieved by carrying out the reaction in a closed system.[12,13]

As summarized in Table 1, various arylboronic esters substituted with an electron-donating or electron-withdrawing group were converted into the corresponding arylcarboxylic acids in good to high yields by carrying out the reaction under the optimized conditions. In some cases, use of 1,3-bis[di(*p*-methoxyphenyl)phosphino]propane ((*p*-MeO)dppp) gave slightly better results compared to simple dppp. It should be noted that arylboronic esters containing a carbonyl or a cyano group could be converted to the corresponding carboxylic acids without affecting these functionalities (entries 6−9 and 11−14). Even a Boc-protected NH functionality could be tolerated in this reaction (entry 10). Furthermore, *o*-substituted arylboronic esters (entries 15 and 16) or heteroaromatic derivatives (entries 20−22) gave the corresponding carboxylic acids in good yield. Some of these substrates could be prepared by the coupling reaction of the aryl halides with bis(neopentyl glycolato)diboron, while the corresponding Grignard or aryllithium reagents are not employable for the reaction with CO_2. Thus, this protocol is particularly useful for the preparation of functionalized arylcarboxylic acids.

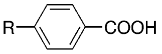
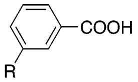
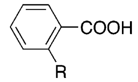
Reactions of alkenylboronic esters also proceeded under similar conditions in reasonable yields, except that $[RhCl(nbd)]_2$ was

10.1021/ja061232m CCC: $33.50 **© 2006 American Chemical Society**



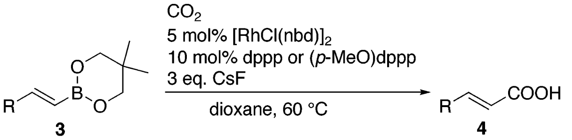
(2)

Table 1. Carboxylation of Arylboronic Esters

Entry	product	yield / %
1	 R = -*t*-Bu (**2b**)	89
2	-CH=CMe$_2$ (**2c**)	90
3	-OMe (**2d**)	95
4	-CF$_3$ (**2e**)	76
5	-F (**2f**)	85
6	-OPiv (**2g**)	68[a]
7	-COOMe (**2h**)	67[a]
8	-COCH$_3$ (**2i**)	74[a]
9	-CH$_2$C≡N (**2j**)	49[a]
10	-NHBoc (**2k**)	88[a]
11	-(CH$_2$)$_2$COCH$_3$ (**2l**)	78
12	-(CH$_2$)$_2$COOMe (**2m**)	78
13	 R = -COOMe (**2n**)	68
14	-CN (**2o**)	63[a]
15	 R = -Me (**2p**)	75[a,b]
16	-OMe (**2q**)	77[a]
17	3,5-Me$_2$C$_6$H$_3$COOH (**2r**)	76
18	2-naphthylCOOH (**2s**)	82
19	1-naphthylCOOH (**2t**)	70[a,b]
20	3-thienylCOOH (**2u**)	64
21	2-benzofuranylCOOH (**2v**)	59[a]
22	2-(1-methyl)indolylCOOMe (**2w**)[c]	54

[a] (*p*-MeO)dppp was employed. [b] The reaction was run at 90 °C. [c] Isolated as its methyl ester.

employed instead of $[Rh(OH)(cod)]_2$ (eq 3). Importantly, further 1,4-addition of alkenylboronic esters to the produced α,β-unsaturated carboxylic acid derivatives was not observed in these reactions. As alkenylboronic esters can readily be synthesized via hydroboration of the corresponding alkynes with catecholborane, followed by a trans-esterification or coupling reaction with the corresponding alkenyl halides or triflates with tetra(alkoxo)diborons,[6] substrates containing various functional groups would be applicable to this carboxylation reaction.



(3)

R= Ph(**4a**) 69%
R=4-MeOC$_6$H$_4$(**4b**) 94%*
R=*n*-Hex(**4c**) 81%*

* (*p*-MeO)dppp was employed.

