

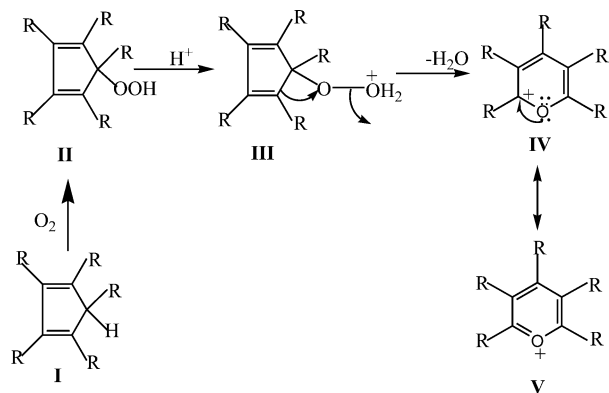
A Facile Oxidation and Oxygen Insertion of the Cyclopentadiene Ring by Molecular Oxygen in Solution

Wei-Tao Gong, Gui-Ling Ning,* Xin-Cheng Li,
Li Wang, and Yuan Lin

State Key Laboratory of Fine Chemicals, Dalian University
of Technology, Dalian 116012, P. R. China

ninggl@dlut.edu.cn

Received April 10, 2005



Oxidation of substituted cyclopentadienes by molecular oxygen afforded the corresponding pyrylium cations in acidic solution, whereby an oxygen atom was inserted into the cyclopentadiene ring. This novel one-step reaction proceeds in a different yield depending on substitution patterns of the cyclopentadiene. A possible reaction pathway and formation mechanism of the pyrylium cation are proposed and discussed.

Since the discovery of ferrocene in which a cyclopentadiene ring is bonded to a transition metal,¹ the cyclopentadiene ring and/or cyclopentadienyl system have enjoyed unabated research interest for more than half a century in organic chemistry and the other research fields,^{1–6} owing to the structure feature and application potentials of these cyclopentadiene derivatives.^{5–9} Some

* To whom correspondence should be addressed.

(1) (a) Kealy, T. J.; Pauson, P. L. *Nature* **1951**, *168*, 1039. (b) Miller, S. A.; Tebboth, J. A.; Tremaine, J. F. *J. Chem. Soc.* **1952**, 632.

(2) Wilkinson, G.; Stone, F. G.; Abel, E. W. *Comprehensive Organometallic Chemistry*; Pergamon: Oxford, 1982; Vols. 3–7.

(3) (a) Coville, N. J.; Du Plooy, K.; Pickl, W. *Coord. Chem. Rev.* **1992**, *116*, 1. (b) Siemeling, U. *Chem. Rev.* **2000**, *100*, 1495.

(4) Butenschön, H. *Chem. Rev.* **2000**, *100*, 1527.

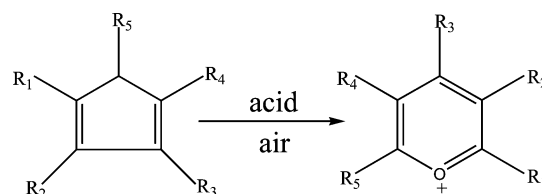
(5) (a) Allen, A. D.; Tidwell, T. T. *Chem. Rev.* **2001**, *101*, 1333. (b) Allen, A. D.; Tidwell, T. T. *J. Org. Chem.* **2001**, *66*, 7696. (c) Nair, V.; Menon, R. S.; Beneesh, P. B.; Sreekumar, V.; Bindu, S. *Org. Lett.* **2004**, *6*, 767.

(6) (a) Gutnov, A.; Heller, B.; Drexler, H.-J.; Spannenberg, A.; Oehme, G. *Organometallics* **2003**, *22*, 1550. (b) Beachley, O. T., Jr.; MacRae, D. J.; Churchill, M. R.; Kovalevsky, A. Y.; Robirds, E. S. *Organometallics* **2003**, *22*, 3991.

(7) Dyker, J.; Heiermann, J.; Miura, M. *Adv. Synth. Catal.* **2003**, *345*, 1127.

(8) Ouchi, M.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2001**, *34*, 3176.

