

Bond Strengths of Toluenes, Anilines, and Phenols: To Hammett or Not

DEREK A. PRATT,^{*,†} GINO A. DILABIO,^{*,‡}
PETER MULDER,^{*,§} AND K. U. INGOLD^{*,⊥}

Department of Chemistry, University of Illinois,
Urbana, Illinois 61801, National Institute for
Nanotechnology, National Research Council of Canada,
W6-010 ECERF, 9107 116th Street, Edmonton,
Alberta T6G 2V4, Canada, Leiden Institute of Chemistry,
Leiden University, P.O. Box 9502,
2300 RA Leiden, The Netherlands, and
National Research Council of Canada, 100 Sussex Drive,
Ottawa, Ontario K1A 0R6, Canada

Received August 26, 2003

ABSTRACT

The Hammett equation correlates the effects of Y on many different chemical properties of YC₆H₄ZX families of compounds. One of the most surprising is that the Z–X bond dissociation enthalpy (BDE), a homolytic property, can be correlated for some 4-YC₆H₄-ZX families with electrophilic substituent constants, $\sigma_p^+(Y)$, which were largely derived from the rates of the heterolytic S_N1 solvolyses of para-substituted cumyl chlorides. Although there is no Hammett correlation of the C–X BDEs in 4-YC₆H₄CH₂X (X = H, halide, OPh) families, there are good correlations of N–X BDEs with $\sigma_p^+(Y)$ in 4-YC₆H₄NHX (X = H, CH₃, OH, F) and excellent correlations of O–X BDEs with $\sigma_p^+(Y)$ in 4-YC₆H₄OX (X = H, CH₃, CH₂Ph) families. The reasons for this varied behavior are discussed.

Introduction

Free radical chemists have a strong and abiding interest in the bond dissociation enthalpies, BDEs (commonly referred to as bond strengths or bond energies), of organic molecules. This is because the overall enthalpy change in a homolytic reaction is determined by the BDEs of the bonds being made and broken and it is the overall enthalpy change that determines whether the reaction will be exothermic (and probably fast) or endothermic (and

definitely slow). This Account describes the resolution, thanks to a combination of experimental measurements and theoretical calculations, of controversies regarding the influence, or lack of influence, of para-substituents, Y, on Z–X BDEs in compounds having the general formula 4-YC₆H₄Z–X.

The view that had become well established by the mid-1990s was that Z–X BDEs in 4-YC₆H₄Z–X gave Hammett-type linear free energy correlations with the substituent constant of Y, either the Hammett constants, $\sigma_p(Y)$ (based on 4-YC₆H₄CO₂H pK_as) or the Brown and Okamoto¹ electrophilic substituent constants, $\sigma_p^+(Y)$ (largely based on 4-YC₆H₄C(CH₃)₂Cl rates of S_N1 solvolysis). However, the evidence favoring a correlation of {BDE(4-YC₆H₄Z–X) – BDE(C₆H₅Z–X)} = Δ BDE(Z–X) with $\sigma_p(Y)$ or $\sigma_p^+(Y)$, varied from “overwhelming” for Z–X = O–H(σ^+), through “reasonably good” for Z–X = NH–H(σ^+) to “unconvincing” for Z–X = CH₂–H(σ). Nevertheless, we will start this Account with discussions of various Z = C(H₂) families of compounds because it was here that a controversy erupted that piqued our interest and initiated the work described herein.

To set the stage, in 1963, the logarithms of the rate constants for reaction 1 were shown to correlate linearly



with σ^+ , a result that was attributed to an electronic effect of Y, which might favor or disfavor the polar transition state shown:²



Then in 1970, Mahoney and DaRooge³ showed that a phenol with an electron-donating (ED) Y substituent (4-MeO) had an O–H BDE that was weaker by several kilocalories per mole than a phenol with an electron-withdrawing (EW) Y substituent (3-EtOC(O)). These workers concluded³ that the effects of Y on the rates of H-atom abstraction from YC₆H₄OH by radicals were primarily due to Y-induced changes in O–H BDEs and not to the polar effects of Y on the transition state. This conclusion has received overwhelming support from experimental measurements^{4–6} and by theoretical methods.⁷

C–X Δ BDEs for 4-YC₆H₄CH₂–X

By 1991, it was firmly established that EW Ys increased and ED Ys decreased the O–H BDEs in 4-YC₆H₄O–H^{3,4} and the O–C BDEs in 4-YC₆H₄O–CH₃⁸ and that the EW/ED character of Y had little effect on C–C BDEs in 4-YC₆H₄CH₂–CH₃^{9,10} and C–H BDEs in 4-YC₆H₄CH₂–H.¹² It was therefore rather exciting when Clark and Wayner (CW)¹⁴ reported that C–Br BDEs in 4-YC₆H₄CH₂–Br were *decreased* by EW Ys. These BDEs were measured by

Derek Pratt received a B.Sc. from Carleton University (1999) and a Ph.D from Vanderbilt University (2003). He is currently a postdoctoral fellow at the University of Illinois at Urbana-Champaign. His research interests include physical, theoretical, and bio-organic chemistry.

Gino DiLabio received his B.Sc. (1991) and M.Sc. (1993) degrees from Carleton University and his Ph.D. (1997) from Clarkson University (Potsdam, NY). He joined the National Research Council (NRC) of Canada in 2001 and is currently a scientist with the National Institute for Nanotechnology (NINT) where he studies self-assembly processes on silicon surfaces using computational chemistry techniques. His research interests also include antioxidant chemistry and computational models development.

Peter Mulder received his M.Sc. (1979) from the Delft University of Technology and his Ph.D. (1987) from Leiden University. His research interests include thermokinetic properties and mechanistic aspects of (bio)organic processes in solution.

Keith Ingold received his B.Sc. from University College London (1949) and D.Phil. from Oxford (1951). He is currently the Distinguished Research Scientist at the NRC, which he joined in 1955.

[†] University of Illinois.

[‡] National Institute for Nanotechnology.

[§] Leiden University.

[⊥] National Research Council of Canada.

