Zeitschrift für Physikalische Chemie, Bd. 196, S. 73–84 (1996)

Evidence by NMR of Temperature-dependent Solvent Electric Field Effects on Proton Transfer and Hydrogen Bond Geometries

By Nicolai S. Golubev, Gleb S. Denisov, Sergei N. Smirnov,
Dimitri N. Shchepkin

Institute of Physics, St. Petersburg State University, 198904 St. Petersburg,
Russian Federation

and Hans-Heinrich Limbach

Institut für Organische Chemie, Takustr. 3, Freie Universität Berlin, D-14195 Berlin,
Germany

Dedicated to Prof. Dr. H. Baumgärtel on the occasion of his 60th birthday

(Received January 1, 1996; accepted February 24, 1996)

NMR / Proton transfer / Hydrogen bonding / Solvent effects

The ^1H NMR spectra of hydrogen bonded complexes AHB of the acids AH≡HCl, acetic acid, and chloroacetic acid with pyridine-^{15}N as base B dissolved in 2:1 mixtures of $CDClF_2$ with CDF_3 were measured in the temperature range between 100 K and 150 K. Under these conditions, the regime of slow proton and hydrogen bond exchange is reached where the intrinsic concentration independent NMR parameters of AHB are observed. The chemical shifts δ of the hydrogen bonded protons and their scalar coupling constants $^1J_{^1H-^{15}N}$ with the ^{15}N nucleus of B provide information on the hydrogen bond geometry and its temperature dependence. When the temperature is decreased the following phenomena are observed: (i) the average proton positions are shifted away from A towards B; (ii) the molecular complex A-H···B with AH≡acetic acid contracts; (iii) the zwitterionic complex $A^-\cdots H\text{-}B^+$ with AH≡HCl lengthens, (iv) the chloroacetic acid-pyridine complex A-H···B firstly contracts until the quasisymmetric structure $A^{\delta-}\cdots H\cdots B^{\delta+}$ is reached and then the zwitterionic form $A^-\cdots H\text{-}B^+$ in which the heavy atom distance A...B increases again. These findings are interpreted in terms of electric dipole moments induced in AHB by the electric field arising from the solvent dipoles. Due to solvent ordering around AHB, this field increases at low temperature. In A-H···B, the dipole moment is increased mainly by charge transfer from B to AH because of the large polarizability of the hydrogen bond, and is associated with a contraction of the latter. By contrast, in $A^-\cdots H\text{-}B^+$ the dipole moment increase arises from a lengthening of the hydrogen bond. As a result, the electric field created at the solute by the solvent dipoles is the driving force for the hydrogen bond contraction assisted proton transfer. The acidity of the proton donor decreases with increasing strength of the electric field required for the proton transfer to occur.

Die ${}^1H$ NMR Spektren von wasserstoffbrückengebundenen Komplexen des Typs AHB (AH$\equiv$HCl, CH_3COOH, CCl_3COOH, B$\equiv$Pyridin-${}^{15}N$) wurden im Temperaturintervall von 100 K bis 150 K unter Verwendung von $CDClF_2/CDF_3$ (2:1) als Lösungsmittel vermessen. Unter diesen Bedingungen wird der Bereich des langsamen Protonen- und Wasserstoffbrückenaustauschs erreicht, in dem die intrinsischen NMR Parameter von AHB beobachtet werden. Die chemischen Verschiebungen δ der waserstoffbrückengebundenen Protonen und die zugehörigen skalaren Kopplungskonstanten ${}^1J_{{}^1H-{}^{15}N}$ ergeben Informationen über die Wasserstoffbrückengeometrien und deren Temperaturabhängigkeit. Bei Temperaturerniedrigung werden die folgenden Phänomene beoachtet. (i) Die mittleren Protonenlagen verschieben sich von A nach B. (ii) Der molekulare Komplex $A\text{-}H\cdots B$ (A$\equiv$$CH_3COOH$) kontrahiert. (iii) Der zwitterionische Komplex $A^-\cdots H\text{-}B^+$ (AH$\equiv$HCl) expandiert. (iv) Der Chloressigsäure-Pyridin Komplex $A\text{-}H\cdots B$ kontrahiert zunächst bis zur quasisymmetrischen Struktur $A^{\delta-}\cdots H\cdots B^{\delta+}$ und expandiert dann in der zwitterionic form $A^-\cdots H-B^+$. Diese Befunde werden mit einer Erhöhung der lokalen elektrischen Feldstärke bei Temperaturerniedrigung in Verbindung gebracht, die durch die Orientierung der Solvensdipole verursacht ist. Dieser Umstand führt zur Erhöhung des Dipolmomentes von AHB. Bei einem molekularen Komplex $A\text{-}H\cdots B$ ist diese Erhöhung durch Ladungstransfer von B nach AH verursacht, eine Folge der hohen Polarisierbarkeit der Wasserstoffbrücke, und führt zu deren Kontraktion und zur Verschiebung des Protons in Richtung B. Im Gegensatz dazu wird die Erhöhung des Dipolmomentes in $A^-\cdots H\text{-}B^+$ durch eine Aufweitung der Wasserstoffbrücke und die vollständige Protonenübertragung erreicht. Damit ist das durch die Lösungsmitteldipole erzeugte elektrische Feld die treibende Kraft für den Protonentransfer, der durch die Wasserstoffbrückenkontraktion unterstützt wird. Die für den Protonentransfer erforderliche Feldstärke ist damit ein Maß für die Azidität des Protonendonors.

