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The Chemiexcitation of the Chemiluminescence of Lophine Peroxide Anions via a Partially Cyclic Transition State

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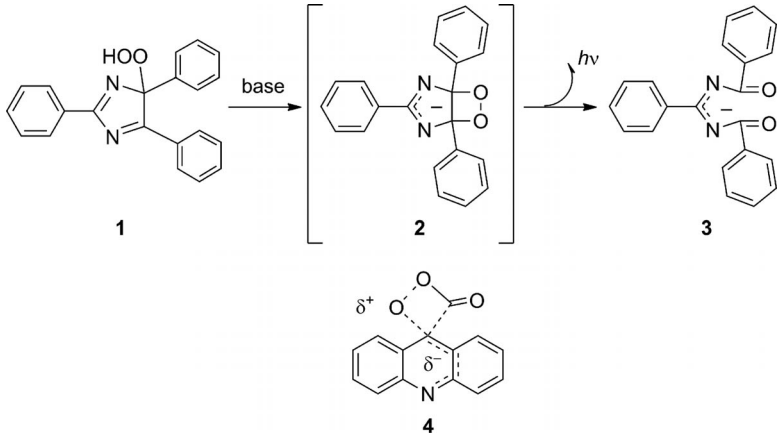
It was shown that acyclic intermediates play a role in the chemiexcitation of the chemiluminescence (CL) of lophine peroxides in addition to the dioxetane intermediates. Because the CL efficiencies of position-isomers (*R*)-**9** and (*R*)-**10**, which theoretically give the common dioxetane intermediate, were different, the different CL efficiencies are attributable to the CL mechanism involving a partially cyclic transition structure at the chemiexcitation step.

Introduction

In many studies of bioluminescence (BL) and chemiluminescence (CL), four-membered cyclic peroxide intermediates such as dioxetanes and dioxetanones are believed to be key intermediates in the chemiexcitation steps.[1] It has been established that in the CL of lophine peroxide **1**, a cyclic dioxetane intermediate **2** is involved in the chemiexcitation step (Scheme 1).[2–4] In studies on the related CL of 9-acridinecarboxylate, however, White et al. proposed that a true dioxeatanone is not an intermediate, but instead the "open form" dioxetane transition state **4** (Scheme 1) is a key intermediate species.[1c] The proposed transition structure was based on the observations of anion emission in the CL of the 9-acridinepercarboxylate anion.[1c] Furthermore, White suggested that the study of isomeric lophine peroxides such as 4-hydroperoxy-2-phenyl-4-(4-X-phenyl)-5-(4-Y-phenyl)-4*H*-isoimidazoles (**7**, X = CF_3, Y = F and **8**, X = F, Y = CF_3) could confirm the existence of partially cyclic transition states in the chemiexcitation step. This is because these positional isomers can give distinguishable "open form" transition state structures in the course of CL reactions,



Scheme 1. CL reaction of lophine peroxide **1** involving dioxetane intermediate **2** and amidine anion **3**. "Open form" partially cyclic transition structure **4** for CL of 9-acridinecarboxylate.

which should display different CL efficiency. Instead, if the CL mechanism proceeds in accord with the dioxetane intermediate, compounds **7** and **8** should share a common intermediate with identical CL efficiencies (Scheme 2). In this study, we investigated White's proposal with the intent of gaining a fuller, more detailed understanding of the CL mechanism.

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Results and Discussion

We began by synthesizing isomeric compounds **7** and **8** (Scheme 2). First, 5-(4-fluorophenyl)-2-phenyl-4-[4-(trifluoromethyl)phenyl]imidazole (**6**) was prepared from 4-fluoro-4′-(trifluoromethyl)benzil (**5**)[5] and benzaldehyde.[6] A mixture of isomeric peroxides **7** and **8** was then obtained from imidazole **6** and singlet oxygen (Scheme 2). Attempts to separate and isolate peroxides **7** and **8** by fractional crystallization and column chromatography were unsuccessful, in part due to the instability of the peroxy group. We then protected the reactive functionality with *tert*-butyldimethylsilylchloride, introducing a protecting group that could be readily removed to initiate CL.[6] A mixture of 4-*tert*-butyldimethylsilylperoxy-2-phenyl-4-(4-X-phenyl)-5-(4-Y-phenyl)-4*H*-isoimidazoles (**9**, X = CF_3, Y = F and **10**, X = F, Y = CF_3) were obtained as shown in Scheme 3.

The ratio of **9** and **10** was determined by ^{1}H NMR analysis to be 4:1. Racemic **9** was isolated by fractional recrystallization with 2-propanol; however, the position-isomer **10** was not isolated by this method. We were able to separate a mixture of **9** and **10** into three groups of peaks by using HPLC with a Daicel Chiralpak AD-H column developed with hexane/ethanol (9:1) (Figure 1). The first fraction (F-I) was composed of a mixture of (*S*)-**9** and (*S*)-**10**, the second fraction (F-II) was optically active (*R*)-**9**, and the third fraction (F-III) was optically active (*R*)-**10**. Therefore, only optically active (*R*)-**10** was available as a representative sample of **10**. The stereochemistry of (*R*)-**9**, (*S*)-**9**, (*R*)-**10**, and (*S*)-**10** was assigned by comparison of their CD spectra with their calculated spectra.[6]

