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The Reaction of Triplet Nitrenes with Oxygen: A Computational Study

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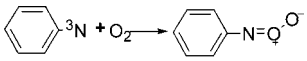
ABSTRACT



Triplet carbenes react much more rapidly with oxygen than do triplet nitrenes. This trend is explained by DFT and MO calculations.

Triplet aromatic carbenes react with oxygen at rates that approach diffusion control.[1] Triplet aromatic nitrenes react with oxygen much more slowly than the analogous carbene processes.[2] Gritsan and Pritchina have reported that triplet *p*-aminophenylnitrene reacts with oxygen with a rate constant of $(4.5 \pm 1.2) \times 10^6$ M^{-1} s^{-1} in hexane and that the corresponding rate constant for the para nitro analogue is $(0.8 \pm 0.1) \times 10^6$ M^{-1} s^{-1} under the same conditions.[2a] Similar results were obtained with *p*-tolylnitrene. Liang and Schuster[2b] reported that triplet *p*-nitrophenylnitrene reacts with oxygen with a rate constant smaller than 2×10^5 M^{-1} s^{-1} in acetonitrile. To investigate the origin of the different reactivity of triplet carbenes and nitrenes with oxygen, density functional theoretical (DFT) and ab initio molecular orbital calculations were performed.[3,4]

For the DFT calculations, all structures of interest were completely optimized at the B3LYP/6-31G* level. Analytical vibrational frequencies were calculated at the same level for each stationary point to verify a minimum energy structure and to provide zero-point vibrational energy corrections, which were scaled by a factor of 0.9806.[5] Each transition state was verified to connect to the respective reactant and product by careful optimization (opt = calcfc or calcall) after displacement (typically 10%) along the reaction path for the normal coordinate of the imaginary vibrational frequency. The zero-point vibrational energies as well as the thermal and entropic contributions to the free energies were taken from the B3LYP/6-31G* frequency calculations. Single-point energy calculations for all stationary points were performed at the B3LYP/6-311+G**(6d) level using the corresponding B3LYP/6-31G* geometries. In some cases, CASPT2 single-point energies were calculated with the B3LYP/6-31G* geometries, and CBS-QB3[6] calculations were performed. The energies provided are enthalpies and free energies at 298.15 K. In some cases, solvation calculations were performed with the polarizable continuum model (PCM)[7] using acetonitrile as the solvent. All of the calculations were performed using Gaussian 98 at the Ohio Supercomputer Center.

Calculations have been reported that predict that carbene[8] and nitrene[9] oxides have singlet ground states. Zelentsov *et al*. using CASSCF[9] methods predicted that the singlet−triplet energy gap of C_6H_5NOO is −13.6 kcal/mol. Our DFT, CBS-

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QB3, and CASPT2 calculations also indicate that CH_3-NOO, CH_3-O-N-O-O and C_6H_5NOO have singlet ground states, as shown in Table 1, in agreement with previous reports.

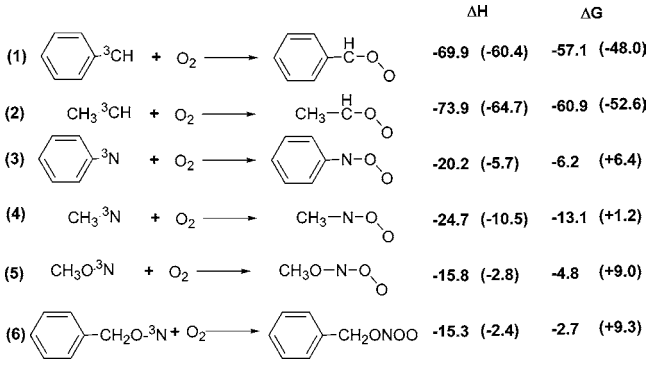
Table 1. DFT, CASPT2, and CBS-QB3 Calculated Energy Separations ΔH (298 K) (kcal/mol)[a]

	CH_3-N-O-O	Ph-N-O-O	CH_3O-N-O-O
open-shell singlet	51.8	53.6	48.3
triplet	20.1	14.8	16.0
	(24.1)	(16.4)	(18.5)
	[13.7]	[8.5]	[10.0]
closed-shell singlet	0	0	0
	(0)	(0)	(0)
	[0]	[0]	[0]

[a] CBS-QB3 numbers are in parentheses, and B3LYP/6-311+G**//B3LYP/6-31G* values are in brackets.

