

pH values of the original, undiluted buffers were observed; pK values were calculated according to eq. 1 where a is the optical density of a solution of the phenol in acid at a given wave length,

$$pK = pH + \log(b - \epsilon/\epsilon - a) - \log \gamma \quad (1)$$

b the optical density of the phenolate anion at the same wave length, and ϵ the optical density in a buffer medium of known pH; $\log \gamma$ is a small correction (0.05–0.10 pK unit) for the activity coefficient of the buffer.³⁸

For those di-*t*-butylphenols which were insoluble in water, solutions were prepared in 0.01 *N* sodium hydroxide. When such solutions were diluted to concentrations appropriate to spectral measurement, the additional ions made a negligible change in the ionic strength of the buffer. However, pH values of the buffers were altered slightly, and the values of pH used in pK_a calculations were those obtained by direct measurement of the spectral sample.

Determination of Dissociation Constants in 50% Ethanol.—Acid, alkaline, and buffer media were prepared as above, at twice the ionic strength, and each diluted with ethanol in the volume ratio 3:2. Volume changes accompanying such a procedure were disregarded. When 2.5 ml. of each solution was mixed with 0.5 ml. of ethanol containing a low concentration of the phenol, the final solution (3.0 ml.) was 50% in ethanol and at the same ionic strength as the aqueous buffer mixture. Immediately following spectral measurements, pH values of the spectral samples were determined, using a blue tip electrode (Beckman Type E-2) for such highly alkaline media. Micro-beakers containing the buffer solution were fitted with polyethylene caps and a stream of purified nitrogen passed through during the measurement to exclude both oxygen and carbon dioxide. Since meter readings drifted gradually in the mixed solvent system, the average of three readings, taken at 2-min. intervals immediately following immersion of the electrodes, was used. Calculations were based on apparent pH values determined in this way as far as a meter reading of pH 12. For those phenols which were too weakly acidic to ionize sufficiently at pH 12, the following extrapolation procedure was used.

(38) A number of values for $\log \gamma$ were taken from the literature: see D. T. Y. Chen and K. J. Laidler, *Trans. Faraday Soc.*, **58**, 480 (1962); A. I. Biggs, *ibid.*, **52**, 35 (1956).

Determination of pK Values by Spectral Extrapolation.—Carbonate-free *M* sodium hydroxide and *M* potassium chloride were mixed in appropriate ratios to yield solutions varying in alkali content from *M* to 0.001 *M* and of constant ionic strength. Each solution (50 ml.) was diluted with 33.3 ml. of ethanol and stored in a polyethylene bottle under nitrogen. Titration of the solutions at 3-day intervals demonstrated that their alkali content did not drop appreciably over several weeks at 0°. Ethanolic solutions of di-*t*-butylphenols (0.5 ml.) were added to 2.5 ml. of aqueous, ethanolic alkali and optical density determined at a wave length at which the contribution to spectral absorption of the undissociated phenol was small. When values of D/c ($=1/\epsilon'$, where ϵ' = apparent extinction coefficient) were plotted against $1/[\text{OH}^-]$, straight line plots were obtained (Fig. 3) whose slopes and intercepts were calculated by the method of least squares. Since the intercept on the ordinate corresponds to $1/\epsilon$, the true extinction coefficient for the phenolate ion may be calculated, although it is spectrophotometrically inaccessible. The dissociation constant for the weak acid (K_a) may be obtained from the equation¹¹ $K_a = K_s/m\epsilon$, where m is the slope of the line, ϵ the true extinction coefficient, and K_s the ion product for the solvent. Although ion products are known for both water and ethanol,³⁹ no data were available for 50% ethanol. A value for K_s (50% ethanol) was obtained indirectly by applying the extrapolation technique to several phenols whose pK values had been determined by the spectrophotometric procedure described above, but which were sufficiently weak to remain incompletely dissociated in 0.001 *M* to 0.05 *M* alkali (e.g., 111, R = Br, COO⁻). From the slopes and intercepts obtained for these phenols, values of K_s were calculated. A mean value of $1.2 \pm 0.2 \times 10^{-15}$ was obtained, which was then used in K_a calculations for less acidic phenols.

Acknowledgments.—The authors are indebted to Mr. H. G. McCann and his associates of this Institute for performing the microanalyses, to Dr. E. D. Becker and Mr. R. B. Bradley for measurement of n.m.r. spectra, and to Dr. H. A. Saroff for valuable discussion.

(39) From estimated data of P. Ballinger and E. A. Long (*J. Am. Chem. Soc.*, **82**, 795 (1960)), a K_s value of 1.7×10^{-15} (6% aqueous ethanol) may be calculated.

!CONTRIBUTION FROM THE NATIONAL INSTITUTE OF ARTHRITIS AND METABOLIC DISEASES, NATIONAL INSTITUTES OF HEALTH, BETHESDA 14, MD.]

