JOC The Journal of Organic Chemistry

Featured Article

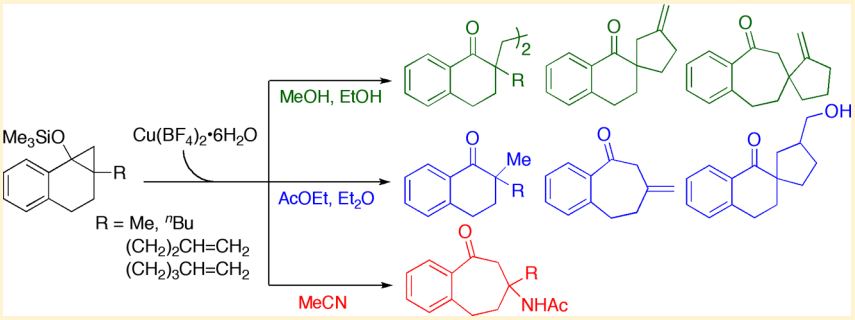
pubs.acs.org/joc

Solvent-Dependent Reaction Pathways Operating in Copper(II) Tetrafluoroborate Promoted Oxidative Ring-Opening Reactions of Cyclopropyl Silyl Ethers

Eietsu Hasegawa,* Kazuki Nemoto, Ryosuke Nagumo, Eiji Tayama, and Hajime Iwamoto

Department of Chemistry, Faculty of Science, Niigata University, 8050 Ikarashi-2, Nishi-ku, Niigata 950-2181, Japan

Supporting Information

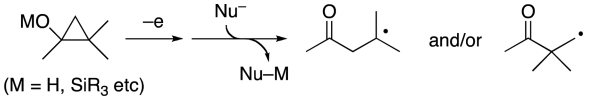


ABSTRACT: Oxidative ring-opening reactions of benzene-fused bicyclic cyclopropyl silyl ethers, promoted by copper(II) tetrafluoroborate, were investigated. The regioselectivity of cyclopropane ring-opening as well as product distributions were found to be highly dependent on the nature of the solvent. In alcohols, dimeric substances arising from external bond cleavage are major products. Radical rearrangement products are also formed in solvents such as ether and ethyl acetate. On the contrary, nucleophile addition to carbocation intermediates, generated by internal bond cleavage, occurs mainly in reactions taking place in acetonitrile. It is proposed that the observed solvent effects that govern the reaction pathways followed are a consequence of varying solvation of copper intermediates, which governs their reactivity and redox properties. In addition, the influence of counteranions of the copper salts, organonitriles, cyclic dienes, and substrate structures on the pathways followed in these reactions was also examined.

INTRODUCTION

Single-electron transfer (SET) is a fundamental chemical process that occurs in a wide variety of reduction and oxidation (redox) reactions.[1] Moreover, free radicals often serve as key intermediates in SET-promoted redox reactions of organic substances.[1f,g] Because cyclopropanols and their derivatives are versatile synthetic building blocks, they have been frequently used in organic synthesis.[2] In addition, owing to the expectation that they produce useful β-keto alkyl radical intermediates, oxidation reactions of cyclopropanol derivatives have been explored in detail (Scheme 1).[3−6] In continuing studies focusing on SET-promoted processes, we have studied oxidative ring-opening reactions of selected bicyclic cyclopropanol derivatives that occur under ground- and excited-state oxidation conditions.[7]

Scheme 1. β-Keto Alkyl Radical Generation by Oxidative Ring-Opening of Cyclopropanol Derivatives



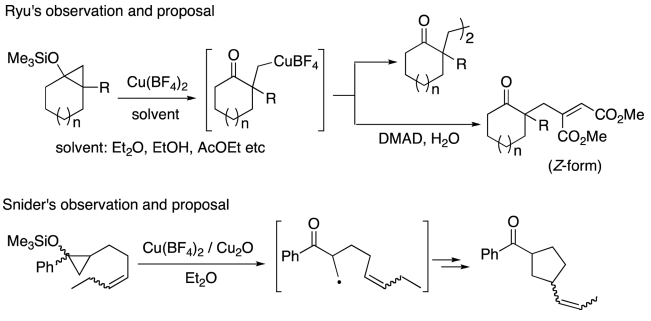
Although copper(II) salts are often employed as SET oxidants in organic chemistry,[1a,e,8,9] their use in inducing ring-opening reactions of cyclopropanol derivatives is limited.[4,5,7h,10] About three decades ago, Ryu and co-workers reported the results of seminal studies which demonstrated that $Cu(BF_4)_2$ promotes reactions of bicyclic cyclopropyl silyl ethers that form dimeric products (upper path in Scheme 2).[4] When these reactions are carried out in the presence of dimethyl acetylenedicarboxylate (DMAD) and water, addition of the β-acylalkyl species occurs to give *Z*-adducts. It was proposed that organocopper(II) intermediates are involved in these reactions. On the other hand, Snider and co-workers suggested the involvement of radical intermediates in this process based on the observation that a typical intramolecular radical trapping product is formed albeit in low yield (lower path in Scheme 2).[5]

Recently, we observed that the nature of counteranions in copper(II) salts significantly influences the pathways followed in ring-opening reactions of fused benzene ring containing bicyclic cyclopropanols in MeCN (Scheme 3).[7h] In this effort, we did not observe the formation of dimeric products like those

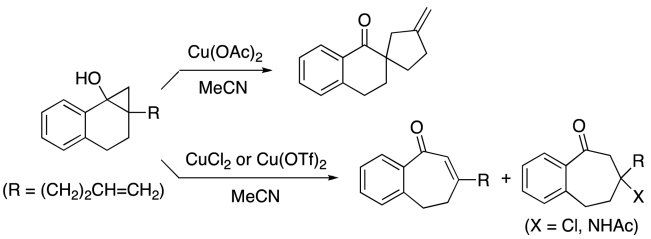
Received: December 13, 2015
Published: January 14, 2016

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

Scheme 2. Previously Studied $Cu(BF_4)_2$ Promoted Ring-Opening Reactions of Cyclopropyl Silyl Ethers



Scheme 3. Our Study on Copper(II) Salt Promoted Ring-Opening Reaction of a Bicyclic Cyclopropanol



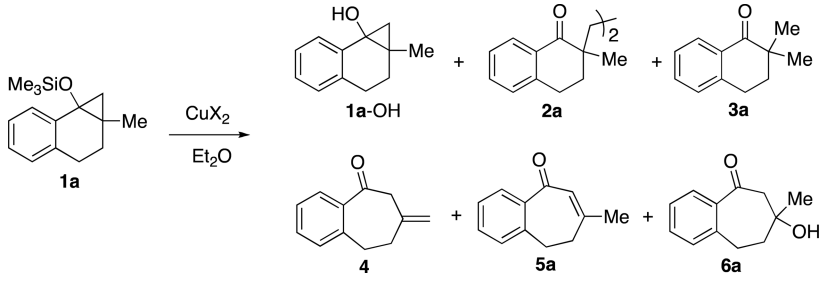
detected by Ryu,[4] nor did we probe the use of $Cu(BF_4)_2$ as an oxidant. In the earlier study, Ryu also noted that $Cu(BF_4)_2$ promotes reactions of bicyclic cyclopropyl silyl ethers in MeCN and DMF that produce dimeric products in minimal yields.[4] However, no information was provided about other products produced in these reactions. Owing to our interest in this area, we carried out an investigation aimed at more thoroughly investigating $Cu(BF_4)_2$ promoted ring-opening reactions of cyclopropyl silyl ethers in various solvents including MeCN.

RESULTS AND DISCUSSION

In the first phase of this effort, reactions of cyclopropyl silyl ether **1a** with $Cu(BF_4)_2$ and other copper(II) salts in Et_2O were investigated (Table 1).[11] We observed that reaction of **1a** with $Cu(BF_4)_2 \cdot 6H_2O$ leads to formation of several products including dimer **2a**, dimethyl ketone **3a**, desilylated alcohol **1a**-OH, and a small amount of ring-expanded β-hydroxy ketone **6a** (entry 1).[12] The β,γ-enone **4** generated in this process could not be isolated by using silica gel chromatography, and consequently, its structure was tentatively determined by using ^{1}H NMR analysis of the crude reaction mixture (see the Supporting Information). Moreover, α,β-enone **5a** was isolated in 21% yield by using column chromatography even though it was not present in large quantities in the crude reaction mixture. These findings suggest that **4** undergoes acid-promoted conversion to the more stable **5a** during the separation process. Thus, the ^{1}H NMR yields of **4** and **5a** in the crude reaction mixture are reported in Table 1. An increase in the quantity of $Cu(BF_4)_2$ causes a slight decrease in the yields of **2a**, **3a**, and **4**, and **1a**-OH is nearly completely consumed (entry 2). In the reactions of **1a** with $Cu(ClO_4)_2$ and $Cu(OTf)_2$, **2a** is the major product (entries 3 and 4).[13]

Because $Cu(BF_4)_2$ is not completely soluble in Et_2O, solvents in which it is more soluble were employed for this reaction (Table 2).[14] Reactions of **1a** with $Cu(BF_4)_2 \cdot 6H_2O$ in alcohol solvents were found to produce **2a** as a major product, while the yield of this substance gradually decreases as the alkyl portion of the alcohol solvent becomes more bulky (entries 1, 3, and 6). Reactions of **1a** promoted by 1.1 molar equiv of $Cu(ClO_4)_2 \cdot 6H_2O$ in EtOH and $Cu(OTf)_2$ in aqueous EtOH produced **2a** in 82% and 83% yields, respectively, along with small quantities of **3a** (5%) for each case (not shown in Table 2). The use of 2.2 molar equiv of $Cu(BF_4)_2$ leads to a significantly increased yield of **2a** (compare entries 2 and 5 with entries 1 and 3, respectively), while reaction at 80 °C results in an increase in both the yield of **2a** and the extent of isomerization of **4** to **5a** (compare entry 4 to entry 3). While **2a** is generated as a major product in acetone, THF, and DMF, the formation of **6a** becomes significant in the first two solvents (entries 7 and 8), and some quantity of **1a**-OH is recovered in the last solvent (entry 9). In contrast, reaction in AcOEt produces **3a** and **4** predominantly along with **2a** (entry 10). When the quantity of $Cu(BF_4)_2$ used for reaction in AcOEt is increased to 2.2 molar equiv, **2a** becomes the major product (entry 11). In marked contrast is the observation that **2a** does not form in the reaction of **1a** with 1.1 or 2.2 molar equiv of $Cu(BF_4)_2$ in MeCN (entries 12 and 13). In this solvent, the MeCN adduct,[7h] acetamide **7a**, and **6a** are major products. A

Table 1. Reaction of 1a with Various Copper(II) Salts in Et_2O[a]

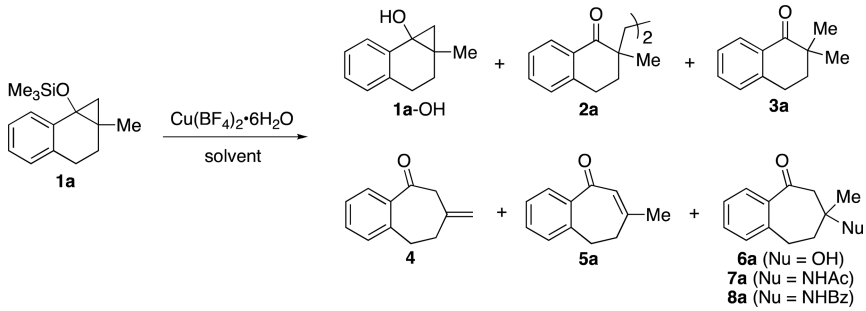


		yields (%)					
entry	CuX_2 (equiv vs **1a**)	**1a**-OH[b]	**2a**	**3a**[b]	**4**[b]	**5a**[b]	**6a**
1	$Cu(BF_4)_2 \cdot 6H_2O$ (1.1)	9	23[b]	25	21	2	3
2	$Cu(BF_4)_2 \cdot 6H_2O$ (2.2)	trace	21	18	17	3	2
3	$Cu(ClO_4)_2 \cdot 6H_2O$ (1.1)	0	52[b]	9	4	4	4[b]
4[c]	$Cu(OTf)_2$ (1.1)	18	50[b]	8	4	5	5[b]

[a]Reaction conditions: **1a** (0.30 mmol), Et_2O (3 mL), under N_2, rt, 6 h. [b]Determined by ^{1}H NMR. [c]6.6 equiv of H_2O was added.

