The cyclic acetals **1a**-**4a** were alkylated with hexadecyl methanesulfonate in the presence of KOH in xylene according to established procedures[8] of glycerol ether synthesis, and each of the reaction products was purified by preparative tlc[10] (hexane-$Et_2O$, 95:5, v/v). For nmr data, see Table II.

*cis*-**2-Pentadecyl-5-hexadecyloxy-1,3-dioxane (1c)**: mp 95-96°; ir ($CS_2$, $C_2Cl_4$)[25] 2715, 2652, 1408, 1339 (m), 1284, 1244, 1161 (s), 1139, 1116 (s), 1099 (s), 1006 (s), 955, 893, 804 $cm^{-1}$; mass spectrum (70 eV) *m/e* (rel intensity) 538 (1.0), 537 (1.7), 327 (100), 57 (49). *Anal.* Calcd for $C_{35}H_{70}O_3$: C, 78.00; H, 13.09; O, 8.91. Found: C, 77.85; H, 12.87; O, 9.20.

Hydrolysis of **1c** in aqueous hydrochloric acid-methanol[8] and purification by tlc (hexane-$Et_2O$, 10:90, v/v) yielded 2-hexadecyl glycerol ether: mp 62° (lit.[13] 62.5-63.3°); migration rate on boric acid impregnated plates (chloroform-methanol, 98:2, v/v) was identical with that of a standard.

*trans*-**2-Pentadecyl-5-hexadecyloxy-1,3-dioxane (2c)**: mp 86-87°; ir ($CS_2$, $C_2Cl_4$)[25] 2660, 1369, 1327, 1297, 1271, 1222, 1150 (m), 1138 (sh), 1116 (s), 1042 (m), 962 (m), 900, 802, 680, 665 $cm^{-1}$; mass spectrum (70 eV) *m/e* (rel intensity) 538 (0.4), 537 (1.7), 327 (100), 57 (39). *Anal.* Calcd for $C_{35}H_{70}O_3$: C, 78.00; H, 13.09; O, 8.91. Found: C, 78.00; H, 12.95; O, 9.10.

Hydrolysis of **2c** and purification, as described above, yielded 2-hexadecyl glycerol ether, mp 63°.

**2-Pentadecyl-4-hexadecyloxymethyl-1,3-dioxolanes (3c, 4c)**: mp 71-73°; ir ($CS_2$, $C_2Cl_4$)[25] 1411, 1350, 1302, 1258, 1140 (m), 1119 (s), 1045 (m), 960, 803 $cm^{-1}$; mass spectrum (70 eV) *m/e* (rel intensity) 538 (0.6), 537 (0.9), 327 (100), 57 (41). *Anal.* Calcd for $C_{35}H_{70}O_3$: C, 78.00; H, 13.09; O, 8.91. Found: C, 78.00; H, 12.83; O, 9.29.

Hydrolysis of the mixture of **3c** plus **4c**, and purification, as described above, yielded 1-hexadecyl glycerol ether: mp 63-64° (lit.[8] 65.5°); migration rate on boric acid impregnated plates (chloroform-methanol, 98:2, v/v) was identical with that of a standard.

**Registry No.**—**1a**, 30889-22-6; **1b**, 30889-23-7; **1c**, 30889-24-8; **2a**, 30889-25-9; **2b**, 30889-26-0; **2c**, 30889-27-1; **3a**, 30889-28-2; **3b**, 30889-29-3; **3c**, 30889-30-6; **4a**, 30889-31-7; **4b**, 30889-32-8; **4c**, 30889-33-9; **5**, 14739-11-8.

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# Conformational Analysis. LXXIV. Studies on Phenol and Anisole Derivatives[1-3]

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The orientation of the hydroxyl or methoxyl in a number of ortho-substituted phenols and anisoles has been studied by experimental (dipole moment) and theoretical (molecular mechanics) methods. The phenolic hydroxyl is coplanar with the ring, even in di-*o-tert*-butylphenol. The rotational barrier about the $C_{Ar}$–O bond in anisole is negligibly small. Di-*o*-methylanisole has the methoxyl perpendicular to the ring plane.

Conformational properties of phenols have been studied in some detail *via* their infrared spectra. The hydroxyl overtone region was observed at an early date by Wulf.[5] An ortho halogen on a phenol may interact (hydrogen bond) with the hydroxyl, and Pauling[6] interpreted the doublet in the O–H stretching overtone region as due to the existence of cis and trans orientations of the hydroxyl, which lies in the plane of the benzene ring. Baker,[7] in his study of the fundamental hydroxyl stretching region, reaffirmed and more fully explained the observed shifts.

