J. Am. Chem. Soc. **1995**, *117*, 2929−2930

Dramatic Solvent Effects on the Absolute Rate Constants for Abstraction of the Hydroxylic Hydrogen Atom from *tert*-Butyl Hydroperoxide and Phenol by the Cumyloxyl Radical. The Role of Hydrogen Bonding[1]

David V. Avila,[2] K. U. Ingold, and J. Lusztyk*

Steacie Institute for Molecular Sciences
National Research Council of Canada
Ottawa, Ontario, Canada K1A 0R6

W. H. Green and D. R. Procopio

Exxon Research and Engineering
Clinton Township, Route 22 East
Annandale, New Jersey 08801

Received September 6, 1994

There is a very extensive literature regarding the absolute rate constants for the reactions of alkoxyl radicals with organic substrates in the liquid phase.[3] Attention has naturally focused on those substrates which are likely to be involved in autoxidation and lipid peroxidation, e.g., alkanes, polyunsaturated fatty acids, etc.,[3] and in the prevention of autoxidation, e.g., phenols, including vitamin E.[3−6] Surprisingly, there is almost no such information regarding the reaction of alkoxyl radicals with hydroperoxides[7] and not much more regarding their reaction with phenol itself.[4] Because these reactions must play an important role in many autoxidation processes, we decided to make use of our recent discovery[8,9] that the cumyloxyl radical, $C_6H_5(CH_3)_2O^\bullet$ ($RO^\bullet$), has an absorption in the visible (λ_{max} = 485 nm) to investigate the effect of solvents, S, on the absolute rate constants for its reaction with *tert*-butyl hydroperoxide, k_1^S, and phenol, k_2^S.

$$RO^\bullet + (CH_3)_3COOH \xrightarrow{k_1^S} ROH + (CH_3)_3COO^\bullet \qquad (1)$$

$$RO^\bullet + C_6H_5OH \xrightarrow{k_2^S} ROH + C_6H_5O^\bullet \qquad (2)$$

Cumyloxyl radicals were generated "instantaneously" by 308 nm laser flash photolysis (LFP) of dicumyl peroxide in the presence of various, relatively low, concentrations of *tert*-butyl hydroperoxide or phenol at room temperature. The solvents and rate constants for reactions 1 and 2, which were determined by measuring the experimental pseudo-first-order rate constants for cumyloxyl radical decay at various concentrations of substrate, XOH, viz., $(k_n^S)_{exptl} = k_0^S + (k_n^S)_{meas}[XOH]$, are listed in Table 1.[10]

On examining Table 1, it is immediately apparent that $(k_1^S)_{meas}$ and $(k_2^S)_{meas}$ decrease by about 2 orders of magnitude on changing the solvent from CCl_4 to $(CH_3)_3COH$. It is also obvious that $(k_1^S)_{meas}$ and $(k_2^S)_{meas}$ are of similar magnitude in each solvent, and, in fact, a plot of $\log(k_1^S)_{meas}$ vs $\log(k_2^S)_{meas}$ yields an excellent straight line.

Our kinetic results raise a most intriguing question: What is the cause of the observed effect of solvents on $(k_1^S)_{meas}$ and $(k_2^S)_{meas}$? This question takes on added piquancy because we recently demonstrated that there is no measurable solvent effect on hydrogen atom abstraction from cyclohexane by the cumyloxyl radical.[9] That is, for six of the solvents used in the present work (anisole was not employed in the earlier study), $k_H^{30°C} = (1.2_4 \pm 0.1_2) \times 10^6\ M^{-1}\ s^{-1}$. By way of contrast, the rate constant for scission of the cumyloxyl radical, k_β^S, exhibited a rather substantial solvent effect[9] (see final column in Table 1). It is quite clear that the solvent effect on k_β^S bears no resemblance to the solvent effect on $(k_1^S)_{meas}$ and $(k_2^S)_{meas}$.