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

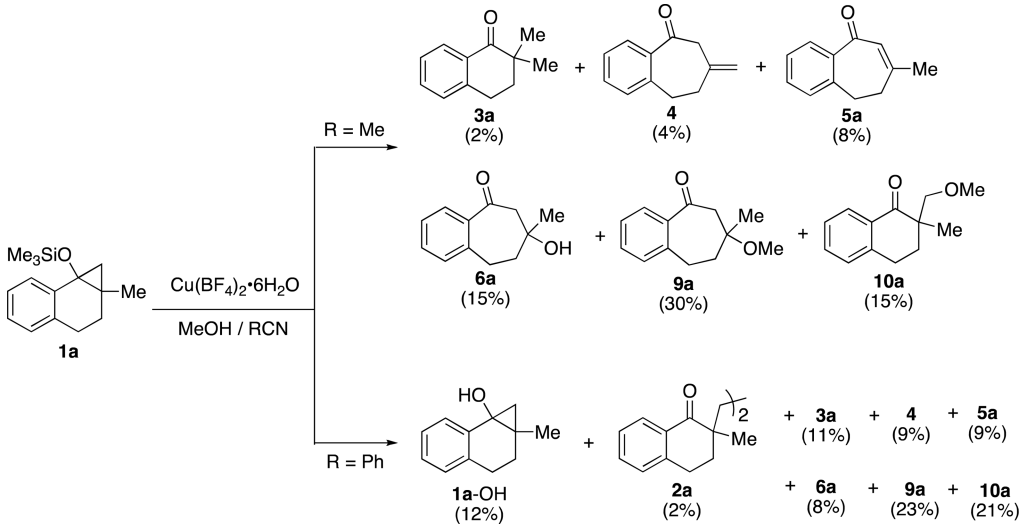
Table 2. Reaction of 1a with $Cu(BF_4)_2 \cdot 6H_2O$ in Various Solvents[a]



			yields (%)						
entry	solvent	Cu salt (equiv)	1a-OH[b]	2a	3a	4[b]	5a[b]	6a	7a or 8a
1	MeOH	1.1	11	79	trace	trace	0	0	
2	MeOH	2.2	0	97	0	0	0	0	
3	EtOH	1.1	0	69	4[b]	7	trace	trace	
4[c]	EtOH	1.1	0	83	4	0	7	0	
5	EtOH	2.2	0	85[b]	4[b]	7	0	trace	
6	*i*PrOH	1.1	0	56[b]	12[b]	13	5	0	
7	Acetone	1.1	0	53	9[b]	13	0	21	
8	THF	1.1	0	33	7[b]	9	trace	15	
9	DMF	1.1	31	32[b]	1[b]	7	3	trace	
10	AcOEt	1.1	0	15[b]	32	28	0	8	
11	AcOEt	2.2	4	26[b]	11	10	trace	5[b]	
12	MeCN	1.1	0	0	trace	trace	trace	13	40
13	MeCN	2.2	0	0	0	0	0	23	53
14	PhCN	2.2	0	0	0	0	6	35	44

[a]Reaction conditions: **1a** (0.30 mmol), Cu salt: Cu(BF4)2·6H2O (1.1 or 2.2 equiv vs **1a**), solvent (3 mL), under N_2, rt, 6 h. [b]Determined by ^{1}H NMR. [c]Heated at 80 °C.

Scheme 4. Nitrile (RCN) Solvent Effect on the Reaction of 1a with $Cu(BF_4)_2 \cdot 6H_2O$ in MeOH



further exploration of nitrile solvents showed that reaction of **1a** in PhCN produces benzamide **8a** (entry 14).

In order to gain more information about solvent effects on these processes, reaction of **1a** with $Cu(BF_4)_2 \cdot 6H_2O$ (2.2 equiv) in a mixed solvent system composed of MeOH and MeCN (9/1) was explored. The results show that dimer **2a** and acetamide **7a** are not produced under these conditions (upper path in Scheme 4). Instead, methyl ethers **9a** and **10a** are generated along with **6a** and small amounts of **3a**, **4**, and **5a** (compare to entries 2 and 13 in Table 2). In addition, reaction of **1a** in a mixture of PhCN (6.5 equiv vs **1a**) and MeOH (lower path in Scheme 4) generates **2a** in a significantly lower yield. In this solvent system, no benzamide **8a** is produced and **9a** and **10a** are major products.

On the basis of the results described above as well as those made in previous studies of related reactions,[4,5,7h] it is possible to propose the plausible mechanistic pathways outlined in Scheme 5 for formation of observed products. In these routes, addition of $Cu(BF_4)_2$ to **1a** along with loss of the silyl group occurs to form the copper alkoxide **11a**,[7h] which undergoes

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

Scheme 5. Plausible Mechanistic Pathways for Reaction of 1a with $Cu(BF_4)_2 \cdot 6H_2O$

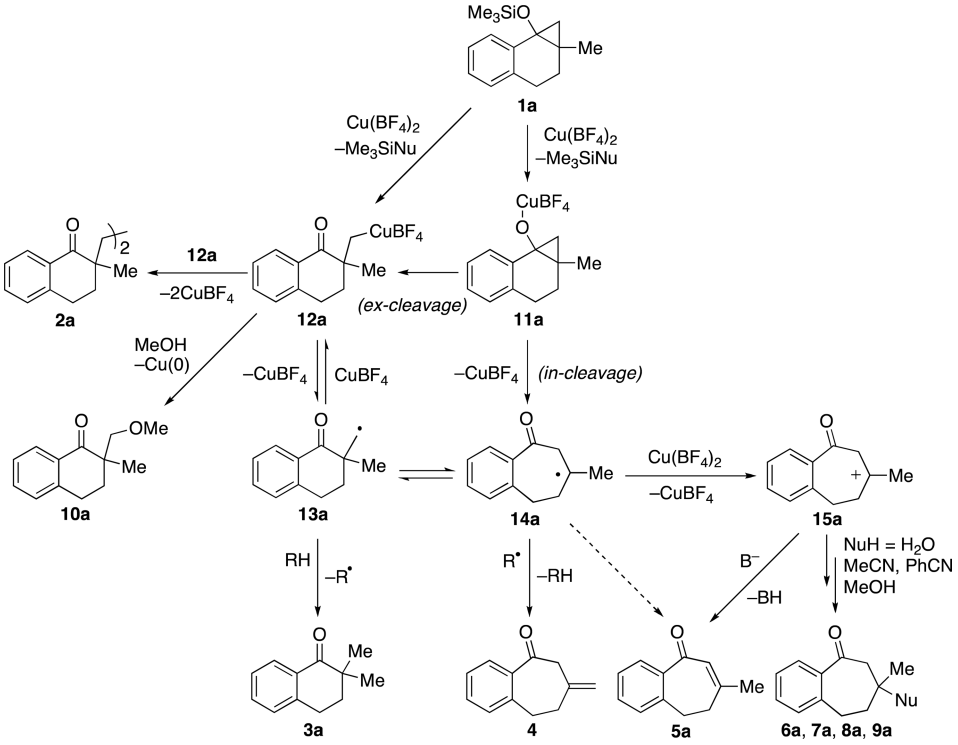
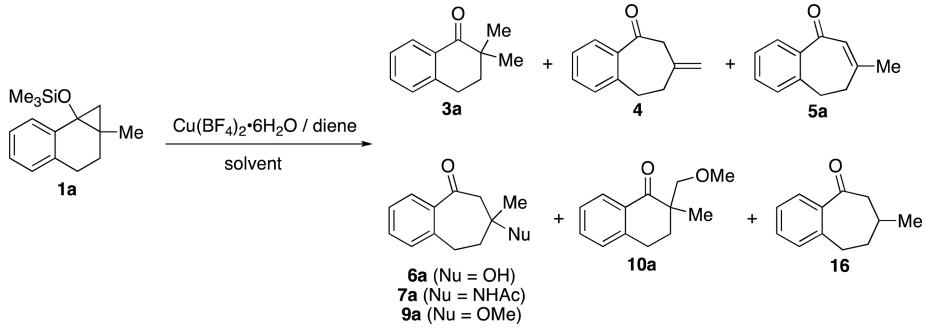


Table 3. Reaction of 1a with $Cu(BF_4)_2 \cdot 6H_2O$ in the Presence of Cyclic Dienes[a]



			yields (%)							
entry	solvent	diene	**3a**	**4**[b]	**5a**[b]	**6a**	**7a**	**9a**	**10a**	**16**
1[c]	MeOH	CHD	36	7	5	10		0	0	~19[e]
2[d]	MeOH	COD	24	5	3	~9[e]		12	~10[e]	0
3	AcOEt	CHD	30	27	trace	13				0
4	MeCN	CHD	0	0	0	25	50			0

[a]Reaction conditions: **1a** (0.30 mmol), $Cu(BF_4)_2 \cdot 6H_2O$ (2.2 equiv vs **1a**), diene (6.8 equiv vs **1a**), solvent (3 mL), under N_2, rt, 6 h. [b]Determined by ^1H NMR. [c]**1a**-OH(11%), **2a** (trace). [d]**1a**-OH (6%). [e]Crude yield.

either external or internal bond cleavage (*ex-cleavage* or *in-cleavage*) in the cyclopropane ring.[15] Among candidates to act as effective nucleophiles in the initial steps could be solvents as well as water since nucleophilic species are known to promote desilylation of cationic intermediates of silyl compounds.[16] The former process gives the corresponding organocopper intermediate **12a**, which then undergoes dimerization to produce **2a**. Electrophilic addition of $Cu(BF_4)_2$ to a cyclopropane carbon of **1a**, as proposed by Ryu and co-workers, is an alternative route for formation of **12a**.[4] Because an equilibrium possibly exists between the organocopper and carbon radical intermediates,[4b,17,18] **12a** could also undergo homolysis to give primary alkyl radical **13a**. Cyclization and ring expansion[19] of **13a** produces the stable tertiary alkyl radical **14a**. An alternate route for formation of **14a** involves simultaneous copper(I) elimination and homolytic cleavage of an internal carbon–carbon bond in the cyclopropane ring in **11a** (i. e., inner sphere electron transfer).[3c] Kinetically controlled hydrogen atom abstraction from **14a** forms β,γ-enone **4** instead of thermodynamically more stable α,β-enone **5a**. While **13a** probably abstracts hydrogen atom from solvents, it could also serve to abstract a hydrogen atom from **14a**, which is consistent with the fact that **3a** and **4** are typically coproduced in similar yields (see Tables 1 and 2). Oxidation of **14a** by SET to

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692–2703

copper(II) gives the tertiary carbocation **15a**,[17] which undergoes deprotonation, and nucleophilic addition of H_2O, MeCN, PhCN, or MeOH to produce **5a**, **6a**, **7a** **8a**, and **9a**, respectively. Finally, methyl ether **10a** could arise by a substitution process involving simultaneous addition of MeOH to **12a** and metallic copper elimination.

