

Multicomponent Reactions

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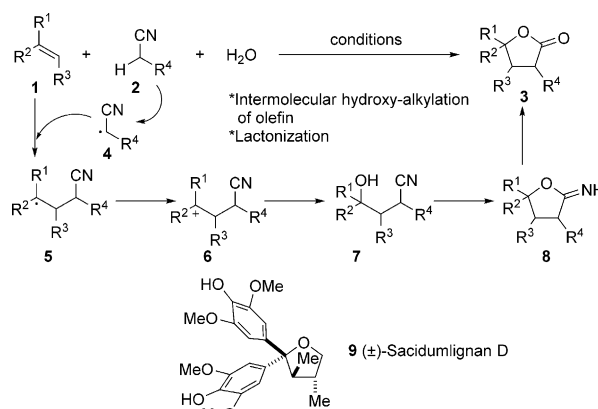
Copper-Catalyzed Formal [2+2+1] Heteroannulation of Alkenes, Alkynitriles, and Water: Method Development and Application to a Total Synthesis of (±)-Sacidumlignan D

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Abstract: A copper-catalyzed three-component reaction of alkenes, alkynitriles, and water affords γ -butyrolactones in good yields. The domino process involves an unprecedented hydroxy-cyanoalkylation of alkenes and subsequent lactonization with the creation of three chemical bonds and a quaternary carbon center. The synthetic potential of this novel [2+2+1] heteroannulation reaction was illustrated by a concise total synthesis of (±)-sacidumlignan D.

Copper-catalyzed difunctionalization of unactivated alkenes involving a C–C and a C–X bond formation is one of the most attractive transformations in organic chemistry. Although copper-mediated and copper-catalyzed carboamidation,^[1] carboxygenation,^[2] carboboration,^[3] and other difunctionalization reactions of alkenes have been intensively investigated,^[4] most of them involve the intramolecular formation of a C(sp²)–C(sp³) bond using substrates in which one of the reaction partners is tethered to the alkene. The copper-catalyzed intermolecular carboxygenation of alkenes are limited mainly to those reactions initiated by aryl radicals^[5] and the CF₃ radical.^[6,7] In this regard, one notable and important exception involving the formation of a C(sp³)–C(sp³) bond is the manganese(III) acetate mediated annulation of olefins with acetic acid, thus leading to γ -butyrolactones [2.0 equiv of Mn(OAc)₃ in refluxing acetic acid].^[8] γ -Butyrolactone is an important core structure found in many biologically active natural products^[9] and is also a useful synthetic building block.^[10] It is therefore not surprising that many different strategies have been developed for the efficient synthesis of this heterocycle. For example, Jiang and co-workers have recently reported a copper-catalyzed formal [3+2] heteroannulation of terminal alkenes with acetic anhydride for the synthesis of γ -butyrolactones.^[11,12]

Our group has recently initiated a research program aimed at developing copper-catalyzed alkylative difunctionalization of alkenes using alkynitriles as a key reactant.^[13–15] As a continuation of this project, we became interested in



Scheme 1. Difunctionalization of alkenes to γ -butyrolactones: A copper-catalyzed three-component reaction of alkenes, alkynitriles, and water.

developing a novel synthesis of γ -lactones (**3**) by a copper-catalyzed three-component [2+2+1] heteroannulation of alkenes (**1**), alkynitriles (**2**), and water (Scheme 1). The underlying principle is outlined in Scheme 1. Addition of the in situ generated α -cyanoalkyl radical **4** to an alkene **1** would afford the adduct radical **5**, which could be further oxidized to the carbenium ion **6**.^[16] Trapping of the latter by water would afford the γ -hydroxy alkynitrile **7**, which, upon intramolecular cyclization, would provide the cyclic imidate **8**. Acidic work-up would then convert **8** into the γ -butyrolactone **3**. For the desired domino sequence to proceed towards the formation of **3**, the catalytic conditions should satisfy the following mechanistic criteria: a) selective generation of **4**, which adds rapidly to the double bond of **1**, b) fast oxidation of the resulting nucleophilic radical **5** to **6** to avoid the dimerization of the former, c) rapid addition of water to **6** to avoid its cationic polymerization with the remaining alkene, and d) proper activation of the cyano group to accelerate the lactonization process. The realization of this synthetic scheme and its application to the total synthesis of (±)-sacidumlignan D (**9**)^[17] is reported herein.