In summary, we have succeeded in developing a rhodium-catalyzed carboxylation reaction of aryl- and alkenylboronic esters under mild conditions. As organoboronic esters are easily available without using organolithiums or Grignard reagents, various functional groups are tolerated in this reaction.

Acknowledgment. This research was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

Supporting Information Available: Preparative methods and spectral and analytical data of compounds **1**−**4**. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Reviews: (a) Behr, A. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 661. (b) Braunstein, P.; Matt. D.; Nobel, D. *Chem. Rev.* **1988**, *88*, 747. (c) Leitner, W. *Coord. Chem. Rev.* **1996**, *153*, 257. (d) Yin, X.; Moss, J. R. *Coord. Chem. Rev.* **1999**, *181*, 27. (e) Walther, D.; Ruben, M.; Rau, S. *Coord. Chem. Rev.* **1999**, *182*, 67. (f) Marks, T. J. et al. *Chem. Rev.* **2001**, *101*, 953.

(2) (a) Kolomnikov, I. S.; Gusev, A. O.; Belopotapova, T. S.; Grigoryan, M. Kh.; Lysyak, T. V.; Struchkov, Yu. T.; Vol'pin, M. E. *J. Organomet. Chem.* **1974**, *69*, C10. (b) Albano, P.; Aresta, M.; Manassero, M. *Inorg. Chem.* **1980**, *19*, 1069. (c) Darensbourg, D. J.; Grötsch, G.; Wiegreffe, P.; Rheingold, A. L. *Inorg. Chem.* **1987**, *26*, 3827.

(3) For reviews on Rh-catalyzed carbon−carbon bond-forming reactions, see: Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169. For aldehydes, see: (a) Sakai, M.; Ueda, M.; Miyaura, N. *Angew. Chem., Int. Ed.* **1998**, *37*, 3279. (b) Fürstner, A.; Krause, H. *Adv. Synth. Catal.* **2001**, *4*, *343*, 343. (c) Ueda, M.; Miyaura, N. *J. Org. Chem.* **2000**, *65*, 4450. (d) Pucheault, M.; Darses, S.; Genet, J.-P. *J. Am. Chem. Soc.* **2004**, *126*, 15356. For ketones, see: (e) Takezawa, A.; Yamaguchi, K.; Ohmura, T.; Yamamoto, Y.; Miyaura, N. *Synlett* **2002**, 1733. (f) Matsuda, T.; Makino, M.; Murakami, M. *Org. Lett.* **2004**, *6*, 1257. (g) Miura, T.; Shimada, M.; Murakami, M. *Synlett* **2005**, 667. (h) Miura, T.; Shimada, M.; Murakami, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 7598. For acid anhydrides, see: (i) Frost, C. G.; Wadsworth, K. J. *Chem. Commun.* **2001**, 2316. (j) Oguma, K.; Miura, M.; Satoh, T.; Nomura, M. *J. Organomet. Chem.* **2002**, *648*, 297. For esters, see: (k) Shintani, R.; Okamoto, K.; Otomaru, Y.; Ueyama, K.; Hayashi, T. *J. Am. Chem. Soc.* **2005**, *127*, 54. (l) Miura, T.; Sasaki, T.; Nakazawa, H.; Murakami, M. *J. Am. Chem. Soc.* **2005**, *127*, 1390.

(4) Review: (a) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829. (b) Hayashi, T. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 13. Recent studies, see: (c) Shintani, R.; Tsurusaki, A.; Okamoto, K.; Hayashi, T. *Angew. Chem., Int. Ed.* **2005**, *44*, 3909. (d) Paquin, J.-F.; Defieber, C.; Stephenson, C. R. J.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, 10850. (e) Yamamoto, Y.; Kurihara, K.; Sugishita, N.; Oshita, K.; Piao, D.; Miyaura, N. *Chem. Lett.* **2005**, *34*, 1224. (f) Chen, F.-X.; Kina, A.; Hayashi, T. *Org. Lett.* **2006**, *8*, 341.

