

Proton-Coupled Electron Transfer versus Hydrogen Atom Transfer in Benzyl/Toluene, Methoxyl/Methanol, and Phenoxy/Phenol Self-Exchange Reactions

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Abstract: Degenerate hydrogen atom exchange reactions have been studied using calculations, based on density functional theory (DFT), for (i) benzyl radical plus toluene, (ii) phenoxy radical plus phenol, and (iii) methoxyl radical plus methanol. The first and third reactions occur via hydrogen atom transfer (HAT) mechanisms. The transition structure (TS) for benzyl/toluene hydrogen exchange has C_{2h} symmetry and corresponds to the approach of the $2p-\pi$ orbital on the benzylic carbon of the radical to a benzylic hydrogen of toluene. In this TS, and in the similar C_2 TS for methoxyl/methanol hydrogen exchange, the SOMO has significant density in atomic orbitals that lie along the C–H vectors in the former reaction and nearly along the O–H vectors in the latter. In contrast, the SOMO at the phenoxy/phenol TS is a π symmetry orbital within each of the C_6H_5O units, involving $2p$ atomic orbitals on the oxygen atoms that are essentially orthogonal to the $O\cdots H\cdots O$ vector. The transferring hydrogen in this reaction is a proton that is part of a typical hydrogen bond, involving a σ lone pair on the oxygen of the phenoxy radical and the O–H bond of phenol. Because the proton is transferred between oxygen σ orbitals, and the electron is transferred between oxygen π orbitals, this reaction should be described as a proton-coupled electron transfer (PCET). The PCET mechanism requires the formation of a hydrogen bond, and so is not available for benzyl/toluene exchange. The preference for phenoxy/phenol to occur by PCET while methoxyl/methanol exchange occurs by HAT is traced to the greater π donating ability of phenyl over methyl. This results in greater electron density on the oxygens in the PCET transition structure for phenoxy/phenol, as compared to the PCET hilltop for methoxyl/methanol, and the greater electron density on the oxygens selectively stabilizes the phenoxy/phenol TS by providing a larger binding energy of the transferring proton.

Introduction

The mechanisms of reactions in which an electron and a proton are transferred in a single step can be divided into two distinct classes, hydrogen atom transfer (HAT) and proton-coupled electron transfer (PCET). In HAT, the proton and the electron are transferred together, as a hydrogen atom. HAT is the familiar mechanism of organic free radical chemistry. For instance, this mechanism is of fundamental importance in the combustion, partial oxidation, and halogenation of hydrocarbons.^{1,2} PCET is less well understood but is of much current interest because of its possible importance in a wide range of biochemical and other processes.³ While there is, as yet, no widely accepted definition of PCET,⁴ this term is often applied

to mechanisms in which the proton and electron are transferred between different sets of orbitals.

We have recently shown that a set of rate constants for HAT/PCET reactions obey the Marcus cross relation, indicating that self-exchange rates are important indicators of reactivity.⁵ Here we report the results of computational studies of three self-exchange reactions, $PhCH_2\cdot + PhCH_3$, $PhO\cdot + PhOH$, and $CH_3O\cdot + CH_3OH$. Despite the fact that CH_2 and O are isoelectronic and that phenol and methanol are both alcohols, we find that the second of these reactions takes place by a different mechanism than the first and the third. Transfer of a

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(1) See, for example: (a) *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973. (b) Perkins, M. J. *Free Radical Chemistry*; Ellis Horwood: New York, 1994. (c) Olah, G. A.; Molnár, A. *Hydrocarbon Chemistry*; Wiley: New York, 1995.
(2) Compendia of HAT rate constants: *Radical Reaction Rates in Liquids*; Fischer, H., Ed.; Landolt-Börnstein New Series; Springer-Verlag, New York, (a) 1984; Vol. 13, subvol. a–e, and (b) 1997; Vol. 18, subvol. a–e. (c) Reference 2b, pp 284–5.

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hydrogen atom from toluene to benzyl radical and from methanol to methoxyl radical takes place by a HAT mechanism, but a PCET mechanism is predicted to be strongly favored in the superficially similar exchange of a hydrogen atom between phenol and phenoxyl radical. The latter finding is of considerable interest, because conversion of a phenol to a phenoxyl radical is important in a variety of biological and other processes, including reduction of ribonucleotides,^{3f,6} oxygen utilization and production in cytochrome *c* oxidase (CcO) and in photosystem II (PSII),⁷ and in the functioning of antioxidants such as BHT and vitamin E (tocopherol).⁸

Computational Methodology

To investigate the mechanisms of the above three hydrogen self-exchange reactions, we carried out calculations based on density functional theory (DFT). Unrestricted (U)DFT calculations were performed using Becke's three-parameter functional⁹ and the correlation functional of Lee, Yang, and Parr.¹⁰ An integration grid consisting of 99 radial points and 974 angular points was employed. These UB3LYP calculations were carried out with both the 6-31G*¹¹ and the 6-311G(2d,2p)¹² basis sets. Geometry optimizations, transition structure searches, and vibrational analyses were performed with the smaller basis set; the larger basis set was used for single-point calculations. All of the calculations were carried out with the Gaussian 98 suite of programs.¹³

The relative energies and the activation enthalpies, obtained by correcting the relative energies for zero-point and thermal energies, are summarized in Figure 1.¹⁴ Optimized geometries, energies, and vibrational frequencies for all of the species on which we performed calculations are available as Supporting Information.

