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LETTERS

Synthesis of 1-(3-*tert*-butyldimethylsiloxy)phenyl-5,5-dimethyl-2,7,8-trioxabicyclo[4.2.0]octanes: new dioxetanes giving high chemiexcitation yields in thermolysis and in fluoride-induced CIEEL-decay

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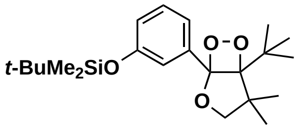
Abstract—Dioxetanes with annelated six-membered ring, 1-(3-*tert*-butyldimethylsiloxy)phenyl-5,5-dimethyl-2,7,8-trioxabicyclo[4.2.0]octanes (**2a**–**2c**) were synthesized by singlet oxygenation of the corresponding aryl-substituted dihydropyrans (**3**). Thermolysis of **2a**–**2c** gave the corresponding ketoesters (**5a**–**5c**) as a normal decomposition product together with a considerable amount (23–26%) of ester (**6**) derived from Norrish type I reaction of the triplet-excited ester (**5**). On the other hand, treatment with tetrabutylammonium fluoride (TBAF) in DMSO induced rapid decomposition of **2** to emit blue light in high chemiexcitation yield (72–75%) of the oxyanion of a ketoester (**10**). These results show that the chemiexcitation efficiency of dioxetanes (**2**) was higher than that of their five-membered ring analog (**1**) not only for thermolysis and but also for the base-induced CIEEL. © 2002 Elsevier Science Ltd. All rights reserved.

Rather simple dioxetanes with annelated six-membered rings have been known to be far less stable thermally than their analogs with annelated five- or seven-membered rings.[1–6] On the other hand, it has very recently been reported for a dioxetane with annelated five-membered ring (**1**) and related dioxetanes that the steric interaction of a bulky *tert*-butyl group at the 5-position with two methyls at the 4-position should improve markedly the thermal persistency of the peroxide ring.[7,8] We report here that (a) this substitution pattern is also very effective to design a thermally stable dioxetane with an annelated six-membered ring, and (b) the thus-realized dioxetanes[9–12] namely, 6-*tert*-butyl-1-(3-*tert*-butyldimethylsiloxy)phenyl-5,5-dimethyl-2,7,8-trioxabicyclo[4.2.0]octane (**2a**) and its 6-isopropyl- and 6-(1,1-dimethyl-2-phenylethyl)- derivatives (**2b**, **2c**) exhibit chemiexcitation more effectively than their five-membered ring analog (**1**) not only for thermolysis but also for base-induced intramolecular CIEEL (chemically initiated electron exchange luminescence).[13,14]



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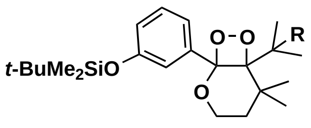

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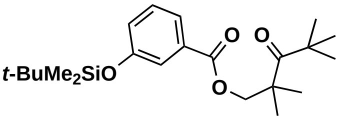
a: R = Me
b: R = H
c: R = -CH$_2$Ph



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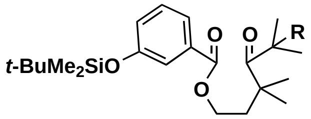

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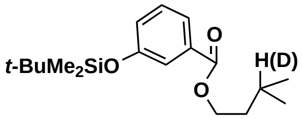

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Keywords: singlet oxygenation; 1,2-dioxetane; Norrish type I decomposition; CIEEL.

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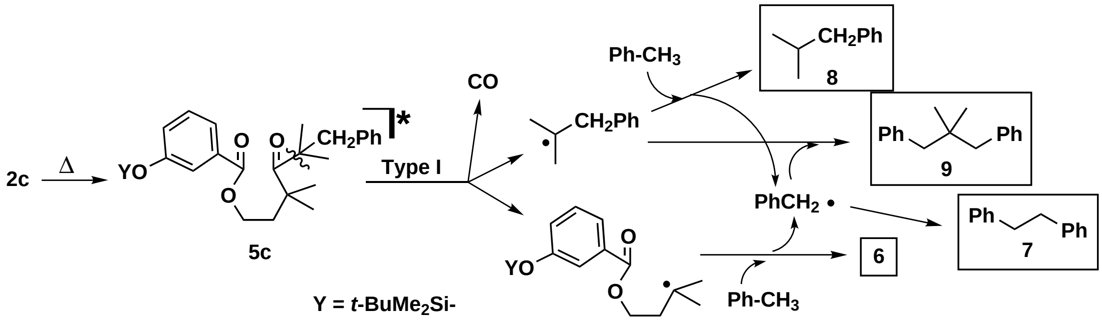
A dihydropyran (**3a**) (100 mg) and a catalytic amount of tetraphenylporphin (TPP) were irradiated with a 940 W Na lamp in CH_2Cl_2 (5 mL) under an O_2 atmosphere at 0°C for 9 h. It should be noted that the singlet oxygenation of **3a** proceeded far more slowly than in the case to produce **1** from the corresponding dihydrofuran, and a substantial reaction did not take place at −78°C. After the irradiation, the photolysate was chromatographed on silica gel and eluted with hexane–ether (30:1) to give a dioxetane (**2a**) as an oil in 74% yield. The structure of dioxetane (**2a**) was determined by ^1H, ^{13}C NMR, IR, and HRMass spectral analysis.[15] Isopropyl- (**2b**) and 1,1-dimethyl-2-phenylethyl-analog (**2c**) were similarly synthesized from the corresponding dihydropyrans (**3b**) and (**3c**) in 85 and 58% yield, respectively.

