

Oxygen–Carbon Bond Dissociation Enthalpies of Benzyl Phenyl Ethers and Anisoles. An Example of Temperature Dependent Substituent Effects¹

Derek A. Pratt,^{*,2a,b} Martine I. de Heer,^{2c} Peter Mulder,^{2c} and K. U. Ingold^{2a}

Contribution from the Steacie Institute for Molecular Sciences, National Research Council of Canada, 100 Sussex Drive, Ottawa, Canada K1A 0R6, Department of Chemistry, Vanderbilt University, Nashville, Tennessee 37215, and Leiden Institute of Chemistry, University of Leiden, P.O. Box 9502, 2300 RA, Leiden, The Netherlands

Received November 27, 2000. Revised Manuscript Received March 30, 2001

Abstract: For some time it has been assumed that the direction and magnitude of the effects of Y-substituents on the Z–X bond dissociation enthalpies (BDE's) in compounds of the general formula 4-YC₆H₄Z-X could be correlated with the polarity of the Z–X bond undergoing homolysis. Recently we have shown by DFT calculations on 4-YC₆H₄CH₂-X (X = H, F, Cl, Br) that the effects of Y on CH₂-X BDE's are small and roughly equal for each X, despite large changes in C–X bond polarity. We then proposed that when Y have significant effects on Z–X BDE's it is due to their stabilization or destabilization of the radical. This proposal has been examined by studying 4-YC₆H₄O-X BDE's for X = H, CH₃, and CH₂C₆H₅ both by theory and experiment. The magnitudes of the effects of Y on O–X BDE's were quantified by Hammett type plots of Δ BDE's vs σ^+ (Y). Calculations reveal that changes in O–X BDE's induced by changing Y are large and essentially identical ($\rho^+ = 6.7$ – 6.9 kcal mol⁻¹) for these three classes of compounds. The calculated ρ^+ values are close to those obtained experimentally for X = H at ca. 300 K and for X = CH₂C₆H₅ at ca. 550 K. However, early literature reports of the effects of Y on O–X BDE's for X = CH₃ with measurements made at ca. 1000 K gave $\rho^+ \approx 3$ kcal mol⁻¹. We have confirmed some of these earlier, high-temperature O–CH₃ BDE's and propose that at 1000 K, conjugating groups such as –OCH₃ are essentially free rotors, and no longer lie mainly in the plane of the aromatic ring. As a consequence, the 298 K DFT-calculated Δ BDE for 4-OCH₃-anisole of -6.1 kcal mol⁻¹ decreases to -3.8 kcal mol⁻¹ for free rotation, in agreement with the ca. 1000 K experimental value. In contrast, high-temperature O–CH₃ Δ BDE's for three anisoles with strongly hindered substituent rotation are essentially identical to those that would be observed at ambient temperatures. We conclude that substituent effects measured at elevated temperatures may differ substantially from those appropriate for 298 K.

The effects of para substituents, Y, on the Z–X bond dissociation enthalpies (BDE's) of compounds having the general formula 4-YC₆H₄Z-X are a subject of intense experimental and theoretical interest.³ The prevailing view has been that the effect of the Y substituents on Z–X BDE's, as derived from the slope, ρ or ρ^+ , of Hammett type plots in the form {BDE(4-YC₆H₄Z-X) – BDE(C₆H₅Z-X)} = Δ BDE(Z-X) vs σ (Y) or σ^+ (Y), depended on, and could be correlated with, the difference in the Pauling electronegativities of Z and X, $\Delta\chi = \chi(Z) - \chi(X)$. According to this dipole interaction model, and with a positive $\Delta\chi$, Z–X BDE's were believed to be weakened by electron-donating (ED) Y's and strengthened by electron-withdrawing (EW) Y's, and the greater the magnitude of $\Delta\chi$, the greater would be the effect of Y on Z–X BDE's. If $\Delta\chi$ was negative, then ED and EW Y's would strengthen and weaken, respectively, the Z–X BDE's.³

There was extensive support for the views just described, the most important of which can be summarized as follows:

1. In 4-YC₆H₄OH, the effect of Y on O–H BDE's ($\Delta\chi = 1.4$) was in the expected direction (i.e., ED Y's weakened and

EW Y's strengthened the O–H bond) and was very large.^{3,5} The O–H BDE's (or Δ BDE's) of 17 different phenols measured by photoacoustic calorimetry (PAC) at room temperature plotted versus σ^+ (Y) were found to be linear with an experimental slope $\rho^+ = 6.9$ kcal mol⁻¹,^{5a,b} while theory^{5c} gave a slope $\rho^+ = 6.4$ kcal mol⁻¹ for 4-YC₆H₄OH.

2. The nature of the Y substituent has little effect on C–H BDE's ($\Delta\chi = 0.4$) in 4-YC₆H₄CH₂-H,^{6,7} with $\rho^+ = 0.5$ kcal mol⁻¹ from an AM1 study,⁶ and on C–C BDE's ($\Delta\chi = 0$) in YC₆H₄CH₂-CH₃⁸ and 4-YC₆H₄C(CH₃)₂-CH₃⁹ as measured by gas-phase pyrolytic methods.

3. The PAC measured C–Br BDE's ($\Delta\chi = -0.3$) in 4-YC₆H₄CH₂-Br were reported to be *decreased* by EW Y's and a plot of C–Br BDE's versus σ (Y) yielded $\rho = -5.5$ kcal mol⁻¹.¹⁰

(4) Pratt, D. A.; Wright, J. S.; Ingold, K. U. *J. Am. Chem. Soc.* **1999**, *121*, 4877–4882.

(5) (a) Mulder, P.; Saastad, O. W.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 4090–4092. (b) Dorrestijn E.; Laarhoven L. J. J.; Arends I. W. C. E.; Mulder P. *J. Anal. Appl. Pyrolysis* **2000**, *54*, 153–192. (c) DiLabio, G. A.; Pratt, D. A.; LoFaro, A. D.; Wright, J. S. *J. Phys. Chem. A* **1999**, *103*, 1653–1661. (d) Mahoney, L. R.; DaRooge, M. A. *J. Am. Chem. Soc.* **1975**, *97*, 4722–4731.

(6) Wayner, D. D.; Sim, B. A.; Dannenberg, J. J. *J. Org. Chem.* **1991**, *56*, 6, 4853–4858.

(1) Issued as NRCC No.43887.

(2) (a) NRCC. (b) Vanderbilt University. (c) University of Leiden.

(3) An extensive bibliography is given in ref 4.

4. The O–C BDE's ($\Delta\chi = 1.0$) in 4- $\text{YC}_6\text{H}_4\text{O-CH}_3$ determined using very low-pressure pyrolysis (VLPP) were reported to be decreased by ED Y's with $\rho^+ = 3.0 \text{ kcal mol}^{-1}$,¹¹ a value between that found for phenol (6.9–6.4) and toluene (0.5), consistent with the trend in $\Delta\chi$ along the O–H (1.4), O–C (1.0), and C–H (0.4) bond series.

5. The N–H BDE's in 4- $\text{YC}_6\text{H}_4\text{NH-H}$ ($\Delta\chi = 0.9$) measured electrochemically gave $\rho^+ = 3.0 \text{ kcal mol}^{-1}$,¹² thus showing a behavior similar to the O–C bond and intermediate between the O–H and C–H bonds referred to above.

This well-butressed and beautiful picture relating the direction and magnitude of the effect of Y on Z–X BDE's in compounds of the general formula 4- $\text{YC}_6\text{H}_4\text{Z-X}$ to the differences in the electronegativities of Z and X, i.e., to ground-state polar effects, began to unravel in 1997. In that year, Laarhoven et al.⁹ reported a reexamination of 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-Br}$ BDE's (item 3 above) using both PAC (that had earlier¹⁰ yielded $\rho^+ = -5.5 \text{ kcal mol}^{-1}$) and a gas-phase pyrolytic method. Both procedures indicated that Y substituents had no experimentally detectable effect on the benzylic C–Br BDE's. Since the experimental approach to 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-Br}$ BDE's gave inconsistent data, we turned to theory.⁴ Using density functional theory (DFT) model calculations with the B3LYP functional and a locally dense basis set, the BDE's in 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-X}$ with X = H, F, Cl, Br were calculated. From this study it was found that Y has only a very minor ($<2 \text{ kcal mol}^{-1}$) effect on 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-Br}$ BDE's ($\Delta\chi = -0.3$). More significantly, for 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-Cl}$ ($\Delta\chi = -0.5$) and 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-F}$ ($\Delta\chi = -1.5$), the effects of Y on these carbon–halogen BDE's were found to be not only very small but also quite similar to their effects on C–Br BDE's. For example, comparing the strongest ED group studied, $-\text{NH}_2$ ($\sigma_p^+ = -1.30$), with the strongest EW group studied, $-\text{NO}_2$ ($\sigma_p^+ = 0.79$), the calculated ΔBDE values, $\text{BDE}(4\text{-H}_2\text{NC}_6\text{H}_4\text{CH}_2\text{-X}) - \text{BDE}(4\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_2\text{-X})$, were 1.6, 1.3, 1.4, and 0.5 kcal mol^{-1} for X = H, Br, Cl, and F, respectively, i.e., actually smaller for F than for H, Br, and Cl. Obviously, polar effects on carbon–halogen BDE's in benzyl halides are of only minor significance. More importantly, and in view of the large range in Z–X electronegativity differences covered in this study⁴ ($\Delta\chi$ from -1.5 to 0.4), the idea that the sign and magnitude of the effects of Y on Z–X BDE's could be correlated with $\Delta\chi$ (Z–X) would have to be discarded.

