small extent in Figure 1a. If the probe wavelength is tuned farther to the red for 7AI in water, the 70-ps transient is obscured by this long-lived transient; at 450 nm the transient is no longer observable, presumably because the extinction coefficient for the long-lived species increases toward redder wavelengths. To the red of 580 nm, the 950-ps rise time is also obscured by the long-lived species. On the basis of the data displayed in Figure 1c, we attribute this species to a solvated electron, e^-_{aq}. The long-lived absorption that we detect with the white-light continuum from our picosecond absorption apparatus from 400 to 720 nm is consistent with published spectra for e^-_{aq}.[12,13] This assignment is strengthened by the observation that the electron scavenger,[14] KNO_3, transiently quenches this absorbing species. Collins suggested the possibility of photoinduced electron ejection in excited-state complexes of 7AI and solvent.[15] We provide the first direct evidence for the production of e^-_{aq}. Because the rise time of the electron appearance is instantaneous on the time scale of our experiment, we propose that the origin of e^-_{aq} is an electronic state lying slightly above the fluorescent state. This assignment is strengthened by our observation of two overlapping electronic states in the fluorescence-excitation anisotropy spectrum of 7AI.[16]

Finally, the 950-ps rise time for the transient absorbance at 392 nm of 7AI in water agrees, within experimental error, with the 915-ps fluorescence decay of 7AI in water.[11] There is evidence[17] for triplet formation in 7AI, and we tentatively assign the rising absorption at 392 nm to a triplet species. Bent and Hayon observe triplet absorption for indole and tryptophan at similar wavelengths.[13]

Conclusions

Our earlier hypothesis concerning the "tautomer-like" nature of the fluorescent species requires modification. The 70-ps decay of the excited-state absorbance of 7AI in water (Figure 1a) and the similar decay and rise times on the blue and red edges of the 7AI emission spectrum (Figure 2) indicate that *at least a fraction* of the 7AI in aqueous solution is capable of executing excited-state tautomerization. This suggests that the observed single exponential decay of the 7AI chromophore in water, when monitoring the *entire* emission band, is a fortuitous consequence of compensating the small contributions of decaying and rising lifetime components. We have also detected additional products of nonradiative decay from the 7AI excited state: the solvated electron and a species that is assigned to a triplet. In order to unravel the photophysics of 7AI and 7AT and to understand why 7AT appears to be such a well-behaved probe molecule, it will be necessary to take these nonradiative channels into account.

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One-Electron Reduction of Methyl(trifluoromethyl)dioxirane by Iodide Ion. Evidence for an Electron-Transfer Chain Reaction Mediated by the Superoxide Ion

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Abstract: One-electron-transfer processes, triggered by I^- in catalytic amounts, convert methyl(trifluoromethyl)dioxirane (**1**) into 1,1,1-trifluoropropanone (trifluoroacetone) and dioxygen. It is proposed that the initially formed bis(oxy)methylene radical anion **1′** performs nucleophilic attack at the dioxirane **1**, yielding a dimeric radical anion **2′**; the latter then fragments into trifluoroacetone and superoxide ion ($O_2^{\bullet-}$). The intermediacy of superoxide ion (the propagator of the electron-transfer chain reaction) is demonstrated by its trapping with either benzoyl chloride or chlorotrimethylsilane. Also, potassium superoxide in catalytic amounts induces the fast and complete conversion of **1** into trifluoroacetone with evolution of dioxygen. The redox reaction between dioxirane **1** and iodide ion in acidic medium yields substantial amounts of hydrogen peroxide, which was detected by the catalase probe.

Introduction

Methyl(trifluoromethyl)dioxirane (**1**), obtained[1] in a solution of 1,1,1-trifluoropropanone (hereafter trifluoroacetone) by reaction of the latter ketone with potassium peroxomonosulfate (Caroate, the triple salt $2KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$), is one of the most powerful yet selective oxygen-transfer reagents toward a variety of substrates.[2] During the last two years, new aspects concerning

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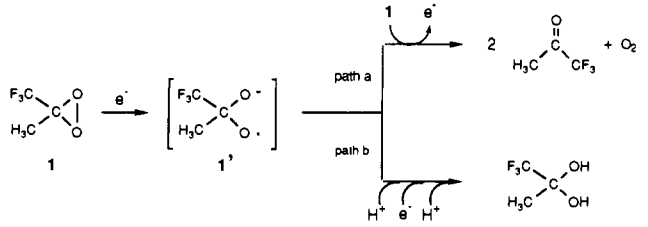
Scheme I



the chemistry of this oxidant have been investigated,[3] especially the possibility of one-electron transfer with suitable donors.[4-6]

