Diffusion of Disubstituted Aromatic Compounds in Ethanol

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Received: June 15, 1998; In Final Form: August 13, 1998

Limiting mutual diffusion coefficients of aromatic compounds containing two polar groups in ethanol have been measured at 298.2 K by using the chromatographic peak-broadening method. The data are compared with those of nonpolar pseudoplanar solutes, and the effects due to hydrogen bonding on diffusion together with the solvation numbers are evaluated. It is found that the effects and the solvation numbers are generally large and dependent on the nature and position of the polar groups attached. For all hetero-disubstituted aromatic isomers studied, the diffusivity trends are $p < m < o$, which are different from the previous results for the nonpolar isomers. The findings are discussed in terms of the chemical structure of the solutes as well as the intra- and intermolecular interactions.

Introduction

Diffusion, in particular mutual diffusion, plays an important role in many chemical processes and biological systems. Although mutual diffusion data of nonassociated molecules have been successfully interpreted[1−10] using the rough-hard-sphere (RHS) theory[11] in terms of the simple van der Waals picture,[12] our knowledge of the diffusion behavior of associated molecules in dense fluids is rudimentary at present. This may be due largely to the fact that effects of molecular association on diffusion are difficult to ascertain and quantify experimentally. Previously, Skipp and Tyrell[13] and Longsworth[14] have used the Stokes−Einstein numbers to show evidence of the effects of hydrogen bonding on diffusion in propane-1,2-diol and in water, respectively. However, the Stokes−Einstein equation applied is generally known to be invalid at the molecular scale, particularly when solute molecules are small in size as compared to solvent molecules.[15,16] Without taking into account the effects of solute shape on diffusion, Easteal and Woolf[17] have reported that solutes which can undergo solute−solvent interactions with solvents such as water and octamethylcyclotetrasiloxane are different from those which cannot. Although Akgerman et al.[18] have recently extracted from experimental data the combined effects of translational−rotational coupling and hydrogen bonding, they were unable to separate the effects of molecular association from the effects of coupling. Recently, we have developed a method[19] by comparing the data of associated and nonassociated solutes to ascertain the effects of solute−solvent association on diffusion. In other recent papers,[20,21] we have also been able to extract information concerning the relative strength of hydrogen bonding and have determined the solvation number for solutes diffusing in ethanol at 298.2 K by comparing the diffusion data of pseudoplanar nonassociated solutes and solutes capable of hydrogen bonding with ethanol at one site.

Compounds capable of hydrogen bonding with solvents at multisites are commonly found in drugs, biological molecules, and chemical reactants. Nonetheless, the molecular dynamics of such solutes and the nature of their hydrogen bonding are still relatively unclear. In this paper, we present the limiting mutual diffusion coefficients of some aromatic solutes containing two polar groups in ethanol at 298.2 K. All solutes studied are pseudoplanar in shape. The data are compared with those of similar nonassociated solutes as well as solutes containing one polar group reported here and in the literature. Our purpose for this work is to provide a deeper understanding of the nature and consequences of hydrogen bonding and to demonstrate how chemical structures, in particular one with intramolecular interactions, and the nature of polar substituents may affect the solute−solvent associations and also the molecular motions of doubly associated solutes in dense fluids.

Experimental Section

Limiting mutual diffusion coefficients were measured by using the chromatographic peak-broadening method, known also as the Taylor dispersion technique. The apparatus and procedures used in the experiment were similar to those described previously.[3,20] Briefly, a small 50 μL sample of a dilute solution was injected via an injection valve (Rheodyne, Model 7725) into a stream of solvent in a capillary diffusion tube which was an 85.7 m length of 304 stainless steel tube of 0.98 mm i.d. and 1.59 mm o.d. The capillary tubing was coiled in a 40 cm diameter circle and placed in a constant-temperature bath which was controlled to 298.15 ± 0.02 K. The solvent flow rate was adjusted so that the constant volume flow was only between 0.1 and 0.2 cm^3 min^{-1} to ensure laminar flow. In this study, the solvent was delivered by a Bio-Rad HPLC pump (Model 1350) with a flow rate precision of ±0.1%. At the end of the diffusion tube, the solute dispersion peak was detected with a Dynamax differential refractometer (Model RI-1) with output to a chart recorder. The diffusion coefficient was determined from the following equation:[22]