To assess the difference between carbenes and nitrenes, CBS-QB3 calculations were used to calculate the ΔH and ΔG of reactions 1−6 (kcal/mol) (Scheme 1).

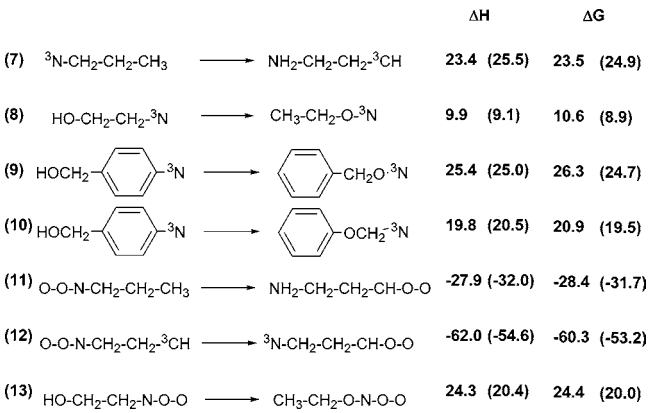
Scheme 1. CBS-QB3 and DFT Calculations of Carbenes and Nitrenes with Oxygen (298 K, kcal/mol); B3LYP/6-311+G**//B3LYP/6-31G* Numbers Are in Parentheses



The reaction of triplet phenylcarbene with oxygen is exceedingly exoergic (−57.1 kcal/mol), but the analogous reaction of triplet phenylnitrene is much less exoergic (−6.2 kcal/mol) at 298 K. This explains the very different rates of reaction of these intermediates with oxygen. The C−O bond formed in the reaction of a triplet carbene with oxygen is much stronger than the bond formed between N and O in the analogous nitrene reaction, hence the faster rate of the former process.

To better understand these results, the series of reactions 7−13 were calculated (Scheme 2).

Scheme 2. CBS-QB3 and DFT Calculations of Reactions (298 K, kcal/mol); B3LYP/6-311+G**//B3LYP/6-31G* Numbers Are in Parentheses



As shown in eq 7, a triplet alkylnitrene is considerably more stable than an isomeric triplet alkyl carbene. This effect was deduced by experiment and confirmed by theory for phenylnitrene and isomeric pyridylcarbenes.[10−12]

Equation 8 clearly indicates that triplet nitreno-ethanol is more stable than triplet ethoxynitrene. The dominant effect in this equation is the weakness of the N−O bond of the nitrene relative to the OH bond of the alcohol. This same effect is also evident in eqs 9 and 10, which reveal that a phenyl group is a far more stabilizing triplet nitrene substituent than either a benzyloxy or alkyl group.

Reaction 11 reveals that carbene oxides are much more stable than the isomeric nitrene oxides. As N−H and C−H bond dissociation energies are rather similar,[13] it is clear that the bond formed in the carbene reaction is much stronger than the corresponding bond in the nitrene oxidation process. This explains the increased exothermicity and rate of the carbene reaction with oxygen, relative to triplet phenylnitrene.

A triplet nitrene-carbene oxide is much more stable (eq 12) than a nitrene oxide-triplet carbene because a triplet nitrene is more stable than a triplet carbene and a nitrene oxide is less stable than a carbene oxide. The two effects are nearly additive.

Equation 13 demonstrates that the nitrene-oxide ethanol is more stable than ethoxynitrene oxide. The alkoxy group destabilizes a nitrene oxide more than it destabilizes a triplet nitrene. This makes the reaction of the triplet alkoxy nitrene

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with oxygen slightly less favorable than the corresponding reaction of a triplet arylnitrene.