We recently reported[3] on the preparation of ketone-free solutions of **1** in halocarbon solvents. This allows investigation of the mechanistic details concerning the chemistry of this powerful oxidant, which hitherto had remained obscure because of the presence of trifluoroacetone (parent ketone and solvent of **1**). For example, by employing ketone-free solutions of **1** in halocarbon solvents, we showed that no significant amounts of trifluoroacetone were produced in the thermal and photochemical decomposition of **1** in the gas phase, in solution, and under matrix isolation conditions. In another recent study, using nitroxides,[4] we proposed that dioxirane **1** may act as a one-electron acceptor leading to trifluoroacetone. For this study, again, ketone-free solutions were necessary. We speculated that the resulting radical anion **1'** may react with dioxirane **1** in a complex electron-transfer chain process, to yield trifluoroacetone and dioxygen (path a, Scheme I).

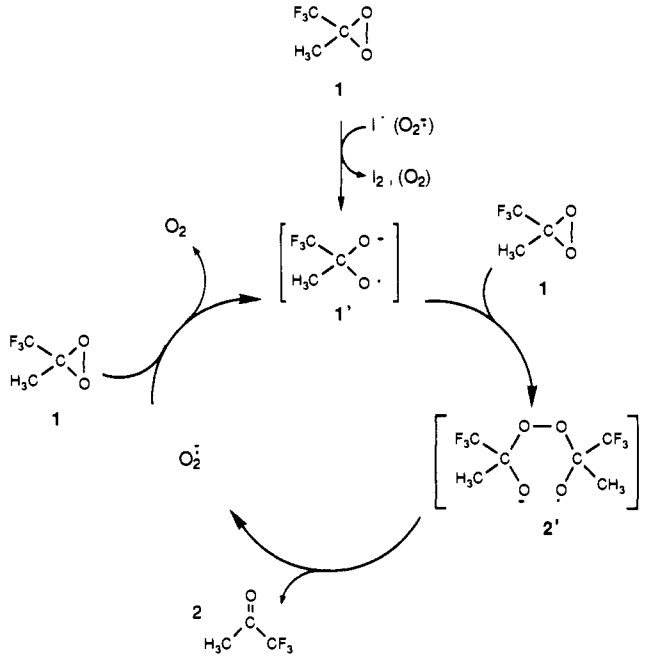
To establish the intermediacy of the radical anion **1'** in the redox chemistry of dioxirane **1** requires an electron donor with the following characteristics: (1) The one-electron reductant should not undergo oxygen transfer by the dioxirane. (ii) The donor should preferentially generate a neutral product upon electron transfer, thereby favoring the escape of the radical anion **1'** from the geminate pair in the solvent cage. We chose iodide ion for this purpose. Iodine is formed in the reduction of dioxiranes by potassium iodide; however, iodine is not further oxidized by oxygen transfer with dioxirane **1**. In fact, this reaction is employed as a routine method for the quantitative determination of the peroxide content of dioxiranes.[7] Of course, employing ketone-free dioxirane solutions is essential to enable observation of the complete product spectrum of this redox chemistry.

In line with our expectations, we now report that catalytic amounts of tetrabutylammonium iodide or lithium iodide promote the conversion of dioxirane **1** into trifluoroacetone and dioxygen as the sole products. A one-electron-transfer chain reaction, mediated by the superoxide anion, is envisaged for the observed electron-transfer chemistry (Scheme II) between dioxirane **1** and iodide ion.

Results and Discussion

Methyl(trifluoromethyl)dioxirane (**1**) solutions in ketone-free chlorinated solvent were prepared as described previously.[3] The decomposition of **1** by iodide anion was performed by using ketone-free solutions of **1** in methylene chloride or deuteriochloroform. The source of iodide anion was either tetrabutylammonium iodide or lithium iodide. In acetone-d_6 solutions, LiI was employed for reactions to be monitored by ^{1}H NMR; in halocarbon solvents, Bu_4NI was used because of its higher solubility.