SCHEME 1



1: ($R_1=R_3=R_4=Ph$, $R_2=R_5=H$)

2: ($R_1=R_2=R_3=R_4=Ph$, $R_5=H$)

3: ($R_1=R_2=R_3=R_4=R_5=Ph$)

4: ($R_1=R_2=R_3=R_4=R_5=CH_3$)

typical reaction patterns have been revealed and widely investigated, including the coordination toward metal ions,^{3,4,10} formation of cyclopentadienyl cations, anions, and radicals,^{4,5} rearrangement of cyclopentadiene ring,⁶ and substitution/diene-addition reactions.^{6,7} In almost all of these cases the cyclopentadiene moiety retains its five-membered ring throughout various reaction processes. By comparison, we have reported a novel silver(I)-promoted oxygen-insertion reaction of phenylated cyclopentadienes, in which the five-membered cyclopentadiene ring is oxidized to generate a six-membered pyrylium ring by silver (I) ion.¹¹ Recently, the use of molecular oxygen as terminal oxidant has received considerable attention for both economic and environmental benefits.¹² With the aim to examine whether molecular oxygen can be used in place of silver(I) ion in the cyclopentadiene ring oxidation and to investigate the scope and limitations of this synthetic method, we have targeted several substituted cyclopentadienes, including phenylated and methylated ones. Herein we report the oxidation process and propose a possible mechanism.

Treatment of substituted cyclopentadienes in a mixed solvent of toluene/acetonitrile in the presence of air and perchloric acid afforded the corresponding pyrylium cations (Scheme 1) in which the cyclopentadiene ring underwent an oxidation and oxygen-insertion reaction. The selected substrates and reaction results are summarized in Table 1.

It is noted that this one-step reaction proceeds in different yields and rates, depending on the substitution patterns of cyclopentadiene ring. For the substrate having at least one abstractable hydrogen atom (Table 1, entries 1–4), the reaction is efficient and nearly quantitative, whereas for that having no abstractable hydrogen (Table 1, entry 5), the reaction seems impossible


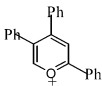

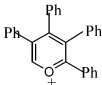

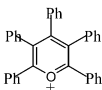
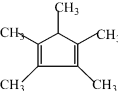
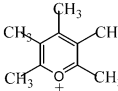

(9) Leach, A. G.; Goldstein, E.; Houk, K. N. *J. Am. Chem. Soc.* **2003**, *125*, 8330.

(10) Deck, P. A.; Konate, M. M.; Kelly, B. V.; Slobodnick, C. *Organometallics* **2004**, *23*, 1089.

(11) Ning, G. L.; Li, X. C.; Munakata, M.; Gong W. T. Maekawa, M.; Kamikawa, T. *J. Org. Chem.* **2004**, *69*, 1432.

(12) (a) Liu, R.; Liang, X.; Dong, C.; Hu, X. *J. Am. Chem. Soc.* **2004**, *126*, 4112. (b) Kamata, K.; Kasai, J.; Yamaguchi, K.; Mizuno, N. *Org. Lett.* **2004**, *6*, 3577. (c) Simadi, L. I., Ed. *Dioxygen Activation and Homogeneous Catalytic Oxidation*; Elsevier: New York, 1991.

TABLE 1. Oxidation of Substituted Cyclopentadienes

Entry ^a	Substrate	time [h]	product	yield ^b [%]
1		6		82
2		3		81
3		8		93
4		4		94
5		72	no pyrylium salt	0

^a All reactions were performed on a 0.5 mmol scale for substrates with 2 equiv of HClO₄ in a mixed solvent of toluene/ acetonitrile (40 mL/2 mL). ^b Isolated yields.

because no pyrylium salt was isolated. This indicates that the abstractable hydrogen of the cyclopentadiene ring plays a key role for the ring oxidation and/or pyrylium formation. Furthermore, by changing the substrate from pentaphenylcyclopentadiene to pentamethylcyclopentadiene, the reaction time, to a similar reaction extent, is reduced by 50% from 8 to 4 h (Table 1, entries 3 and 4), implying the steric hindrance. On the other hand, the pyrylium salts with five substituents displayed a better yield than those with less than five, probably due to the partly occupied active orbital of allylic (abstractable) hydrogen, which changed the reaction selectivity.

A detailed investigation revealed that the reaction in Scheme 1 is oxygen- and acid-dependent. By using standard Schlenk techniques under N₂ atmosphere, we failed to obtain any oxidized products, whereas the bubbling of O₂ into the solution makes the oxidation process much faster. On the other hand, the addition of acid into the solution leads to oxidation. It is proved that in the absence of acid these substituted cyclopentadienes fail to react, even over the course of 7 days. Nevertheless, some other acids such as H₂SO₄, HCOOH, and typical Lewis acid AlCl₃ can also promote oxidation, but in lower yields.

