Catalytic Boracarboxylation of Alkynes with Diborane and Carbon Dioxide by an N-Heterocyclic Carbene Copper Catalyst

Liang Zhang, Jianhua Cheng, Béatrice Carry,† and Zhaomin Hou*

Organometallic Chemistry Laboratory and Advanced Catalyst Research Team, RIKEN Advanced Science Institute, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Supporting Information

ABSTRACT: By the use of an N-heterocyclic carbene copper(I) complex as a catalyst, the boracarboxylation of various alkynes (e.g., diaryl alkynes, aryl/alkyl alkynes, and phenylacetylene) with a diborane compound and carbon dioxide has been achieved for the first time, affording the α,β-unsaturated β-boralactone derivatives regio- and stereoselectively via a borylcupration/carboxylation cascade. Some important reaction intermediates were isolated and structurally characterized to clarify the reaction mechanism.

The use of CO₂ as a low-cost and renewable C₁ building block for the synthesis of value-added chemicals is of great importance and has attracted increasing interest.¹ The direct carboxylation of carbon nucleophiles with CO₂ as an electrophile is a straightforward protocol for the synthesis of carboxylic acids.²,³ It was recently demonstrated that α,β-unsaturated carboxylic acids and their derivatives can be prepared by transition-metal-catalyzed carboxylations (e.g., hydrocarboxylation, alkylative/arylative carboxylation, and double carboxylation) of alkynes with CO₂.⁴⁻⁷ In principle, the heterocarboxylation of alkynes (such as boracarboxylation) with CO₂, which would lead to the addition of both a heteroatom unit (e.g., boryl) and a carboxylate group to the C–C triple bond could serve as a useful method for the synthesis of multifunctionalized alkenes, which are potentially versatile building blocks for various synthetic applications. However, there have been only a few reports on stoichiometric heterocarboxylation of highly reactive substrates. Previously, aminative carboxylation⁸a and hydroxy(carboxylation)⁸b of alkenes were achieved by the use of a stoichiometric amount of a Ni complex. The insertion of CO₂ into copper intermediates formed by silylcupration of dienes was reported to give the corresponding silacarboxylation products.⁸c Three-component coupling reactions of arynes, imines, and CO₂ were reported to afford benzoazinone derivatives.⁸d In contrast, the catalytic heterocarboxylation of simple unsaturated C–C bonds with CO₂ has remained almost unexplored to date.⁹

Boracarboxylation of alkynes with a boron compound and CO₂ is of particular interest and importance in view of the wide utility of C–B bonds in various chemical transformations.¹⁰ Moreover, the catalytic regio- and stereoselective synthesis of multifunctionalized alkenes remains one of the most difficult tasks in synthetic organic chemistry.¹¹ Herein we report the first catalytic boracarboxylation of alkynes with a diborane compound and CO₂ using an N-heterocyclic carbene (NHC) copper catalyst (eq 1). Both a boryl moiety and a carboxylate group are added regio- and stereoselectively to the C–C triple bond via a borylcupration/carboxylation sequence to afford α,β-unsaturated β-boralactone derivatives. Several reaction intermediates were isolated and structurally characterized, thus providing important insight into the mechanistic aspects of the catalytic cycle.

We previously demonstrated that NHC−copper(I) complexes such as [(IPr)Cu(OtBu)], where IPr = 1,3-bis(2,6-dimethylphenyl)imidazol-2-ylidene, can serve as excellent catalysts for the carboxylation of various nucleophiles.¹² To see whether an NHC−Cu catalyst is suitable for the boracarboxylation of alkynes, we examined first the sequential reactions of [(IPr)Cu(OtBu)] with bis(pinacolato)diboron [B₂(pin)₂], diphenylacetylene, and CO₂ (Scheme 1). As reported previously,¹² the reaction of [(IPr)Cu(OtBu)] with B₂(pin)₂ at room temperature instantly gave the borylcopper complex [(IPr)CuB(pin)]. The subsequent reaction of [(IPr)CuB(pin)] with CO₂ immediately gave the borylcupration/carboxylation product [(IPr)CuB(pin)] without purification.
copper complex 1 in 92% isolated yield through insertion of the C−C triple bond into the Cu−B bond in a syn fashion (Scheme 1 and Figure 1). Exposure of 1 to a CO2 atmosphere gave carboxylation product 2 in 95% isolated yield. X-ray crystallographic analysis revealed that complex 2 adopts a cyclic structure through a bonding interaction between the boron atom and the carboxylate unit, and the NHC–copper moiety is bonded to an O atom of the boronic ester group (Figure 2).

