Article

JOURNAL OF THE CHINESE
CHEMICAL SOCIETY

The Aerobic Oxidation and C=C Bond Cleavage of Styrenes Catalyzed by Cerium(IV) Ammonium Nitrate (CAN)

Lei Yu,[a]* Yaping Huang,[a] Zengbing Bai,[a] Bingchun Zhu,[b] Kehong Ding,[a] Tian Chen,[a]
Yuanhua Ding[a] and Yuguang Wang[a,b]*
[a]*Jiangsu Co-innovation Center for Prevention and Control of Important Animal Infectious Diseases and Zoonoses, School of Chemistry and Chemical Engineering, Yangzhou University, Yangzhou, 225002, P. R. China*
[b]*College of Biological and Environmental Engineering, Zhejiang University of Technology, Hangzhou, 310014, P. R. China*

(Received: Oct. 3, 2014; Accepted: Apr. 27, 2015; Published Online: May 19, 2015; DOI: 10.1002/jccs.201400421)

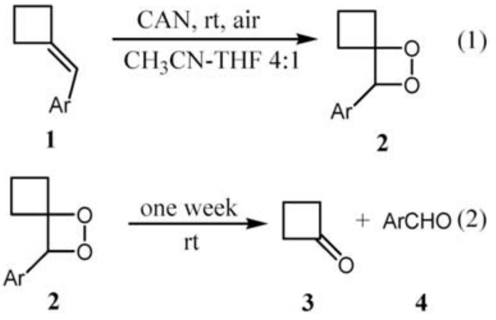
The CAN-catalyzed aerobic oxidation severed the C=C bond selectively through the single electron transfer mechanism, giving a green method to decompose olefins. Compared with the literature reported examples, this method required simple catalyst, cheap, abundant and clean oxidant and was very safe to operate due to the mild conditions.

Keywords: Aerobic oxidation; Single electron transfer (SET); Green chemistry.

INTRODUCTION

Due to the wide applications in organic synthesis and environment protection, oxidative cleavage of carbon-carbon bond is one of the most important topics in organic methodology research and has attracted chemists' attentions much for a long time.[1] In the past 10 years, a plenty of novel reactions involving carbon-carbon bond cleavage have been reported, providing a series of convenient accesses to many useful and complex compounds.[2] However, many of these reactions require ozone that consumes large amount of electric energy or chemical oxidants that bring waste after the reaction. Moreover, expensive or complex catalysts were always employed in high loadings and special factors on substrates were also required, such as the release of strain energy, the chelation assistance and the functional fragment as the leaving group (*e.g.* carbonyls, nitriles, carboxylic acids *et al.*). Therefore, developing novel cheap and clean technologies to sever the simple carbon-carbon bond selectively without any cooperated factors still remains a tremendous challenge. For a long time, our group aimed to develop novel green synthetic methodologies.[3-5] During our continuous investigations on oxidation, we preferred to use cheap, abundant and clean oxidant, such as oxygen and hydrogen peroxide.[4-5] Recently, we have reported a novel cerium(IV) ammonium nitrate (CAN)-catalyzed aerobic oxidation of alkylenecyclobutanes (ACBs), which could generate the interesting products spirocyclobutyl-1,2-dioxethanes **2** (Scheme 1, eq. 1).[5] However, unfortunately, compounds **2** were not stable enough to be kept. After one week's storage, they might decompose to cyclobutanone **3** and aldehydes **4**, which could be observed from NMR and IR spectrums obviously (Scheme 1, eq. 2). As a neat result, this CAN-catalyzed aerobic oxidation and the following decomposition severed the C=C bond of olefins directly with high atom economic without waste. The result showed the possibility to severe the C=C bond of simple olefins with air, which is abundant, cheap and clean oxidant and intrigued our further investigations. Herein, we wish to report our recent findings on the CAN-catalyzed aerobic oxidative cleavage of C=C bond of styrenes.