1. Introduction

${}^1H$ NMR spectroscopy is a well established tool for studying hydrogen bond phenomena in the liquid state [1–6]. This is due to the circumstance that the formation of a hydrogen bond and its contraction is associated with a shift of the hydrogen bond proton signal to low magnetic field. Unfortunately, because of the particular timescale, the NMR signals normally correspond to an average over many fast exchanging hydrogen bonded sites and solvent configurations, thus complicating the determination of intrinsic NMR parameters of individual hydrogen bonded complexes. Substantial progress, however, has been achieved in recent years [7–10] by using liquefied deuterated gas mixtures as NMR solvents which are fluid enough to allow high resolution NMR measurements down to 100 K where the regime of slow hydrogen bond exchange can be reached for certain hydrogen bonded systems. The NMR spectral parameters are then characteristic for the individual hydrogen bonded sites although they still present averages over fast exchanging solvent configurations.

Using this approach, several of us have recently shown that carboxylic acids form at 110 K slowly interconverting 1:1, 2:1 and 3:1 complexes with pyridine in which the average proton positions are gradually displaced from oxygen to nitrogen as the complex size increases [9]. Moreover, by observing hydrogen/deuterium isotope effects on the ^{1}H, ^{2}H, and ^{15}N chemical shifts of the nuclei involved in the hydrogen bonds information about their geometry could be obtained as a function of the proton locations [10]. As the proton donating power of the acid was increased and the proton displaced towards the base the hydrogen bonds firstly contract and then lengthen again after the proton has crossed the hydrogen bond center.

In this paper we report the results of an NMR study of the intrinsic temperature dependent chemical shifts and coupling constants $^1J_{^1\mathrm{H}\text{-}^{15}\mathrm{N}}$ of the hydrogen bonded protons in 1:1 complexes of a variety of acids AH with pyridine-^{15}N (B) dissolved in a 2:1 mixture of $CDClF_2/ClCDF_3$. The main result of this study shows that temperature dependent solute-solvent interactions constitute driving forces for hydrogen bond contraction assisted proton transfer, similar to chemical structure variations.

The paper is organized as follows. After a short experimental part the results are presented and then discussed, in particular, the implications for the mechanism of proton transfer in the liquid state.

2. Experimental section

All experiments reported in this paper were performed on a 500 MHz Bruker NMR spectrometer AMX 500. The deuterated freon solvent mixture $CDClF_2/CDF_3$ (2:1) was synthesized from $CDCl_3$ as described previously [7–10]; the NMR samples were prepared using well-established vacuum techniques [6].

3. Results

In Fig. 1, the low-field parts of the low-temperature NMR spectra of acetic acid, chloroacetic acid and HCl dissolved in the presence of a small excess of pyridine-^{15}N in the solvent mixture $CDClF_2/CDF_3$ (2:1) are shown as a function of temperature. Under these experimental conditions the regime of slow hydrogen bond exchange is realized and the signals observed refer to the intrinsic 1:1 complexes $\mathrm{AHB} \equiv \{\mathrm{A\text{-}H \cdots B} \leftrightarrow \mathrm{A}^{\delta-} \cdots \mathrm{H} \cdots \mathrm{B}^{\delta+} \leftrightarrow \mathrm{A}^- \cdots \mathrm{H\text{-}B}^+\}$. This is corroborated by the finding that the chemical shifts are independent of concentration in the range between 10^{-4} and $3 \cdot 10^{-2}$ M. All NMR parameters determined are listed in Table 1.