In contrast to the silver(I)-promoted system, where water is the source of pyrylium oxygen, the reaction in Scheme 1 is independent of water. With freshly dried starting materials, such as, dried triphenylcyclopentadiene, anhydrous perchloric acid,¹³ dried solvents, and dried air, the pyrylium salt **1** could be readily isolated. This suggests that the molecular oxygen is incorporated in the ring.

The most striking feature of this study is the acid-assisted autoxidation and oxygen-insertion of cyclopentadiene ring.

As documented in the literature,¹⁴ molecular oxygen can exist in its normal triplet state (³O₂) and more reactive singlet (¹O₂). The singlet oxygen (¹O₂) was generally produced by photoirradiation,¹⁵ and in the dark, there would appear to be no way in which ¹O₂ could be generated in solution despite the existence of acid.¹⁶ On the other hand, the reactivity of ³O₂ toward most organic molecules is inhibited by the spin barrier.¹⁷ In particular, the autoxidation (oxidation from ³O₂) of cyclic conjugated dienes is a seldom-observed reaction because of the spin restriction between triplet oxygen and these singlet molecules.¹⁷ Interestingly, the reaction in Scheme 1 can proceed normally in the dark at room temperature although it can be catalyzed by light, indicating an autoxidation process.¹⁸ Such a phenomenon has not been reported before. There are only two references in the literature describing an oxidation of naphthalene and ergosteryl acetate by ³O₂ forming the peroxide and/or endoperoxide compounds.¹⁹

In addition, it is worth mentioning that in organic synthesis the autoxidation of hydrocarbons has not become a synthetic tool due to the complexity of the peroxides formed.²⁰ This study presents a facile and economical approach to synthesize substituted pyrylium salts, including those without substituents on the α position, which could not be synthesized readily by traditional method.²¹ As mentioned in the literature,²² pyrylium salts have opened up broad prospects in practical applications including Q-switchers, laser dyes, organic luminophores, secondary nonaqueous-electrolyte battery and the like. The current synthetic strategy exhibits a reasonable potential for preparing some novel functional pyrylium derivatives due to the active α-position.²³

In contrast to the silver(I)-promoted oxidation system,¹¹ a possible mechanism to account for the current oxidation process can be proposed as shown in Scheme 2. First, the allylic hydrogen in **I** undergoes an autoxidation reaction forming hydroperoxide **II** because the bis-allylic hydrogen

(14) (a) Schweitzer, C.; Schmidt, R. *Chem. Rev.* **2003**, *103*, 1685. (b) Cordova, A.; Sundén, H.; Engqvist, M.; Ibrahim, I.; Casas, J. *J. Am. Chem. Soc.* **2004**, *126*, 8914.

(15) (a) Zhang, D.; Wu, L. Z.; Yang, Q. Z.; Li, X. H.; Zhang, L. P.; Tung, C. H. *Org. Lett.* **2003**, *5*, 3221. (b) Suzuki, M.; Bartels, O.; Gerdes, R.; Schneider, G.; Wohrle, D. *Phys. Chem. Chem. Phys.* **2000**, *2*, 109.

(16) Barton, D. H. R.; Haynes, R. K.; Leclerc, G.; Magnus, P. D.; Menzies, D. *J. Chem. Soc., Perkin Trans. 1* **1975**, 2055.

(17) (a) Maldotti, A.; Molinari, A.; Amadelli, R. *Chem. Rev.* **2002**, *102*, 3811. (b) Tung, C. H.; Wu, L. Z.; Zhang, L. P.; Chen, B. *Acc. Chem. Res.* **2003**, *36*, 39. (c) Ho, D. G.; Gao, R. M.; Celaje, J.; Chung, H. Y.; Selke, M. *Science*. **2003**, *302*, 259.

(18) Bhattacharya, G.; Su, T. L.; Chia, C. M.; Chen, K. T. *J. Org. Chem.* **2001**, *66*, 426.

(19) (a) Haynes, R. K. *Aust. J. Chem.* **1978**, *31*, 121. (b) Haynes, R. K.; Hilliker, A. E. *Tetrahedron Lett.* **1986**, *27*, 509. (d) Zhou, X.; Kitamura, M.; Shen, B. J.; Nakajima, K.; Takahashi, T. *Chem. Lett.* **2004**, *33*, 410.