Similar shifts result when other groups such as nitro or carbonyl are placed ortho to the phenol, since hydrogen bonding again takes place.[8]

While most phenolic hydroxyls which are not hydrogen bonded absorb at 3608 ± 2 $cm^{-1}$, important exceptions include those phenols which are alkylated in the ortho position. In particular, di-*o-tert*-butyl substitution shifts the free hydroxyl to a much higher frequency (3643 $cm^{-1}$).[9] The increase seems too large to be accounted for by resonance or inductive contributions of the alkyl group alone. It might be reasonably attributed to twisting of the O–H bond out of the plane of the benzene ring. This would decrease the resonance interaction between the oxygen and the ring, raise the electron density on oxygen, and increase the bond strength of the O–H bond, thereby increasing the absorption frequency. That this is probably not the case, however, was deduced by Ingold[10] when, by using the $\sigma$ values derived by Taft[11] for ortho substituents, he found that the frequencies of the O–H bands for 4-substituted phenols and 4-substituted 2,6-di-*tert*-butylphenols can be correlated by a Hammett $\sigma$–$\rho$ relationship. A plot of the $\sigma$ values of the two types of phenols *vs.* absorption frequency gave two parallel straight lines. The conclusion was that both types of phenols had similar structures. From a study of models, Ingold calculated that with the cis phenolic hydrogen selectively placed in the most favorable coplanar position, a maximum compression energy with the *tert*-butyl group of the order of 0.1-0.2 kcal/mol is present, which is rather small compared with the 7.0-kcal/mol resonance energy postulated from maintaining the O–H bond in the plane of the ring.

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[2] Abstracted in part from the Ph.D. dissertation submitted to Wayne State University by J. J. M., Nov 1966.

[3] Paper LXXIII: N. L. Allinger and M. T. Wuesthoff, *J. Org. Chem.*, **36**, 2051 (1971).

[4] Correspondence concerning this work should be directed to this author at the University of Georgia, Athens, Ga. 30601.

[5] O. R. Wulf, U. Liddel, and S. B. Hendricks, *J. Amer. Chem. Soc.*, **58**, 2287 (1936).

[6] L. Pauling, *ibid.*, **58**, 94 (1936).

[7] A. W. Baker, *ibid.*, **80**, 3598 (1958).

[8] (a) M. S. C. Flett, *Spectrochim. Acta*, **10**, 21 (1957); (b) L. J. Bellamy and H. E. Hallam, *Trans. Faraday Soc.*, **55**, 220 (1959); (c) P. M. Boll, *Acta Chem. Scand.*, **12**, 1777 (1958).

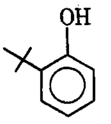
[9] R. F. Goddu, *J. Amer. Chem. Soc.*, **82**, 4533 (1960).

[10] (a) K. U. Ingold, *Can. J. Chem.*, **38**, 1092 (1960); (b) K. U. Ingold and D. R. Taylor, *ibid.*, **39**, 471 (1961); (c) *ibid.*, **39**, 481 (1961).

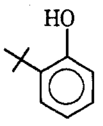
[11] R. W. Taft, "Steric Effects in Organic Chemistry," Wiley, New York, N. Y., 1956, Chapter 13.

LeFevre and coworkers,[12] employing Kerr constant measurements, calculated the O–H bond to be 14° out of the plane of the benzene ring in the 2,6-di-*tert*-butylphenol. Allowing for torsional vibration and experimental error, the agreement between these conclusions seems good.

Ingold reasoned that the increase in the hydroxyl stretching frequency of the 2,6-di-*tert*-butylphenol, over and above that due to the electropositivity of the 2-*tert*-butyl groups, must be due to the snug fitting of the phenolic hydrogen into the adjacent *tert*-butyl group. Repulsion of the latter will build up as the O–H bond stretches, which will result in a narrowing of the potential well, which leads to an upward spreading of the vibrational levels, thus raising the frequency of the vibration. If the hydroxyl group of 2-*tert*-butylphenol is considered to be coplanar, or nearly so, with the benzene ring, then one would expect cis and trans conformational isomers of the types shown.



trans



cis

In addition, one would predict two O–H stretching frequencies in the infrared: one band approximately in the region where unsubstituted phenols absorb and one in the region where 2,6-di-*tert*-butyl substituted phenols appear. Indeed such is the case, as shown by Goddu and Ingold. An intense band appears at the same frequency as phenol (3608 cm$^{-1}$), and a small, incompletely resolved band is found at a frequency approximately that of the 2,6-di-*tert*-butyl analog (3643 cm$^{-1}$). On the basis of earlier work,[13] Ferguson[14] attributed these bands to free and intermolecular bonded hydroxyl. However, this assignment was erroneous, as the doublet appears at concentrations where even phenol does not intermolecularly hydrogen bond. In addition, the work of earlier investigators had been limited in both the resolving power of the instrumentation used, and the choice of solvents.