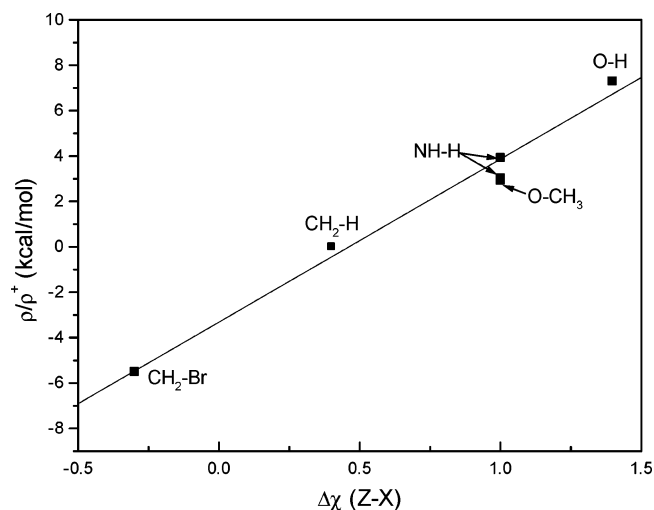


FIGURE 1. Purported correlation of ρ/ρ^+ with $\Delta\chi(Z-X)$, adapted from ref 19.

photoacoustic calorimetry (PAC) and a plot of C–Br BDEs vs $\sigma_p(Y)$ gave a reasonably good straight line with a ρ value equal to -5.5 kcal/mol. CW believed¹⁴ that since the then-accepted correlation of 4- $YC_6H_4CH_2-H$ BDEs with σ had a small but positive slope, their C–Br BDE results could not be attributed to the stabilizing effects of Y on the 4- $YC_6H_4CH_2\cdot$ radicals. Instead, the substituent must exert its “important (i.e., greater) effect on the ground state of the parent” bromide.¹⁴ An EW Y was presumed to decrease the C–Br BDE because it destabilized 4- $YC_6H_4CH_2Br$ relative to $C_6H_5CH_2Br$ by the interaction of Y with the C–Br bond’s dipole. CW¹⁴ also pointed out that “the magnitude of this effect will depend on the electronegativity difference of the atoms or groups in the bond being broken.” Furthermore, the then-available ρ/ρ^+ values for $Z-X = CH_2-Br$, CH_2-H , $O-CH_3$, and $O-H$ gave a reasonable straight line when plotted against (Pauling)¹⁵ electronegativity differences for the bonding atoms, $\Delta\chi$. However, it should be noted that the atomic χ value for carbon (2.5) is not identical to the χ value for carbon-centered groups because of interactions within the group, for example,¹⁶ $\chi(CH_3) = 2.525$ and $\chi(C(CH_3)_3) = 2.378$. Thus, $\chi(4-YC_6H_4CH_2)$ will not be constant but will vary as the ED/EW character of Y varies.

The correlation between ρ/ρ^+ and atomic $\Delta\chi$ received additional support within 2–3 years from two sources. First, some electrochemical measurements provided additional evidence that EW Ys weakened C–Br bonds in 4- $YC_6H_4CH_2Br$.¹⁷ Second, measurements of N–H BDEs for 4- $YC_6H_4NH_2$ gave fair linear correlations when plotted against $\sigma_p^+(Y)$,^{18,19} and the slopes of these plots²⁰ were of a sign and magnitude fully consistent with CW’s suggested linear correlation of ρ/ρ^+ with $\Delta\chi[Z-X]$, see Figure 1.

By 1995, the BDEs measured over the preceding decade gave the dipole interaction model description of the origin of the effects of Y on Z–X BDEs in 4- YC_6H_4Z-X every appearance of being an unassailable fact when Z was from the first row of the periodic table,²¹ see Figure 1. Furthermore, with the assumption that the covalent term in Pauling’s equation was more or less invariant, a first-order

Table 1. Calculated Gas-Phase C–X $\Delta BDE = \{BDE(4-YC_6H_4CH_2X) - BDE(C_6H_5CH_2X)\}$ in kcal/mol^a

Y ^b (C–X $\Delta\chi$)	X = H (0.4)	X = Br (–0.3)	X = Cl (–0.5)	X = F (–1.5)
NH ₂	–1.7	–0.2	–0.2	–0.5
OCH ₃	–0.9	0.1	0.0	–0.4
CH ₃	–0.4	0.1	0.0	–0.4
H	0.0 ^c	0.0 ^c	0.0 ^c	0.0 ^c
CF ₃	0.5	–0.8	–0.5	–0.2
CN	–0.5	–1.6	–1.6	–1.3
NO ₂	–0.1	–1.5	–1.6	–1.0

^a Reference 24. ^b Values of the substituent constants for Y (σ_p and σ_p^+) increase monotonically from NH₂ through to NO₂, see Table 2. ^c BDE $CH_2-H = 90.4$, $CH_2-Br = 57.1$, $CH_2-Cl = 68.6$, and $CH_2-F = 97.2$ kcal/mol.

treatment had been presented indicating that ρ^+ should be related to $\Delta\chi[Z-X]$;²² a comprehensive discussion pertaining to the precise physical foundation of this correlation is, however, beyond the scope of this Account. Unfortunately, a 1951 study of the unimolecular decomposition rates of benzyl bromides in the gas phase²³ appears to have been overlooked. This early work failed to reveal any substantial effect of ring substituents on C–Br BDEs.²³ More devastating for the dipole interaction model was a 1997 report by Laarhoven et al.¹¹ in which the same PAC technique was used as had earlier been employed by CW with no substituent effect on $YC_6H_4CH_2-Br$ BDEs being detected for Y = 4-CN, 4-C(CH₃)₃ or 3-CF₃.¹¹ Furthermore, competitive thermolysis of benzyl bromides in the gas phase indicated that any variation in $YC_6H_4CH_2-Br$ BDEs (Y = H, 4-CN, 4-CF₃, 4-C(CH₃)₃, 4-Br, 4-CH₃O and 3-CF₃) was less than 1 kcal/mol.¹¹

Since experimental approaches gave conflicting $YC_6H_4CH_2-Br$ BDEs, we turned to theory. The calculation of reliable gas-phase BDEs (298 K) requires an extremely high level of theory and enormous computing power. In contrast, and thanks to the cancellation of errors, the calculation of gas-phase BDEs that will yield reliable differences in BDEs ($\Delta BDEs$) within a closely related family of compounds can be carried out quickly and cheaply using density functional theory (DFT) to calculate electronic energies for AM1-optimized structures.⁷ Some C–X $\Delta BDE = [BDE(4-YC_6H_4CH_2X) - BDE(C_6H_5CH_2X)]$ for X = H, Br, Cl, and F are given in Table 1.²⁴ In agreement with earlier^{25–28} and later²⁹ work, the polar effects of Y on 4- $YC_6H_4CH_2-H$ BDEs are much less important than the abilities of Y to delocalize the unpaired electron in 4- $YC_6H_4CH_2\cdot$;³⁰ only CF₃ being bond-strengthening. Despite the large decrease in $\Delta\chi$ along the C–H, C–Br, C–Cl, C–F series, the effects of Y on CH_2-X BDEs are small (<2.0 kcal/mol) and roughly equal for each Y for the three halides (Table 1). We therefore recommended^{24,31} that CW’s¹⁴ “intriguing hypothesis that the direction and magnitude of the effects of Y-substituents on 4- YC_6H_4Z-X BDEs depends on the difference in the electronegativities of the bonding atoms in Z and X should be discarded.” We continued “However, this does not mean that Y has no “purely polar” effect on carbon–halogen BDEs in benzyl halides. To “see” this purely polar effect it is, of course, necessary to correct for the major...stabilizing effect of