Results and Discussion

PhCH₂•/PhCH₃ versus PhO•/PhOH Hydrogen Exchange.

The degenerate hydrogen exchange reaction between benzyl

- (4) In principle, HAT could be considered one class of PCET, but a distinction is commonly made. For an early and perhaps overly specific definition of PCET, see: (a) Binstead, R. A.; Moyer, B. A.; Samuels, G. J.; Meyer, T. J. *J. Am. Chem. Soc.* **1981**, *103*, 2897–9. (b) Lebeau, E. L.; Binstead, R. A.; Meyer, T. J. *J. Am. Chem. Soc.* **2001**, *123*, 10535–10544 and references therein. (c) For a different view, see: Roth, J. P.; Lovell, S.; Mayer, J. M. *J. Am. Chem. Soc.* **2000**, *122*, 5486–5498.
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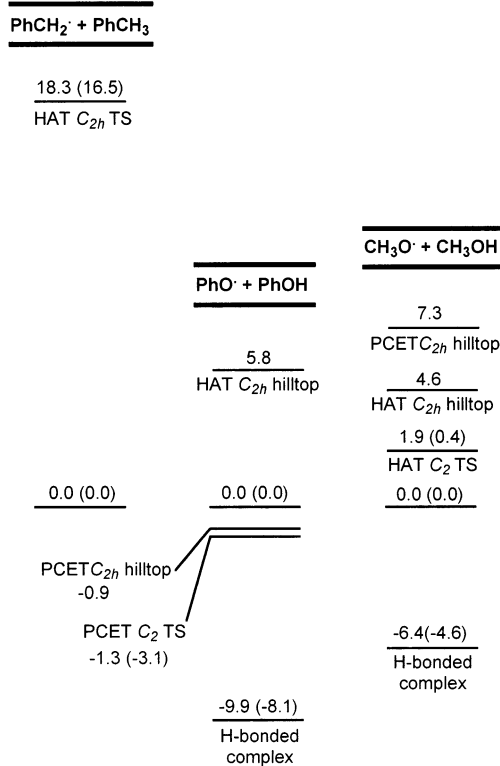


Figure 1. Schematic representation of the energies and enthalpies (in parentheses) of transition structures (TS), hilltops, and H-bonded complexes relative to the separated reactants at the (U)B3LYP/6-311G(2d,2p)//(U)B3LYP/6-31G* level of theory.

radical and toluene has a transition structure (TS) with C_{2h} symmetry. As shown in Figure 2A,¹⁵ the TS geometry allows the $2p-\pi$ orbital on the benzylic carbon of the radical to approach a benzylic hydrogen of toluene. This geometry permits the benzyl radical being formed and the benzyl radical to which the hydrogen is being donated both to maintain some benzylic conjugation in the TS. The singly occupied (SO) MO in the three-electron, three-center TS (Figure 2B) has a node at the hydrogen and is largely localized on the two CH_2 groups; yet the SOMO also has nonnegligible density on the ortho and para carbons of the benzene rings.

The calculated B3LYP/6-311G(2d,2p)//B3LYP/6-31G* activation energy for the PhCH₂•/PhCH₃ hydrogen exchange reaction is $E_a = 17.1$ kcal mol⁻¹.¹⁶ This computed value is in

- (14) (a) The treatment of PCET between phenoxyl and phenol, used in our calculations, assumes that this reaction is electronically adiabatic. This assumption might be invalid if the overlap of the electron donor and acceptor orbitals were small, so that coupling between the diabatic states (PhO•...HOPh and PhO⁻...HOPh⁺) was weak. However, at the geometry of the transition structure, the oxygens are only about 2.4 Å apart, and the donor and acceptor orbitals on them are reasonably well aligned. Consequently, at this geometry our UB3LYP calculations find the diabatic states couple to give adiabatic states that are split by 3.7 kcal/mol, and (15/14)CASPT2 calculations, which are presumably more accurate than UB3LYP, give a splitting that is larger by ca. 1 kcal/mol. With a splitting of the adiabatic states this large, a simple Landau–Zener calculation indicates that the effect of nonadiabaticity on reducing the rate of this reaction should be small. In fact, hydrogen atom tunneling is likely to provide much larger corrections (see refs 31 and 14b) to the calculations described here, increasing all of the rates and lowering the computed activation enthalpies. (b) Alhambra, C.; Corchado, J. C.; Sanchez, M. L.; Gao, J.; Truhlar, D. G. *J. Am. Chem. Soc.* **2000**, *122*, 8197–8203. Garrett, B. C.; Truhlar, D. G.; Bowman, J. M.; Wagner, A. F.; Robie, D.; Arepalli, S.; Presser, N.; Gordon, R. J. *J. Am. Chem. Soc.* **1986**, *108*, 3515. Billeter, S. R.; Webb, S. P.; Iordanov, T.; Agarwal, P. K.; Hammes-Schiffer, S. *J. Chem. Phys.* **2001**, *114*, 6925.
- (15) Graphics were prepared using MacMolPlot v5.2.7: Bode, B. M.; Gordon, M. S. *J. Mol. Graphics Modell.* **1998**, *16*, 133–138.
- (16) The activation energy is RT greater than the activation enthalpy, a difference that amounts to 0.6 kcal mol⁻¹ at room temperature.