What then determines the effect of Y on 4- $\text{YC}_6\text{H}_4\text{Z-X}$ BDE's? The obvious answer is the stabilization/destabilization by Y of the 4- $\text{YC}_6\text{H}_4\text{Z}^\bullet$ radical. If this is true, differences in BDE's for 4- $\text{YC}_6\text{H}_4\text{O-X}$ compounds caused by changes in Y should be largely independent of X, just as we have demonstrated for 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-X}^4$ (see above). Clearly, therefore, the experimental results regarding the effects of Y on 4- $\text{YC}_6\text{H}_4\text{O-CH}_3$ BDE's¹¹ (item 4 above) are anomalous ($\rho^+ = 3.0 \text{ kcal mol}^{-1}$).

(7) Various estimates of the effects of Y-substituents on the benzylic C–H BDE in toluene have been made from kinetic data for the abstraction of the benzylic H-atom by free radicals, but it is perfectly clear that kinetic polar effects play a role in these atom transfer reactions because the magnitude of ρ or ρ^+ depends on the nature of the attacking radical. See, for example: Howard, J. A.; Chenier, J. H. B. *J. Am. Chem. Soc.* **1973**, *95*, 3054–3055; Pryor, W. A.; Church, D. F.; Tang, F. Y.; Tang, R. H. *Frontiers of Free Radical Chemistry*; Pryor, W. A., Ed.; Academic Press: New York, 1980; p 355–379. Also: Zavitsas, A. A.; Fogel, G.; Halwagi, K. E.; Donnaruma Legotte, P. A. *J. Am. Chem. Soc.* **1983**, *105*, 6960–6962.

(8) Suryan, M. M.; Stein, S. E. *J. Phys. Chem.* **1989**, *93*, 7362–7365.

(9) Laarhoven, L. J. J.; Born, J. G. P.; Arends, I. W. C. E.; Mulder, P. *J. Chem. Soc., Perkin Trans. 2* **1997**, 2307–2312.

(10) Clark, K. B.; Wayner, D. D. M. *J. Am. Chem. Soc.* **1991**, *113*, 9363–9365.

(11) (a) Suryan, M. M.; Kafafi, S. A.; Stein, S. E. *J. Am. Chem. Soc.* **1989**, *111*, 4594–4600. (b) This value of ρ^+ was taken directly from Figure 2 in ref 11a.

We would have expected a much larger substituent effect that was closely comparable to the well-established experimental effect of substituents on O–H BDE's in phenols ($\rho^+ = 6.9 \text{ kcal/mol}$). There is, in fact, a recent theoretical study by Wu and Lai¹³ that indicates that the effects of Y on 4- $\text{YC}_6\text{H}_4\text{O-CH}_3$ BDE's and 4- $\text{YC}_6\text{H}_4\text{O-H}$ BDE's are “nearly identical”.

Since experiment and theory disagree regarding the effect of substituents on O–C BDE's in phenyl ethers we decided to examine this problem both by experiment and theory. We reexamined the O–C bond cleavage of substituted anisoles in the gas phase at around 1000 K and studied substituted benzyl phenyl ether homolysis in the liquid phase at around 550 K in the presence of a radical scavenger, 9,10-dihydroanthracene. In benzyl phenyl ethers a substituent on the phenoxy group, 4- $\text{YC}_6\text{H}_4\text{O-CH}_2\text{C}_6\text{H}_5$, would be expected to have a different (and larger) effect than the same substituent on the benzyl group, 4- $\text{YC}_6\text{H}_4\text{CH}_2\text{-OC}_6\text{H}_5$, analogous to the known effects of substituents in phenols and in benzyl halides or toluenes, respectively. We also studied phenols and phenyl ethers with the same substituents by several density functional theory (DFT) procedures for direct comparisons.

Experimental Section

Method of Calculation. This has been described elsewhere.^{5c,14} In short, geometry optimizations and vibrational frequency calculations were performed using the semiempirical AM1 method,¹⁵ and zero-point energies were scaled by 0.973.^{5c} At the AM1 minima, B3LYP^{16,17} single-point energies were obtained for phenols and anisoles (hereafter referred to as DFT I), and B3P86^{16,18} single-point energies were calculated for anisoles and benzyl phenyl ethers (DFT II). A restricted open-shell Hartree–Fock guess was used for the open-shell (radical) calculations^{5c} with a locally dense basis set:¹⁹ primary = O–X, 6-311+G(2d,2p) (B3LYP) and 6-311G(d,p) (B3P86); secondary = aromatic carbons, 6-311+G(d) (B3LYP) and 6-311G(d) (B3P86); tertiary = all remaining atoms, 6-31G(d). The electronic energy of the hydrogen atom was set to its exact value of -0.5 hartree.^{5c} Vibrational frequencies for anisoles, used in the RRKM computation of the Arrhenius parameters at the high-pressure limit (vide infra), were obtained with (RO)B3LYP/6-31G(d,p)//B3LYP/6-31G(d,p) (DFT III). Enthalpies of the species involved were differenced to give the gas-phase bond dissociation enthalpy (BDE), i.e., for $\text{X-Y} \rightarrow \text{X}^\bullet + \text{Y}^\bullet$, $\Delta H_{298}^\circ = \{H_{298}^\circ(\text{X}^\bullet) + H_{298}^\circ(\text{Y}^\bullet)\} - H_{298}^\circ(\text{X-Y})$.

Thermolysis of Benzyl Phenyl Ethers. The decomposition of benzyl phenyl ethers was studied using 9,10-dihydroanthracene (9,10-DHA) as the hydrogen atom donating solvent. For each benzyl phenyl ether five glass ampules (ca. 2 mL in volume) were prepared. The ether (0.25 mmol) was added to a clean ampule that was then filled to its neck with solid, finely divided 9,10-DHA and sealed under vacuum after three or more cool–pump–heat melting cycles. The ampules were placed in a temperature-controlled GC oven. Ampules were removed at known times, cooled to room temperature, opened, and their contents dissolved in acetone (50 mL) containing 0.25 mmol of anisole as external standard. Products were identified by GC/MS (at 70 eV) and quantified by GC/FID (average of three injections). The detailed results of these experiments are given as Supporting Information.

Very Low-Pressure Pyrolysis. The VLPP instrument and the experimental procedures have been described.²⁰ In short, the reactants

(12) Jonsson, M.; Lind, J.; Eriksen, T. E.; Merenyi, G. *J. Am. Chem. Soc.* **1994**, *116*, 1423–1427.

(13) Wu, Y.-D.; Lai, D. K. W. *J. Org. Chem.* **1996**, *61*, 7904–7910.

(14) DiLabio, G. A.; Pratt, D. A. *J. Phys. Chem. A* **2000**, *104*, 1938–1943.

(15) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902–3909.

(16) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648–5652.

(17) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785–789.

(18) Perdew, J. P. *Phys. Rev. B* **1986**, *33*, 8822–8824.

(19) DiLabio, G. A. *J. Phys. Chem. A* **1999**, *103*, 11414–11424.