The possibility that the two hydroxyl stretching bands observed in *tert*-butylphenol result from Fermi resonance[15] rather than from two isomers has been postulated for hydroxyl compounds containing the $-CH_2OH$ group,[16] but this is unlikely here, since the intensity of the subsidiary cis band decreases slightly as the two bands get closer together on going from *o*-*tert*-butyl to *o*-*tert*-amylphenol.[10] This is contrary to what would be expected from Fermi resonance.

If, instead of the phenols, we now consider the corresponding methyl ethers (anisoles), we expect an even greater interaction between the ortho tertiary alkyl group and the methyl than is exhibited by the phenolic hydrogen. Employing Kerr constants in studying the conformations of anisoles with methyl, chloro, or bromo substituents in both ortho positions, LeFevre[12] reported that the molecules existed preferentially in a conformation in which the $C_{Ar}$–O–$C_{Me}$ plane was orthogonal to the benzene ring. Therefore, when ortho *tert* alkyl groups are present, a similar situation must exist.

The present investigation was undertaken for the following reasons. First, the bond and group polarity and polarizability data required for the calculation of Kerr constants is not always known with as much accuracy as one would desire.[17] Second, even accepting the general correctness of the results of the previous investigations, Kerr constant measurements and the Hammett correlation with the infrared are more suggestive than definitive. More quantitative data were therefore desirable, both experimental and theoretical.

## Synthesis

The experimental method employed for the present work utilized dipole moments in an effort to determine the relative orientation of the hydroxyl or methoxyl in various phenol and anisole derivatives. The compounds examined are those shown in Table I.

Most of the compounds required for the present work have been previously described in the literature. In general, we used either the original procedure or a modernized modification of it for the preparation of such compounds. The final product in each case had properties which corresponded to the compound described in the literature; thus the properties are merely summarized in Table V, together with the literature references. The only compounds which require special comment are 5-bromo-2-*tert*-butylphenol (VI) and its methoxy derivative (X). The latter was prepared in 24% yield from 3-bromoanisole by alkylation with *tert*-butyl chloride in the presence of anhydrous aluminum chloride at room temperature. Carpenter[18] has demonstrated the position of the *tert*-butyl group in this compound by preparing the same material *via* the alkylation with dimethyl sulfate of 5-bromo-2-*tert*-butylphenol. The nmr spectrum of this methyl ether consists of an intense singlet at $\delta$ 1.23 ($A = 9$), a singlet at $\delta$ 3.81 ($A = 3$), and an unresolved multiplet at $\delta$ 7.0 ($A = 3$). The $\delta$ 1.23 singlet was assigned to the 9-*tert*-butyl protons. The singlet at $\delta$ 3.81 was attributed to the methoxyl protons and the multiplet to the three aromatic protons. The compound is reported as a liquid in the literature, but in our hands it was obtained as a solid, mp 55–56.3°. Considering ways to prepare the free phenol, it was hoped that HBr cleavage of the ether would be a satisfactory method. In our hands, however, 3-bromophenol was isolated in high yield, and the odor of isobutylene was noted as the reaction progressed. Obviously the *tert*-butyl group was cleaved concurrently with the ether linkage. Stroh[19] has reported similar dealkylations when 2-*tert*-butylphenol was heated with acid. The hydroxy compound was therefore synthesized *via* the alternate route which had

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(12) M. J. Aroney, M. G. Corfield, and R. J. W. LeFevre, *J. Chem. Soc.*, 2954 (1964).

(13) (a) N. D. Coggeshall, *J. Amer. Chem. Soc.*, **69**, 1620 (1947); (b) N. D. Coggeshall, *ibid.*, **73**, 5414 (1951); (c) R. A. Freidel, *ibid.*, **73**, 2881 (1951); (d) E. E. Pickett and H. E. Ungnade, *ibid.*, **71**, 1311 (1949); (e) R. E. Richards and H. W. Thompson, *J. Chem. Soc.*, **69**, 1260 (1947).

(14) L. N. Ferguson, "The Modern Structural Theory of Organic Chemistry," Prentice-Hall, Englewood Cliffs, N. J., 1963, p 536.

(15) E. Fermi, *Z. Physik*, **71**, 250 (1931).

(16) T. D. Flynn, R. L. Werner, and B. M. Graham, *Aust. J. Chem.*, **12**, 575 (1959).

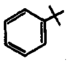
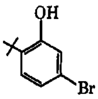
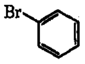
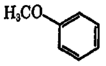
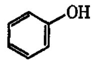
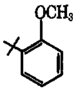
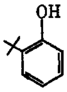
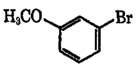
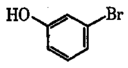
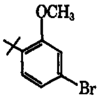
(17) (a) R. F. Zürcher, *J. Chem. Phys.*, **37**, 2421 (1962); (b) E. L. Eliel, N. L. Allinger, S. J. Angyl, and G. A. Morrison, "Conformational Analysis," Interscience, New York, N. Y., 1965, p 178.

