

## Experimental Validation of the $\alpha$ -Effect in the Gas Phase

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**ABSTRACT:** The  $\alpha$ -effect—enhanced nucleophilicity of an anion with a lone pair of electrons adjacent to the attacking atom—has been well documented in solution; however, there is continuing disagreement about whether this effect is a purely solvent-induced phenomenon or an intrinsic property of the  $\alpha$ -nucleophiles. To resolve these discrepancies, we explore the  $\alpha$ -effect in the bimolecular nucleophilic substitution reaction in the gas phase. Our results show enhanced nucleophilicity for  $\text{HOO}^-$  relative to “normal” alkoxides in three separate reaction series (methyl fluoride, anisole, and 4-fluoroanisole), validating an intrinsic origin of the  $\alpha$ -effect. Caution must be employed when making comparisons of the  $\alpha$ -effect between the condensed and gas phases due to significant shifts in anion basicity between these media. Variations in electron affinities and homolytic bond strengths between the normal and  $\alpha$ -anions indicate that  $\text{HOO}^-$  has distinctive thermochemical properties.

Gas-phase kinetic studies<sup>1,2</sup> have provided an indispensable means to probe the energetics and intrinsic reactivity of prototypical organic reactions, free of solvent and counterion effects. Experimental and computational work<sup>3–10</sup> has provided a wealth of knowledge on the dynamic, energetic, and steric factors inherent to bimolecular nucleophilic substitution ( $\text{S}_{\text{N}}2$ ) reactions. Reaction rates are strongly influenced by non-covalent interactions, particularly the ion-stabilizing effect of solvents. These “solvent effects” can not only mask intrinsic differences but also become the controlling factor that governs nucleophilicity. One of the most complex areas of interest with regard to these factors is the enhanced reactivity of  $\alpha$ -nucleophiles. The term “ $\alpha$ -effect”<sup>11</sup> has been used to describe the increased reactivity relative to a given basicity for nucleophiles with a lone pair of electrons adjacent to the attacking atom (e.g., hydrazine, hydroxylamine, the hypochlorite ion, and the hydroperoxide anion). When compared to normal nucleophiles of similar basicity as measured by their  $\text{p}K_{\text{a}}$  values, an unusually high nucleophilic reactivity at carbonyl carbons, phosphorous centers, saturated carbon centers, carbocations, and double and triple carbon bonds has been found.<sup>12</sup> Due to the key role these reactions play in chemical decontamination, environmental cleanup, and biochemical processes, these supernucleophiles hold significant interest at a national and international level. Magnitudes of the  $\alpha$ -effect ( $k_{\alpha}/k_{\text{normal}}$ ) in the range of 5–1000 have been reported in solution for numerous reactions, yet it is mysteriously absent in others.<sup>13</sup> Variations in the magnitude of the  $\alpha$ -effect can be attributed to solvent effects generating differential transition-state stabilization and ground-state destabilization. Depending on the nucleophile–substrate system studied, either transition-state stabilization<sup>14</sup> or ground-state destabilization<sup>15</sup> can dominate as the controlling factor in the overall effect. Differential solvation energies between normal

and  $\alpha$ -nucleophiles of 16 and 24  $\text{kJ mol}^{-1}$  can lead to ground-state  $\alpha$ -effect rate enhancements by factors of 750 and 15000.<sup>13,15</sup> Due to this complexity, gas-phase studies provide a vital link to resolving the intrinsic nature of the  $\alpha$ -effect and providing insight into solvent effects.