Table 1. Calculated O–H and O–C Gas-Phase Bond Dissociation Enthalpies of 4-Substituted Phenols (4-YC₆H₄O-H), Anisoles (4-YC₆H₄O-CH₃), and Benzyl Phenyl Ethers (4-YC₆H₄O-CH₂C₆H₅, 4-YC₆H₄CH₂-OC₆H₅)^a

Y	σ^{+b}	4-YC ₆ H ₄ O-H		4-YC ₆ H ₄ O-CH ₃		4-YC ₆ H ₄ O-CH ₂ C ₆ H ₅	4-YC ₆ H ₄ CH ₂ -OC ₆ H ₅
		DFT I	DFT I	DFT II	DFT III	DFT II	DFT II
–H	0	87.2	59.3	65.2	63.5	52.8; 52.5 ^c	52.8
–NH ₂	–1.30	–9.4	–9.2	–9.5	–8.9	–9.3	–1.4
–OCH ₃	–0.78	–6.1	–6.0	–6.1	–5.5	–6.1	–0.5
–CF ₃	0.61	+3.1	+3.7	+3.0	+2.8	+3.0	–0.1
–NO ₂	0.79	+4.5	+5.2	+4.6	+4.5	+4.7	–0.9
4-OH-3-CHO	–0.43 ^d			–4.5 ^e	–4.7 ^e		
ρ^{+f}		6.67	6.94	6.70	6.29	6.67	
intercept		–0.67	–0.38	–0.69	–0.57	–0.63	
R ^{2f}		0.996	0.998	0.995	0.996	0.995	

^a For Y = H the absolute BDE is given, for all other substituents the Δ BDE (difference from unsubstituted species with Y = H), all values in kcal mol^{–1}. For computational details see the Experimental Section. ^b Values are taken from ref 24 unless otherwise noted. ^c Value determined for 548 K. ^d See footnote 25. ^e Data not used in Hammett correlation. ^f Slopes ρ^+ of Hammett plots of Δ BDE vs σ^+ and R², the linear correlation coefficient.

were introduced into a Knudsen quartz reaction chamber of 28.1 mL volume via a glass capillary by evaporation or sublimation from a temperature-controlled (± 0.5 °C) evaporation vessel that could be operated between –10 and +20 °C. Typically, the inlet flux was about 2×10^{13} molecules s^{–1} and the pressure inside the reaction vessel was 5×10^{-5} Torr. After escape through a single aperture (diameter 1.2 mm) the molecular beam was sampled continuously by a HP 5970 mass selective detector. The mass spectra were recorded using an ionization energy of 20 eV to avoid a large degree of fragmentation of the reactant and its products. After temperature equilibration, >1000 scans were averaged to improve the signal/noise ratio. From the decrease of the molecular ion abundance (*I*) relative to *I*₀ (intensity at zero conversion recorded before and after each set of temperatures for the compound under study), the rate constants for unimolecular decay, *k*_{uni}, were calculated at each temperature according to $k_{\text{uni}} = k_e(I_0 - I)/I$, with *k*_e as the escape rate constant: $k_e = 1.47(T/M)^{1/2}$ (*M* = molar mass of the reactant and 1.47 is an instrument constant containing the collision number for our reactor of 9200). Typically, for between 20% and 80% decomposition of the substrate, the error in the *k*-values is around 2%. The decompositions followed first-order kinetics for all compounds (since the rates of reactant loss were not changed on varying the initial reactant concentration). The Arrhenius expression at the high-pressure limit was obtained by application of the Stein-Rabinovitch RRKM algorithm (which employs a purely vibrational model without taking into account the presence of internal rotors)^{20b} and using DFT III frequencies scaled by a factor of 0.96,²¹ which are available as Supporting Information.

Materials. Benzyl phenyl ether and 9,10-dihydroanthracene were used as received. Anisole, 2-methoxyanisole, 2-hydroxyanisole, and 4-hydroxy-3-formylanisole (2-hydroxy-5-methoxybenzaldehyde) were distilled, and 4-methoxyanisole and 4-hydroxyanisole were sublimed before use.

The 4-substituted benzyl phenyl ethers were synthesized by adding the corresponding 4-substituted benzyl chloride to a solution of phenol in acetone containing potassium carbonate. Benzyl 4-substituted phenyl ethers were prepared in a similar manner from the corresponding

4-substituted phenol and benzyl chloride. Products were characterized by melting point and ¹H NMR and ¹³C NMR spectroscopy on a Bruker DRX 400 MHz spectrometer, purified by column chromatography on silica gel, and dried under vacuum prior to thermolysis. Details are available as Supporting Information.

4-(Trifluoromethyl)anisole was synthesized following a standard procedure by methylation of 4-(trifluoromethyl)phenol with methyl iodide in the presence of K₂CO₃. The product was obtained as a light-yellow oil (purity by GC: 98.5%) and characterized by GC-MS.

Results

Theoretical Calculations. Calculated O–H and O–C gas-phase bond dissociation enthalpies at 298 K for para-substituted phenols (4-YC₆H₄O-H), anisoles (4-YC₆H₄O-CH₃), benzyl 4-substituted phenyl ethers (4-YC₆H₄O-CH₂C₆H₅), and 4-substituted benzyl phenyl ethers (4-YC₆H₄CH₂-OC₆H₅) are given in Table 1. The 4-Y substituents for the anisoles and phenols were chosen to cover a wide range of substituent effects from the strongly electron-donating –NH₂ group to the strongly electron-withdrawing –NO₂ group. Thermodynamic data for the anisoles as computed by DFT III became available as well, and are presented in Table 1 together with the DFT I and DFT II results.

Benzyl Phenyl Ether Thermolysis. The rates of thermolysis of five benzyl phenyl ethers (reaction 1) in 9,10-DHA were measured, each at a single temperature with ether conversions ranging from 2 to 32%. The resulting phenoxy and benzyl radicals abstract a hydrogen atom from 9,10-DHA to form the corresponding phenol and toluene. The disproportionation of the 9,10-dihydroanthracenyl radical then yields 9,10-DHA and anthracene.²⁷ These reactions all followed clean first-order

(22) Green J. H. S. *Spectrochim. Acta* **1962**, *18*, 39–50.

(23) Scott A. P.; Radom L. *J. Phys. Chem.* **1996**, *100*, 16502–16513.

(24) Hansch, C.; Leo, A.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165–195.

(25) Contrary to most σ_p^+ values, the value of –0.92 for $\sigma_p^+(\text{OH})$ ²⁶ was not determined from the solvolysis of the corresponding *tert*-cumyl chloride but is based on the rate of acid cleavage of phenyltrimethylsilanes in aqueous methanol (see: Eaborn, C. J., *J. Chem. Soc.* **1956**, 4858–4864). It is unreasonable that an un-ionized –OH should be a stronger ED group than –OCH₃ and it is therefore unreasonable that $\sigma_p^+(\text{OH})$ should be greater than $\sigma_p^+(\text{OCH}_3)$. Indeed, for Y = OH the calculated Δ BDE's are virtually identical to those given in Table 1 for Y = OCH₃ irrespective of the compound and the theoretical method used. We have therefore assumed throughout this paper that $\sigma_p^+(\text{OH}) = \sigma_p^+(\text{OCH}_3) = -0.78$. Thus, for the 4-OH and 3-CHO substituents together $\sum\sigma^+ = \sigma_p^+(\text{OH}) + \sigma_m(\text{CHO}) = -0.78 + 0.35 = -0.43$.

(26) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979–4987.

(27) Tetrahydroanthracene and octahydroanthracene were also formed in trace amounts at 548 K and in larger amounts at 573 K with tetrahydroanthracene the predominant byproduct. Anthraquinones were produced when samples were incompletely deoxygenated.

(20) (a) Golden, D. M.; Spokes, G. N.; Benson, S. W. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 534–546. (b) Robaugh, D. A.; Stein, S. E. *Int. J. Chem. Kinet.* **1981**, *13*, 445–462. (c) Ciriano, M. V.; Korth, H.-G.; Van Scheppingen W. B.; Mulder, P. *J. Am. Chem. Soc.* **1999**, *121*, 6375–6381. (d) Van Scheppingen, W. B.; Dorrestijn, E.; Arends, I.; Mulder, P.; Korth, H.-G. *J. Phys. Chem. A* **1997**, *101*, 5404–5411. (e) Dorrestijn, E.; Hemmink, S.; Hulstman, G.; Monnier, L.; Van Scheppingen, W. B.; Mulder, P. *Eur. J. Org. Chem.* **1999**, 607–616; correction: *Eur. J. Org. Chem.* **1999**, 1267. (f) In all cases (especially 20d and 20e), a purely vibrational model has been used. Although this may be an oversimplification for the description of the transition state, it has yielded remarkably precise enthalpic data. This may be because the falloff ($k_{\text{uni}}/k_{\text{uni}}^\infty$) for the unimolecular reactions investigated in refs 20d and 20e and here is rather limited and ranges from only 0.2 to 0.5.

(21) The DFT III frequencies for anisole were compared to experimental frequencies from ref 22, resulting in an average scaling factor of 0.96, in perfect agreement with the scaling factor of 0.9614 suggested by Scott and Radom.²³

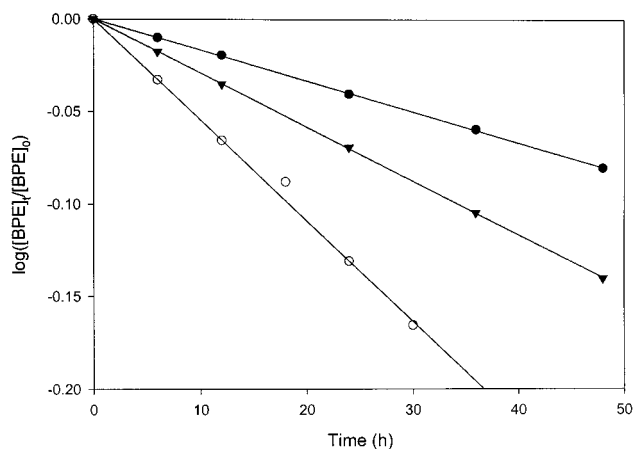


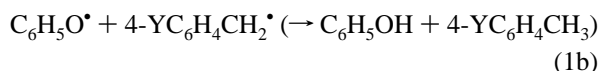
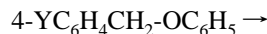
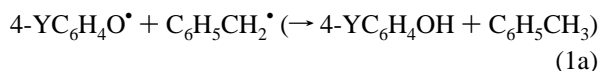
Figure 1. Plots of $\log([BPE]_t/[BPE]_0)$ vs time for the thermal decomposition of $C_6H_5CH_2OC_6H_5$ (●), $4-CF_3C_6H_4CH_2OC_6H_5$ (▼), and $4-CH_3OC_6H_4CH_2OC_6H_5$ (○) in 9,10-DHA at 548 K (BPE = benzyl phenyl ether).

