JOC The Journal of Organic Chemistry
Note
pubs.acs.org/joc

Iron/ABNO-Catalyzed Aerobic Oxidation of Alcohols to Aldehydes and Ketones under Ambient Atmosphere

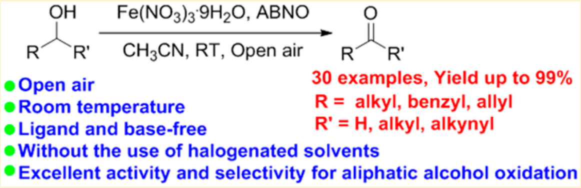
Lianyue Wang,*[†] SenSen Shang,[†,‡] Guosong Li,[†] Lanhui Ren,[†,‡] Ying Lv,[†] and Shuang Gao*[†]

[†]Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian National Laboratory for Clean Energy, Dalian 116023, China

[‡]Graduate School of the Chinese Academy of Sciences, Beijing 100049, China

S Supporting Information

ABSTRACT: We report a new $Fe(NO_3)_3·9H_2O$/9-azabicyclo[3.3.1]nonan-*N*-oxyl catalyst system that enables efficient aerobic oxidation of a broad range of primary and secondary alcohols to the corresponding aldehydes and ketones at room temperature with ambient air as the oxidant. The catalyst system exhibits excellent activity and selectivity for primary aliphatic alcohol oxidation. This procedure can also be scaled up. Kinetic analysis demonstrates that C−H bond cleavage is the rate-determining step and that cationic species are involved in the reaction.



Alcohols are selectively oxidized into the corresponding carbonyl compounds, which is one of the most fundamental reactions in organic chemistry.[1] Numerous classical methods have been proven to achieve this transformation very well with stoichiometric amounts of oxidants, among which, MnO_2, chromium salts, and the Dess−Martin reagent produce large amounts of inorganic and organic toxic waste.[2] With the increasing focus on environmental problems, molecular oxygen as oxidant has attracted great attention because of its advantages, such as economy and water as the only byproduct. In this regard, many of the significant improvements in catalytic methods have been made for aerobic alcohol oxidation. Among these, the developed catalyst systems for the aerobic alcohol oxidation with molecular oxygen as terminal oxidant are involved in transition metals or coordination complexes of transition metal, but the use of noble metals (e.g., Pd, Ru, Au) and commercially unavailable ligands limits their applications.[3] In addition, these catalytic systems usually use pure O_2 as the oxidant. Substitution of noble metals in catalysts for cheap and abundant metals is of obvious importance. Therefore, recent efforts have been made to develop earth-abundant metal catalysts based on first-row transition metals such as Cu,[4−6] Co,[7] Fe,[8] and V,[9] which have been well proven to show effective implementation for aerobic alcohol oxidation.

Iron as an earth-abundant metal in the geosphere has been developed as a catalyst for many organic reactions,[10] but there are not many reports on Fe as the catalyst for aerobic alcohol oxidation. The mainly catalytic systems were based on TEMPO in combination with Fe salts. The Fe/TEMPO catalytic system for alcohol oxidation was first reported by Wang et al.[8a] Further developments of the Fe/TEMPO catalyst system were reported by Ma et al. The performance and substrate scope were improved in the presence of NaCl as an additive.[8d] Despite the advantages of these reactions, most of them use halogenated hydrocarbon ($PhCF_3$, CH_2Cl_2, or $C_2H_4Cl_2$) as the solvent. In this context, our group is particularly interested in Fe/TEMPO catalytic systems for the oxidation of alcohols.[8e] Another major problem of Fe/TEMPO systems is their moderate selectivity regarding the form of aliphatic aldehydes. As we know, the oxidation of unactivated primary aliphatic alcohols to aldehydes is a challenging issue in alcohol oxidation reactions. The products of the aliphatic aldehydes are more reactive than aliphatic alcohols and more conducive to over-oxidation to the carboxylic acids. There are several reports on the highly selective oxidation of unactivated primary aliphatic alcohols to aldehydes.[11] The limitation of the Fe/TEMPO system in obtaining high selectivity of primary aliphatic aldehydes is probably caused by the low catalytic activity of TEMPO. We envisioned that the selectivity and reactivity of primary aliphatic alcohol oxidation could be improved by replacing TEMPO with a nitroxyl radical having different redox and steric properties. Recently, sterically unhindered nitroxyl radicals have begun to be used (Figure 1). Such nitroxyl radicals have been well used for the catalytic oxidation in Cu- or transition-metal-free catalytic systems[12] and show high reactivity in contrast to

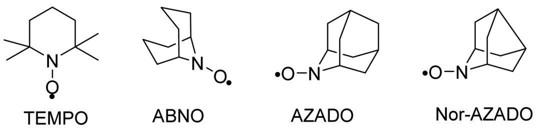


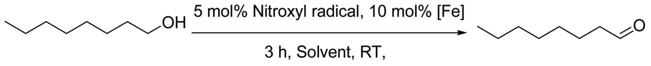
Figure 1. Structures of reported nitroxyl radicals. ABNO = 9-azabicyclo[3.3.1]nonan-*N*-oxyl, AZADO = 2-azaadamantane-*N*-oxyl, nor-AZADO = 9-azanoradamantane-*N*-oxyl.