A dioxetane (**2a**) was as stable thermally as the fused five-membered ring dioxetane (**1**): $\Delta G^{\ddagger}=29.3$ kcal mol^{-1}, $t_{1/2}$ at 25°C = 28.9 y for **2a**, while $\Delta G^{\ddagger}=29.1$ kcal mol^{-1}, $t_{1/2}$ at 25°C = 22.1 y for **1**.[7] However, features of the thermolysis for **2** were markedly different from those for **1**, which affords ketoester (**4**) exclusively as the normal decomposition product.[7] When the thermolysis of dioxetane (**2a**) was carried out in hot toluene, the expected normal product (**5a**) was produced in 74% yield along with a considerable amount (26%) of the 3-methylbutyl ester of *m*-siloxybenzoic acid (**6**). The other dioxetanes (**2b**, **2c**) also decomposed thermally to give the corresponding ketoesters (**5b**, **5c**) together with **6** (**5b**:**6** = 77:23, and **5c**:**6** = 78:22). All reaction mixtures after the thermolysis of dioxetanes (**2a**–**2c**) included 1,2-diphenylethane (**7**), which should be a coupling product of benzyl radicals. In addition to these products, thermolysis of **2c** gave 2-methylpropylbenzene (**8**) and 2,2-dimethyl-1,3-diphenylpropane (**9**). Both products (**8** and **9**) should be derived from a 1,1-dimethyl-2-phenylethyl fragment produced concomitantly with **6**, though the corresponding products derived from a *tert*-butyl fragment for **2a** or isopropyl fragment for **2b** were scarcely detected. It should be noted here that (a) thermolysis of **2a**–**2c** in toluene-d_8 gave a 3-deuterio-3-methylbutyl ester (deuterio-**6**) in place of **6**, and (b) esters (**5a**–**5c**) were stable and did not undergo any decomposition in hot toluene.

The results described above suggest strongly that Norrish type I reaction[16,17] of a branched-alkyl ketone moiety in ketoesters (**5**) should occur to produce ester (**6**) together with radical fragments leading to **7**–**9**, as illustrated in Scheme 1, where a plausible decomposition pathway of **2c** is shown as a representative. In analogy with di-*tert*-butyl ketone, which undergoes Norrish type I photodecomposition very effectively ($\Phi=0.71$),[18] the type I decomposition of a branched-alkyl ketone moiety of **5** at an excited state(s) would proceed very effectively. Thus, thermolysis of **2a**–**2c** in toluene can be reasonably assumed to produce an excited carbonyl (**5a**–**5c**) with an efficiency of 31–37%, based on the yields of **6**. Considering that (a) thermolysis of a dioxetane produces in general a triplet-excited carbonyl fragment predominantly, and (b) the type I process of di-*tert*-butyl ketone has been reported to occur much more rapidly from the triplet state than the singlet excited state,[18] the type I reaction producing **6** is thought to be attributed predominantly to the triplet excited state of **5**. On the other hand, a keto-ester (**4**) was a sole product formed from a five-membered ring analog (**1**) on thermolysis in hot toluene as reported,[7] though **4** possesses a di-*tert*-alkyl ketone moiety similarly to **5a**. This fact suggests that a five-membered ring analog (**1**) produces an excited ketoester (**4**) far less effectively on thermolysis than a six-membered analog (**2**). It is noteworthy that the thermal decomposition of **2a** in toluene was accompanied with light emission ($\lambda_{max}=408$ nm, $\Phi=1.4\times10^{-4}$), which is presumably derived from the singlet-excited ketone moiety of **5a**,[19–21] while a similar thermolysis of **1** gave little light. Conclusively, the present results reveal that dioxetane with fused six-membered ring (**2**) decomposes thermally to produce an excited ketoester (**5**), which undergoes type I decomposition, far more effectively than the five-membered ring analog (**1**).