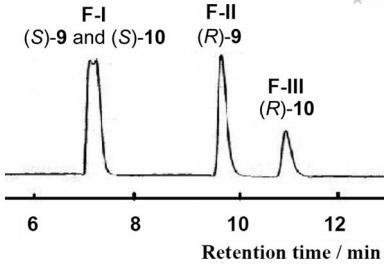
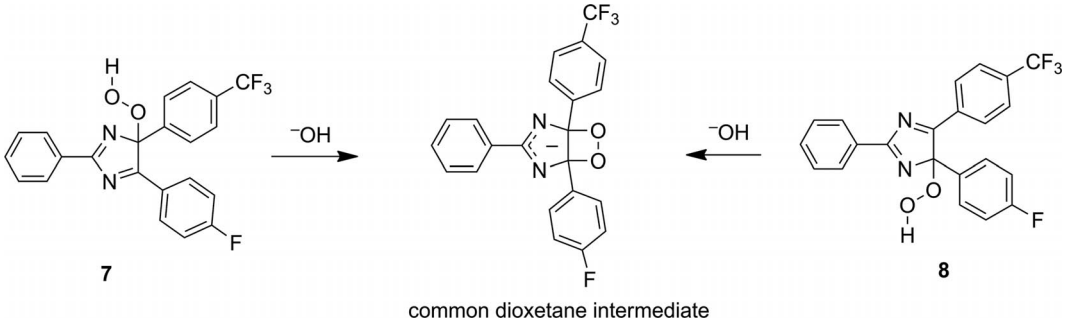
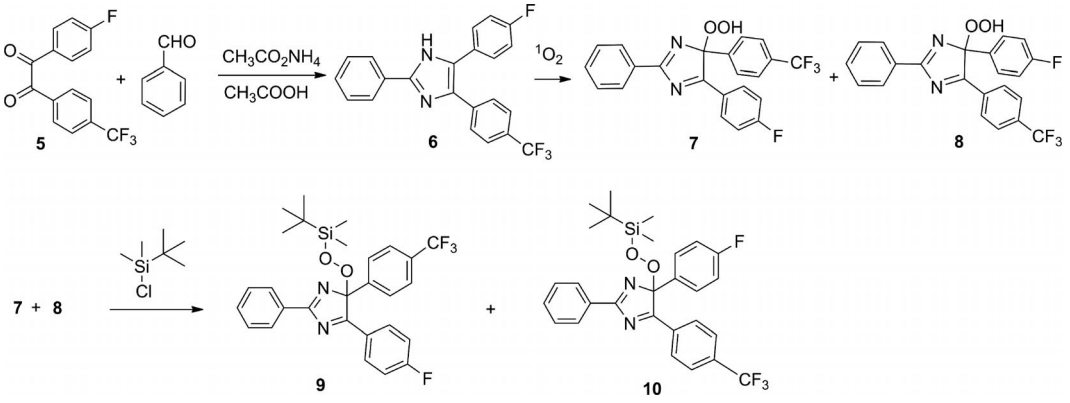


Figure 1. HPLC chart for the isolation of (*R*)-**9** and (*R*)-**10**.

The CL reaction of the silylated peroxides was initiated by the addition of a 0.1 M solution of tetrabutylammonium fluoride (TBAF) in tetrahydrofuran (THF). The CL intensities were measured by using a photodiode array Photonic Multi-channel Analyzer (Hamamatsu Photonics Model C-249). The results of the reaction are summarized in Table 1. In acetone, the decomposed compounds of the corresponding amidines were obtained as byproducts.[2b] In $CHCl_3$ and acetone, (*R*)-**9** and (*R*)-**10** gave the same amount of the common amidine **11**, respectively (Table 2). The Φ_{CL} of the resulting mixture of silylated peroxides (**9**/**10**, 4:1) was measured in four solvents [CH_2Cl_2, $CHCl_3$, *N*,*N*-dimethylformamide (DMF), and acetone], and the order of the efficiencies with respect to the solvent was: CH_2Cl_2 [$\Phi_{CL}(\times 10^{-6}) = 13.8 \pm 1.0$] > $CHCl_3$ (10.9 ± 0.3) > acetone (4.12 ± 0.2) > DMF (4.00 ± 0.2). The efficiency of CL was highest in CH_2Cl_2, but the experimental error was also higher. The efficiency was lowest in CH_3CN. Solvents $CHCl_3$ and acetone were selected as representative solvents for subsequent



Scheme 2. Introduction of the common intermediate from position-isomeric peroxides **7** and **8**.



Scheme 3. Synthetic scheme for isomeric peroxides.

CL experiments upon consideration of the CL efficiency, the dielectric constant of the solvent, and the experimental error (S.D).

Table 1. Products of the CL reaction of (*R*)-**9** or (*R*)-**10**.[a]

Peroxide	Solvent	Conversion [%]	**6** [%]	**11** [%]	Byproduct [%][b]
(*R*)-**9**	$CHCl_3$	100	17	83	0
(*R*)-**9**	acetone	100	0	93	7
(*R*)-**10**	$CHCl_3$	100	14	86	0
(*R*)-**10**	acetone	100	0	90	10

[a] Trigger base = TBAF (0.1 M) in THF. [b] Decomposed products of amidine **11**.

Table 2. CL efficiencies and CL peaks (λ_{max}, nm) of racemic **9**, optical active (*R*)-**9** and optical active(*R*)-**10**.[a]

Peroxide	Solvent	Concentration [M]	λ_{max} [nm]	Φ_{CL} ($\times 10^{-6}$)	SD
9	$CHCl_3$	1×10^{-2}	564	10.3	0.2
(*R*)-**9**	$CHCl_3$	1×10^{-2}	564	10.6	0.5
9	acetone	1×10^{-2}	564	4.35	0.4
(*R*)-**9**	acetone	1×10^{-2}	564	4.35	0.2
(*R*)-**10**	$CHCl_3$	1×10^{-2}	557	10.2	0.5
(*R*)-**10**	acetone	1×10^{-2}	557	3.07	0.5

[a] Trigger base = TBAF (0.1 M) in THF.