A Study of Free Energy Relationships in Hindered Phenols. Correlation of Spectral Properties with Substituent Constants¹

BY LOUIS A. COHEN AND WILLIAM M. JONES

RECEIVED JANUARY 26, 1963

A linear correlation of ultraviolet spectral data with substituent parameters has been achieved for 4-substituted phenols, 2,6-di-*t*-butyl-4-substituted phenols, and for their corresponding anions. The incorporation of both electron-withdrawing and electron-releasing substituents into a single slope was achieved by: (a) the use of $\Delta\nu$, the difference in the ultraviolet frequencies of the 4-substituted phenol and the corresponding monosubstituted benzene, and (b) the use of σ_R' , a new resonance parameter. The latter was calculated as $\sigma_p - (2/3)\sigma_m$, on the basis that the inductive effect of a substituent in the *p*-position is only two-thirds as great as when in the *m*-position. From the fact that ρ (ultraviolet spectral shifts) for the 2,6-di-*t*-butylphenols is only slightly greater than that for the unhindered phenols, it is concluded that the phenolic O-H bond is coplanar with the aromatic ring in the former series. Chemical shifts for the hydroxyls in the n.m.r. spectra of hindered phenols have been shown to vary linearly with σ_p^- . Similarly, a linear dependence on σ_p^- is demonstrated for the infrared stretching frequencies of the phenolic hydroxyl groups.

The demonstration that the pK values of 2,6-di-*t*-butylphenols vary directly with σ -constants for 4-substituents, but with almost twice as great a ρ value as in the unhindered series,¹ prompted us to attempt the correlation of other physical properties of the hindered phenols with substituent parameters. Accordingly, their ultraviolet, nuclear magnetic resonance, and infrared spectra have been examined and are discussed in sequence.

The conformation of the hydroxyl group is a matter of particular interest in the chemistry of 2,6-di-*t*-butylphenols. Space-filling models indicate that the proton of a planar phenolic hydroxyl is barely accommodated between two CH₃'s of an adjacent *t*-butyl group. Al-

ternatively, the O-H bond may be rotated about the C-O axis until it is perpendicular to the aromatic plane. Should coplanarity of the O-H bond with the aromatic ring be altered to any extent, overlap of the *p*-electrons of oxygen with the aromatic π -system would be impaired, as would resonance coupling between the phenol and a 4-substituent.² The infrared stretching frequencies of phenolic hydroxyl groups have been shown to vary linearly with σ_p values for 4-substituents, both in the simple and in the 2,6-di-*t*-butyl series.³ Since ρ was found to be the same for both series, it was con-

(2) I. L. Ingraham, in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 11; R. W. Taft, Jr., and H. D. Evans, *J. Phys. Chem.*, **61**, 1427 (1957); B. M. Wepster, *Rec. trav. chim.*, **76**, 335, 357 (1957).

(3) K. U. Ingold, *Can. J. Chem.*, **38**, 1092 (1960), and references cited therein.

(1) Paper VI of a series on phenol-dienone tautomerism. For paper V, see L. A. Cohen and W. M. Jones, *J. Am. Chem. Soc.*, **85**, 3397 (1963).

TABLE I

SUBSTITUENT CONSTANTS FOR *m*- AND *p*-SUBSTITUTED PHENOLS

R	pK _a (<i>meta</i>)	σ _m ^b	σ _p ^{-a}	σ _R ⁻	σ _R [']	σ _R ^{-k}
H	9.99 ^e	0	0	0	0	0
CH ₃	10.09 ^e	-0.076	-0.15	-0.07	-0.10	-0.13
C(CH ₃) ₃	10.08 ^f	-0.070	-0.14	-0.07	-0.09	
CH ₃ O	9.65 ^e	.12	.13	.25	.21	-0.50
COO [⊖]	9.98 ^f	-0.020	.24	.25	.25	
Br	9.03 ^e	.40	.25	-0.15	-0.02	-0.22
SO ₃ [⊖]	9.29 ^e	.28	.40	.12	.21	
CONH ₂	9.30 ^f	.28	.61	.33	.42	
CO ₂ Et	9.10 ^f	.37	.64	.27	.39	0.36
N(CH ₃) ₃ [⊖]	8.03 ^h	.85	.77	-0.08	.20	
COCH ₃	9.19 ⁱ	.33	.84	.51	.62	0.60
CN	8.61 ^d	.59	.88	.29	.48	0.41
CHO	8.85 ^e	.48	1.04	.56	.72	
NO ₂	8.38 ^e	.69	1.24	.55	.78	0.64
COOH		.56 ^j	0.77 ^j	.21	.40	0.36

^a For derivation of these values, see ref. 1. ^b For calculation from pK_a values, see Experimental. ^c A. I. Biggs and R. A. Robinson, *J. Chem. Soc.*, 388 (1961). ^d M. M. Fickling, A. Fischer, B. R. Mann, J. Packer, and J. Vaughan, *J. Am. Chem. Soc.*, **81**, 4226 (1959). ^e E. E. Sager, H. R. Schooley, A. S. Carr, and S. F. Acree, *J. Research Natl. Bureau Standards*, **35**, 521 (1945). ^f Previously unreported. ^g Revision of published value: H. Pauley, K. Schubel, and K. Lockemann, *Ann.*, **383**, 288 (1911). ^h S. Oae and C. C. Price, *J. Am. Chem. Soc.*, **80**, 3425 (1958). ⁱ F. G. Bordwell and G. D. Cooper, *ibid.*, **74**, 1058 (1952). ^j J. M. Vandenberg, C. Henrich, and S. G. Van den Berg, *Anal. Chem.*, **26**, 726 (1954). ^k For comparison, literature values of σ_R⁻ are included (column 7) where available; see R. W. Taft, Jr., *J. Am. Chem. Soc.*, **79**, 1045 (1957).