A siloxyphenyl-substituted dioxetane is triggered with tetrabutylammonium fluoride (TBAF) in aprotic solvent such as DMSO and acetonitrile; its desilylation with fluoride affords an unstable phenolate-substituted dioxetane, which decomposes rapidly by the CIEEL process. It has been reported very recently for the fluoride-triggered CIEEL process of a siloxyphenyl-substituted dioxetane that the CIEEL-decay rate of dioxetane follows pseudo-first-order kinetics independent of the TBAF concentration when an excess of fluoride concentration is used.[22] To simplify the analysis of fluoride-induced decomposition of the present dioxe-



Scheme 1.

tanes (**2**), we also used a large excess of TBAF. When solutions of **2a**–**2c** in DMSO (1.0×10^{-6} mol dm^{-3}, 1 mL) were added to TBAF solutions in DMSO (1.0×10^{-3} mol dm^{-3}, 2 mL) at 25°C, the dioxetanes (**2a**–**2c**) emitted intense blue light. The results summarized in Table 1 show that the present dioxetanes (**2a**–**2c**) afford light more effectively than their five-membered ring analog (**1**) in DMSO. The chemiluminescence spectra for **2a**–**2c** coincided with fluorescence spectra for the oxyanions (**10**) formed from **5** on treatment with TBAF in DMSO. Fluorescence efficiency (Φ^{fl}) of the authentic emitters (**10a**–**10c**) was observed to differ little from that of the authentic emitter for **1** (Scheme 2).[23] These results show that the singlet-chemiexcitation yield ($\Phi_s = \Phi^{CIEEL}/\Phi^{fl}$) from dioxetanes with an annelated six-membered ring (**2a**–**2c**) is higher than that of their five-membered ring analog (**1**) for fluoride-induced CIEEL-decay in DMSO (Table 1).

Table 1. Fluoride-induced chemiluminescent decomposition of dioxetanes (**2**) in TBAF/DMSO[a]

Dioxetane	λ_{max} (nm)	k (s^{-1})	$t_{1/2}$ (s)	$\Phi^{CIEEL b}$	$\Phi_s^{c,d}$
2a	469	0.063	11	0.23	0.72
2b	469	0.16	4.3	0.23	0.72
2c	469	0.042	16	0.24	0.75
1	466	0.15	4.6	0.20	0.63

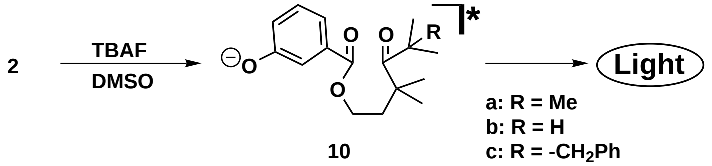
[a] Solutions of **2a**–**2c** in DMSO (1.0×10^{-6} mol dm^{-3}, 1 mL) were added to TBAF solutions in DMSO (1.0×10^{-3} mol dm^{-3}, 2 mL) at 25°C.

[b] Chemiluminescence yields (Φ^{CIEEL}) were based on the reported value for 3-(2′-spiroadamantane)-4-methoxy-4-(3″-*tert*-butyldimethylsiloxy)phenyl-1,2-dioxetane: $\Phi^{CIEEL} = 0.29$.[22]