In acetone, (*R*)-**9** and (*R*)-**10** provided clearly different Φ_{CL}($\times 10^{-6}$) values of 4.35 ± 0.4 and 3.07 ± 0.5, along with the amidine **11** at 93 and 90% yields, respectively, accompanied by the corresponding dibenzoylamine and benzoylamine as byproducts.[6,7] If the formation of dioxetane **12**$^-$ (DO) as the common intermediate is inevitable in the CL reaction of lophine peroxides, the CL efficiencies should be the same for both position isomers (*R*)-**9** and (*R*)-**10**. The different CL efficiencies are attributed to a mechanism involving different partially cyclic transition states (TS-pc **9** and TS-pc **10**).

Because the CL reactions of (*R*)-**9** and (*R*)-**10** afforded the common excited amidine anion **11**$^{-*}$ with different efficiencies, it is unlikely that only common DO**12**$^-$ is involved in the excitation step.[1c] In $CHCl_3$, the CL efficiencies [Φ_{CL} ($\times 10^{-6}$)] for (*R*)-**9** and (*R*)-**10** were 10.6 ± 0.5 and 10.15 ± 0.2, and the yields of common amidine **11** were 83 and 86%, respectively. In $CHCl_3$, the CL efficiencies of (*R*)-**9** and (*R*)-**10** were equal within experimental error, which suggests that the common DO**12**$^-$ plays a main role in the chemiexcitation. The CL spectra of (*R*)-**9** and (*R*)-**10** in acetone and $CHCl_3$ are shown in Figure 2. Furthermore, to investigate the relationship between the efficiencies and the reaction rates, which reflects the height of the barrier on ground state surface, these peroxides were subjected to rate determination. Both in acetone and in $CHCl_3$ at 25 °C, the CL decay rates for (*R*)-**9** ($k_{acetone} = 0.165\ s^{-1}$, $k_{CHCl3} = 0.0312\ s^{-1}$) were slower than those for (*R*)-**10** ($k_{acetone} = 0.226\ s^{-1}$, $k_{CHCl3} = 0.0335\ s^{-1}$). In acetone, the activation of the free energy level for (*R*)-**9** in the partially cyclic transition state (TS-pc) seems to be higher than that for (*R*)-**10**. The isomer (*R*)-**9** seems to have an advantage over (*R*)-**10** in CL efficiency. In $CHCl_3$, (*R*)-**9** and (*R*)-**10** seem to mainly pass a common intermediate because the reaction rates are similar and the CL efficiencies are the same within error.

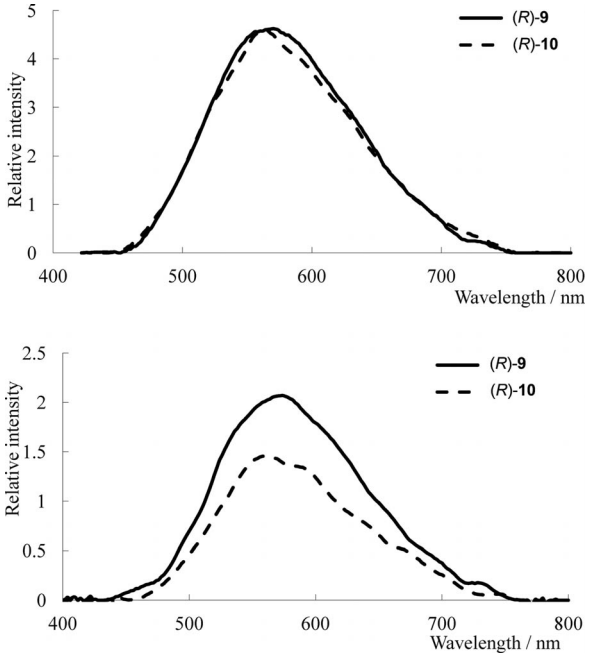
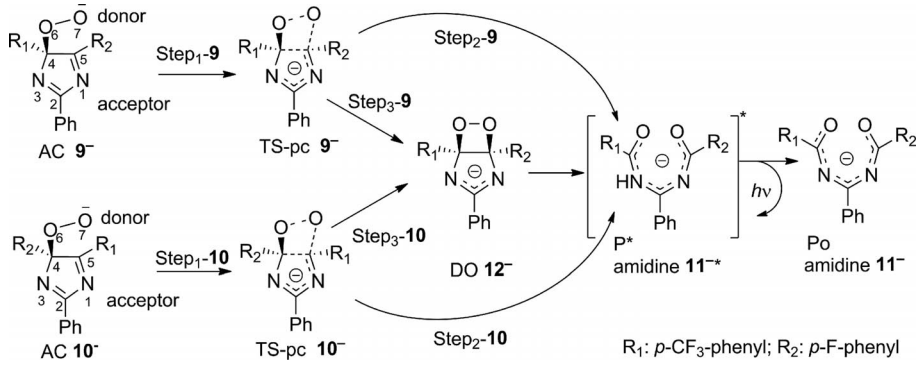


Figure 2. CL spectra for the CL reaction of (*R*)-**9** and (*R*)-**10** with TBAF/THF in acetone (bottom) and in chloroform (top).

These findings are rationalized by considering that two intermediates, cyclic DO**12**$^-$ and acyclic peroxide anions (AC**9**$^-$ and AC**10**$^-$), are involved in chemiexcitation (Scheme 4). Even in the case of the different CL efficiencies



Scheme 4. The chemiluminescence mechanism of lophine peroxides.

in acetone, a contribution of cyclic DO**12**$^-$ to chemiexcitation cannot be discounted. It is possible that the contribution of TS-pc is larger in acetone than in $CHCl_3$.

