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Homogeneous Catalysis

Copper-Catalyzed Silacarboxylation of Internal Alkynes by Employing Carbon Dioxide and Silylboranes**

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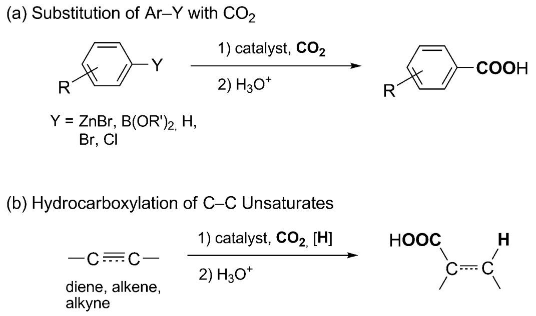
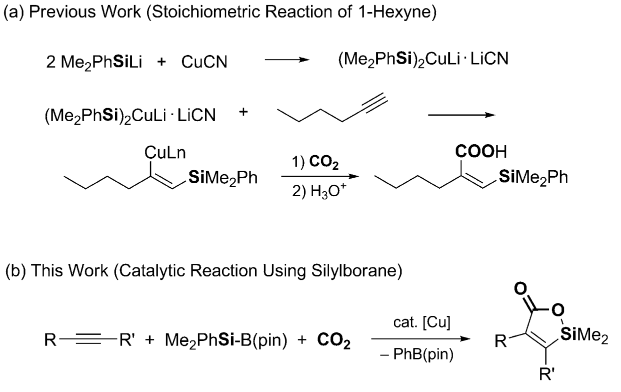
Carbon dioxide (CO_2) is a nontoxic, abundant, and renewable carbon source.[1] The utilization of this environmentally friendly raw material in carbon–carbon bond-forming reactions is one of the most important challenges in homogeneous transition metal catalysis.[2] To date, two types of catalytic transformations using CO_2 with C–C bond formation have been investigated intensively: a) the substitution of Ar–Y with CO_2 (Scheme 1a) and b) the hydrocarboxylation of C–C unsaturates (Scheme 1b). The former reactions involve the carboxylations of organozinc[3a,b] and organoborane[3c–f] compounds, C–H bonds,[3g-j] and bromoarenes[3k] (Scheme 1a). Recently, we reported the Ni-catalyzed carboxylation of chloroarenes with CO_2 in the presence of Mn powder under ambient conditions.[4a] As for the hydrocarboxylation (Scheme 1b), the reactions of dienes,[5a,b] alkenes,[5c] and alkynes[5d] have been reported. However, in all these cases, highly reactive and pyrophoric Et_3Al[5a,b] or Et_2Zn[5a,c,d] must be used as a hydride source. We recently reported the hydrocarboxylation of alkynes, by employing stable and easy-to-handle hydrosilanes as the hydride source.[4b]



Scheme 1. Typical transformations using CO_2 with C–C bond formations.

Besides these reactions, catalytic heterocarboxylation, in which the heteroatom functionality and CO_2 are simultaneously and catalytically incorporated into unsaturated substrates, is extremely useful, since the reaction will provide a valuable synthetic route employing CO_2 for the formation of highly functionalized carboxylic acid derivatives. For the silacarboxylation of alkynes, the only precedent is the stoichiometric reaction of 1-hexyne (one example) reported by Fleming et al., who carried out the reaction of 1-hexyne with a stoichiometric amount of $(Me_2PhSi)_2CuLi{\cdot}LiCN$ followed by trapping of the resulting Cu species with CO_2 (Scheme 2a).[6] Herein, we report the first catalytic silacarboxylation of internal alkynes employing CO_2 and silylborane in the presence of a copper catalyst (Scheme 2b).[7] The reaction afforded silalactone products regioselectively in good to high yields.



Scheme 2. Silacarboxylation of alkynes.

First, the silacarboxylation of 1-phenyl-1-propyne (**1a**) was carried out using the readily available $Me_2PhSi\text{-}B(pin)$[8,9] as the silicon source in the presence of a copper catalyst in octane at 100 °C under an atmospheric pressure of CO_2 (Table 1).[10] A mixture of CuCl and PCy_3 ($P/Cu = 1$) was employed as the catalyst, and silalactones[11] were afforded in 97% yield with high regioselectivity (**2a**/**2a'** = 97:3, Table 1, entry 1). $PtBu_3$ is also an efficient ligand and the products were obtained regioselectively in high yield (Table 1, entry 2). On the other hand, PBu_3, PPh_3, Xantphos, *rac*-BINAP, and DPPBz were not effective ligands, affording **2a** and **2a'** in low yields (Table 1, entries 3–7). [CuCl(IMes)][12a] bearing IMes, an N-heterocyclic carbene (NHC) ligand, gave **2** in high yield, but with slightly lower regioselectivity (**2a**/**2a'** = 88:12; Table 1, entry 8). [CuCl(IPr)],[12b] bearing the sterically demanding IPr ligand, gave a considerably lower yield