Our research group has conducted several studies in an attempt to reveal the intrinsic nature and origin of the  $\alpha$ -effect. Our initial work showed similar reactivity with methyl formate<sup>16</sup> for the reagent pairing of  $\text{HOO}^-$  and  $\text{HO}^-$  (a standard reference employed in solution). Patterson and Fountain<sup>17</sup> suggest that the minor differences in these experimental data actually support an  $\alpha$ -effect and rationalize enhanced reactivity in  $\text{HOO}^-$  due to a high degree of single-electron-transfer<sup>18</sup> character. They argue that assessment of the  $\alpha$ -effect in the gas phase requires strict adherence to the matched acidities in reagent pairing between the normal and  $\alpha$ -nucleophiles. More recently, calculations by Ren and Yamataka<sup>12,19</sup> advocate for the existence of a large  $\alpha$ -effect i.e.,  $\Delta\Delta H^{\ddagger}(\text{HOO}^- \text{ vs } \text{X}^-) = 17.1 \text{ kJ mol}^{-1} \approx 960$  times rate enhancement) in the gas-phase reactions of  $\alpha$ -nucleophiles with methyl chloride. However, we found no significant deviations in the Brønsted correlation for a series of  $\text{S}_{\text{N}}2$  reactions of normal and  $\alpha$ -nucleophiles with methyl chloride.<sup>20</sup> This result may reflect difficulties in experimentally examining the computed systems or an overestimation of the magnitude of the  $\alpha$ -effect based on the series and range of anionic reactions used to define “normal” barrier heights. Interestingly, McAnoy et al.<sup>21</sup> reported major differences in the branching ratios in the reactions of  $\text{HOO}^-$  and  $\text{CD}_3\text{O}^-$  with dimethyl methylphosphonate. Since  $\text{HOO}^-$  and  $\text{CD}_3\text{O}^-$  have similar proton affinities (PAs), this difference in branching ratios was attributed to greater nucleophilicity of  $\text{HOO}^-$ ; however, the absolute rate coefficients were not measured. It is not clear if the branching reflects differences in barriers or simply reaction dynamics. In an effort to resolve the conflicting results, we investigate the kinetics of  $\text{S}_{\text{N}}2$  reactions of low exothermicity ( $\Delta H_{\text{rxn}}$ ), where a smaller thermodynamic component to the activation barrier may expose  $\alpha$ -nucleophilicity. Our results clearly show enhanced reactivity for an  $\alpha$ -nucleophile ( $\text{HOO}^-$ ) relative to a series of normal nucleophiles ( $\text{HO}^-$ ,  $\text{CH}_3\text{O}^-$ ,  $\text{C}_2\text{H}_5\text{O}^-$ , and  $i\text{-C}_3\text{H}_7\text{O}^-$ ) in reactions with methyl fluoride, anisole, and 4-fluoroanisole. Our most definitive evidence is exhibited in the methyl fluoride reactions where only the  $\text{S}_{\text{N}}2$  pathways are present, thus simplifying (versus competitive reaction systems) the identification of the  $\alpha$ -effect.

*Experimental Details.* The overall reaction rate coefficients ( $300 \pm 2 \text{ K}$ ) and branching fractions were measured using a tandem flowing afterglow-selected ion flow tube (FA-SIFT) instrument.<sup>22,23</sup> Briefly, this instrument consists of an ion source, an ion selection region, a reaction flow tube, and a detection system (quadrupole mass filter coupled to an electron multiplier).

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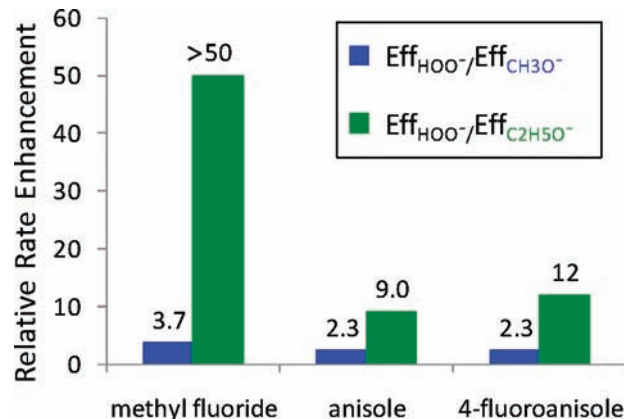
**Table 1.** Thermodynamic Parameters, Kinetic Data, and Branching Fractions To Evaluate the  $\alpha$ -Effect for  $\text{HOO}^-$  Relative to Normal Oxyanions ( $\text{HO}^-$ ,  $\text{CH}_3\text{O}^-$ ,  $\text{C}_2\text{H}_5\text{O}^-$ , and  $i\text{-C}_3\text{H}_7\text{O}^-$ ) in a Series of Bimolecular Nucleophilic Substitution Reactions