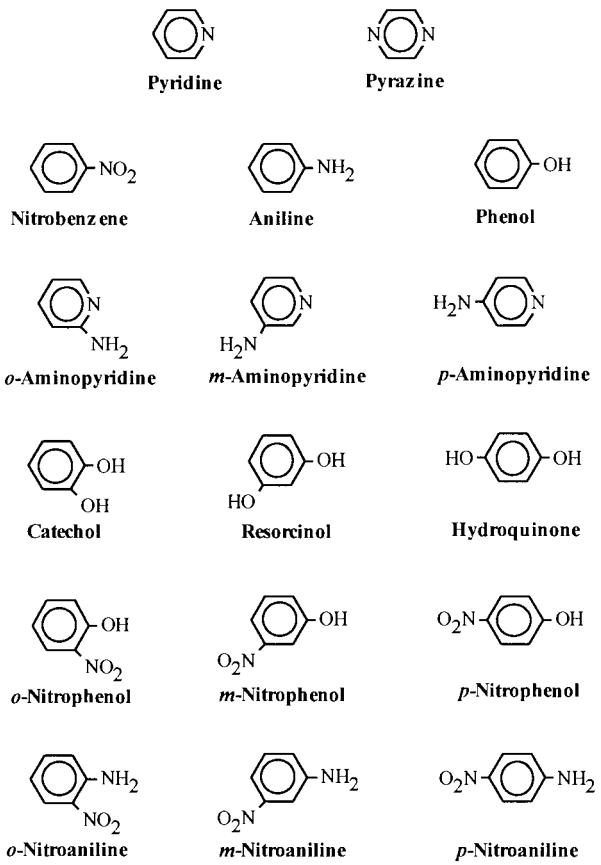
$$D_{12} = 0.2310R^2t_r/(W)^2 \quad (1)$$

where D_{12} is the mutual diffusion coefficient, R is the internal radius of the diffusion tube, t_r is the residue time of the solute in the tube, and W is the width at half-height of the eluted peak.

In this work, the solute mesitylene (98%, Riedel-de Haen) was purified by fractional distillation; 1,2,4-trichlorobenzene (99%+, Aldrich), biphenyl (99%+, Koch-Light), nitrobenzene (99%+, Aldrich), pyrazine (99%+, Aldrich), *o*-aminopyridine

10.1021/jp982615c CCC: $15.00
Published on Web 10/09/1998

CHART 1: Structures of the Polar Aromatic Solutes Studied



(99%+, Aldrich), *m*-aminopyridine (99%, Aldrich), *p*-aminopyridine (99%+, Aldrich), *o*-nitrophenol (99%+, E. Merck), *m*-nitrophenol (99%+, E. Merck), *p*-nitrophenol (99.5%+, E. Merck), catechol (99%+, Aldrich), resorcinol (99%+, Aldrich), hydroquinone (99%+, Aldrich), *o*-nitroaniline (99%+, Fluka), *m*-nitroaniline (99%+, E. Merck), and *p*-nitroaniline (99%+, Fluka) were used as received. All solutes are pseudoplanar aromatic compounds; the structures of the polar solutes studied are shown in Chart 1. The solvent ethanol (99.8%+, E. Merck) was degassed before use by ultrasonic bath. All data were measured at 298.15 ± 0.02 K. At least three measurements were made to obtain a diffusion coefficient, the average error being normally ±1%.

Results and Discussion

The limiting mutual diffusion coefficients (D_{12}) as determined by the chromatographic peak-broadening apparatus are summarized in Table 1. The uncertainty listed is the average absolute error. The reproducibility of data in this study is consistent with that reported in our previous works using the same technique.[19−21] To test our apparatus again, we have determined the diffusivities of mesitylene, 1,2,4-trichlorobenzene, and biphenyl in ethanol at 298.2 K. Our present $D_{12}/10^{-9}$ m^2 s^{-1} values of 1.32 ± 0.01, 1.30 ± 0.01, and 1.20 ± 0.01, respectively, for these solutes agree with the previous data[3] within experimental error.

For the nonassociated pseudoplanar solutes, there exists a linear relationship between the reciprocal of the diffusion coefficients ($1/D_{12}$) and the molecular volume (V) of the solutes. The linear regression line for the nonassociated aromatic compounds in ethanol at 298.2 K is displayed in Figure 1. The

TABLE 1: Limiting Mutual Diffusion Coefficients (D_{12}) of Aromatic Compounds in Ethanol at 298.2 K

