



Spin selectivity in the oxygenation of singlet phenylhalocarbenes with oxygen

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Abstract—Singlet phenylhalocarbenes are shown to react with triplet oxygen and the apparent spin-forbidden oxygenation rates are strongly dependent on substituents, i.e. in the decreasing order of Br>Cl \gg F for halogen and of p-NO₂>H \gg p-MeO for p-substituents. These results suggest the oxygenation of triplet halocarbene equilibrated with ground-state singlet, resulting in the first estimation of energy difference between the singlet and triplet states. © 2003 Elsevier Science Ltd. All rights reserved.

The reaction of oxygen with various substrates are known to be relatively slow in spite of their high exothermicity. The apparent discrepancy is sometimes explained by the spin-forbidden step in the reaction of triplet oxygen, ${}^{3}O_{2}$, and singlet substrates. In fact, it is well known that excited singlet oxygen, ${}^{1}O_{2}$, reacts facilely with various olefins and sulfides.¹ In relation to the spin selectivity on oxygenations, we became interested in the reaction of oxygen with carbenes of various spin-states.

Arylcarbenes of triplet ground-state are known to react smoothly with ${}^{3}O_{2}$ to yield carbonyl oxides² as established by laser flash spectroscopy.³ On the contrary, only a little is known on the oxygenation of singlet carbenes. Imidazolylidenes are a quite stable singlet carbene and could be treated under air.⁴ Recently we have reported that the singlet carbene reacts fast with ${}^{1}O_{2}$ to form a characteristic carbonyl oxide.⁵ Likewise, phenylhalocarbenes, a more reactive singlet intermediate, are reported not to react with oxygen⁶ except for the case of the *p*-nitrophenyl one.⁷ It is an open question whether the apparent spin-forbidden process for the reactive singlet carbenes does occur or not. Herein, we report an interesting aspect on the spin selectivity in the oxygenation of phenylhalocarbenes with ${}^{3}O_{2}$.

Phenylhalocarbenes (ArCX, 1), conveniently produced by photolyzing the corresponding diazirines (2)⁸ are known to be singlet⁹ and reactive for various substrates as studied by laser-flash spectroscopy.¹⁰ Since the decay of phenylchlorocarbene (1a) was unchanged by the presence of oxygen, the parent carbene has been assumed not to be reactive toward oxygen.6b-d We could reveal the moderate reactivity of 1a with oxygen by using Freon 113 as a non-reactive solvent,¹¹ i.e. the major product changed from dimer olefin under argon to benzoyl chloride under oxygen.¹² A laser-flash spectroscopy (YAG laser, 355 nm, $\sim 5 \text{ mJ}$)¹³ indicated that the decay of **1a** at 300 nm^{14a} is accelerated by oxygen, resulting in the oxygenation rate constant: $k_{O_2} = 1.2 \times 10^6$ M^{-1} s⁻¹ (in Freon 113 at room temperature).² A similar result was obtained for the case of phenylbromocarbene (1b); the decay of 1b at 347 nm^{14b} (lifetime $t=5.8 \ \mu s$) was decreased by oxygen (t=1.1 µs) affording k_{0_2} = 1.7×10^6 M⁻¹ s⁻¹. Now it is apparent that the reported no reaction of these carbenes with oxygen is simply due to the fast reaction toward solvent hydrocarbons.

Liu et al. reported on the exceptional reactivity of *p*-nitrophenylchlorocarbene (1c) with oxygen; its absorption at 320 nm in isooctane was quenched by oxygen producing carbonyl oxide absorption at 400 nm.⁷ We could reproduce similar results; the decay rate $(1.5 \times 10^6 \text{ s}^{-1})$ of 1c in Freon 113 under oxygen was practically identical with the growth of carbonyl oxide $(1.6 \times 10^6 \text{ s}^{-1})$. The rate constant for the reaction with oxygen, $k_{O_2} = 2.0 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$, was ca. 8-fold faster than that of 1a.¹⁵ Products from 2c (irradiated at >400 nm) were azine 5c under argon and aroyl chloride 6c, suggesting an efficient oxygenation of carbene 1c. Quite similar data were obtained for bromocarbene (1d); the

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absorption of 1d was observed at 335 nm and the oxygenation rate, $k_{O_2} = 5.3 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$, was slightly faster than that of 1c.