cluded that the *t*-butyl groups do not impair resonance and that coplanarity of the O-H bond with the ring is indicated. With the considerable amount of ultraviolet spectral data for hindered phenols at hand,¹ it became of interest to study the problem by the alternative spectral method, particularly since ultraviolet spectral bands for benzenoid systems are determined largely by resonance effects⁴ and are, therefore, highly sensitive to loss of coplanarity.²

Ultraviolet Spectra.—Earlier efforts to demonstrate a linear correlation between ultraviolet spectral bands and substituent parameters have met with limited success.⁵ Plots of λ_{max} (first primary band for a *p*-substituted benzene)^{5b} or of Δλ (shift in λ_{max} from that for the monosubstituted benzene)^{5c} vs. σ_p provide linear correlation only if the two substituents have opposing electrical properties. Similar limitations in the nature of substituents are observed in plots of Δλ vs. σ_R^{6d} (the resonance component of the total σ_p value),⁶ which is, undoubtedly, a more logical parameter for correlation than σ_p.⁷ For the general purpose of correlating ultraviolet spectral data with substituent constants and for our purpose, in particular, it was desirable to achieve a linear Hammett-type plot for all substituents, regardless of the direction of their electrical effects.

A set of σ_p⁻ values,⁸ based solely on thermodynamic ionization constants of 4-substituted phenols, was presented on the preceding paper,¹ and is reproduced in

(4) A. L. Sklar, *J. Chem. Phys.*, **7**, 984 (1939); F. A. Matsen, *J. Am. Chem. Soc.*, **72**, 5243 (1950); *et seq.*

(5) (a) L. Doub and J. M. Vandenberg, *ibid.*, **69**, 2714 (1947); (b) T. C. Bruice, *Bol. colegio quim. Puerto Rico*, **12**, 14 (1955) [*Chem. Abstr.*, **50**, 2289 (1956)]; (c) C. N. R. Rao, *Chem. Ind.* (London), 666 (1956); (d) *ibid.*, 1239 (1957); (e) J. E. Bloor and D. B. Copley, *ibid.*, 526 (1960); (f) B. G. Gowenlock and K. J. Morgan, *Spectrochim. Acta*, **17**, 310 (1961); (g) M. Rapaport, C. K. Hancock, and E. A. Meyers, *J. Am. Chem. Soc.*, **83**, 3489 (1961).

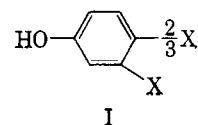
(6) R. W. Taft, Jr., in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 13; R. W. Taft, Jr., *J. Am. Chem. Soc.*, **79**, 1054 (1957).

(7) An approximate correlation of ν_{max} with σ_p⁺ values (H. C. Brown and Y. Okamoto, *J. Am. Chem. Soc.*, **80**, 4979 (1958)) has been demonstrated for 4-substituted 2-nitrophenols (ref. 5g).

(8) For the sake of consistency in symbolism, all σ_p values are reported as σ_p⁻ since they are based on the ionization of phenols. It should be realized, however, that σ_p⁻ ≅ σ_p for saturated 4-substituents.

Table I, column 4. In the same manner, σ_m values (Table I, column 3) were calculated from pK_a values for 3-substituted phenols (Table I, column 2). Some of the pK_a values were taken from the literature while others, determined spectrophotometrically, are revised values or are reported for the first time. The algebraic difference, σ_p⁻ - σ_m, was then taken as σ_R⁻ (Table I, column 5).⁹ Plots of σ_R⁻ vs. a variety of parameters calculated from λ_{max} (for the first primary band of 4-substituted phenols) were linear, only if limited to certain +σ_p substituents.^{9a}

Such a derivation of σ_R requires the following assumptions: (1) the electrical effect of a substituent *meta* to the phenol is purely inductive; (2) σ-constants reflect only inductive and resonance effects; and (3) the inductive effect has the same magnitude in either the *m*- or *p*-position. The last assumption is the most questionable and we, therefore, considered an alternative derivation of σ_R. Assuming that inductive effect changes regularly with distance, and that it is altered by 1/3 for each position on a benzene ring, factors may be assigned as in I, in which σ_m (= X) is considered to be purely inductive.¹⁰ A new series of resonance parameters for 4-substituents (Table I, column 6)¹¹ was then