To investigate the heat of formation and the net-charge of intermediates AC (**9**$^-$ and **10**$^-$), TS-pc, DO, P_o (**11**$^-$ at the ground state), and P* (**11**$^-$ at the excited state) on the CL reaction surface, B3LYP energy-gradient calculations were performed. We employed a qualitative procedure by using the GAUSSIAN 03w software package.[8] First, the conformation diagram was examined to find the most stable starting anion against the torsion angles of N(3)–C(4)–O(6)–O(7) (Figure 3). As shown in Scheme 4, the reaction starts with the approach of the peroxide oxygen atom to the C=N

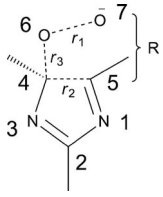


Figure 3. The model of AC for calculation of energies of heat of formation and net charges for ST, TS-pc DO, and the final product amidine in the ground state (P_o) and in the excited state (P*); C5···O7 (R), O6–O7 ($r1$), C4–C5 ($r2$), C4–O6 ($r3$).

of the imidazole moiety. Calculated energies were obtained under the condition that bond formation between C5···O7 (R), and bond elongation at bonds O6···O7 (r_1), C4···C5 (r_2), and C4–O6 (r_3) take place simultaneously. The optimized geometries of ST, TS-pc, DO, P_0 and P* were obtained. The relative energies and net charges for the starting state (ST), the partially cyclic transition state (TS-pc), the cyclic state (DO), product at the ground state P_0 and at the excited state P* for the reaction are given in Table 3. Even at the starting stage of the reaction, the sizeable negative charge on the peroxide oxygen fed into the imidazole acceptor moiety. From computational results, r_3 and R at TS-pc are different, and the molecular structure at TS-pc resembles that at ST. During the process from the TS-pc to the product ground state P_0, the computational results support the existence of a common cyclic intermediate (DO) because the optimized DO from **9**$^-$ and that from **10**$^-$ are equivalent (Table 3). The energy of P* is lower than those of peroxide anions (AC's) and DO, and the energies of the peroxide anions **9**$^-$ and **10**$^-$ are sufficient as a new CL key intermediate.

We would like to propose that an acyclic mechanism such as that shown in Scheme 4 is an important, although not exclusive, pathway in the CL process. Step 1 leads to the

Table 3. Heat of formation and net charge of peroxide anions **9**$^-$, **10**$^-$, **11**$^-$ and **12**$^-$; $r1$, $r2$ and $r3$ against C5···O7 distance (R).

Solvent	Anion	State	SCF energy [A.U.]	$E - E_{P0}$ [kcal]	R	Bond length [Å] r_1	r_2	r_3
	9$^-$	ST	–1505.48849685	105.95	3.17652	1.46419	1.55860	1.41558
		TS-pc	–1505.46996343	117.58	2.14355	1.48761	1.56456	1.38605
	10$^-$	ST	–1505.48628965	107.33	3.18961	1.45918	1.55403	1.42152
$CHCl_3$		TS-pc	–1505.46815947	118.71	2.25640	1.48723	1.56399	1.38405
	11$^-$	P_0	–1505.65733589	0	1.23948			1.24297
		P*	–1505.61936641	23.83	1.28221			1.24376
	12$^-$	DO	–1505.50617927	94.85	1.47802	1.49663	1.61145	1.47610
	9$^-$	ST	–1505.50417728	105.19	3.18052	1.46695	1.55918	1.41598
		TS-pc	–1505.48760860	115.59	2.16587	1.48987	1.56799	1.38737
	10$^-$	ST	–1505.50192519	106.61	3.20310	1.46392	1.55547	1.42057
Acetone		TS-pc	–1505.48560385	116.85	2.21114	1.48855	1.56599	1.38571
	11$^-$	P_0	–1505.67181936	0	1.24159			1.24441
		P*	–1505.63185254	25.08	1.24400			1.28421
	12$^-$	DO	–1505.52030062	95.08	1.47873	1.49651	1.60856	1.47893

Solvent	Anion	Mulliken atomic charges N1	C2	N3	C4	C5	O6	O7
	9$^-$	–0.583095	0.421028	–0.516062	0.337594	0.277928	–0.385789	–0.545499
		–0.610816	0.414572	–0.567115	0.395904	0.316305	–0.409324	–0.518755
	10$^-$	–0.579488	0.419580	–0.512703	0.333007	0.274463	–0.379863	–0.538069
$CHCl_3$		–0.577311	0.413428	–0.538878	0.399308	0.302366	–0.402055	–0.534178
	11$^-$	–0.583997	0.441599	–0.596793	0.521641	0.531620	–0.584891	–0.575869
		–0.594384	0.443946	–0.576802	0.510166	0.496216	–0.541564	–0.643912
	12$^-$	–0.625929	0.409595	–0.625732	0.355970	0.360902	–0.374355	–0.372559
	9$^-$	–0.581054	0.419614	–0.526134	0.339615	0.276079	–0.397885	–0.562481
		–0.588940	0.409067	–0.571220	0.399396	0.289835	–0.396217	–0.512671
	10$^-$	–0.575454	0.417854	–0.522323	0.336858	0.272174	–0.393616	–0.556919
Acetone		–0.58313	0.411248	–0.55505	0.399352	0.296101	–0.39914	–0.52342
	11$^-$	–0.582400	0.429369	–0.594009	0.514868	0.524600	–0.595249	–0.588262
		–0.595061	0.436146	–0.574950	0.503916	0.490197	–0.551354	–0.654826
	12$^-$	–0.632384	0.401340	–0.633859	0.355522	0.360700	–0.378245	–0.377637

TS-pc from which the excitation step (Step 2) to P* and the conversion (Step 3) into DO also occurs. Regardless of the nature of the intermediate, the reaction proceeds further to give product P* and P_0. The involvement of the acyclic mechanism in solvent acetone is consistent with the different observed CL efficiencies between **9**$^-$ and **10**$^-$. Since the lophine peroxide system consists of a π-conjugated imidazole (charge acceptor) and a part of the peroxide anion (charge donor), the charge transfer (CT) from the donor to the acceptor may stabilize the energy at the transition state.