reaction ( $\text{X}^- + \text{M}$ )	thermodynamic data <sup>a</sup>		kinetic data <sup>b</sup>	branching fraction (Eff) <sup>c</sup>			$\alpha$ -effect
	PA ( $\text{X}^-$ )	$\Delta H_{\text{rxn}}$	$k_{\text{expt}} (\times 10^{-10})$	$\text{S}_{\text{N}}2$	PT	assoc	$\text{Eff}_{\text{HOO}^-}/\text{Eff}_{\text{X}^-}$
$\text{HO}^- + \text{CH}_3\text{F}$	1633	-91	$0.120 \pm 0.021$	100 (0.0042)	—	—	0.62
$\text{CH}_3\text{O}^- + \text{CH}_3\text{F}$	$1598 \pm 2$	-70	$0.017 \pm 0.001$	100 (0.0007)	—	—	3.7
$\text{C}_2\text{H}_5\text{O}^- + \text{CH}_3\text{F}$	$1585 \pm 3$	-60	$<0.001$	$<0.00005$	—	—	>50
$\text{HOO}^- + \text{CH}_3\text{F}$	$1575 \pm 4$	-65	$0.060 \pm 0.002$	100 (0.0026)	—	—	
$\text{HO}^- + \text{CH}_3\text{OC}_6\text{H}_5$	1633	-162	$13.1 \pm 0.2$	28 (0.13)	51	20	0.69
$\text{CH}_3\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_5$	$1598 \pm 2$	-141	$2.74 \pm 0.01$	32 (0.04)	—	68	2.3
$\text{C}_2\text{H}_5\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_5$	$1585 \pm 3$	-131	$1.38 \pm 0.10$	10 (0.01)	—	90	9.0
$\text{HOO}^- + \text{CH}_3\text{OC}_6\text{H}_5$	$1575 \pm 4$	-135	$3.49 \pm 0.05$	54 (0.09)	—	46	
$i\text{-C}_3\text{H}_7\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_5$	$1576 \pm 3$	-121	—	—	—	100	
$\text{HO}^- + \text{CH}_3\text{OC}_6\text{H}_4\text{F}$	1633	-174	$23.0 \pm 0.6$	—	100	—	
$\text{CH}_3\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_4\text{F}$	$1598 \pm 2$	-153	$10.7 \pm 0.4$	32 (0.10)	10	58	2.3
$\text{C}_2\text{H}_5\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_4\text{F}$	$1585 \pm 3$	-143	$6.88 \pm 0.21$	9 (0.02)	—	91	12
$\text{HOO}^- + \text{CH}_3\text{OC}_6\text{H}_4\text{F}$	$1575 \pm 4$	-147	$10.4 \pm 0.5$	70 (0.23)	—	30	
$i\text{-C}_3\text{H}_7\text{O}^- + \text{CH}_3\text{OC}_6\text{H}_4\text{F}$	$1576 \pm 3$	-133	—	—	—	100	

<sup>a</sup> Units of  $\text{kJ mol}^{-1}$ ; proton affinity (PA) from refs 26 and 27; exothermicity of the  $\text{S}_{\text{N}}2$  reaction ( $\Delta H_{\text{rxn}}$ ) calculated using heats of formation from ref 27, where  $\Delta H_{\text{rxn}}$  for 4-fluoroanisole reactions was estimated from anisole reactions on the basis of PA difference ( $12 \text{ kJ mol}^{-1}$ ). <sup>b</sup> Overall experimental rate coefficient ( $k_{\text{expt}}$ ) in units of  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . <sup>c</sup> Bimolecular nucleophilic substitution, proton transfer, and association product branching fractions (%), determined by extrapolating the observed product yields to zero reaction distance. Efficiency (Eff) is the ratio of the branching rate coefficients ( $k_{\text{S}_2} = k_{\text{expt}} \times \text{branching fraction}$ ) to the collision rate coefficient ( $k_{\text{col}}$ ), calculated using parametrized trajectory collision theory from ref 24 and dipole moments and polarizabilities from ref 25.