Received: January 3, 2016
Published: February 9, 2016

© 2016 American Chemical Society

DOI: 10.1021/acs.joc.6b00009
J. Org. Chem. 2016, 81, 2189−2193

Table 1. Optimization of the Reaction Conditions for 1-Octanol Oxidation[a]



entry	nitroxyl radical	[Fe]	solvent	yield[b] (%)	selectivity[b] (%)
1	TEMPO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	15	65
2	HO-TEMPO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	31	71
3	4-acetamido-TEMPO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	46	74
4	Oxo-TEMPO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	10	65
5	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	87	97
6		$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	NR	
7	ABNO	$FeCl_3{\cdot}6H_2O$	CH_3CN	trace	
8[c]	ABNO	$FeCl_3{\cdot}6H_2O$	CH_3CN	49	93
9[c]	ABNO		CH_3CN	trace	
10[d]	ABNO		CH_3CN	trace	
11	ABNO	$Zn(NO_3)_2{\cdot}6H_2O$	CH_3CN	trace	
12	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	Toluene	39	86
13	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	MeOH	trace	
14[e]	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	87	97
15[f]	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	90	99
16[f,g]	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	59	93
17[f,h]	ABNO	$Fe(NO_3)_3{\cdot}9H_2O$	CH_3CN	35	99
18[f,i]	TEMPO	$Fe(NO_3)_3{\cdot}9H_2O$	DCE	45	81
19[c,f]	4-acetamido-TEMPO	$FeCl_3$	DCE	3	

[a] 1-Octanol (0.25 mmol), CH_3CN (2 mL); entries 1−12, oxygen balloon as the oxidant. [b] Yield and selectivity were determined by GC analysis using biphenyl as internal standard, and the products were confirmed by GC−MS. [c] 10 mol % of $NaNO_2$, [d] 30 mol % $NaNO_2$, [e] Air balloon. [f] Open air, reaction time 4 h. [g] 3 mol % of ABNO. [h] 5 mol % of $Fe(NO_3)_3{\cdot}9H_2O$. [i] 10 mol % of NaCl, NR = no reaction.

TEMPO owing both to the smaller steric hindrance around the *n*-oxyl radical and increased stability in the condition of oxidation. Inspired by these studies, we can make a reasonable conjecture that such nitroxyl radicals might be able to solve the limitation of poor selectivity for primary aliphatic alcohol oxidation in Fe catalytic systems. To the best of our knowledge, this is no report on the use of less hindered nitroxyl radicals in Fe catalytic systems for alcohol oxidation.

Herein, we report a new, highly selective, and active $Fe(NO_3)_3$/ABNO (9-azabicyclo[3.3.1]nonan-*N*-oxyl) catalyst system for the aerobic oxidation of alcohols. A broad range of alcohols, including unactivated aliphatic, allylic, and benzylic alcohols, are oxidized to the corresponding aldehydes and ketones in high yields at room temperature with ambient air as the oxidant. For primary aliphatic alcohols, overoxidation to the corresponding carboxylic acids was not observed. The catalyst system exhibits a wide range of functional-group compatibility, including alkenes, alkynes, halides, heterocyclic atoms, nitro groups, and alkyl ethers. Our catalytic system uses the traditional organic solvent acetonitrile without the use of environmentally unfriendly halogenated solvents ($PhCF_3$, CH_2Cl_2, or $C_2H_4Cl_2$). These very mild reaction conditions make the present catalysts useful, particularly for practical applications in organic synthesis. In addition, a plausible overall mechanism for the present catalytic system was discussed. Kinetic isotope effects (KIE) and Hammett values were also studied in this work.