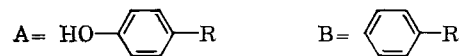


calculated from the relationship

$$\sigma_{R'} = \sigma_p^- - 2/3\sigma_m$$

Ultraviolet spectral measurements were carried out using 50% ethanol as solvent, values of λ_{max} (first primary band) for phenols and phenolate ions being recorded in Table II.¹² The frequency shift, Δν̄ was calculated from the equation

$$\Delta\bar{\nu} = \bar{\nu}_A - \bar{\nu}_B, \text{ where}$$



and is considered to reflect the increased resonance coupling of R with the phenolic system relative to resonance in the monosubstituted benzene. Only by use of the parameters σ_R['] and Δν̄ could a linear plot be obtained for all types of R substituents (Fig. 1 and 2). The success of such a correlation, we believe, supports the somewhat arbitrary basis for calculating σ_R['].¹³

The presence of two *o*-*t*-butyl groups increases ρ both for phenols (Fig. 1) and for phenolate ions (Fig. 2) by 11%.¹⁴ Since the variation in ρ is rather small and is not altered by ionization of the phenol, it seems unlikely that it could be attributed to partial steric inhibi-

(9) Based on the assumptions that σ₁ ≅ σ_m and σ_R = σ_p - σ₁. The values of σ_m given in Table I are approximately equal to the values of σ₁ reported by Taft. For a discussion of these relationships, see (a) R. W. Taft, Jr., *J. Am. Chem. Soc.*, **79**, 1045 (1957); (b) R. W. Taft, Jr., and I. C. Lewis, *ibid.*, **80**, 2436 (1958); (c) R. W. Taft, Jr., S. Ehremon, I. C. Lewis, and R. E. Glick, *ibid.*, **81**, 5352 (1959).

(10) No attempt is made to differentiate among the several forms of inductive transmission, such as σ-bond or electrostatic field. For a detailed discussion of the transmission problem, see M. J. S. Dewar and P. J. Grisdale, *J. Am. Chem. Soc.*, **84**, 3539 (1962), *et seq.*

(11) Such calculations lead to a significant value of σ_R['] (0.20) for the trimethylammonium group. Although the quaternary nitrogen cannot be involved in extending the resonant system in the usual sense, it can certainly affect the distribution of π-electron density within the aromatic ring.¹⁰ We consider any factor which determines the distribution of π-electron density to be a component of the resonance term.

(12) Extinction coefficients are tabulated in ref. 1.

(13) Pending the accumulation of additional data, we assume these values of σ_R['] and their correlation with spectral bands to be limited in applicability to phenols and phenolate ions.

(14) All ρ values in this paper were calculated by the method of least squares.

TABLE II
 ULTRAVIOLET SPECTRAL DATA FOR SUBSTITUTED PHENOLS (50% ALCOHOL)

R	Ph-R λ_{\max} , m μ	First primary band							
		4-R-Phenol				2,6-Di- <i>t</i> -Bu-4-R-phenol			
		$\lambda_{\max}^{N HCl}$, m μ	$\Delta\bar{\nu}$, cm. ⁻¹	$\lambda_{\max}^{N NaOH}$, m μ	$\Delta\bar{\nu}$, cm. ⁻¹	$\lambda_{\max}^{N HCl}$, m μ	$\Delta\bar{\nu}$, cm. ⁻¹	$\lambda_{\max}^{N NaOH}$, m μ	$\Delta\bar{\nu}$, cm. ⁻¹
H	199	211	2858	232	7148	214	3522	244 ^e	9267
CH ₃	208	219	2415	239	6236	222	3032	250 ^e	8077
C(CH ₃) ₃	208	219	2415	238	6060	223	3234	251 ^e	8236
OCH ₃	216	226	2048	242	4974	229	2628	^d	
COO ^e	224 ^a	244 ^a	3659	278	8672	250 ^a	4643	302	11530
Br	210	223	2776	244	6635	226	3371	257	8708
SO ₃ ^e	211 ^b	228 ^b	3533	253	7867	233 ^b	4475	270	10356
CONH ₂	227	252	4370	292	9806	258	5293	321	12900
CO ₂ Et	230	255	4262	296	9694	261	5164	324	12614
N(CH ₃) ₃ ^{ac}	204	220	3565	243	7868	224	4377	261	10706
COCH ₃	243	277	5051	327	10571	284	5941	363	13604
CN	222	247	4559	282	9584	252	5362	307	12472
CHO	247	285	5398	336	10724	293	6356	370	13459
NO ₂	268	316	5667	401	12375	325	6544	450	15091
COOH	230	255	4262			260	5016		

^a At pH 7. ^b At pH 3. ^c As the chloride in each case. ^d Spectra could not be determined for the anion because of rapid oxidation to the quinone. ^e Although λ_{\max} is estimated from spectra of partially ionized material, higher concentrations of alkali did not alter λ_{\max} significantly.

tion of resonance, and may be the result of a gradual increase in the release of electrons from the *t*-butyl groups as the σ value of the 4-substituent increases. Thus, the demonstration, by means of ultraviolet spectra, of the coplanarity of the O-H bond with the aromatic ring in the di-*t*-butylphenols is in full agreement with the conclusion derived from studies of infrared spectra.³

the chemical shift of a phenolic hydroxyl is dependent on both inductive and resonance effects. Since the two aromatic protons appear as a sharp singlet in the n.m.r. spectra of all the 2,6-di-*t*-butyl-4-substituted