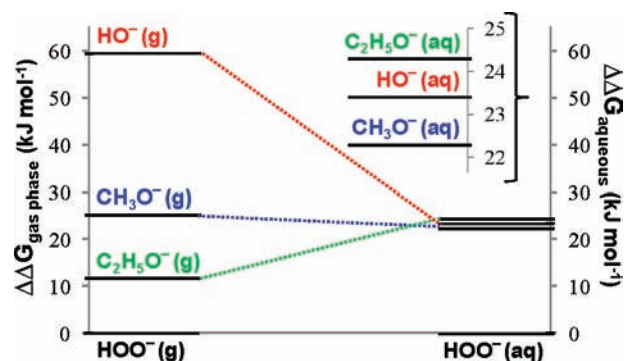
Reaction rate coefficients are measured by monitoring ion signal as a function of reaction distance. Product branching ratios are determined by extrapolating the observed product yields to zero reaction distance in order to extract the intrinsic ratios due to primary reactions. The reported reaction efficiencies are the experimental rate coefficient ( $k_{\text{expt}}$ ) divided by the calculated collision rate coefficients; these values represent the fraction of collisions that result in reaction. Collision rate coefficients were calculated from parametrized trajectory collision rate theory.<sup>24,25</sup> Error bars represent one standard deviation of the mean in the averages of at least three individual measurements; absolute uncertainties in these rate coefficient measurements are  $\pm 20\%$ .

**Kinetic Data.** The PA<sup>26,27</sup> of the anions,  $\Delta H_{\text{rxn}}$ , overall  $k_{\text{expt}}$ , branching fractions,  $\text{S}_{\text{N}}2$  reaction efficiency (Eff), and magnitude of the  $\alpha$ -effect as a function of relative reaction efficiencies for the gas-phase reactions of  $\text{HOO}^-$  relative to the normal oxyanions ( $\text{HO}^-$ ,  $\text{CH}_3\text{O}^-$ ,  $\text{C}_2\text{H}_5\text{O}^-$ , and  $i\text{-C}_3\text{H}_7\text{O}^-$ ) with methyl fluoride ( $\text{CH}_3\text{F}$ ), anisole ( $\text{CH}_3\text{OC}_6\text{H}_5$ ), and 4-fluoroanisole ( $\text{CH}_3\text{OC}_6\text{H}_4\text{F}$ ) are listed in Table 1. No reaction or association products were observed for the reaction of  $\text{C}_2\text{H}_5\text{O}^-$  with methyl fluoride. Therefore, we place an upper limit for the rate coefficient and efficiency limit for this reaction. While the  $\text{S}_{\text{N}}2$  mechanism is observed in most of the reactions, access to the proton-transfer (PT) channel is limited due to the relatively high PA of anisole ( $1637 \pm 2 \text{ kJ mol}^{-1}$ )<sup>28</sup> and 4-fluoroanisole ( $1614 \pm 3 \text{ kJ mol}^{-1}$ ).<sup>29</sup> Association products ( $\text{X}^- \cdot \text{M}$ ) were observed in the larger reaction systems corresponding to the longer lifetimes of the reactant ion–dipole complex, allowing for collisional stabilization by the He buffer gas. The reaction of  $i\text{-C}_3\text{H}_7\text{O}^-$  with anisole and 4-fluoroanisole formed only association products and therefore did not provide insight into the  $\text{S}_{\text{N}}2$  reactivity.