Table 2. Experimental First-Order Rate Constants for the Thermal Decomposition of Substituted Benzyl Phenyl Ethers in 9,10-DHA at the Temperatures Indicated

benzyl phenyl ether	T (K)	$10^7 k_1$ (s^{-1})	$E_{a,1}$ ($kcal\ mol^{-1}$) ^{a,b}
$CH_3OC_6H_4O-CH_2C_6H_5$	498	21.2	47.6 (−5.5)
$CF_3C_6H_4O-CH_2C_6H_5$	573	10.7	56.3 (3.2)
$C_6H_5O-CH_2C_6H_5$	548	5.18	53.1 (0.0)
$CH_3OC_6H_4CH_2-OC_6H_5$	548	35.1	51.8 (−1.3)
$CF_3C_6H_4CH_2-OC_6H_5$	548	18.7	52.5 (−0.6)

^a Activation enthalpies were calculated using $\log(A_1/s^{-1}) = 15.2$,⁴⁰ see text. ^b Differences from unsubstituted species are given in parentheses.

kinetics (see Figure 1), with good to acceptable mass balances.²⁸ First-order rate constants were calculated from the sum of the yields of the products, phenol and toluene, as a function of time (relative standard deviations of 3% or less), see Table 2. Rate constants were calculated from product formation because small quantities of products can be measured more accurately than small decreases in the concentrations of the starting materials.



Very Low-Pressure Pyrolysis of Substituted Anisoles: Products. Unimolecular O–CH₃ bond cleavage for seven anisoles (4-H; 2-OH; 2-OCH₃; 4-OH; 4-OCH₃; 4-CF₃; and 4-OH, 3-CHO), reaction 2, were studied using VLPP with conversions between 5 and 95%. At 20 eV and zero conversion



the mass spectrum of the substituted anisoles consisted of the molecular ion ($m/z = M$) and the corresponding phenoxy moiety

(28) Mass balances were >95% for $CH_3OC_6H_4OCH_2C_6H_5$, $CF_3C_6H_4OCH_2C_6H_5$, and $CF_3C_6H_4CH_2OC_6H_5$, but less good for the unsubstituted benzyl phenyl ether (92%–82%) and $CH_3OC_6H_4CH_2OC_6H_5$ (70–58%), see Supporting Information. We had expected slightly poorer mass balances since it has been shown that the thermolysis of benzyl phenyl ether at 598 K gives ca. 20% 2-OH-diphenylmethane via an in-cage recombination of the phenoxy and benzyl radicals.²⁹

($m/z = M-15$), typically about 30–50% of the molecular ion. For anisole and 4-CF₃-anisole the $m/z = M-15$ intensity was only 3–5% of the molecular ion.

For all the anisoles studied the major product, based on mass spectra, was the corresponding phenol, which arises from C–O bond cleavage followed by hydrogen atom transfer from the wall of the reactor to the phenoxy radical.^{20d,30} Other products³⁰ result from phenoxy radical decomposition into CO and the corresponding cyclopentadienyl radical which, by hydrogen atom transfer reactions, is converted to cyclopentadiene derivatives.

Very Low-Pressure Pyrolysis of Substituted Anisoles: Kinetics. Under VLPP conditions the bond fission reactions are in the falloff or pressure-dependent region for unimolecular reactions. The RRKM theory provides a method for deriving high-pressure rate constants. The applied algorithm uses a purely vibrational model that does not take internal rotors into account. Although this may be a simplified approach, this methodology has proven to be quite accurate.^{20b–f} The VLPP data cannot simultaneously yield the enthalpy of activation, E_a , and the preexponential factor. In the RRKM analyses a constant preexponential factor of $\log(A_2/s^{-1}) = 15.3$ was employed since this value has been reported for the homolytic bond dissociation of anisole by the toluene carrier method.³¹ For 2-OCH₃- and 4-OCH₃-anisole a statistical correction of two was incorporated into the preexponential factor to give $\log(A_2/s^{-1}) = 15.6$. Plots of the experimental rate constants, $k_{2,uni}$, and RRKM fitted lines are shown in Figure 2. The kinetic parameters obtained from the RRKM calculations are given in Table 3, which are valid for the temperature region studied (800–1100 K). The gas-phase O–CH₃ BDE's at 298 K can be derived from the activation enthalpy with the use of eq 3, with $T_{50\%}$ the

$$BDE = E_{a,2} + RT_{50\%} - \Delta_2 C_p(T_{50\%} - 298) \quad (3)$$

temperature at 50% conversion and $\Delta_2 C_p$ the average change in heat capacity for the reaction on going from $T_{50\%}$ to 298 K.³² It should be noted that any deviation in the applied preexponential factors may affect the absolute $E_{a,2}$ but will have no impact on the relative BDE's derived using eq 3, and given in Table 3. The O–C BDE for anisole calculated in this way is 65.3 kcal mol^{−1}, which is in excellent agreement with the value determined earlier by the toluene carrier method, viz., 65.2 kcal mol^{−1}.³¹

(29) (a) Korobkov, V. Yu.; Grigorieva, E. N.; Bykov, V. I.; Senko, O. V.; Kalechitz, I. V. *Fuel* **1988**, *67*, 657–662. (b) Korobkov, V. Yu.; Grigorieva, E. N.; Bykov, V. I.; Kalechitz, I. V. *Fuel* **1988**, *67*, 663–665.

(30) The following products were detected for the different anisoles with, in parentheses, the relative intensities at approximately 50% conversion with respect to the intensity of the molecular ion at zero conversion. Relative intensities are not corrected for differences in ionization efficiencies: Anisole (0.51): phenol (0.24), 5-methyl-1,3-cyclopentadiene (0.008), 5, 5'-bis(1,3-cyclopentadiene) (0.001), 4-OCH₃-anisole (0.48): 1,4-benzoquinone (0.07), hydroquinone (0.03), cyclopentadienone (0.02), 5-hydroxy-1,3-cyclopentadiene (0.02). 4-OH-anisole (0.52): hydroquinone (0.19), 1,4-benzoquinone (0.05), cyclopentadienone (0.02), 5-hydroxy-1,3-cyclopentadiene (0.03). 4-CF₃-anisole (0.48): 4-(trifluoromethyl)phenol (0.16), 5-difluoromethylene-1,3-cyclopentadiene (0.07), 5-trifluoromethyl-1,3-cyclopentadiene (0.006). 4-OH, 3-CHO-anisole (0.49): 2,5-dihydroxybenzaldehyde (0.15), hydroquinone (0.04), 1,4-benzoquinone (0.02). 2-OCH₃-anisole (0.54): 2-hydroxybenzaldehyde (0.18), phenol (0.04), 1,2-dihydroxybenzene (0.02). 2-OH-anisole (0.49): 1,2-dihydroxybenzene (0.26), cyclopentadienone (0.05), 5-hydroxy-1,3-cyclopentadiene (0.01).

(31) Arends, I. W. C. E.; Louw, R.; Mulder, P. J. *Phys. Chem.* **1993**, *97*, 7, 7914–7925.

(32) $\Delta_2 C_p$ for unimolecular bond dissociation of anisole is 0.78 cal mol^{−1} K^{−1} on going from $T_{50\%} = 1007$ to 298 K, as computed by DFT III. This $\Delta_2 C_p$ value was used for all the other anisoles. $T_{50\%}$ values were the following: anisole 1007 K; 4-OH-anisole 955 K; 4-OH, 3-CHO-anisole 935 K; 4-OCH₃-anisole 921 K; 4-CF₃-anisole 1005 K; 2-OH-anisole 893 K; and 2-OCH₃-anisole 909 K.