Using α -methyl styrene (**1a**) and acetonitrile (**2a**) as test substrates, the reaction conditions were surveyed by varying the copper sources, the ligands, the oxidants, the bases, and the additives (for details, see the Supporting Information). Preliminary results indicated that the reaction can indeed take place, thus providing, after acidic treatment (1.0 N HCl, 80 °C), the lactone **3a** in 60 % yield (NMR; Table 1, entry 1). Since the intermediate **7a** ($R^1 = \text{Ph}$, $R^2 = \text{Me}$, $R^3 = R^4 = \text{H}$; Scheme 1) was detected before the acidic treatment, various Lewis acids were tested to accelerate the lactonization step.

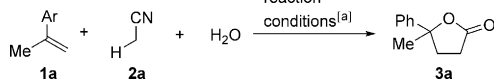
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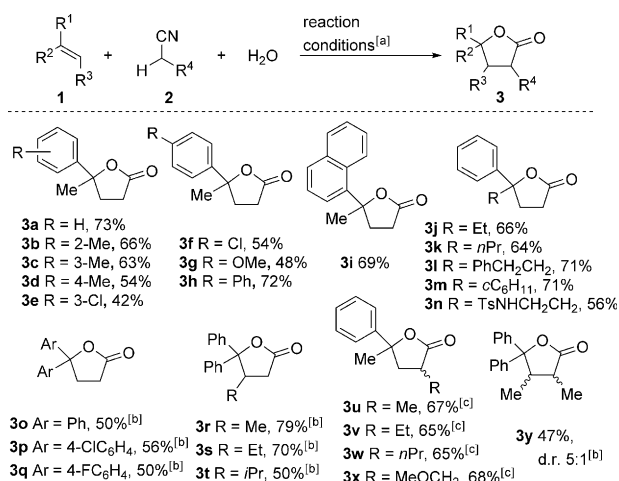
Table 1: Copper-catalyzed formal [2+2+1] annulation of **1a**, **2a**, and water to **3a**: optimization of reaction conditions.


Entry	Base (equiv)	Lewis acid (equiv)	Yield [%] ^[b]
1	K ₃ PO ₄ (0.1)	none	60
2	K ₃ PO ₄ (0.1)	In(OTf) ₃ (0.2)	66
3	K ₃ PO ₄ (0.1)	Yb(OTf) ₃ (0.2)	69
4	K ₃ PO ₄ (0.1)	Mg(OTf) ₂ (0.2)	68
5	K ₃ PO ₄ (0.1)	Ca(ClO ₄) ₂ (0.2)	65
6	K ₃ PO ₄ (0.1)	Mg(ClO ₄) ₂ (0.2)	79
7	K ₃ PO ₄ (0.1)	Zn(OTf) ₂ (0.2)	75
8	K ₃ PO ₄ (0.1)	Ca(OTf) ₂ (0.2)	81 (69) ^[c]
9	K ₃ PO ₄ (0.2)	Ca(OTf) ₂ (0.2)	74
10	Na ₃ PO ₄ (0.2)	Ca(OTf) ₂ (0.2)	75
11	KOrBu (0.1)	Ca(OTf) ₂ (0.2)	56
12	LiOrBu (0.1)	Ca(OTf) ₂ (0.2)	54
13	DBU (0.15)	Ca(OTf) ₂ (0.2)	89 (73) ^[c]
14	DBN (0.15)	Ca(OTf) ₂ (0.2)	79
15	N-methylimidazole (0.15)	Ca(OTf) ₂ (0.2)	79
16	2,6-lutidine (0.15)	Ca(OTf) ₂ (0.2)	56