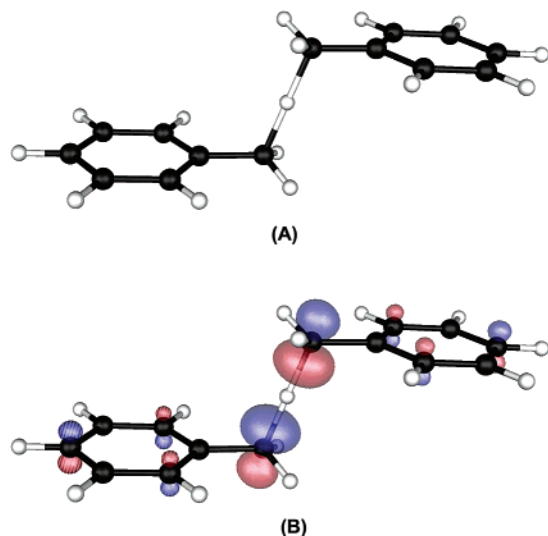


Figure 2. Benzyl/toluene: (A) the geometry and (B) the SOMO at the HAT transition structure.¹⁵

reasonably good agreement with the experimental value of $E_a = 19.9 \pm 2.1$ kcal mol⁻¹ in toluene solution and with a previous calculation.¹⁷

In the reaction of phenoxy radical with phenol, the reactants can form a hydrogen-bonded complex (Figure 3A), which is computed to be lower in enthalpy (energy) than the separated reactants by 8.1 (9.9) kcal mol⁻¹.¹⁸ As a possible TS for the phenoxy/phenol hydrogen exchange reaction, a structure similar to that of the C_{2h} HAT TS for the benzyl/toluene reaction can be considered. This type of TS might be expected to be disfavored for the phenoxy/phenol reaction by the fact that it requires the O–H bond in phenol to rotate 90° from its preferred conformation.¹⁹ However, when such a TS geometry with C_{2h} symmetry was optimized, it was found to have a UB3LYP/6-311G(2d,2p) energy only 5.8 kcal mol⁻¹ above that of the isolated reactants.²⁰

Nevertheless, this C_{2h} geometry is 15.7 kcal mol⁻¹ above the hydrogen-bonded complex. Moreover, vibrational analysis showed this stationary point to have three imaginary frequencies, two of them for vibrations that destroy the plane of symmetry. Clearly, this stationary point is a multidimensional hilltop and not the TS for the phenoxy/phenol hydrogen exchange reaction.

A search in lower symmetry led to the true TS, which is shown in Figure 3B. This C_2 TS is close to being planar, with

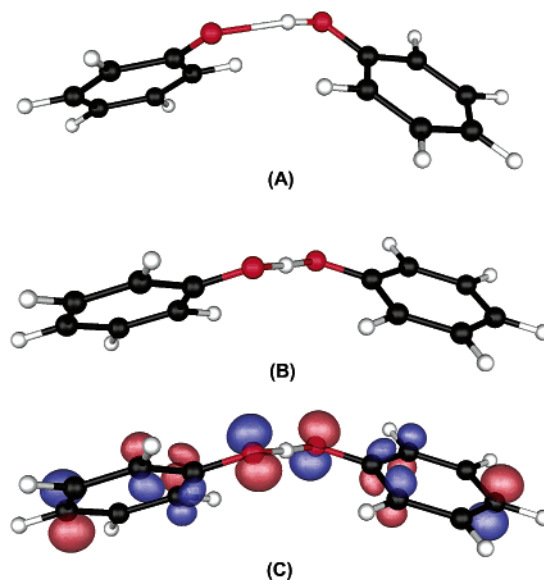


Figure 3. Phenoxy/phenol: (A) geometry of the hydrogen-bonded complex, (B) the geometry and (C) the SOMO at the PCET transition structure.¹⁵

the proton being transferred lying nearly in the plane of the two phenoxy groups. This contrasts with the benzyl/toluene C_{2h} TS (Figure 2A), in which the symmetry plane that contains the C···H···C bond is orthogonal to the planes of the benzene rings. As shown in Figure 1, the energy of the phenoxy/phenol C_2 TS is fully 7.1 kcal mol⁻¹ lower than that of the C_{2h} hilltop, whose geometry is analogous to that of the benzyl/toluene HAT TS in Figure 2A. The enthalpy of the C_2 TS is 3.1 kcal mol⁻¹ lower than that of separated phenoxy + phenol. Starting from the hydrogen-bonded complex, $\Delta H^\ddagger = 5.0$ kcal mol⁻¹ for passage over this TS.²¹