Treatment of 2 with 1 equiv of LiOttBu in tetrahydrofuran (THF) quantitatively yielded the copper alkoxide complex \[[\text{IPr}]\text{Cu(OttBu)}\] and lithium borolactone derivative 3 through a transmetalation reaction. An X-ray crystallographic study showed that 3 possesses a dimeric structure resulting from an "intermolecular" interaction between the Li atom and the carbonyl group (Scheme 1 and Figure 3). To the best of our knowledge, complexes 2 and 3 represent the first examples of structurally characterized α,β-unsaturated borolactone compounds.

With these well-established stoichiometric reactions in mind, we then attempted the catalytic boracarboxylation of diphenylacetylene with B2(pin)2 and CO2. However, when \[[\text{IPr}]\text{CuCl}\] (5 mol %) was used as the catalyst in the presence of LiOttBu (1.1 equiv), only a trace amount of the CO2 insertion product was observed (Table 1, entry 1). To our delight, replacing the IPr ligand with the less sterically demanding 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene (IMes) ligand in the copper complex (i.e., using \[[\text{IMes}]\text{CuCl}\] instead of \[[\text{IPr}]\text{CuCl}\]) resulted in a significant increase of the catalytic activity, giving the boracarboxylation product 4a in 73% isolated yield (entry 2). Using the saturated NHC ligand 1,3-bis(2,4,6-trimethylphenyl)imidazolin-2-ylidene (SIMes) further increased the product yield to 81% under the same conditions.

Table 1. Catalytic Boracarboxylation of Diphenylacetylene with B2(pin)2 and CO2

<table>
<thead>
<tr>
<th>entry</th>
<th>([\text{Cu}]) solvent</th>
<th>T (°C)</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(IPr)CuCl THF</td>
<td>80</td>
<td>trace</td>
</tr>
<tr>
<td>2</td>
<td>(IMes)CuCl THF</td>
<td>80</td>
<td>73</td>
</tr>
<tr>
<td>3</td>
<td>(SIMes)CuCl THF</td>
<td>80</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>(SIMes)CuCl dioxane</td>
<td>100</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>(SIMes)CuCl toluene</td>
<td>100</td>
<td>86</td>
</tr>
<tr>
<td>6</td>
<td>(SIMes)CuCl THF</td>
<td>rt</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>(SIMes)CuCl THF</td>
<td>rt</td>
<td>26</td>
</tr>
</tbody>
</table>

*Reaction conditions: \([\text{Cu}]\) (5 mol %), diphenylacetylene (0.5 mmol), B2(pin)2 (1.0 equiv), CO2 (1 atm), LiOttBu (1.1 equiv), solvent (3.0 mL), 80 °C, 14 h, unless otherwise noted. Isolated yields. S h.
conditions (entry 3). The catalyst remained similarly active even at 100 °C (entries 5 and 6). At room temperature, the catalyst was not very efficient, and a yield of only 26% was observed (entry 7).

We then used [(SIMes)CuCl] as a catalyst to examine the boracarboxylation reactions of various alkynes. Some representative results are summarized in Table 2. Diaryl alkynes with various substituents on the aromatic ring were generally suitable for this reaction, affording the expected products in good to excellent yields. Aromatic C−Cl bond (4e) and ester (4f) functional groups could survive the reaction conditions. Dithienylacetylene was also transformed into the corresponding α,β-unsaturated borolactone derivative 4g in high yield. In the case of 1-phenyl-1-propyne and 1-phenyl-1-butyne, the carboxylation took place exclusively at the carbon atom having the phenyl substituent, and the borylation occurred at the carbon atom having an alkyl group, selectively giving the α-phenylacrylic acid derivatives 4h and 4i, respectively. Remarkably, phenylacetylene could also undergo the boracarboxylation reaction with B2(pin)2 and CO2 to afford α-phenylacrylic acid derivative 4k with high selectivity.14 In the case of 2-tert-butyl-substituted phenylacetylene, only a trace amount of the carboxylation product 4j was obtained, probably because of steric hindrance by the bulky tert-butyl group.15

On the basis of the above experimental observations, a possible mechanism for the current boracarboxylation reactions is shown in Scheme 2. At first, the metathesis reaction between [(SIMes)CuCl] and LiOtBu would afford [(SIMes)Cu(OtBu)], which upon reaction with B2(pin)2 could generate the borylcopper complex [(SIMes)CuB(pin)]. Subsequent insertion of an alkyne into the Cu−B bond in a syn fashion would give β-boryl alkenylcopper complex A. Nucleophilic addition of the alkenylcopper species to CO2 followed by replacement of the Cu moiety in the resulting carboxylate with the B atom would yield β-boralactone derivative B. Finally, the transmetalation reaction between copper complex B and LiOtBu should regenerate [(SIMes)Cu(OtBu)] and release the final product 4.