[a] Reaction was performed in a sealed tube: **1a** (0.1 mmol), Cu(BF₄)₂·6H₂O (0.2 equiv), H₂O (30 equiv), Bipy (0.6 equiv), DTBP (4.0 equiv), base and Lewis acid in MeCN (0.025 M), N₂ atmosphere, 140 °C, 3.5 h, then 1.0 N HCl, 80 °C, 45 min. [b] Yield was determined by ¹H NMR spectroscopy with CH₂Br₂ as an internal standard. [c] Yield of isolated product. Bipy = 2,2'-bipyridine, DBN = 1,5-diazabicyclo-[4.3.0]non-5-ene, DTBP = di-*tert*-butyl peroxide, DBU = 1,8-diazabicyclo-[5.4.0]undec-7-ene, Tf = trifluoromethanesulfonyl.

Some representative results are summarized in Table 1. Adding lanthanide triflates (entries 2 and 3), Mg(OTf)₂ (entry 4), and Ca(ClO₄)₂ (entry 5) to the reaction mixture slightly increased the yield of **3a**. A significant improvement was observed by performing the reaction in the presence of a catalytic amount of either Mg(ClO₄)₂, Zn(OTf)₂, or Ca(OTf)₂ (entries 6–9),^[18] with the latter furnishing the cleaner reaction.^[19] Including Ca(OTf)₂ as a Lewis acid, the influence of base on the reaction outcome was re-investigated. Na₃PO₄ (entry 10), DBN and *N*-methylimidazole (entries 14 and 15) were as efficient as K₃PO₄, whereas a lower yield of **3a** was isolated when KOrBu, LiOrBu, and 2,6-lutidine (entries, 11, 12, and 16) were used as bases. Gratefully, a clear improvement of the reaction efficiency was observed when the reaction was performed in the presence of DBU (entry 13). Overall, under optimum reaction conditions, **3a** was isolated in 73% yield. We note that the reaction proceeded equally well in the dark.^[19] Since three chemical bonds were created in this domino process, the average yield per chemical bond formation is around 90%.

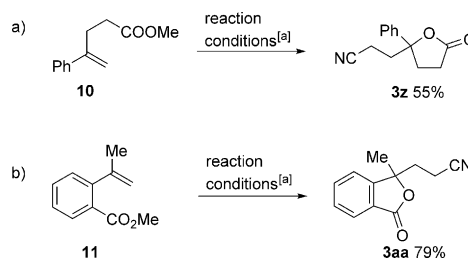
With the optimized reaction conditions [Cu(BF₄)₂·6H₂O, (0.2 equiv), Bipy (0.6 equiv), DBU (0.15 equiv), H₂O (30 equiv), Ca(OTf)₂ (0.2 equiv), DTBP (4.0 equiv), 3.5 h, N₂ atmosphere, MeCN, 140 °C, then 1.0 N HCl, 80 °C, 45 min], the scope of this copper-catalyzed, formal [2+2+1] heteroannulation was investigated. As shown in Scheme 2, the α-methyl styrenes with both electron-donating (Me, OMe) and electron-withdrawing (Cl) substituents on the aromatic ring, regardless of their positions, afforded the γ-butyrolactones **3b–i** in good yields. Methyl, ethyl, isopropyl, phenethyl, and