The product study for phenylhalocarbenes is summarized in Scheme 1. Photolysis of diazirines (2) produces halocarbenes (1), which are converted to dimer olefins (4) or azines (5). Under oxygen carbenes (1) are trapped to form carbonyl oxides (3) yielding finally benzoyl halides (6). Facile conversions of carbonyl oxides to the corresponding carbonyl compounds are well established as a reaction between two molecules of the oxide.^{2,3}

Intermediates and products for the photolysis of diazirines 2 under argon and oxygen are summarized in Table 1. For the case of **2a–d**, the corresponding carbenes 1a-d were observed with λ_{max} at 300-350 nm and their decay was accelerated by oxygen, the major pathway being the oxygenation to yield 3 and finally 6. On the other hand, the oxygenation of carbene 1e (X=F)and 1f (Ar = p-MeOC₆H₄) was inefficient. The major product from fluorocarbene 1e was dimer olefin 4e even under oxygen, oxygenated product being only <1%. Here the oxygenation rate may be estimated to be $<1\times10^5$ M⁻¹ s⁻¹ in comparison to the efficient reaction for carbenes 1c and 1d under the same conditions. For the case of p-MeO isomer (1f) its absorption maximum was observed at 360 nm,¹⁶ but the decay was not altered by oxygen and 6f was not detected. From the decay rate of 1f (i.e. 5×10^5 s⁻¹) and detection limit (0.5%), the k_{O_1} value for **1f** may be estimated to be $<1 \times 10^5$ M⁻¹ s⁻¹. $<1\times10^{5}$ M⁻¹ s⁻¹

Products and oxygenation rates for six phenylhalocarbenes are summarized in Table 1. It is clear that the oxygenation efficiencies are profoundly dependent on aryl substituents and α -halogens. The oxygenation was accelerated by the order of p-NO₂>H \gg p-MeO on phenyl and of Br>Cl»F for halogens. These experimental results are discussed in relation to two possible mechanisms: (a) spin-forbidden oxygenation of halocarbene 1 and (b) spin-allowed oxygenation via $^{3}1$ as shown in Scheme 2. Mechanism (a) is the spin-forbidden oxygenation between singlet carbene ${}^{1}\mathbf{1}$ and ${}^{3}\mathbf{O}_{2}$. Oxidations are classified as the charge or electron transfer from substrates to oxidants and so it is generally accepted that electron-donating substituents on sub-strates facilitate the reaction.^{1a,17} Such a trend was not observed for the present case and the reactivity order of p-NO₂>H \gg p-MeO is not explicable on the basis of charge or electron transfer from halocarbenes to oxygen.

Mechanism (b) is the spin-allowed oxygenation of triplet ³**1** with ³O₂ by assuming an equilibrium between ¹**1** and ³**1**. Here, the equilibrium should be established because the oxygenation rate was proportional to oxygen concentration.¹⁸ Assumption of the allowed reaction of ³**1** with ³O₂ (Mechanism b) explains our experimental results reasonably as discussed in the following. The spin-allowed reaction of triplet ³Ph₂C: and ³O₂ is known to be as fast as $k_{O_2} = (1-5) \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$;¹⁹ these values are acceptable since the formation of singlet products from the two triplet materials is 1/9,²⁰ i.e. 1/9 of the diffusion rate constant. Thus, the equilibrium constant K for ¹**1** and ³**1** could be calculated from the





Table 1. Products and oxygenation rates in the photolysis of diazirines (2) in Freon 113

	ArXCN ₂ (2)		ArXC: $(1)^a$	Products ^b		0
	X	Ar	(λ_{\max}, nm)	Argon	0 ₂	- Oxygen. of Γ^{c} ($k_{O_2}, M^{-1} s^{-1}$)
a	Cl	C ₆ H ₅	300	4	6	1.2×10^{6}
b	Br	C_6H_5	347	4	6	1.7×10^{6}
c	Cl	$p-NO_2C_6H_4$	315	5	6	2.0×10^{7}
d	Br	p-NO ₂ C ₆ H ₄	335	5	6	5.3×10^{7}
e	F	$p-NO_2C_6H_4$	d	4	4+6 (<1%)	<1×10 ^{5,e}
f	Br	p-MeOC ₆ H ₄	360	5	5	<1×10 ^{5,e}

^a Transient spectra of carbenes (1) 250 ns after laser flash at 355 nm at room temperature.

^b Products from the photolysis of **2** under argon or oxygen. See Ref. 12 for details.

^c Second-order rate constants, k_{O_2} (M⁻¹ s⁻¹), obtained from the dependence of decay of 1 on [O₂].

^d Could not be determined due to the strong absorption of unknown by-product.