(5) For imines, see: (a) Ueda, M.; Miyaura, N. *J. Organomet. Chem.* **2000**, *595*, 31. (b) Kuriyama, M.; Soeta, T.; Hao, X.; Chen, Q.; Tomioka, K. *J. Am. Chem. Soc.* **2004**, *126*, 8128. (c) Tokunaga, N.; Otomaru, Y.; Okamoto, K.; Ueyama, K.; Shintani, R.; Hayashi, T. *J. Am. Chem. Soc.* **2004**, *126*, 13584. (d) Weix, D. J.; Shi, Y.; Ellman, J. A. *J. Am. Chem. Soc.* **2005**, *127*, 1092. For nitriles, see: (e) Miura, T.; Nakazawa, H.; Murakami, M. *Chem. Commun.* **2005**, 2855. (f) Ueura, K.; Satoh, T.; Miura, M. *Org. Lett.* **2005**, *7*, 2229. (g) Miura, T.; Murakami, M. *Org. Lett.* **2005**, *7*, 3339.

(6) For the preparation of arylboronic esters, see: (a) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508. (b) Ishiyama, T.; Itoh, Y.; Kitano, T.; Miyaura, N. *Tetrahedron Lett.* **1997**, *38*, 3447. (c) Ishiyama, T.; Ishida, K.; Miyaura, N. *Tetrahedron* **2001**, *57*, 9813. For the preparation of alkenylboronic esters, see: (d) Takahashi, K.; Takagi, J.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* **2000**, *29*, 126. (e) Takagi, J.; Takahashi, K.; Ishiyama, T.; Miyaura, N. *J. Am. Chem. Soc.* **2002**, *124*, 8001.

(7) (a) Chen, H.; Schlecht, S.; Semple, T. C.; Hartwig, J. F. *Science* **2000**, *287*, 1995. (b) Cho, J.-Y.; Iverson, C. N.; Smith, M. R., III. *J. Am. Chem. Soc.* **2000**, *122*, 12868. (c) Cho. J.-Y.; Tse, M. K.; Holmes, D.; Maleczka, R. E., Jr.; Smith, M. R., III. *Science* **2002**, *295*, 305. (d) Ishiyama, T.; Takagi, J.; Ishida, K.; Miyaura, N.; Anastasi, N. R.; Hartwig, J. F. *J. Am. Chem. Soc.* **2002**, *124*, 390. (e) Ishiyama, T.; Takagi, J.; Hartwig, J. F.; Miyaura, N. *Angew. Chem., Int. Ed.* **2002**, *41*, 3056. (f) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263. (g) Chotana, G. A.; Rak, M. A.; Smith, M. R., III. *J. Am. Chem. Soc.* **2005**, *127*, 10539.

(8) (a) Itooka, R.; Iguchi, Y.; Miyaura, N. *Chem. Lett.* **2001**, *30*, 722. (b) Hayashi, T.; Takahashi, M.; Takaya, Y.; Ogasawara, M. *J. Am. Chem. Soc.* **2002**, *124*, 5052. For synthesis, see: (c) Uson, R.; Oro, L. A.; Cabeza, J. A. *Inorg. Synth.* **1985**, *23*, 126.

(9) (a) Sakuma, S.; Miyaura, N. *J. Org. Chem.* **2001**, *66*, 8944. (b) Itooka, R.; Iguchi, Y.; Miyaura, N. *J. Org. Chem.* **2003**, *68*, 6000.

(10) de la Herrán, G.; Mba, M.; Murcia, M. C.; Plumet, J.; Csákÿ, A. G. *Org. Lett.* **2005**, *7*, 1669.

(11) It is not yet clear whether the product in the reaction mixture is Cs carboxylate or boron carboxylate (or its fluoroborate salt). We are currently under study to clarify the exact mechanism of the reaction.

(12) After the catalyst, dppp, CsF, and the substrate were mixed in dioxane under 1 atm of CO$_2$ using a balloon, the reaction mixture was cut off from the balloon, kept closed, and heated at 60 °C. Although the temperature is below the boiling point, sufficient care should be taken for high pressure. The reaction was carried out behind a safety shield.

(13) Most reactions could be carried out under 1 atm of CO$_2$ using a balloon without problem.

JA061232M