Scheme 1



RESULTS AND DISCUSSION

We initially chose stryrene 1a as the model compound and heated it in THF in the presence of 3 mol% of CAN. After 24 h, the mixture was sent to gas chromatogram (GC)

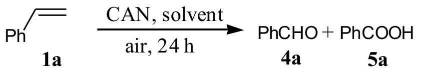
---

* Corresponding author. Email: yulei@yzu.edu.cn; yuguangw@zjut.edu.cn

for analysis. The comparisons with internal standard curve (biphenyl as internal standard) disclosed that products benzenealdehyde 4a and benzoic acid 5a were generated in 46% total yield with the molar ratio 54/46 (Table 1, entry 1). Further screening demonstrate that 1,4-dioxane should be a better solvent (Table 1, entries 2-6) and the yield could be enhanced to 64% yield (Table 1, entry 6). With 1,4-dioxane as solvent, experiments employing different dosages of CAN were examined. Results in Table 1, entries 6-10 showed that 5 mol% of CAN should be the better condition and the yield of 4a and 5a could be enhanced to 83% with the molar ratio 74/26 (Table 1, entry 8).

With the optimized conditions in hand, a series of olefins 1 were employed as substrates. In the presences of 5 mol% CAN, they were heated at 80 °C in 1,4-dioxane with air. The results were summarized in Table 2. For substituted styrenes, the results were generally good and the oxidation product aldehydes and carboxylic acids were obtained in

Table 1. Optimization of the CAN catalyzed aerobic oxidation of styrene[a]



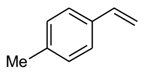
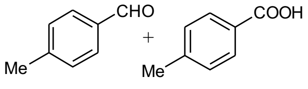
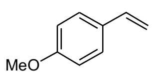
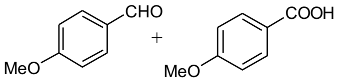
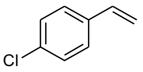
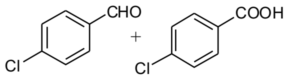
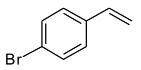
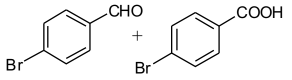
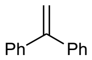
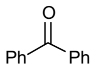
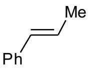
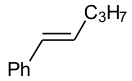
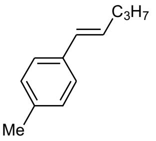
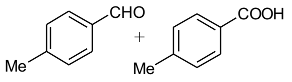
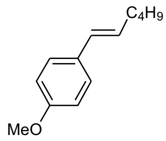
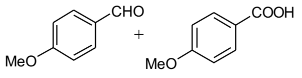
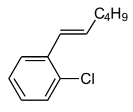
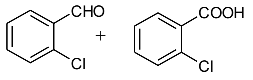
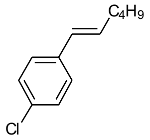
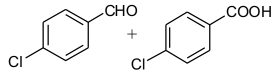
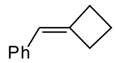
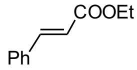
1a **4a** **5a**

Entry	CAN/%	Solvent, T/°C	Yield/%(**4a/5a**)[b]
1	3	THF/60	46 (54/46)
2	3	MeCN/80	3 (100/0)
3	3	Cyclohexane/80	0 (-)
4	3	Toluene/110	32 (84/16)
5	3	EtOH/78	5 (80/20)
6	3	1,4-Dioxane/80	64 (66/34)
7	1	1,4-Dioxane/80	61 (61/39)
8	5	1,4-Dioxane/80	83 (77/23)
9	10	1,4-Dioxane/80	73 (74/26)
10	20	1,4-Dioxane/80	56 (80/20)

[a] 1 mmol of styrene 2 mL of solvent were employed; The amount of CAN was based on styrene. [b] GC yield with biphenyl as internal standard.