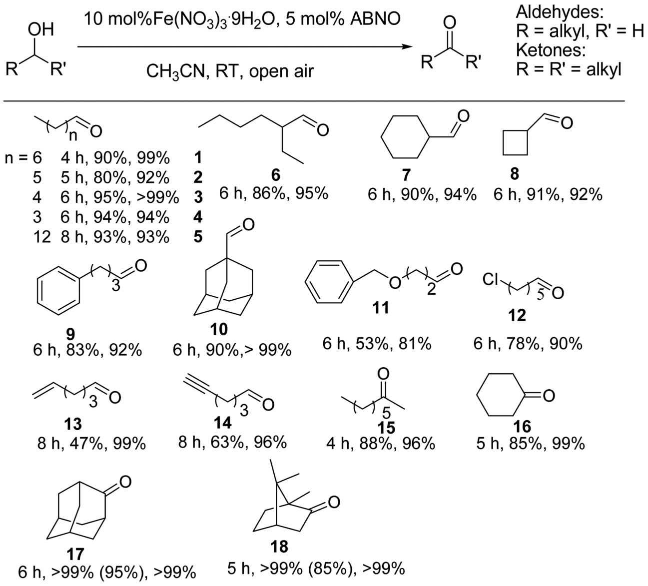
The investigation began with 1-octanol as the model substrate with a comparison of the catalytic efficiencies of different diversities of nitroxyl radicals using 10 mol % $Fe(NO_3)_3{\cdot}9H_2O$ in CH_3CN as the solvent under oxygen atmosphere at room temperature. The results are summarized in Table 1. ABNO showed a relatively high selectivity under our screening conditions (Table 1, entries 1−5). 4-Acetamido-TEMPO provided a moderate selectivity under our reaction conditions compared with the reported literature (Table 1, entry 3).[8c] These results demonstrated that the catalytic activity of TEMPO and 4-substituted TEMPOs was not so effective to selectively oxidize unactivated aliphatic alcohols to the aldehydes under the present reaction conditions. It is worth noting that overoxidation of the aldehyde did not occur and that *n*-octyl nitrite was a main byproduct in our reaction conditions. It was reported that only $Fe(NO_3)_3{\cdot}9H_2O$ can achieve the oxidation of benzyl alcohol.[8b] However, in our case, no reaction occurred without ABNO, and *n*-octyl nitrite was not detected (Table 1, entry 6). When $FeCl_3{\cdot}6H_2O$ was utilized as catalyst, this led to a trace yield (Table 1, entry 7). As suggested by some authors, NO_x is playing a key role in Fe/TEMPO systems. $NaNO_2$ was added into the $FeCl_3{\cdot}6H_2O$/ABNO catalytic system resulting in good selectivity of the desired product, but moderate yield was obtained (Table 1, entry 8). To test whether only NO_x can achieve this catalytic process, only $NaNO_2$ and $Zn(NO_3)_2{\cdot}6H_2O$ were used, respectively (Table 1, entries 9−11). Only trace product was obtained, indicating that Fe^{3+} is necessary for the achievement of the catalytic reaction. Other solvents such as toluene showed good selectivity under the same reaction conditions (Table 1, entry 12).The use of a polar solvent such as MeOH resulted in trace product (Table 1, entry 13). An important improvement for the aerobic oxidation system applicability is to take the place of pure O_2 with air since this reduces cost and is also safer. While optimization of the reaction conditions employs an oxygen balloon, the reaction can also be conducted under air balloon and even under open air, albeit with slightly longer reaction time (Table 1, entries 14 and 15). The effect of catalyst loadings was also investigated. When the amount of $Fe(NO_3)_3{\cdot}9H_2O$ and ABNO was reduced, the yields were decreased, but good selectivity was still obtained (Table 1, entries 16 and 17). In order to make further comparison with the reported literature,[8c,d] the reactions were performed with catalysts from

DOI: 10.1021/acs.joc.6b00009
J. Org. Chem. 2016, 81, 2189−2193

the literature used under open air conditions (Table 1, entries 18 and 19). The results obtained amplify the higher activity of the present catalyst system.

Under the optimized reaction conditions, we explored the substrate scope of this catalytic oxidation system. On the basis of our initial efforts to achieve high selectivity of unactivated alcohol oxidation, the oxidation of aliphatic alcohols with various functional groups was examined. The results are summarized in Scheme 1. Linear and annular unactivated primary alcohols were smoothly oxidized to the desired aldehydes with high yields and selectivity (Scheme 1, **1**−**14**). A wide range of functional groups such as aryl (Scheme 1, **9**), alkyl ethers (Scheme 1, **11**), alkyl halides (Scheme 1, **12**), alkenes (Scheme 1, **13**), and alkynyl (Scheme 1, **14**) were tolerated under the optimized reaction conditions, and the corresponding aldehydes were obtained in good to moderate yields with excellent selectivity. Most importantly, secondary aliphatic alcohols could also be oxidized to the desired ketones in good to excellent yields under our mild conditions (Scheme 1, **15** and **16**). Moreover, the oxidation of challenging hindered secondary alcohols furnished the expected products in excellent yields (Scheme 1, **17** and **18**).