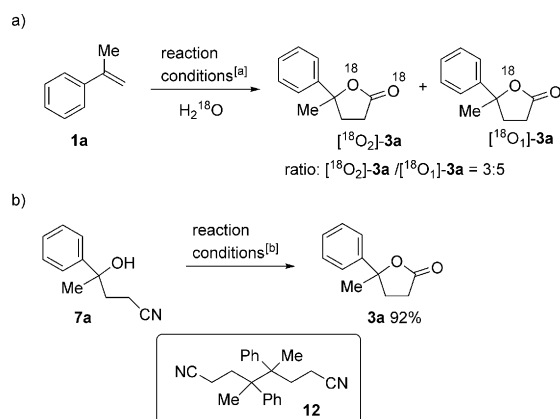
**Scheme 2.** Substrate scope. [a] Standard reaction conditions. [b] DTBP (2.5 equiv) under otherwise identical conditions. [c] d.r. = 1:1.

functionalized alkyl-substituted styrenes participated in the reaction without event to provide the corresponding γ-butyrolactones (**3j–n**). 1,1-Diaryl-substituted alkenes are excellent substrates leading to the corresponding lactones (**3o–t**). Importantly, trisubstituted alkenes participated in the reaction equally well to efficiently give the 3,4,4-trisubstituted γ-butyrolactones **3r–t**. Propionitrile, butyronitrile, valeronitrile, and 3-methoxypropionitrile are competent alkylating agents to initiate the domino process leading to the corresponding γ-butyrolactones **3u–3x** as a mixture of two diastereomers. Pleasingly, reaction of trisubstituted alkenes with propionitrile afforded the 2,3,4,4-tetrasubstituted γ-butyrolactone **3y**, albeit in a slightly reduced yield (47%).

The reaction of methyl-4-phenylpent-4-enoate (**10**) with acetonitrile under standard reaction conditions afforded the lactone **3z** in which the cyano group remained untouched (Scheme 3a). Similarly, methyl 2-(prop-1-en-2-yl)benzoate (**11**) was converted, under identical reaction conditions, into the lactone **3aa** (Scheme 3b). The observed highly chemoselective cyclization could be accounted for by the direct interception of the benzylic cation by the tethered methoxycarbonyl function.

Performing the reaction of **1a** in MeCN under an oxygen atmosphere with or without DTBP led only to the decomposition of the alkenes. In contrast, performing the same reaction under strictly inert atmosphere afforded **3a** in 73% yield. An isotope-labelling experiment was conducted to gain further mechanistic insights. Reaction of **1a** with acetonitrile

**Scheme 3.** Additional examples on the synthesis of functionalized γ-lactones. [a] Standard reaction conditions.

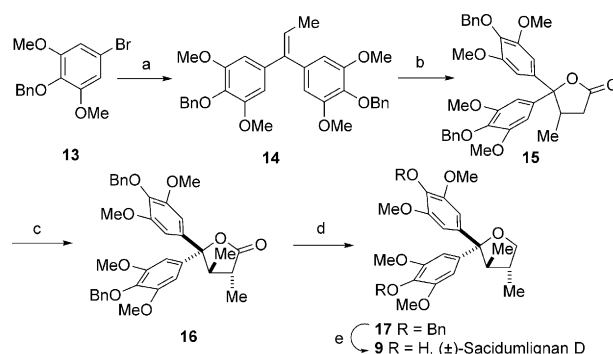


Scheme 4. ¹⁸O-Labeling and control experiments. [a] H₂¹⁸O (30 equiv), under otherwise standard reaction conditions. [b] Standard reaction conditions.

(2a) in the presence of H₂¹⁸O (¹⁸O content 97%) under otherwise standard reaction conditions afforded the double and mono ¹⁸O-labeled products [¹⁸O₂]-3a and [¹⁸O₁]-3a, respectively (Scheme 4a). The upfield shift of ¹³C NMR signals of C1 and C4 in [¹⁸O₂]-3a/[¹⁸O₁]-3a relative to those of 3a [$\Delta\delta_{(C=O)}^{16O-^{18}O} = +2.5$ Hz, [$\Delta\delta_{(C4)}^{16O-^{18}O} = +4.9$ Hz] is in agreement with literature reports.^[20] The results of these control experiments indicated that the oxygen atoms in the lactones 3 came from water rather than from adventitious oxygen or DTBP (Scheme 1). Furthermore, submitting an authentic sample of the tertiary alcohol 7a to the standard reaction conditions afforded 3a in 92% yield, thus indicating that the tertiary alcohol 7 could indeed be an intermediate on the way to lactone 3 (Scheme 4b).