There is no experimental value for the phenoxy/phenol self-exchange reaction, but related reactions are known to proceed with very low barriers.^{2,22} For example, in a reaction that is exothermic by 2 kcal mol⁻¹,²³ phenoxy radical abstracts a hydrogen atom from 2-naphthol with $E_a = 2.3$ kcal mol⁻¹ in di-*tert*-butylperoxide and benzene.²² For the phenoxy/phenol self-exchange reaction in the gas phase, we compute $E_a = 5.6$ kcal mol⁻¹.^{14,16}

The proton and electron are transferred between different sets of orbitals in the TS for the phenoxy/phenol self-exchange reaction. Unlike the case at the C_{2h} hilltop for the HAT mechanism, where the transferring hydrogen participates in a three-electron, three-center bond, in the C_2 TS for the PCET mechanism the transferring hydrogen is part of a four-electron, three-center, hydrogen bond, involving a σ lone pair on the oxygen of the phenoxy radical and the O–H bond of phenol. Therefore, the species that is being transferred between the oxygens in the C_2 TS in Figure 3B is not a hydrogen atom but a proton, and this mechanism is best described as proton-coupled electron transfer.

Accompanying this proton transfer between oxygen σ lone pairs is the transfer in the same direction of an electron from the doubly occupied 2p- π AO on oxygen in phenol to the singly occupied oxygen 2p- π AO of phenoxy. This results in transfer

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(18) This B3LYP enthalpy difference is in reasonable agreement with the PUMP2/6-311G(2d,2p)//B3LYP/6-31G* enthalpy difference between the complex and the separated reactants of 10.2 kcal/mol.

(19) We calculate the barrier to rotation in phenol to be 3.8 kcal mol⁻¹. When the O–H bond is stretched to its length (1.187 Å) in the C_{2h} HAT hilltop structure, the calculated barrier to rotation drops, but only to 3.6 kcal mol⁻¹. Thus, the necessity of rotating the pair of electrons in the 2p- π AO on oxygen in phenol out of conjugation with the benzene ring in the C_{2h} HAT structure is responsible for about one-half of the energetic preference for the C_2 PCET TS over the C_{2h} HAT hilltop.

(20) This energy difference between separated phenoxy and phenol and the C_{2h} HAT hilltop is 12.5 kcal mol⁻¹ smaller than the energy difference between separated benzyl and toluene and the C_{2h} HAT TS for their reaction. We compute a difference of similar size to exist between the activation enthalpies for the degenerate HAT reactions from ethane to ethyl radical ($\Delta H^\ddagger = 14.3$ kcal/mol) and from methanol to methoxy radical ($\Delta H^\ddagger = 0.4$ kcal/mol). Population analyses indicate that at least one contributor to the lower activation enthalpies for the TSs in which a hydrogen atom is transferred between oxygens, rather than between carbons, is a polar effect in the TS—the favorability of having a hydrogen with a partial positive charge being transferred between two oxygens that bear partial negative charges in an HAT TS.^{1a,b}

(21) Loss in the TS of an O–H stretching vibration in the reactant makes ΔH^\ddagger 3.6 kcal mol⁻¹ smaller than the difference between the electronic energies.

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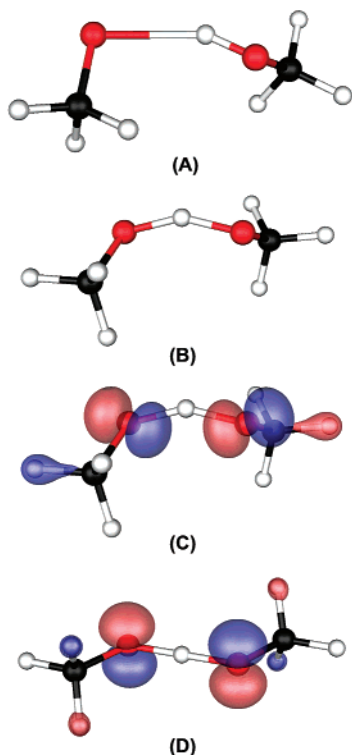


Figure 4. Methoxyl/methanol: (A) geometry of the hydrogen-bonded complex, (B) the geometry and (C) the SOMO at the HAT transition structure, and (D) the SOMO at the C_{2h} PCET hilltop structure.¹⁵

of unpaired spin density from one oxygen to the other in proceeding toward the PCET TS. The electron transferred is the one in the doubly occupied π HOMO that has spin opposite to that of the unpaired electron in the SOMO.²⁴ The delocalization of unpaired spin in the π systems of the two phenoxyls in the PCET TS can be seen by inspection of the SOMO in Figure 3C.