(20) (a) Courtneidge, J. L.; Bush, M.; *J. Chem. Soc., Perkin Trans. 1* **1992**, 1531. (b) Dimitrov, D.; Sirakova, V.; Stefanova, R. *Oxid. Commun.* **1984**, *7* (3–4), 399.

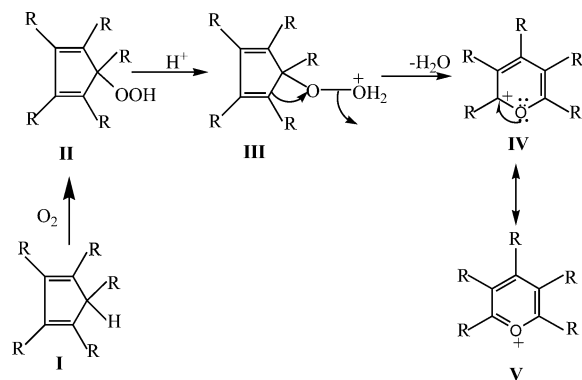
(21) Katritzky, A. R.; Marson, C. M. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 420.

(22) (a) Katritzky, A. R.; Czeney, P.; Levell, J. R. *J. Org. Chem.* **1997**, *62*, 8198. (b) Nikolov, P.; Metzov, S. *J. Photochem. Photobiol. A: Chem.* **2000**, *135*, 13. (c) Ilies, M. A.; Seitz, W. A.; Ghiviriga, I.; Johnson, B. H.; Miller, A.; Thompson, E. B.; Balaban, A. T. *J. Med. Chem.* **2004**, *47*, 3744.

(23) Balaban, A. T.; Ficher, G. W.; Dinculescu, A.; Koblik, A. V.; Dorofeenko, G. N.; Mezheritskii, V. V.; Schroth, W. Pyrylium salts: synthesis, reactions and physical properties. In *Advances in Heterocyclic Chemistry, Suppl. 2*; Katritzky, A. R., Ed.; Academic Press: New York, 1982.

(13) Barton, J. M.; Pepper, D. C. *J. Chem. Soc.* **1964**, *5*, 1573.

SCHEME 2



atom of polysubstituted cyclopentadienes is more active and more vulnerable to oxygen attacking than that at other positions.²⁴ Second, in the presence of protic acid, the hydroperoxide **II** generates cation **III** after protonation. The driving force of this rearrangement is the electron deficiency of oxygen atom, which is in complete accordance with Whitmore's intramolecular rearrangement.²⁵ Then, from **III** to **V** may be a Criegee type rearrangement²⁶ involving nearly synchronous O–O scission and C–O bond formation leading to the carbon–carbon bond cleavage and an oxygen insertion of cyclopentadiene-ring. The last step, from **IV** to **V**, is a conversion of resonant structure, which is evident and has been well documented.²³

In summary, we have demonstrated that polysubstituted cyclopentadienes undergo oxidation and oxygen-insertion by using molecular oxygen in the presence of protic acid. The unprecedented reaction pathway provides a facile and direct approach for the synthesis of polysubstituted pyrylium salts, particularly, α -unsubstituted pyrylium salts, which cannot be readily prepared by traditional methods. Further studies will be directed toward the exploration of other cyclic diene systems for the general sense of the current oxidation strategy.

Experimental Section

Safety note: Organic perchlorates are notoriously unstable and potentially explosive! Only small amounts of materials should be prepared, and these should be handled with great caution.

(24) Tallman, A. T.; Bill, R. J.; Porter, N. A. *J. Am. Chem. Soc.* **2004**, *126*, 9240.

(25) (a) Yablokov, A. V. *Russ. Chem. Rev.* **1980**, *49*, 833. (b) Frank, C. E. *Chem. Rev.* **1950**, *46*, 155 and references cited therein.

(26) Krasutsky, P. A.; Kolomitsyn, I. V. Kiprof, P.; Carlson, R. M.; Sydorenko, N. A.; Fokin, A. A. *J. Org. Chem.* **2001**, *66*, 1701.