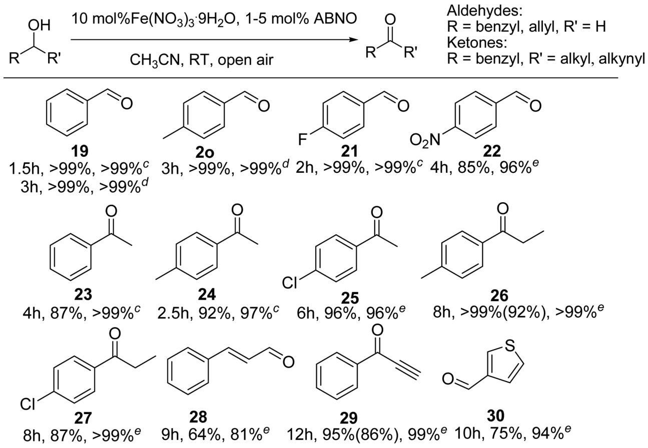
Scheme 1. Oxidation of Primary and Secondary Unactivated Alcohols[a,b]



[a]Alcohol (0.25 mmol), CH$_3$CN (2 mL). [b]Yield and selectivity were determined by GC analysis using biphenyl as internal standard, and the products were confirmed by GC−MS. Values in parentheses are the isolated yields. Entries are shown as follows: reaction time, yield (isolated yield), selectivity.

Having obtained good results for the oxidation of unactivated alcohols, we next examined the ability of the Fe(NO$_3$)$_3$·9H$_2$O/ABNO catalytic system to catalyze the oxidation of certain activated alcohols. The results are summarized in Scheme 2. By reducing the amount of ABNO, excellent results could also be obtained, as could be expected. All benzylic alcohols with electron-donating and -withdrawing groups were oxidized into the corresponding aldehydes or ketones with excellent selectivity (Scheme 2, **19**−**30**). As expected, electron-deficient benzylic alcohols were less reactive than electron-rich benzylic alcohols. It is worth noting that primary benzylic alcohols can be quantitatively oxidized to the corresponding aldehydes (Scheme 2, **19**−**21**). Compared with primary benzylic alcohols, secondary benzylic alcohols are less reactive. Excellent results can be achieved in the case of increased loading of ABNO (Scheme 2, **23**−**27**). Although a slightly lower yield of product was obtained for the oxidation of cinnamyl alcohol (Scheme 2, **28**), this reaction was highly efficient for propargylic alcohol oxidation (Scheme 2, **29**). 3-Thiophene-ylmethanol, usually regarded as difficult substrate, was oxidized into the desired product in good yield (Scheme 2, **30**).

Scheme 2. Oxidation of Activated Alcohols[a,b]



[a]Alcohol (0.25 mmol), CH$_3$CN (2 mL). [b]Yield and selectivity were determined by GC analysis using biphenyl as internal standard and confirmed by GC−MS. [c]3 mol % of ABNO. [d]1 mol % of ABNO. [e]5 mol % of ABNO. Values in parentheses are the isolated yields. Entries are shown as follows: reaction time, yield (isolated yield), selectivity.

Our previous work and the pertinent literature have given a plausible mechanism for the Fe/TEMPO catalytic system.[8a,d,e] We speculate that the present aerobic alcohol oxidation shows a similar reaction process: (1) substrate oxidation mediated by Fe(III) and ABNO via an Fe(III) alkoxide intermediate and (2) catalyst oxidation in which Fe(II) and reduced ABNO are oxidized by O$_2$ via NO$_x$ generated in situ by NO^{3-}. In order to gain more insight into the present alcohol oxidation system, we then investigated the kinetic isotope effect (KIE). 1-Phenylethanol and its deuterated alcohol were selected as test substrates. A linear relationship exists between $-\ln(1 - C)$ and reaction time, indicating that the reaction is first order with respect to 1-phenylethanol as shown in Figure 1S. The KIE value for this Fe/ABNO-catalyzed oxidation of secondary alcohol was 2.1. Intramolecular competition experiment for the oxidation of PhCHDOH was also carried out. The KIE was determined to be 3.7 as an average of two measurements. From these results, we concluded that C−H cleavage is the rate-determining step. To pursue a better understanding of the transition state, Hammett correlation study was conducted with various *para*-substituted benzyl alcohols. A linear relationship was obtained between the logarithm of the initial rate and the σ value of the *para*-substituent (Figure 2S). The resulting Hammett parameter ρ is −1.8, thus suggesting the reaction exhibits preferential oxidation of electron-rich alcohols and carbocation is involved, which is also consistent with the observation that electron-donating substituents accelerate the overall rate of oxidation.

