

Thermolysis of 3-Methyl-3-(*o*-aryl)-1,2-dioxetanes: Activation Parameters and Chemiexcitation Yields

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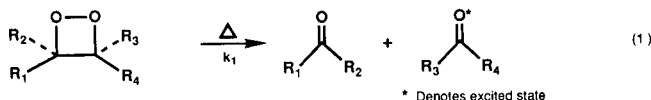
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3-Methyl-3-(*o*-tolyl)-1,2-dioxetane **1** and 3-methyl-4-(*o*-bromophenyl)-1,2-dioxetane **2** were synthesized in low yield by the β -bromo hydroperoxide method. The activation parameters were determined by the chemiluminescence method (for **1** $\Delta G^\ddagger = 24.7 \pm 0.3$ kcal/mol, $\Delta H^\ddagger = 25.4$, $\Delta S^\ddagger = +1.9$ e.u., $k_{60} = 3.4 \times 10^{-4}$ s $^{-1}$; for **2** $\Delta G^\ddagger = 24.7 \pm 0.4$ kcal/mol, $\Delta H^\ddagger = 24.7$, $\Delta S^\ddagger = 0.0$ e.u., $k_{60} = 4.1 \times 10^{-4}$ s $^{-1}$). Thermolysis of **1-2** directly produced high yields of excited triplets as expected for this type of dioxetane [triplet chemiexcitation yields (ϕ^T) for **1** 0.03; for **2** 0.02; the ϕ^T/ϕ^S ratios were estimated to be approximately 200 for both compounds]. The effect of *ortho*-aryl substituents was inconsistent with electronic effects. The *ortho* substitution in **1-2** resulted in a marked increase in stability of the dioxetanes. The results are discussed in relation to a diradical-like mechanism.

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The thermolysis of simple alkyl and/or aryl substituted dioxetanes has been shown to produce carbonyl fragments, one of which may be produced in an excited state, resulting in direct, high yields of excited triplets (Reaction 1) [1]. Historically, two mechanisms have been employed

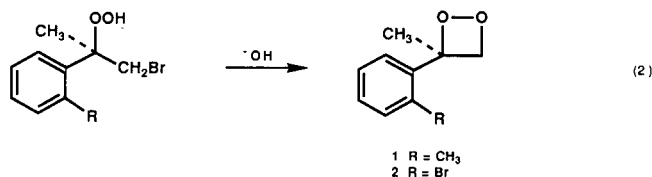


[1,2] to describe the thermal decomposition of simply substituted dioxetanes: (a) diradical and (b) concerted. Studies, including steric effects [3a-c], lack of additional ring-strain effect on E_a [3d], lack of ring position deuterium isotope effect [3e], Hammett-type studies [3f-g], insensitivity of E_a to phenyl for methyl substitution [3i], absence of solvent effects [3j], *cis/trans* isomer stability [3k], and group additivity-type calculations [3l], have been interpreted to support a diradical-type two-step process. A merged mechanism has been proposed by Adam [4] based on effect of the degree and pattern of methyl substitution. The results of a recent MC-SCF/MP2 study on the chemiluminescent decomposition of 1,2-dioxetanes by Robb and co-workers [5] have been interpreted to suggest a diradical mechanism in which the rate-determining step occurs on the T_1 surface. Our study [6] on the properties of *trans*-3-methyl-4-(*o*-anisyl)-1,2-dioxetane, the only reported *o*-aryl substituted dioxetane, suggested that the increased stability might be due to an unusual steric effect of the *o*-aryl substituent. We report here the synthesis and characterization of two 3,3-disubstituted dioxetanes that show the effect of *ortho*-aryl substitution is general.

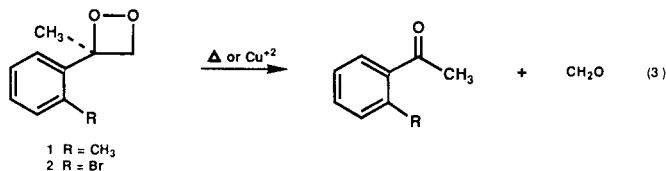
Results.