(18) M. S. Carpenter, W. M. Easter, and T. F. Wood, *J. Org. Chem.*, **16**, 586 (1951).

(19) R. Stroh, R. Seydel, and W. Hahn, "Newer Methods of Preparative Organic Chemistry," Vol. II, W. Foerst, Ed., Academic Press, New York, N. Y., 1963.

TABLE I

COMPOUNDS STUDIED BY DIPOLE MOMENT MEASUREMENTS

| Compd | Structure | Compd | Structure |
|---|---|---|---|
| I *tert*-Butylbenzene |  | VI 5-Bromo-2-*tert*-butylphenol |  |
| II Bromobenzene |  | VII Anisole |  |
| III Phenol |  | VIII 2-*tert*-Butylanisole |  |
| IV 2-*tert*-Butylphenol |  | IX 3-Bromoanisole |  |
| V 3-Bromophenol |  | X 5-Bromo-2-*tert*-butylanisole |  |

been previously used by Carpenter.[18] 5-Bromo-2-*tert*-butylphenol showed an nmr spectrum which exhibited five major bands, an intense singlet at δ 1.35, a broad singlet at δ 4.88, a quartet at δ 6.78, a doublet at δ 7.01, and a doublet at δ 7.05. The δ 1.35 singlet was interpreted as resulting from the 9-*tert*-butyl protons, and the broad singlet at δ 4.88 was attributed to the phenolic proton. The quartet at δ 6.78 was attributed to the aromatic proton in the four position, which was split into a doublet ($J = 1.8$ Hz) by coupling with the aromatic proton in the three position. The doublet was then split into a quartet by long-range coupling ($J = 0.6$ Hz) with the aromatic proton at C-6. The doublet at δ 7.01 was attributed to the proton at C-3 coupled ($J = 1.8$ Hz) with the proton at C-4, and the doublet at δ 7.05 was attributed to the proton at C-6 split by long-range coupling with the proton at C-4 ($J = 0.6$ Hz). The band areas were all consistent with this assignment.

## Discussion

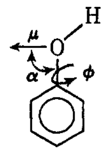
The phenols will be discussed first. In his paper, Goddu mentions that the extinction coefficients are similar in phenol and in 2,6-di-*tert*-butylphenol, and therefore, in *o-tert*-butylphenol the ratio of the isomers can reasonably be approximated by the extinction coefficients of the two stretching frequencies. This led to a conclusion that the trans isomer predominates over the cis and comprises about 93% of the mixture, which seems qualitatively reasonable.

The *o-tert*-butylphenol chosen for dipole moment study was 5-bromo-2-*tert*-butylphenol. This compound was selected because the bromine substituent has a dipole moment whose magnitude and direction are sufficiently large and well established to act as a convenient reference in determining the magnitude and direction of the other moments, and hence the orientation of the substituents and different conformations.

Because the dipole moment of a particular conformer is the resultant of the dipole moments of its substituents, by treating the substituent moments as vector quantities, the dipole moment of any conformer may be calculated, making the usual approximation that dipole–dipole interactions change the individual moments and their energies to a negligible extent. Therefore, the solution of this problem consists of determining the magnitudes and directions of the dipole moments of the various substituents of an *o-tert*-butylphenol, and then calculating the theoretical dipole moments of the two (cis and trans) conformers. From these values, together with the experimental value for the moment of the compound, the relative populations of two conformers may be calculated from eq 1.

$$(\mu_{\text{obsd}})^2 = N_{\text{trans}}(\mu_{\text{trans}})^2 + N_{\text{cis}}(\mu_{\text{cis}})^2 \qquad (1)$$

In this study, the value of each substituent dipole moment was determined as the dipole moment of its benzene derivative. Thus, the dipole moment of a *tert*-butyl substituent was taken as equal to the dipole moment of *tert*-butylbenzene, $\mu = 0.52$ D. In a similar manner, the dipole moments of the hydroxyl, bromo, and methoxyl groups were equated to those of phenol ($\mu = 1.50$ D), bromobenzene ($\mu = 1.55$ D), and anisole ($\mu = 1.32$ D). The direction of the $C_{Ar}$–Br dipole moment is along the $C_{Ar}$–Br bond, toward bromine, while that of $C_{Ar}$–*tert*-Bu is along the $C_{Ar}$–C bond, toward the ring. For the $C_{Ar}$–O–H group (and similarly for the $C_{Ar}$–O–R) the group moment makes an angle ($\alpha$) with the $C_{Ar}$–O bond in the $C_{Ar}$–O–H plane and is directed away from the H (or the R) group, as shown.