As can be seen by viewing the results presented above, the preferential pathways followed in reaction of **1a** are highly dependent on the nature of solvent. It has been reported that the strength of the coordination bond in solvent−copper(I) complexes decreases in the order of MeCN, AcOMe, Et_2O, acetone, EtOH, and MeOH.[20] Thus, fragmentation of **12a** to produce $Cu(BF_4)$ and **13a** should be less favorable in MeOH. This phenomenon would increase the lifetime of **12a** and, thus, enable it to undergo effective dimerization. On the other hand, it has been suggested that MeCN forms a strong coordination complex with copper(I), and thus, the resulting stabilization of Cu(I) leads to an increase in the oxidizing ability of copper(II).[21] This conclusion is supported by the observation that the redox potential of $Cu(ClO_4)_2$ in MeCN (0.95 V vs SCE) is much greater than that in MeOH (0.0 V vs SCE).[22] Thus, electron transfer between $Cu(BF_4)_2$ and **1a**, giving **14a** via **11a**, should be preferred in MeCN.[23] On the other hand, this electron-transfer step would not take place efficiently in MeOH and other alcohols because the oxidizing ability of Cu(II) in these solvents should be much lower than that in MeCN. Consequently, rearrangement of **11a** to **12a** would proceed. Although difficult to rationalize, reaction pathways followed by radical intermediates **13a** and **14a** in other solvents, particularly AcOEt, generate the observed products **3a** and **4**.

On the basis of the discussion described above, we anticipated that the presence of substances that serve as hydrogen atom donors and/or coordinate with metals should have an effect on the preferred reaction pathways followed. To test this proposal, reactions of **1a** with $Cu(BF_4)_2{\cdot}6H_2O$ (2.2 equiv) in the presences of 1,4-cyclohexadiene (CHD)[24,25] and 1,5-cyclooctadiene (COD)[26] were explored (Table 3). As expected, the presence of both CHD and COD nearly completely suppresses formation of **2a** in MeOH (compare entries 1 and 2 in Table 3 to entry 2 in Table 2). In the presence of CHD, **3a** as well as **16** are formed as major products, likely formed via trapping of **13a** and **14a** by effective hydrogen atom donation from the diene.[24] On the other hand, the formation of **9a** and **10a** becomes significant, while **16** is not generated when COD is present in the reaction mixture. In addition to being a less effective hydrogen atom donor than CHD, COD[24] could both destabilize the copper intermediates **12a** by coordinating with Cu(I) and enhance the oxidizing ability of $Cu(BF_4)_2$.[26] In AcOEt, while no formation of **16** was unexpected, the yields of **3a** and **4** were similar to those in the reaction using 1.1 equiv of $Cu(BF_4)_2$ and significantly increased compared to the reaction using same quantity of $Cu(BF_4)_2$ in the absence of CHD (compare entry 3 in Table 3 to entries 10 and 11 in Table 2), which could be ascribed to the fact that CHD-coordinated Cu(II) assists the transformation of **12a** to **13a**. Notably, CHD caused no effect on the product distribution in the reaction in MeCN (entry 4), which is consistent with the strong coordination ability of MeCN as discussed above.

Insight into the existence of radical intermediates in the pathways for $Cu(BF_4)_2$-promoted reactions of cyclopropyl silyl ethers was gained from studies with **1b** and **1c**, which contain alkenyl side chains that can serve as internal radical traps transforming radicals **13b** to **17** (eq 1) and **14c**, derived from **13c**, to **18** (eq 2), respectively (Scheme 6).[7c,h,27] As the data in

Scheme 6. Expected 5-*exo* Hexenyl Radical Cyclizations of 1b and 1c

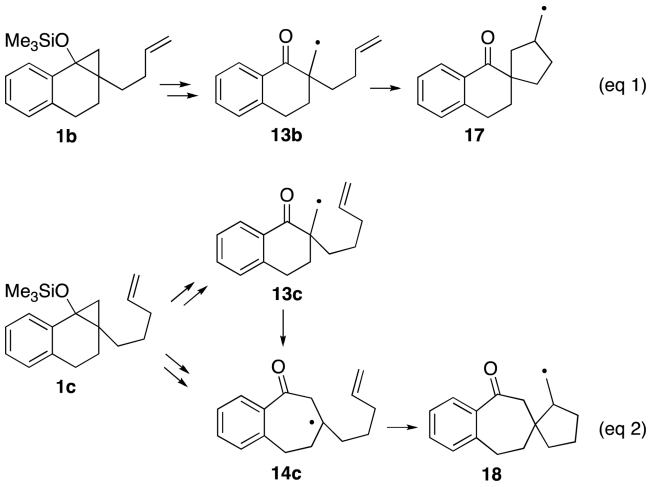


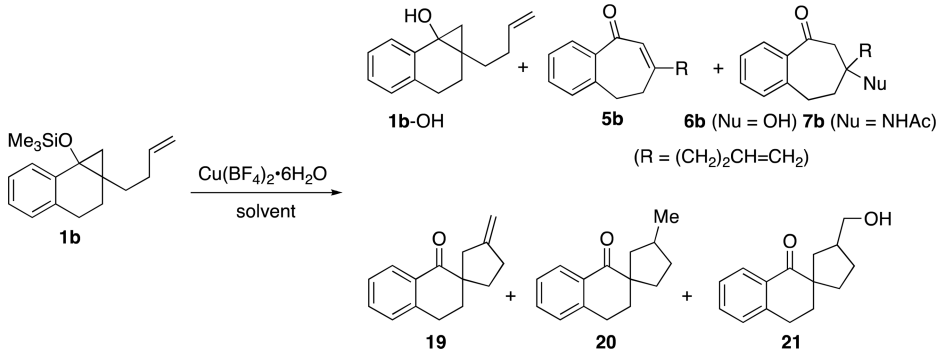
Table 4 show, reaction of **1b** with $Cu(BF_4)_2{\cdot}6H_2O$ in EtOH was found to produce spirocyclic products such as **19**, **20**, and **21** and no dimeric product (entry 1). The presence of O_2 in the reaction mixture causes a decrease in the yield of **19** and an increase in the yield of **21** (entry 2), which suggests that O_2 traps radical **18** to give **23**, precursor of alcohol **21**, in competition with capture by copper(I) to produce **22**, precursor of alkene **19** (Scheme 7).[7c,h] In addition, reaction of **1b** in MeCN generates acetamide **7b** mainly (entry 4), which is similar to observation made previously in studies with **1b**-OH.[7h]

To probe the influence of steric effect of the butenyl side chain in **1b** on the efficiency of dimeric product formation, reaction of sterically analogous butyl-substituted substrate **1d** with $Cu(BF_4)_2{\cdot}6H_2O$ (2.2 equiv) in EtOH was explored (Scheme 8). The results show that dimer **2d** is generated as a major product while **1b** formed **6b** (21%), **19** (29%) and **21** (23%) under the same conditions (not shown in Table 4). This finding suggests that dimerization of organocopper intermediate **12d** does proceeds, and absence of dimeric product formation in the reaction of **1b** is a consequence of fast cyclization of radical intermediate **13b** to form **17**, which moves equilibrium between **12b** and **13b** forward, and not by reduction in the rate of dimerization caused by sterically repulsive butenyl side chain (Scheme 9).

Reactions of desilylated alcohol **1b**-OH with various copper salts were also examined (Table 5). The yields of **6b**, **19**, and **21** in these reactions in EtOH are similar to those produced from **1b** (compare entry 1 to entry 1 in Table 4). Because **1b**-OH is more reactive than its silyl protected analogue **1b**,[7h,12] $Cu(OAc)_2$ effectively promotes the reaction to give **19** as the major product. In contrast, in a manner that is similar to **1b**, reactions of **1b**-OH with $Cu(BF_4)_2$ and $Cu(ClO_4)_2$ in MeCN produce **6b** and **7b** as major products (compare entries 3 and 4 to entry 4 in Table 4). Thus, the fact that reactions in MeCN do not produce spirocyclic products such as **19** and **21** (see Table 4 and 5), which are diagnostic of the formation of the primary alkyl radical **13b**, suggests that direct formation of ring expanded radical **14b** from **11b** giving tertiary carbocation **15b**,

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

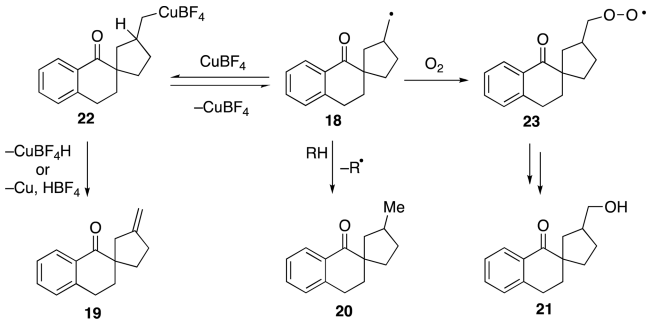
Table 4. Reaction of 1b with $Cu(BF_4)_2{\cdot}6H_2O$ in Various Solvents[a]



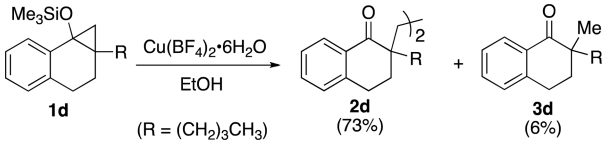
		yields (%)						
entry	solvent	1b-OH[b]	5b[b]	6b	7b	19[b]	20[b]	21
1	EtOH	13	0	13		35	3	18
2[c]	EtOH	0	0	15		14	0	32
3	AcOEt	8	0	10		11	0	51
4	MeCN	24	13	13	43	0	trace	trace

[a]Reaction conditions: **1b** (0.30 mmol), $Cu(BF_4)_2{\cdot}6H_2O$ (1.1 equiv vs **1b**), solvent (3 mL), under N_2, rt, 6 h. [b]Determined by ^1H NMR. [c]O_2 prepurged solution was used.

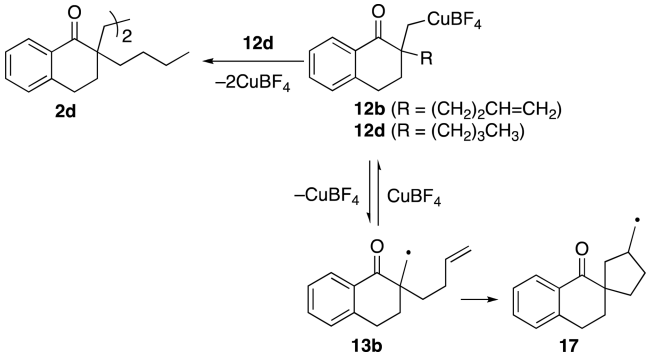
Scheme 7. Competitive Trap of Radical Intermediate 18 by Copper or Molecular Oxygen



Scheme 8. Reaction of Butyl Possessing Substrate 1d with $Cu(BF_4)_2{\cdot}6H_2O$ in EtOH



Scheme 9. Reaction Pathways of Organocopper Intermediates 12b and 12d



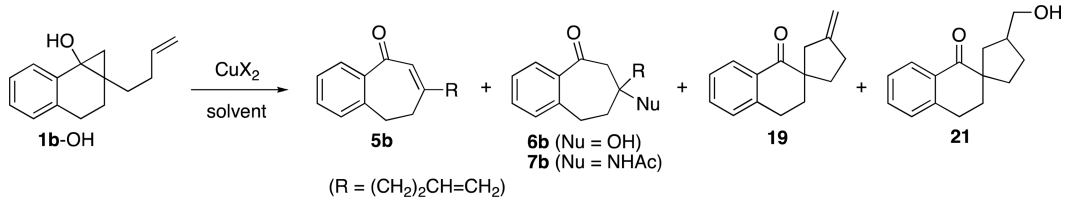
a precursor of the products **5b**, **6b** and **7b**, is the main pathway followed in MeCN (Scheme 10).