Finally, we demonstrated the gram-scale application of this catalytic system. Benzyl alcohol was used as a test substrate.

Reaction of benzyl alcohol (25 mmol, 2.7 g) was performed with 0.2 mol % of ABNO and 5 mol % of $Fe(NO_3)_3{\cdot}9H_2O$ in CH_3CN under ambient atmosphere at room temperature. The desired product was obtained in 95% isolated yield with >99% selectivity within 16 h. These results suggest that in the case of a low catalytic amount of ABNO our system shows high activity, selectivity, and practicability for the aerobic oxidation of alcohols.

In summary, we have developed a highly efficient $Fe(NO_3)_3{\cdot}9H_2O$/ABNO-catalyzed oxidation systems for a variety of alcohols. The catalyst system exhibits a wide substrate tolerance. The oxidation reaction is carried out under ambient atmosphere and at room temperature. This catalytic system takes safety into account and avoids using any ligand and base, which is beneficial for its use in pharmaceuticals, fragrances, and food additives. The distinctive feature of this catalytic system is that unactivated alcohols can be smoothly oxidized into the aldehydes and ketones with excellent selectivity. The utilization of a low catalytic amount of ABNO (0.2 mol %) in a scaled-up reaction can afford an excellent yield of the desired product. The present catalyst system might also be useful for other types of functional-group transformations.

EXPERIMENTAL SECTION

General Information. All chemicals were purchased from Reagent Co. and used without further purification. The yield and selectivity were obtained by GC. All products were confirmed by GC−MS. ^1H NMR and ^{13}C NMR spectra were recorded on a 400 MHz NMR spectrometer in $CDCl_3$ with TMS as an internal reference (δTMS = 0.00 ppm; $CDCl_3$: δC = 77.1 ppm; residual $CHCl_3$ in $CDCl_3$: δH = 7.26 ppm).

General Procedure for Aerobic Alcohol Oxidation. To a 10 mL, dried culture tube were added $Fe(NO_3)_3{\cdot}9H_2O$ (0.025 mmol, 10 mg), ABNO (1.25 mL, 0.01 M), alcohol (0.25 mmol), and 0.75 mL of CH_3CN. The resulting suspension was stirred at room temperature open to air. The progress of the reaction was monitored by GC using biphenyl as an internal standard. After completion of the reaction, the diethyl ether was added to the resulting mixture. The mixture was dried over anhydrous $MgSO_4$ and then filtered through a short column of silica gel to remove the inorganic salts. CH_3CN and diethyl ether were removed by rotary evaporation, and the product was further purified by column chromatography over silica gel with a mixture of ethyl acetate/hexane as eluent. ^1H and ^{13}C NMR spectra data of all isolated products were in accord with the literature.

Methods for Determination of Kinetic Isotope Effects. *Synthesis of d_1-Benzyl Alcohol.* A solution of benzaldehyde (0.212 g, 2 mmol) in MeOH (20 mL) was cooled to 0 °C under N_2. $NaBD_4$ (0.17 g, 4 mmol) was added portionwise over 1 h. The reaction was allowed to warm to room temperature with stirring. After 2 h, the mixture was cooled to 0 °C and quenched by the careful addition of HCl (1 M) followed by extraction with ethyl acetate (100 mL). The collected organic layers were dried with $NaSO_4$ and filtered, and the solvent was evaporated. The crude material was purified by silica column chromatography (ethyl acetate/hexane = 1/20) to afford d_1-benzyl alcohol (0.194 g, 90% yield). Characterization data are given below. Spectral parameters are consistent with literature values.[13]

Synthesis of 1-Deutero-1-phenylethanol. A solution of acetophenone (0.24 g, 2 mmol) in MeOH (25 mL) was cooled to 0 °C under N_2. $NaBD_4$ (0.17 g, 4 mmol) was added portionwise over 1 h. The reaction was allowed to warm to room temperature with stirring. After 2 h, the mixture was then cooled to 0 °C and quenched by the careful addition of HCl (1 M) followed by extraction with ethyl acetate (100 mL). The collected organic layers were dried with $NaSO_4$ and filtered, and the solvent was evaporated. The crude material was purified by silica column chromatography (ethyl acetate/hexane = 1/20) to afford 1-deutero-1-phenylethanol (0.207 g, 85% yield). Characterization data are given below. Spectral parameters are consistent with literature values.[14]

Representative Procedures for the Measurement of Kinetic Isotope Effects. *Kinetic Isotope Effect for 1-Phenethyl Alcohol.* To a 10 mL, dried culture tube were added $Fe(NO_3)_3{\cdot}9H_2O$ (0.025 mmol, 10 mg), ABNO (1.25 mL, 0.01 M), 1-phenethyl alcohol or 1-deuterated-1-phenylethanol (0.25 mmol), and 0.75 mL of CH_3CN. The resulting suspension was stirred at room temperature open to air. Reaction sample spectra were collected every 30 min and determined by GC.