**Figure 1.** Magnitude of the  $\alpha$ -effect for  $\text{HOO}^-$  (PA =  $1575 \text{ kJ mol}^{-1}$ ) relative to  $\text{CH}_3\text{O}^-$  (PA =  $1598 \text{ kJ mol}^{-1}$ ) and  $\text{C}_2\text{H}_5\text{O}^-$  (PA =  $1585 \text{ kJ mol}^{-1}$ ).

**Evaluating the  $\alpha$ -Effect.** The exothermicity of an  $\text{S}_{\text{N}}2$  reaction is equal to the difference in the methyl cation affinity of the nucleophile and nucleofuge. Since both nucleophilicity and basicity involve the donation of electrons to an electrophile, it is not surprising that a strong linear correlation also exists between PA ( $\text{X}^- + \text{H}^+ \rightarrow \text{HX}$ ) and methyl cation affinity ( $\text{X}^- + \text{CH}_3^+ \rightarrow \text{CH}_3\text{X}$ ).<sup>30</sup> Deviations from linearity in reactivity–basicity correlations can reflect the influence of additional variables or the manifestation of unique energetics in the transition state. The enhanced reactivity of an  $\alpha$ -nucleophile is typically evaluated relative to normal anions of similar basicity through a Brønsted-type correlation or anionic reagent pairing ( $k_{\alpha}/k_{\text{normal}}$ ).



**Figure 2.** Suppression of the differences in relative free energies of deprotonation in aqueous solution [ $\Delta\Delta G = \Delta G_{\text{base}}(X^-) - \Delta G_{\text{base}}(\text{HOO}^-)$ ] for both the gas phase and aqueous solution in  $\text{kJ mol}^{-1}$ .

Trends in reaction efficiencies show enhanced nucleophilicity for  $\text{HOO}^-$  compared to the normal alkoxides ( $\text{CH}_3\text{O}^-$  and  $\text{C}_2\text{H}_5\text{O}^-$ ). Unfortunately, a two- or three-point Brønsted-type correlation limits the reliability of estimating the reactivity of a normal nucleophile having the same basicity as  $\text{HOO}^-$ . However, the ratio of reaction efficiencies,  $\text{Eff}_{\text{HOO}^-}/\text{Eff}_{X^-}$ , provides a method to assess the magnitude of the  $\alpha$ -effect (Figure 1). As predicted by the Marcus relationship, the largest shifts in relative reactivity occur in the  $\text{CH}_3\text{F}$  system, where intrinsic differences would be least masked by thermodynamic driving forces. The  $\text{HOO}^-$  reaction is 50 times more efficient than the  $\text{C}_2\text{H}_5\text{O}^-$  reaction, even though the PA of ethoxide is  $10 \text{ kJ mol}^{-1}$  higher than that of the peroxide. This result most clearly reveals the  $\alpha$ -effect in the gas phase. More modest rate enhancements are observed relative to  $\text{C}_2\text{H}_5\text{O}^-$  with anisole (9 times) and 4-fluoroanisole (12 times), and comparatively small differences exist for all the  $\text{CH}_3\text{O}^-$  reactions (2.3–3.7 times). The ratio of rate coefficients of  $\text{HOO}^-$  to  $\text{HO}^-$  ( $k_{\text{HOO}^-}/k_{\text{HO}^-}$ ) is a standard reference employed in solution to assess the magnitude of the  $\alpha$ -effect. While  $\text{HOO}^-$  displays enhanced reactivity in the gas phase relative to alkoxides, the peroxide rate does not exceed that of  $\text{HO}^-$ . This is likely related to the much greater relative basicity of  $\text{HO}^-$  in the gas phase (see below).