Table 2. Calculated Gas-Phase RSEs, MSEs, and TSEs (= RSE – MSE = ΔBDE) for 4-YC₆H₄CH₂[•] and 4-YC₆H₄CH₃ in kcal/mol^a

Y	σ^{+b}	RSE	MSE	TSE ^c
(CH ₃) ₂ N	-1.70	-1.3	0.7	-2.0
H ₂ N	-1.30	-0.9	0.8	-1.7
CH ₃ O	-0.78	-0.1	0.6	-0.7
CH ₃	-0.31	-0.2	0.3	-0.5
H	0.0	0.0	0.0	0.0
CF ₃	0.61	-0.3	-0.6	0.3
CN	0.66	-1.2	-0.8	-0.4
NO ₂	0.79	-1.2	-0.9	-0.3

^a Reference 20. ^b Reference 1. ^c Slight differences from Table 1 are due to the higher level of theory employed in this work.

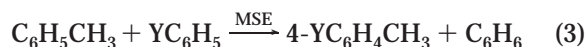
each Y on the 4-YC₆H₄CH₂[•] radicals” arising from electron delocalization into Y. This can be accomplished from the data in Table 1 via

$$\Delta\Delta\text{BDE} = [\Delta\text{BDE}(4\text{-YC}_6\text{H}_4\text{CH}_2\text{-X} - \text{C}_6\text{H}_5\text{CH}_2\text{-X}) - [\Delta\text{BDE}(4\text{-YC}_6\text{H}_4\text{CH}_2\text{-H} - \text{C}_6\text{H}_5\text{CH}_2\text{-H})] \quad (2)$$

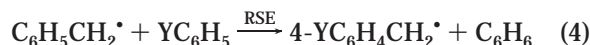
and ΔΔBDE (C–Br, C–Cl, and C–F) correlates well with $\sigma_p^+(Y)$, $\rho^+ = -1.43, -1.36,$ and -0.90 kcal/mol, respectively. Note that the signs of ρ^+ are in the direction suggested by CW,¹⁴ namely, ED Ys strengthen and EW Ys weaken the C–X bonds. Nau³³ had earlier drawn rather similar conclusions regarding his “polar ground-state stabilization energy” effect of Y on 4-YC₆H₄CH₂–Br BDEs. Our calculations²⁴ and Nau’s³³ indicate that substituents do exert a *purely polar* effect on the BDEs of benzyl halides. However, the magnitudes of these effects are remarkably similar and ρ^+ correlates with the dipole moments of the benzyl halides—namely, C₆H₅CH₂Br, 2.03 D; C₆H₅CH₂Cl, 1.94 D; C₆H₅CH₂F, 1.66 D—and not with $\Delta\chi$ (C–X).²⁴

Molecule and Radical Stabilization/Destabilization.

Like other workers in this field,^{26,27,33,34} we have also separated the effects of Y on 4-YC₆H₄CH₃ from its effect on 4-YC₆H₄CH₂[•].²⁰ We refer to the interaction enthalpies between Y and the CH₃ group as the *molecule stabilization enthalpies* (MSE),³⁵ which were determined using the isodesmic reaction



The interaction enthalpies between Y and the CH₂[•] group, which we refer to as the *radical stabilization enthalpies* (RSE), were determined using the isodesmic reaction



The *total stabilization (destabilization) enthalpy* (TSE) is equal to ΔBDE and is comprised of both the MSE and RSE, that is,

$$\text{TSE} = \text{RSE} - \text{MSE} = \Delta\text{BDE} \quad (5)$$

Some results²⁰ are given in Table 2. All ED and EW Ys slightly stabilize the radical, indicating that polar effects are unimportant in stabilizing/destabilizing 4-YC₆H₄CH₂[•] (contrast 4-YC₆H₄O[•] and 4-YC₆H₄NH[•], vide infra). However, ED Ys destabilize and EW Ys stabilize 4-YC₆H₄CH₃. This

Table 3. Homolyses of Benzyl Phenyl Ethers and Anisoles, Differences in E_a and BDE from the Unsubstituted Compounds (kcal/mol)^a

Y	4-YC ₆ H ₄ O–CH ₂ Ph		4-YC ₆ H ₄ O–CH ₃	
	ΔE _a	ΔBDE (calcd)	ΔE _a	ΔBDE (calcd)
CH ₃ O	-5.5	-6.1	-3.1	-6.1
CF ₃	3.2	3.0	2.2	3.0

^a Reference 13.

indicates that two ED groups, Y and CH₃, interact to destabilize the molecule (a push–push effect), increasing the MSE and hence decreasing the TSE and ΔBDE, whereas an EW Y and the CH₃ group interact to stabilize 4-YC₆H₄CH₃ (a pull (Y)–push (CH₃) effect), decreasing the MSE and hence increasing the TSE and ΔBDE, the latter to a positive value for 4-CF₃. Toluene RSEs and TSEs do not correlate with $\sigma^+(Y)$. However, MSEs for toluenes, like those for phenols and anilines, do correlate with σ^+ , but poorly.²⁰ This is because the push–push destabilizing effects of ED Ys are smaller for all three families than the pull–push stabilizing effects of EW Ys having comparable $|\sigma^+|$ ($|\sigma|$). Presumably push–push effects rapidly “saturate” the electron-accepting capacity of the aromatic ring (vide infra).

O–X ΔBDEs for 4-YC₆H₄O–X

Experiment and theory agree that O–H ΔBDEs in 4-YC₆H₄–OH give excellent linear correlations with $\sigma^+(Y)$.^{4–7,13,20,29} Our work on 4-YC₆H₄CH₂–X BDEs (X = H, halogen) led us to believe that “differences in BDEs for 4-YC₆H₄O–X compounds caused by changes in Y should be *largely independent of X*.”¹³ This forced us to address one glaring inconsistency, namely, Suryan et al.’s⁸ experimental determination of 4-YC₆H₄O–CH₃ BDEs for which ρ^+ was only 3.0 kcal/mol¹³ consistent with $\Delta\chi(\text{O–C})$, see Figure 1, but less than half of the value we expected. It is also inconsistent with Wu and Lai’s³⁴ conclusion that the effects of Y on 4-YC₆H₄O–H and O–CH₃ BDEs were “nearly identical”.