In principle, the proton signals are split into doublets by scalar coupling with the ^{15}N nucleus of pyridine-^{15}N, characterized by the coupling constant aaaa$^1J_{^1\mathrm{H}\text{-}^{15}\mathrm{N}}$. This constant is smaller than the signal line-width in the case of acetic acid (Fig. 1a) indicating the presence of a molecular 1:1 complex $\mathrm{AHB} \equiv \{\mathrm{A\text{-}H \cdots B}\}$. By contrast, in the HCl/pyridine case (Fig. 1c) a zwitterionic structure $\mathrm{A}^- \cdots \mathrm{H\text{-}B}^+$ is adopted, characterized by $^1J_{^1\mathrm{H}\text{-}^{15}\mathrm{N}}$ = 87 Hz, which is of the order of the value of free solvated pyridinium chloride

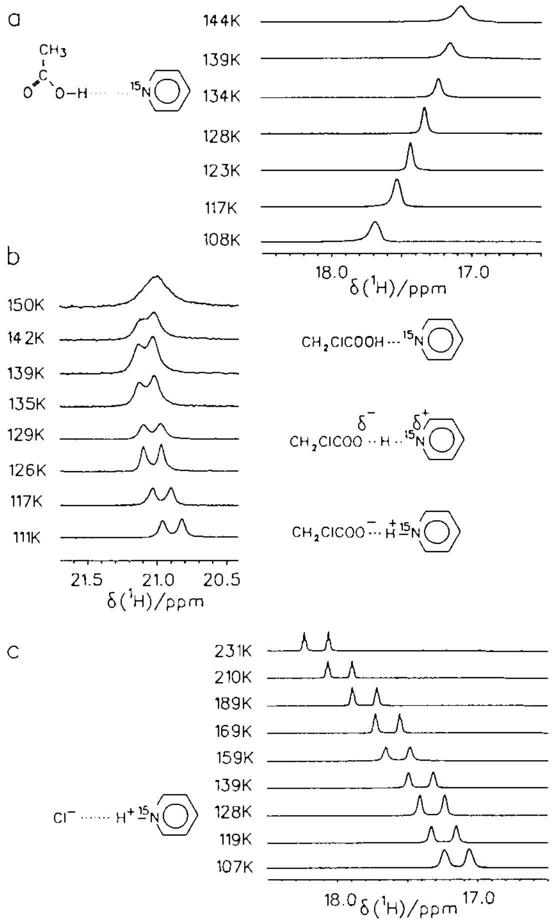

Fig. 1. Temperature dependent 500 MHz NMR signals of the hydrogen bond protons in 1:1 complexes of pyridine-^{15}N with (a) acetic acid (0.2 M) and (b) chloroacetic acid (0.21 M) and (c) HCl (0.2 M) dissolved in a 2:1 mixture of $CDClF_2/CDF_3$. The samples always contained a 10% excess of pyridine-^{15}N.

dissolved in water [11]. In the case of the chloroacetic acid-pyridine complex (Fig. 1b) a substantially smaller coupling constant of $^1J_{^1H^{15}N} \approx 65$ Hz is observed at 111 K, which decreases with increasing temperature. Above 140 K line broadening occurs leading to a loss of the coupling due to hydrogen bond and proton exchange.

The intrinsic chemical shifts of the hydrogen bond protons of the three complexes show interesting dependencies with temperature. In the case of the acetic acid-pyridine complex the signal is displaced from 18 ppm to

Table 1. Chemical shifts δ and coupling constants $^1J_{^1\mathrm{H}\text{-}^{15}\mathrm{N}}$ of the H-bond proton in 1 : 1 complexes of acids with pyridine-^{15}N dissolved in the solvent mixture $CDClF_2/CDF_3$ (2 : 1) as a function of temperature T.