*Common Scale for Acidity/Basicity (Condensed and Gas Phases).* In the gas phase, acidity is defined as the free energy change associated with the deprotonation ( $\text{HX} \rightarrow \text{X}^- + \text{H}^+$ ) of a given chemical species. In contrast, for solution, acidity is evaluated using the equilibrium constants of proton transfer. We can devise a common scale for acidity by translating aqueous  $\text{p}K_{\text{a}}$  values [ $\text{p}K_{\text{HOH}} = 15.74$ ,  $\text{p}K_{\text{CH}_3\text{OH}} = 15.54$ ,  $\text{p}K_{\text{C}_2\text{H}_5\text{OH}} = 15.9$  (extrapolated), and  $\text{p}K_{\text{HOOH}} = 11.64$ ]<sup>31,32</sup> to free energies of deprotonation at 298 K using the Gibbs free energy relationship with equilibrium constants [ $\Delta G_{\text{base}}(\text{HO}^-) = 89.84$ ,  $\Delta G_{\text{base}}(\text{CH}_3\text{O}^-) = 88.70$ ,  $\Delta G_{\text{base}}(\text{C}_2\text{H}_5\text{O}^-) = 90.8$ , and  $\Delta G_{\text{base}}(\text{HOO}^-) = 66.44 \text{ kJ mol}^{-1}$ ]. Figure 2 depicts the relative free energy of deprotonation with respect to  $\text{HOO}^-$  for both the gas phase and aqueous solution. While there is little difference in free energies of deprotonation for the normal nucleophiles in solution relative to  $\text{HOO}^-$  [ $\Delta\Delta G(\text{HO}^-) = 23.4$ ,  $\Delta\Delta G(\text{CH}_3\text{O}^-) = 22.3$ , and  $\Delta\Delta G(\text{C}_2\text{H}_5\text{O}^-) = 24.3 \text{ kJ mol}^{-1}$ ], significant differences exist in the gas phase [ $\Delta\Delta G(\text{HO}^-) = 59.4$ ,  $\Delta\Delta G(\text{CH}_3\text{O}^-) = 25.1$ , and  $\Delta\Delta G(\text{C}_2\text{H}_5\text{O}^-) = 11.7 \text{ kJ mol}^{-1}$ ].<sup>26,27</sup> Methoxide is the nucleophile that maintains the most similar relative basicity to  $\text{HOO}^-$  in both media. On the other hand,  $\text{HO}^-$  is much more basic in the gas phase relative to  $\text{HOO}^-$ .

**Table 2.** Gas-Phase Thermochemical Ion Cycle<sup>a</sup> To Determine the Homolytic Bond Strength of  $\text{CH}_3\text{OH}$  and  $\text{HOOH}$

			$X^-$	
			$\text{CH}_3\text{O}^-$	$\text{HOO}^-$
$\text{CH}_3\text{X} \rightarrow \text{CH}_3^+ + \text{X}^-$	(1)	–MCA	1140	1135
$\text{X}^- \rightarrow \text{X} + \text{e}^-$	(2)	EA (X)	151	104
$\text{CH}_3^+ + \text{e}^- \rightarrow \text{CH}_3$	(3)	–IE ( $\text{CH}_3$ )	–949	–949
$\text{CH}_3\text{X} \rightarrow \text{X} + \text{CH}_3$	(4)	$D_0(\text{CH}_3\text{–X})$	342	290

<sup>a</sup> Methyl cation affinity (eq 1), electron affinity (eq 2), ionization energy (eq 3), and homolytic bond strength (eq 4) in  $\text{kJ mol}^{-1}$ ; refs 25,27.

Therefore,  $\text{HO}^-$  would act as a “supernucleophile” in the gas phase relative to solution, and it is unlikely that an  $\alpha$ -effect could overcome this difference in relative basicity in order for  $\text{HOO}^-$  to be more reactive in our studies.

