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Studies of the Solvent Effects on the Chemical Shifts in NMR Spectroscopy. IV. Methoxyl Proton Signals of Methoxybenzenes in the Benzene Solutions[*1,*2,*3]

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The chemical shifts of methoxyl protons of a series of methoxybenzenes and the related compounds in cyclohexane, carbon tetrachloride, and benzene solutions have been investigated. The benzene-induced high-field shifts for methoxyl protons are large if the substituent at the benzene ring is a highly electron-withdrawing group. In carbon tetrachloride, the methoxyl proton signals appear at lower field than those in cyclohexane solutions. The low-field shifts also increase with the electronegativities of the substituents. An attempt has been made to interpret the solvent effects by the use of a model where benzene molecules are assumed to cluster around the methoxyl group and the benzene ring of the solute molecule. The attraction between solute and solvent molecules has been suggested to be due to the van der Waals interactions and partly to the charge-transfer interaction.

The methoxyl proton signals of methoxybenzenes in benzene solutions have been known to appear at considerably higher field than those in non-aromatic solvents. Fujiwara, Nakagawa, and Shimizu have reported that the benzene-induced high-field shifts for methoxyl protons of nitroanisole isomers are larger than that for either anisole or *o*-tolylanisole.1) Nakayama and Matsuo have studied the variation in the chemical shifts of methoxyl protons of *p*-dimethoxybenzene as the function of the benzene concentration in carbon tetrachloride.2) Formation of weak complexes between the methoxyl group and benzene has been suggested there, and the enthalpy for the complex formation has been estimated to be of the order of 1 kcal/mol. Recently, Bowie, Ronayne and Williams reported the results of a systematic survey of the benzene-induced high-field shifts for methoxy benzenes.3) A good correlation between the high-field shifts for methoxyl protons and the Hammett's σ_p-values for the substituents on the methoxybenzenes has been observed. From a variable-temperature study of the high-field shift in toluene solutions, thermodynamic parameters for the complex formation between the solute and the solvent have been obtained. At almost the same time as Bowie and his coworker's paper appeared, the present authors also reported the results of an independent study of benzene-induced high-field shifts for anisole and the related compounds.4) In the present paper, the authors wish to analyze the data, and propose a revised model for the solute-solvent interactions.

Experimental

Chemicals. Anisole, benzene, carbon tetrachloride and cyclohexane were purchased from Wako Pure Chemicals Industries Ltd. ; all the other compounds were synthesized by the authors. Samples were repeatedly purified either by vacuum distillation or by recrystallization until they became pure as justified by the gas chromatographs or the melting points.

Measurement of NMR Spectra. The spectra were obtained by the use of a Varian A-60 analytical NMR spectrometer. The concentration of the sample was 0.63 mol% in every cases. Tetramethylsilane was used as the internal standard.

Results and Discussion

The chemical shifts of the methoxyl protons of *p*-substituted anisoles in carbon tetrachloride,

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[*2] Previous paper of this series: Ref. 5.

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1) S. Fujiwara, N. Nakagawa and H. Shimizu, "Kōbunkaino Kakujiki-kyōmei (High Resolution NMR Spectroscopy)," Maruzen Co., Ltd., Tokyo (1962), pp. 113—114.

2) Y. Nakayama and T. Matsuo, *Kogyo Kagaku Zasshi (J. Chem. Soc. Japan, Ind. Chem. Sect.)*, **69**, 1925 (1966).

3) J. H. Bowie, J. Ronayne and D. H. Williams, *J. Chem. Soc. (B)*, **1966**, 785.

4) T. Yoshida, O. Higuchi and T. Matsuo, Abstract of the Papers Presented at the 5th Symposium NMR Spectroscopy, Sendai, September, 1966, p. 91.