Scheme II



When ketone-free solutions of dioxirane **1** in deuteriochloroform or deuterated methylene chloride were treated at 0 °C with a catalytic amount of tetrabutylammonium iodide (**1**:Bu_4NI ratio, ca. 20:1), gas evolution was immediately noticed. Quantitative ^{1}H NMR analysis showed the complete conversion of dioxirane **1** into trifluoroacetone (path a, Scheme I). No other products could be detected by ^{1}H NMR. The gas evolved was identified as dioxygen by GC–MS and quantified by volumetric analysis.

The same results were obtained when a methylene chloride/acetone-d_6 solution of **1** was treated with LiI in acetone-d_6. In a control experiment it was shown that dioxirane **1** was stable toward an excess of tetrabutylammonium hexafluorophosphate under the above described reaction conditions.

The absence of the characteristic products derived from the dioxyl diradical of **1** (i.e., methyl trifluoroacetate, methyl acetate, trifluoromethyl acetate, trifluoroacetic acid, and 1,1,1-trifluoroethane),[3] rules out the intervention of this species in the iodide ion-induced decomposition of dioxirane **1**.

The fact that a catalytic amount of tetrabutylammonium iodide or lithium iodide promoted the complete conversion of dioxirane **1** into trifluoroacetone and dioxygen as the only products suggests the involvement of an electron-transfer chain mechanism (Scheme II), which involves the generation of the radical anion **1'**.

We propose that the consecutive reaction of **1'** with another molecule of dioxirane **1** affords the dimeric radical anion **2'**, which would then fragment into two molecules of trifluoroacetone and the superoxide anion. Subsequent reduction of dioxirane **1** by $O_2^{\cdot-}$ would then afford dioxygen and radical anion **1'**; the latter would again react with dioxirane **1** to produce the radical anion **2'**, thereby completing an effective electron-transfer chain decomposition of **1** into O_2 and trifluoroacetone. The superoxide serves as the propagating species. Experimental evidence herein supports this mechanistic hypothesis.

Control experiments confirmed that catalytic amounts of potassium superoxide can induce the fast and complete conversion of dioxirane **1** into trifluoroacetone with evolution of oxygen gas. This suggests that superoxide ion $O_2^{\cdot-}$ is capable of reducing dioxirane **1** by one-electron transfer, which is akin to that reported for other less reactive peroxides.[8,9]

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An important mechanistic feature in Scheme II consists of envisaging dimeric radical anion **2'** as the precursor of $O_2^{\bullet-}$. Indeed, that radical anion **2'** can fragment into trifluoroacetone and $O_2^{\bullet-}$ is supported by recent experimental evidence.[10] We found that treatment of 3,6-dimethyl-3,6-bis(trifluoromethyl)-1,2,4,5-tetroxane (**2**) with Bu_4NI or KO_2 gives exclusively trifluoroacetone and dioxygen, most likely via an electron-transfer chain process. The dimeric radical anion **2'** should arise from the attack of the radical anion **1'** at the O–O bond of the dioxirane **1**, as pointed out by the data below.

The alternative fragmentation of the tetroxane radical anion **2'** to yield directly dioxygen, trifluoroacetone, and the radical anion of the latter would be thermodynamically unfavored; in fact we find that the reduction potential of trifluoroacetone is more negative [$E°(Ag/Ag^+) = -1.5$ V, in acetone] than that of dioxygen [$E°(Ag/Ag^+) = -0.6$ V, in acetone]. Furthermore, an estimate of the irreversible reduction potential of dioxirane **1** gave as a lower limit a positive value of $E°(Ag/Ag^+)$ in excess of 0.4 V (in acetone).[11] This makes dioxirane **1** the most easily reduced species in this complex redox process and, in fact, the most easily reducible peroxide known to date. Therefore, it is not surprising that the most favored electron-transfer process by the in situ generated $O_2^{\bullet-}$ is the reduction of dioxirane **1** to generate dioxygen and the radical anion **1'**.