*Variations in Electron Affinities and Homolytic Bond Strengths.* In Table 1, we note a large shift between the relative gas-phase PA and the  $\Delta H_{\text{rxn}}$  for  $\text{HOO}^-$  when compared to trends in the normal anions ( $14\text{–}15 \text{ kJ mol}^{-1}$  versus  $\text{C}_2\text{H}_5\text{O}^-$ ). While the  $\alpha$ -nucleophile displays enhanced reactivity relative to PA, part of this effect must be attributed to the larger  $\Delta H_{\text{rxn}}$ . Furthermore, this inversion would suggest there is a larger disparity between PA and methyl cation affinity for the peroxide than for the normal alkoxides. The methyl cation affinities of  $\text{CH}_3\text{O}^-$  ( $1140 \text{ kJ mol}^{-1}$ ) and  $\text{HOO}^-$  ( $1135 \text{ kJ mol}^{-1}$ ) are the same within experimental error (from heats of formation).<sup>15</sup> If we use the gas-phase thermochemical ion cycle (Table 2) to evaluate other factors associated with methyl cation affinity, we see the huge divergence in electron affinities (EAs) reflected in the homolytic bond strengths.  $\text{CH}_3\text{O}^-$  has a higher electron binding energy ( $\Delta\text{EA} = 47 \text{ kJ mol}^{-1}$ )<sup>25</sup> that is balanced by the homolytic bond (C–O) strength of  $\text{CH}_3\text{OH}$ , which is about  $52 \text{ kJ mol}^{-1}$  higher than for the peroxy system. These large variations in EAs and homolytic bond strengths between the normal and  $\alpha$ -anions indicate that  $\text{HOO}^-$  has distinctive thermochemical properties. In fact, by these measures (electron binding energy and homolytic bond strengths),  $\text{HOO}^-$  more closely resembles a species from an entirely different family of nucleophiles—the benzyl anion—than methoxide or the other alkoxides.<sup>33</sup> Valence bond state correlation diagrams (VBSCDs) have proven an effective model for explaining nucleophilic substitution reactions.<sup>4</sup> Since the VBSCD intrinsic reaction barrier is based on the ion–dipole complex vertical charge-transfer energy (approximated by the ionization energy of the nucleophile minus the EA of the substrate), the lower electron binding energy of  $\text{HOO}^-$  is consistent with lower intrinsic barriers. This supports arguments that the origin of the enhanced reactivity of the  $\alpha$ -nucleophiles is primarily electronic in nature and the extent of extra stabilization can be characterized by the extent of electron transfer in the transition state.<sup>17,18</sup>

In summary, we report enhanced nucleophilicity for  $\text{HOO}^-$  relative to normal alkoxides in three reaction systems, validating an intrinsic origin of the  $\alpha$ -effect. Similarities in the relative basicities (in both the condensed and gas phases) suggest that the reagent pairing of  $\text{CH}_3\text{O}^-$  and  $\text{HOO}^-$  would have similar correlations; however, reaction energy may prove to be a more effective parameter for correlations than basicity. Large shifts between the relative gas-phase proton affinity and the exothermicity of reaction for  $\text{HOO}^-$  when



compared to trends in the normal anions indicate differences in the natures of the nucleophiles. Variations in electron affinities and homolytic bond strengths between the methoxy and peroxy systems imply that significant variations would exist between electrostatic and orbital interactions within the transition states of normal and  $\alpha$ -nucleophiles. When analyzed in the context of valence bond theory, these variations in thermochemical properties support an electronic origin of the  $\alpha$ -effect, characterized by the degree of electron transfer in transition-state stabilization.

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- (29) This work:  $\text{HO}^- + \text{FC}_6\text{H}_4\text{OCH}_3 \rightarrow \text{FC}_6\text{H}_3\text{OCH}_3^- + \text{H}_2\text{O}$ ,  $k_r = (1.1 \pm 0.4) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ , and  $\text{FC}_6\text{H}_3\text{OCH}_3^- + \text{H}_2\text{O} \rightarrow \text{HO}^- + \text{FC}_6\text{H}_4\text{OCH}_3$ ,  $k_r = (7.85 \pm 0.12) \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$ ;  $\Delta_{\text{acid}}G_{298} = 1582 \pm 3 \text{ kJ mol}^{-1}$  and  $\Delta_{\text{acid}}H_{298} = 1614 \pm 3 \text{ kJ mol}^{-1}$ , where  $T\Delta_{\text{acid}}S_{298} = 32 \text{ kJ mol}^{-1}$ .
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