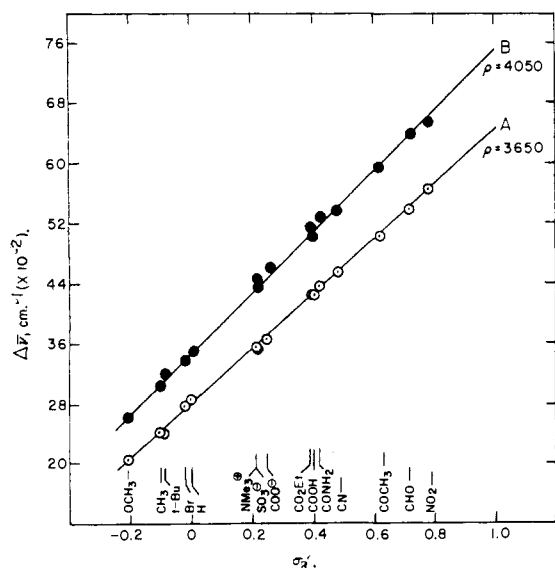


Fig. 1.—Correlation of $\Delta\bar{\nu}$ with $\sigma_{R'}$ for phenols (50% ethanol, *N* HCl): A, 4-substituted phenols; B, 2,6-di-*t*-butyl-4-substituted phenols.

Nuclear Magnetic Resonance Spectra.—The 2,6-di-*t*-butylphenols are almost unique among hydroxylic compounds in showing no association effects and very little interaction with polar solvents. Thus the chemical shift (in CCl₄) for the hydroxyl proton of 2,6-di-*t*-butyl-*p*-cresol is essentially independent of concentration¹⁵ whereas, for less hindered phenols, a marked concentration dependence is observed.¹⁶ Nuclear magnetic resonance spectra for a number of 2,6-di-*t*-butyl-4-substituted phenols were measured in CCl₄, the chemical shift data being recorded in Table III. A plot of δ_{OH} vs. σ_p proved to be linear (Fig. 3),¹⁷ indicating that

(15) I. Yamaguchi, *Bull. Chem. Soc. Japan*, **34**, 451 (1961).

(16) W. G. Paterson and N. R. Tipman, *Can. J. Chem.*, **40**, 2122 (1962), and references cited therein.

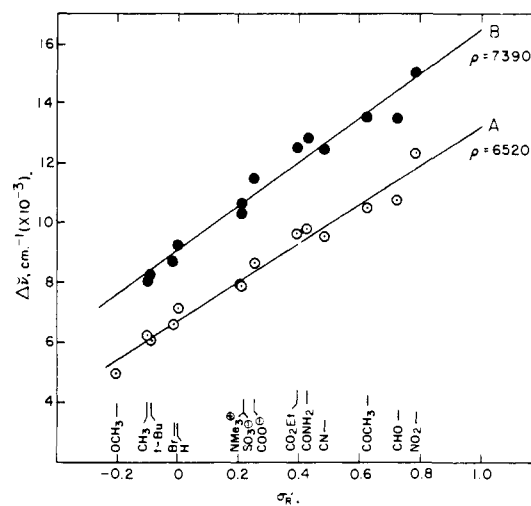


Fig. 2.—Correlation of $\Delta\bar{\nu}$ with $\sigma_{R'}$ for phenolate ions (50% ethanol, *N* NaOH): A, 4-substituted phenols; B, 2,6-di-*t*-butyl-4-substituted phenols.

phenols, their chemical shift positions are readily obtained. However, these chemical shifts are not independent of concentration and extrapolation to infinite dilution is necessary to obtain a linear relationship with σ_p ¹⁸; n.m.r. studies at varying concentration were not included in the present investigation.

Infrared Spectra.—Nonassociation of the hindered phenols facilitates the measurement of hydroxyl stretching frequencies in the infrared by eliminating band multiplicity and concentration dependence. Spectra were determined in CCl₄ solution at high resolution, the hydroxyl stretching frequencies being recorded in Table IV. A linear correlation is demonstrated by plotting ν_{OH} vs. σ_p (Fig. 4) with a ρ value of -13.3 .¹⁹ Since it was shown in the preceding paper¹

(17) The basis for the poor correlation of the 4-methoxy compound has yet to be elucidated. Paterson and Tipman (ref. 12) were unable to demonstrate any relationship between δ_{OH} and the nature of ring substituents in simple 4-substituted phenols.

(18) P. Diehl, *Helv. Chim. Acta*, **44**, 829 (1961); **45**, 568 (1962); P. L. Corio and B. P. Dailey, *J. Am. Chem. Soc.*, **78**, 3043 (1956); A. A. Bothner-By and R. E. Glick, *ibid.*, **78**, 1071 (1956).