3-Methyl-3-(*o*-tolyl)-1,2-dioxetane **1** and 3-methyl-3-(*o*-bromophenyl)-1,2-dioxetane **2** were synthesized in low yield ($\sim 2\%$) by the Kopecky method [7], closure of the

corresponding β -bromo hydroperoxides with base at low temperature (Reaction 2). The β -bromo hydroperoxides



were synthesized by treatment of the corresponding alkenes with an electrophilic bromine source in the presence of concentrated hydrogen peroxide at low temperature [7]. The dioxetanes were purified by low-temperature column chromatography. Dioxetanes **1-2** were characterized by ^1H nmr spectroscopy and by analysis of their cleavage products; in all cases only the expected cleavage products were produced (Reaction 3).



The rates of thermolysis of dioxetanes **1-2** were monitored by the decay of chemiluminescence intensity in aerated xylenes with or without added fluorescers at constant temperatures. The rates of thermal decomposition were cleanly first order for at least three half-lives and showed no dependence on the type or amount of added fluorscer. The first-order rate constants (k_1) were determined over a 50° temperature range. Correlation coefficients were 0.995 or greater for all cases. The activation parameters, shown in Table 1, were determined by the Arrhenius method.

Table 1
Activation Parameters [a] for the Thermolysis of Dioxetanes **1-5** in Xylenes

No.	Dioxetane	Ea kcal/mol	ΔH^\ddagger [a]	ΔS^\ddagger e.u. [a]	ΔG^\ddagger kcal/mol [a]	k_{1s}^{-1}
1		26.1±0.3	25.4	1.9	24.7±0.3	3.4×10 ⁻⁴ (60°)
2		25.4±0.4	24.7	0.0	24.7±0.4	4.1×10 ⁻⁴ (60°)
3		22.9 [b]	22.2	-5.0	23.9	2.8×10 ⁻⁴ (45°)
4		23.6 [b]	22.9	-2.3	23.7	3.5×10 ⁻⁴ (45°)
5		23.5 [b]	22.8	-2.9	23.8	3.1×10 ⁻⁴ (45°)

[a] Calculated at 60°. [b] Reference [3f].

As expected for this type of dioxetane, the thermolyses of **1-2** without the presence of added fluorescers showed only weak chemiluminescence. Addition of 9,10-dibromoanthracene (DBA) or 9,10-diphenylanthracene (DPA) to solutions of the dioxetanes greatly increased the intensity of chemiluminescence without affecting the kinetics. The yields of chemiexcitation generated during dioxetane thermolysis at 60° were determined by the chemiluminescence (DBA/DPA) method. For both dioxetanes, thermolysis directly produced high yields of excited triplets (ϕ^T), $\phi^T = 0.03$ for **1** and 0.02 for **2**, and low yields of excited singlets (ϕ^S). The ϕ^T values for **1** and **2** are within experimental error for the method. The ϕ^S values were extremely low and were not determined. The ratio of ϕ^T/ϕ^S was estimated to be approximately 200 for both compounds.

Discussion.

In general, Hammett studies on aryl dioxetanes have shown that the electronic effect of a *p*-aryl electron-donating group should produce a slight decrease in dioxetane stability [1,3g,h,6] while that of a *p*-aryl electron-withdrawing group should yield a slight increase in stability of the dioxetane [3g,h]. However, both dioxetanes **1** and **2** are more stable than the unsubstituted compound of the series, 3-methyl-3-phenyl-1,2-dioxetane, **3**, [3f] by ~1 kcal/mol (in ΔG^\ddagger , Table 1). For this series, the para-substituted analogs, 3-methyl-3-(*p*-tolyl)-1,2-dioxetane, **4**, and 3-methyl-3-(*p*-bromophenyl)-1,2-dioxetane, **5**, have been

found [3f] to be of similar stability to that of 3-methyl-3-phenyl-1,2-dioxetane, **3** (see Table 1). Thus, the relative stabilities of **1** and **2** can not be due to electronic effects.

The increased stability noted for compounds **1** and **2** is similar to that noted for a *trans*-3,4-disubstituted dioxetane. The study [6] of *trans*-3-methyl-4-aryl-1,2-dioxetanes found that the *o*-anisyl compound, **6**, was more stable than the *p*-anisyl isomer, **7**, by 0.8 kcal/mol in ΔG^\ddagger . The results were interpreted in terms of a steric (buttressing) effect. The present study shows that effect of *o*-substitution in aryl dioxetanes is an increase in the stability of the compound regardless of the electronic character of the substituent.