	V^a/Å^3	$D_{12}/10^{-9}$ m^2 s^{-1}
nonassociated solutes		
benzene	81.1	1.79 ± 0.01[b]
chlorobenzene	97.2	1.61 ± 0.01[b]
toluene	97.6	1.62 ± 0.02[b]
ethylbenzene	113.8	1.45 ± 0.01[b]
naphthalene	125.4	1.32 ± 0.01[b]
1,2,4-trichlorobenzene	129.3	1.30 ± 0.01
propylbenzene	130.0	1.32 ± 0.02[b]
mesitylene	130.7	1.32 ± 0.01
biphenyl	152.4	1.20 ± 0.01
monosubstituted polar solutes		
pyridine	76.2	1.20 ± 0.02[c]
phenol	89.6	0.878 ± 0.009[d]
aniline	93.8	1.19 ± 0.01[c]
nitrobenzene	104.1	1.44 ± 0.01
disubstituted polar solutes		
pyrazine	71.3	1.54 ± 0.02
o-aminopyridine	88.9	0.922 ± 0.008
m-aminopyridine	88.9	0.778 ± 0.007
p-aminopyridine	88.9	0.696 ± 0.006
catechol	98.1	0.769 ± 0.008
resorcinol	98.1	0.585 ± 0.006
hydroquinone	98.1	0.595 ± 0.006
o-nitroaniline	116.8	1.05 ± 0.01
m-mitroaniline	116.8	0.945 ± 0.009
p-nitroaniline	116.8	0.846 ± 0.009
o-nitrophenol	112.6	1.27 ± 0.01
m-nitrophenol	112.6	0.762 ± 0.008
p-nitrophenol	112.6	0.744 ± 0.006

[a] The values are averages from refs 23−26. [b] From ref 3. [c] From ref 19. [d] From ref 21.

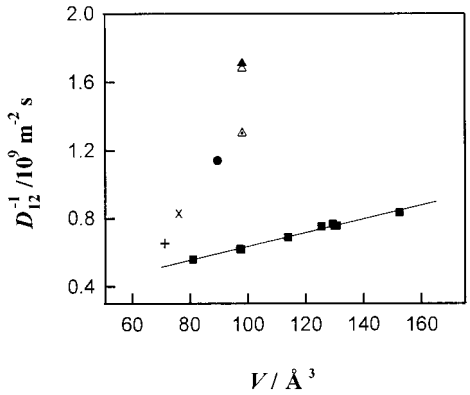


Figure 1. Variation of $1/D_{12}$ with molecular volume of homo-disubstituted polar solutes diffusing in ethanol at 298.2 K: (+) pyrazine, (△) hydroquinone, (▲) resorcinol, (◬) catechol, (■) nonassociated solutes, (×) pyridine, and (●) phenol.

straight line in the figure can be expressed by

$$(D_{12}^{-1}/10^9\ \mathrm{m}^{-2}\ \mathrm{s}) = 4.05 \times 10^{-3}(V/\text{Å}^3) + 0.230 \quad (2)$$

The correlation coefficient of eq 2 is 0.995, and this equation fits all data of the nonassociated solutes within 2.0%, the average deviation being only 0.89%. Also presented in this figure are the values for the homo-disubstitued polar solutes (i.e. pyrazine and the dihydroxybenzenes) as well as the monosubstituted pyridine and phenol. All $1/D_{12}$ data for the monosubstituted and homo-disubstituted aromatic compounds show positive deviation from the "nonassociated" line in Figure 1, indicating that the diffusivities of the polar solutes are retarded by solute−solvent interactions. For the homo-disubstituted solutes, the deviations vary from 25% in the case of pyrazine to a significantly large 168% for hydroquinone. In this work, the

TABLE 2: Effects of Hydrogen Bonding on Diffusion and Solvation Numbers (*n*) for Polar Aromatic Compounds in Ethanol at 298.2 K

	% effect	*n*
solutes with one polar group		
nitrobenzene	7 ± 2	0.2 ± 0.1
pyridine	55 ± 3	1.4 ± 0.1
aniline	38 ± 3	1.1 ± 0.1[a]
p-chloroaniline	35 ± 3	1.1 ± 0.1[a]
p-toluidine	33 ± 3	1.1 ± 0.1[a]
4-chloro-2-methylaniline	31 ± 3	1.1 ± 0.1[a]
1-naphthylamine	28 ± 3	1.0 ± 0.1[a]
phenol	92 ± 5	2.6 ± 0.2[a]
p-chlorophenol	84 ± 4	2.6 ± 0.2[a]
p-cresol	79 ± 4	2.5 ± 0.2[a]
1-naphthol	69 ± 4	2.5 ± 0.2[a]
2-naphthol	72 ± 4	2.6 ± 0.2[a]
biphenyl-2-ol	58 ± 3	2.4 ± 0.2[a]
solutes with two polar groups		
pyrazine	25 ± 3	0.6 ± 0.1
catechol	107 ± 5	3.3 ± 0.2
resorcinol	172 ± 6	5.2 ± 0.4
hydroquinone	168 ± 6	5.1 ± 0.4
o-aminopyridine	84 ± 4	2.4 ± 0.2
m-aminopyridine	118 ± 5	3.4 ± 0.2
p-aminopyridine	143 ± 5	4.1 ± 0.3
o-nitrophenol	15 ± 2	0.5 ± 0.1
m-nitrophenol	91 ± 5	3.0 ± 0.2
p-nitrophenol	96 ± 5	3.2 ± 0.2
o-nitroaniline	35 ± 3	1.2 ± 0.1
m-nitroaniline	50 ± 3	1.7 ± 0.1
p-nitroaniline	68 ± 4	2.3 ± 0.2

[a] From ref 21.