Table 1. The chemical shifts of the methoxyl protons of *p*-substituted anisoles in various solvents*

No.	Substituent group	Solvent			Δ_1	Δ_2
		CCl_4	C_6H_{12}	C_6H_6		
1	Amino	220.5	216.0	203.0	17.5	4.5
2	*N*,*N*-Dimethylamino	220.5	217.0	206.0	14.5	3.5
3	Methoxyl	221.0	218.0	202.5	18.5	3.0
4	*t*-Butyl	224.0	220.0	204.5	19.5	4.0
5	Cyclohexyl	223.0	219.0	202.5	20.5	4.0
6	Methyl	223.0	219.0	201.0	22.0	4.0
7	Hydrogen (anisole)	225.0	220.0	200.0	25.0	5.0
8	Fluoro	226.0	220.0	192.5	33.5	6.0
9	Chloro	225.0	220.0	190.0	35.0	5.0
10	Bromo	226.0	220.0	189.0	37.0	6.0
11	Iodo	224.0	219.0	188.0	36.0	5.0
12	Acetyl	233.0	227.0	195.0	38.0	6.0
13	Cyano	230.0	224.0	182.5	47.5	6.0
14	Nitro	233.0	226.5	182.0	51.0	6.5
15	Methyl cyclohexyl ether	194.0	193.5	190.5	3.5	0.5

* Chemical shifts are in cps from internal TMS signal.

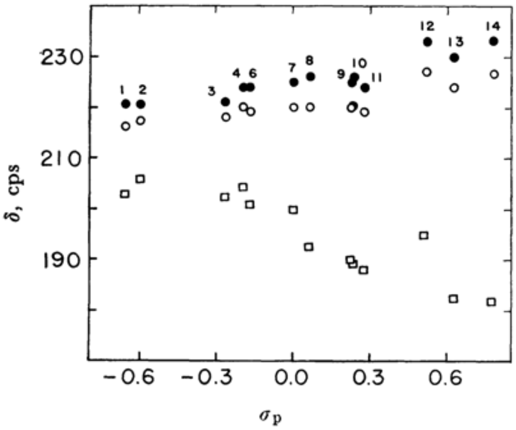

Fig. 1. The chemical shifts of methoxyl protons of *p*-substituted anisoles in carbon tetrachloride (●), in cyclohexane (○), and in benzene (□). The numbering of the compounds is the same as that in Table 1. The data are plotted against the σ_p-values as compiled by Hine (J. Hine, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York (1956), p. 72.)

cyclohexane, and in benzene are summarized in Table 1. The data for methyl cyclohexyl ether are also included in the table for the comparison. The values are also plotted in Fig. 1 against Hammett's σ_p-values of the substitutents. In either carbon tetrachloride or cyclohexane, the methoxyl proton signal of methoxybenzene with an electron-withdrawing group is found at slightly lower field than the case where the substituent is an electron-donating group. In the benzene solutions, on the other hand, the more electron-withdrawing the substituent is, the larger the shielding of a methoxyl proton becomes. Then the high-field shifts in the benzene solutions may be reasonably ascribed to the effect of this particular solvent. These benzene-induced high-field shifts Δ_1 ($\Delta_1 = \delta_{\text{in } CCl_4} - \delta_{\text{in } C_6H_6}$) are well related to the electronic natures of the substituents as may be seen in Fig. 2. It is also noticed that the Δ_1-value for methyl cyclohexyl ether is only one fifth of the smallest among the Δ_1-values for substituted anisoles. Then, the benzene ring linked to the methoxyl group is believed to play a very important role in the mechanism for the benzene-induced shift of the methoxyl proton signal.

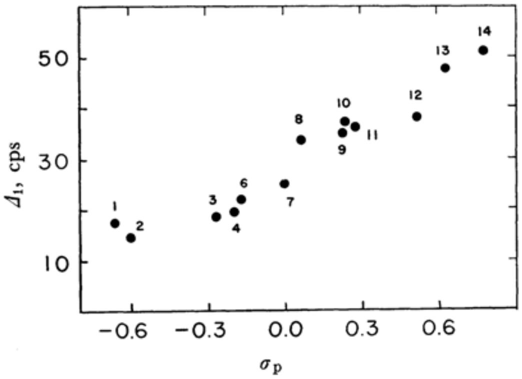

Fig. 2. The relationship between the benzene-induced high-field shift, Δ_1, and the Hammett's σ_p-values.