As is our custom, this inconsistency was examined by experiment and theory.¹³ Rates of O–C bond cleavage were measured for substituted anisoles in the gas phase at ca. 1000 K and for substituted benzyl phenyl ethers in the liquid phase at ca. 550 K in the presence of a radical scavenger, 9,10-dihydroanthracene. The effect of Y on 4-YC₆H₄O–CH₂C₆H₅ was, as expected, much greater than that on 4-YC₆H₄CH₂–OC₆H₅ BDEs.

The O–H and O–C BDEs were calculated for phenols and phenyl ethers for two ED (NH₂, CH₃O) Ys, two EW (CF₃, NO₂) Ys, and Y = H and gave essentially identical ρ^+ values (6.7 kcal/mol) for O–H, O–CH₃, and O–CH₂Ph BDEs. The 4-YC₆H₄CH₂–OC₆H₅ ΔBDEs did not correlate with σ^+ , and BDEs were weaker for the four substituents than for Y = H as found previously for other 4-YC₆H₄–CH₂–X (Table 1). Differences in the experimental activation enthalpies for 4-YC₆H₄O–CH₂Ph bond cleavage, ΔE_a, were in remarkably good agreement with calculated ΔBDEs, see Table 3. For the anisoles, the E_a’s (and the

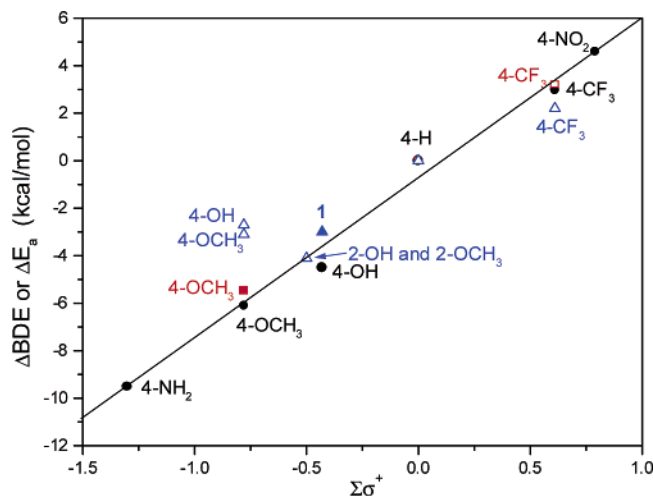
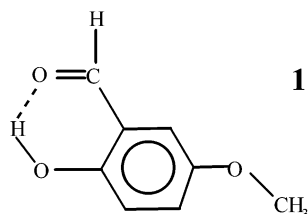


FIGURE 2. Correlation of calculated $\Delta\text{BDE}(\text{O}-\text{C})$ in $4\text{-Y}_6\text{H}_4\text{OCH}_3$ (●) and of ΔE_a from the thermolysis of benzyl phenyl ethers (□) and pyrolysis of anisoles (Δ) with $\Sigma\sigma^+$.

ΔBDEs) were in excellent agreement³⁶ with those obtained by Suryan et al.⁸ who employed the same experimental technique, reinforcing the $\rho^+ = 3.0$ kcal/mol anomaly.¹³ Theoretical and experimental values of O–C ΔBDEs and ΔE_a 's are in good agreement for all anisoles *except* $4\text{-HOC}_6\text{H}_4\text{OCH}_3$ and $4\text{-CH}_3\text{OC}_6\text{H}_4\text{OCH}_3$ (Figure 2).

Temperature-Dependent Substituent Effects. Two literature “explanations” for the difference between computational and experimental $4\text{-YC}_6\text{H}_4\text{O}-\text{CH}_3$ ΔBDEs were inconsistent with certain facts and were discarded.¹³ The experimental temperatures remained the only possible source of the discrepancies in the effects of substituents on $4\text{-YC}_6\text{H}_4\text{O}-\text{H}$ (~ 300 K) and $4\text{-YC}_6\text{H}_4\text{O}-\text{CH}_3$ (~ 1000 K) ΔBDEs . The OH and OCH₃ groups exert their maximum substituent effects when their conjugating oxygen 2p-type lone pair is perpendicular to the aromatic ring plane. At ambient temperatures, these groups lie in the aromatic plane and have significant Ph–OX rotation barriers, for example, ~ 3.5 kcal/mol for X = H. Consider $4\text{-ROC}_6\text{H}_4\text{OCH}_3$: Out-of-plane rotation of RO will increase the O–CH₃ BDE because nonplanar $4\text{-ROC}_6\text{H}_4\text{O}^\bullet$ will be less stabilized than its planar conformer and because ED conjugating substituents (RO) have a larger effect on RSE than on MSE, *vide infra*. At high temperatures, conformational changes are expected, and the rotational configuration of both the substituent and dissociating group become important. To ensure that the substituent exerts its maximum effect at elevated temperatures, it must be “held” in the coplanar position. This was achieved with the disubstituted anisole **1**.



The strong intramolecular H-bond in **1** (~ 10 kcal/mol)³⁷

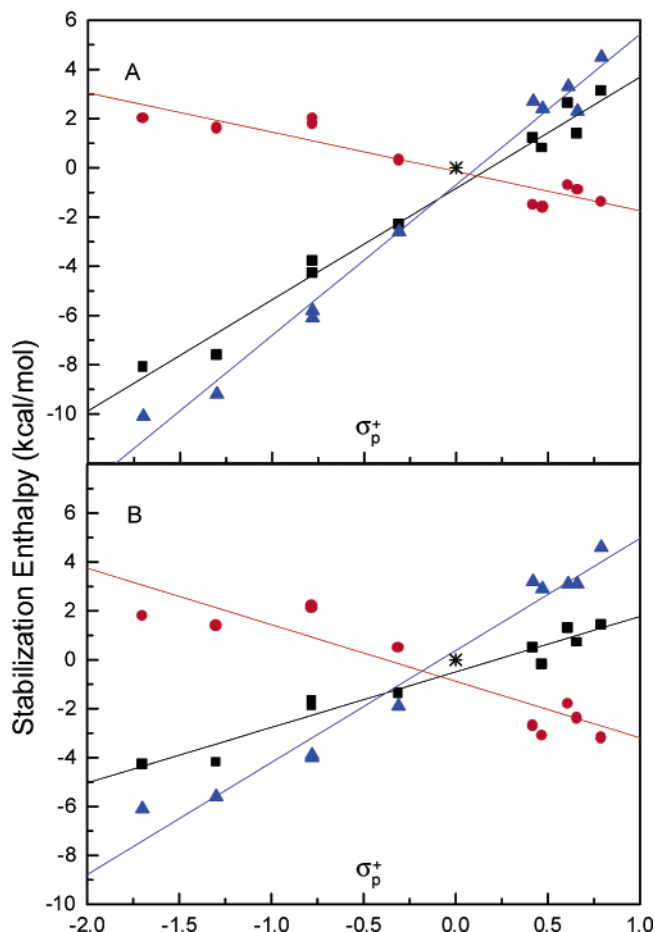


FIGURE 3. Correlation of stabilization enthalpies in (A) $4\text{-YC}_6\text{H}_4\text{OH}$ and $4\text{-YC}_6\text{H}_4\text{O}^\bullet$ and in (B) $4\text{-YC}_6\text{H}_4\text{NH}_2$ and $4\text{-YC}_6\text{H}_4\text{NH}^\bullet$ (●, MSE; ■, RSE; ▲, TSE). The asterisks indicate the (0,0) point.