Because the C=N bond in **10**$^-$ has a conjugated moiety with more electron-withdrawing substituent CF_3, the activation energy for **10**$^-$ is lower than that of **9**$^-$, which has the C=N conjugated with the substituent F. The C=N bond possessing F in **9**$^-$ is likely to be a higher TS-pc than that of **10**$^-$ possessing CF_3. This substituent effect is parallel to that of CL reaction of 2-(*p*-dimethylaminophenyl)-4,5-di(*p*-X-phenyl)-1,4-hydroperoxy-4*H*-isoimidzole, for which in the case of X = F the efficiency is higher than that of X = CF_3.[4] A TS-pc with higher energy is favorable to transfer to the surface of P* (Figure 4). These findings support the presence of a new acyclic peroxide anion intermediate at chemiexcitation in addition to the dioxetane intermediate.[1d,9]

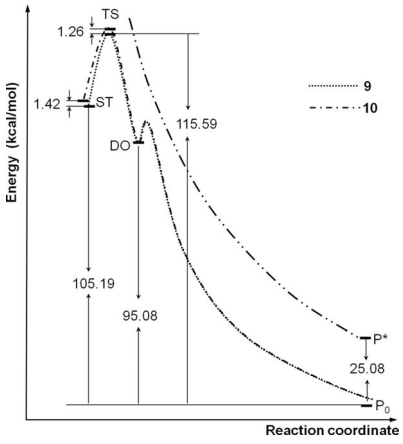


Figure 4. Potential energy profile for CL of peroxides **9** and **10** in acetone.

Conclusions

Acyclic intermediates play a role in the chemiexcitation of the chemiluminescence (CL) of lophine peroxides in addition to the dioxetane intermediates. Because the CL efficiencies of position-isomers (*R*)-**9** and (*R*)-**10**, which theoretically give the common dioxetane intermediate, were different, the different CL efficiencies are attributable to the CL mechanism involving a partially cyclic transition structure at the chemiexcitation step.

Experimental Section

Materials and Methods: Melting points were determined with a Yanagimoto micro melting-point apparatus and are uncorrected. Infrared (IR) spectra were recorded with a JASCO FT/IR-5000 spectrometer. The UV/Vis spectra were measured with a HITACHI UV-288 spectrophotometer. The ^{1}H NMR spectra (chemical shifts referenced to residual $CHCl_3$ in $CDCl_3$ at 7.26) were recorded with a Varian VXR-300 spectrometer operating at 300 MHz, or with a Varian VXR-500 spectrometer operating at 500 MHz. The elemental analysis was performed with a Yanagimoto CHN recorder MI-2 type. Benzil was purchased from the Aldrich Chemical Company Inc. Lophine peroxide **1** was prepared by a modified method described by White et al.[2b] 4-(3-Hydroxyphenyl)-4-methoxyspiro[1,2-dioxetane-3,2′-adamantane] was prepared by a modified method described by Blonstain.[9]

Measurement of Chemiluminescence (CL) Efficiency: The CL was measured by using a photodiode array (PMA, HAMAMATSU PHOTONICS), which recorded integrated light yield in terms of the number of photons. First, the CL emissions of silylated peroxides **9**, (*R*)-**9**, and (*R*)-**10** (1×10^{-2} M) in CH_2Cl_2, $CHCl_3$, acetone, or DMF (1 mL) were counted by PMA by initiation with 0.2 mL of a THF solution of tetrabutylammonium fluoride (TBAF; 0.1 M) at 25 °C. Second, the CL emission of 4-(3-hydroxyphenyl)-4-methoxyspiro[1,2-dioxetane-3,2′-adamantane] (1×10^{-5} M) in DMSO (1 mL) was measured by PMA by initiation with a solution of TBAF in DMSO (3 M, 0.2 mL) at 25 °C.[10] The CL efficiency was estimated by comparison with that of dioxtane as a standard (Φ_{CL} = 0.22).[11] The error (SD) is the deviation from the average of three measurements.

Measurement of CL Decay Rate: The CL decay rates were measured with a CLD-300 (TOHOKU DENSHI). After an initial rise of intensity (I), CL exponential (ln) decay followed. The CL decay rates followed first-order kinetics. A plot of ln I, measured at 15 °C, against time (in seconds) gave a straight line and the rates were measured by the least square method (see the Supporting Information).

Calculation of Energy, Net Charge, and Translation State: The calculations were carried out by using GAUSSIAN 03w, with the B3LYP method, and molecular structures were visualized with GaussView.

The most stable conformations of the peroxide anions are shown in Figure 5. It can clearly be seen that the peroxidic anions are positioned between the two phenyl groups. The negative charge is delocalized over the π-conjugated imidazole ring with two phenyl groups even at the most stable conformation. The heat of formation of anion **9** is higher than that of anion **10** (Table 3).