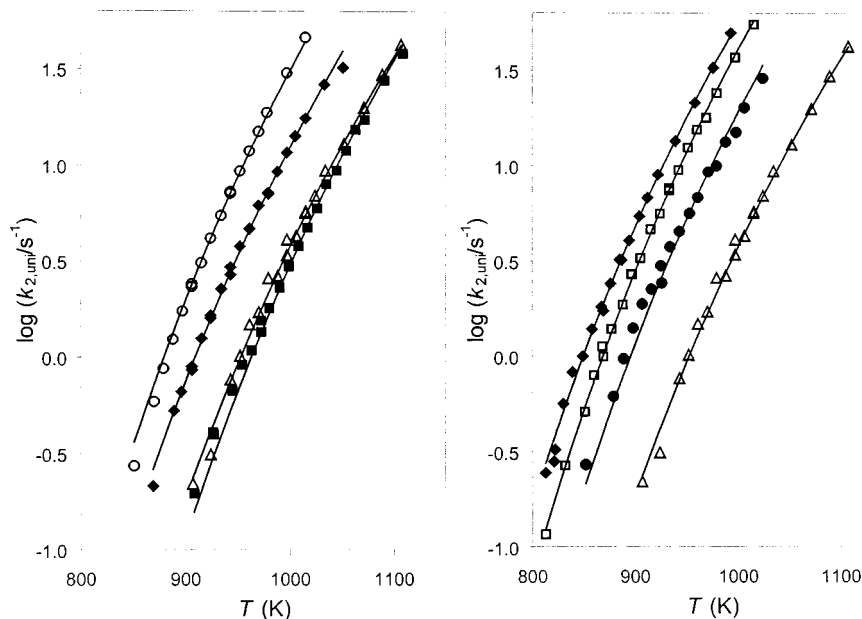


Figure 2. VLPP results for unimolecular bond dissociation of the O–C bond in substituted anisoles. Left panel: (○) 4-OCH₃-anisole, (◆) 4-OH-anisole, (△) anisole, and (■) 4-CF₃-anisole, with the RRKM curve fittings (solid lines). Right panel: (◆) 2-OH-anisole, (□) 2-OCH₃-anisole, (●) 4-OH,3-CHO-anisole, and (△) anisole, with the RRKM curve fittings (solid lines).

Table 3. Experimental Rate Parameters between 800 and 1100 K and BDE's at 298 K for the Thermal Decomposition of Substituted Anisoles

Y	log(A ₂ /s ⁻¹) ^a	E _{a,2} ^b	O-C BDE ^{b,c}	ΔBDE ^{b,d}	est. ΔBDE ^{b,e}
H	15.3	63.9	65.3	0 (0)	0
2-OH	15.3	56.8	58.1	-7.2 ^f (-7.1)	
4-OH	15.3	61.2	62.6	-2.7 (-2.5)	-3.6
2-OH, 3-CHO	15.3	61.0	62.3	-3.0	-4.2 ^g
2-OCH ₃	15.6 ^h	59.9	61.2	-4.1 (-4.2)	
4-OCH ₃	15.6 ^h	60.9	62.2	-3.1 (-3.9)	-3.8
4-CF ₃	15.3	66.0	67.5	+2.2	+2.6

^a From ref 31, see text. ^b Values in kcal mol⁻¹. ^c Calculated from eq 3: BDE = E_{a,2} + RT_{50%} - Δ₂C_p(T_{50%} - 298) (see text).³¹ ^d Values in parentheses are for VLPP data from ref 11a. ^e Estimated ΔBDE's for free rotation of the substituent when relevant and free rotation of the dissociating O-CH₃ group, see text. ^f Becomes -4.1 kcal mol⁻¹ when compensated for the intramolecular hydrogen bond. ^g Assuming that only the rotation of the dissociating methoxyl group is significant. ^h Including a statistical factor of 2.

Discussion

Calculated O–H and O–C BDE's. Several earlier studies^{13,33,34} have reported good agreement between the calculated and experimental O–H BDE for phenol and the substituent effects upon it. Most recently, DiLabio et al.^{5c} calculated, using various computational models and uniform basis sets, an O–H BDE of 87.0 ± 0.2 kcal mol⁻¹ for phenol, indistinguishable from the reviewed “best” experimental value of 87 ± 1 kcal mol⁻¹.³⁵ Moreover, calculations using a uniform basis set^{5c} on phenol and eight 4-substituted phenols yielded O–H BDE's which correlated with the σ⁺ value of the substituent to yield ρ⁺ of 6.4 kcal mol⁻¹. Our present calculations, which use the same DFT model, but which employ a locally dense basis set with phenol and four 4-substituted phenols, give ρ⁺ = 6.67 kcal

mol⁻¹ (DFT I, see Table 1), in very good agreement with the experimental value (based on 17 phenols) of 6.9 kcal mol⁻¹.^{5b} Although similarly good agreement between experimental and calculated substituent effects can be achieved with a variety of DFT methods (due to error cancellation), the absolute values of the O–H BDE's in substituted phenols calculated by other models and methods are largely underestimated relative to experiment.^{5c}

Our calculations on 4-YC₆H₄OCH₃ compounds using the same methodology with a locally dense basis set (DFT I) as for the phenols gave BDE(C₆H₅O-CH₃) = 59.3 kcal mol⁻¹, considerably lower than the experimental value of 65.3 kcal mol⁻¹ (see Table 3). These calculations also gave O–C BDE's which correlated with σ_p⁺ yielding ρ⁺ = 6.94 kcal mol⁻¹, essentially identical to that for phenols. For more accurate calculations of the absolute O–C BDE's the B3P86 model (DFT II) was used, which has been shown to yield better absolute heavy atom–heavy atom BDE's for a wide variety of bond types (including O–C).^{14,36} These calculations gave BDE(C₆H₅O-CH₃) = 65.2 kcal mol⁻¹, in excellent agreement with our experimental value of 65.3 kcal mol⁻¹. More importantly, in the present context, these calculations yielded ρ⁺ = 6.70 kcal mol⁻¹, almost the same as the calculated ρ⁺ for phenols (6.67 kcal mol⁻¹). These DFT II calculated ΔBDE's for 4-YC₆H₄O-CH₃ have been plotted in Figure 3 (filled circles, solid line). For DFT I and DFT II the ρ⁺ values range only from 6.67 to 6.94 kcal mol⁻¹ for phenols and anisoles. This reinforces the fact that when considering ΔBDE's, the results are going to be roughly the same regardless of whether DFTI or DFTII (or really any reasonable model/basis combination) is used due to error cancellation, whereas for accurate absolute BDE's where the chance for error cancellation is absent it is important to use DFTI for X–H BDE's and DFTII for X–Y or X–X BDE's.

The DFT II calculated C₆H₅O–CH₂C₆H₅ BDE is 52.8 kcal mol⁻¹. For this ether linkage no precise experimental BDE is available, but a group increment approach³⁷ yields an O–C BDE of 54 ± 1 kcal mol⁻¹. Four separate kinetic (liquid phase) studies

(33) Wright, J. S.; Carpenter, D. J.; McKay, D. J.; Ingold, K. U. *J. Am. Chem. Soc.* **1997**, *119*, 4245–4252.

(34) Brinck, T.; Haerberlein, M.; Jonsson, M. *J. Am. Chem. Soc.* **1997**, *119*, 4239–4244.

(35) Wayner D. D. M.; Luszyk E.; Pagé D.; Ingold K. U.; Mulder P.; Laarhoven L. J. J.; Aldrich H. S. *J. Am. Chem. Soc.* **1995**, *117*, 8737–8744.

(36) Reints, W.; Pratt, D. A.; Korth, H.-G.; Mulder, P. *J. Phys. Chem. A* **2000**, *104*, 10713–10720.

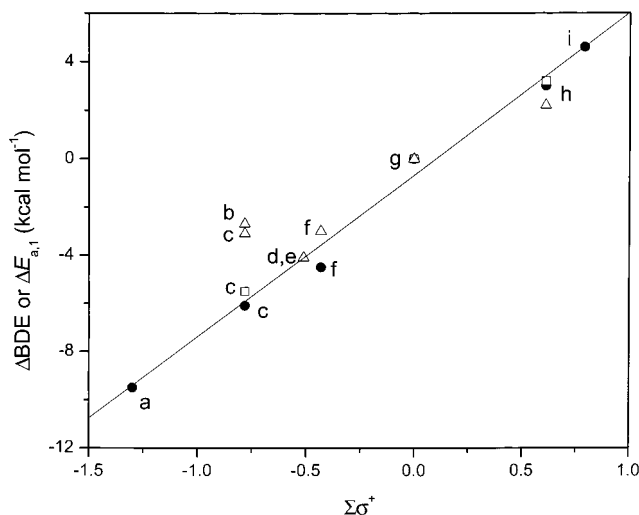


Figure 3. Correlation of $\Sigma\sigma^+$ with DFT II Δ BDE's in 4-substituted anisoles (●). The DFT Δ BDE value for 4-OH,3-CHO-anisole was not used for the linear correlation. $\Delta E_{a,1}$ for the thermolyses of 4-substituted phenyl benzyl ethers (□) and VLPP Δ BDEs in substituted anisoles (△) are indicated for comparison. Letters refer to substituents: (a) 4-NH₂, (b) 4-OH, (c) 4-OCH₃, (d) 2-OH, (e) 2-OCH₃, (f) 4-OH, 3-CHO, (g) H, (h) 4-CF₃, and (i) 4-NO₂.

have produced the following activation enthalpies: 50.2 (Tetralin),²⁹ 55.0 (Tetralin),³⁹ 53.2 (Tetralin),⁴⁰ and 51.0 kcal mol⁻¹ (on silica).⁴¹ However, it should be noted that an activation enthalpy measured in the liquid phase cannot be directly equated to a BDE because the kinetic parameter contains small, solvent-dependent components.⁴² In all cases, the actual BDE will be lower than the measured activation enthalpy.