The chemiexcitation yields for the thermolysis of **1** and **2** of 2-3% are within the range of 2-10% that is normally observed for disubstituted dioxetanes [1]. The ϕ^S values were estimated to be extremely low, around 0.01%. The overall chemiexcitation yields and the high ratios of ϕ^T/ϕ^S were as expected [1] for the thermolysis of simple dioxetanes. The data suggest that these dioxetanes are undergoing thermolysis by the standard process; no change in mechanism has occurred.

The relative stability of **1** and **2** can not be electronic in nature but must be the result of conformational or steric effects. Studies have shown that changes in dioxetane-ring torsion angle can affect dioxetane stability [1a,8]. The relative stabilities of simple dioxetanes have been shown [1a,3b] to correlate with the number of formal substitu-

tions on a 3-“methyl” group. This effect is thought to lead to an increase in steric interactions which hinder O–O bond scission. This type of steric effect appears to be due to direct interactions (3,3 interactions) with the oxygen closest to the site rather than interactions with groups across the ring. Molecular mechanics calculations (MM2) [9] have been found to be of value in understanding dioxetane properties [1a,8,10]. Molecular mechanics calculated structures for dioxetanes **1–5** were essentially identical. Thus, torsion-angle changes appear not to be involved in the observed stabilization of *o*-aryl substituted dioxetanes. The study [6] on *trans*-3-methyl-4-(*o*-anisyl)-1,2-dioxetane noted a large rotational barrier around the aryl-dioxetane ring bond. The results were interpreted as a possible 3,4-buttressing effect. The present cases do not show an interaction between the *o*-aryl substituent and the dioxetane ring hydrogens. The results appear consistent with a 3,3-interaction and predict that dioxetanes with 2,6-disubstituted aryl groups should show large increases in stability.

EXPERIMENTAL

All solvents were of reagent grade. The ¹H nmr spectra were recorded on a Varian EM-360L NMR spectrometer. 9,10-Diphenylanthracene (Aldrich) and 9,10-dibromoanthracene (Aldrich) were recrystallized from xylenes (Aldrich) before use. The alkenes, 2-(*o*-tolyl)-1-propene and 2-(*o*-bromophenyl)-1-propene, were prepared from the corresponding ketones (Aldrich) by the Wittig route. Molecular mechanics calculations were carried out on a microVAX using the MM2 program MODEL Version KS 2.94 available from Professor K. Steliou, University of Montreal, Canada.

Dioxetane Synthesis.

The following two-step procedure for the synthesis of 3-methyl-3-(*o*-tolyl)-1,2-dioxetane **1** was employed for the preparation of both compounds. A 30 mmole sample of 2-(*o*-tolyl)-1-propene was converted to 1-bromo-2-(*o*-tolyl)-2-hydroperoxypropane (**Caution!**) by the Kopecky procedure [7]. The β -bromo hydroperoxide, a clear, viscous oil (**Caution!**), was purified by precipitation from pentane at -78° ; ¹H nmr (deuteriochloroform): δ 1.78 (s, 3H), δ 2.55 (s, 3H), δ 3.86 (s, 2H), δ 7.1-7.5 (m, 4H), δ 8.3 (br s, 1H); ¹H nmr data for 1-bromo-2-(*o*-bromophenyl)-2-hydroperoxypropane: δ 1.85 (s, 3H), δ 4.11 (s, 2H), δ 7.0-8.0 (m, 4H), δ 8.4 (br s, 1H). Both β -bromo hydroperoxides, active oxygen content was approximately $94 \pm 4\%$, were isolated in $60 \pm 5\%$ yields.