On the basis of the above observations, it is quite likely that one is tempted to believe the presence of a one-to-one complex between the solute and the solvent as has been proposed by many people (including the present authors themselves). In this paper, however, the authors are against the complex-formation theory. Williams and his associates have implied that the formation of a charge-transfer complex is the possible reason for the high-field shifts of solute proton signals.³⁾ According to the data for *p*-dimethoxybenzene in Ref. 2, however, the Δ_1-values for the ring proton and the methoxyl proton are -5 and $+19$ cps, respectively. The low-field shift for ring proton is hardly conceivable, if the planes of the benzene rings of the solute and the solvent are parallel each other as it is usual for π-π charge-transfer complexes. Since the Δ_1-value for the methoxyl proton of *p*-dimethoxybenzene is much larger than that for the ring proton, it appears that the methoxyl group itself takes a part in the solute-solvent interaction. One of the most reasonable speculations is that electric dipole moments are induced in the solvent benzene molecules around the methoxyl group which bears not only the permanent but also instantaneous electric-dipole moments. Then, one should expect the presence of van der Waals interactions between the polar functional group and the solvent benzene molecules as pointed out in the preceding paper of this series.⁵⁾ The interaction should become stronger with the increase in the polarizability of the functional group. Since the lone pair electrons of the ethereal oxygen are delocalized to benzene ring, the polarizability of the methoxyl group in aromatic ether is larger than that in non-aromatic ethers. The more electron-withdrawing the substituent at methoxybenzene is, the higher the polarizability of the methoxyl group becomes. Then one can give very reasonable explanations to the fact that Δ_1 for the methoxyl proton of methylcyclohexyl ether is considerably smaller than those for methoxybenzenes, and also to the fact that a linear relationship between the Δ_1-, and σ_p-values for methoxybenzenes is obtained. In relation to the above discussion, it should be pointed out also that the Δ_2-values ($\Delta_2 = \delta_{\text{in CCl}_4} - \delta_{\text{in cyclohexane}}$) increase with the Δ_1-values as it is seen in Table 1. The proton signals of many polar molecules have been known to show considerable low-field shifts upon variation of the solvent from cyclohexane to carbon tetrachloride.⁶⁾ The main reason has been also ascribed to the van der Waals interactions between the proton and the chlorine atoms of carbon tetrachloride.

The present authors have found also that the Δ_1-values for the proton ortho and meta to the methoxyl group of *p*-nitroanisole are 45.5 and 25.5 cps, respectively. The values indicate that the affinities between the phenyl groups of the solute and the solvent molecules should be also taken into consideration if the substituent on the methoxybenzene is a highly electronegative group. In this type of interaction, it is quite likely that a charge-transfer interaction is as important as the dipole-induced dipole interactions.

In a summary, it is suggested that the affinity between methoxybenzene and solvent benzene is due to the presence of two strongly polarizable groups, *i. e.* methoxyl and phenyl groups, in the solute molecule. The aromatic solvent molecules, such as benzene or toluene, are considered to cluster around the functional groups in the orientations suited to the particular modes of interactions. The benzene-induced shifts for the solute protons may be obtained by summing up the contributions from the magnetic anisotropies of the clustering benzene molecules with the appropriate weighting factors. The weighting factor may be decided by the strength (or the importance) of the interaction at each site. Up to the present time, the presence of a one-to-one complex has been customarily proposed on the basis of the fact that a plot of the benzene-induced shift for a proton against the mole fraction of benzene in the inert diluent shows a linear relationship. In the case of the orientational-clustering model here proposed, the linear relationship is expected to hold simply because the number of the relevant benzene molecules around the solute is proportional to the mole fraction of benzene.