Although the C_2 PCET TS lacks the plane of symmetry that is necessary to distinguish rigorously between σ and π orbitals, this distinction can be made in the planar (C_{2h}) analogue. It is a hilltop on the potential energy surface, but only 0.4 kcal mol⁻¹ higher in energy than the C_2 TS. In the planar C_{2h} hilltop structure, the proton transfer involves σ orbitals that are rigorously orthogonal to the π orbitals between which electron transfer occurs.

PhO•/PhOH versus CH₃O•/CH₃OH Hydrogen Exchange.

To test whether a similar PCET mechanism provides the lowest energy TS for all RO• + ROH hydrogen transfer reactions, as a model,²⁵ we have investigated the mechanism for self-exchange between methoxyl radical and methanol. As in the phenoxyl/phenol reaction, in methoxyl/methanol there is a hydrogen-bonded reactant complex (Figure 4A), in this case $\Delta H = -4.6$ kcal mol⁻¹ below the separated reactants. Relative to the H-bonded complex, passage over the TS for methoxyl/

methanol hydrogen exchange has $E_a = 5.6$ kcal mol⁻¹. This is fortuitously the same as the barrier height for hydrogen exchange in the H-bonded phenoxyl/phenol complex. The low barrier computed for CH₃O• + CH₃OH is consistent with the one reported experimental value for alcohol-alkoxy exchange, $E_a = 6.4$ kcal mol⁻¹, for the more sterically encumbered reaction ${}^t\text{BuO}^\bullet + {}^t\text{Bu}_3\text{COH} \rightarrow {}^t\text{BuOH} + {}^t\text{Bu}_3\text{CO}^\bullet$.²⁶

The methyl groups in the CH₃O• + CH₃OH TS are gauche, and the O...H...O bond is nonlinear (Figure 4B). Orbitals of σ and π symmetry cannot be rigorously distinguished in this geometry. However, the orbitals on oxygen in the SOMO (Figure 4C) lie close to the O–H vectors; so the H being transferred in the methoxyl/methanol TS is apparently involved in a *three*-electron interaction, as opposed to the four electrons that participate in proton transfer in the PCET TS for phenoxyl/phenol. Consequently, the C_2 TS more closely resembles the TS for a hydrogen atom transfer process than for PCET.

A C_{2h} HAT structure, in which the methyl groups are anti and the O...H...O bond is linear, is 2.7 kcal mol⁻¹ higher in energy than the TS for methoxyl/methanol hydrogen exchange. The C_{2h} structure is a hilltop. As shown in Figure 1, relative to the reactants, this HAT hilltop for methoxyl/methanol is 1.2 kcal mol⁻¹ lower in energy than the HAT hilltop for phenoxyl/phenol.

It seems that in two similar HAT reactions the reactant radical which is more localized has the lower barrier height,²⁷ as previously reported by Camaioni, et al.^{17b} In addition, as already noted, the HAT mechanism is disfavored for phenoxyl/phenol hydrogen exchange by the necessity at the C_{2h} hilltop of rotating the O–H bond from its preferred conformation in phenol.¹⁹ Therefore, the finding that the energy difference, computed between the HAT hilltop and the reactant, is nearly the same for methoxyl/methanol and phenoxyl/phenol is somewhat surprising; we return to this point later.

We were also able to optimize a C_{2h} energy maximum along a PCET reaction pathway for methoxyl/methanol. The geometry of and the SOMO at this stationary point are depicted in Figure 4D. This structure has three imaginary frequencies and, thus, is not a true TS. As shown in Figure 1, this PCET hilltop on the multidimensional potential energy surface is 5.4 kcal mol⁻¹ higher in energy than the HAT TS. Relative to the isolated reactants, the energy maximum along the PCET reaction pathway is 8.6 kcal mol⁻¹ higher in energy for CH₃O• + CH₃OH than for PhO• + PhOH.

Why does phenoxyl/phenol hydrogen atom exchange prefer a PCET mechanism, whereas benzyl/toluene and methoxyl/methanol both follow HAT mechanisms? As discussed above, the formation of a hydrogen bond between the hydrogen donor and the radical appears to be a requirement for a PCET mechanism; benzyl and toluene lack the unshared pairs of electrons that are necessary for hydrogen bonding. However, hydrogen bond formation is insufficient to ensure that a PCET mechanism will be preferred to HAT, as shown by the methoxyl/methanol reaction.