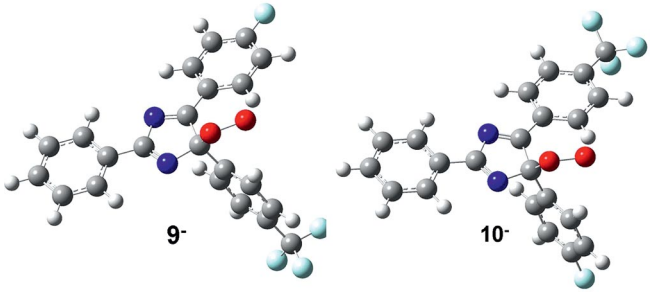


Figure 5. The most stable conformations of the peroxide anions were calculated by using the B3LYP functional with 6-31G* basis sets.

Assignment of Absolute Configuration: The isolated fractions were determined as a mixture of **9** and **10** (**F-I**), **9** (**F-II**), and **10** (**F-III**) by ^{1}H NMR analysis. To determine the absolute configuration, the

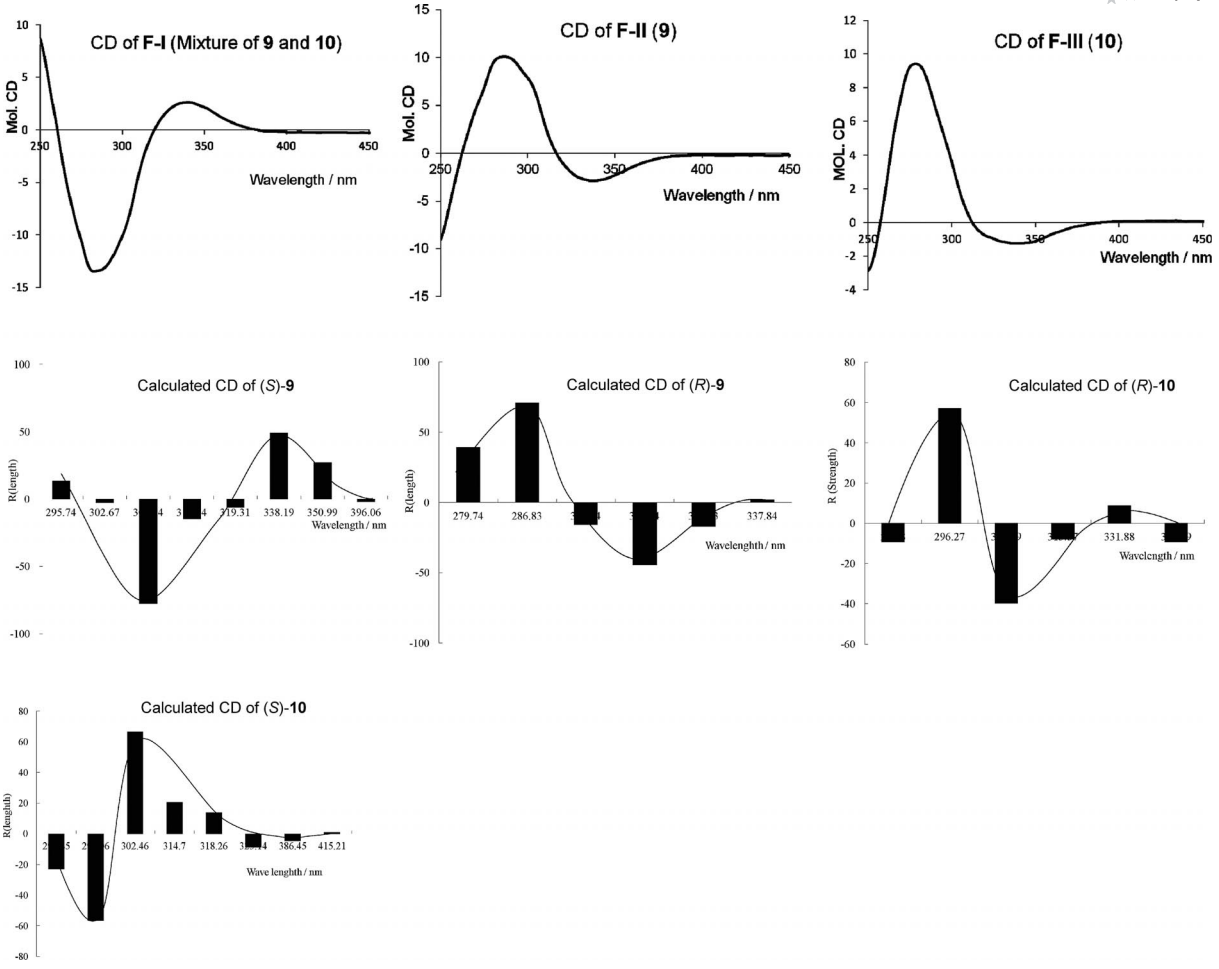
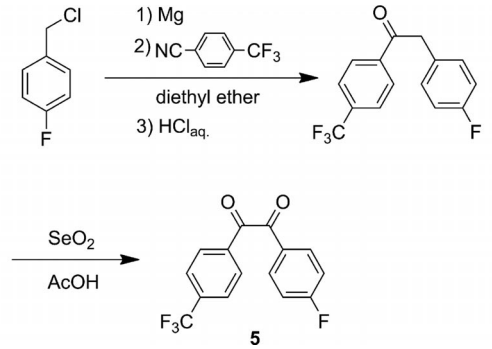


Figure 6. The CD spectra of **F-I**, **F-II**, and **F-III** recorded in ethanol and the calculated CD spectra of **9** and **10** by using the TDDFT-B3LYP method. Rotational strengths (R) are given in cgs (10^{-40} erg esu cm/G).