DFT II again performs better than DFT I, which yields a C₆H₅O–CH₂C₆H₅ BDE of only 47.4 kcal mol⁻¹. However, with these two models the differences between the O–C BDE in anisole and benzyl phenyl ether are similar, 12.4 (DFT II) and 11.9 (DFT I) kcal mol⁻¹, and in reasonable agreement with the known benzylic resonance stabilization enthalpy (11.2 kcal mol⁻¹).³⁷

Turning to the substituted benzyl phenyl ethers, DFT II gave O–C BDE's for 4-YC₆H₄O–CH₂C₆H₅ which correlated with σ_p^+ yielding $\rho^+ = 6.67$ kcal mol⁻¹. As expected (see Introduction), this ρ^+ value is in full agreement with the ρ^+ values calculated for phenols (6.67 kcal mol⁻¹) and anisoles (6.70 kcal mol⁻¹),

(37) The resonance stabilization enthalpy, RSE, can be defined as RSE = BDE(CH₃X–H) – BDE(C₆H₅X–H) and is 17.4 for X = O (phenoxy) and 11.2 kcal mol⁻¹ for X = CH₂ (benzyl), using data from ref 38 except for the O–H BDE for phenol of 87 kcal mol⁻¹ from ref 35. Thus, with the BDE(O–C) in CH₃O–CH₃ of 82.7 kcal mol⁻¹,³⁸ the BDE(O–C) in C₆H₅O–CH₃ and C₆H₅O–CH₂C₆H₅ are 82.7 – 17.4 = 65.3 (exp 65.3) and 82.7 – 17.4 – 11.2 = 54.1 kcal mol⁻¹. Because of the uncertainties in the ΔH values, a BDE(C₆H₅O–CH₂C₆H₅) of 54 ± 1 kcal mol⁻¹ seems reasonable.

(38) Tsang, W. In *Energetics of Organic Free Radicals*; Simões, J. A. M., Greenberg, A., Liebman, F., Eds.; Black Academic and Professional: London, 1996; pp 22–58.

(39) Miller, R. E.; Stein, S. E. *Prepr. Pap. Am. Chem. Soc. Div. Fuel Chem.* **1979**, *24*, 271–277.

(40) Sato, Y.; Yamakawa, T. *Ind. Eng. Chem. Fundam.* **1985**, *24*, 12–15.

(41) Buchanan, A. C., III; Britt, P. F.; Skeen, J. T.; Struss, J. A.; Elam, C. L. *J. Org. Chem.* **1998**, *63*, 9895–9903.

(42) The geminate radical pair formed on bond cleavage may either recombine or escape from the solvent cage and this yields a more complex kinetic equation than for a gas-phase homolysis. If the rate data are treated as first-order rate constants and plotted in the Arrhenius format, a convolution takes place between the preexponential factor, *A*, and the activation enthalpy, *E_a*, associated only with the bond rupture. This has been noticed for the thermolysis of C₆H₅CH₂–CH₂C₆H₅ which gives *E_a* values of 66.6 in the liquid phase but 62.6 kcal mol⁻¹ in the gas phase while the preexponential factors differ by a factor of 10.⁴³

see Table 1. The calculated 4-YC₆H₄CH₂–OC₆H₅ BDE's do not correlate with σ_p^+ . Indeed, both electron-donating and electron-withdrawing groups cause very slight bond weakening as we have previously reported for 4-YC₆H₄CH₂–X with X = H, F, Cl, and Br.⁴

Measured Rates of O–C Bond Homolysis in Benzyl Phenyl Ethers and Substituent Effects on O–C BDE's. Theory is still occasionally suspect, particularly when it contradicts prevailing views. For this reason, we decided to examine the thermal decomposition of five benzyl phenyl ethers in a good hydrogen atom donating solvent (9,10-dihydroanthracene). We decided at the outset that the effort involved in a detailed Arrhenius-type study of all five compounds could never be justified because the compounds are all so similar in structure that the Arrhenius preexponential factors for O–C bond homolysis must be very similar, possibly identical. For our purposes, it was therefore sufficient to measure the rate of O–C bond homolysis at a single temperature for each compound (see Table 2). The four earlier Arrhenius-type studies^{29,39–41} on the decomposition of benzyl phenyl ether display a considerable variation in both the preexponential factor and *E_{a,1}*. One of these studies²⁹ determined the effects of 4-OH, 4-CH₃, 3-CH₃, and 4-CHO on the thermolysis rate of benzyl phenyl ether in Tetralin as the hydrogen atom donating solvent. While the trends in the substituent effects are as expected, the magnitude of the substituent effects on the apparent *E_{a,1}* values (from three-point Arrhenius plots over a 50 K range) are much larger than one would expect, e.g., $\Delta E_{a,1}(4\text{-HOC}_6\text{H}_4\text{O-CH}_2\text{C}_6\text{H}_5 - \text{C}_6\text{H}_5\text{O-CH}_2\text{C}_6\text{H}_5) = -14.7$ kcal mol⁻¹. Because our experimental rate constant for benzyl phenyl ether decomposition is closest to the results of Sato and Yamakawa,^{40,44} we decided to use their Arrhenius equation, viz. eq 4, which was obtained in Tetralin at four temperatures between 533 and 593 K.

$$\log(k_1/s^{-1}) = 15.2 - 53.2/2.3RT \quad (4)$$

Combining $\log(A_1/s^{-1}) = 15.2$ with the rate constant we measured for benzyl phenyl ether homolysis at 548 K (Table 2) yields an activation enthalpy for its decomposition of 53.1 kcal mol⁻¹, in full agreement with our DFT II BDE (52.5 kcal mol⁻¹ at 548 K, see Table 1). Keeping the same *A*-factor, we obtain the *E_{a,1}* values for the substituted benzyl phenyl ethers (see Table 2). Although the calculated O–C BDE's and experimental activation enthalpies are not directly comparable the substituent effects are because, for all compounds, the effect of the solvent on the observed kinetic parameters will be the same. The $\Delta E_{a,1}$ values for the benzyl phenyl ethers given in Table 2 are in remarkably good agreement with the DFT II Δ BDE's given in Table 1 (largest difference, 0.6 kcal mol⁻¹). We conclude that our calculations properly reflect the influence of 4-substituents on O–C BDE's in benzyl phenyl ethers and, by extension, in anisoles. The $\Delta E_{a,1}$ values for 4-YC₆H₄O–CH₂C₆H₅ homolysis for Y = OCH₃, H, and CF₃ are shown plotted against $\sigma^+(Y)$ as open squares in Figure 3.

Measured Rates of O–C Bond Homolysis in Anisoles and Derived O–C BDE's. Because there appeared to be a contradiction between theoretical and experimental substituent effects on the O–C BDE's in substituted anisoles, a new experimental study was deemed necessary. Five of the compounds originally

(43) Stein, S. E.; Robaugh, D. A.; Alfieri, A. D.; Miller, R. E. *J. Am. Chem. Soc.* **1982**, *104*, 6567–6570.

(44) Calculated rate constants, *k₁* in s⁻¹, at the present reaction temperature of 548 K using the reported Arrhenius equations are the following: 1.4 × 10⁻⁵ (Tetralin),²⁹ 3.3 × 10⁻⁶ (Tetralin),³⁹ 1.0 × 10⁻⁶ (Tetralin),⁴⁰ and 1.1 × 10⁻⁵ (on SiO₂).⁴¹ Our measured value of *k₁* is 5.2 × 10⁻⁷ s⁻¹ (see Table 2).

studied by Stein and co-workers^{11a,45} were reexamined using the same VLPP experimental technique, viz., anisole, 2-OH-, 2-OCH₃-, 4-OH-, and 4-OCH₃-anisole. In addition, 4-CF₃-anisole was measured for comparison with the benzyl phenyl ether experiments. The Δ BDE values derived from the VLPP data are given in Table 3 and have been plotted as open triangles in Figure 3. Table 3 also includes the relevant Δ BDE's reported by Stein and co-workers^{11a,45,46} which are in very good agreement with our values. Our results for Y = 4-OH and 4-OCH₃ anisole (see Figure 3) underscore the fact that there is a difference in the experimental substituent effects between phenols and anisoles that is not reflected by our theoretical calculations.