The radical anion **1'**, on account of its negative charge, should possess both nucleophilic and basic character. Thus, significant changes in the reaction pathways are expected in the presence of electrophiles and acids (Scheme II). Actually, iodometry of dioxiranes must be carried out under acidic conditions and with an *excess* of I^-, which constitutes a standard quantitative method to establish peroxide content.[7] However, it is clear that an electron-transfer chain reaction such as in Scheme II is not operative under such conditions, since catalytic rather than stoichiometric iodide would otherwise suffice to induce dioxirane consumption. Therefore, we investigated the reduction of dioxirane **1** by iodide anion in the presence of acids and electrophiles, in order to probe whether the intermediate chain-carrying radical anions **1'**, **2'**, and $O_2^{\bullet-}$ (Scheme II) could be diverted into alternative product channels, either by protonation or by electrophile trapping. We find that when a catalytic amount of tetrabutylammonium iodide (**1**:Bu_4NI ratio, ca. 20:1) was added to a solution of dioxirane **1** in 3:2 $DCCl_3/CF_3CO_2H$ at 0 °C, no oxygen evolution was observed. Quantitative ^1H NMR (80 MHz) analysis after 10 min showed that 20% of the dioxirane **1** initially present was converted exclusively into trifluoroacetone, since the electron-transfer chain reaction is still partially operative under these conditions. No other products were detected. In a control experiment, solutions of dioxirane **1** in 3:2 $DCCl_3$/AcOH and/or CF_3CO_2H at 0 °C were found to be quite stable over a period of 3 h.

These results suggest that the eventual protonation of the radical anion **1'** by strong acid (such as CF_3CO_2H) in methylene chloride, followed by reduction of the resulting α-hydroxyalkoxyl radical by iodide anion (path b, Scheme I), is not as effective as nucleophilic attack by **1'** at the dioxirane **1**. Moreover, protonation of the radical anion **1'** would result in an α-hydroxyalkoxyl radical as the transient species. The latter would in turn be expected to undergo α-cleavage to yield methyl and trifluoromethyl radicals, thus triggering a complex radical chain decomposition of dioxirane **1** to ester products.[3] These were not observed in any of the reactions described herein. Therefore, the familiar stoichiometric redox process involved in the iodometry of peroxides (i.e., two successive one-electron-reduction steps with protonation of the intermediate alkoxide ion) as the *only* reaction channel available to dioxiranes (path b, Scheme I) is ruled out. Additional stoichiometric experiments aimed at firmly establishing this are described below in detail (see Experimental Section).

Table I. Iodometric Titrations of the Reaction of Dioxirane **1** with Bu_4NI in Methylene Chloride at 0 °C[a,b]

run	initial molar ratio **1**:Bu_4NI:acid[c]	molar ratio[d] **1**:$Na_2S_2O_3$
1a	1:1:0	1:0.4
1b[e]	1:1:0	1:0.4
2	1:2:0	1:0.4
3	1:2:63	1:2.0
4	1:3:63	1:1.9
5a	1:1:70	1:1.5
5b[e]	1:1:70	1:1.0
6a	1:1.1:76	1:1.3
6b[f]	1:1.1:76	1:0.9
7	1:3.5:4.5	1:1.6
8[g]	1:3.5:3.3	1:1.8

[a] Initial concentration of **1** ranged from 0.23 to 0.28 M; that of Bu_4NI, from 0.17 to 0.35 M. [b] A 0.02 N aqueous sodium thiosulfate solution was employed; titration volumes are the average of at least three identical runs within a standard error of ±0.05 mL. [c] Except for run 8, pure glacial acetic acid was used. [d] Values equivalent to the ratio of **1** to iodide consumed in the stoichiometric redox reaction. [e] An equimolar amount of thioanisole was added ca. 2 min after iodide addition (see Experimental Section); runs 1a and 6a were carried out as blanks. [f] Catalase was added prior to the iodometric titration (see Experimental Section); run 6a was carried out as a control experiment. [g] Trifluoroacetic acid was employed.

Since in Scheme II the superoxide ion is proposed as the electron-transfer chain carrier in the redox decomposition of dioxirane **1** by iodide ion, and given that $O_2^{\bullet-}$ is known to generate hydrogen peroxide under acidic conditions, we probed for the latter as the secondary oxidant by employing catalase,[12] a reagent specific for H_2O_2 (cf. Experimental Section; runs 6a and 6b, Table I). When the reduction of dioxirane **1** was carried out by Bu_4NI in a 1:1 molar ratio in CH_2Cl_2/AcOH (in large excess), iodometric titration of the reaction mixture revealed a higher amount of iodine than that expected on the basis of the amount of starting iodide (cf. Experimental Section; runs 5a and 6a, Table I). However, when the reaction mixture was treated with catalase before titration, the expected amount of sodium thiosulfate was consumed, which reveals that hydrogen peroxide is produced under these conditions.