In an attempt to check the synthetic utility of the present boracarboxylation products, the Suzuki−Miyaura cross-coupling reaction of 4h with iodobenzene was carried out under standard conditions (unoptimized), and it afforded tetrasubstituted alkene 5 in 45% isolated yield (Scheme 3).16

In summary, we have developed the first catalytic boracarboxylation reaction of alkynes with diborane and CO2, which gives a novel family of α,β-unsaturated β-boralactone derivatives with high regio- and stereoselectivity under mild conditions. Some key reaction intermediates have been isolated and structurally characterized, thus offering important insight into the mechanism of the catalytic cycle. The present reaction may serve as an attractive method for the synthesis of multifunctionalized alkenes, as it uses CO2 and easily available alkynes as building blocks and a relatively cheap copper complex as a catalyst.

Table 2. Catalytic Boracarboxylation of Various Alkynes with B2(pin)2 and CO2

<table>
<thead>
<tr>
<th>R− − R′ + B2(pin)2 + CO2</th>
<th>[SIMes]CuCl</th>
<th>LiOtBu</th>
<th>THF, 80 °C, 14 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a 81%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4b 74%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4c 64%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4d 77%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4e 68%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4f 94%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4g 94%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4h 83%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4i 76%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4j &lt;5%</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
<tr>
<td>4k 71% (4k:4k*, 98:2)</td>
<td>LiOtBu (1.1 equiv)</td>
<td>THF (3.0 mL)</td>
<td></td>
</tr>
</tbody>
</table>

“Reaction conditions: [(IMes)CuCl] (5 mol %), alkyne (0.5 mmol), B2(pin)2 (1.0 equiv), CO2 (1 atm), LiOtBu (1.1 equiv), THF (3.0 mL), 80 °C, 14 h. Isolated yields are shown.

Scheme 2. Possible Mechanism of Catalytic Boracarboxylation

Scheme 3. Suzuki−Miyaura Cross-Coupling Reaction Using 4h

In summary, we have developed the first catalytic boracarboxylation reaction of alkynes with diborane and CO2, which gives a novel family of α,β-unsaturated β-boralactone derivatives with high regio- and stereoselectivity under mild conditions. Some key reaction intermediates have been isolated and structurally characterized, thus offering important insight into the mechanism of the catalytic cycle. The present reaction may serve as an attractive method for the synthesis of multifunctionalized alkenes, as it uses CO2 and easily available alkynes as building blocks and a relatively cheap copper complex as a catalyst.
**COMMUNICATION**

**Feedslocal T.; Choi, J.-C.; Yasuda, H.**

**Iwasawa, N.**

**Lett.**

(c) Ochiai, H.; Jang, M.; Hirano, K.; Yorimitsu, H.; Oshima, K.

(b) Yeung, C. S.; Dong, V. M.

(a) Shi, M.; Nicholas, K. M.

**J. Am. Chem. Soc.**

2011

Cazin, C. S. J.; Nolan, S. P.

**REFERENCES**

**ACKNOWLEDGMENTS**

Financial support by Grants-in-Aid for Scientific Research (S) (21225004) and (B) (24750047) from the Ministry of Education, Culture, Sports, Science and Technology of Japan is gratefully acknowledged. L.Z. thanks RIKEN for a special postdoctoral fellowship. We thank Drs. Masayoshi Nishiura and Ms. Akiko Karube for elemental analysis.

**AUTHOR INFORMATION**

**Corresponding Author** houz@riken.jp

Notes

The authors declare no competing financial interest.

'B.C. is an intern at RIKEN from Université de Toulouse, INP-ENSIACET, UPS, France.

**REFERENCES**


(3) Examples of transition-metal-catalyzed carboxylation with CO₂:


(12) During the preparation of this manuscript, Tsuji and coworkers briefly reported the silicarboxylation of alkynes with CO₂ and silylborane. See: Tani, Y.; Semb, K.; Fujihara, T.; Terao, J.; Tsuji, Y. 92nd Annual Meeting of the Chemical Society of Japan, Tokyo, Japan, March 25–28, 2012; Abstract 3L1-44.


(14) An X-ray diffraction study showed that 4k adopts a tetrameric structure. See the Supporting Information for details.

(15) GC–MS analysis showed that monoborylated intermediates remained in the reaction mixture.