Reactions of the pentenyl linked analogue **1c** with $Cu(BF_4)_2{\cdot}6H_2O$ (2.2 equiv) in EtOH, AcOEt, and MeCN were probed next (Table 6). In contrast to that of **1b**, reaction of **1c** in EtOH produces dimer **2c** and α-methyl ketone **3c** albeit in relatively low yields (entry 1). In contrast, ring-expanded spirocyclic compounds **24** (major) and **25**, which correspond to **19** (major) and **20** derived from **1b** were obtained (see entry 1 in Table 4). Reaction of **1c** in AcOEt forms **3c** as a major product along with lesser amounts of **2c** (entry 2). Similar to product distributions generated from reaction of **1a** and **1b**, **7c** is the major product generated in reaction of **1c** in MeCN (entry 3). A notable observation is that **2c** as well as **3c** are formed in this reaction while products that correspond to those generated from **1b** were not observed (see Tables 4 and 5). This is a likely result of the relative rates of radical intermediates **13b** and **13c**. Specifically, the rate of 5-exo cyclization of **13b** to form **17** should be faster than that of ring-expansion of **13c** to form **14c**[7d] as well as the rate of **14c** to produce **18**[7c] (see Scheme 6).[28,29] Thus, **13c** and its precursor **12c** are more persistent to undergo hydrogen atom abstraction and dimerization to give **3c** and **2c**, respectively.

In the final phase of this investigation, reactions of cyclopropyl silyl ethers **1e**, **1f**, and **1g** with $Cu(BF_4)_2{\cdot}6H_2O$ (2.2 equiv) were briefly examined (Scheme 11; see plausible reaction pathways in the Supporting Information). Dimer **2e** and naphthol **26** are generated in reaction of the five-membered ring containing substrate **1e** in MeOH, while alcohol **6e** and acetamide **7e**, along with **26**, are formed in MeCN (eq 1). In contrast, reaction of the seven-membered ring containing substrate **1f** in MeOH does not produce a dimeric product but it does generate the ring-expanded alcohol **6f** and substituted indanones **27** and **28**, along with a significant amount of desilylated alcohol **1f**-OH (eq 2). These observations show that the ring size of the fused cyclopropanol derivative has a significant effect on the nature of products formed (see Scheme 8).[30,31] Moreover, the results show that dimer **2g** is formed in high yield along with a small amount of

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692–2703

Table 5. Reaction of 1b-OH with Various Copper(II) Salts[a]



					yields (%)			
entry	CuX_2	solvent	conv (%)	**5b**[b]	**6b**	**7b**	**19**	**21**
1	$Cu(BF_4)_2 \cdot 6H_2O$	EtOH	72	0	20[b]		33	13
2	$Cu(OAc)_2$	EtOH	100	trace	17		51	0
3	$Cu(BF_4)_2 \cdot 6H_2O$	MeCN	83	4	27	46	0	0
4	$Cu(ClO_4)_2 \cdot 6H_2O$	MeCN	100	7	33	42	0	0

[a]Reaction conditions: **1b**-OH (0.30 mmol), CuX_2 (1.1 equiv vs **1b**-OH), solvent (3 mL), under N_2, rt, 1 h. [b]Determined by ^1H NMR.

Scheme 10. Plausible Pathways for Reaction of 1b and 1b-OH with CuX_2 in MeCN

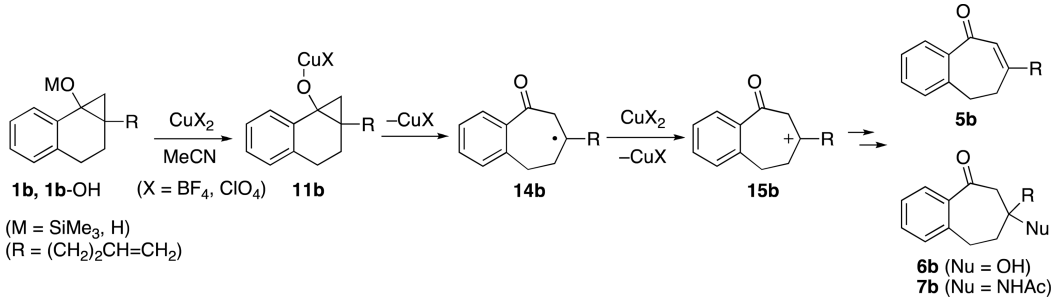
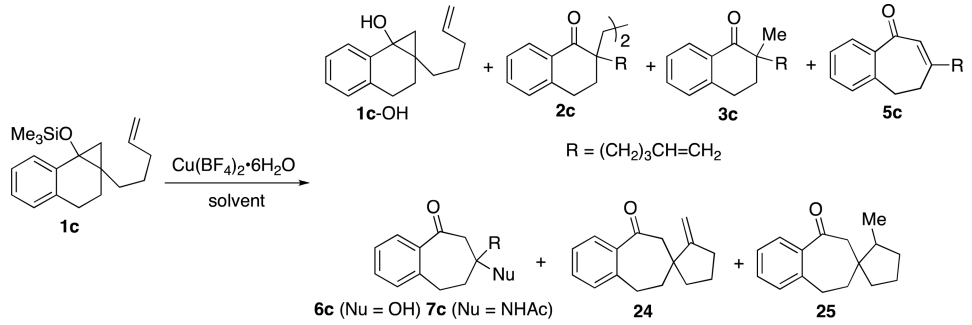


Table 6. Reaction of 1c with $Cu(BF_4)_2 \cdot 6H_2O$ in Various Solvents[a]



						yields (%)			
entry	solvent	**1c**-OH[b]	**2c**	**3c**	**5c**[b]	**6c**	**7c**	**24**[b]	**25**[b]
1	EtOH	0	7	8	8	4		17	3
2	AcOEt	11	7	22	9	~8[c]		6	2
3	MeCN	13	0	0	13	14	42	0	0

[a]Reaction conditions: **1c** (0.30 mmol), $Cu(BF_4)_2 \cdot 6H_2O$ (1.1 equiv vs **1c**), solvent (3 mL), under N_2, rt, 6 h. [b]Determined by ^1H NMR. [c]Crude yield.

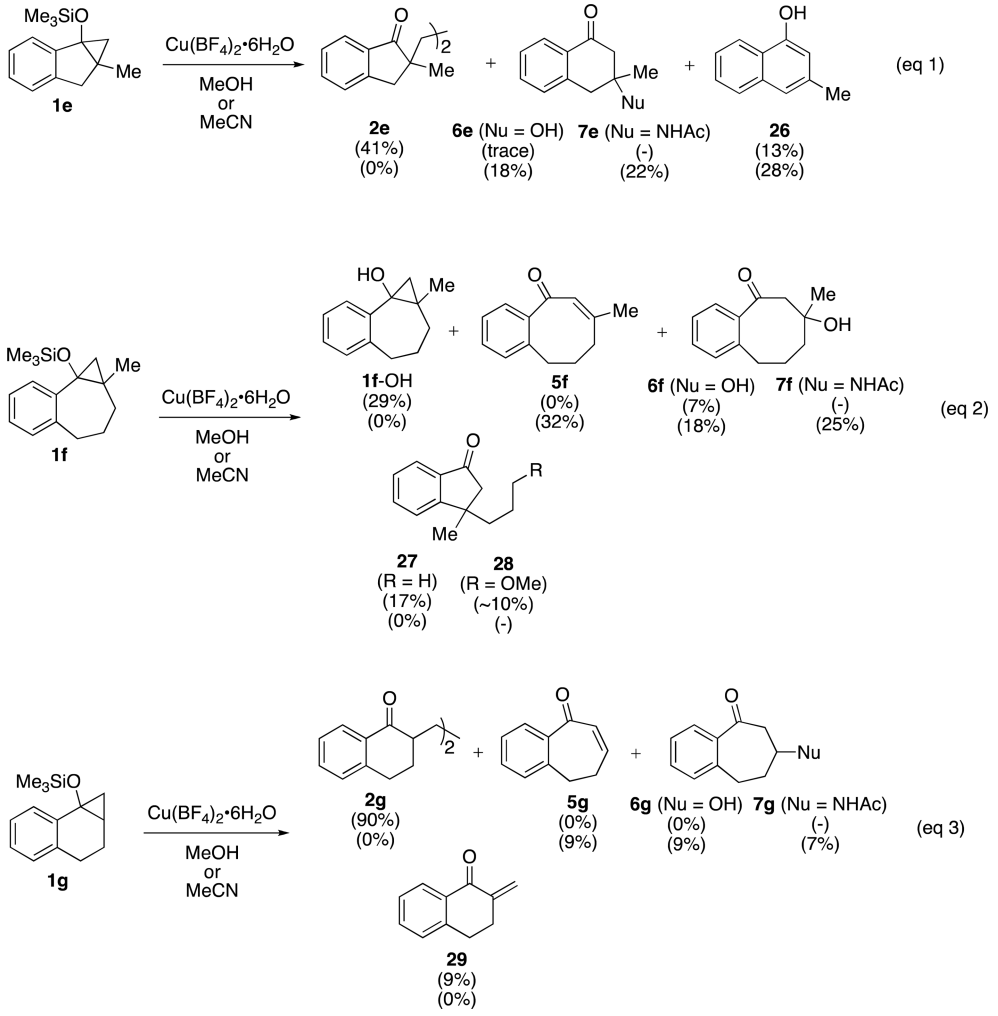
α-exo-methylene ketone **29** in the reaction of **1g**, which lacks a bridgehead substituent (eq 3). However, the complicated nature of reaction of **1g** in MeCN, in which small amounts of **5g**, **6g**, and **7g** are produced, suggest that a bridgehead substituent is necessary to promote smooth reaction in MeCN. The substituent is required to promote rearrangement of **13** to form a stable tertiary alkyl radical **14** and subsequent carbocation **15** (see Scheme 5).