Moreover, we performed a new set of experiments in which the iodide reduction of dioxirane **1** was carried out in the presence of electrophiles such as benzoyl chloride and chlorotrimethylsilane as trapping agents.[8] The results obtained support the intermediacy of superoxide ion proposed above. The reaction of equimolar amounts of dioxirane **1**, Bu_4NI, and benzoyl chloride at 0 °C afforded a 1:1 mixture of benzoic anhydride (the product of reaction of $O_2^{\bullet-}$ with PhCOCl) and unreacted benzoyl chloride (50% conversion). When an analogous experiment was carried out with LiI and chlorotrimethylsilane, hexamethyldisiloxane (the product derived from $O_2^{\bullet-}$ and Me_3SiCl) was formed as the only product. In both cases the dioxirane **1** was completely converted into trifluoroacetone. In control experiments it was found that dioxirane **1** does not react appreciably with excess benzoyl chloride; however, it does react with chlorotrimethylsilane, yielding products other than hexamethyldisiloxane, which were not characterized.

Thus, the three well-established[8] inherent chemical properties of the superoxide ion, i.e., its ability to act as a one-electron reductant, as a base, and as a nucleophile, have been monitored in the complex redox behavior of dioxirane **1**. In fact, in the iodide-initiated electron-transfer-reductive chain decomposition of dioxirane **1** (in the absence of strong acids or electrophiles), superoxide plays the role of a chain carrier. On the other hand, in reductions carried out in the presence of acetic or trifluoroacetic acid, the superoxide ion exhibits its high affinity for protons[8b] to yield hydrogen peroxide (established by the mentioned catalase probe). Finally, when the reactions are carried out in the presence of electrophiles like benzoyl chloride or trimethylchlorosilane,

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typical products derived from the initial nucleophilic attack of superoxide ion on these reagents are found.[8a,c,9] These results corroborate convincingly that the superoxide ion is formed in the reaction of dioxirane **1** with iodide (Scheme II).

The salient finding of the present study is the unprecedented chemistry of radical anion **1'**, derived from one of the smallest possible cyclic peroxides, dioxirane **1**. Remarkable is its propensity for nucleophilic attack on dioxirane **1** to generate superoxide ion via the dimeric radical anion **2'**. The alternative rearrangement of radical anion **1'** into its ester radical anion by a 1,2-alkyl shift[2a,b] or α-cleavage of radical anion **1'** into a carboxylate ion and an alkyl radical[3,4] does not take place. Even protonation or further reduction of **1'** to its dianion are of subordinate importance, compared to the favored bimolecular nucleophilic attack at dioxirane **1**. These observations and the unusually high reduction potential recorded for **1**, i.e., $E^\circ > +0.4$ V,[11] hint at some special factors intervening in determining the reactivity of radical anion **1'**, as well as the observed high electrophilic character of dioxirane **1**.

In conclusion, we believe that this study serves to establish the ability of dioxirane **1** to act as a one-electron acceptor and provides insight into the chemistry of the corresponding radical anion **1'**. This was made possible through the availability of ketone-free solutions of methyl(trifluoromethyl)dioxirane (**1**) in chlorinated solvents and by the finding that iodide ion can act as a one-electron donor, without suffering subsequent oxygen transfer. Future studies on oxidation reactions with dioxirane **1** should consider the participation of electron-transfer processes with the eventual involvement of superoxide ion.

Experimental Section

General Aspects. ^{1}H NMR and ^{13}C NMR spectroscopy was performed on a Bruker WP 80 SY spectrometer (80 MHz) or on a Varian XL 200 instrument. GC–MS spectroscopy was performed on a Hewlett-Packard 3890A instrument (SIM mode, 70 eV) equipped with a 25-m SE 54 capillary column (0.25-μm film thickness, 0.32-mm i.d.).

All the solvents and reagents were purified by standard procedures and were freshly distilled prior to use. 1,1,1-Trifluoropropanone, potassium peroxomonosulfate (Caroate), and catalase from Fluka and lithium iodide, tetrabutylammonium iodide, and potassium superoxide from Aldrich were used as received. Aqueous solutions of sodium thiosulfate (Fluka) were standardized with potassium iodate. Methyl(trifluoromethyl)dioxirane (**1**) solutions in ketone-free CH_2Cl_2 or $DCCl_3$ were obtained by following previously reported methods.[3]