Assuming $\phi$ (the angle which the OH bond moment is rotated out of the plane of the aromatic ring) equals zero in both conformers, the theoretical dipole moments of *trans*- and *cis*-5-bromo-2-*tert*-butylphenol were calculated, and from the experimental value their relative populations were determined.

Because the dipole moments of the *tert*-butyl and bromine substituents are in the same direction, they are additive and their sum composes the vector quantity of one of the sides of the parallelogram of forces. The other vector quantity is the dipole moment of the hydroxyl group, $\mu_{\text{OH}} = 1.50$ D.

The angle between the dipoles ($\theta$) was determined from the angle ($\alpha = 84°$) which the $C_{Ar}$–O–H dipole moment makes with the $C_{Ar}$–O bond in the $C_{Ar}$–O–H plane. The value of $\alpha$ had been previously reported in the literature.[12,20,21] (The correctness of the general value of $\alpha = 84°$ and the particular value of $\phi = 0°$ for the trans conformer of 5-bromo-2-*tert*-butylphenol was verified by the fact that these values give a calculated value for the dipole moment of 3-bromophenol which is in good agreement with experiment ($\mu_{calcd} = 2.21$ D; $\mu_{obsd} = 2.15$ D), assuming a 1:1 cis/trans conformer ratio for 3-bromophenol.)

For the trans conformer of 5-bromo-2-*tert*-butylphenol, one obtains $\theta = 36°$, $\mu_{trans} = 1.23$ D. Similarly, for the cis isomer, $\theta = 156°$, which yields $\mu_{cis} = 3.49$ D. From these calculated dipole moment values of the trans and cis conformers, their relative populations (mole fractions) were calculated by appropriate substitution in eq 1, where

$$N_{trans} + N_{cis} = 1 \qquad (2)$$

Substituting appropriate values, one obtains $N_{trans} = 0.91$ and $N_{cis} = 0.09$. Therefore, dipole moments indicate that 5-bromo-2-*tert*-butylphenol is composed of 9% cis conformer and 91% trans conformer, in good agreement with the infrared results (about 7% cis).

The possibility of error introduced by the assumption that $\phi = 0$ was checked by repeating the calculation of the cis conformer for $\phi = 14°$ and $\phi = 20°$. The conformer population was essentially unchanged, being 9% for the cis conformer in each case. Thus, slight deviation from coplanarity between the O–H and aromatic ring would have essentially no effect on the resultant dipole moment. This is an advantage in that even though the value of $\phi$ is not accurately known, still good values for the mole fractions of cis and trans conformers are obtainable.

There is a possibility that $\alpha$ may be changed slightly in the cis conformer through an interaction between the hydroxyl and *tert*-butyl groups. However, calculations where $\alpha$ is varied $\pm 5°$ predicts cis mole fractions of 0.09 in each case, which values are essentially the same as that indicated assuming $\alpha = 84°$.

***o-tert*-Butylanisole.**—Investigations employing Kerr constants[12] have suggested that the $C_{Ar}$–O–$C_{Me}$ plane defines an angle $\phi$ with the plane of the aromatic ring which is 22° for anisole itself and 90° in 2,6-dimethylanisole. These conclusions are consistent with those one might draw after a visual inspection of models. In anisole there are van der Waals interactions between the ortho hydrogen and the methyl hydrogens of the methoxy group, which are relieved if the methoxyl group is rotated ($\phi \neq 0$) out of the plane of the aromatic ring. When methyl groups are located in ortho positions, this steric interaction is increased, and therefore a greater rotation (large value of $\phi$) of the methoxyl group is required to relieve the interaction.

It was in order to obtain information about the conformation of *o-tert*-butylanisole that the dipole moment investigation of 5-bromo-2-*tert*-butylanisole was undertaken, analogous to the study of the 2-*tert*-butylphenols. The method of attacking the problem was the same as with the phenols, in that the substituent dipole moments were treated as vector quantities and were taken as being equal to the dipole moments of the corresponding benzene derivatives. Like the conformers of 5-bromo-2-*tert*-butylphenol, the dipole moment of the conformer of 5-bromo-2-*tert*-butylanisole and the resultant vector is expressed in terms of its substituent vectors by the law of cosines, eq 3. However, unlike

$$(\mu_{calcd})^2 = [\mu_{Br+tert\text{-}Bu}]^2 + [\mu_{OCH_3}]^2 - 2[\mu_{Br+tert\text{-}Bu}][\mu_{OCH_3}][\cos\theta] \qquad (3)$$

5-bromo-2-*tert*-butylphenol, it was assumed that only one conformation existed, the trans conformation. Models of the 2-*tert*-butylanisole indicate that the closest that the methoxyl group can come to being cis to the *tert*-butyl group is to be in such a conformation that $\phi = 90°$, and eq 4 defines cos $\theta$ for any trans form

$$\cos\theta = \cos 30° \sin\alpha \cos\phi - \sin 30° \cos\alpha \qquad (4)$$

from planar through $\phi = 90°$. In eq 4, $\alpha$ is equal to the angle which the dipole moment of the methoxy group makes with the $C_{Ar}$–O bond in the $C_{Ar}$–O–$C_{Me}$ plane. This angle has been found by Lumbroso and Dumas to be 76°.[22] Substituting appropriate values in eq 3 and 4, $\phi = 29°$.