CONCLUSION

In this study, we explored $Cu(BF_4)_2$-promoted oxidative ring-opening reactions of selected benzene-fused bicyclic cyclopropyl silyl ethers, which provides useful information about the nature and efficiencies of reactions of synthetically useful cyclopropanols and their derivatives. The results show that the nature and distribution of products generated in these processes significantly depend on solvent. In addition, the reaction pathways are also influenced by other factors such as, the nature of the counteranions of copper salts, presence of nitriles and cyclic dienes, and substrate structures. We propose that solvation as well as coordination of solvents and additives with copper influence reactivity of copper intermediates and the redox properties of copper salts, both of which govern the reaction pathways followed. In principle, radical intermediates generated in redox reagent promoted electron transfer (ET)

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692–2703

Scheme 11. Reactions of Miscellaneous Substrates 1e, 1f, and 1g with $Cu(BF_4)_2 \cdot 6H_2O$ (Upper Yields for MeOH and Lower Yields for MeCN)



reactions have a tendency to participate in following ET processes by coexisting ET reagents to generate ionic species (ionic pathway) while radical intermediates formed by a photoinduced ET (PET) are persistent to undergo radical rearrangements (radical pathway) because of low concentrations of PET-generated redox reagents.[1] Observations that are consistent with this expectation were indeed mad by our previous efforts.[7a−h] On the contrary, redox property of Cu(II) salts, disclosed by this and our previous study,[7g] can be properly tuned to control both ET reaction pathways, ionic pathway and radical pathway, by choosing solvents, couter anions, and additives. Thus, if one wants to carry out Cu(II) promoted ET reactions, the use of MeCN as a solvent is recommended. On the other hand, in order for the favorable generation of organocopper intermediates, alcohol solvents are suggested to use. Because copper(II) salts are widely used as single electron transfer oxidants in organic chemistry,[1a,e,8,9] observations made in this effort that solvents and additives control reactivities and redox properties of these oxidants could have far reaching importance. Finally, this study would also suggest that the interplay between solvents and redox reagents, particularly metal salts, is a crucial factor to govern ET reaction pathways in general.[32]

EXPERIMENTAL SECTION

General Methods. NMR spectra were recorded in $CDCl_3$ with Me_4Si as an internal standard at 400 MHz for ^1H NMR and 100 MHz for ^{13}C NMR. Proton-decoupled carbon data of ^{13}C NMR are reported. High-resolution mass spectra (HRMS) were recorded on a double-focusing mass spectrometer by using electrospray ionization (ESI) or atomospheric pressure cheimcal ionization (APCI). Uncorrected melting points are reported. Column chromatography was performed with silica gel (Wakogel C-200). Preparative TLC was performed on 20 × 20 cm plates coated with silica gel (Wakogel B-5F). MeCN was distilled over P_2O_5 and subsequently distilled over K_2CO_3. EtOAc was treated with 5% aqueous Na_2CO_3 and brine and then distilled over K_2CO_3. Other reagents and solvents were purchased and used without further purification.

Substrates **1a**,[7c] **1b**,[7c] **1c**,[7c] **1e**,[7d] **1f**,[7c] and **1g**[4b] and products **1a**-OH,[7f] **1b**-OH,[7f] **1c**-OH,[7c] **2g**,[4b] **3a**,[7c] **3c**,[7h] **5a**,[7c] **5b**,[7c] **5c**,[7d] **5f**,[7c] **5g**,[33] **6a**,[7e] **6e**,[34] **7b**,[7h] **7c**,[7h] **16**,[29] **19**,[7c] **20**,[35] **24**,[7c] **25**,[7c] **26**,[7d] **27**,[7c] and **29**[31b] are known compounds. ^1H NMR and ^{13}C NMR charts of **1d**, **1d**-OH, **1f**-OH, **2a**, **2c**, **2d**, **2e**, **3d**, **6b**, **6c**, **6f**, **6g**, **7a**, **7e**, **7f**, **7g**, **8a**, **9a**, **10a**, **21**, and **28** are presented below.

Preparation of Cyclopropyl Silyl Ethers 1. Cyclopropyl silyl ethers **1** were prepared, using previously reported procedures,[7c,e] by the treatment of silyl enol ethers with Et_2Zn and CH_2I_2 (**1a**, **1e**, **1f**, **1g**) or the reaction of bromomethyl-substituted ketone with SmI_2 followed by silylation (**1b**, **1c**, **1d**).

In the preparation of **1d**, 2-(bromomethyl)-2-butyl-1-tetralone (685.3 mg, 2.32 mmol) in THF (2 mL) was added to 0.1 M SmI_2

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

solution in THF (46 mL). The resulting mixture was stirred under N_2 at room temperature for 1 h, quenched with 0.1 M HCl, and followed by extraction with Et_2O (50 mL × 3). The extract was washed with water, saturated aqueous $Na_2S_2O_3$, saturated aqueous $NaHCO_3$, and brine and dried over anhydrous $MgSO_4$. After concentration, **1d**-OH (481.0 mg, 2.22 mmol, 97%) was obtained. Then, **1d**-OH was dissolved in DMF (4 mL) followed by addition of imidazole (381.6 mg, 5.61 mmol) and chlorotrimethylsilane (0.56 mL, 4.44 mmol). The resulting mixture was stirred for 15h at room temperature, quenched with water, and followed by extraction with Et_2O (50 mL × 3). The extract was washed with water, saturated aqueous $NaHCO_3$, and brine and dried over anhydrous $MgSO_4$. After concentration, the residue was subjected to column chromatography on silica gel (EtOAc/*n*-hexane = 1/10). Distillation under reduced pressure gave **1d** (237.0 mg, 0.82 mmol, 37%).

*6-Buthyl-1-hydroxy-2,3-benzobicyclo[4.1.0]hepthane (**1d**-OH):* white solid; mp 88−90 °C; ^{1}H NMR (400 MHz, δ) 7.71−7.69 (m, 1H), 7.26−7.22 (m, 1H), 7.13−7.10 (m, 1H), 7.09−7.03 (m, 1H), 2.64 (ddd, J = 16.4, 3.6, 2.0 Hz, 1H), 2.40 (td, J = 15.0, 6.4 Hz, 1H), 2.09 (bs, 1H), 2.00−1.85 (m, 1H), 1.83−1.76 (m, 1H), 1.61−1.33 (m, 6H), 1.24 (d, J = 6.0 Hz, 1H), 0.92 (t, J = 7.2 Hz, 3H), 0.85 (d, J = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, δ) 141.1, 133.3, 128.2, 126.4, 125.5, 123.9, 58.9, 32.6, 30.9, 29.7, 27.1, 23.5, 13.2, 21.7, 14.4; HRMS (ESI) calcd for $C_{15}H_{21}O$ $[M + H]^+$ 217.1587, found 217.1586.

*6-Buthyl-1-[(trimethylsilyl)oxy]-2,3-benzobicyclo[4.1.0]heptane (**1d**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 7.52−7.50 (m, 1H), 7.24−7.20 (m, 1H), 7.11−7.07 (m, 1H), 7.03−7.01 (m, 1H), 2.66−2.59 (m, 1H), 2.44−2.35 (m, 1H), 2.01−1.95 (m, 1H), 1.72−1.36 (m, 7H), 1.23 (d, J = 5.6 Hz, 1H), 0.94 (t, J = 7.2 Hz, 3H), 0.89 (d, J = 7.2 Hz, 1H), 0.25 (s, 9H); ^{13}C NMR (100 MHz, δ) 141.2, 133.2, 128.0, 125.9, 125.1, 124.8, 61.0, 32.5, 29.6, 29.3, 27.3, 23.5, 23.1, 21.0, 14.2, 1.4; HRMS (ESI) calcd for $C_{18}H_{29}OSi$ $[M + H]^+$ 289.1982, found 289.1984.

Reactions of 1 with $Cu(BF_4)_2{\cdot}6H_2O$. A typical experiment using **1a** is described (see Scheme 2). To a solution of $Cu(BF_4)_2{\cdot}6H_2O$ (114.0 mg, 0.33 mmol) in Et_2O (3 mL) was added **1a** (74.0 mg, 0.30 mmol). The resulting mixture was stirred under N_2 at room temperature for 6 h, diluted with water, and extracted with Et_2O (30 mL × 3). The extract was washed with water, saturated aqueous $Na_2S_2O_3$, saturated aqueous $NaHCO_3$, and brine, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The residue obtained was subjected to TLC (AcOEt /*n*-hexane = 10/1) to give **6a** (1.7 mg, 0.009 mmol, 3%). The remaining portions were separated by TLC (AcOEt /*n*-hexane = 1/10) to give **2a** (11.7 mg, 0.034 mmol, 23%) and **5a** (10.8 mg, 0.063 mmol, 21%). Because **4** appeared to rearrange to **5a** during TLC separation, the yields of **4** (0.064 mmol, 21%) and **5a** (0.0065 mmol, 2%) were determined by using ^{1}H NMR analysis of the crude reaction mixture (see Figure S1). Similarly, the yields of **1a**-OH (0.027 mmol, 9%) and **3a** (0.074 mmol, 25%) were determined by using ^{1}H NMR analysis. Other reactions using $Cu(BF_4)_2{\cdot}6H_2O$ or other copper(II) salts were performed in a similar manner. The yields of the products, which could not be isolated, were also determined by using ^{1}H NMR analysis with triphenylmethane as an internal standard when necessary.

*1-Hydroxy-7-methyl-2,3-benzobicyclo[5.1.0]octane (**1f**-OH):* pale brown oil; ^{1}H NMR (400 MHz, δ) 7.49−7.47 (m, 1H), 7.26−7.22 (m, 2H), 7.12−7.10 (m, 1H), 2.95 (td, J = 12.9, 7.1 Hz, 1H), 2.61 (dd, J = 13.2, 6.0 Hz, 1H), 2.01−1.91 (m, 2H), 1.81 (dd, J = 14.2, 5.8 Hz, 1H), 1.45 (m, 1H), 1.29 (s, 3H), 0.87 (d, J = 5.2 Hz, 1H), 0.65 (d, J = 5.2 Hz, 1H), 0.42 (td, J = 13.4, 6.7 Hz, 1H); ^{13}C NMR (100 MHz, δ) 141.3, 139.2, 129.6, 128.9, 128.5, 127.1, 62.2, 33.1, 30.4, 26.2, 22.8, 22.6, 15.4; HRMS (APCI), calcd for $C_{13}H_{17}O$ $[M + H]^+$ 189.1274, found 189.1272.

*1,2-Di-1-methyl-3,4-benzocyclohexane-2-one-1-ylethane (**2a**):* pale yellow oil; mixture of diastereomers; ^{1}H NMR (400 MHz, δ) 8.03−7.97 (dd with dd, 2H), 7.47−7.41 (m, 2H), 7.31−7.25 (m, 2H), 7.22−7.19 (m,2H), 2.99−2.92 (m, 4H), 2.13−2.07 (m, 2H),1.91−1.84 (m, 2H), 1.74−1.69 (m, 2H), 1.52−1.46 (m, 2H), 1.18−1.15 (s with s, 6H); ^{13}C NMR (100 MHz, δ) 202.7 (2C), 143.5, 143.4, 133.2 (2C), 131.7, 131.6, 128.8 (2C), 128.1 (2C), 126.8, 126.7, 44.7, 44.6, 33.2 (2C), 30.6, 30.5, 25.5 (2C), 22.3, 22.2; HRMS (ESI) calcd for $C_{24}H_{27}O_2$ $[M + H]^+$ 347.2006, found 347.2006.

*1,2-Di-1-(4′-pentenyl)-3,4-benzocyclohexane-2-one-1-ylethane (**2c**):* pale yellow oil; mixture of diastereomeric isomers; ^{1}H NMR (400 MHz, δ) 8.03−7.96 (dd with dd, 2H), 7.46−7.41 (m, 2H), 7.32−7.18 (m, 4H), 5.81−5.63 (m, 2H), 5.00−4.87 (m, 4H), 2.98−2.93 (m, 4H), 2.13−1.92 (m, 8H), 1.74−1.61 (m, 4H), 1.55−1.44 (m, 4H), 1.39−1.31 (m, 4H); ^{13}C NMR (100 MHz, δ) 202.0 (2C), 143.3, 143.2, 138.7, 138.6, 133.1 (2C), 132.0 (2C), 128.8, 128.1, 126.7 (2C), 114.8 (2C), 47.7 (2C), 34.4(2C), 34.0, 33.8, 30.8, 30.6, 29.9, 28.3, 25.2 (2C), 23.4, 23.2; HRMS (ESI) calcd for $C_{32}H_{38}O_2Na$ $[M + Na]^+$ 477.2764, found 477.2744.