Iodometry. General Procedure. An aliquot of dioxirane **1** solution in CH_2Cl_2, kept at 0 °C, was poured into a mixture of 5 mL of 50% aqueous potassium iodide and 3 mL of 3:2 AcOH/acetone. The developed iodine was then titrated with standardized sodium thiosulfate. To estimate the amount of iodide developed in the reactions of dioxirane **1** with known amounts of Bu_4NI in CH_2Cl_2, both in the presence and in the absence of acid, the sodium thiosulfate aqueous solution was directly added to the reaction mixture and the titration medium homogenized by addition of doubly distilled acetone.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Catalytic Tetrabutylammonium Iodide. NMR Monitoring. A catalytic amount of tetrabutylammonium iodide (approximate **1**:Bu_4NI ratio, 20:1) was added to ca. 0.5 mL of a 0.2–0.4 M standardized solution of dioxirane **1** in CD_2Cl_2 or $DCCl_3$, contained in an NMR tube at 0 °C, and vigorously shaken. Gas evolution was immediately noticed. ^{1}H NMR monitoring (80 MHz) showed the progressive conversion of **1** into trifluoroacetone, which was completed within ca. 5 min. No other products were detected by ^{1}H NMR spectroscopy. Quantitative analyses were performed by comparing the ^{1}H NMR integrals of **1** and trifluoroacetone against $HCCl_3$ as internal standard. When the reaction was carried out by using dioxirane **1** solutions in trifluoroacetone, identical results were obtained. Upon performing the reduction in acetone-d_6 and using lithium iodide instead of Bu_4NI, again, identical results were obtained. Control experiments, carried out by using tetrabutylammonium hexafluorophosphate instead of tetrabutylammonium iodide, did not lead to any significant decomposition of dioxirane **1** under identical conditions.

Qualitative and Quantitative Oxygen Detection. To 0.5 mL of a 0.5 M solution (0.25 mmol) of dioxirane **1** in CH_2Cl_2 placed into a sealed round-bottomed flask was added 0.05 mL of a 0.4 M solution (0.02 mmol) of tetrabutylammonium iodide in CH_2Cl_2 at 0 °C by means of a syringe. After 5 min, a sample of the reaction gas phase was injected into the GC–MS. The N_2:O_2 ratio, determined by the relative intensities of the peaks at $m/z = 28$ and $m/z = 32$, was found to be 100:90 in the reaction gas phase, compared to 100:68 in air. For quantitative analysis, the reaction was carried out in a flask connected to a gas buret. After the apparatus was purged with oxygen gas, 0.05 mL of a 0.4 M solution of tetrabutylammonium iodide (0.02 mmol) in CH_2Cl_2 was injected into 0.5 mL of a 0.5 M solution of the dioxirane **1** (0.25 mmol) in CH_2Cl_2, previously thermostated at 0 °C. The evolved oxygen gas (2.9 mL) was measured at atmospheric pressure (765.5 Torr) and 21 °C. After correction for the water vapor pressure at this temperature (18.7 Torr), the amount of evolved oxygen was estimated to be 0.12 mmol (96% yield).