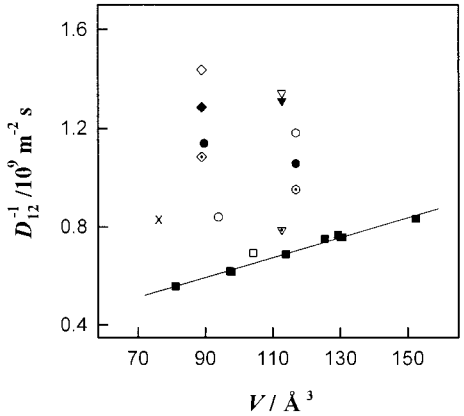


Figure 2. Variation of $1/D_{12}$ with molecular volume of hetero-disubstituted polar solutes diffusing in ethanol at 298.2 K: (◇) *p*-aminopyridine, (◆) *m*-aminopyridine, (dotted ◇) *o*-aminopyridine, (▽) *p*-nitrophenol, (▼) *m*-nitrophenol, (▽) *o*-nitrophenol, (⬡) *p*-nitroaniline, (⬢) *m*-nitroaniline, (dotted ⬡) *o*-nitroaniline, (×) pyridine, (●) phenol, (○) aniline, (□) nitrobenzene, and (■) nonassociated solutes.

decrease in D_{12} of the polar compounds cannot be attributed to solute−solute interactions because the solutions are very dilute and the solvent is polar. The effects of hydrogen bonding on diffusion, as determined from the relative deviation of each polar solute's $1/D_{12}$ value from the nonassociated line, are given together with estimated uncertainties in Table 2. It is an interesting point to notice that the effect for pyrazine with two polar groups is smaller than that of pyridine with only one similar polar substituent.

Figure 2 shows the variation of $1/D_{12}$ with molecular volume for solutes containing two different polar groups. Also given in this figure are the data of nitrobenzene, aniline, pyridine, phenols, and the nonassociated solutes for comparisons. For the hetero-disubstituted polar solutes, the effects of solute−solvent association vary from 15% for *o*-nitrophenol to 143% in the case of *p*-aminopyridine. All other values are presented in Table 2. It is noteworthy that the diffusivity (D_{12}) trends for the hetero-disubstituted polar isomers are $p < m < o$, which are just the opposite of those observed for the nonassociated disubstituted benzenes such as xylenes, chlorotoluene, and dichlorobenzenes.[2] Previously, the differences in shape of the nonassociated pseudoplanar molecules were found[2] to result in slightly greater (∼6%) diffusivities of the *p*-isomers than those of the *m*-isomers, which in turn diffuse about 3% faster than the *o*-isomers in ethanol at 298.2 K. In both Figure 1 and Figure 2, however, the closer $1/D_{12}$ values of the *o*-isomers to the nonassociated line clearly indicate that intramolecular hydrogen bonding occurs to weaken the solute−solvent associations in these isomers. The much closer $1/D_{12}$ value of *o*-nitrophenol than those of other *o*-isomers to the line can be attributed at least in part to the fact that a six-membered ring is formed by intramolecular hydrogen bonding in *o*-nitrophenol (**I**), whereas no such formation is possible for catechol and *o*-aminopyridine. It is generally known that formation of a six-membered ring can provide additional stability to a molecule. Although six-membered ring can also be formed in *o*-nitroaniline (**II**), one of the two hydrogens in the amine group is nevertheless still free for intermolecular hydrogen bonding.