Table 2. The aerobic oxidations of olefins catalyzed by CAN[a]

$$\mathbf{1} \xrightarrow[\text{1,4-dioxane, 80 °C, air, 24 h}]{\text{5 mol \% CAN}} \underset{\mathbf{4}}{\text{RCHO}} + \underset{\mathbf{5}}{\text{RCOOH}}$$

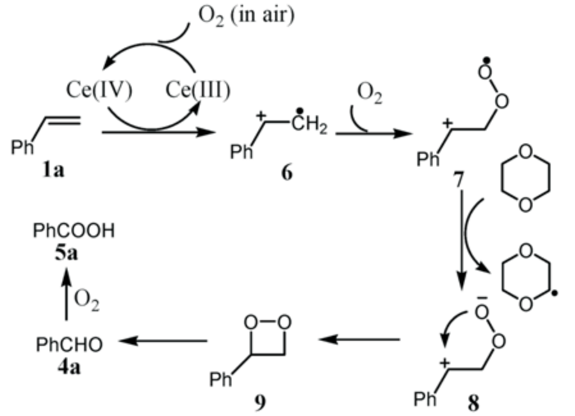
Entry	**1**[b]	Productsyield / %(**4a/5a**)[c]
1	 (**1b**)	 (**4b**, **5b**) 70(75/25)
2	 (**1c**)	 (**4c**, **5c**) 58(71/29)
3	 (**1d**)	 (**4d**, **5d**) 78(80/20)
4	 (**1e**)	 (**4e**, **5e**) 72 (76/24)
5	 (**1f**, 42%)	 (**4f**), 47%[c]
6	 (**1g**)	PhCHO/PhCOOH (**4a**, **5a**) 66% (70/30)
7	 (**1h**)	PhCHO/PhCOOH (**4a**, **5a**) 64% (66/34)
8	 (**1i**)	 (**4b**, **5b**) 63% (80/20)
9	 (**1j**)	 (**4c**, **5c**) 73% (78/22)
10	 (**1k**)	 (**4g**, **5g**) 56% (83/17)
11	 (**1l**)	 (**4d**, **5d**) 72% (80/20)
12	 (**1m**)	PhCHO/PhCOOH (**4a**, **5a**) 57% (78/22)
13	 (**1n**, 65%)	PhCHO/PhCOOH (**4a**, **5a**) 24% (62/38)[d]

[a] Reaction conditions see Table 1, entry 8; [b] Recovered yields of **1** in parentheses; [c] Isolated yields, compounds identity was confirmed by comparison with co-injection with authentic samples and melting point with literature.

moderate yields with aldehydes as the major product (Table 2, entries 1-4). Generally, the yields and selectivities of aldehydes from styrenes with electron withdrawing groups were higher than that from the styrenes with electron donation groups, probably due to the lower reactivity of substrates (entries 3,4 VS 1,2). Styrenes with electron donation groups were more activated, resulting in the generation of unidentified by-products, especially for 4-methoxylstyrene 1c (Table 1, entry 2). We also tried to oxidize the 1,1-disubstituted styrenes such as 1f, but it was quite stable and after 24 h, only 47% of the product 4f was obtained while 42% of 1f was recovered (Table 1, entry 5). Then, 1,2-disubstituted olefins were also tested, giving aldehydes and carboxylic acids in moderate yields (Table 1, entries 6-11). When *othor*-substituted olefin 1k was employed, the product yield decreased while the aldehyde selectivity was enhanced, probably due to the decelerated reaction speed (Table 1, entry 10). Under the above conditions, ACB 1m could also be oxidized to benzyl aldehyde and benzoic acid in moderate yield (Table 1, entry 12) while in our previous works, it was oxidized to spirocyclobutyl-1,2-dioxethanes 2 at room temperature.[5] The electron deficient styrene 1n was also tested, but gave very low product yield and most of the starting material could be recovered (Table 1, entry 13).