Taken at face value, this dipole moment investigation indicated that the $C_{Ar}$–O–$C_{Me}$ plane is rotated 29° out of the plane of the aromatic ring. However, even if it is assumed that $\phi = 0$, the calculated ($\mu_{calcd} = 1.45$ D) and observed ($\mu_{obsd} = 1.63$ D) dipole moments are pretty close, providing (regardless of whether $\phi$ is or is not equal to zero) strong evidence for the transoid structure of 2-methoxy-4-bromo-*tert*-butylbenzene. Still, rotation of the methoxyl group to some degree ($\phi \neq 0$) is indicated.

The correctness of the value $\alpha = 76°$ for the methoxyl group is borne out by the fact that the calculated dipole moments of 3-bromoanisole (assuming a 1:1 cis–trans ratio) whether $\phi = 0$ or 29° (2.14 and 2.14 D, respectively) are in agreement with the observed dipole moment of 3-bromoanisole ($\mu_{obsd} = 2.05$ D).

## Theoretical Studies and Conclusions

The structure of phenol is now known rather accurately, and the barrier to rotation about the C–O bond has been determined by microwave measurements.[23] It was found to be 3.4 kcal/mol, about half the value estimated earlier by Ingold.[10] In addition, it is now known[24,25] that the van der Waals radius of hydrogen is a good deal larger than the value generally accepted in 1960. It is therefore not obvious how large the ortho substituents on a phenol might have to be before the preferred conformation of the phenol would be nonplanar.

We have recently described[24] a force field which has been highly useful for determining structures in hydrocarbons. We have also extended the calculations

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[20] B. Eric, E. V. Goode, and D. A. Ibbitson, *J. Chem. Soc.*, 55 (1960).

[21] Eric gives 84°; Aroney misquotes this as 88°. We have used 84° herein, but parallel calculations show no significant difference in results if 88° is used.

[22] H. Lumbroso and G. Dumas, *Bull. Soc. Chim. Fr.*, 651 (1955).

[23] T. Pedersen, N. W. Larsen, and L. Nygaard, *J. Mol. Struct.*, **4**, 59 (1969).

[24] N. L. Allinger, M. T. Tribble, M. A. Miller, and D. H. Wertz, *J. Amer. Chem. Soc.*, **93**, 1637 (1971).

[25] (a) J. Jacob, H. B. Thompson, and L. S. Bartell, *J. Chem. Phys.*, **47**, 3736 (1967); (b) A. Warshel and S. Lifson, *ibid.*, **53**, 582 (1970); (c) S. Chang, D. McNally, S. Shary-Tehrany, M. J. Hickey, and R. H. Boyd, *J. Amer. Chem. Soc.*, **92**, 3109 (1970).

to handle in a preliminary way a few other atoms, including oxygen. As we have described it, the method is not general for delocalized systems, because bond lengths and force constants are a function of $\pi$ bond order. However, in the particular case of a benzene ring, if there is no conjugation with the substituent, the bond orders, bond lengths, and stretching force constants are all equal and known. In the present case, conjugation of the phenolic oxygen with the ring causes some change and inequalities among these values, but the changes are small enough to be neglected as far as the structure is concerned. Therefore, we have carried out calculations on these molecules treating the phenol ring as though it is strictly benzenoid with respect to the natural bond lengths and force constants, choosing a torsional constant so that the rotational barrier in phenol itself is correctly duplicated, and then we have used these data plus the earlier described force field to calculate conformational energies and rotational barriers for a number of substituted phenols and anisoles.

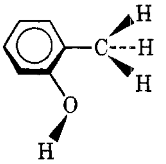
In Table II are assembled the results of our calculations on rotational barriers. The phenol molecule is planar; a 90° rotation of the hydroxyl group leads to an increase in energy of 3.40 kcal/mol, since the torsional constant was chosen to reproduce the experimental result.