Purified β -bromo hydroperoxide (~ 14 mmoles, **Caution!**) was placed in 5 ml of carbon tetrachloride or methylene chloride with rapid magnetic stirring and cooled by an ice bath. A solution of 2.5 g of potassium hydroperoxide in 5-10 ml of cold, deionized water was added dropwise (15 minutes) to the β -bromo hydroperoxide solution in the dark to yield a two-phase mixture. The optimized reaction time for synthesis of **1** and **2** was determined to be 15 to 30 minutes. The pale yellow organic layer was separated, dried over magnesium sulfate and filtered. The solvent was removed under reduced pressure to yield an oil which contained the dioxetane as a minor component (crude yields ~ 10 -15%). The dioxetane was purified by column-chromatography at -78°

using a jacketed 1 cm i.d. column packed with 20 g of silica gel containing 1% Na₂EDTA (pentane). The impure dioxetane in carbon tetrachloride was added to the column and washed with 50 ml of pentane followed by successive 50 ml additions of a 5% methylene chloride/pentane (v/v) step gradient. Fractions were assayed for dioxetane content by placing a 25 μ l aliquot into a heated DBA solution (1 ml) in the chemiluminescence apparatus. Fractions containing the most dioxetane were combined and the solvent removed under reduced pressure. The purified dioxetanes, **1-2**, were pale-yellow oils. The purity was checked by ¹H nmr spectroscopy. Dioxetane samples that were less than 95% pure were passed through a column a second time. The only impurities were the corresponding epoxides the presence of which had no effect on dioxetane properties. The epoxides had slightly longer retention times than the dioxetanes and were only present in the latter half of the dioxetane-containing fractions. Pure samples of the dioxetanes were obtained by removal of solvent from the early fractions. Generally, the latter fractions contained 10 to 50% epoxide in addition to dioxetane. The overall yield of dioxetane was 1-2% for both cases. The dioxetanes were stored in deuteriochloroform at -30° or lower with little decomposition noted even after several months of storage. The ¹H nmr data (deuteriochloroform) are: for **1** δ 2.01 (s, 3H), δ 2.14 (s, 3H), δ 5.15 and δ 5.51, (AB, J = 4 Hz, 2H), δ 7.20 (br s, 4H); for **2**, δ 2.06 (s, 3H), δ 5.40 and δ 5.60 (AB, J = 5 Hz, 2H), δ 7.1-7.8 (m, 4H).

Product Studies.

The following general procedure was employed for the thermolysis of dioxetanes **1-2**. A solution of dioxetane (approximately 0.2 M) in carbon tetrachloride was heated at 60° in a sealed nmr sample tube until the yellow color disappeared. In all cases, the expected carbonyl fragments were the sole products detected by nmr spectroscopy. The formaldehyde generated from the cleavage of **1** and **2** was not observed under thermolysis conditions. However, formaldehyde was observed during the metal-ion catalyzed decomposition of both **1** and **2** at low temperature. Traces of Cu⁺² ions were added to the dioxetane solution by dipping a Cu wire into the solution. The dioxetane was observed to decompose within minutes under those conditions at low temperature. The carbonyl products were identified by comparison with authentic samples.

Kinetic Studies.

The chemiluminescence monitoring system is essentially identical with that previously described [1]. The reaction cell was jacketed and the temperature maintained by using a constant temperature bath $\pm 0.1^\circ$. The temperature in the cell was monitored by use of a YSI Model 425C apparatus with a series 400 probe ($\pm 0.2^\circ$). The cell was pretreated with a concentrated aqueous Na₂EDTA solution and washed with solvent before use. Kinetic experiments were carried out employing xylenes (mixture of isomers) as solvent. The initial dioxetane concentration was low (approximately 10^{-4} M) in order to avoid complications from induced decomposition. Experiments carried out without added fluorescer or with low concentrations ($\sim 10^{-3}$) of DBA or DPA were of the first order for at least three half-lives and showed no measurable dependence on the type or amount of added fluorescer.

Chemexcitation Yields.

The instrument was calibrated with tetramethyl-1,2-dioxetane

[1d,3d] by taking the triplet yield (ϕ^T determined by the DBA method as 0.30 at 60°. All measurements were carried out at 60° with a constant initial concentration of each dioxetane. The ϕ^T yields were calculated by a method that has been discussed in detail [1g]. The concentrations of the dioxetanes were determined by ¹H nmr spectroscopy vs concentration of added standard. The experimental error in the chemiluminescence method [1] is estimated to be ±50% of observed value. The ϕ^T/ϕ^S ratios are an estimate since the light yields are rounded off and because of the large inherent error in the method.

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