$$RO^\bullet + c\text{-}C_6H_{12} \xrightarrow{k_H} ROH + c\text{-}C_6H_{11}^\bullet$$

$$C_6H_5C(CH_3)_2O^\bullet \xrightarrow{k_\beta^S} C_6H_5COCH_3 + CH_3^\bullet$$

The absence of a solvent effect on hydrogen atom abstraction from cyclohexane necessarily implies that the dramatic solvent effects recorded in Table 1 must be due to solvent effects on the substrate, not to solvent effects on the cumyloxyl radical. Our results suggest that the solvent-induced decrease in $(k_1^S)_{meas}$ and $(k_2^S)_{meas}$ is associated with an increase in the strength of complexes formed between the hydroxylic group of the substrate, XOH, and the solvent, S, acting as a hydrogen bond acceptor (HBA), i.e., acting as a Lewis base.

The observed effect of solvents on $(k_n^S)_{meas}$ can be accounted for in a roughly quantitative manner by making three basic assumptions:[14]

(i) Each substrate molecule, XOH, can act as a hydrogen bond donor to only a single HBA molecule, S, at any one time.

(ii) The magnitude of the equilibrium constant, K_n^S for the formation of each XOH−S hydrogen-bonded complex is essentially independent of the nature of the surrounding medium (e.g., the medium's dielectric constant).

(iii) Cumyloxyl radicals cannot directly abstract the hydroxylic H atom from the XOH−S complex (for steric reasons). That is, the solvent molecule in this complex must first be removed and replaced by an $RO^\bullet$ radical. In principle, this could involve

---

(1) Issued as NRCC No. 37311.

(2) NRCC Research Associate 1992−94.

(3) Howard, J. A.; Scaiano, J. C. In *Radical Reaction Rates in Liquids*; Fischer, H., Ed.; Landolt-Börnstein, New Series; Springer Verlag: Berlin, 1984; Vol. 13d.

(4) Das, P. K.; Encinas, M. V.; Steenken, S.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 4162−4166.

(5) Evans, C.; Scaiano, J. C.; Ingold, K. U. *J. Am. Chem. Soc.* **1992**, *114*, 4589−4593.

(6) Foti, M.; Ingold, K. U.; Lusztyk, J. *J. Am. Chem. Soc.* **1994**, *116*, 9440−9447, and footnote 42 therein.

(7) Paul, H.; Small, R. D., Jr.; Scaiano, J. C. *J. Am. Chem. Soc.* **1978**, *100*, 4520−4527.

(8) Avila, D. V.; Ingold, K. U.; Lusztyk, J. *J. Am. Chem. Soc.* **1992**, *114*, 6576−6577.

(9) Avila, D. V.; Brown, C. E.; Ingold, K. U.; Lusztyk, J. *J. Am. Chem. Soc.* **1993**, *115*, 466−470.

(10) There is good evidence that there is little or no self-association of *tert*-butyl hydroperoxide or phenol under our conditions (maximum [XOH] employed are given in footnotes b and c of Table 1). In the first place, all plots of $(k_n^S)_{exptl}$ vs [XOH] gave excellent straight lines ($r > 0.99$ generally). Secondly, the equilibrium constants for substrate dimerization at 30 °C in CCl_4 are fairly small, viz., 1.9 M^{-1} for the hydroperoxide[11] and, for phenol, 4.7 M^{-1} [12] or lower.[13]

(11) Walling, C.; Heaton, L. *J. Am. Chem. Soc.* **1965**, *87*, 48−51.

(12) Clotman, D.; van Lerberghe, D.; Zeegers-Huyskens, Th. *Spectrochim. Acta, Part A* **1970**, *26*, 1621−1631.

(13) (a) Maguire, M. M.; West, R. *Spectrochim. Acta* **1961**, *17*, 369−378. (b) Coggeshall, N. D.; Saier, E. L. *J. Am. Chem. Soc.* **1951**, *73*, 5414−5418. (c) Powell, D. L.; West, R. *Spectrochim. Acta* **1964**, *20*, 983−991.