In the absence of Cu(BF₄)₂·6H₂O or Bipy, only a trace amount of 3a was formed. In contrast, without DTBP, 1a was converted into 3a in 39% yield (NMR) in the presence of a stoichiometric amount of Cu(BF₄)₂. These observations are in accord with our previous conclusion that the copper catalyst played a key role in the generation of the acetonitrile radical 4 and that DTBP served mainly as an oxidant to regenerate the copper(II) species.^[21] In our initial survey of reaction conditions, we isolated the dimer 12, resulting most probably from the dimerization of the benzylic radical 5a (see Scheme 1; R¹ = Ph, R² = Me, R³ = R⁴ = H) because of its inefficient oxidation to 6a. Therefore, the copper catalyst played a dual role in this transformation, that is, to generate the cyanoalkyl radical and to selectively oxidize the adduct radical to the carbenium ion.

(±)-Sacidumlignan D (9) was isolated by Yue and co-workers from the plant *Sarcostemma acidum* (Roxb.) collected from Hainan island, China, where the local people use it for the treatment of chronic cough and postnatal hypogalactia.^[17,22] To illustrate the synthetic potential of our heteroannulation process, a total synthesis of 9 was undertaken (Scheme 5). Lithium–halogen exchange of the aryl bromide 13, readily synthesized in two steps from 2,6-dimethoxyphenol, followed by nucleophilic addition of the resulting aryllithium species to propionyl chloride furnished a tertiary alcohol, which, without purification, was dehydrated under



Scheme 5. Total synthesis of (±)-sacidumlignan D (9): a) *n*BuLi, EtCOCl, THF, 60 °C, then PTSA, toluene, reflux, 56%; b) Cu-(BF₄)₂·6H₂O (0.2 equiv), Bipy (0.6 equiv), DBU (0.15 equiv), H₂O (30 equiv), Ca(OTf)₂ (0.2 equiv), DTBP (2.5 equiv), 140 °C, in MeCN (0.025 M), 3.5 h; then 1.0 N HCl, 80 °C, 45 min, 60%; c) LHMDS (5 equiv), MeOTf (4 equiv), THF, −78 °C, 12 h, 89%; d) LiAlH₄, then TFA, CH₂Cl₂, 91% (2 steps); e) H₂, Pd/C, MeOH/EtOAc (1:1), 93%. LHMDS = lithium hexamethyldisilazide, PTSA = *p*-toluene sulfonic acid, TFA = trifluoroacetic acid, THF = tetrahydrofuran.

acidic conditions to give the alkene 14. The key [2+2+1] heteroannulation of 14 with acetonitrile and water under our standard reaction conditions proceeded smoothly to afford the lactone 15 in 60% yield. Treatment of 15 with LHMDS followed by methylation of the lithium enolate provided the 2,3-*trans* disubstituted lactone 16 as an only isolable stereoisomer. Reduction of 16 with LiAlH₄ afforded the tetrahydrofuran 17, which was converted into 9 in 93% yield under hydrogenolysis conditions.

In summary, we have developed the first examples of copper-catalyzed three-component reactions of alkenes with alkylnitriles and water. The domino process involved an unprecedented copper-catalyzed hydroxy-cyanoalkylation of alkenes and subsequent cyclization leading to γ -butyrolactones with concomitant formation of one C(sp³)–C(sp³) bond and two C–O bonds. This novel [2+2+1] heteroannulation reaction was featured as the key step in a concise total synthesis of (±)-sacidumlignan D.

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