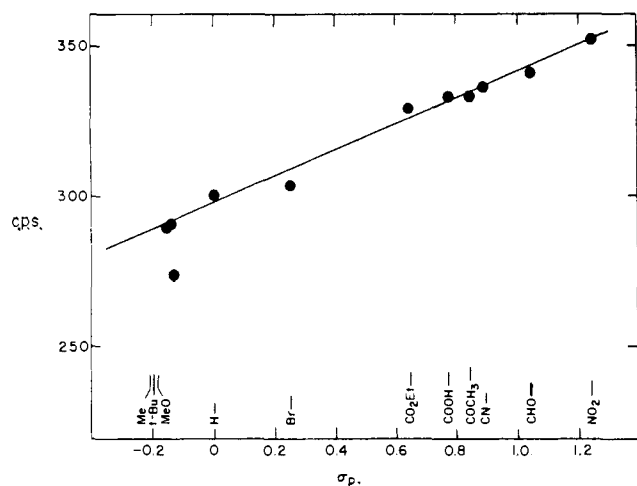


Fig. 3.—Correlation of n.m.r. chemical shift (of phenolic hydroxyl) with σ_p for 4-substituted 2,6-di-*t*-butylphenols [CCl_4 , $(\text{CH}_3)_3\text{Si} = 0$], $\rho = 43.9$.

that pK values for hindered phenols are linearly dependent on σ_p , it is possible to construct a plot of ν_{OH} vs. pK (Fig. 5) which may be used for the determination of dissociation constants for other hindered phenols directly

TABLE III
N.M.R. DATA FOR 2,6-DI-*t*-BUTYL-4-SUBSTITUTED PHENOLS
(CCl_4)^{a,b}

R	PhOH	Aryl H	R	PhOH	Aryl H
OCH ₃	274	395	COOH	334	475
CH ₃	290	409	COCH ₃	334	463
C(CH ₃) ₃	291	424	CN	337	442
H	300	418	CHO	342	457
Br	304	429	NO ₂	353	483
CO ₂ Et	330	467			

^a Chemical shift values are expressed in c.p.s. relative to internal tetramethylsilane; ^b Values of δ for the *t*-butyl protons fall within the range 85–90 c.p.s., with an approximate linear dependence on σ_p .

TABLE IV
INFRARED STRETCHING FREQUENCIES OF PHENOLIC HYDROXYL GROUPS IN 4-SUBSTITUTED 2,6-DI-*t*-BUTYLPHENOLS (CCl_4)

R	$\bar{\nu}$, cm. ⁻¹	R	$\bar{\nu}$, cm. ⁻¹
CH ₃	3649	CO ₂ Et	3636.5
C(CH ₃) ₃	3649	COOH	3634
OCH ₃	3649	COCH ₃	3633
H	3647	CN	3632.5
Br	3643	CHO	3630
		NO ₂	3626.5

from infrared spectral data. In this way, the pK value of 14.82 (in 50% ethanol) was assigned to the 4-methoxy compound, whose anion is too sensitive to oxygen to permit direct pK determination. Although the stretching frequency of 2,6-di-*t*-butyl-4-nitrophenol is normal (Fig. 4), its pK value is anomalous (Fig. 5), a phenomenon which has been discussed previously.¹

Experimental

Materials.—Commercial phenols were purified as necessary. *m*-Hydroxybenzoxime, m.p. 81–82°, was prepared by dehydration of the oxime of *m*-hydroxybenzaldehyde with acetic anhydride, followed by alkaline saponification of the phenolic acetate.^{20,21} *m*-Hydroxybenzamide, m.p. 169–170°, was prepared from the nitrile by oxidation with hydrogen peroxide.^{20,22} Ethyl

(19) Using a somewhat different set of *p*-substituents as well as slightly different σ_p values, Ingold² obtained a ρ value of -14.17 (estimated).

(20) Cf. I. A. Cohen and W. M. Jones, *J. Am. Chem. Soc.*, **84**, 1633 (1962).

(21) W. Baker and G. N. Carruthers, *J. Chem. Soc.*, 479 (1937); A. Clemm, *Ber.*, **24**, 826 (1891).

(22) I. Remsen and E. E. Reid, *Am. Chem. J.*, **21**, 290 (1897).

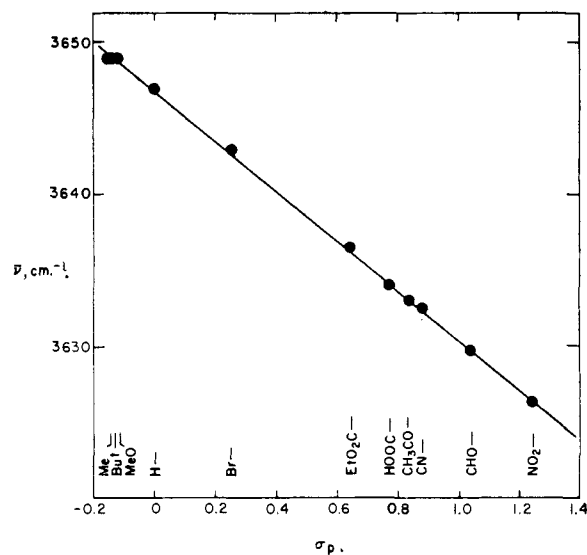


Fig. 4.—Correlation of infrared stretching band of phenolic hydroxyl with σ_p (4-substituted 2,6-di-*t*-butylphenols in CCl_4); $\rho = -16.5$.