CD spectra of **F-I**, **F-II**, and **F-III** were recorded, and the calculation of CD spectra were carried out based on the GAUSSIAN 03w software package, as show in Figure 6. A geometry optimization was performed by using the B3LYP functional with 6-31G* basis sets. The absolute configurations were assigned by comparison of the CD spectra with the calculated CD spectra. The absolute configurations of **F-I**, **F-II**, and **F-III** were assigned as a mixture of (*S*)-**9** and (*S*)-**10**, (*R*)-**9**, and (*R*)-**10**, respectively, as illustrated in Figure 6.

4-Fluoro-4′-(trifluoromethyl)benzil (5)



5

The procedure developed by Lalezari et al. was used.[5] (Trifluoromethyl)benzonitrile (5.70 g, 36.3 mmol) in anhydrous diethyl ether was added dropwise to a Grignard reagent prepared from 4-fluorobenzyl chloride (5.23 g, 36.3 mmol) and Mg (895 mg, 36.8 mmol). The reaction mixture was stirred, first at room temperature and then heated to reflux for 3 h, and decomposed with ice and hydrochloric acid. The product was extracted with diethyl ether, washed with water, and dried with $MgSO_4$. After the removal of the solvent, recrystallization from CH_2Cl_2/hexane gave 4-(trifluoromethyl)phenyl 4-fluorobenzyl ketone (7.72 g, 82%). SeO_2 (3.71 g, 33.0 mmol) was dissolved in glacial acetic acid, and 4-(trifluoromethyl)phenyl 4-fluorobenzyl ketone (9.31 g, 33.0 mmol) was added to the hot solution and the mixture was heated to reflux for 3 h. The Se precipitate was filtered off, the solvent was removed under reduced pressure, and the residue was dissolved in ethyl acetate and washed with aqueous $NaHCO_3$, water and dried with $MgSO_4$. After the removal of the solvent, **5** (9.24 g, 31.2 mmol, 94%) was obtained by recrystallization (CH_2Cl_2/hexane) as yellow crystals; m.p. 111–113 °C. IR (KBr): $\tilde{\nu}$ = 1665 (C=O), 1330 (CF_3) cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.14 (t, J = 8.4 Hz, 2 H), 7.70 (d, J = 9.2 Hz, 2 H), 7.96 (m, 2 H), 7.96 (d, J = 9.2 Hz, 2 H) ppm. $C_{15}H_8F_4O_2$: C, 60.82; H, 2.72; found C, 61.20; H, 1.73.

5-(4-Fluorophenyl)-2-phenyl-4-[4-(trifluoromethyl)phenyl]imidazole (6): Prepared by the method used by Davidson et al.[12] A solution of benzaldehyde (309 mg, 2.91 mmol), 4-fluoro-4′-(trifluoromethyl)benzil (**5**; 595 mg, 2.01 mmol), and ammonium acetate (2.64 g, 34.3 mmol) in acetic acid was heated to reflux under N_2 (the pro-

gress of the reaction was followed by TLC). Upon completion of the reaction, the cooled solution was poured into ice-cooled water to precipitate the product. The crude product was recrystallized-from ethanol to give **6** (457 mg, 59%) as transparent crystals needles; m.p. 252–254 °C. IR (KBr): $\tilde{\nu}$ = 1622 (C=N), 1520 (C=C), 1323 (CF_3), 1228 (C–F) cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ = 7.03 and 7.11 (t, J = 8.7 Hz, 2 H), 7.39–7.53 (m, 5 H), 7.58 (d, J = 8.7 Hz, 2 H), 7.69 (d, J = 8.4 Hz, 2 H), 7.93 (dd, J = 8.4 Hz, 1.2 Hz, 2 H), 9.37 and 9.46 (s, 1 H, NH) ppm. UV/Vis (EtOH): λ_{max} [log (ε/M^{-1} cm^{-1})] = 303 (4.39), 227 (4.30), 208 (4.31) nm. MS (FAB): m/z = 383 [M^+ + 1]. HRMS (FAB): calcd. for $C_{22}H_{15}F_4N_2$ 383.1171; found 383.1128. $C_{22}H_{14}F_4N_2 \cdot 1/2CH_3CH_2OH$: C, 68.14; H, 4.23; N, 6.91; found C, 68.07; H, 3.74; N, 6.92.

5-(4-Fluorophenyl)-4-hydroperoxy-2-phenyl-4-[4-(trifluoromethyl)-phenyl]-4*H*-isoimidazole (7) and 4-(4-Fluorophenyl)-4-hydroperoxy-2-phenyl-5-[4-(trifluoromethyl)phenyl]-4*H*-isoimidazole (8): Prepared by the method used by White et al.[2b] A mixed solution of **6** (150 mg, 0.39 mmol) in CH_2Cl_2 and a catalytic amount of methylene blue in methanol (1 mL) was cooled to –78 °C and irradiated with a sunlamp discharging O_2 gas through a UV-cutoff filter for 1.5 h. The reaction was followed by TLC. Upon completion of the reaction, the sensitizer was removed by syringe column chromatography (silica, CH_2Cl_2). The mixture was concentrated under reduced pressure maintaining a temperature below 15 °C. When the CH_2Cl_2 was removed, one milliliter of alcohol was added to the solvent to give the product as a powder, which was filtered and washed with alcohol. A regioisomeric mixture of compounds **7** and **8** (154 mg, 95%) was obtained as a colorless powder (**7/8** = 4:1 based on ^1H NMR analysis); m.p. 135–137 °C. IR (KBr): $\tilde{\nu}$ = 1603 (C=N), 1325 (CF_3), 1272 (C–F) cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ = 7.18–7.27 (m, 4 H), 7.37–7.44 (m, 1 H), 7.55 (d, J = 8.5 Hz, 2 H), 7.60 (d, J = 8.5 Hz, 2 H), 7.95 (d, J = 7.5 Hz, 2 H), 8.35 (dd, J = 8.5, 5.5 Hz, 2 H) ppm. UV/Vis (CH_2Cl_2): λ_{max} [log (ε/M^{-1} cm^{-1})] = 233 (4.22), 289 (4.29) nm. MS (FAB): m/z = 415 [M^+ + 1]. HRMS (FAB): calcd. for $C_{22}H_{15}F_4N_2O_2$ 415.1070; found 415.1135; $C_{22}H_{14}F_4N_2O_2 \cdot 1/2H_2O$: C, 62.41; H, 3.57; N, 6.62; found C, 62.63; H, 3.45; N, 6.32.