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Potassium Superoxide. To 0.5 mL of a ca. 0.6 M solution (0.30 mmol) of **1** in CD_2Cl_2 or $DCCl_3$, placed into an NMR tube, was added a catalytic amount of potassium superoxide (approximate **1**:KO_2 ratio, ca. 20:1) at 0 °C and vigorously shaken. Gas evolution was immediately noticed, and the successive ^{1}H NMR spectra (80 MHz) showed the progressive conversion (within ca. 10 min) of dioxirane **1** into trifluoroacetone. No other products could be detected. Quantitative NMR analysis was carried out by using $HCCl_3$ as internal standard, as mentioned above.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Catalytic Tetrabutylammonium Iodide in Acid Medium. NMR Monitoring. To a mixture of 0.2 mL of a 0.8 M solution (0.16 mmol) of dioxirane **1** in $DCCl_3$ ($HCCl_3$ as internal standard) and 0.3 mL of pure trifluoroacetic acid, placed into an NMR tube, was added a catalytic amount of tetrabutylammonium iodide (**1**:Bu_4NI ratio, ca. 20:1) at 0 °C. Quantitative ^{1}H NMR (80 MHz) analysis showed, after 10 min, 20% conversion of dioxirane **1** into trifluoroacetone. Control experiments revealed that dioxirane **1** does not decompose appreciably in the presence of an excess of trifluoroacetic acid.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Equimolar Tetrabutylammonium Iodide. To 0.1 mL of a 0.28 M solution (0.028 mmol) of dioxirane **1** in CH_2Cl_2 at 0 °C was added, with vigorous stirring, 0.08 mL of a 0.35 M solution (0.028 mmol) of Bu_4NI in CH_2Cl_2. The developed iodine was titrated directly (cf. Iodometry. General Procedure) by using 0.015 N aqueous sodium thiosulfate (run 1a, Table I). In a parallel experiment, an excess (0.010 mL) of pure thioanisole ($PhSCH_3$) was added to the reaction solution 2 min after the addition of Bu_4NI, and the mixture was titrated directly (run 1b, Table I). Thus, under these nonacidic conditions no secondary oxidizing species was formed in situ able to convert the sulfide to its sulfoxide.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Excess Tetrabutylammonium Iodide in Acidic Medium. Iodometry. In two distinct experiments, to a mixture of 0.1 mL of a 0.28 M solution (0.028 mmol) of dioxirane **1** in CH_2Cl_2 and 0.1 mL (1.76 mmol) of AcOH were respectively added, at 0 °C with vigorous stirring, 0.16 mL of a 0.35 M solution (0.056 mmol; run 3, Table I) and 0.24 mL of a 0.35 M solution (0.084 mmol; run 4, Table I) of Bu_4NI in CH_2Cl_2. The developed iodine was titrated directly by using the above described standard procedure. Both reactions afforded the expected stoichiometric amounts of iodine; excess iodide ion did not cause any change in the titration results.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Equimolar Iodide in Acidic Media. NMR Monitoring. To a mixture of 0.2 mL of a ca. 0.8 M solution (0.16 mmol) of dioxirane **1** in $DCCl_3$ or CD_2Cl_2 ($HCCl_3$ as internal standard) and 0.3 mL of CF_3CO_2H was added, at 0 °C, an equimolar amount of Bu_4NI in $DCCl_3$ or LiI in acetone-d_6. Quantitative ^{1}H NMR (80 MHz) analysis of the resulting mixture after ca. 10 min showed the total conversion of dioxirane **1** into trifluoroacetone. An equimolar amount of thioanisole (based on the initial molar amounts of the reagents) was added to the mixture at 0 °C. ^{1}H NMR monitoring revealed the slow oxidation of thioanisole to the corresponding sulfoxide up to ca. 50% conversion.

Iodometry. To a mixture of 0.1 mL of a 0.23 M solution (0.023 mmol) of dioxirane **1** in CH_2Cl_2 and 0.1 mL (1.61 mmol) of AcOH was added, at 0 °C with vigorous stirring, 0.07 mL of a 0.35 M solution (0.023 mmol) of Bu_4NI in CH_2Cl_2. The developed iodine was titrated directly (run 5a, Table I). The consumption of sodium thiosulfate was higher than expected from the starting amount of iodide, which confirmed that some other oxidizing species was formed under these conditions. In contrast, in a parallel experiment, when the reaction mixture was treated with thioanisole before iodometric titration and allowed to stand for 30 min, the amount of sodium thiosulfate consumed was in agreement with that expected from iodometry (run 5b, Table I). A control experiment showed that the sulfide does not react with I_2 under these conditions and is thus not responsible for the lower iodometric titer.

Detection of Hydrogen Peroxide in the Reaction of Methyl(trifluoromethyl)dioxirane (1) with Equimolar Iodide in Acid Medium. To a mixture of 0.1 mL of a 0.23 M solution (0.023 mmol) of dioxirane **1** in CH_2Cl_2 and 0.1 mL of AcOH was added, at 0 °C with vigorous stirring, an aliquot (0.15 mL) of a 0.17 M solution (0.026 mmol) of Bu_4NI in CH_2Cl_2. After 2 min, doubly distilled water (1.5 mL) was added, and the reaction mixture was stirred for an additional 2 min at room tem-

perature. Catalase (0.2 mL of a 30% solution in glycerol, ca. 274 100 units/mL) was added, and after ca. 5 min the mixture was titrated directly with 0.02 N aqueous sodium thiosulfate; the titer showed a lower consumption of reductant than the parallel experiment carried out in the absence of catalase (runs 6a and 6b, Table I).