ensured that both the HO and CHO substituents remained in-plane even at 1000 K and its experimental high-temperature ΔBDE (the filled blue triangle in Figure 2) does, indeed, lie close to the line drawn through the (298 K) calculated ΔBDEs for all the other anisoles. Experimental $4\text{-ROC}_6\text{H}_4\text{O}-\text{CH}_3$ ΔBDEs for R = H and CH₃ are only about half their calculated values (Figure 2), which, to a first approximation, implies that HO and CH₃O rotate freely at 1000 K. However, the ΔE_a point for $4\text{-CH}_3\text{-OC}_6\text{H}_4\text{O}-\text{CH}_2\text{Ph}$ (a filled red square in Figure 2) lies essentially on the line implying that the CH₃O and PhCH₂O groups are not free rotors at 500 K.

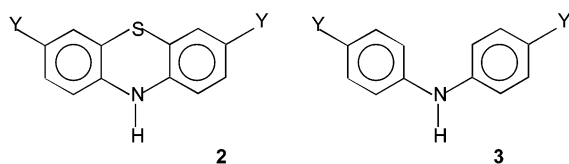
Calculated RSE, MSE, and TSE for $4\text{-YC}_6\text{H}_4\text{O}-\text{H}$.²⁰ The RSEs and TSEs give excellent linear correlations with σ^+ (ρ) for 10 substituents ranging from the strong ED Me₂N to the strong EW NO₂ (see Figure 3A). The MSEs are not really well correlated by σ^+ or σ . However, for phenols, the RSEs ($\rho^+ = 4.5$) make a 3-fold greater contribution to the TSEs than do MSEs ($\rho^+ \approx -1.6$), and hence, the TSEs are still well correlated by σ^+ ($\rho^+ = 6.1$ kcal/mol).

Another method for calculating $4\text{-YC}_6\text{H}_4\text{O}-\text{H}$ BDEs is to use DFT-computed ionization and reduction potentials for $4\text{-YC}_6\text{H}_4\text{O}^\bullet$ in combination with the (local) hard and soft acids and bases (HSAB) principle.^{22,28} Although this “hardness” approach may be useful in predicting substituent effects on heterolytic bond cleavage and has had

some success with homolytic BDEs,^{22,28} recent work is not encouraging.³⁸ Further theoretical development is required.

N–X Δ BDEs for 4-YC₆H₄NH–X

X = H. Measurements of a number of 4YC₆H₄NH–H BDEs using three different experimental techniques^{18,19,39} showed disturbing inconsistencies.²⁰ That is, one procedure²⁰ was certainly unreliable because N–H BDEs were calculated from oxidation potentials of aniliny radicals *estimated* by *irreversible* cyclic voltametry in DMSO combined with the aniline's DMSO pK_a's (which lie far above the normal pK_a range). Another procedure,¹⁹ which involved combining the reduction potentials of aniliny radical cations (generated in water by pulse radiolysis) with their pK_a's (which lie in the normal range), should provide fairly reliable N–H BDEs. There were also a very few PAC measurements.³⁹ Additional measurements by PAC and by the radical equilibrium electron paramagnetic resonance (REqEPR) technique were unsuccessful.²⁰ REqEPR measurements could, however, be made on 3,7-disubstituted phenothiazines, **2**, and 4,4'-disubstituted diphenylamines, **3**,



and Δ BDEs were calculated for some of these compounds.²⁰ Good agreement between theory and experiment for several **2** and **3** compounds gave us the confidence to calculate 4-YC₆H₄NH–H Δ BDEs using the same substituents as those employed in the 4-YC₆H₄O–H calculations. For 4-YC₆H₄NH₂, the correlations with σ^+ of the RSEs and TSEs (see Figure 3B) are not quite as good as those for 4-YC₆H₄OH. The TSEs (Δ BDEs) with EW Ys are remarkably similar for anilines and phenols, although the MSE/RSE mix differs. The MSE contributions for EW Ys are larger in anilines than phenols because the NH₂ group is a stronger π -ED and a weaker σ -EW than the OH group. Hence, NH₂ interacts more strongly than OH with both π - and σ -EW Ys. The MSEs for anilines and phenols with ED Ys are very similar, and there is essentially no difference in their magnitudes for Y = CH₃O, HO, H₂N, and Me₂N despite the large differences in ED abilities of Y. Thus, the law of diminishing returns sets in for destabilization of anilines and phenols when the already electron-rich aromatic ring is substituted with an ED group.

The RSEs are smaller for the anilines than for the phenols because the unpaired electron is more localized on the heteroatom in aniliny radicals than in phenoxy radicals. This has been demonstrated by electron spin resonance (ESR) spectroscopy and is due to smaller 2p– π orbital overlap in aniliny radical, which arises because the C–N bond in C₆H₅–NH \cdot is longer (1.34 Å) than the C–O bond in C₆H₅O \cdot (1.25 Å), though shorter than the C–C \cdot bond in C₆H₅CH_{2 \cdot (1.40}

Table 4. Calculated Gas-Phase N–X Δ BDEs for 4-YC₆H₄NH–X in kcal/mol^a

Y	X = CH ₃	X = H	X = OH	X = F
(CH ₃) ₂ N	–6.4	–6.1	–5.9	–5.0
H ₂ N	–5.9	–5.6	–5.5	–4.8
CH ₃ O	–3.6	–4.1	–3.3	–2.9
CH ₃	–1.5	–1.9	–1.6	–1.3
H	0 ^b	0 ^b	0 ^b	0 ^b
CF ₃	3.7	3.1	2.6	1.5
CN	3.7	3.1	2.3	1.0
NO ₂	5.6	4.7	3.7	2.0
ρ^+ ^c	5.0 \pm 0.3	4.6 \pm 0.3	4.0 \pm 0.2	3.0 \pm 0.2
R ² ^c	0.974	0.967	0.983	0.977

^a Reference 20. ^b BDE N–CH₃ = 66.6, N–H = 91.5, N–OH = 43.5, and N–F = 53.6 kcal/mol. ^c With three additional substituents (HO, COOH, and CHO).