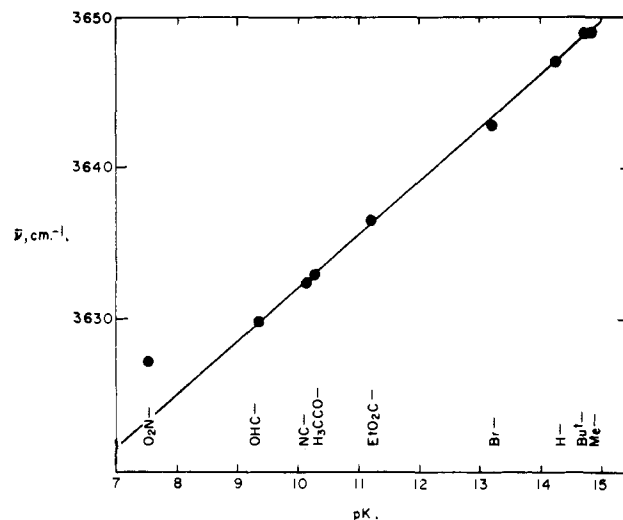


Fig. 5.—Correlation of infrared stretching band of phenolic hydroxyl (CCl_4) with pK (50% ethanol) of 4-substituted 2,6-di-*t*-butylphenols.

m-hydroxybenzoate, m.p. 71–72°, was prepared by esterification of the acid with ethanol–hydrogen chloride.²³

TABLE V
ULTRAVIOLET SPECTRAL DATA FOR 3-SUBSTITUTED PHENOLS
(50% ETHANOL)

R	$\lambda_{\text{max}}^{\text{N HCl}}$, m μ	ϵ	$\lambda_{\text{max}}^{\text{N NaOH}}$, m μ	ϵ
C(CH ₃) ₃	295	1700	309	2400
CN	290	3150	318	4050
CO ₂ Et	294	4710	315	5000
CONH ₂	295	4500	316	5200

Spectral Measurements.—Ultraviolet spectra were determined on a Cary recording spectrophotometer, Model 14. Infrared spectra were recorded on a Perkin–Elmer spectrophotometer, Model 21, using lithium fluoride optics and a scale of 0.02 μ per cm. Band positions were calibrated against water vapor. Nuclear magnetic resonance spectra were measured on a Varian A-60 spectrometer.

Dissociation constants were determined spectrophotometrically in aqueous media at 25°. Ultraviolet spectral data for 3-sub-

(23) M. F. Clark and I. N. Owen, *J. Chem. Soc.*, 2108 (1950)

stituted phenols, hitherto unreported, are recorded in Table V.²⁴ Values for σ_m were calculated from the equation $\text{p}K_a = 9.919 - 2.229 \sigma_m$.

(24) Other data may be found in L. Doub and J. M. Vandenberg, *J. Am. Chem. Soc.*, **71**, 2414 (1949).

Acknowledgments.—We are indebted to Mr. H. K. Miller and Mrs. Anne Wright for determination of high-resolution infrared spectra, and to Dr. E. D. Becker and Mr. R. B. Bradley for measurement of n.m.r. spectra.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, IOWA STATE UNIVERSITY, AMES, IOWA]

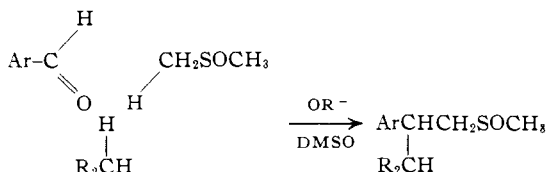
Condensation Reactions of Aromatic Aldehydes in Dimethyl Sulfoxide Solution. Asymmetric Tricarbon Condensation Involving Dimethyl Sulfoxide^{1,2}

BY GLEN A. RUSSELL³ AND HANS-DIETER BECKER

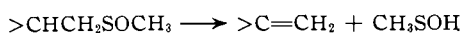
RECEIVED MARCH 1, 1963

An asymmetric tricarbon condensation involving an aromatic aldehyde, diphenylmethane, and the solvent dimethyl sulfoxide has been found to occur in the presence of potassium *t*-butoxide. The condensation product readily undergoes an elimination reaction to yield either of two isomeric triarylpropenes. The mechanism of the condensation reaction has been established by isolation of all probable intermediates.

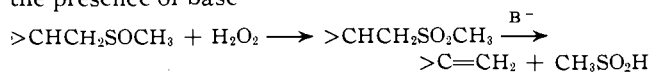
An investigation of the reaction of molecular oxygen with benzyl-type carbanions in dimethyl sulfoxide (80%) and *t*-butyl alcohol (20%) solutions led to the conclusion that the reaction products often resulted from condensation of the initially formed aldehydes with the starting toluenes.⁴ We have therefore studied, in the absence of oxygen, the reaction of aromatic aldehydes with active methylene compounds in dimethyl sulfoxide (DMSO) solution containing potassium *t*-butoxide. This study led to the discovery of a tricarbon condensation involving dimethyl sulfoxide as one of the reactants.