(14) After the present work had been completed, we became aware that Professor M. F. Nielsen and co-workers[15] had made three similar assumptions with regard to phenol acting as a *proton donor* to an aromatic anion radical and had carried out a very similar kinetic treatment. Her data support the validity of our three basic assumptions (read anion and proton instead of cumyloxyl radical and hydrogen atom in assumption (iii)) in CH_3CN *and* in three solvents (propylene carbonate, *N*,*N*-dimethylformamide, and dimethyl sulfoxide), which are even stronger HBAs.

(15) Nielsen, M. F. *Acta Chem. Scand.* **1992**, *46*, 533−548. Nielsen, M. F.; Hammerich, O. *Acta Chem. Scand.* **1992**, *46*, 883−896.

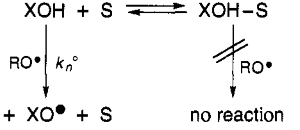
0002-7863/95/1517-2929$09.00/0 Published 1995 by the American Chemical Society

Table 1. Measured Absolute Rate Constants in Various Solvents at 298 ± 2 K for Reactions of Cumyloxyl Radicals[a] with *tert*-Butyl Hydroperoxide and Phenol and Calculated Rate Constants in CCl_4 Based on K_n^S Values Measured in This Work and (in Parentheses) from the Literature

	tert-butyl hydroperoxide[b]			phenol[c]			
solvent (concn, M)[d]	$10^{-7}(k_1^S)_{meas}$[e] (M^{-1} s^{-1})	K_1^S (M^{-1})	$10^{-7}(k_1^{CCl_4})_{calc}$[f] ($M^{-1}$ s^{-1})	$10^{-7}(k_2^S)_{meas}$[e] (M^{-1} s^{-1})	K_2^S (M^{-1})	$10^{-7}(k_2^{CCl_4})_{calc}$[f] ($M^{-1}$ s^{-1})	$k_\beta^s/10^5$[g] (s^{-1})
1. CCl_4	25	0[h]	**25**	86	0[h]	**86**	2.6
2. C_6H_5Cl	16			48			5.5
3. C_6H_6	13	0.15	35	28	0.44	166	3.8
(11.2)		(0.15)[i]	(35)		(0.28)[j]	(116)	
4. $C_6H_5OCH_3$	4.7	0.50	26	5.6	1.2	67	
(9.2)					(1.2−2.1)[k,l]	(67−114)	
5. $CH_3C(O)OH$	1.6			1.8			20
6. CH_3CN	0.87	1.3	23	0.58	4.7	53	6.3
(19.1)					(3.4−9.2)[l,m]	(38−102)	
7. $(CH_3)_3COH$	0.67			0.36			5.8

[a] [Dicumylperoxide] = 0.13 M, which corresponds to an OD of 0.3 at 308 nm, the laser wavelength.
[b] Maximum [$(CH_3)_3COOH$] employed (mM) for each solvent: 1−3, 27; 4, 197; 5, 1320; 6 and 7, 1670.
[c] Maximum [PhOH] employed (mM) for each solvent: 1, 13; 2, 6; 3, 24; 4, 92; 5−7, 475.
[d] Molarity of neat solvent.
[e] The true errors are probably ca. ±20%.
[f] Calculated via eq III.
[g] Data are from ref 9 at 303 K.
[h] By definition.
[i] Reference 11.
[j] Kamlet, M. J.; Abboud, J.-L. M.; Abraham, M. H.; Taft, R. W. *J. Org. Chem.* **1983**, *48*, 2877−2887.
[k] Lower value: Powell, D. L. Ph.D. Thesis, University of Wisconsin, 1962 (quoted in Wayland, B. B.; Drago, R. S. *J. Am. Chem. Soc.* **1964**, *86*, 5240−5244).
[l] Upper value estimated using the relationship $\log K_2^S = 0.92 \log K^S$(4-fluorophenol) given in ref 16. Data for 4-fluorophenol from Gurka, D.; Taft, R. W. *J. Am. Chem. Soc.* **1969**, *91*, 4794−4801.
[m] Lower value: Gramstad, T.; Sandström, J. *Spectrochim. Acta, Part A* **1969**, *25*, 31−38. There are also at least two intermediate values, viz., 4.8 (Epley, T. D.; Drago, R. S. *J. Am. Chem. Soc.* **1967**, *89*, 5770−5773) and 5.0 M^{-1} (Joesten, M. D.; Drago, R. S. *J. Am. Chem. Soc.* **1962**, *84*, 3817−3821).