*1,2-Di-1-butyl-3,4-benzocyclohexane-2-one-1-ylethane (**2d**):* pale yellow oil; mixture of diastereomers; ^{1}H NMR (400 MHz, δ) 8.03−7.97 (dd with dd, 2H), 7.46−7.40 (m, 2H), 7.31−7.18 (m, 4H), 2.98−2.93 (m, 4H), 2.14−1.97 (m, 4H), 1.74−1.61 (m, 4H), 1.54−1.45 (m, 4H), 1.28−1.17 (m, 8H), 0.89−0.80 (t with t, 6H); ^{13}C NMR (100 MHz, δ) 202.2 (2C), 143.4, 143.3, 133.1, 133.0, 132.1, 132.0, 128.8 (2C), 128.1 (2C), 126.7, 126.6, 47.8, 47.7, 34.2, 34.1, 30.7, 30.6, 28.3 (2C), 26.3, 26.1, 25.3 (2C), 23.6, 23.5, 14.2 (2C); HRMS (ESI) calcd for $C_{30}H_{38}O_2Na$ $[M + Na]^+$ 453.2764, found 453.2739.

*1,2-Di-1-methyl-3,4-benzocyclopentane-2-one-1-ylethane (**2e**):* pale yellow oil; mixture of diastereomers; ^{1}H NMR (400 MHz, δ) 7.75 (d, J = 7.6 Hz, 1.3 H), 7.69 (d, J = 7.6 Hz, 0.7H), 7.62−7.55 (m, 2H), 7.46−7.32 (m, 4H), 3.16 (d, J = 17.6 Hz, 1.3H), 3.09 (d, J = 17.2 Hz, 0.7H), 2.87 (d, J = 7.8 Hz, 1.2 H), 2.83 (d, J = 7.8 Hz, 0.8 H), 1.71−1.59 (m, 2H, overlap with H_2O peak), 1.48−1.43 (m, 2H), 1.21 (s, 2.1H), 1.12 (s, 3.9H); ^{13}C NMR (100 MHz, δ) 211.4, 211.3, 153.0, 152.8, 136.2, 135.8, 135.1, 135.1, 127.6, 127.5, 126.8 (2C), 124.4, 124.3, 48.8, 48.8, 40.2, 39.8, 32.9, 32.8, 24.8, 23.8; HRMS (ESI) calcd for $C_{22}H_{23}O_2$ $[M + H]^+$ 319.1693, found 319.1687.

*2-Buthyl-2-methyl-1-tetralone (**3d**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 8.05−8.01 (m, 1H), 7.47−7.43 (m, 1H), 7.32−7.21 (m, 2H), 3.04−2.89 (m, 2H), 2.11−2.05 (m, 1H), 1.96−1.89 (m, 1H), 1.69−1.62 (m, 1H), 1.54−1.46 (m, 1H), 1.32−1.22 (m, 4H), 1.18 (s, 3H), 0.88 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, δ) 202.9, 143.4, 133.0, 131.8, 128.8, 128.1, 126.7, 44.8, 36.2, 33.8, 26.3, 25.5, 23.5, 22.3, 14.2; HRMS (ESI) calcd for $C_{15}H_{21}O$ $[M + H]^+$ 217.1587, found 217.1584.

*3-(3′-Butenyl)-3-hydroxy-1-benzosuberone (**6b**).* pale yellow oil; ^{1}H NMR (400 MHz, δ) 7.79−7.77 (m, 1H), 7.40−7.36 (m, 1H), 7.29−7.22 (m, 2H), 5.91−5.81 (m, 1H), 5.10−4.97 (m, 2H), 3.25 (dd, J = 17.2, 9.2 Hz, 1H), 3.04 (d, J = 11.6 Hz, 1H), 2.97−2.91 (dd with dd, 2H), 2.31−2.17 (m, 2H), 2.05−1.99 (m, 1H), 1.93−1.87 (m, 1H), 1.79−1.71 (m, 3H); ^{13}C NMR (100 MHz, δ) 200.6, 144.3, 138.5, 138.3, 132.1, 130.4, 128.9, 126.6, 115.4, 73.7, 54.3, 41.0, 41.0, 31.0, 27.9; HRMS (ESI) calcd for $C_{15}H_{19}O_2$ $[M + H]^+$ 231.1380, found 231.1374.

*3-Hydroxy-3-(4′-pentenyl)-1-benzosuberone (**6c**):* pale brown oil; ^{1}H NMR (400 MHz, δ) 7.79−7.77 (m, 1H), 7.40−7.36 (m, 1H), 7.29−7.22 (m, 2H), 5.85−5.75 (m, 1H), 5.04−4.94 (m, 2H), 3.24 (dd, J = 16.8, 8.8 Hz, 1H), 3.02 (d, J = 11.6 Hz, 1H), 2.96−2.90 (dd with dd, 2H), 2.11−1.86 (m, 5H), 1.66−1.49 (m, 4H); ^{13}C NMR (100 MHz, δ) 200.8, 144.3, 138.5, 138.3, 132.0, 130.4, 128.9, 126.6, 115.1, 73.6, 54.3, 41.7, 40.9, 34.0, 31.1, 22.6; HRMS (ESI) calcd for $C_{16}H_{20}O_2Na$ $[M + Na]^+$ 267.1356, found 267.1349.

*3-Hydroxy-3-methyl-7,8-benzocyclooct-1-one (**6f**):* white solid; mp 92−96 °C; ^{1}H NMR (400 MHz, δ) 8.08 (dd, J = 7.8, 1.4 Hz, 1H), 7.48 (td, J = 7.4, 1.6 Hz, 1H), 7.30 (td, J = 7.7, 1.3 Hz, 1H), 7.21 (dd, J = 7.6, 0.8 Hz, 1H), 3.37 (d, J = 12.8 Hz, 1H), 3.30−3.23 (m, 1H), 3.18−3.09 (m, 2H) 2.07 (bs, 1H), 1.96−1.80 (m, 2H), 1.56−1.51 (m, 2H), 1.38 (s, 3H); ^{13}C NMR (100 MHz, δ) 200.7, 140.7, 138.4, 133.6, 132.3, 130.0, 127.1, 71.8, 55.7, 36.6, 34.2, 29.1, 23.7; HRMS (ESI) calcd for $C_{13}H_{16}O_2Na$ $[M + Na]^+$ 227.1043, found 227.1038.

*3-Hydroxy-1-benzosuberone (**6g**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 7.76 (dd, J = 7.8, 1.4 Hz, 1H), 7.41 (td, J = 7.5, 1.5 Hz, 1H), 7.30 (td, J = 7.6, 1.1 Hz, 1H), 7.26−7.23 (m, 1H), 4.39−4.32 (m, 1H), 3.19 (ddd, J = 16.2, 8.7, 2.4 Hz, 1H), 3.09 (dd, J = 13.2, 4.8 Hz, 1H), 3.03 (dd, J = 13.0, 7.4 Hz, 1H), 2.92 (ddd, J = 16.3, 8.3, 2.3 Hz, 1H), 2.24 (ddt, J = 12.1, 10.5, 6.1 Hz 1H), 1.99−1.92(m, 1H); ^{13}C NMR (100 MHz, δ) 200.9, 143.0, 138.7, 132.2, 130.3, 128.8, 126.8, 67.3,

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

50.7, 36.1, 30.3; HRMS (ESI) calcd for $C_{11}H_{13}O_2$ $[M + H]^+$ 177.0910, found 177.0910.

*3-(Acetylamino)-3-methyl-1-benzosuberone (**7a**):* colorless oil; ^{1}H NMR (400 MHz, δ) 7.77 (dd, J = 7.8, 2.0 Hz, 1H), 7.40 (td, J = 7.4, 2.3 Hz, 1H), 7.31−7.23 (m, 2H), 5.68 (bs, 1H), 3.14−2.96 (m, 4H), 2.33 (dd, J = 14.0, 8.2 Hz, 1H), 2.12 (dd, J = 14.2, 9.4 Hz, 1H), 1.94 (s, 3H), 1.57 (s, 3H); ^{13}C NMR (100 MHz, δ) 200.9, 169.9, 144.1, 138.1, 132.0, 130.3, 128.5, 126.5, 54.9, 52.9, 40.0, 31.2, 26.1, 24.3; HRMS (ESI) calcd for $C_{14}H_{17}NO_2Na$ $[M + Na]^+$ 254.1152, found 254.1149.

*3-(Acetylamino)-3-methyl-1-tetralone (**7e**):* pale brown oil; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 7.98 (dd, J = 7.6, 1.2 Hz, 1H), 7.50(td, J = 7.5, 1.3 Hz, 1H), 7.34−7.31(m, 1H), 7.27−7.25(m, 1H), 5.50(bs, 1H), 3.80(d, J = 16.4 Hz, 1H), 3.35 (dd, J = 16.8, 1.2 Hz, 1H), 3.02 (d, J = 16.4 Hz, 1H), 2.60 (dd, J = 16.8, 1.2 Hz, 1H), 1.85 (s, 3H), 1.49 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ) 197.0, 170.4, 141.2, 134.3, 131.5, 129.6, 127.2, 127.0, 55.3, 49.9, 40.1, 26.0, 24.4; HRMS (ESI) calcd for $C_{13}H_{15}NO_2Na$ $[M + Na]^+$ 240.0995, found 240.0990.

*3-(Acetylamino)-3-methyl-7,8-benzocyclooct-1-one (**7f**):* colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.07 (dd, J = 7.8, 1.4 Hz, 1H), 7.48 (td, J = 7.4, 1.5 Hz, 1H), 7.35 (td, J = 7.6, 1.2 Hz, 1H), 7.22 (dd, J = 7.6, 0.8 Hz, 1H), 3.43 (d, J = 12.8, 1H), 3.38−3.30 (m, 1H), 3.11−3.04 (d with m, 2H), 2.02−1.92 (s with m, 5H), 1.80−1.72 (m, 1H), 1.62−1.53 (s with m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$, δ) 200.6, 169.7, 140.8, 138.4, 133.8, 132.4, 129.9, 127.1, 55.4, 52.6, 34.8, 32.9, 25.1, 24.7, 23.8; HRMS (ESI) calcd for $C_{15}H_{20}NO_2$ $[M + H]^+$ 246.1489, found 246.1482.

*3-(Acetylamino)-1-benzosuberone (**7g**):* colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 7.74 (dd, J = 7.8, 1.4 Hz, 1H), 7.43 (td, J = 7.5, 1.5 Hz, 1H), 7.32 (td, J = 7.6, 1.1 Hz, 1H), 7.24 (d, J = 7.6 Hz, 1H), 5.63(bs, 1H), 4.54−4.45 (m, 1H), 3.18 (dd, J = 13.6, 1.2 Hz, 1H), 3.04−2.97 (m, 2H), 2.53−2.45 (m, 1H), 1.97 (s, 3H), 1.61−1.52 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, δ) 202.2, 169.6, 142.6, 138.7, 132.4, 130.4, 128.7, 127.0, 47.1, 45.4, 33.4, 31.5, 23.6; HRMS (ESI) calcd for $C_{13}H_{15}NO_2$ $[M + H]^+$ 218.1176, found 218.1167; calcd for $C_{11}H_{11}O$ $[M - C_2H_4NO]$ 159.0804, found 159.0798.

*3-(Benzoylamino)-3-methyl-1-benzosuberone (**8a**):* pale yellow oil; H NMR (400 MHz, $CDCl_3$, δ) 7.78 (dd, J = 7.6, 1.2 Hz, 1H), 7.73−7.71 (m, 1H), 7.71−7.70 (m, 1H), 7.48 (tt, J = 7.3, 1.7 Hz, 1H), 7.44−7.39 (m, 3H), 7.31 (dd, J = 7.6, 0.8 Hz, 1H), 7.29−7.24 (m, 1H), 6.44 (bs, 1H), 3.22−3.19 (m, 4H), 2.56 (dd, J = 14.6, 7.2 Hz, 1H), 2.24 (ddd, J = 9.9, 9.5, 1.7 Hz, 1H), 1.71 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) 201.4, 167.1, 144.1, 138.3, 135.2, 132.2, 131.6, 130.5, 128.7, 126.9, 126.7, 55.4, 53.5, 40.1,31.6, 26.3; HRMS (ESI) calcd for $C_{19}H_{20}NO_2$ $[M + H]^+$ 294.1489, found 294.1490.