TABLE II
CALCULATED ROTATIONAL BARRIERS FOR PHENOLS AND ANISOLES

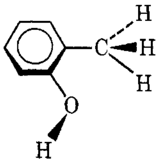
| Compd | Structure | Barrier for rotation of group |
|---|---|---|
| Phenol | Planar | 3.40 Hydroxyl |
| 2,6-Dimethylphenol | Planar | 2.31 Hydroxyl |
| 2,6-Di-*tert*-butylphenol | Planar | 2.11 Hydroxyl |
| Anisole | Planar and perpendicular | 0.4[a] Methoxyl |
| 2,6-Dimethylanisole | Perpendicular | 6.17 Methoxyl |
| 2,6-Di-*tert*-butylanisole | Perpendicular | 19.74 Methoxyl |
| *p*-Methylphenol | Planar | 3.45 Hydroxyl |
| *o*-Methylphenol | *a* | 0.60 Methyl |
| *o*-*tert*-Butylphenol | Planar–trans | 0.47 *tert*-Butyl |

[a] See discussion in text.

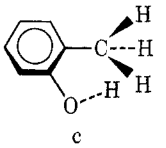
For *o*-methylphenol, we have considered three planar conformations (a–c). The conformation of lowest energy is calculated to be that with the hydroxyl hydrogen away from the methyl and with the methyl hydrogens that are toward oxygen above and below the ring plane (a) rather than a single hydrogen toward oxygen in the plane (b). The conformations with the hydroxyl hydrogen toward the methyl are higher in energy.



a
$E = 0$



b
0.62



c
0.86

For 2,6-dimethylphenol, the molecule again has a preferred planar conformation, but there is considerable repulsion between the nearest methyl and the hydroxyl hydrogen in this planar molecule, which is relieved when the hydroxyl is rotated perpendicular to the ring plane. The rotational barrier in this compound is therefore reduced slightly from what it is in phenol and is found to have the value 2.31 kcal/mol. With 2,6-di-*tert*-butylphenol, the same effect is seen with a larger magnitude, and the rotational barrier here is 2.11 kcal/mol.

Looking next at anisole, there is a substantial hindrance between the ortho hydrogen and the nearest hydrogen on the methoxyl group, which is relieved when the methoxyl is rotated out of the aromatic plane. The rotational barrier is anisole is not known experimentally, so that the value for the rotational force constant to be used here is uncertain. The torsional constants for ethane and propane are the same,[24] while those for methanol and methyl ether differ by only about 0.1 kcal/mol, so as an approximation we have assumed that the torsional constant is the same in anisole as in phenol. With this assumption, the rotational barrier about the ring-oxygen bond is calculated to be essentially zero; *i.e.*, the group is almost freely rotating.[26] With 2,6-dimethylanisole and 2,6-di-*tert*-butylanisole, the repulsion between the methoxyl and the ortho alkyl group is excessive when the methoxyl is in the plane of the ring, and it is found that the conformation with the methoxyl perpendicular to the ring is more stable by 6.17 and 19.74 kcal/mol, respectively.

In Table III are summarized a number of calculated conformational equilibria for ortho-substituted phenols. Qualitatively, the results are as one would expect. With phenols, the hydroxyl hydrogen tends to be away from the ortho substituent in the case of *o*-cresol or *o*-*tert*-butylphenol, and if there are two ortho substituents, it tends to be in the direction of the smaller one. The numbers are summarized in Table III. Qualitatively, similar features are found with the anisoles. The methoxyl will be away from the ortho substituent, or, in the case of di-ortho substitution, it will be out of the plane.

TABLE III
CALCULATED CONFORMATIONAL EQUILIBRIA[a] OF PHENOLS

| Small group | Large group | $\Delta H^\circ_{\text{calcd}}$ | $\Delta G^\circ_{\text{exptl}}$ |
|---|---|---|---|
| H | $CH_3$ | 0.86 | |
| H | *tert*-Bu | 3.04 | 1.5–1.7 |
| $CH_3$ | *tert*-Bu | 2.22 | 0.9–1.2 |

[a] The equilibrium favors the hydroxyl hydrogen being toward the smaller group in each case.

It may be noted (Table III) that when there is steric repulsion of the hydroxyl hydrogen by an alkyl, the calculated values tend to be too large. This is probably due at least in part to the fact that the phenolic hydrogen is given the same van der Waals properties in the calculation as are all other hydrogens. In fact, both $E$ and $r^*$ should be reduced, because the electron density about the phenolic hydrogen must be less polarizable and pulled in more tightly than for the other hydrogens. Part of the disagreement may stem from the fact that a calculated $\Delta H^\circ_{(\text{gas})}$ is being compared with an experimental $\Delta G^\circ_{(\text{soln})}$.

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(26) The calculations actually give a fourfold barrier, with minima at 0, 90, 180, and 270°, and maxima of 0.4 kcal/mol in between. The barrier is thus small, and seems almost an artifact of the method, so we prefer to simply say it is "essentially zero."

In addition, *p*-methyl- and *p-tert*-butylphenol and their methyl ethers have been studied. The interaction energy between the substituents is small with the para isomers, so that the difference in energies between the conformations of minimum energy for the analogous ortho- and para-substituted compounds is a measure of the strain energies of the former. These are given in Table IV.