As already noted, relative to the isolated reactants, the PCET hilltop in the methoxyl/methanol reaction is higher in energy by 8.6 kcal mol⁻¹ than the PCET TS in the phenoxyl/phenol reaction. If comparison is made between the C_{2h} PCET hilltop

(24) MOs for electrons of the same spin can be added and subtracted without changing an electronic wave function. Adding and subtracting the wave functions for electrons of the same spin in the HOMO and SOMO of the PCET TS leave each of these two electrons in an orbital that is largely localized on just one of the two oxygens. Thus, in molecular orbital theory, the electron that is transferred between the two oxygens in the PCET TS is not the electron in the SOMO, but the one in the HOMO with spin opposite to the electron in the SOMO.

(25) In reality, methoxyl radical would, of course, abstract a methyl hydrogen, not the hydroxyl hydrogen, from methanol. Studying hydroxyl hydrogen abstraction experimentally requires the use of a tertiary alcohol.²⁶

(26) Griller, D.; Ingold, K. U. *J. Am. Chem. Soc.* **1974**, *96*, 630–2.

(27) For example, our calculations find that $\Delta H^\ddagger = 14.3$ kcal mol⁻¹ for HAT in ethyl/ethane is 2.2 kcal mol⁻¹ lower than $\Delta H^\ddagger = 16.5$ kcal mol⁻¹ for HAT in benzyl/toluene.

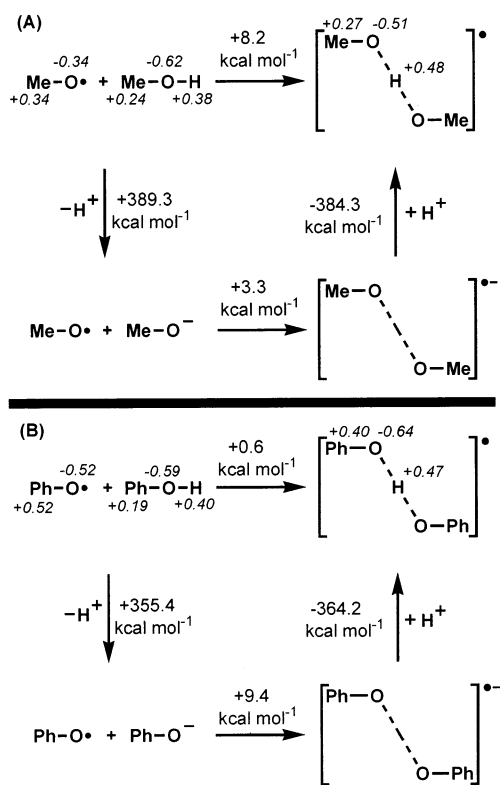


Figure 5. Thermocycles comparing the proton binding energies of the reactants and the C_{2h} PCET hilltops for (A) methoxy/methanol and (B) phenoxy/phenol at the (U)B3LYP/6-311++G(2d,2p)//(U)B3LYP/6-31G* level of theory. CHELPG charges, computed at the same level of theory, are given in italics.

in each reaction, the energy difference decreases slightly, to 8.2 kcal mol⁻¹. To understand why a PCET mechanism is more favorable for phenoxy/phenol than for methoxy/methanol, we computed the energies for the thermocycles that are shown in Figure 5, using the structures of the C_{2h} PCET hilltops for both reactions.

The first step of the thermocycles gives the energy necessary to remove a proton from the alcohol in the reactant. The second step measures the energy necessary to bring the radical and the anion, formed in the first step, together at the geometry of the C_{2h} hilltop, but in the absence of the proton. The third step gives the energy liberated when the proton is placed between the pair of oxygens to form the PCET hilltop.

Because the thermocycles involve the formation of anions, for computing the B3LYP energies in Figure 5 we augmented the 6-311G(2d,2p) basis set with diffuse functions on all of the atoms.²⁸ This change in the basis set increases the energy difference between the PCET hilltop and the reactants from 7.3 to 8.2 kcal mol⁻¹ for methoxy/methanol and from -0.9 to 0.6 kcal mol⁻¹ for phenoxy/phenol. Thus, the energy difference between the PCET hilltops and the reactants goes from being 8.2 kcal mol⁻¹ smaller to being 7.6 kcal mol⁻¹ smaller for the hydrogen exchange reaction of phenoxy with phenol than for the reaction of methoxy with methanol.

Figure 5 shows that, at the B3LYP/6-311++G(2d,2p) level, loss of a proton is computed to require 33.9 kcal mol⁻¹ more energy for methanol than for phenol. This calculated value is in good agreement with the experimental difference in gas-phase acidities of 31.6 kcal mol⁻¹.²⁹

To bring the oxygen-centered anion and radical together at the C_{2h} geometry that they have at the PCET hilltop requires energy. For methoxy/methoxide, $\Delta E = +3.3$ kcal mol⁻¹, and for phenoxy/phenoxide, $\Delta E = +9.4$ kcal mol⁻¹. Presumably, the endothermicity is due to the four-electron, repulsive interactions between the in-plane oxygen lone pairs of the radical and the anion. Because the O–O distance at the geometry of the PCET hilltop is 0.07 Å shorter for methoxy/methanol than for phenoxy/phenol, this destabilizing interaction between oxygen lone pairs cannot be the reason the overall interaction between methoxy and methoxide is 6.1 kcal mol⁻¹ less energetically costly than that between phenoxy and phenoxide.