On the basis of our previous experiments as well as the literature,[5] we supposed the possible mechanism (Scheme 2). Take styrene 1a for example, it was initially oxidized by CAN and generated the intermediate free radical cation 6,[5-6] which was further oxidized by O_2 (in air) and afforded the intermediate 7.[5] Capturing a proton from the solvent 1,4-dioxane, 7 was transformed to 8,[7] which soon led to 9 through the intramolecular cyclization.[8-9] Compounds 9 was unstable and decomposed to aldehyde 4a under heat.

Scheme 2



CONCLUSIONS

In conclusion, CAN catalyzed aerobic oxidation of olefins provided a clean method to severe the C=C double bond. The oxidant air is cheaper, cleaner and safer than other oxidant such as hydrogen peroxide, ozone or pure oxygen. The catalyst loading of this reaction was low and only 5 mol% of CAN was required. Deeper investigations on the Ce-catalyzed aerobic oxidations of organic compounds are on the way in our laboratory.

EXPERIMENTAL

General Methods: All of the metal salts and solvents were purchased from reagent merchant and were analytical grade pure. The olefins were synthesized through know methodologies[10-11] or purchased from reagent merchant. The purchased styrenes may contain stabilizer hydroquinone that hinders the free radical reactions. Therefore, they should be purified by distillation or column chromatography before use. The gas chromatography for the analysis of the reaction products used a capillary DB1701 column and a FID. The oven temperature was programmed at 70-260 °C (heating rate 30 °C/min). Melting points were measured by WRS-2A digital melting point instrument.

General Procedure for Oxidation of Olefins: To a reaction tube, 1 mmol of olefin 1, 0.05 mmol $(NH_4)_2Ce(NO_3)_6$ and 2 mL of 1,4-dioxane were added. Then, air was slowly introduced with a tiny glass tunnel. The liquid was heated kept 80 °C for 24 h. Then, solvent was distilled under vacuum and the residue was purified by column chromatography to give the corresponding 4 and 5. The products were identified by comparison with co-injection with authentic samples and melting point with literature (Table 3).

Table 3. Comparison of melting points of products with literature

Entry	Compd.	m. p./°C	*Lit.* m. p./°C	*Lit.*
1	**5a**	122.0-122.3	122-122.5	12a
2	**5b**	180.1-180.9	180-181	12b
3	**5c**	180.8-182.1	181-183	12c
4	**4d**	46.1-47.8	47	12d
5	**5d**	237.8-238.9	238-240	12e
6	**4e**	56.7-57.5	57	12f
7	**5e**	251.5-252.8	252-253	12g
8	**4f**	45.6-47.2	47.7	12h
9	**5g**	137.2-138.4	138-138.5	12i

ACKNOWLEDGEMENTS

We thank National Science Foundation of China (21202141, 21202151, 21173182), Yangzhou Nature Science Foundation (YZ2014040) and the Priority Academic Program Development of Jiangsu Higher Education Institutions for financial support. We also thank the analysis centre of Yangzhou University for assistance.