Srinivasan et al.[14] have generated benzyloxynitrene in acetonitrile solution and used TRIR spectroscopy to demonstrate that this nitrene reacts with oxygen with a large rate constant of 10^{9-10} M^{-1} s^{-1}. This result cannot be explained by a difference in reaction thermodynamics of triplet phenyl versus triplet methoxynitrene (see Scheme 1, reaction 3 versus reaction 5), which are rather similar. We, therefore, investigated an electron transfer route to form the nitrene oxides. Our calculations predict that oxynitrenes are much more readily ionized than arylnitrenes (Figure 1). Triplet

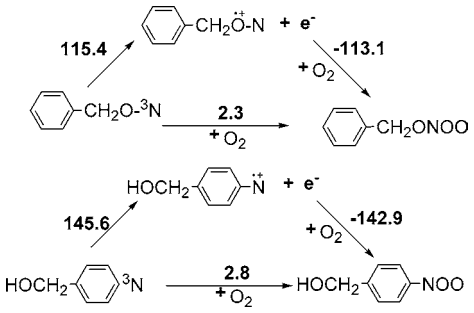
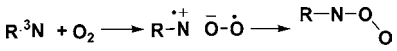


Figure 1. Reactions of nitrenes with oxygen, ΔG (298 K) (kcal/mol), calculated at the B3LYP/6-311+G**//B3LYP/6-31G* level in acetonitrile (PCM).

benzyloxynitrene is more readily ionized than its hydroxymethylphenylnitrene analogue by ~30 kcal/mol in acetonitrile.

Thus we speculate that oxynitrenes react faster with oxygen than do arylnitrenes because of partial electron transfer in the transition state followed by rapid collapse of the "ion pair" to form the nitrene oxide.



Based on our speculation that the oxynitrenes may react faster due to an electron transfer component, we searched for transition states for the conversion of the nitrenes to the nitrene oxides at the B3LYP level in both the gas phase and with the PCM model for solvation (using acetonitrile). There is, of course, some ambiguity about the multiplicity of the spin state for the transition states, as the nitrene and molecular oxygen are triplet states but the nitrene oxide product is a singlet. All attempts to locate transition states on the singlet surface (using both closed- and open-shell methods) were unsuccessful. However, using a triplet state description for the transition state provided a number of transition states for the reactions of methylnitrene, methoxynitrene, benzyloxynitrene and hydroxymethylphenylnitrene in the gas phase

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Table 2. Activation Barriers ($\Delta H^{\ddagger}$) for the Direct Reaction of O_2 with Various Nitrenes[a]

reaction	CBS-QB3 (gas)	B3LYP (gas)[b]	B3LYP (CH_3CN)[b]
CH_3-N	10.9	12.9	12.3
CH_3O-N	11.6	14.3	11.3
$HOCH_2Ph$-N	*c*	13.2	11.8
$PhCH_2O$-N	*c*	11.3	8.7

[a] In kcal/mol at 298 K, relative to the energies of infinitely separated reactants being set at zero in energy. In each case, the transition state was treated as a triplet with an unrestricted wave function. [b] Energies at the B3LYP/6-311+G** level based on fully optimized geometries at the B3LYP/6-31G* level in either the gas phase or with the PCM model for acetonitrile. [c] Not calculated.

and with the PCM model for acetonitrile. The enthalpic activation barriers are provided in Table 2 for the four different nitrenes that were investigated. For the smaller nitrenes in the gas phase, the CBS-QB3 level verified the B3LYP energetic trends were qualitatively reliable.

From Table 2, methylnitrene will react more slowly than methoxynitrene with molecular oxygen due to the relative activation barriers in the gas phase. At the CBS-QB3 and B3LYP levels, the preference for CH_3N over CH_3ON is 0.7 and 1.4 kcal/mol, respectively; however, the trend is inverted on going to acetonitrile where CH_3ON is predicted to have a 1.0 kcal/mol preference for reaction at the B3LYP level. For the larger nitrenes ($HOCH_2Ph$-N and $PhCH_2O$-N), both the gas phase and PCM levels show that the oxynitrene is predicted to have a strong preference for reaction with O_2. Indeed, the difference in activation barriers is 3.1 kcal/mol for the oxynitrene and the predicted (theoretical) relative rate difference would be 1.9×10^2 by traditional transition state theory. This theoretical rate preference for the oxynitrene compares favorably to the experimental 10^3-10^4 rate enhancement noted by Toscano and co-workers.[14]

We further investigated the electronic wave functions for the different transition states, and indeed, there is more electron transfer to the O_2 unit for the oxynitrenes as evaluated by the natural population analysis[15] method (see Table 3). There is a significant amount of negative charge