It has been proposed¹³ that the difference between computational and experimental results for the substituted anisoles can be related to the fact that the latter are derived from activation enthalpies rather than reaction enthalpies. Thus, in the late transition state the oxygen-carbon bond is not fully cleaved and, as a result, the effect exerted by the substituent is diminished. It has also been proposed⁴⁷ that for this particular reaction there is an additional exit barrier from the transition state of ca. 3 kcal mol⁻¹. However for anisole, our O-C BDE at 298 K is 65.3 kcal mol⁻¹ which, when combined with the heats of formation (in kcal mol⁻¹) for anisole (-18.33), methyl (35.1), hydrogen (52.1), and phenol (-23.03),⁴⁸ leads to an O-H BDE for phenol of 87.0 kcal mol⁻¹, in perfect agreement with the best available value (87 ± 1 kcal mol⁻¹).³⁵ Therefore, both the foregoing proposals must be discarded. Our experimental method clearly yields the reaction enthalpy since the reverse reaction (radical-radical recombination) is, by definition, without an activation barrier.

When the VLPP technique is applied to substituted anisoles, gas-phase kinetic data are obtained at temperatures between 800 and 1100 K. The PAC method of measuring the BDE's of substituted phenols operates at room temperature in the liquid phase. However, these solution BDE's for phenols can be corrected for hydrogen bonding interactions with the solvent so as to obtain gas-phase BDE values. This leaves the difference in the experimental temperatures as the only possible source of the discrepancies in the effects substituents have on 4-YC₆H₄O-CH₃ and 4-YC₆H₄O-H BDE's. It is, therefore, reasonable to suggest that substituent effects may be temperature dependent.

Effect of Substituent Orientation. Conjugating groups attached to the aromatic ring will have their maximum substituent effect when their conjugating orbitals (e.g., the 2p-type lone pair of the oxygen in a -OCH₃ or -OH group) are perpendicular to the plane of the aromatic ring. For -OH and -OCH₃, this means that the substituent has to lie in the ring plane. There are significant barriers for the out-of-plane rotation of the -OH group in phenol (3.47 kcal mol⁻¹)⁴⁹ and of the -OCH₃ group in anisole (<3.1 kcal mol⁻¹)⁵⁰ and thus these groups prefer to lie in the aromatic plane at ambient temperatures. Rotation of an electron-donating, conjugating substituent

in anisole would increase the O-CH₃ BDE as the phenoxy radical will be relatively less stabilized. On the other hand, rotation of the dissociating O-CH₃ group in anisole will decrease the O-CH₃ BDE. Hence, at elevated reaction temperatures conformational changes are to be expected and the rotational configuration of both the substituent and the dissociating group should be taken into consideration. Since we have shown that conjugating substituents exert a larger effect on the radical than on its parent, the O-X bond-weakening effect of the para substituent in 4-HOC₆H₄O-X and 4-CH₃-OC₆H₄O-X should decline as the temperature is raised, *unless* the substituent is, in some way, held in the coplanar position. To test this concept we chose 4-hydroxy-3-formylanisole because the strong intramolecular hydrogen bond in such compounds⁵¹ should ensure that both hydroxyl and formyl groups are held in the aromatic plane even at fairly high temperatures. Of course, the formyl group will strengthen the O-C bond (see Table 1). Nevertheless, the observed VLPP O-CH₃ BDE for 4-OH,3-CHOC₆H₃O-CH₃ is slightly smaller (0.3 kcal mol⁻¹) than that for 4-HOC₆H₄O-CH₃, see Table 3. Furthermore, the VLPP high-temperature Δ BDE point for 4-OH,3-CHO-anisole in Figure 3 (a triangle) lies close to the line drawn through the DFT II calculated, room temperature, Δ BDE's for all the other anisoles (filled circles). We conclude that the intramolecular hydrogen bond in this compound is capable of holding the -OH group in the aromatic plane even at the high temperatures of a VLPP experiment and this allows the -OH group to exert more of its full (room temperature) substituent effect on the O-CH₃ bond.

Temperature-Dependent Substituent Effect on the O-CH₃ BDE's in Anisoles. For 4-OH- and 4-OCH₃-anisole the VLPP measurements give Δ BDE's which are only about half as large as their DFT II calculated values (cf. Tables 1 and 3). This factor of 2 implies, to a first approximation, that at ca. 1000 K the -OH and -OCH₃ groups undergo free rotation with respect to the aromatic ring. DFT II calculations on 4-OCH₃-anisole give for a coplanar dissociating O-CH₃ group Δ BDE's = -6.1 and -2.45 kcal mol⁻¹, respectively, for a coplanar and perpendicular 4-OCH₃ substituent. For free rotation,⁵⁵ the expected Δ BDE is then -(6.1 + 2.45)/2 = -4.3 kcal mol⁻¹. However, a coplanar 4-OCH₃ substituent is calculated to reduce the barrier to rotation of the dissociating O-CH₃ group by 1.0 kcal mol⁻¹ compared to that of anisole. Thus, the expected Δ BDE at high temperatures becomes -4.3 + 1.0/2 = -3.8 kcal mol⁻¹, which compares remarkably well with the VLPP experimental O-CH₃ Δ BDE of -3.1 kcal mol⁻¹ and for 4-OH-anisole (for which calculations give essentially the same O-CH₃ BDE's as found for 4-OCH₃-anisole, see footnote 25) -2.7 kcal mol⁻¹ (see Table 3). Similarly, we measured a VLPP Δ BDE of +2.2 kcal mol⁻¹ for 4-CF₃C₆H₄O-CH₃. Theory (Table 1) implies that this last Δ BDE is about +3.0 kcal mol⁻¹ at room temperature. However, this must be corrected for rotation of the dissociating O-CH₃ group in the parent, and the barrier to rotation of this group is increased

(45) Suryan M. M.; Kafafi S. A.; Stein S. E. *J. Am. Chem. Soc.* **1989**, *111*, 1423-1429.

(46) The absolute values given as O-C BDE's in ref 11a and 45 are actually activation enthalpies, without the RT and C_p correction. This, however, will not affect the substituent effects upon the BDE's.

(47) Schmoltner, A. M.; Anex, D. S.; Lee, Y. T. *J. Phys. Chem.* **1992**, *96*, 1236-1240.

(48) *NIST Chemistry WebBook*; Mallard, W. G., Ed.; NIST Standard Reference Database 69, November 1998 Release; National Institute of Standards and Technology: Gaithersburg, MD, 1998.

(49) Berden, G.; Meerts, W. L.; Schmitt, M.; Kleinermanns, K. *J. Chem. Phys.* **1996**, *104*, 972-982.

(50) Spellmeyer, D. C.; Grootenhuis, P. D. J.; Miller, M. D.; Kuyper, L. F.; Kollman, P. A. *J. Phys. Chem.* **1990**, *94*, 4483-4491.

(51) Intramolecular hydrogen bond enthalpies for 2-formylphenol: experimental $\Delta H_{\text{IHB}} = -8.2$ kcal mol⁻¹,^{52,53} DFT III $\Delta H_{\text{IHB}} = -9.2$ kcal mol⁻¹.⁵⁴

(52) Denisov, G. S.; Sheikh-Zade, M. I.; Éskina, M. V. *Zh. Prikl. Spektrosk.* **1977**, *27*, 1049-1054.

(53) Skvortsov, I. M.; Fedorov, E. E.; Mushtakova, S. P. *Zh. Fiz. Khim.* **1986**, *60*, 2065-2066.

(54) de Heer, M. I.; Korth, H. G.; Mulder, P. To be submitted for publication.

(55) For free rotation, the average dihedral angle is 45° and cos² 45° = 0.5. In these calculations, substituent effects on BDE's were calculated as energy differences only, i.e., all enthalpic corrections were omitted. All structures with rotated substituents were optimized to the first-order saddle points by AM1 followed by the DFT calculation as outlined in the Method of Calculation section.

by the 4-CF₃ substituent by 0.8 kcal mol⁻¹ compared to that of anisole. Thus, ΔBDE at the free rotation limit is expected to be (3.0 – 0.8/2) = +2.6 kcal mol⁻¹. Although the approximations used to estimate the ΔBDE's for freely rotating substituent and dissociating groups are somewhat crude, the results are in fair agreement with the VLPP data (see column 6 of Table 3). The fact that the ΔE_{a,1} point (open square) for 4-CH₃OCH₂C₆H₄OCH₂-C₆H₅ lies essentially on the room temperature ΔBDE vs σ⁺ line (see Figure 3) implies that both the 4-OCH₃ and the dissociating –OCH₂C₆H₅ groups are not freely rotating at ca. 500 K.

It should, perhaps, be reemphasized that although the room temperature ΔBDE vs σ⁺ line is based on DFT II calculations on 4-YC₆H₄O-CH₃ compounds, essentially the same line would be obtained using room temperatures experimental (PAC) or calculated O–H BDE's of 4-YC₆H₄O-H compounds.