a simple predissociation of XOH−S to form a "free" XOH (and S), or by a direct substitution of S by RO• to form XOH−•OR, or by some mixture of these two processes. The simple predissociation model is illustrated below, together with the corresponding kinetic analysis.



$$[XOH]_{total} = [XOH] + [XOH-S] = [XOH](1 + K_n^S[S])$$

$$(k_n^S)_{meas}[XOH]_{total} = (k_n^S)_{meas}[XOH](1 + K_n^S[S]) = k_n°[XOH]$$

That is,

$$k_n° = (k_n^S)_{meas}(1 + K_n^S[S]) \qquad (I)$$

where $k_n°$ is the bimolecular rate constant which would obtain with "free" XOH, i.e., with XOH in a hypothetical solvent which in no way retarded formation of an XOH−•OR complex.

Equilibrium constants for hydrogen bond formation between XOH and many HBA solvents have been determined in CCl_4 by spectroscopic methods. This is most commonly done using IR spectroscopy with a constant low concentration of XOH and then measuring the decrease in the intensity of the O−H fundamental stretching vibration which is produced by the addition of known concentrations of the HBA.[11,12,13c,16] These measured equilibrium constants, K_n^S, represent HBA solvent-induced shifts in the XOH/CCl_4 system, i.e.,

$$XOH/CCl_4 + S \overset{K_n^S}{\rightleftharpoons} XOH{-}S + CCl_4 \qquad (II)$$

From eq I, there would therefore appear to be a simple relationship between the rate constant measured in CCl_4 and that measured in a different solvent, i.e.,

$$(k_n^{CCl_4})_{meas} = (k_n^S)_{meas}(1 + K_n^S[S]) \qquad (III)$$

Equation III implies that $(k_n^S)_{meas}$ and K_n^S can be used to calculate $(k_n^{CCl_4})_{meas}$ or, alternatively, that $(k_n^{CCl_4})_{meas}$ and $(k_n^S)_{meas}$ can be used to calculate K_n^S. To test this equation, we chose benzene, anisole, and acetonitrile because these solvents cover a wide range in $(k_n^S)_{meas}$ values and because four of the six required K_n^S values were available from the literature. Unfortunately, where comparison was possible, the reported K_n^S values varied significantly. We therefore measured or remeasured all six K_n^S values by the IR method (see Table 1), but we will not pretend that our values are likely to be any more reliable than the literature values. *Calculated* values of $k_n^{CCl_4}$, i.e., $(k_1^{CCl_4})_{calc}$ and $(k_2^{CCl_4})_{calc}$, in these three solvents were found to be in satisfactory agreement with the corresponding rate constants measured in CCl_4 (indicated in bold face, see Table 1). To a first approximation, therefore, our three basic assumptions are consistent with the experimental data.

Although predissociation of XOH−S followed by H atom abstraction from "free" XOH is *not* a prerequisite for the observed agreement between $(k_n^{CCl_4})_{meas}$, $(k_n^S)_{meas}$, and K_n^S, it does provide a simple picture of what is probably a rather complex situation. It should be noted that although the magnitude of the solvent effect (e.g., k^{CCl_4}/k^{Me_3COH}) will depend on the Lewis acidity of XOH, it will generally be independent of the nature of the radical which abstracts the hydrogen atom, since the solvent effect is determined by the strength of the interaction between XOH and the HBA solvent. Experiments are planned to explore the validity and utility of these concepts.

Acknowledgment. We thank Professor M. F. Nielsen, Dr. L. J. Johnston, and Dr. J. Courtneidge for fruitful discussions, Mr. R. Kolt for the measurement of the K_n^S values, and the Association for International Cancer Research and the National Foundation for Cancer Research for partial support of this work.

JA942954T

---

(16) Arnett, E. M.; Mitchell, J. E.; Murty, T. S. S. R.; Gorrie, T. M.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1970**, *92*, 2365−2377.