In contrast to the four-electron interaction between the in-plane oxygen lone pairs, the three-electron interaction between the out-of-plane 2p- π AOs on oxygen is stabilizing. The three electrons in the SOMO and the HOMO are more localized on oxygen in the methoxy/methoxide radical anion complex than in the phenoxy/phenoxide complex. Therefore, at the C_{2h} geometry of the hilltop, the bonding O–O π interaction in the HOMO provides more stabilization for methoxy/methoxide than for phenoxy/phenoxide.

The final step of the thermocycles in Figure 5 returns the proton to each of the radical anions to form the PCET hilltops. Not surprisingly, this step is more exothermic for the less delocalized radical anion, methoxy/methoxide, than for phenoxy/phenoxide. However, the 20.1 kcal mol⁻¹ greater energy liberated in forming the PCET hilltop for methoxy/methoxide than for phenoxy/phenoxide is less than the 33.9 kcal mol⁻¹ difference between the gas-phase acidities of methanol and phenol. Thus, the proton is bound 13.8 kcal mol⁻¹ more strongly in the PCET hilltop structure than in the reactant for phenoxy/phenol than for methoxy/methanol.

The 13.8 kcal mol⁻¹ greater proton binding energy at the PCET hilltop for phenoxy/phenol is able to overcome the 6.1 kcal mol⁻¹ greater O–O π interaction energy for methoxy/methoxide. The result is that the energy difference between the PCET hilltop and the reactants is 13.8–6.1 = 7.7 kcal mol⁻¹ smaller for the reaction of phenoxy with phenol than for the reaction of methoxy with methanol.

As shown in Figure 5, the PCET hilltop binds a proton 5.0 kcal mol⁻¹ less strongly than the alcohol in the reaction between methoxy and methanol but 8.8 kcal mol⁻¹ more strongly in the reaction between phenoxy and phenol. The CHELPG³⁰ population analyses, shown in Figure 5, reveal the reason for this difference between the two reactions.

In methoxy and methanol the CHELPG charges on the oxygens are, respectively, -0.34 and -0.62, so that the total charge on oxygen is -0.96. At the PCET hilltop, the total charge on oxygen is $2 \times -0.51 = -1.02$. The population analysis thus shows that the proton is capable of inducing 0.06 more negative charge on oxygen at the PCET hilltop than in methanol. However, at the PCET hilltop, the partial O–H bonds are longer than the O–H bond in methanol, and, presumably, this is why the proton is bound 5.0 kcal mol⁻¹ more strongly in methanol than at the PCET hilltop.

In phenoxy and phenol, the CHELPG charges on the oxygens are, respectively, -0.52 and -0.59, so that the total charge on oxygen is -1.11. The π electrons of the benzene ring in

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phenoxy radical are delocalized into the singly occupied $2p-\pi$ AO on oxygen, thus making the negative charge on oxygen 0.18 greater in phenoxy than in methoxy. However, at the equilibrium geometry of phenol, a pair of electrons occupy the $2p-\pi$ AO on oxygen, and some donation of these electrons into the benzene ring makes the charge on oxygen 0.03 less in phenol than in methanol.

At the PCET hilltop for phenoxy/phenol, the total negative charge on oxygen is $2 \times -0.64 = -1.28$. Thus, at this PCET hilltop, -0.17 more negative charge resides on oxygen than in the reactants. The increase in negative charge on oxygen at the PCET hilltop is greater by 0.11 electrons in phenoxy/phenol than in methoxy/methanol, and this greater increase is what makes the difference between the proton binding energies at the PCET hilltop and in the reactant $13.8 \text{ kcal mol}^{-1}$ larger for the reaction of phenoxy with phenol than for the reaction of methoxy with methanol.³¹

Why is the difference between the charge on oxygen at the PCET hilltop and in the reactants greater for phenoxy/phenol than for methoxy/methanol? At the PCET hilltop, the SOMO is equally distributed over both oxygens, and both phenyl groups simultaneously donate electron density into it. The population analyses find that each phenyl group at the PCET hilltop donates 0.12 less electrons to oxygen than the phenyl group in phenoxy does. However, the total electron donation from both phenyl groups is 0.09 greater in the PCET TS than in the phenoxy/phenol reactants. In contrast, at the PCET hilltop for the reaction of methoxy with methanol, the population analyses find that the methyl groups provide a total of 0.04 fewer electrons to the oxygens than they do in the reactants.