Å).⁴⁰ These differences in C–Z \cdot bond lengths explain why there is no monotonic change in the Z–H BDEs of toluene (90.4),²⁴ aniline (91.5),²⁰ and phenol (87.2 kcal/mol).^{13,41} Another consequence is that the unpaired electron in aniliny radicals interacts less strongly with π -ED and EW Ys than that in phenoxy radicals.

X = CH₃, OH, and F. The strong ED character of the NH₂ group and strong EW character of the NH \cdot moiety cause the effects of Y on MSEs and RSEs to be of comparable magnitude. This contrasts with the role of Y on O–X¹³ and CH₂–X^{13,24} Δ BDEs in 4-YC₆H₄ZX. In these two families, MSEs are small relative to RSEs, which therefore dominate, and for molecules of practical interest to organic chemists, the effects of Y are essentially independent of X (≤ 1.5 kcal/mol for the examined X, see, for example, Table 1). However, substitution by X of one H in NH₂ could substantially modify the ED effect of the amino group, which would influence MSEs and hence N–X Δ BDEs. Our original proposal²⁴ that the effect of Y on Z–X Δ BDEs in 4-YC₆H₄Z–X would be independent of X, while essentially true for Z = O and CH₂, seemed unlikely to be true for Z = NH. Since dissociation of the N–X bond yields the same 4-YC₆H₄NH \cdot radical, N–X Δ BDEs reflect MSE differences, which can be substantial for EW Ys, see Table 4. Nevertheless, despite large changes in the magnitude and direction of bond polarity, namely, N ^{δ^-} –C ^{δ^+} ($\Delta\chi = 0.6$), N ^{δ^-} –H ^{δ^+} ($\Delta\chi = 1.0$), N ^{δ^+} –O ^{δ^-} ($\Delta\chi = -0.4$), and N ^{δ^+} –F ^{δ^-} ($\Delta\chi = -0.9$), the signs of ρ^+ are all the same (Table 4) and lie between those for 4-YC₆H₄O–X (6–7 kcal/mol) and 4-YC₆H₄CH₂–X (~ 0). This provides additional evidence that Z–X bond polarity (even in the favorable N–X case) has no more than a minor effect on the magnitude of ρ^+ , not the major effect once advocated.¹⁴

Conclusion and Why Only Some 4-YC₆H₄Z–X Δ BDEs Correlate with σ_p^+

The constants $\sigma_p^+(Y)$ describe the relative abilities of Y to stabilize the positive charge in the carbocation, 4-YC₆H₄C–(CH₃)₂⁺, formed in the S_N1 solvolysis of 4-YC₆H₄C(CH₃)₂–Cl.¹ The RSEs of 4-YC₆H₄O \cdot and 4-YC₆H₄NH \cdot correlate well with σ_p^+ because O \cdot and NH \cdot are, like a positive charge, strong EW moieties (estimated²⁰ σ_p^+ or $\sigma_p \approx 2$ and 1,

respectively, vs 0.79 for NO₂). The O–H and N–H ΔBDEs (the TSEs) in phenols and anilines also correlate very well and well, respectively, with σ_p^+ because the RSE, relative to the MSE, makes the major (OH) or an equal (NH) contribution to the TSE. The MSEs for 4-YC₆H₄OH, 4-YC₆H₄NH₂, and 4-YC₆H₄CH₃ correlate poorly with σ_p^+ and σ_p because the “push–push” interactions of ED Ys readily “saturate”. The C–H ΔBDEs do not correlate with σ_p^+ or σ_p because CH₂[•] is neither EW nor ED and 4-YC₆H₄-CH₂[•] radicals are stabilized by any group that can delocalize the unpaired electron. Hence, RSEs (and TSEs) in toluenes do not correlate with σ_p^+ (Y) or σ_p (Y).

Two Directions for Future Work

First, calculations yield gas-phase BDEs, but many experimental measurements are made in solution, and liquid-phase BDEs can differ from gas-phase values by several kilocalories per mole largely as a consequence of hydrogen bonding with solvent molecules. This is usually H-bonding by the substrate, for example, phenol, which increases the measured O–H BDE,⁴² but in some solvents, H-bonding of the radical is more important,⁴³ which would decrease the measured O–H BDE. An understanding of solvent effects on (readily calculated or already known) gas-phase BDEs would be of immense help in synthetic planning and in mechanistic organic chemistry.

Second, compared with first row elements, elements in the next row have lower electronegativities (viz., C/Si 2.5/1.8; N/P 3.0/2.1; O/S 3.5/2.5), form longer bonds, and have poorer (3p–2π) orbital overlap in C₆H₅Z[•]. Substituent effects on second row Z–H BDEs are therefore expected to have a negligible effect on RSEs for 4-YC₆H₄Z[•]. For Z = SiH₂³² and PH₄⁴⁴ substituent effects on MSEs will be negligible because SiH₃ and PH₂ must be weak EDs. In contrast, substituent effects on MSEs for Z = S are expected to be nonnegligible because SH must be a fairly strong ED group ($\sigma_p^+(\text{CH}_3\text{S}) = -0.60$ vs $\sigma_p^+(\text{CH}_3) = -0.31$ and $\sigma_p^+(\text{CH}_3\text{O}) = -0.78$). If RSEs could be ignored, TSE would equal –MSE (eq 5) and a plot of S–H ΔBDEs for 4-YC₆H₄SH vs σ_p^+ would be expected to yield a ρ^+ value of 1.6, comparable to the phenol and anisole –MSE ρ^+ values with the usual relatively poor correlation coefficients found for MSE plots because of saturation effects. The experimental S–H ΔBDEs in 4-YC₆H₄SH^{45,46} are consistent with this analysis. However, calculations⁴⁷ on 4-YC₆H₄SH (which, at the same level of theory, we have confirmed) indicate that substituents exert a larger effect on RSEs than on MSEs. This disagreement between our present understanding of substituent effects on S–H BDEs for 4-YC₆H₄-SH (which lead us to expect large MSEs and small RSEs) and calculations (which indicate the reverse) will have to be resolved by careful measurements of the heats of formation of these compounds.

We thank an anonymous referee for some extremely helpful comments.

References

- (1) Brown, H. C.; Okamoto, Y. Electrophilic Substituent Constants. *J. Am. Chem. Soc.* **1958**, *80*, 4979–4987.

