

Experimental study of hydrogen bonding by mutual diffusion

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The use of diffusion data to determine the relative strength of hydrogen bonding and the number of solvent molecules associated with a pseudo-planar solute is demonstrated; the solvation numbers are found to be approximately equal for solutes containing the same polar group in ethanol at 298.2 K.

Hydrogen bonding is one of the most common and important molecular phenomena which has received intense attention from the earliest days of the subject. Although experimental and theoretical publications on hydrogen bonding abound,¹ however, our knowledge of this phenomenon in liquids is still in its relative infancy. In particular, the nature and consequences of solute–solvent interactions involving hydrogen bonding in very dilute solutions are not well known. This may be due largely to the fact that hydrogen bonding in very dilute solutions is difficult to study by current experimental methods. Nonetheless, the lack of such information may hinder further understanding of the behaviour of many drugs and biological molecules.

Previously, we have found² that a linear relationship exists between the reciprocal of the limiting mutual diffusion coefficients ($1/D_{12}$) and the molecular volume (V) of non-associated solutes with similar shape. In a preliminary report,³ we have recently shown evidence of the effect of strong solute–solvent interactions on diffusion and also that the effect can be quantified. This has prompted us to measure more diffusion data, with the primary aim to understand the transport properties of associated molecules. Also, we believe that diffusion measurements can be alternatively designed to probe information about hydrogen bonding. Here, we report the limiting mutual diffusion coefficients of aromatic solutes containing one polar functional group capable of hydrogen bonding in ethanol at 298.2 K. All solutes studied are pseudo-planar in shape. The purpose of this work is to demonstrate how hydrogen bonding in dilute solution can be studied by diffusion data.

Mutual diffusion coefficients at trace concentrations were measured by the Taylor dispersion method, known also as the chromatographic peak-broadening technique. The apparatus and procedures used in the experiment were the same as those described before.^{2,3} In this work, the solvent ethanol (99.9%+, E. Merck) was filtered before use with 20 μm stainless-steel HPLC solvent filter. The solute mesitylene (98%, Riedel-de Haen) was purified by fractional distillation; aniline (99.5%+, Aldrich), *p*-chloroaniline (99%+, Fluka), *p*-toluidine (99.9%, Aldrich), 4-chloro-2-methylaniline (99%, Aldrich), 1-naphthylamine (99%+, E. Merck), phenol (99.5%, E. Merck), *p*-chlorophenol (99.5%+, BDH), *p*-cresol (99%+, Fluka), 1-naphthol (99%+, Aldrich), 2-naphthol (99%, Aldrich), biphenyl-2-ol (99%+, E. Merck), anisole (99%+, E. Merck), *p*-chloroanisole (98%+, Fluka), *p*-methylanisole (99%+, E. Merck), 2-methoxynaphthalene (99%, Aldrich), acetophenone (99%, Aldrich), propiophenone (99%+, E. Merck), and 2-acetylnaphthalene (99%+, E. Merck) were used as received. All data were measured at 298.15 ± 0.02 K.

The limiting mutual diffusion coefficients as determined by the Taylor dispersion method are summarized in Table 1. These values are the averages resulting from three or more diffusion

measurements. The uncertainty listed is the average absolute error. The reproducibility of data here is consistent with those reported in our previous works using the same technique.^{2–5} Also shown in the table are values of the van der Waals volume of the solute monomers, which are calculated from group increments given in the literature.^{6–9} When $1/D_{12}$ was plotted against V of the non-associated pseudo-planar solutes, a linear relationship was obtained. The linear regression line is shown in Fig. 1. Also presented in this figure are values for other solutes given in Table 1. Except for aromatic ethers, all $1/D_{12}$ data of these solutes deviate positively from the ‘non-associated’ line. The deviations indicate that the diffusivities of the solutes are retarded by the volume increase due to hydrogen bonding with the solvent molecules. In this study, the increase in solute size cannot be attributed to solute–solvent interaction because the solutions are very dilute and the solvent ethanol is polar. In fact, experimental evidence has already shown that aniline molecules are not even self-associated in non-polar *n*-tetradecane.³ It is

Table 1 Limiting mutual diffusion coefficients (D_{12}) of aromatic compounds in ethanol at 298.2 K.