For Benzyl Alcohol. To a 10 mL, dried culture tube were added $Fe(NO_3)_3{\cdot}9H_2O$ (0.025 mmol, 10 mg), ABNO (1.25 mL, 0.01 M), PhCHDOH (0.25 mmol, 27.3 mg), and 0.75 mL and CH_3CN. The resulting suspension was stirred at room temperature open to air until the starting material was consumed as determined by GC. The crude reaction was filtered through a silica plug with EtOAc. The solvent was removed by evaporation (in many cases, some solvent remained to avoid evaporation of any aldehyde products), and an ^1H NMR spectrum of the reaction mixture was acquired to determine the ratio of products.

d_1-Benzyl alohol:[13] colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ 7.21−7.11 (m, 5H), 4.40 (s, 1H), 3.07 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.9, 128.5, 127.6, 127.1, 64.8, 64.7, 64.4.

1-Phenyl-1-deuteroethanol:[14] colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ 7.27−7.19 (m, 4H), 7.19−7.12 (m, 1H), 2.49 (s, 1H), 1.34 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 145.8, 128.5, 127.4, 125.5, 70.1, 69.9, 69.7, 24.8

Benzaldehyde:[4e] colorless oil; yield 2.5 g, 95%; ^1H NMR (400 MHz, $CDCl_3$) δ 9.88 (s, 1H), 7.75 (d, J = 8.1 Hz, 2H), 7.49 (dd, J = 11.9, 4.1 Hz, 1H), 7.39 (t, J = 7.5 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.6, 135.3, 133.4, 128.6, 127.9.

2-Adamantanone (Scheme 1, **17**):[15] white solid, yield 36 mg, 95%; ^1H NMR (400 MHz, $CDCl_3$) δ 2.53 (s, 2H), 2.09−1.92 (m, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 218.8, 47.0, 39.3, 36.4, 27.5.

Camphor (Scheme 1,**18**):[16] white solid; yield 32 mg, 85%; ^1H NMR (400 MHz, $CDCl_3$) δ 2.34 (d, J = 18.2 Hz, 1H), 2.07 (t, J = 4.2 Hz, 1H), 2.00−1.88 (m, 1H), 1.83 (d, J = 18.2 Hz, 1H), 1.70−1.60 (m, 1H), 1.46−1.26 (m, 2H), 0.94 (s, 3H), 0.90 (s, 3H), 0.82 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 57.8, 46.9, 43.3, 43.1, 29.9, 27.1, 19.8, 19.2, 9.3.

4′-Methylypropiophenone (Scheme 2,**26**):[17] colorless oil; yield 34 mg, 92%; ^1H NMR (400 MHz, $CDCl_3$) δ 7.76 (d, J = 8.0 Hz, 2H), 7.14 (d, J = 7.8 Hz, 2H), 2.89−2.83 (m, 2H), 2.29 (s, 3H), 1.11 (td, J = 7.2, 1.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 200.4, 143.6, 134.4, 129.2, 128.1, 31.6, 21.6, 8.3.

1-Phenyl-2-propyn-1-one (Scheme 2 ,**29**):[9f] yellow solid; yield 28 mg, 86%; ^1H NMR (400 MHz, $CDCl_3$) δ 8.09 (d, J = 7.3 Hz, 2H), 7.56 (t, J = 7.4 Hz, 1H), 7.43 (t, J = 7.7 Hz, 2H), 3.37 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.5, 136.2, 134.6, 129.8, 128.8, 80.9, 80.3.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00009.

Measurement of kinetic isotope effects, Hammett plots, and NMR spectra of the isolated products (PDF)

AUTHOR INFORMATION

Corresponding Authors

*E-mail: lianyuewang@dicp.ac.cn.
*E-mail: sgao@dicp.ac.cn.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support from the National Natural Science Foundation of China (No. 21403219).