I **II**

It is of interest to compare the solvation numbers for the solutes studied. These numbers can be found by considering in the diffusion process that a polar solute is diffusing to a certain extent as a solute−solvent complex instead of only as a monomer. The average size increase of a polar solute due to association can be evaluated from the deviation of its $1/D_{12}$ value from the nonassociated line at the same monomeric solute volume. This is equivalent to the increase in the van der Waals volume that produces such an amount of $1/D_{12}$ deviation on the nonassociated line. The solvation number, which is the average number of ethanol molecules associated with a solute in this study, can be calculated by dividing the solute volume increased by the van der Waals volume of the ethanol monomer (i.e. 50.99 Å^3). The solvation numbers thus determined for the polar solutes, together with their estimated errors, are given also in Table 2. For large values of solvation number that required extrapolation of the nonassociated line in the calculation, the errors were estimated greater in this work to account for any uncertainties in the extrapolation. It is unfortunate that solubility of nonpolar aromatic compounds in ethanol does not permit our measurements to include more data of larger nonassociated solutes. Nonetheless, we are confident that the extrapolation is applicable in the range of molecules studied, as it has been shown[3] that the linear relationship exists up to 320 Å^3 for pseudospherical solutes diffusing in acetone, ethanol, and *n*-tetradecane at 298.2 K.

Solvation number (*n*) as determined above can be considered as a measure of the extent of solute−solvent association and is proportional to the effect of intermolecular interactions on diffusion. Comparisons between the solvation numbers of the *p*-isomers here are simple and straightforward, as the molecules are similar in shape and the substituents in these isomers are separated far enough such that the effect of intramolecular hydrogen bonding can be neglected. It should be noted that,

for aromatic compounds containing one polar group, the solvation number is dependent only on the type of polar group attached.[20,21] From Table 2, the average *n* values for the phenols and the aromatic amines in ethanol at 298.2 K are 2.5 ± 0.2 and 1.1 ± 0.1, respectively. For the doubly associated *p*-isomers in this study, however, the values of solvation number as shown in Table 2 are not necessary additive (i.e., they are not necessarily contributed from each polar group with the following: −OH, 2.5; $-NH_2$, 1.1; $-NO_2$, 0.2; nitrogen in pyridines, 1.4). The nitrogen in pyridines and the nitro group in aromatic compounds are well-known for their electron-withdrawing capability, whereas $-NH_2$ is recognized as electron-donating.[27] In general, −OH can also be considered as an electron-donating group, although it is a relatively weak one.[27] The lower *n* value of pyrazine than the "additive" value may be due to the same but opposite electron-withdrawing effects by both nitrogen atoms in pyrazine, which renders these atoms less negatively charged as compared to the nitrogen atom in pyridine. Thus, it is not surprising to find that the effect of hydrogen bonding on diffusion as well as the solvation number of pyrazine are even smaller than those of pyridine. Also, pyrazine is capable of associating with an average of 0.6 ethanol molecule, even though the symmetrical molecule has no dipole moment. On the other hand, nitrobenzene with a large dipole moment of 4.22 D[28] shows very little association with the solvent. This indicates that the overall dipole moment of a molecule is unimportant as compared to the existence and nature of local polar groups in determining the degree of solute−solvent association. Due to the weak electron-donating nature of −OH, it is remarkable that the values of solvation number for both resorcinol and hydroquinone are nearly additive. For *p*-aminopyridine, however, the higher than additive value of *n* is probably because the presence of both electron-donating ($-NH_2$) and electron-withdrawing (=N−) groups in the ring is such to reinforce the charge separation in the molecule, making the nitrogen more negative and the protons in $-NH_2$ more positive for strong hydrogen bonding. Similar reasons can be given to account for the *n* values of *p*-nitroaniline and *p*-nitrophenol, although the latter value is not much higher than the additive value since $-NO_2$ is only weakly associated with ethanol and −OH is a weak electron-donating group. Generally, both electron-donating and electron-withdrawing effects have greater impact on the *ortho* and *para* positions than on the *meta* position.[27] Consequently, the reinforcement effect for the hetero-disubstituted compounds mentioned above is comparatively weaker for the *m*-isomers than for the *p*-isomers. As shown in Table 2 and Figure 2, the solvation numbers as well as the $1/D_{12}$ values of the *m*-isomers are indeed lower than those of the *p*-counterparts.

Conclusion

Comparisons between diffusivities of associated and nonassociated solutes can yield useful information on solute−solvent interactions and on the molecular dynamics of associated molecules. The diffusion behavior and relative strength of hydrogen bonding of doubly associated molecules are found here to be more complicated than those of the monoassociated counterparts. In this study, the diffusivities and the solvation numbers of the former are dependent not only on the type of polar groups attached but also on the chemical structure and the cooperative electronic effects of the substituents present. The evidence herein also suggests that coupling between intra- and intermolecular interactions is important in determining the molecular motions of molecules. More works in connection with this study are in progress.

Acknowledgment. The authors wish to thank J. B. Bao and O. K. Kong for their technical assistance. This work was supported in part by the Hong Kong Research Grants Council under Grants No. 88/94P and No. 29/96P.

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