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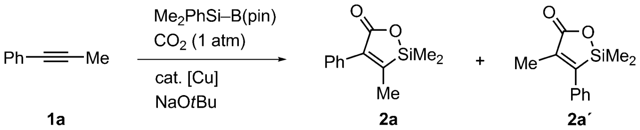
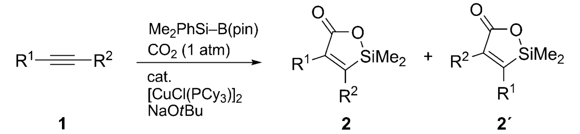
Table 1: Copper-catalyzed silacarboxylation of **1a** with CO_2 employing Me_2PhSi-B(pin).[a]

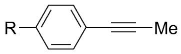
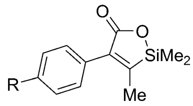
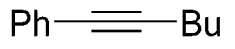
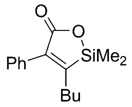
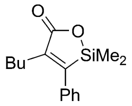
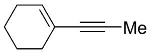
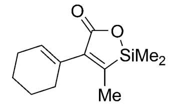
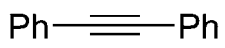
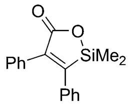
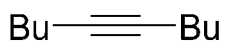
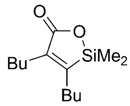


Entry	Cu catalyst	Ligand	Yield of **2a**+**2a′** [%][b]	Ratio of **2a**/**2a′**[c]
1	CuCl	PCy_3	97	97:3
2	CuCl	P*t*Bu_3	90	97:3
3	CuCl	PBu_3	15	90:10
4	CuCl	PPh_3	28	74:26
5	CuCl	Xantphos	0	–
6	CuCl	*rac*-BINAP	7	–
7	CuCl	DPPBz	0	–
8	[CuCl(IMes)]		96	88:12
9	[CuCl(IPr)]		18	77:23
10	$[CuCl(PCy_3)]_2$[d]		99 (81)[e]	96:4
11[f]	$[CuCl(PCy_3)]_2$[d]		98	95:5
12[g]	$[CuCl(PCy_3)]_2$[d]		84	94:6

[a] Reaction conditions; 1-phenyl-1-propyne (**1a**, 0.50 mmol), copper catalyst (0.015 mmol, 3.0 mol%), ligand (0.015 mmol, 3.0 mol%), NaO*t*Bu (0.060 mmol, 12 mol%), Me_2PhSi-B(pin) (0.60 mmol, 1.2 equiv), under CO_2 (1 atm) in octane (0.50 mL), at 100°C for 20 h. [b] Total yield of **2a** and **2a′** determined by GC analysis using tetradecane as an internal standard. [c] Determined by GC. [d] $[CuCl(PCy_3)]_2$ (0.0125 mmol, 2.5 mol%) was used as the catalyst. [e] Yield of isolated **2a**. [f] Toluene was used as the solvent. [g] 1,4-Dioxane was used as the solvent.

Table 2: Copper-catalyzed silacarboxylation of internal alkynes.[a]



Entry	Substrate	Yield of **2**+**2′** [%][b] (Ratio of **2/2′**)[c]	Yield of isolated major isomer: **2** [%]
			
1	**1b**: R = Me	93 (95:5)	**2b**: 85
2	**1c**: R = OMe	91 (94:6)	**2c**: 84
3	**1d**: R = Br	97 (96:4)	**2d**: 64
4	**1e**: R = CO_2Et	82 (98:2)	**2e**: 80
5	 **1f**	86 (87:13)	 **2f**: 70  **2f′**: 11
6	 **1g**	84 (92:8)	 **2g**: 76
7[d]	 **1h**	92	 **2h**: 77
8[e]	 **1i**	88	 **2i**: 81

[a] Reaction conditions; alkyne (**1**, 0.50 mmol), $[CuCl(PCy_3)]_2$ (0.0125 mmol, 2.5 mol%), NaO*t*Bu (0.060 mmol, 12 mol%), Me_2PhSi-B(pin) (0.60 mmol, 1.2 equiv), under CO_2 (1 atm) in octane (0.50 mL), at 100°C, for 16 h. [b] Total yield of **2** and **2′** determined by GC analysis using tetradecane as an internal standard. [c] Determined by GC. [d] For 60 h. [e] At 90°C, for 2 h.