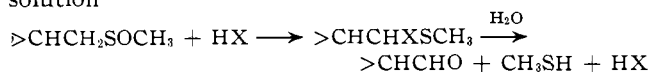
Sulfoxides are potentially valuable intermediates for the synthesis of sulfur-free compounds by virtue of their ability (a) to undergo pyrolysis or base-catalyzed elimination



(b) to form sulfones which can undergo elimination in the presence of base



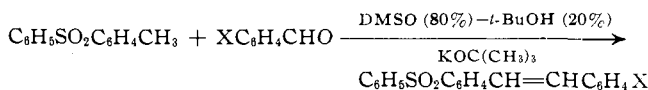
(c) to undergo the Pummerer rearrangement in acid solution



Results

Benzaldehydes and substituted benzaldehydes readily undergo condensation reactions in DMSO solution containing potassium *t*-butoxide either with DMSO itself⁴ or with added active methylene compounds. Because of the unique ability of DMSO to promote the formation of carbanions by the reaction of alkoxide ions with saturated carbon-hydrogen bonds,^{4,5} we have investi-

gated the reactivity in condensation reactions of methylene compounds that are generally considered to be unactive in alcoholic solvents. We first investigated the reaction of phenyl *p*-tolyl sulfone with aromatic aldehydes to form stilbenes. Table I summarizes the pertinent results.



No attempts were made to optimize the yields.

TABLE I
CONDENSATION OF PHENYL *p*-TOLYL SULFONE WITH BENZALDEHYDE IN DMSO (80%)–*t*-BuOH (20%)

RC ₆ H ₄ CHO (mmoles) R =	Sulfone, mmoles	KOC- (CH ₃) ₃ , ^a g.	Sol- vent, ^b ml.	Yield of stilbene, ^c	
				mg.	%
H (10)	2.5	0.56	16	320	40
<i>p</i> -CH ₃ O (22)	5.0	1.12	32	560	32
<i>p</i> -C ₆ H ₅ SO ₂ (1.5)	1.5	0.33	7	270	39
<i>p</i> -(CH ₃) ₂ N (3.0)	2.5	0.60	18	100	11
3,4-Methylenedioxy (5.0)	5.0	1.12	37	100	5.5

^a Sublimed. ^b DMSO (80%)–*t*-BuOH (20%). ^c Recrystallized; reaction period 40–50 min. at room temperature.

The condensation of *p*-carbomethoxybenzaldehyde and methyl *p*-toluate was thoroughly investigated due to its pertinence to the autoxidation of methyl *p*-toluate in basic solution.⁴ At room temperature yields of the dimethyl ester of *p,p'*-stilbenedicarboxylic acid in excess of 75% were achieved.

Attempts to produce a triphenylethylene derivative by the reaction of phenyl *p*-tolyl sulfone or diphenylmethane with benzophenone in DMSO always led to the benzophenone–DMSO adduct^{4,6} as the major product. When diphenylmethane was substituted for the phenyl *p*-tolyl sulfone only a small amount of a reaction product was formed from reaction with *p*-anisaldehyde at room temperature in DMSO (80%)–*t*-butyl alcohol (20%) mixtures. However, in alcohol-free DMSO at 60° either Va or VIIa, or a mixture of the two, can be formed depending upon the reaction conditions. Shorter reaction times and lower concentrations of potassium *t*-butoxide lead to the asymmetric tricarbon condensation⁷ product Va while longer reaction

(6) E. J. Corey and M. Chaykovsky, *ibid.*, **84**, 867 (1962).

(7) Asymmetric tricarbon condensations involving formaldehyde and two acidic methylene compounds, such as 1,3-diketones, have been extensively studied by H. Hellmann and co-workers (H. Hellmann and M. Schroder, *Ann.*, **656**, 85 (1962); H. Hellmann, *Bull. soc. chim. France*, 2197 (1961)).

(1) Reactions of Resonance Stabilized Anions. Part IX.

(2) This work was supported by the Air Force Office of Scientific Research.

(3) Alfred P. Sloan Foundation Fellow, 1959–1963.

(4) G. A. Russell, E. G. Janzen, H.-D. Becker, and F. J. Smentowski, *J. Am. Chem. Soc.*, **84**, 2652 (1962).

(5) (a) D. J. Cram, J. L. Matos, F. Hauck, A. Langemann, K. R. Kopecky, W. D. Nielsen, and J. Allinger, *ibid.*, **81**, 5774 (1959); D. J. Cram, B. Rickborn, and G. R. Knox, *ibid.*, **82**, 6412 (1960). (b) C. C. Price and W. H. Snyder, *ibid.*, **83**, 1773 (1961); A. Schriesheim, J. E. Hofmann, and C. A. Rowe, *ibid.*, **83**, 3731 (1961).