Table 3. Charge on the O_2 Unit in the Transition State for O_2 Reaction with Various Nitrenes at the B3LYP Level[a]

	gas phase		PCM (CH_3CN)	
reaction	6-31G*	6-311+G**	6-31G*	6-311+G**
CH_3-N	−0.068	−0.078	−0.072	−0.086
CH_3O-N	−0.072	−0.078	−0.158	−0.181
$HOCH_2Ph$-N	−0.071	*b*	−0.094	*b*
$PhCH_2O$-N	−0.145	−0.160	−0.183	−0.212

[a] In electrons, using the respective B3LYP/6-31G* geometry, which was fully optimized in either the gas phase or with the PCM model for acetonitrile. [b] Attempts to localize the orbitals with the NPA method failed with this basis set.

that accumulates on the O_2 fragment in the transition state (for the gas and PCM calculations), and the effect is more pronounced for the oxynitrenes. For example, the alkyl- and phenylnitrenes have about −0.08 e on the O_2 fragment in the transition state; however, the oxynitrenes have about −0.15 e in their analogous transition states. The effect is amplified at the PCM level.

Finally, the rearrangement of an alkoxynitrene oxide to a nitrate is predicted to be exceedingly exoergic and to involve a dioxaziridine intermediate (Figure 2). Such a pathway was

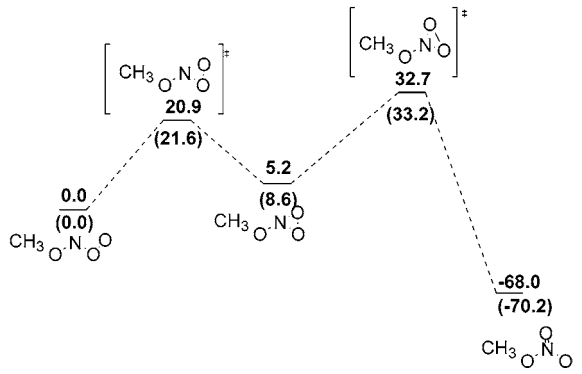

Figure 2. Rearrangement of an alkoxynitrene oxide to a nitrate, Δ*G* (298 K) (kcal/mol), calculated at the CBS-QB3 (top) and B3LYP/6-311+G**//B3LYP/6-31G* (bottom) levels.

proposed by Toscano and co-workers.[14] The dioxaziridine intermediates can be formed by photolysis of nitrene oxides.[16] Our results mirror those of Makareeva et al.[16]

Both the nitrene oxide and the dioxaziridine intermediate are predicted to react extremely exothermically with triplet

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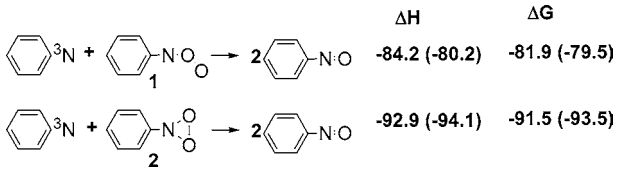
Scheme 3. CBS-QB3 and DFT Calculations of Triplet Phenylnitrene with Nitrene Oxide and Dioxaziridine Intermediate (298 K, kcal/mol); B3LYP/6-311+G**//B3LYP/6-31G* Numbers Are in Parentheses



phenylnitrene (Scheme 3). In this sense, aromatic nitrene oxidation is autocatalytic. The reaction of a triplet arylnitrene with oxygen produces intermediates, such as **1** and **2**, which more rapidly oxidize additional nitrene substrates than does molecular oxygen.

In summary, triplet phenylcarbene reacts more rapidly with oxygen than does triplet phenylnitrene because the former reaction is much more exoergic than the latter. The C−O bond formed in the carbene reaction is much stronger than the N−O bond formed in the analogous nitrene process. We propose that triplet benzyloxynitrene will react with oxygen faster than triplet phenylnitrene due to charge separation in the transition state. This electron-transfer mechanism rationalizes the rapid reaction of molecular oxygen with triplet benzyloxynitrene, whereas phenylnitrene reacts slowly. The oxidation of phenylnitrene is autocatalytic. The nitrene oxides and diazidines react more exothermically with triplet phenylnitrene than does oxygen.

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Supporting Information Available: Tables of energies and Cartesian coordinates. This material is available free of charge via the Internet at http://pubs.acs.org.

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