	$V/\text{\AA}^3$	$10^9 D_{12}/\text{m}^2 \text{s}^{-1}$
Non-associated 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	1.28 ± 0.01^b
Propylbenzene	130.0	1.32 ± 0.02^b
Mesitylene	130.7	1.33 ± 0.02
Biphenyl	152.4	1.19 ± 0.01^b
Phenols		
Phenol	89.6	0.878 ± 0.009
<i>p</i> -Chlorophenol	105.7	0.827 ± 0.009
<i>p</i> -Cresol	106.2	0.845 ± 0.007
1-Naphthol	133.9	0.765 ± 0.008
2-Naphthol	133.9	0.752 ± 0.008
Biphenyl-2-ol	160.9	0.716 ± 0.007
Aromatic amines		
Aniline	93.8	1.19 ± 0.01^c
<i>p</i> -Chloroaniline	109.9	1.10 ± 0.01
<i>p</i> -Toluidine	110.4	1.11 ± 0.01
4-Chloro-2-methylaniline	126.4	1.03 ± 0.01
1-Naphthylamine	138.1	0.991 ± 0.008
Phenones		
Acetophenone	117.0	1.29 ± 0.01
Propiophenone	133.2	1.22 ± 0.01
2-Acetylnaphthalene	161.3	1.04 ± 0.01
Aromatic ethers		
Anisole	106.2	1.54 ± 0.01
<i>p</i> -Chloroanisole	122.3	1.43 ± 0.02
<i>p</i> -Methylanisole	122.7	1.44 ± 0.01
2-Methoxynaphthalene	150.5	1.20 ± 0.01

^a van der Waals volumes are averages from refs. 6–9. ^b From ref. 2. ^c From ref. 3.

interesting that linear relationships also exist between $1/D_{12}$ and V of all pseudo-planar solutes containing the same polar group. The regression lines for phenols, aromatic amines and phenones are shown also in Fig. 1. Remarkably, the slopes for all straight lines in the figure are nearly the same. From Fig. 1, it can be seen that aromatic ethers behave practically as non-associated solutes, and that the strengths of polar groups associated with the solvent through hydrogen bonding decrease in the sequence $-\text{OH} > -\text{NH}_2 > -\text{C}(\text{O})-$.

The increase in size of a polar solute after association can be evaluated from the deviation of its $1/D_{12}$ value from the 'non-associated' line at the same monomeric solute volume in Fig. 1. This is equivalent to the increase in the van der Waals volume that produces such amount of $1/D_{12}$ deviation on the 'non-associated' line. That the linear regression lines of solutes containing $-\text{OH}$, $-\text{NH}_2$ and $-\text{C}(\text{O})-$ groups are nearly parallel with those of the non-associated solutes indicates that the increased sizes are approximately equal for all solutes containing the same polar group. The average number of ethanol molecules associated with a solute can be determined subsequently from the solute volume increased and the van der Waals volume of the ethanol monomer. The solvation numbers thus calculated for phenols, aromatic amines and phenones are given

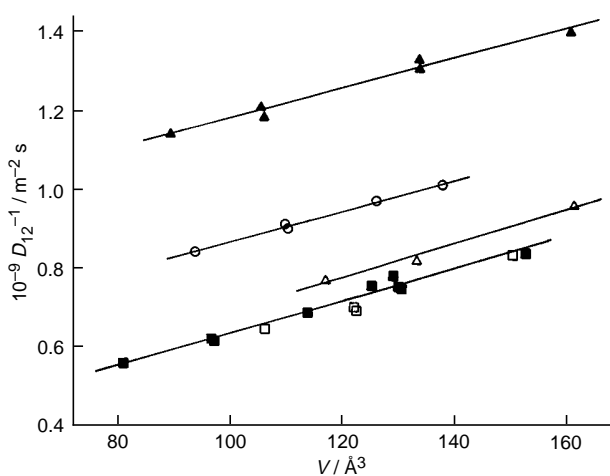


Fig. 1 Variation of $1/D_{12}$ with molecular volume of solutes diffusing in ethanol at 298.2 K: (■) non-associated solutes, (□) aromatic ethers, (△) phenones, (○) aromatic amines and (▲) phenols