REFERENCES

(1) (a) Hudlicky, M. *Oxidations in Organic Chemistry*; American Chemical Society: Washington, DC, 1990. (b) Larock, R. C. *Comprehensive Organic Transformations*; Wiley: New York, 1999. (c) Tojo, G.; Fernandez, M. *Oxidations of Alcohols to Aldehydes and Ketones*; Springer: New York, 2006.

(2) March, J. *Advanced Organic Chemistry: ReactionsMechanisms, and Structure*, 4th ed.; John Wiley & Sons: New York, 1992.

(3) For more recently representative reviews of transition-metal-catalyzed aerobic oxidation of alcohols, see: (a) Parmeggiani, C.; Cardona, F. *Green Chem.* **2012**, *14*, 547−564. (b) Ryland, B. L.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2014**, *53*, 8824−8838. (c) Shi, Z. Z.; Zhang, C.; Tang, C. H.; Jiao, N. *Chem. Soc. Rev.* **2012**, *41*, 3381−3430. (d) Allen, S. E.; Walvoord, R. R.; Padilla-Salinas, R.; Kozlowski, M. C. *Chem. Rev.* **2013**, *113*, 6234−6458. (e) Cao, Q.; Dornan, L. M.; Rogan, L.; Hughes, N. L.; Muldoon, M. J. *Chem. Commun.* **2014**, *50*, 4524−4543.

(4) For a representative Cu/TEMPO catalyst system, see: (a) Semmelhack, M. F.; Schmid, C. R.; Cortés, D. A.; Chou, C. S. *J. Am. Chem. Soc.* **1984**, *106*, 3374−3376. (b) Gamez, P.; Arends, I. W. C. E.; Reedijk, J.; Sheldon, R. A. *Chem. Commun.* **2003**, 2414−2415. (c) Jiang, N.; Ragauskas, A. J. *J. Org. Chem.* **2006**, *71*, 7087−7090. (d) Kumpulainen, E. T. T.; Koskinen, A. M. P. *Chem. - Eur. J.* **2009**, *15*, 10901−10911. (e) Hoover, J. M.; Stahl, S. S. *J. Am. Chem. Soc.* **2011**, *133*, 16901−16910 and references cited therein. (f) Hoover, J. M.; Ryland, B. L.; Stahl, S. S. *J. Am. Chem. Soc.* **2013**, *135*, 2357−2367. (g) Zhang, G. F.; Han, X. W.; Luan, Y. X.; Wang, Y.; Wen, X.; Ding, C. R. *Chem. Commun.* **2013**, *49*, 7908−7910. (h) Sasano, Y.; Nagasawa, S.; Yamazaki, M.; Shibuya, M.; Park, J.; Iwabuchi, Y. *Angew. Chem., Int. Ed.* **2014**, *53*, 3236−3240.

(5) Copper/dialkyl azodicarboxylate catalyst systems; primary references: (a) Markó, I. E.; Giles, P. R.; Tsukazaki, M.; Brown, S. M.; Urch, C. J. *Science* **1996**, *274*, 2044−2046. (b) Markó, I. E.; Tsukazaki, M.; Giles, P. R.; Brown, S. M.; Urch, C. J. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2208−2210. (c) Markó, I. E.; Gautier, A. *J. Org. Chem.* **1998**, *63*, 7576−7577. (d) Markó, I. E.; Gautier, A.; Mutonkole, J.-L.; Dumeunier, R.; Ates, A.; Urch, C. J.; Brown, S. M. *J. Organomet. Chem.* **2001**, *624*, 344−347. (e) Markó, I. E.; Gautier, A.; Dumeunier, R.; Doda, K.; Philippart, F.; Brown, S. M.; Urch, C. J. *Angew. Chem., Int. Ed.* **2004**, *43*, 1588−1591.

(6) Other more recent references: Xu, B.; Lumb, J. P.; Arndtsen, B. A. *Angew. Chem., Int. Ed.* **2015**, *54*, 4208−4211.

(7) (a) Iwahama, T.; Yoshino, Y.; Keitoku, T.; Sakaguchi, S.; Ishii, Y. *J. Org. Chem.* **2000**, *65*, 6502−6507. (b) Sharma, V. B.; Jain, S. L.; Sain, B. *Tetrahedron Lett.* **2003**, *44*, 383−386.