Thus, the reason that reaction by a PCET mechanism is more favorable for phenoxy/phenol than for methoxy/methanol can be reduced to the well-known fact that phenyl is a better π donor than methyl.^{32,33} Greater electron donation from phenyl to oxygen at the PCET hilltop (and at the nearly isoenergetic PCET TS) than in the reactants results in proton binding being $8.8 \text{ kcal mol}^{-1}$ stronger at the phenoxy/phenol PCET hilltop than in phenol. In contrast, at the methoxy/methanol PCET hilltop, the proton is bound by $5.0 \text{ kcal mol}^{-1}$ less than in methanol.

This $13.8 \text{ kcal mol}^{-1}$ difference in proton binding energies is more than twice as large as the $6.1 \text{ kcal mol}^{-1}$ greater π delocalization energy for methoxy/methoxide. The $7.7 \text{ kcal mol}^{-1}$ smaller energy difference between the PCET hilltop and the reactants is the amount of energy by which a PCET mechanism is more favorable in the reaction of phenoxy with phenol than in the reaction of methoxy with methanol.

(31) The results of natural population analyses (NPA), using the Gaussian 98 implementation of Weinhold's natural bond orbital (NBO) program (Glendening, E. D.; Reed, A. E.; Carpenter, J. E.; Weinhold, F. NBO Version 3.1) were qualitatively similar to the results of the CHELPG population analyses. The NPA results are provided in the Supporting Information.

(32) The difference between the electron-donating abilities of methyl and phenyl is probably the reason the relative energies of the two HAT hilltops are quite similar. As already noted, the HAT hilltop for methoxy/methanol should be favored for two reasons. First, the unpaired electron is more localized in methoxy than in phenoxy, and, second, at the HAT hilltop the O-H bond in phenol must be rotated from its preferred conformation in the plane of the benzene ring. However, the greater electron-donating ability of phenyl, relative to methyl, makes the oxygens more negative for phenoxy/phenol than for methoxy/methanol, not only at the C_{2v} PCET hilltops but also at the HAT hilltops. The greater polar effect^{1a,b} for phenoxy/phenol that results partially compensates for the two advantages that the methoxy/methanol reaction has.

(33) Our calculations find that the stronger hydrogen bond in the phenoxy/phenol complex, relative to that in the methoxy/methanol complex, is due to the same effect, which makes the negative charge on oxygen larger in phenoxy than in methoxy.

Variations on the PhO•/PhOH PCET TS. The rapid hydrogen exchange in semiquinones, such as *ortho*- $C_6H_4(O^\bullet)-OH$ ($k = 2 \times 10^7 \text{ s}^{-1}$ at 295 K),^{2c} can be regarded as an intramolecular variant of the phenoxy/phenol PCET mechanism. Both reactions occur by a TS that involves proton transfer in the molecular plane, coupled to electronic rearrangement in the π system.

A PCET TS may also be favored in other reactions where formal transfer of a phenolic hydrogen to other oxygen-centered radicals occurs, for instance, in the trapping of peroxy radicals by the phenolic functionality of vitamin E⁸ and in the reactions of tyrosyl radicals in both PSII and CcO.⁷ However, in the one known biological system where there is a tyrosyl/tyrosine pair, the ribonucleotide reductase enzyme constrains the two aromatic rings to be face-to-face, and radical transfer apparently occurs by a HAT mechanism.^{6a}

Conclusions

Our calculations find that benzyl/toluene and methoxy/methanol undergo hydrogen exchange by an HAT mechanism, but that phenoxy/phenol reacts by a PCET mechanism. The latter mechanism involves transfer of a proton between lone pairs of electrons in σ orbitals on the oxygens, synchronous with the transfer of an electron from the doubly occupied π orbital on the oxygen of phenol to the singly occupied π orbital on the oxygen of phenoxy.

The inability of toluene to form a hydrogen bond with the benzyl radical rules out the possibility of a PCET mechanism for their reaction. However, this cannot be the reason the energy difference is computed to be much smaller between the PCET TS and the reactants for phenoxy/phenol than between the PCET hilltop and the reactants for methoxy/methanol. Our analysis shows that the better π donating ability of phenyl, relative to methyl, is responsible for the lower barrier to PCET in the phenoxy/phenol hydrogen transfer reaction.

Finally, we note that the PCET mechanism provides a possible rationale for the results of Luszyk, Ingold, and co-workers, that only phenols which are not hydrogen-bonded to solvent molecules react with oxygen-centered radicals.³⁴ These reactions have been studied for a wide variety of phenols, radicals, and solvents, and the finding – that the fraction of phenol, hydrogen-bonded to solvent, is unreactive – has been found to hold over a remarkable range of 10^{11} in rate constants. The PCET mechanism requires that the phenol make a hydrogen bond with the abstracting radical, so only the fraction of phenol not hydrogen-bonded to solvent could react if the PCET mechanism were operative.

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Supporting Information Available: Optimized geometries, energies, vibrational frequencies, and thermal corrections for all of the structures discussed in the text, and the detailed results of the CHELPG and natural population analyses (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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