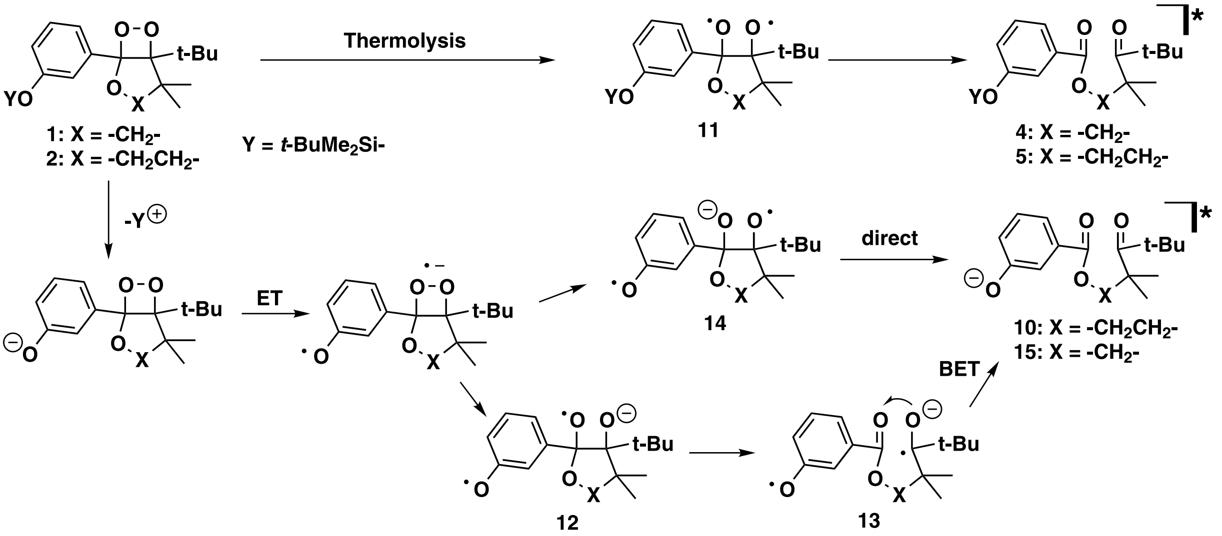
[c] Singlet-chemiexcitation yields (Φ_s) were estimated in accord with an equation $\Phi_s = \Phi^{CIEEL}/\Phi^{fl}$.

[d] Fluorescence yield (Φ^{fl}) of the authentic emitters: $\Phi^{fl} = 0.34$ for **2a**–**2c** based on $\Phi^{fl} = 0.32$ for **1**.[23]

The present results show that dioxetanes with an annelated six-membered ring (**2**) cause chemiexcitation more effectively than the analog (**1**) with an annelated five-membered ring, not only for thermolysis but also for TBAF-induced CIEEL-decay in DMSO. This trend of chemiexcitation efficiency poses a question, which has been little discussed so far, whether the chemiexcitation process for thermolysis of dioxetane relates or does not relate to that for intramolecular CIEEL. The thermolysis of dioxetane has been believed to involve a two-step mechanism, in which O–O bond homolysis occurs first, leading to a diradical intermediate, followed by fast C–C bond cleavage (**11**→**4** or **5** in Scheme 3). A very recent theoretical study by Tanaka and Tanaka has elucidated that (a) the energy curve of a dioxetane at the ground state (S_0) intersects the energy curve of the excited state (T_1) after the O–O bond cleavage, so that an excited carbonyl fragment is produced, (b) the magnitude of activation energy ($E_a^{C–C}$) requisite for the C–C bond cleavage (the second step) affects chemiexcitation efficiency significantly, and (c) the chemiexcitation occurs effectively for tetramethyldioxetane possessing a considerably puckered four-membered ring, which requires far smaller $E_a^{C–C}$ than unsubstituted dioxetane giving very low chemiexcitation yield.[24] According to this elucidation, the marked difference in the thermal chemiexcitation



Scheme 2.



Scheme 3.

efficiency between **1** and **2** might be attributed to the difference in stereochemistry of the dioxetane ring.[25]

Two mechanisms have been proposed for the intramolecular CIEEL. The first mechanism (ET-BET mechanism) comprises an initial electron transfer causing decomposition of dioxetane to form a radical ion pair of two carbonyl fragments as the first elementary step and successive annihilation of the radical ion pair by electron back transfer (BET) to give an excited carbonyl as the secondary step (**12**→**13**→BET→**10** or **15** in Scheme 3).[22,23,26–28] According to the ET-BET mechanism, the radical ion pair produced from **2** should possess a structure(s) to cause BET more effectively than that from **1**, since the BET step should affect decisively the yield of a carbonyl at the singlet-excited state as suggested by Adam.[28] The second is a mechanism in which an intermediate produced by charge-transfer-induced O–O bond cleavage gives an excited carbonyl directly and not through the distinct formation of a radical ion pair (**14**→direct→**10** or **15** in Scheme 3).[29,30] The second mechanism for the intramolecular CIEEL resembles the thermal chemiexcitation mechanism especially in the C–C bond cleavage at the second step, and appears to be in agreement with ab initio molecular orbital studies.[31] Although the present results do not give definitive information either to rationalize the mechanism of charge-transfer induced chemiluminescent decomposition of dioxetane or to answer the above question, they clarify that the structure of dioxetane not participating formally in chemiexcitation affects the yield of excited carbonyls, and provides a clue to study the relation between thermal chemiexcitation and CIEEL.

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