*3-Methyl-3-methoxy-1-benzosuberone (**9a**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 7.79 (dd, J = 7.8, 1.4 Hz, 1H), 7.39 (td, J = 15.0, 1.5 Hz, 1H), 7.29−7.26 (t, 1H, overlapped with $CHCl_3$ peak), 7.24 (d, J = 7.6 Hz, 1H), 3.31−3.24 (s with m, 4H), 3.15 (d, J = 11.2 Hz, 1H), 2.92−2.85 (m, 2H), 2.20 (ddt, J = 8.1, 7.5, 1.3 Hz, 1H), 1.71 (ddd, J = 10.2, 7.5, 1.1 Hz, 1H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, δ) 200.8, 144.6, 138.4, 131.9, 130.3, 128.9, 126.5, 52.8, 49.6, 39.5, 30.8, 23.7; HRMS (ESI) calcd for $C_{12}H_{13}O$ $[M - CH_3O]^+$ 173.0961, found 173.0960.

*2-Methyl-2-(methoxymethyl)-1-tetralone (**10a**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 8.04 (dd, J = 8.0, 1.2 Hz, 1H), 7.46 (td, J = 7.5, 1.5 Hz, 1H), 7.30 (t, J = 7.4 Hz, 1H), 7.23 (d, J = 7.6 Hz, 1H), 3.76 (J = 9.2 Hz, 1H), 3.34 (s, 3H), 3.32 (d, J = 9.2 Hz, 1H), 3.08−2.93 (m, 2H), 2.35 (ddd, J = 14.5, 5.9, 4.5 Hz, 1H), 1.92 (td, J = 5.2, 13.6 Hz, 1H), 1.18(s, 3H); ^{13}C NMR (100 MHz, δ) 201.1, 143.8, 133.3, 131.9, 128.8, 128.1, 126.7, 77.9, 59.6, 46.4, 31.7, 25.5, 19.8; HRMS (ESI) calcd for $C_{13}H_{17}O_2$ $[M + H]^+$ 205.1223, found 205.1225.

*Spiro[[(3-(hydroxymethyl)cyclopentyl]-1,2′-1′-tetralone] (**21**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 8.03 (dd, J = 7.8 Hz, 1.0 Hz, 1H), 7.45 (td, J = 7.5, 1.5 Hz, 1H), 7.32−7.28 (m, 1H), 7.22−7.20 (m, 1H), 3.73−7.63 (m, 2H), 3.09−2.90 (m, 2H), 2.42−2.31 (m, 1H), 2.20−1.99 (m, 5H), 1.88−1.81 (m, 1H), 1.74−1.52 (m, 3H); ^{13}C NMR (100 MHz, δ) 202.9, 143.7, 133.3, 131.6, 128.7, 128.1, 126.7, 66.4, 53.3, 41.7, 37.6, 35.4, 35.3, 28.3, 26.6; HRMS (ESI) calcd for $C_{15}H_{19}O_2$ $[M + H]^+$ 231.1380, found 231.1374.

*3-(3′-Methoxypropyl)-3-methyl-1-indanone (**28**):* pale yellow oil; ^{1}H NMR (400 MHz, δ) 7.70 (ddd, J = 7.6, 1.2, 0.8 Hz, 1H), 7.63−7.59 (m, 1H), 7.46 (dt, J = 7.7, 0.9 Hz, 1H), 7.38−7.34 (m, 1H), 3.29 (td, J = 6.4, 1.6 Hz, 2H), 3.27 (s, 3H), 2.67 (d, J = 18.8 Hz, 1H), 2.46 (δ, J = 18.8 Hz, 1H), 1.84−1.69 (m, 2H), 1.58−1.46 (m, 1H), 1.42 (s, 3H), 1.28−1.17 (m, 1H); ^{13}C NMR (100 MHz, δ) 206.1, 162.7, 136.2, 135.1, 127.7, 124.0, 123.5, 72.9, 58.7, 50.3, 41.9, 38.8, 28.5, 25.5; HRMS (ESI) calcd for $C_{14}H_{19}O_2$ $[M + H]^+$ 219.1380, found 219.1376.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02827.

^{1}H NMR of the product mixture containing **4**; additional discussion; ^{1}H NMR and ^{13}C NMR charts of substrates and products (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: ehase@chem.sc.niigata-u.ac.jp.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study was partly supported by a grant from the Uchida Energy Science Promotion Foundation (Japan) (No. 27-1-9). We are grateful to Professor Ilhyong Ryu (Osaka Prefecture University) for his highly valuable comments.

■ REFERENCES

(1) (a) Eberson, L. *Electron Transfer Reactions in Organic Chemistry*; Springer: Berlin, 1987. (b) *Advances in Electron Transfer Chemistry*; Mariano, P. S., Ed.; JAI: Greenwich, CT, 1991−1999; Vols. *1*−*6*. (c) *Electron Transfer in Chemistry*; Balzani, V., Ed.; Wiley-VCH: Weinheim, 2001; Vols. *1*−*5*. (d) *Organic Electrochemistry*, 4th ed.; Lund, H., Hammerich, O., Eds.; Marcel Dekker: New York, 2001. (e) Todres, Z. V. *Ion-Radical Organic Chemistry Principles and Applications*, 2nd ed.; CRC Press: Boca Raton, 2009. (f) Zhang, N.; Samanta, S. R.; Rosen, B. M.; Percec, V. *Chem. Rev.* **2014**, *114*, 5848−5958. (g) Studer, A.; Curran, D. P. *Angew. Chem., Int. Ed.* **2016**, *55*, 58−102.

(2) (a) Gibson, D. H.; DePuy, C. H. *Chem. Rev.* **1974**, *74*, 605−623. (b) Ryu, I.; Murai, S. *Houben-Weyl Methods of Organic Chemistry*; Thieme: Stuttgart, 1997; Vol. *E17c*, pp 1985−2040. (c) Kuwajima, I.; Nakamura, E. In *Small Ring Compounds in Organic Synthesis IV*; de Meijere, A., Ed.; Springer Verlag: Berlin, 1990; Topics in Current Chemistry, Vol. *155*, pp 1−39. (d) Kulinkovich, O. G. *Chem. Rev.* **2003**, *103*, 2597−2632. (e) Wolan, A.; Six, Y. *Tetrahedron* **2010**, *66*, 15−61. (f) Cha, J. K.; Kulinkovich, O. G. *Org. React.* **2012**, *77*, 1−160. (g) Haym, I.; Brimble, M. A. *Org. Biomol. Chem.* **2012**, *10*, 7649−7665.

(3) (a) Ito, Y.; Fujii, S.; Saegusa, T. *J. Org. Chem.* **1976**, *41*, 2073−2074. (b) Iwasawa, N.; Hayakawa, S.; Funahashi, M.; Isobe, K.; Narasaka, K. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 819−827. (c) Booker-Milburn, K. I.; Thompson, D. F. *J. Chem. Soc., Perkin Trans. 1* **1995**, 2315−2321. (d) U, J. S.; Lee, U. J.; Cha, J. K. *Tetrahedron Lett.* **1997**, *38*, 5233−5236. (e) Highton, A.; Volpicelli, R.; Simpkins, N. S. *Tetrahedron Lett.* **2004**, *45*, 6679−6683. (f) Kirihara, M.; Kakuda, H.; Ichinose, M.; Ochiai, Y.; Takizawa, S.; Mokuya, A.; Okubo, A.; Hatano, K.; Shiro, M. *Tetrahedron* **2005**, *61*, 4831−4839. (g) Chiba, S.; Cao, Z.; El Bialy, S. A. A.; Narasaka, K. *Chem. Lett.* **2006**, *35*, 18−19. (h) Li, L. Z.; Xiao, B.; Guo, Q. X.; Xue, S. *Tetrahedron* **2006**, *62*, 7762−7771. (i) Jiao, J.; Nguyen, L. X.; Patterson, D. R.; Flowers, R. A., II *Org. Lett.* **2007**, *9*, 1323−1326. (j) Jida, M.; Guillot, R.; Ollivier, J. *Tetrahedron Lett.* **2007**, *48*, 8765−8767. (k) Wang, Y. F.; Toh, K. K.; Ng, E. P. J.; Chiba, S. *J. Am. Chem. Soc.* **2011**, *133*, 6411−6421. (l) Ilangovan, A.; Saravanakumar, S.; Malayappasamy, S. *Org. Lett.* **2013**, *15*, 4968−4971. (m) Ren, S.; Feng, C.; Loh, T. P. *Org. Biomol. Chem.* **2015**, *13*, 5105−