REFERENCES

1. (a) Larock, R. C. *Comprehensive Organic Transformations*, 2nd ed.; Wiley-VCH: New York, 1999; p 1234. (b) Lee, D. G.; Chen, T. In *Comprehensive Organic Synthesis*; Trost, B. M.; Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. 7, p 541. (c) Hudlicky, M. *Oxidations in Organic Chemistry*; American Chemical Society Monograph 186; American Chemical Society: Washington D.C., 1990. (d) Sheldon, R. A.; Kochi, J. K. *Metal Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981. (e) Stewart, R. In *Oxidation in Organic Chemistry*; Wiberg, K., Ed.; Academic Press: New York, 1965.
2. (a) Pal, B. *Int. J. Chem. Kinet.* **2014**, *46*, 31-40. (b) Nelson, A. C.; Kalinowski, E. S.; Czerniecki, N. J.; Jacobson, T. L.; Grundt, P. *Org. Biomol. Chem.* **2013**, *11*, 7455-7457. (c) Willand-Charnley, R.; Fisher, T. J.; Johnson, B. M.; Dussault, P. H. *Org. Lett.* **2012**, *14*, 2242-2245. (d) Dhakshinamoorthy, A.; Alvaro, M.; Garcia, H. *ACS Catal.* **2011**, *1*, 836-840. (e) O'Brien, M.; Baxendale, I. R.; Ley, S. V. *Org. Lett.* **2010**, *12*, 1596-1598. (f) Wang, A.; Jiang, H. *J. Org. Chem.* **2010**, *75*, 2321-2326. (g) Thottumkara, P. P.; Vinod, T. K. *Org. Lett.* **2010**, *12*, 5640-5643. (h) Miyamoto, K.; Sei, Y.; Yamaguchi, K.; Ochiai, M. *J. Am.Chem. Soc.* **2009**, *131*, 1382. (i) Singh, F. V.; Milagre, H. M. S.; Eberlin, M. N.; Stefani, H. A. *Tetrahedron Lett.* **2009**, *50*, 2312-2316. (j) Schiaffo, C. E.; Dussault, P. H. *J. Org. Chem.* **2008**, *73*, 4688-4690. (k) Biradar, A. V.; Sathe, B. R.; Umbarkar, S. B.; Dongare, M. K. *J. Mol. Catal. A: Chem.* **2008**, *285*, 111-119. (l) Neisius, N. M.; Plietker, B. *J. Org. Chem.* **2008**, *73*, 3218-3227. (m) Liu, S.-T.; Reddy, K.; Venugopal; Lai, R.-Y. *Tetrahedron* **2007**, *63*, 1821-1825. (n) Xing, D.; Guan, B.; Cai, G.; Fang, Z.; Yang, L.; Shi, Z.-J. *Org. Lett.* **2006**, *8*, 693-696.
3. For recent articles, please see: (a) Zhang, K.; Wang, H.; Zheng, J.-F.; Yu, L.; Ding, H.-F. *Chem. Commun.* **2015**, *51*, 6399-6402. (b) Xu, L.; Huang, J.-J.; Liu, Y.-B.; Wang, Y.-N.; Xu, B.-L.; Ding, K.-H.; Ding, Y.-H.; Xu, Q.; Yu, L.; Fan, Y.-N. *RSC Adv.* **2015**, *5*, ASAP, DOI: 10.1039/C5RA05741H. (c) Xu, Q.; Xie, H.-M.; Chen, P.-L.; Yu, L.; Chen, J.-H.; Hu, X.-G. *Green Chem.* **2015**, *17*, ASAP, DOI: 10.1039/C5GC00284B. (d) Jia, X.-J.; Yu, L.; Liu, J.-P.; Xu, Q.; Sickert, M.; Chen, L.-H.; Lautens, M. *Green Chem.* **2014**, *16*, 3444-3449. (e) Chen, H.-N.; Dai, W.-J.; Chen, Y.; Xu, Q.; Chen, J.-H.; Yu, L.; Zhao, Y.-J.; Ye, M.-D.; Pan, Y.