- (2) Howard, J. A.; Ingold, K. U. The inhibited autoxidation of styrene. Part II. The relative inhibiting efficiencies of meta- and para-substituted phenols. *Can. J. Chem.* **1963**, *41*, 1744–1751. Howard, J. A.; Ingold, K. U. Part III. The relative inhibiting efficiencies of ortho-alkyl phenols. *Can. J. Chem.* **1963**, *41*, 2800–2806.
- (3) Mahoney, L. R.; DaRooge, M. A. Kinetic and thermochemical study of the reaction of 2,4,6-tri-*tert*-butylphenoxy radical with substituted phenols. *J. Am. Chem. Soc.* **1970**, *92*, 890–899.
- (4) Mulder, P.; Saastad, O. W.; Griller, D. O–H bond dissociation energies in para-substituted phenols. *J. Am. Chem. Soc.* **1988**, *110*, 4090–4092. Equation 5 therein should read $83.6 + 6.6\sigma^+$.
- (5) Jonsson, M.; Lind, J.; Eriksen, T. E.; Merényi, G. O–H bond strengths and one-electron reduction potentials of multisubstituted phenols and phenoxy radicals. Predictions using free energy relations. *J. Chem. Soc., Perkin Trans. 2* **1993**, 1567–1568.
- (6) Dorrestijn, E.; Laarhoven, L. J. J.; Arends, I. W. C. E.; Mulder, P. The occurrence and reactivity of phenoxy linkages in lignin and low rank coal. *J. Anal. Appl. Pyrolysis* **2000**, *54*, 153–192.
- (7) DiLabio, G. A.; Pratt, D. A.; LoFaro, A. D.; Wright, J. S. Theoretical study of X–H bond energetics (X = C, N, O, S): Application to substituent effects, gas-phase acidities, and redox potentials. *J. Phys. Chem. A* **1999**, *103*, 1653–1661.
- (8) Suryan, M. M.; Kafafi, S. A.; Stein, S. E. Dissociation of substituted anisoles: substituent effects on bond strengths. *J. Am. Chem. Soc.* **1989**, *111*, 4594–4600.
- (9) Suryan, M. M.; Stein, S. E. Stabilities of substituted benzyl radicals: dissociation rates of amino-, hydroxy-, and cyanoethylbenzenes. *J. Phys. Chem.* **1989**, *93*, 7362–7365.
- (10) Later¹¹ it was shown that Y had essentially no effect on C–C BDEs in the 4-YC₆H₄C(CH₃)₂ family.
- (11) Laarhoven, L. J. J.; Born, J. G. P.; Arends, I. W. C. E.; Mulder, P. Substituent effects on the benzylic bond dissociation enthalpy in benzyl bromides (C–Br) and *tert*-butylbenzenes (C–CH₃): a gas phase thermolysis and liquid-phase photoacoustic study. *J. Chem. Soc., Perkin Trans. 2* **1997**, 2307–2312.
- (12) Attempts to derive thermodynamic data from rates of H-atom abstraction from substituted toluenes are confounded by the convolution of kinetic polar effects, see footnote 7 in ref 13.
- (13) Pratt, D. A.; de Heer, M. I.; Mulder, P.; Ingold, K. U. Oxygen–carbon bond dissociation enthalpies of benzyl phenyl ethers and anisoles. An example of temperature-dependent substituent effects. *J. Am. Chem. Soc.* **2001**, *123*, 5518–5526.
- (14) Clark, K. B.; Wayner, D. D. M. Are relative bond energies a measure of radical stabilization energies? *J. Am. Chem. Soc.* **1991**, *113*, 9363–9365.
- (15) CW used a different electronegativity scale. However, the original Pauling scale has recently received very strong support.¹⁶
- (16) Matsunaga, N.; Rogers, D. W.; Zavitsas, A. A. Pauling's electronegativity equation and a new corollary accurately predict bond dissociation enthalpies and enhance current understanding of the nature of the chemical bond. *J. Org. Chem.* **2003**, *68*, 3158–3172.
- (17) Andrieux, C. P.; Le Gorand, A.; Saveant, J.-M. Electron transfer and bond breaking. Examples of passage from a sequential to a concerted mechanism in the electrochemical reductive cleavage of arylmethyl halides. *J. Am. Chem. Soc.* **1992**, *114*, 6892–6904.
- (18) Bordwell, F. G.; Zhang, X.-M.; Cheng, J.-P. Bond dissociation energies of the N–H bonds in anilines and in the corresponding radical anions. Equilibrium acidities of aniline radical cations. *J. Org. Chem.* **1993**, *58*, 6410–6416.
- (19) Jonsson, M.; Lind, J.; Eriksen, T. E.; Merényi, G. Redox and acidity properties of 4-substituted aniline radical cations in water. *J. Am. Chem. Soc.* **1994**, *116*, 1423–1427.
- (20) Pratt, D. A.; DiLabio, G. A.; Valgimigli, L.; Pedulli, G. F.; Ingold, K. U. Substituent effects on the bond dissociation enthalpies of aromatic amines. *J. Am. Chem. Soc.* **2002**, *124*, 11085–11092.
- (21) For 4-YC₆H₄S–CH₃ BDEs, the ρ/ρ^+ did not fit such a plot, see Figure 7 in ref 19.
- (22) Jonsson, M.; Lind, J.; Merényi, G.; Eriksen, T. E. Remote substituent effects on polar and nonpolar covalent bonds. *J. Chem. Soc., Perkin Trans. 2* **1994**, 2149–2154.
- (23) Leigh, C. H.; Sehon, A. H.; Szwarc, M. The C–Br bond dissociation energy in substituted benzyl bromides. *Proc. R. Soc. London* **1951**, *A209*, 97–110.
- (24) Pratt, D. A.; Wright, J. S.; Ingold, K. U. Theoretical study of carbon–halogen bond dissociation enthalpies of substituted benzyl halides. How important are polar effects? *J. Am. Chem. Soc.* **1999**, *121*, 4877–4882.
- (25) Fox, T.; Kollman, P. Calculation of ionization potentials and C–H bond dissociation energies of toluene derivatives. *J. Phys. Chem.* **1996**, *100*, 2950–2956.
- (26) Wu, Y.-D.; Wong, C.-L.; Chan, K. W. K.; Ji, G.-Z.; Jiang, X.-K. Substituent effects on the C–H bond dissociation energy of toluene. A density functional study. *J. Org. Chem.* **1996**, *61*, 746–750.