In view of the fact that the reaction of dioxirane **1** with an excess of iodide in acidic medium obeys the iodometric stoichiometry (runs 3 and 4, Table I), we can argue that the iodine titer derives from both dioxirane **1** and hydrogen peroxide. Furthermore, it was found that the formation of iodine depends on the amount and strength of the acid employed. In the presence of an excess of iodide and at a lower concentration of acid, less iodine is liberated (runs 4 and 7, Table I) than when higher concentrations and stronger acid are used (runs 7 and 8, Table I). These latter results reflect the effectiveness of superoxide trapping to afford hydrogen peroxide.[8]

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Equimolar Iodide in the Presence of Benzoyl Chloride. To a mixture of 1 mL of a 0.27 M solution (0.27 mmol) of methyl(trifluoromethyl)dioxirane (**1**) in CH_2Cl_2 and 0.04 mL (0.35 mmol) of freshly distilled benzoyl chloride at 0 °C was added, with stirring, 0.8 mL of a 0.34 M solution (0.27 mmol) of tetrabutylammonium iodide in CH_2Cl_2. After 10 min at 0 °C the solvent was removed under vacuum and the residue dissolved in $DCCl_3$ and analyzed by NMR. The ^{13}C NMR spectrum (50 MHz) showed ca. 50% conversion of benzoyl chloride to benzoic anhydride. A control experiment revealed that under identical conditions dioxirane **1** is unreactive toward an excess of benzoyl chloride.

Reaction of Methyl(trifluoromethyl)dioxirane (1) with Lithium Iodide in the Presence of Chlorotrimethylsilane. To 0.1 mL of a 0.88 M solution (0.08 mmol) of dioxirane **1** in CH_2Cl_2 at 0 °C was added 0.01 mL (0.08 mmol) of freshly distilled chlorotrimethylsilane, quickly followed by the addition of 0.40 mL of a 0.2 M solution (0.08 mmol) of lithium iodide in acetone-d_6, with stirring. After 20 min, a ^1H NMR (80 MHz) spectrum was run; this showed total conversion of chlorotrimethylsilane into hexamethyldisiloxane. A control experiment revealed that dioxirane **1** oxidized chlorotrimethylsilane, but hexamethyldisiloxane was not found in the product mixture.

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Furans in Synthesis. 11.[1] Total Syntheses of (±)- and (-)-Fastigilin C

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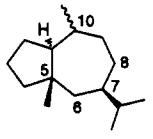
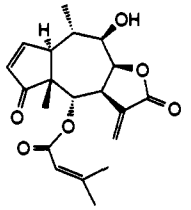
Abstract: Fastigilin C (**2**), a complex helenanolide, has been reported to exhibit cytotoxic and antineoplastic activity, thus making it an attractive target for total synthesis. We wish to report the first total syntheses of (±)- and (-)-fastigilin C ((±)- and (-)-**2**). As a result of our interest in the utilization of furan-terminated cyclizations as the key step in the construction of diverse ring systems, we envisioned (eq 1) furan **3** as the precursor to bicyclo[5.3.0]decane furan **4**, which should afford **2**. In the forward direction, a Mukaiyama Michael-aldol protocol affords **3** with complete control of relative stereochemistry. A mercury(II)-mediated-furan-terminated cyclization gives **4**, which is ultimately converted (17 steps, 24.6% overall yield) to (±)-fastigilin C ((±)-**2**). A porcine pancreatic lipase mediated resolution of 4-hydroxy-2-methyl-2-cyclopentenone leads to (*S*)-(+)-4-methoxy-2-methyl-2-cyclopentenone, which is converted (17 steps) to (-)-fastigilin C ((-)-**2**) in 14% overall yield.

The pseudoguaianolides, a group of butyrolactone-containing bicyclo[5.3.0]decanoid sesquiterpenes, are divided into the ambrosanes (**1a**) (10β-CH_3, lactone fused via C-6-C-7 or C-7-C-8)



1a 10-β-CH_3 Ambrosanes
1b 10-α-CH_3 Helenanes



2 Fastigilin-C

and the helenanes (**1b**) (10α-CH_3, lactone fused via C-7-C-8). The helenanes are more highly oxygenated and stereochemically complex and have been associated with diverse biological activities which include cytotoxic,[2] antileukemic,[2] and antiinflammatory properties.[3] Fastigilin C (**2**),[4a,b] one of the most intriguing of the helenanolides, was isolated from *Gaillardia fastagiata* by Herz[4a] and from *Baileya multiradiata* by Pettit.[4b] Fastigilin C (**2**), which exhibits substitution at each position about the seven-membered B-ring, has been reported to exhibit cytotoxic and antineoplastic activity,[4] thus making it an attractive target for

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