-J. *Green Chem.* **2014**, *16*, 2136-2141. (f) Yu, L.; Wang, J.; Zhang, X.; Cao, H.-E.; Wang, G.-L.; Ding, K.-H.; Xu, Q.; Lautens, M. *RSC Adv.* **2014**, *4*, 19122-19126. (g) Wang, Y.-G.; Zhu, B.-C.; Xu, Q.; Zhu, Q.; Yu, L. *RSC Adv.* **2014**, *4*, 49170-49179. (h) Yu, L.; Wu, Y.-L.; Chen, T.; Pan, Y.; Xu, Q. *Org. Lett.* **2013**, *15*, 144-147. (i) Yu, L. *Mini-Rev. Med. Chem.* **2013**, *13*, 783. (j) Fan, L.; Yi, R.; Yu, L.; Wu, Y.-L.; Chen, T.; Guo, R. *Catal. Sci. Techno.* **2012**, *2*, 1136-1139.
4. (a) Zhang, X.; Ye, J.-Q.; Yu, L.; Shi, X.-K.; Zhang, M.; Xu, Q. *Adv. Synth. Catal.* **2015**, *357*, 955-960. (b) Yu, L.; Wu, Y.-L.; Cao, H.-E.; Zhang, X.; Shi, X.-K.; Luan, J.; Chen, T.; Pan, Y.; Xu, Q. *Green Chem.* **2014**, *16*, 287-293. (c) Yu, L.; Li, H.-Y.; Zhang, X.; Ye, J.-Q.; Liu, J.-P.; Xu, Q.; Lautens, M. *Org. Lett.* **2014**, *16*, 1346-1349. (d) Yu, L.; Wang, J.; Chen, T.; Wang, Y.-G.; Xu, Q. *Appl. Organometal. Chem.* **2014**, *28*, 652-656. (e) Yu, L.; Wang, J.; Chen, T.; Ding, K.-H.; Pan, Y. *Chin. J. Org. Chem.* **2013**, *33*, 1096-1099. (f) Zhang, X.; Yi, R.; Chen, T.; Ni, S.-C.; Wang, G.-L.; Yu, L. *Sci. J. Front. Chem. Dev.* **2013**, *3*, 25-29.
5. Yu, L.; Ren, L.-F.; Rong, Y.; Guo, R. *Synth. Commun.* **2011**, *41*, 2530-2538.
6. Nair, V.; Suja, T. D.; Mohanan, K. *Synthesis* **2006**, 2531-2534.
7. Cheng, K.; Huang, L.-H.; Zhang, Y.-H. *Org. Lett.* **2009**, *11*, 2908-2911.
8. Nair, V.; Balagopal, L.; Rajan, R.; Mathew, J. *Acc. Chem. Res.* **2004**, *37*, 21-30.
9. Rossle, M.; Wermer, T.; Frey, W.; Christoffers, J. *Eur. J. Org. Chem.* **2005**, 5031-5038.
10. Yu, L.; Ren, L.-F.; Yi, R.; Wu, Y.-L.; Chen, T.; Guo, R. *Synlett* **2011**, 579-581.
11. Fan, L.; Ren, L.-F.; Chen, T.; Yi, R.; Yu, L. *Chin. J. Org. Chem.* **2012**, *32*, 1439-1444.
12. (a) Bonner, W. A. *J. Am. Chem. Soc.* **1954**, *76*, 6350-6353. (b) Berger, P.; Bessmernykh, A.; Caille, J.-C.; Mignonac, S. *Synthesis* **2006**, 3106-3110. (c) Huang, Z.-Z.; Zhou, X.-J. *Synthesis* **1989**, 693-694. (d) Kim, M. S.; Choi, Y. M.; An, D. K. *Tetrahedron Lett.* **2007**, *48*, 5061-5064. (e) Menegheli, P.; Rezende, M. C.; Zucco, C. *Synth. Commun.* **1987**, *17*, 457-464. (f) Suzuki, T.; Morita, K.; Tsuchida, M.; Hiroi, K. *J. Org. Chem.* **2003**, *68*, 1601-1602. (g) Nagira, K.; Kikukawa, K.; Wada, F.; Matsuda, T. *J. Org. Chem.* **1980**, *45*, 2365-2368. (h) Lee, H. H.; Warner, J. C. *J. Am. Chem. Soc.* **1933**, *55*, 209-214. (i) Kaslow, C. E.; Summers, R. M. *J. Org. Chem.* **1955**, *20*, 1738-1742.