(Table 1, entry 9). $[CuCl(PCy_3)]_2$,[12c] prepared from CuCl and PCy_3, was the best catalyst, giving **2** in quantitative yield while maintaining high regioselectivity (Table 1, entry 10). Through simple filtration and washing with hexane, the major regioisomer **2a** was isolated in 81% yield in pure form (Table 1, entry 10). The structure of **2a** was confirmed by X-ray crystallographic analysis[10] (Figure S1 in the Supporting Information) as well as 2D NMR spectroscopy measurements. In toluene or 1,4-dioxane as the solvent, the products were obtained in 98% and 84% yields, respectively (Table 1, entries 11 and 12), while acetonitrile and *N*,*N*-dimethylformamide did not afford the product at all.

The silacarboxylation of various alkynes (**1b**–**i**) was carried out (Table 2). The reactions of 1-aryl-1-propynes bearing both electron-rich and electron-poor substituents on the aryl ring gave the corresponding silalactones (Table 2, entries 1–4). The GC and GC–MS analyses of the crude products indicated that these reactions proceeded regioselectively, and major regioisomers (**2b**–**e**) were isolated in good to high yields. Gratifyingly, the bromo (Table 2, entry 3) and ester (entry 4) functionalities remained intact under these reaction conditions. 1-Phenyl-1-hexyne (**1f**) afforded the products in 86% total yield (by GC) with slightly lower regioselectivity (**2f**/**2f′** = 87:13). Pure **2f** and **2f′** were isolated from the reaction mixture by silica gel column chromatography in 70% and 11% yields, respectively (Table 2, entry 5). The conjugated enyne **1g** as the substrate gave **2g** and **2g′** in 84% total yield (**2g**/**2g′** = 92:8), from which the major isomer **2g** was isolated in 76% yield in pure form (Table 2, entry 6). Diphenylacetylene (**1h**) also afforded the corresponding product **2h** in good yield with a longer reaction time (Table 2, entry 7). The reaction of 5-decyne (**1i**) proceeded smoothly at 90°C for two hours and **2i** was isolated in 81% yield (Table 2, entry 8).

Et_3Si-B(pin)[13] (in place of Me_2PhSi-B(pin)) was reacted with **1a** under the same reaction conditions as for entry 10 in Table 1 [Eq. (1)]. However, the reaction of Et_3Si-B(pin) was not as clean as that with Me_2PhSi-B(pin), and some unidentified byproducts were formed. In the reaction, the corresponding silalactone **2a-Et** was afforded in only trace yield

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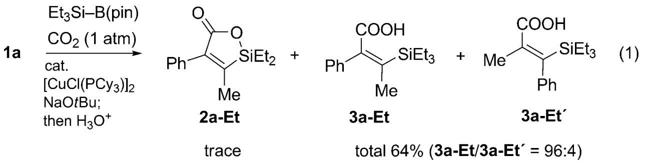
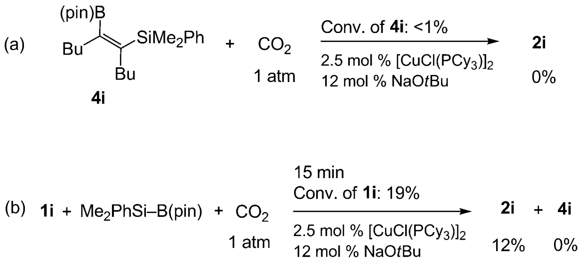


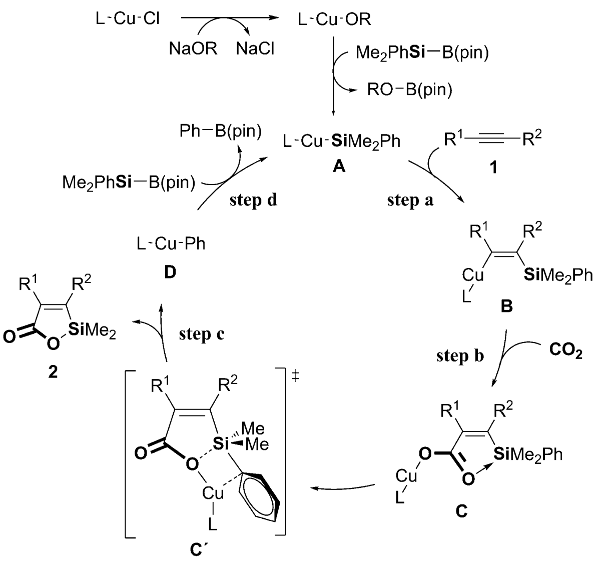
(determined by GC–MS). Instead, a mixture of two β-silyl-α,β-unsaturated carboxylic acids (**3a-Et**/**3a-Et′** = 96:4) was isolated in 64% yield [Eq. (1)]. Disilanes such as Me_2PhSi-$SiPhMe_2$ could not replace Me_2PhSi-B(pin) as the silicon source in the present silacarboxylation reaction, since neither silalactones (**2**) nor β-silyl-α,β-unsaturated carboxylic acids (**3**) were detected in the reaction mixture. Thus, the readily and commercially available Me_2PhSi-B(pin) is the best silicon source for this reaction.[14] Regarding the alkynes, terminal alkynes could not be used as the substrates.