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

5109. (n) Zhao, H.; Fan, X.; Yu, J.; Zhu, C. *J. Am. Chem. Soc.* **2015**, *137*, 3490−3493.
(4) (a) Ryu, I.; Ando, M.; Ogawa, A.; Murai, S.; Sonoda, N. *J. Am. Chem. Soc.* **1983**, *105*, 7192−7194. (b) Ryu, I.; Matsumoto, K.; Kameyama, Y.; Ando, M.; Kusumoto, N.; Ogawa, A.; Kambe, N.; Murai, S.; Sonoda, N. *J. Am. Chem. Soc.* **1993**, *115*, 12330−12339.
(5) Snider, B. B.; Kwon, T. *J. Org. Chem.* **1992**, *57*, 2399−2410.
(6) (a) Sheller, M. E.; Mathies, P.; Petter, B.; Frei, B. *Helv. Chim. Acta* **1984**, *67*, 1748−1754. (b) Gassman, P. G.; Burns, S. J. *J. Org. Chem.* **1988**, *53*, 5576−5578. (c) Rinderhagen, H.; Mattay, J. *Chem. - Eur. J.* **2004**, *10*, 851−874. (d) Waske, P. A.; Mattay, J. *Tetrahedron* **2005**, *61*, 10321−10330. (e) Rinderhagen, H.; Waske, P. A.; Mattay, J. *Tetrahedron* **2006**, *62*, 6589−6593. (f) Bloom, S.; Bume, D. D.; Pitts, C. R.; Lectka, T. *Chem. - Eur. J.* **2015**, *21*, 8060−8063.
(7) (a) Iwaya, K.; Tamura, M.; Nakamura, M.; Hasegawa, E. *Tetrahedron Lett.* **2003**, *44*, 9317−9320. (b) Hasegawa, E.; Tsuchida, H.; Tamura, M. *Chem. Lett.* **2005**, *34*, 1688−1689. (c) Hasegawa, E.; Yamaguchi, N.; Muraoka, H.; Tsuchida, H. *Org. Lett.* **2007**, *9*, 2811−2814. (d) Hasegawa, E.; Ogawa, Y.; Kakinuma, K.; Tsuchida, H.; Tosaka, E.; Takizawa, S.; Muraoka, H.; Saikawa, T. *Tetrahedron* **2008**, *64*, 7724−7728. (e) Tsuchida, H.; Tamura, M.; Hasegawa, E. *J. Org. Chem.* **2009**, *74*, 2467−2475. (f) Hasegawa, E.; Kakinuma, K.; Yanaki, T.; Komata, S. *Tetrahedron* **2009**, *65*, 10876−10881. (g) Tsuchida, H.; Hasegawa, E. *Tetrahedron* **2010**, *66*, 3447−3451. (h) Hasegawa, E.; Tateyama, M.; Nagumo, R.; Tayama, E.; Iwamoto, H. *Beilstein J. Org. Chem.* **2013**, *9*, 1397−1406.
(8) (a) Connelly, N. G.; Geiger, W. E. *Chem. Rev.* **1996**, *96*, 877−910. (b) Astruc, D. In *Electron Transfer in Chemistry*; Balzani, V., Ed.; Wiley-VCH: Weinheim, 2001; Vol. 2, pp 714−803. (c) Rorabacher, D. B. *Chem. Rev.* **2004**, *104*, 651−697.
(9) (a) Zhang, C.; Tang, C.; Jiao, N. *Chem. Soc. Rev.* **2012**, *41*, 3464−3484. (b) Allen, S. E.; Walvoord, R. R.; Padilla-Salinas, R.; Kozlowski, M. C. *Chem. Rev.* **2013**, *113*, 6234−6458. (c) Guo, X. X.; Gu, D. W.; Wu, Z.; Zhang, W. *Chem. Rev.* **2015**, *115*, 1622−1651. (d) McCann, S. D.; Stahl, S. S. *Acc. Chem. Res.* **2015**, *48*, 1756−1766.
(10) Recent examples of copper(I) catalyzed ring-opening reaction of cyclopropanols: (a) Li, Y.; Ye, Z.; Bellman, T. M.; Chi, T.; Dai, M. *Org. Lett.* **2015**, *17*, 2186−2189. (b) Ye, Z.; Dai, M. *Org. Lett.* **2015**, *17*, 2190−2193. (c) Kananovich, D. G.; Konik, Y. A.; Zubrytski, D. M.; Järving, I.; Lopp, M. *Chem. Commun.* **2015**, *51*, 8349−8352.
(11) It should be noted that the concentrations of the substrates as well as copper salts in the reactions reported in this manuscript are approximately 10 times lower than those used in the previously reported reactions (ref 4).
(12) A use of predried $Cu(BF_4)_2{\cdot}6H_2O$ (3 d at 120 °C at ca.1 mmHg) led to a significantly slower reaction: 43% recovery of **1a** and 29% of **1a**-OH were observed. On the other hand, the use of a five times more diluted condition resulted in the decreased yields of **2a** (9%), **3a** (11%), **4** (14%), and **5a** (trace) along with **6a** (5%).
(13) Both $Cu(OAc)_2$ and $CuCl_2$ were not effective in promoting reactions to give the expected products in wet Et_2O. Significant quantity of **1a** (>70%) was recovered in the former case, while only small quantity of **5** (3%) was obtained along with **1a**-OH (32%) and 2-(chloromethyl)-2-methyl-1-tetralone (23%) in the latter.
(14) When reaction with 1.1 equiv of $Cu(BF_4)_2{\cdot}H_2O$ was conducted in DMSO, a significant amount of **1a**-OH (84%) was obtained along with **4** (8%) and **6a** (8%), although **1a** was completely consumed. The same reaction in CH_2Cl_2 produced recovered **1a** (30%), **1a**-OH (51%), and small amounts of **3** (9%), **4** (4%), and **6a** (6%). On the other hand, the reaction did not proceed, and most of **1a** was recovered in benzene with the observation that this copper salt did not dissolve during reaction.
(15) The mechanism of the fragmentation of initially formed metal−organic complexes in the metal salts promoted oxidation reactions of these types of substrates, giving β-ketoalkyl radicals (ref 3c), cyclopropoxy radicals (refs 7c 7e, and 7h), or β-metalated carbonyls (ref 4), is still controversial (ref 3). Thus, we propose reaction pathways presented in Scheme 5, but the possibility that cyclopropoxy radical, which may also exist in the equilibrium between **13a** and **14a**, is derived from **11a** and serves as a reaction intermediate can not be ruled out.
(16) Representative publications noting assistance of nucleophilic solvents to promote desilylation of radical cations as well as carbocations of silyl compounds: (a) Hasegawa, E.; Xu, W.; Mariano, P. S.; Yoon, U. C.; Kim, J. U. *J. Am. Chem. Soc.* **1988**, *110*, 8099−8111. (b) Dinnocenzo, J. P.; Farid, S.; Goodman, J. L.; Gould, I. R.; Todd, W. P.; Mattes, S. L. *J. Am. Chem. Soc.* **1989**, *111*, 8973−8975. (d) Zhang, X.; Yeh, S. R.; Hong, S.; Freccero, M.; Albini, A.; Falvey, D. E.; Mariano, P. S. *J. Am. Chem. Soc.* **1994**, *116*, 4211−4220. (e) Bockman, T. M.; Kochi, J. K. *J. Chem. Soc., Perkin Trans. 2* **1996**, 1633−1643. (f) Su, Z.; Mariano, P. S.; Falvey, D. E.; Yoon, U. C.; Oh, S. W. J. *J. Am. Chem. Soc.* **1998**, *120*, 10676−10686. (g) D'Oca, M. G. M.; Moraes, L. A. B.; Pilli, R. A.; Eberlin, M. N. *J. Org. Chem.* **2001**, *66*, 3854−3864. (h) Zhang, Y.; Flowers, R. A., II *J. Org. Chem.* **2003**, *68*, 4560−4562. (i) Zhang, Y.; Raines, A. J.; Flowers, R. A., II *J. Org. Chem.* **2004**, *69*, 6267−6272.
(17) (a) Kochi, J. K. *Acc. Chem. Res.* **1974**, *7*, 351−360. (b) Snider, B. B. *Chem. Rev.* **1996**, *96*, 339−364.
(18) Masarwa, M.; Cohen, H.; Meyerstein, D. *Inorg. Chem.* **1991**, *30*, 1849−1854.
(19) (a) Dowd, P.; Choi, S. C. *J. Am. Chem. Soc.* **1987**, *109*, 3493−3494. (b) Dowd, P.; Choi, S. C. *J. Am. Chem. Soc.* **1987**, *109*, 6548−6549. (c) Beckwith, A. L. J.; O'Shea, D. M.; Westwood, S. W. *J. Chem. Soc., Chem. Commun.* **1987**, 666−667. (d) Bowman, W. R.; Westlake, P. J. *Tetrahedron* **1992**, *48*, 4027−4038. (e) Dowd, P.; Zhang, W. *Chem. Rev.* **1993**, *93*, 2091−2115 and references cited therein.
(20) (a) Deng, H.; Kebarle, P. *J. Am. Chem. Soc.* **1998**, *120*, 2925−2931. (b) Yang, Z.; Rannulu, N. S.; Chu, Y.; Rodgers, M. T. *J. Phys. Chem. A* **2008**, *112*, 388−401.
(21) (a) Irangu, J.; Ferguson, M. J.; Jordan, R. B. *Inorg. Chem.* **2005**, *44*, 1619−1625. (b) Sreenath, K.; Suneesh, C. V.; Gopidas, K. R.; Flowers, R. A., II *J. Phys. Chem. A* **2009**, *113*, 6477−6483. (c) Brennan, B. J.; Kenney, M. J.; Liddell, P. A.; Cherry, B. R.; Li, J.; Moore, A. L.; Moore, T. A.; Gust, D. *Chem. Commun.* **2011**, *47*, 10034−10036.
(22) Sumalekshmy, S.; Gopidas, K. R. *Chem. Phys. Lett.* **2005**, *413*, 294−298.
(23) On the basis of the oxidation potentials of the substrates **1** (1.36−1.80 V vs SCE, ref 7c) and the reduction potentials of copper(II) (refs 21 and 22), outer sphere electron transfer from **1** to $Cu(BF_4)_2$ giving radical cations of **1** is unlikely.
(24) (a) Fossey, J.; Lefort, D.; Sorba, J. *Free Radicals in Organic Chemistry*; Wiley: Chchester, 1995. (b) Agapito, F.; Nunes, P. M.; Cabral, B. J. C.; dos Santos, R. M. B.; Simões, J. A. M. *J. Org. Chem.* **2007**, *72*, 8770−8779.
(25) Tayim, H. A.; Kharboush, M. *Inorg. Chem.* **1971**, *10*, 1827−1828.
(26) (a) Manahan, S. E. *Inorg. Chem.* **1966**, *5*, 2063−2065. (b) Bulusheva, L. G.; Okotrub, A. V.; Liskovskaya, T. I.; Krupoder, S. A.; Gusel'nikov, A. V.; Manaev, A. V.; Traven, V. F. *J. Phys. Chem. A* **2001**, *105*, 8200−8205. (c) Kunkely, H.; Vogler, A. *Z. Naturforsch.* **2003**, *58b*, 704−707.
(27) (a) Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1980**, *13*, 317−323. (b) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925−3941. (c) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151−1176. (d) Beckwith, A. L. J.; Schiesser, C. H. *Org. Biomol. Chem.* **2011**, *9*, 1736−1743.
(28) The rate constants for 5-*exo*-hexenyl radical cyclizations of neopentyl-type primary radical and tertiary alkyl radical, corresponding to **13b** and **14c**, were reported to be 5×10^6 s^{-1} and 3×10^5 s^{-1}, respectively (ref 27c). On the other hand, the rate of cyclization and ring expansion of the primary alkyl radical, related to **13c**, was estimated to be 4×10^3 s^{-1} (ref 29).
(29) Hasegawa, E.; Tateyama, M.; Hoshi, T.; Ohta, T.; Tayama, E.; Iwamoto, H.; Takizawa, S.; Murata, S. *Tetrahedron* **2014**, *70*, 2776−2783.
(30) In a related study, Ryu and co-workers observed the formation of a organostannyl intermediate in which β-carbonyl coordinates with stannyl center to form a chelate complex (ref 31). If organocopper

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703

intermediates such as **12** have similar structures, the ring size of cyclic ketone moiety would significantly influence stability of the conformation suitable for such chelating structures.
(31) (a) Ryu, I.; Murai, S.; Sonoda, N. *J. Org. Chem.* **1986**, *51*, 2389−2391. (b) Nakahira, H.; Ryu, I.; Ikebe, M.; Oku, Y.; Ogawa, A.; Kambe, N.; Sonoda, N.; Murai, S. *J. Org. Chem.* **1992**, *57*, 17−28.
(32) Representative examples of significant solvent effects on reductive electron-transfer reactions promoted by samarium(II): (a) Chopade, P.; Davis, T. A.; Prasad, E.; Flowers, R. A., II *Org. Lett.* **2004**, *6*, 2685−2688. (b) Sadasivam, D. V.; Antharjanam, P. K. S.; Prasad, E.; Flowers, R. A., II *J. Am. Chem. Soc.* **2008**, *130*, 7228−7229. (c) Chciuk, T. V.; Hilmersson, G.; Flowers, R. A., II. *J. Org. Chem.* **2014**, *79*, 9441−9443. (d) Choquette, K. A.; Sadasivam, D. V.; Flowers, R. A., II *J. Am. Chem. Soc.* **2010**, *132*, 17396−17398.
(33) Trost, B. M.; Parquette, J. R. *J. Org. Chem.* **1993**, *58*, 1579−1581.
(34) Okuma, K.; Itoyama, R.; Sou, A.; Nagahora, N.; Shioj, K. *Chem. Commun.* **2012**, *48*, 11145−11147.
(35) Hasegawa, E.; Takizawa, S.; Seida, T.; Yamaguchi, A.; Yamaguchi, N.; Chiba, N.; Takahashi, T.; Ikeda, H.; Akiyama, K. *Tetrahedron* **2006**, *62*, 6581−6588.

DOI: 10.1021/acs.joc.5b02827
J. Org. Chem. 2016, 81, 2692−2703