The chemical shifts of methoxyl protons of *o*-alkylanisoles in various solvents are summarized in Table 2. The Δ_1-values for *o*-tolyl- and *o*-(*t*-butyl)-anisoles are much larger than those for the para isomers in Table 1. One of the possible explanations may be obtained by examining the conformation of the methoxyl group with respect to the benzene ring. Methoxybenzenes, in general, are considered to take several conformations as shown in Fig. 3.⁷⁾ The methoxyl group is twisted around the O–C axis so that the methyl group is located a little above or below the plane of the benzene ring. In the time scale of NMR spectroscopy, the methoxyl group should behave as if

TABLE 2. THE CHEMICAL SHIFTS OF THE METHOXYL PROTONS OF *o*-ALKYLANISOLES IN VARIOUS SOLVENTS*

Substituent	Solvent			Δ_1	Δ_2
	CCl_4	C_6H_{12}	C_6H_6		
Methyl	227.5	222.5	201.0	26.5	5.0
t-Butyl	229.0	224.0	200.5	28.5	5.0
2,6-Di-*t*-butyl	220.5	216.0	204.0	16.5	4.5

* Chemical shifts are in cps from internal TMS signal.

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5) Y. Ichikawa and T. Matsuo, This Bulletin, **40,** 2030 (1967).

6) T. Matsuo, *Can. J. Chem.,* **45**, 1829 (1967).

7) M. Aroney, R. J. W. Le Fevre and S. Chang, *J. Chem. Soc,* **1960**, 3173.

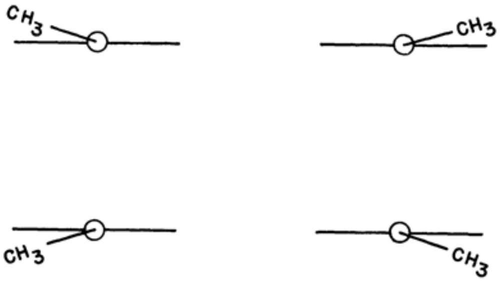

Fig. 3. Four effective conformations of anisole. The horizontal line indicates the plane of benzene ring, and the central circle represents the bond axis connecting the ethereal oxygen to the benzene ring.

it is rather freely rotating around the bond axis connected to the benzene ring. In the case of *o*-substituted anisole, the movement of the methoxyl group is considerably hindered by the substituent. Therefore, the methoxyl group will stay longer in the plane of benzene ring than the case without the substituent. Then the lone-pair electrons in *o*-alkylanisole is expected to be more delocalized than those in the para isomer. The increases in the Δ_1- and Δ_2-values for *o*-methyl- and *o*-(*t*-butyl)-anisoles are in good agreement with the expectation. The other possible explanation is that the deshielding effect may be reduced because the substituent interferes the approach of benzene molecule to certain positions around the methoxyl group. In the case of 2, 6-di-(*t*-butyl)-anisole, the methoxyl group is believed, analogously to 2, 4, 6-trimethylanisole,8) to be perpendicular to the plane of the benzene ring. As the consequence, the Δ_1-value is considerably small.

TABLE 3. THE CHEMICAL SHIFTS OF THE PROTONS IN THE ALKOXYL GROUP OF ALKYL *p*-TOLYL ETHERS IN CARBON TETRACHLORIDE AND IN BENZENE*

Alkoxyl group	Solvent		Δ_1
	CCl_4	C_6H_6	
Methoxyl group			
CH_3O	223.0	201.0	22.0
Ethoxyl group			
CH_2O	234.4	216.4	18.0
CH_3	81.2	67.0	14.2
Isopropoxyl group			
CHO	263.7	254.1	9.6
CH_3	76.3	68.1	8.2

* Chemical shifts are in cps from internal TMS signal.

In Table 3 are given the data for the protons of alkoxyl group of alkyl *p*-tolyl ethers. The Δ_1-values for the protons alpha to the ethereal oxygen rapidly decrease in the order of methoxyl, ethoxyl and isopropoxyl group. The trend may be explained as due to the increase of crowding around the relevant proton. It is also interesting that the Δ_1-values for the protons beta to the oxygen are only slightly less than those for the alpha protons. These data also are in favor of the orientational-clustering model described above.

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8) M. J. Aroney, M. G. Corfield and R. J. W. Le Fevre, *ibid.*, **1964**, 2954.