Scheme 3. Control experiments relevant to the mechanism.

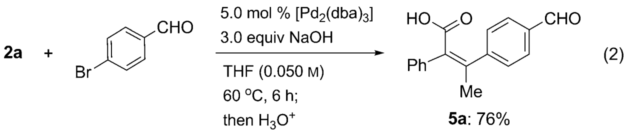
Some control experiments were carried out (Scheme 3) to provide an insight into the silacarboxylation mechanism. There is some possibility that the reaction could proceed stepwise through two sequential known reactions, that is, the silaboration of an alkyne[15] followed by the carboxylation of the resulting vinylboronic ester.[3c–f] Thus, we first prepared a possible intermediate **4i**[15a] through the silaboration of **1i** with Me_2PhSi-B(pin). Then the reaction of **4i** with CO_2 was carried out under the same reaction conditions as for entry 8 in Table 2. As a result, **4i** was not converted at all and no **2i** was provided (Scheme 3a). Furthermore, **4i** was not detected at all in the reaction mixture at a low conversion of **1i** (reaction time: 15 min; conversion of **1i**: 19%; yield of **2i**: 12%) under otherwise the same reaction conditions as for entry 8 in Table 2 (Scheme 3b). Thus, in the present catalytic system, the silacarboxylation must proceed in one step, and not through silaboration of the alkyne followed by carboxylation.

With consideration of these observations, a possible catalytic cycle for the silacarboxylation of alkynes with CO_2 is proposed (Scheme 4). First, the reaction of the alkoxocopper species with silylborane affords the silylcopper complex **A**.[16,17] *Syn* addition of **A** to the alkyne initiates the catalytic cycle and affords the β-silylalkenylcopper intermediate **B** (step a). Then, insertion of CO_2 into the Cu–C(vinyl) bond occurs,[4b] providing the corresponding copper carboxylate species **C** (step b). Intramolecular cyclization via **C′** affords the phenylcopper species **D** by extrusion of the silalactone **2** (step c). As shown in Equation (1), Et_3Si-B(pin) afforded the corresponding silalactone **2a-Et** in only trace yield. Thus, the phenyl moiety on the Si atom is indispensable for efficient Si–C bond cleavage.[18] Finally, σ-bond metathesis of **D** with silylborane provides PhB(pin), and the silylcopper species **A** is regenerated (step d). In fact, PhB(pin) was found (86% yield) in the reaction mixture in entry 10 of Table 1.



Scheme 4. Plausible reaction mechanism.

The silalactones are good substrates for the Hiyama cross-coupling reaction.[11b] Indeed, in the reaction of **2a** with 4-bromobenzaldehyde in the presence of $[Pd_2(dba)_3]$ as a catalyst, the trisubstituted α,β-unsaturated carboxylic acid **5a** was isolated in 76% yield [Eq. (2)].



In conclusion, the first catalytic silacarboxylation of an alkyne has been achieved by utilizing silylborane as the silicon source under atmospheric pressure of CO_2 to afford the silalactone selectively in high yield. Further studies on applications and the reaction mechanism are now in progress.

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Keywords: alkynes · carboxylation · copper · homogeneous catalysis · silylborane

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[8] Abbreviations: Me$_2$PhSi-B(pin): (dimethylphenylsilyl)pinacolborane, PCy$_3$: tricyclohexylphosphine, Xantphos: 4,5-bis(diphenylphosphino)-9,9-dimethylxanthene, *rac*-BINAP: 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl, DPPBz: 1,2-diphenylphosphinobenzene, IMes: 1,3-bis-(2,4,6-trimethylphenyl)imidazol-2-ylidene, IPr: 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-ylidene, dba: dibenzylideneacetone, 1,5-diphenyl-1,4-pentadien-3-one.

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