(8) (a) Wang, N.; Liu, R.; Chen, J.; Liang, X. *Chem. Commun.* **2005**, 5322−5324. (b) Dressen, M. H. C. L.; Stumpel, J. E.; van de Kruijs, B. H. P.; Meuldijk, J.; Vekemans, J. A. J. M.; Hulshof, L. A. *Green Chem.* **2009**, *11*, 60−64. (c) Yin, W.; Chu, C.; Lu, Q.; Tao, J.; Liang, X.; Liu, R. *Adv. Synth. Catal.* **2010**, *352*, 113−118. (d) Ma, S. M.; Liu, J. X.; Li, S. H.; Chen, B.; Cheng, J. J.; Kuang, J. Q.; Liu, Y.; Wan, B. Q.; Wang, Y. L.; Ye, J. T.; Yu, Q.; Yuan, W. M.; Yu, S. C. *Adv. Synth. Catal.* **2011**, *353*, 1005−1017. (e) Wang, L. Y.; Li, J.; Zhao, X. P.; Lv, Y.; Zhang, H. Y.; Gao, S. *Tetrahedron* **2013**, *69*, 6041−6045 and references cited therein. (f) Song, H.; Kang, B.; Hong, S. H. *ACS Catal.* **2014**, *4*, 2889−2895.

(9) (a) Kirihara, M.; Ochiai, Y.; Takizawa, S.; Takahata, H.; Nemoto, H. *Chem. Commun.* **1999**, 1387−1388. (b) Maeda, Y.; Kakiuchi, N.; Matsumura, S.; Nishimura, T.; Kawamura, T.; Uemura, S. *J. Org. Chem.* **2002**, *67*, 6718−6724. (c) Velusamy, S.; Punniyamurthy, T. *Org. Lett.* **2004**, *6*, 217−219. (d) Jiang, N.; Ragauskas, A. J. *J. Org. Chem.* **2007**, *72*, 7030−7033. (e) Du, Z. T.; Miao, H.; Ma, H.; Sun, Z. Q.; Ma, J.; Xu, J. *Adv. Synth. Catal.* **2009**, *351*, 558−562. (f) Hanson, S. K.; Wu, R.; Silks, L. A. *Org. Lett.* **2011**, *13*, 1908−1911.

(10) (a) Bolm, C.; Legros, J.; Le Paih, J.; Zani, L. *Chem. Rev.* **2004**, *104*, 6217−6254. (b) Sherry, B. D.; Fürstner, A. *Acc. Chem. Res.* **2008**, *41*, 1500−1511. (c) Correa, A.; Mancheño, O. G.; Bolm, C. *Chem. Soc. Rev.* **2008**, *37*, 1108−1117. (d) Enthaler, S.; Junge, K.; Beller, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 3317−3321. (e) Bauer, I.; Knölker, H. J. *Chem. Rev.* **2015**, *115*, 3170−3387.

(11) For leading references based on Cu/TEMPO systems, see ref 4b,d,e. For copper/ dialkylazodicarboxylate systems: see ref 5e. For other Cu systems, see ref 6. For Pd systems, see: (a) Brink, G. J.; Arends, I. W. C. E.; Sheldon, R. A. *Science* **2000**, *287*, 1636−1639. (b) Kakiuchi, N.; Maeda, Y.; Nishimura, T.; Uemura, S. *J. Org. Chem.* **2001**, *66*, 6620−6625. (c) Schultz, M. J.; Park, C. C.; Sigman, S. M. *Chem. Commun.* **2002**, 3034−3035.

(12) For representative reviews, see: (a) Sheldon, R. A.; Arends, I. W. C. E.; ten Brink, G.-J.; Dijksman, A. *Acc. Chem. Res.* **2002**, *35*, 774−781. (b) Sheldon, R. A.; Arends, I. W. C. E. *Adv. Synth. Catal.* **2004**, *346*, 1051−1071. (c) Tebben, L.; Studer, A. *Angew. Chem., Int. Ed.* **2011**, *50*, 5034−5068. (d) Wertz, S.; Studer, A. *Green Chem.* **2013**, *15*, 3116−3134. (e) Ryland, B. L.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2014**, *53*, 8824−8838.

(13) Wang, Q.; Sheng, X.; Horner, J. H.; Newcomb, M. *J. Am. Chem. Soc.* **2009**, *131*, 10629−10636.

(14) Klomp, D.; Maschmeyer, T.; Hanefeld, U.; Peters, J. A. *Chem. - Eur. J.* **2004**, *10*, 2088−2093.

(15) Shibuya, M.; Tomizawa, M.; Sasano, Y.; Iwabuchi, Y. *J. Org. Chem.* **2009**, *74*, 4619−4622.

(16) Lauber, M. B.; Stahl, S. S. *ACS Catal.* **2013**, *3*, 2612−2616.

(17) Katritzky, A. R.; Le, K. N. B.; Khelashvili, L.; Mohapatra, P. P. *J. Org. Chem.* **2006**, *71*, 9861−9864.