^e Estimated from product selectivity for 6e and 6f. See text for details.

Table 2. Estimated K and ΔG_{ST} values for ¹1 and ³1

Carbene	K ^a	$\Delta G_{\rm ST}{}^{\rm b}$	$\Delta G_{ m ST}^{ m calcd,c}$
1a	1.2×10^{-3}	-17	$-40; -15^{d}$
1b	1.7×10^{-3}	-16	-28
1c	2.0×10^{-2}	-10	-8.8
1d	5.3×10^{-2}	-7.5	-5.4
1e	$< 1 \times 10^{-4}$	<-23	$-40; -27^{d}$
1f	$< 1 \times 10^{-4}$	<-23	-38 ^d

^a Equilibrium constants (K) between ¹1 and ³1 by assuming the k_T value (Scheme 2) as $1 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$.

^b Singlet-triplet energy gap (kJ mol⁻¹) from $-RT \ln K$.

^c Energy gap (kJ mol⁻¹) by DFT of BLYP/6-311G*.

^d DFT calculations of pBP/DN** (Spartan).

observed value by assuming the oxygenation rate of $k_{\rm T} = 1 \times 10^9 {\rm M}^{-1} {\rm s}^{-1}$ via pathway (b) of Scheme 2. The free energy differences $\Delta G_{\rm ST}$ between the S and T states may be obtained from $\Delta G_{\rm ST} = -RT \ln K$ and the resulting values are listed in Table 2. It is clear that halocarbenes suffering with more efficient oxygenation possess a smaller negative $\Delta G_{\rm ST}$ value, i.e. the smaller energy differences between '1 and '31.

In the last column of Table 2 are listed $\Delta G_{\rm ST}^{\rm calcdd}$ values calculated theoretically by the DFT method; mostly with BLYP/6-311G^{*21} and partially with pBP/DN^{**22} (Spartan). It is interesting to note that these $\Delta G_{\rm ST}^{\rm calcd}$ values are roughly in line with those of experimental $\Delta G_{\rm ST}$ ones. In other words, the theoretical prediction reproduces well the observed substituent effect of *p*-NO₂C₆H₄>C₆H₅ \gg *p*-MeOC₆H₅ and of Br>Cl \gg F for the present oxygenation via the triplet sate. For the simple cases of halocarbenes their singlet state has been calculated to be stabilized in the order of F \gg Cl>Br for halogens.²³ Similarly, theoretical calculations predicted that for the case of aryl carbenes their triplet state is stabilized by a *p*-nitro group and destabilized by a *p*-methoxy substituent.²⁴

Temperature effect on the oxygenation has been studied for the case of carbene **1c**. The k_{O_2} values in Freon 113 were 1.01, 1.20. 1.23, 1.43, and 1.83×10^7 M⁻¹ s⁻¹ at 263.0, 273.0, 283.0, 293.0, and 303.0 K, respectively. From the plot of $\ln k_{O_2}$ versus 1/T were calculated $E_a = 9.0$ kJ mol⁻¹ and $A = 6.13 \times 10^8$. The activation energy of 9.0 kJ mol⁻¹ is close to the ΔG_{ST} value of 10.0 kJ mol⁻¹, supporting Mechanism (b) involving the equilibrium between ¹1 and ³1.

All of the results are explained reasonably by assuming the spin-allowed oxygenation of triplet halocarbenes with ${}^{3}O_{2}$ (Mechanism (b)). The observed substituent effects on phenyl and halogens are only understood by the stabilizing or destabilizing effect of these groups. For example, the p-NO₂C₆H₄ group interacts strongly with the p-orbital of carbene (cf. Scheme 2), resulting in the stabilization, compared to phenyl one, of the T state. In contrast, the fluoro group interacts with the s-orbital, stabilizing the S state significantly. In the field of carbene reactions, singlet-triplet energy gaps are an important factor for controlling their reactivity and selectivity.²⁵ The present oxygenation of halocarbenes is shown to be one of typical examples governed by the spin-selection rule.²⁶

In conclusion, the apparent spin-forbidden oxygenation of singlet halocarbenes (1) with ${}^{3}O_{2}$ is shown to proceed via the spin-allowed reaction between ${}^{3}O_{2}$ and ${}^{3}1$ equilibrated with ${}^{1}1$. Only by this mechanism are explicable the substituent effects of p-NO₂>H \gg p-MeO and Br> Cl \gg F. This is the first successful study in determining singlet–triplet energy gap of 'singlet' phenylhalocarbenes.

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