Synthesis of 2,4,5-Triphenylpyrylium Perchlorate (1). To a solution of triphenyl-substituted cyclopentadiene (Ph₃H₃C₅) (147 mg, 0.5 mmol) in a mixed solvent of toluene/acetonitrile (40 mL/2 mL) was added 2 equiv of HClO₄·2H₂O (150 mg in 2 mL of acetonitrile). The mixture was stirred at room temperature in air, and the conversion was periodically monitored by HPLC. When HPLC showed the reaction to be complete, a large amount of diethyl ether was poured into the solution. The green solid was isolated through suction filtration and then washed with toluene (2 × 5 mL) and diethyl ether (2 × 10 mL), respectively. The product was dried for 24 h in a vacuum desiccator, giving about 127 mg of **1** in 82% yield. ¹H NMR (acetone-*d*₆, 400 MHz) δ : 9.17 (s, 1H), 9.09 (s, 1H), 7.45–7.92 (15H). ¹³C NMR (DMSO-*d*₆, 100 MHz) δ : 172.6, 168.8, 163.8, 136.6, 134.8, 133.3, 131.8, 130.9, 130.8, 130.5, 129.5, 129.7, 128.9, 128.6, 127.6, 125.8, 122.6. IR (KBr) ν : 1611, 1092, 622 cm⁻¹. MS (API-ES) *m/z*: 309.1 (M⁺). Anal. Calcd for (C₂₃H₁₇O⁺)(ClO₄⁻): C, 67.57; H, 4.19. Found: C, 67.98; H, 4.18.

2,3,4,5-Tetraphenylpyrylium Perchlorate (2). Yellow powder of **2** was obtained in the same process as **1** using Ph₄H₂C₅ (185 mg, 0.5 mmol) instead of Ph₃H₃C₅. Yield: 81%. ¹H NMR (acetone-*d*₆, 400 MHz) δ : 9.84 (s, 1H), 7.12–7.67 (20H). ¹³C NMR (DMSO-*d*₆, 100 MHz) δ : 171.4, 168.1, 163.7, 137.8, 136.7, 133.1, 131.7, 131.1, 130.7, 130.2, 129.8, 129.4, 129.2, 128.9, 128.8, 128.45, 127.8, 127.5, 127.2, 127.0, 125.0. IR (KBr) ν : 1595, 1093, 623 cm⁻¹. MS (API-ES) *m/z*: 385.1 (M⁺). Anal. Calcd for (C₂₉H₂₁O⁺)(ClO₄⁻): C, 71.85; H, 4.33. Found: C, 71.96; H, 4.31.

2,3,4,5,6-Pentaphenylpyrylium Perchlorate (3). Pentaphenyl cyclopentadiene (Ph₅HC₅) (223 mg, 0.5 mmol) was treated also in the same way as **1**, and a yellow powder of **3** was obtained in 93% yield. ¹H NMR (acetone-*d*₆, 400 MHz) δ : no pyrylium proton, 7.06–7.73 (20H). IR (KBr) ν : 1598, 1094, 624 cm⁻¹. MS (API-ES) *m/z*: 461.1 (M⁺). Anal. Calcd for (C₃₅H₂₅O⁺)(ClO₄⁻): C, 70.59; H, 4.31. Found: C, 70.18; H, 4.23.

2,3,4,5,6-Pentamethylpyrylium Perchlorate (4). Purple powder of **4** was obtained also in the same way as **1**, using pentamethyl cyclopentadiene (68 mg, 0.5 mmol) in place of Ph₃H₃C₅, 94% in yield. The structure of the powder was identified by GC/MS and accorded well with the results in the literature.²⁷ ¹H NMR (acetone-*d*₆, 400 MHz) δ : 2.93 (s, 6H), 2.67 (s, 3H), 2.48 (s, 6H). IR (KBr) ν : 1617, 1087, 620 cm⁻¹. MS (API-ES) *m/z*: 151.1 (M⁺).

Acknowledgment. This work was partially supported by the National Nature Science Foundation of China (No. 20072003) and a Grant-in-Aid for excellent researcher from the Ministry of Education in China.

Supporting Information Available: Spectra for pyrylium cations **1–4** (NMR, MS, and IR). This material is available free of charge via the Internet at <http://pubs.acs.org>.

JO050715Q

(27) Balaban, A. T.; Bota, A.; Chiraleu, F.; Sliam, E.; Hanes, A.; Draghici, C. *Rev. Roum. Chim.* **1977**, *22*, 1003 and references therein.