TABLE IV

STRAIN ENERGIES OF ORTHO-SUBSTITUTED COMPOUNDS

| Compd | Strain, kcal/mol |
|---|---|
| Phenol, *o*-methyl | 0.25 |
| *o-tert*-butyl | 3.80 |
| Anisole, *o*-methyl | 1.49 |
| *o-tert*-butyl | 4.93 |

The conclusions of the theoretical and experimental studies are in qualitative agreement, and in moderately good quantitative agreement, and can be summarized as follows. Phenol is planar, and there is a barrier to rotation of the hydroxyl of 3.40 kcal/mol, which is attributed mainly to the resonance interactions of the unshared pairs on the oxygen with the ring. The presence of an *o*-methyl introduces a repulsion with the hydroxyl hydrogen, forcing it preferentially to the other side of the molecule. The remaining deformation from the oxygen–methyl repulsion introduces a small strain energy (0.25 kcal/mol) into this ground state, which lowers slightly the rotational barrier for the hydroxyl. The phenolic hydrogen in *o*-cresol remains in the plane, and there is a moderate preference (0.86 kcal) for the position away from the methyl. The same is qualitatively true for *o-tert*-butylphenol, but the energy differences are larger.

Anisole has a methoxyl which is essentially freely rotating. The adverse steric effect of the planar form and the lack of resonance in the nonplanar form closely balance one another. The presence of an ortho alkyl substituent is sufficient to clearly force the methoxyl to the other side of the plane from the substituent. Two ortho alkyl groups assure nonplanarity.

## Experimental Section

Most of the physical data concerning the compounds studied in this work are summarized in Table V.

TABLE V

| Compd | Bp, °C (mm) | Mp, °C | Ref | $n^{25}D$ |
|---|---|---|---|---|
| Bromoanisole | 99–100 (10) | | 18 | 1.5547 |
| 5-Bromo-2-*tert*-butylanisole | 120 (7) | 55–56.3 | 18 | 1.5380 |
| *tert*-Butylbenzene | 167–168 | | *b* | |
| 5-Bromo-2-*tert*-butylphenol[a] | 120–122 (3) | | 18 | 1.5539 |

[a] *Anal.* Calcd for $C_{10}H_{13}OBr$: C, 52.42; H, 5.72; Br, 34.88. Found: C, 52.44; H, 5.72; Br, 35.08. [b] A. I. Vogel, "Practical Organic Chemistry," Longmans, Green and Co., New York, N. Y., 1957, p 513.

**Dipole Moments.**—The dipole moments of the various compounds were determined at 25° in benzene solution using the dipole moment apparatus described previously.[27] The moments were calculated essentially by the method of Halverstadt and Kumler,[28] utilizing an IBM 7074 computer as described earlier.[29] The molar refractivities were obtained from tables,[30] and atomic polarization was neglected. The data are summarized in Table VI.

TABLE VI

DIPOLE MOMENT DATA

| Compd | Dipole moment,[a] D |
|---|---|
| *tert*-Butylbenzene | 0.52 ± 0.068 |
| Bromobenzene | 1.55 ± 0.03 |
| Phenol | 1.50 ± 0.04 |
| 2-*tert*-Butylphenol | 1.35 ± 0.03 |
| 3-Bromophenol | 2.15 ± 0.03 |
| 5-Bromo-2-*tert*-butylphenol | 1.57 ± 0.03 |
| Anisole | 1.30 ± 0.03 |
| 2-*tert*-Butylanisole | 1.18 ± 0.01 |
| 3-Bromoanisole | 2.05 ± 0.01 |
| 5-Bromo-2-*tert*-butylanisole | 1.63 ± 0.01 |

[a] The errors listed are standard deviations from the statistical treatment of the data.

**Registry No.**—3-Bromoanisole, 2398-37-0; 5-bromo-2-*tert*-butylanisole, 30788-02-4; *tert*-butylbenzene, 98-06-6; 5-bromo-2-*tert*-butylphenol, 30715-50-5; bromobenzene, 108-86-1; phenol, 108-95-2; 2-*tert*-butylphenol, 88-18-6; 3-bromophenol, 591-20-8; anisole, 100-66-3; 2-*tert*-butylanisole, 2944-48-1.

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[27] N. L. Allinger, H. Blatter, M. A. DaRooge, and L. A. Freiberg, *J. Org. Chem.*, **26**, 2550 (1961).

[28] I. F. Halverstadt and W. D. Kumler, *J. Amer. Chem. Soc.*, **64**, 2988 (1942).

[29] N. L. Allinger and J. Allinger, *J. Org. Chem.*, **24**, 1613 (1959).

[30] A. I. Vogel, W. T. Cresswell, G. J. Jeffery, and J. Leicester, *Chem. Ind. (London)*, 358 (1950).