Further evidence that hindrance to free rotation at elevated temperatures can influence measured O–CH₃ BDE's comes from the present VLPP study of 2-OCH₃-anisole.⁵⁶ In this compound rotation of both methoxy groups will be strongly hindered. As a consequence, the VLPP high-temperature O–CH₃ BDE in 2-OCH₃-anisole would be expected to be weaker than that in 4-OCH₃-anisole. This is observed experimentally, the O–CH₃ ΔBDE's are –4.1 and –3.1 kcal mol⁻¹ for 2-OCH₃- and 4-OCH₃-anisole, respectively. These results are all the more remarkable in that it is now well established^{57,58} that σ⁺_{ortho}(OCH₃) = 0.66σ⁺_{para}(OCH₃) (=0.51). The VLPP ΔBDE for 2-OCH₃-anisole has been plotted vs this σ⁺ value (as a triangle) in Figure 3. This point falls on the DFT II-calculated, room temperature ΔBDE line for the other anisoles, confirming the absence of free rotation in 2-OCH₃-anisole at ca. 1000 K.

The situation with 2-OH-anisole is similar to that for 2-OCH₃-anisole. That is, for 2-OH-anisole our VLPP O–CH₃ ΔBDE = –7.2 kcal mol⁻¹. However, DFT III calculations indicate that the intramolecular hydrogen bonds have strengths of 4.5 kcal mol⁻¹ in 2-OH-anisole and 7.6 kcal mol⁻¹ in the 2-OH-phenoxy radical, i.e., the radical has an “extra” stabilization worth 3.1 kcal mol⁻¹. If the effects of these intramolecular hydrogen bonds are allowed for, then the VLPP O–CH₃ ΔBDE would be –7.2 + 3.1 = –4.1 kcal mol⁻¹ in 2-OH-anisole, which is identical to the O–CH₃ ΔBDE of –4.1 kcal mol⁻¹ for 2-OCH₃-anisole (see Figure 3).

What Then Determines the Effect of Y on 4-YC₆H₄Z–X BDE's? This question was posed in the Introduction. Our present results support and extend our earlier studies on families of compounds having Z = CH₂ and X = H, F, Cl, and Br,⁴ and the earlier conclusion that the effects of Y on Z–X BDE's are almost independent of X. In that earlier work,⁴ the effects of Y on CH₂–X BDE's were small with both electron-donating and electron-withdrawing substituents very slightly reducing C–X BDE's. To the four X listed above, we can now add the C₆H₅O– group. More interestingly, the calculated effects of 4-Y substituents on the O–H BDE's in phenols and on the O–C BDE's in anisoles and 4-substituted phenyl benzyl ethers are essentially identical. For all three classes of compounds, there is strong and equal bond weakening and bond strengthening by electron-donating and electron-withdrawing Y, respectively, and each set of BDE's can be correlated with σ_p⁺ yielding ρ⁺ values

which are indistinguishable. The *main* answer to the above question must, therefore, be the stabilization/destabilization by Y of the 4-YC₆H₄Z• radical.

The influence of 4-Y substituents on Z–X BDE's is much greater for Z = O than for Z = CH₂. This can be attributed to both the greater degree of delocalization of the unpaired electron in 4-YC₆H₄Z• radicals when Z is O than when it is CH₂ as well as the greater inductive effect of the strongly electron-withdrawing oxy radical center when compared to the merely “conjugating” carbon-centered radical.⁵⁹ The greater degree of delocalization of the unpaired electron in C₆H₅O• than in C₆H₅CH₂• radicals is experimentally established (ESR) and can be attributed to better 2p/π overlap because the C₆H₅–O• bond length is only 1.25 Å, whereas the C₆H₅–CH₂• bond length is 1.40 Å.⁵⁹ Hence, since the inductive effects of substituents are not significant to the stability of the benzyl radical, and all substituents, both ED and EW (except –CF₃), delocalize the radical electron, all substituents stabilize the benzyl radical (again, with the exception of –CF₃). In contrast, the inductive effect of substituents plays a more significant role in the stabilization/destabilization of the electron-poor phenoxy radical than does radical delocalization, and hence even though all substituents (except –CF₃) delocalize the radical electron, EDG's stabilize the phenoxy radical and EWG's destabilize the phenoxy radical because of the inductive interactions they have with the radical center. Since the C₆H₅–NH• bond is of intermediate length (1.34 Å), so is the degree of delocalization of the unpaired electron in the anilino radical.⁵⁹ Furthermore, NH• is less electron poor than –O•. Thus, the effects of Y on N–X BDE's in 4-YC₆H₄-NH-X are expected to be not only independent of X⁶⁰ but also of a magnitude intermediate between that of the 4-YC₆H₄O-X and 4-YC₆H₄CH₂-X families of compounds. Indeed, this appears to be the case, viz.,¹² the N–H BDE's in 4-YC₆H₄NH₂ correlate with σ_p⁺(Y) and yield ρ⁺ = 3.0 kcal mol⁻¹.⁶¹

Although the *main* effects of Y on 4-YC₆H₄Z–X BDE's are due to stabilization/destabilization of the 4-YC₆H₄Z• radicals they may also have some effects on these BDE's if they stabilize/destabilize the ground state 4-YC₆H₄Z–X molecule with respect to the unsubstituted C₆H₅Z–X compound.^{4,13,62,63} We have discussed these minor effects for Z = CH₂, X = H, F, Cl, and Br in terms of Z–X bond dipole/Y substituent dipole interaction mechanisms.⁴

In conclusion, we can summarize our work with the following equation:

$$\text{BDE}(4\text{-YC}_6\text{H}_4\text{Z-X}_a) - \text{BDE}(\text{C}_6\text{H}_5\text{Z-X}_a) \approx \text{BDE}(4\text{-YC}_6\text{H}_4\text{Z-X}_b) - \text{BDE}(\text{C}_6\text{H}_5\text{Z-X}_b) \quad (5)$$

(59) Ingold, K. U.; Wright, J. S. *J. Chem. Educ.* **2000**, *77*, 1062–1064.

(60) There would appear to be no data available to check this prediction.

(61) The N–H BDE's in four 3,7-disubstituted phenothiazines and the unsubstituted compound can also be correlated with σ_p⁺(Y) to yield ρ⁺ = 1.8 kcal mol⁻¹, see: Lucarini, M.; Pedrielli, P.; Pedulli, G. F.; Valgimigli, L.; Gignees, D.; Tordo, P. *J. Am. Chem. Soc.* **1999**, *121*, 11546–11553.

(62) Nau, W. M. *J. Org. Chem.* **1996**, *61*, 8312–8314.

(63) With DFT it is possible to disentangle ground state and radical effects by using isodesmic reactions of the type Y-C₆H₄-OCH₃ + C₆H₆ → C₆H₅-OCH₃ + C₆H₅-Y. The enthalpy difference for this reaction gives the stabilization/destabilization of the molecule caused by the group Y relative to unsubstituted anisole (Y = H). From these computations it can be seen that the effect of Y on the ground state molecule is smaller than that on the radical, but still constitutes between 21 and 36% of the total effect for the substituents studied here, clearly showing that the fluctuation in the relative heat of formation of the molecules cannot be ignored. For the monosubstituted anisoles B3LYP/6-31G(d,p) yields the following ground-state contributions to the ΔBDE in kcal mol⁻¹, with the percentage of the total substituent effect in parentheses: 4-NH₂, –1.89 (21%); 4-OCH₃, –1.43 (26%); 4-CF₃, 0.76 (28%); 4-NO₂, 1.64 (36.3%). Also see ref 13.

(56) Very similar results were reported in an earlier study at a slightly lower temperature, see: Schraa G.-J.; Arends I. W. C. E.; Mulder P. J. *Chem. Soc., Perkin Trans. 2* **1994**, 189–197.

(57) Jonsson M.; Lind J.; Eriksen T. E.; Merényi G. *J. Chem. Soc., Perkin Trans. 2* **1993**, 1567–1568.

(58) de Heer, M. I.; Korth, H.-G.; Mulder, P. *J. Org. Chem.* **1999**, *64*, 6969–6975.

which will hold at room temperature regardless of the nature of Y, Z, X_a, and X_b. Furthermore, for Z = O the BDE's can be correlated with σ_p^+ with $\rho^+ = 6.9 \text{ kcal mol}^{-1}$ (and probably similarly for Z = NH with $\rho^+ = 3 \text{ kcal mol}^{-1}$), whereas for Z = CH₂ the BDE's cannot be correlated with σ_p^+ (or σ_p). Finally, BDE's measured at elevated temperatures may differ substantially from BDE's appropriate for the usual standard temperature of 298 K.

Acknowledgment. The authors would like to thank Dr. Gino A. DiLabio and Prof. Jan Cornelisse for helpful discussions and Brad Sheeler for his timely assistance with some of the GC measurements. We also thank the National Foundation for Cancer Research for financial support. One of us (D.A.P.) would

like to thank the Natural Sciences and Engineering Research Council of Canada and Vanderbilt University for financial support.

Supporting Information Available: Characterization of the four substituted benzyl phenyl ethers (mp, ¹H and ¹³C NMR), tabulated product yields, percentage conversions, and mass balances obtained in the thermal decomposition of substituted benzyl phenyl ethers, and DFT III frequencies for substituted anisoles used for the RRKM calculations (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

JA004081A