4-(*tert*-Butyldimethylsilylperoxy)-5-(4-fluorophenyl)-2-phenyl-4-[4-(trifluoromethyl)phenyl]-4*H*-isoimidazole [9 and (*R*)-9] and 4-(*tert*-Butyldimethylsilylperoxy)-4-(4-fluorophenyl)-2-phenyl-5-[4-(trifluoromethyl)phenyl]-4*H*-isoimidazole [(*R*)-10]: Prepared by the method used by Corey et al.[13] A Mixture of hydroperoxides **7** and **8** (209.0 mg, 0.504 mmol), imidazole (171.4 mg, 2.52 mmol), and *tert*-butyldimethylsilyl chloride (304.2 mg, 2.02 mmol) in pyridine (1 mL) was stirred for 20 min at 0 °C. Upon completion of the reaction, the solvent was removed under reduced pressure. The residue was washed with hexane, filtered, and the filtrate was purified by chromatography (silica; hexane/EtOAc, 40:1). After combining and concentrating the fractions, a regioisomeric mixture of products **9** and **10** was obtained as transparent crystals (234.2 mg, 88%; molar ratio, **9/10** = 4:1, based on ^1H NMR analysis). Recrystallization from 2-propanol gave **9** (89.0 mg, 38%) as colorless crystals; m.p. 93–94 °C. IR (KBr): $\tilde{\nu}$ = 2934 (C–H), 1605 (C=N), 1325 (CF_3), 1223 (C–F) cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 0.155 (s, 3 H), 0.213 (s, 3 H), 0.843 (s, 9 H), 7.13 (t, J = 9.0 Hz, 2 H), 7.42 (d, J = 8.4 Hz, 2 H), 7.51–7.61 (m, 5 H), 8.22 (dd, J = 9.0, 5.4 Hz, 2 H), 8.46 (d, J = 6.6 Hz, 2 H) ppm. UV/Vis (CH_2Cl_2): λ_{max} [log (ε/M^{-1} cm^{-1})] = 281 (4.26). $C_{28}H_{28}F_4N_2O_2Si$: C, 63.62; H, 5.34; N, 5.30; found C, 63.61; H, 5.28; N, 5.52.

The residue (3:1 mixture of **9** and **10**) was subjected to the HPLC with a Daicel Chiralpak AD-H column (hexane/2-propanol, 9:1). The structures of (*R*)-**9** and (*R*)-**10** were assigned by analysis of their ^1H NMR spectra. ^1H NMR (300 MHz, $CDCl_3$) spectra of (*R*)-**9** was same as that of **9**.

Compound (*R*)-**9**: M.p. 69–72 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 0.155 (s, 3 H), 0.213 (s, 3 H), 0.843 (s, 9 H), 7.14 (t, J = 9.0 Hz, 2 H), 7.42 (d, J = 8.4 Hz, 2 H), 7.51–7.61 (m, 5 H), 8.22 (dd, J = 9.0, 5.4 Hz, 2 H), 8.45 (d, J = 6.6 Hz, 2 H).

Compound (*R*)-**10**: M.p. 42–45 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 0.017 (s, 3 H), 0.072 (s, 3 H), 0.843 (s, 9 H), 6.98 (t, J = 8.7 Hz, 2 H), 7.51–7.61 (m, 5 H), 7.72 (d, J = 8.4 Hz, 2 H), 8.32 (d, J = 8.4 Hz, 2 H), 8.46 (d, J = 6.6 Hz, 2 H) ppm. $C_{28}H_{28}F_4N_2O_2Si$: C, 63.62; H, 5.34; N, 5.30; found C, 63.58; H, 5.29; N, 5.43.

***N*-(4-Fluorobenzyl)-*N*′-[4-(trifluoromethyl)benzyl]benzamidine (11):** A solution of peroxides **7/8** (107 mg) in acetone (1 mL) was added to TBAF/THF solution. When chemiluminescence was finished, the solution was neutralized with acetic acid. Components in the solution were isolated by chromatography (silica; hexane/EtOAc, 3:1), from which amidine **11** was obtained (33 mg) as a colorless powder; m.p. 121–128 °C. IR (KBr): $\tilde{\nu}$ = 1707 (C=O), 1328 (CF_3), 1238 (C-F in the phenyl group) cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ = 7.27 (t, J = 8.5 Hz, 2 H), 7.51 (t, J = 8.0 Hz, 2 H), 7.61 (t, J = 8.0 Hz, 1 H), 7.86 (d, J = 8.0 Hz, 2 H), 7.97 (d, J = 7.0 Hz, 2 H), 8.09 (br. t, J = 1.0 Hz, 2 H), 8.22 (d, J = 8.0 Hz, 2 H), 10.71 (br. s, 1 H) ppm. UV/Vis (EtOH): λ_{max} [log (ε/M^{-1} cm^{-1})] = 247 (4.38) nm. MS (FAB): m/z = 415 [M^+ + 1].

Supporting Information (see footnote on the first page of this article): ^1H NMR spectra of **6**–**10**, and the decay rates of CL reactions of (*R*)-**9** and (*R*)-**10**.

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