Table 2 Solvation numbers (n) for solutes in ethanol

	n
Phenols	
Phenol	2.6 ± 0.2
<i>p</i> -Chlorophenol	2.6 ± 0.2
<i>p</i> -Cresol	2.5 ± 0.2
1-Naphthol	2.5 ± 0.2
2-Naphthol	2.6 ± 0.2
Biphenyl-2-ol	2.4 ± 0.2
Aromatic amines	
Aniline	1.1 ± 0.1
<i>p</i> -Chloroaniline	1.1 ± 0.1
<i>p</i> -Toluidine	1.1 ± 0.1
4-Chloro-2-methylaniline	1.1 ± 0.1
1-Naphthylamine	1.0 ± 0.1
Phenones	
Acetophenone	0.3 ± 0.1
Propiophenone	0.2 ± 0.1
2-Acetylnaphthalene	0.3 ± 0.1

in Table 2. From this table, it is clear that all phenols on average diffuse together with *ca.* 2.5 ethanol molecules and all aromatic amines with *ca.* one. Phenones are nonetheless only weakly associated with ethanol. The fact that there is little association between phenones (also aromatic ethers) and ethanol is not surprising as the solutes have to compete with other ethanol molecules for forming hydrogen bonds with the solvent. Due to steric hindrance and lack of a proton contribution to form hydrogen bonds, phenones and aromatic ethers are expected to be less competitive in this respect. It should be noted that ethanol is self-associated with an association number of 2.8 in the liquid state at 298.2 K.^{10,11} Although solvation numbers can also be calculated¹² from the well known Stokes–Einstein equation, however, the applicability of this equation is not valid for non-spherical solute molecules and for solute molecules small in size compared to the solvent molecules.^{13–16} The effects of shape on mutual diffusion have been shown² to be as large as 26% in the case of *n*-tetradecane as solvent at 298.2 K.

It is interesting that the diffusion coefficients of *p*-chloroaniline (*p*-ClC₆H₄NH₂) and *p*-toluidine (*p*-MeC₆H₄NH₂) are approximately equal. These two solutes are of similar size and shape. The close resemblance in size between a chloride group and a methyl group has already been discussed.¹⁷ The two solutes are nevertheless different in molecular mass by 19%. Similar results are observed for *p*-chlorophenol (*p*-ClC₆H₄OH) and *p*-cresol (*p*-MeC₆H₄OH) as well as for *p*-chloroanisole (*p*-ClC₆H₄OMe) and *p*-methylanisole (*p*-MeC₆H₄OMe). The present data thus further indicate that solvation numbers are insensitive to the mass as well as the size of the monomeric solutes but dependent only on the type of polar group attached.

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References

- For reviews, see: G. A. Jeffrey and W. Saenger, *Hydrogen Bonding in Biological Structures*, Springer-Verlag, Berlin, 1991; *Modeling the Hydrogen Bond*, ed. D. A. Smith, *ACS Symp. Ser.*, 569, American Chemical Society, Washington, DC, 1994; *The Hydrogen Bond*, ed. P. Schuster, North-Holland Publishing Co., Amsterdam, 1976.
- T. C. Chan and M. L. Chan, *J. Chem. Soc., Faraday Trans.*, 1992, **88**, 2371; 1993, **89**, 867.
- M. L. Chan and T. C. Chan, *J. Phys. Chem.*, 1995, **99**, 5765.
- T. C. Chan, *J. Chem. Phys.*, 1984, **80**, 5862.
- T. C. Chan, *J. Chem. Phys.*, 1983, **79**, 3591.
- A. Bondi, *J. Phys. Chem.*, 1964, **68**, 441.
- J. T. Edward, *Chem. Ind. (London)*, 1956, 774.
- A. I. Kitaigorodskii, *Organic Chemical Crystallography*, Consultants Bureau, New York, 1961.
- A. E. Luzkii, *Russ. J. Phys. Chem.*, 1954, **28**, 204.
- A. H. Narten and A. Habenschuss, *J. Chem. Phys.*, 1984, **80**, 3387.
- C. K. J. Sun and S. H. Chen, *AIChE J.*, 1986, **32**, 1367.
- L. G. Longworth, *J. Phys. Chem.*, 1963, **67**, 689.
- D. F. Evans, T. C. Chan and B. C. Lamartine, *J. Am. Chem. Soc.*, 1977, **99**, 6492.
- D. F. Evans, T. Tominaga and T. C. Chan, *J. Solution Chem.*, 1979, **8**, 461.
- D. F. Evans, T. Tominaga and H. T. Davis, *J. Chem. Phys.*, 1981, **74**, 1298.
- S. H. Chen, H. T. Davis and D. F. Evans, *J. Chem. Phys.*, 1982, **77**, 2540.
- S. J. Bertucci and W. H. Flygare, *J. Chem. Phys.*, 1975, **63**, 1.

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