- (27) Nau, W. M. An electronegativity model for polar ground-state effects on bond dissociation energies. *J. Phys. Org. Chem.* **1997**, *10*, 445–455.
- (28) Bean, G. P. An AM1 MO study of bond dissociation energies in substituted benzene and toluene derivatives relative to the principle of maximum hardness. *Tetrahedron* **1998**, *54*, 15445–15456.
- (29) Bean, G. P. An AM1 study of the effect of substituents on the bond dissociation energies of anilines, phenols, and *o*-substituted toluenes. *Tetrahedron* **2002**, *58*, 9941–9948.
- (30) Similarly, both ED and EW Ys accelerate the decarbonylation: $4\text{-YC}_6\text{H}_4\text{CH}_2\text{C}\cdot\text{O} \rightarrow \text{C}_6\text{H}_4\text{CH}_2\cdot + \text{CO}$. See: Zhang, X.; Nau, W. M. Aryl substituent effects and solvent effects on the decarbonylation of phenylacetyl radicals. *J. Phys. Org. Chem.* **2000**, *13*, 634–639.
- (31) This recommendation has been rejected, and the results and conclusions of Clark and Wayner have been cited with favor,³² while the earlier²³ and later¹¹ experimental studies on 4- $\text{YC}_6\text{H}_4\text{-CH}_2\text{-Br}$ were ignored.³² There certainly are polar effects on 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-X}$ BDEs (see following text herein and in ref 24), but they are of very minor significance. The hypothesis¹⁴ that the sign and magnitude of ρ/ρ^+ for 4- $\text{YC}_6\text{H}_4\text{Z-X}$ BDEs correlates with $\Delta\chi\text{-}(Z\text{-X})$ is certainly incorrect and should be discarded.
- (32) Cheng, Y.-H.; Zhao, X.; Song, K.-S.; Liu, L.; Guo, Q.-X. Remote substituent effects on bond dissociation energies of para-substituted aromatic silanes. *J. Org. Chem.* **2002**, *67*, 6638–6645.
- (33) Nau, W. M. Computational assessment of polar ground-state effects on the bond dissociation energies of benzylic and related bonds. *J. Org. Chem.* **1996**, *61*, 8312–8314.
- (34) Wu, Y.-D.; Lai, D. K. W. A density functional study of substituent effects on the O–H and O–CH₃ bond dissociation energies in phenols and anisoles. *J. Org. Chem.* **1996**, *61*, 7904–7910.
- (35) The importance of polar effects on MSEs (usually termed (polar) ground-state effects,^{26,27,33,34} although there is no corresponding “excited” state) has been emphasized for many years; see, for examples, Rüchardt, C. Relations between structure and reactivity in free-radical chemistry. *Angew. Chem., Int. Ed. Engl.* **1970**, *9*, 830–843. Nicholas, A. M. de P.; Arnold, D. R. Thermochemical parameters for organic radicals and radical ions. Part 3. The relationship between bond dissociation enthalpy and radical stability in alkyl systems. *Can. J. Chem.* **1984**, *62*, 1850–1859. In principle, MSEs can be determined from the heats of formation of the compounds but, for disubstituted benzenes, there are few values available and these are of very variable reliability.
- (36) Four substituents in common; ΔBDE (kcal/mol) our data (ref 8): 2-OH –7.2 (–7.1); 4-OH –2.7 (–2.5); 2-CH₃O –4.1 (–4.2); 4-CH₃O –3.1 (–3.9).
- (37) Korth, H. G.; de Heer, M. I.; Mulder, P. A DFT study on intramolecular hydrogen bonding in 2-substituted phenols: conformations, enthalpies and correlation with solute parameters. *J. Phys. Chem. A* **2002**, *106*, 8779–8789.
- (38) For example, O–H ΔBDEs have been grossly overestimated for 4-CHO- and 4-CO₂H-substituted phenols (16.8 and 6.3 kcal/mol, respectively) see: Romero, M. de L.; Méndez, F. The local HSAB principle and bond dissociation energy of *p*-substituted phenol. *J. Phys. Chem. A* **2003**, *107*, 5874–5875.
- (39) MacFaul, P. A.; Wayner, D. D. M.; Ingold, K. U. Measurement of N–H bond strengths in aromatic amines by photoacoustic calorimetry. *J. Org. Chem.* **1997**, *62*, 3413–3414.
- (40) Ingold, K. U.; Wright, J. S. Understanding trends in C–H, N–H and O–H bond dissociation enthalpies. *J. Chem. Educ.* **2000**, *77*, 1062–1064.
- (41) Monotonic increases in Z–H BDEs along the series Z = CH₂, NH, and O are observed for HZH and CH₃ZH because there is no (HZ[•]) or reduced (CH₃Z[•] vs C₆H₅Z[•]) electron delocalization.⁴⁰
- (42) Wayner, D. D. M.; Lusztyk, E.; Page, D.; Ingold, K. U.; Mulder, P.; Laarhoven, L. J. J.; Aldrich, H. S. Effects of solvation on the enthalpies of reaction of *tert*-butoxyl radicals with phenol and the calculated bond strength in phenol. *J. Am. Chem. Soc.* **1995**, *117*, 8737–8744.
- (43) Lucarini, M.; Mugnaini, V.; Pedulli, G. F.; Guerra, M. Hydrogen-bonding effects on the properties of phenoxyl radicals. An EPR, kinetic and computational study. *J. Am. Chem. Soc.* **2003**, *125*, 8318–8329.
- (44) Fu, X.; Liu, L.; Lin, B.-L.; Mou, Y.; Cheng, Y.-H.; Guo, Q.-X. Remote substituent effects on homolytic bond dissociation energies. *J. Org. Chem.* **2003**, *68*, 4657–4662.
- (45) Armstrong, D. A. In *S-Centered Radicals*; Alfassi, Z. B., Ed.; Wiley: New York, 1999; p 41.
- (46) Borges dos Santos, R. M.; Muralha, V. S. F.; Correia, C. F.; Guedes, R. C.; Costa Cabral, B. J.; Martinho Simões, J. A. S–H bond dissociation enthalpies in thiophenols: a time-resolved photoacoustic calorimetry and quantum chemistry study. *J. Phys. Chem. A* **2002**, *106*, 9883–9889.
- (47) Fu, Y.; Lin, B.-L.; Song, K.-S.; Guo, Q.-X. Substituent effects on the S–H bond dissociation energies of thiophenols. *J. Chem. Soc., Perkin Trans. 2* **2002**, 1223–1230. Chandra, A. K.; Nam, P.-C.; Nguyen, M. T. The S–H Bond Dissociation Enthalpies and Acidities of Para and Meta Substituted Thiophenols: A Quantum Chemical Study. *J. Phys. Chem. A* **2003**, *107*, 9182–9188.

AR010010K