AH	T/K	δ/ppm	$^1J_{^1\mathrm{H}\text{-}^{15}\mathrm{N}}$/Hz
HCl	107.3	17.146	88.6
	117.7	17.241	88.5
	128.3	17.322	88.3
	138.9	17.404	88.1
	159.5	17.569	87.6
	169.2	17.643	87.4
	189.5	17.808	86.9
	210.1	17.986	86.3
	231.1	18.155	85.8
	250.8	18.317	84.9
Chloroacetic acid	110.5	20.893	68.9
	116.6	20.967	67.3
	126.3	21.035	63.7
	129.0	21.038	61.4
	135.2	21.073	53.4
	139.4	21.079	51.5
	141.7	21.069	46.8
	149.7	21.01	–
Acetic acid	108.0	17.689	
	117.3	17.533	
	122.6	17.437	
	128.0	17.335	
	129.8	17.317	
	133.5	17.236	
	138.8	17.154	
	143.6	17.078	
	147.5	16.994	
	158.2	16.811	

17 ppm as the temperature is increased from 100 K to 150 K. By contrast, in the pyridinium chloride complex (Fig. 1c) an inverse temperature dependence is observed: the signal is displaced from 17 ppm to 18.2 ppm as the temperature is increased from 100 K to 230 K. Finally, the signal of the chloroacetic acid-pyridine complex (Fig. 1b) appears in the region around 21 ppm corresponding to the maximum value found for this type of complex [10]. Here in the low temperature region where the zwitterionic complex $A^-\cdots H\text{-}B^+$ is present, the signal shifts to low field as temperature is increased as in the case of the pyridinium chloride complex. At about 140 K the maximum value is reached, thus corresponding to the quasisymmetric hydrogen bonded complex $A^{\delta-}\cdots H\cdots B^{\delta+}$. Above this temperature, where

the molecular complex A-H····B is formed – as indicated by the values of $^{1}J_{^{1}\mathrm{H}\text{-}^{15}\mathrm{N}}$ – the signal shifts upfield as temperature is further increased, as in the acetic acid-pyridine complex.

4. Discussion

In this section we show that the results obtained in the previous section give rise to some interesting insights into the properties of hydrogen bonded acid-base complexes in aprotic polar environments. Firstly, we note again that the NMR signals of Fig. 1 were obtained in the regime of slow hydrogen bond and proton exchange, and the concentrations were chosen in such a way that only 1:1 complexes are formed. The chemical shifts and coupling constants obtained are, therefore, intrinsic values and not affected by averaging over different hydrogen bonded sites. If these conditions are not met, the determination of intrinsic chemical shifts is difficult and may be affected by systematic errors.

So far, whenever intrinsic chemical shifts of hydrogen bonded protons have been measured, they were found to decrease with increasing temperature corresponding to high field shifts of the proton signals [1–5]. This effect has been explained in terms of a thermal vibrational excitation of the hydrogen bond vibrations $\nu_{\mathrm{H}\cdots\mathrm{B}}$ at elevated temperatures [1–3, 12, 13], corresponding to frequencies of the order of 60–200 cm^{-1}. Because of the anharmonicity of these vibrations, the hydrogen bonds widen and become weaker with increasing temperature, leading to an increased chemical shielding of the proton. This explanation applies both to molecular and zwitterionic complexes. Therefore, vibrational excitation cannot be the main factor influencing the temperature dependence of the chemical shifts of the acid-base hydrogen bonded complexes reported here because in the case of the zwitterionic pyridinium chloride complex (Fig. 1c), a low-field shift of the hydrogen bond proton signal was observed as the temperature was increased, indicating a lengthening of the hydrogen bond at low temperatures. To our knowledge this phenomenon has not yet been described in the literature.

One has, therefore, to look for another explanation which is also applicable in the vibrational groundstate. As mentioned in the introduction, the proton signals observed are still averages over many different solvent sites; since solvation is strongly dependent on temperature, it is therefore natural to explain the results obtained in terms of temperature dependent hydrogen bond geometries induced by solute-solvent interactions. Since the chemical shifts of the hydrogen bonded proton are a measure of the distance between the two heavy atoms of the hydrogen bond we conclude that – as the temperature is increased – the solute-solvent interactions lead to a lengthening of the hydrogen bond in the case of a molecular complex A-H····B and a contraction in the case of the zwitterionic complex $\mathrm{A}^{-}\cdots\mathrm{H}\text{-}\mathrm{B}^{+}$.

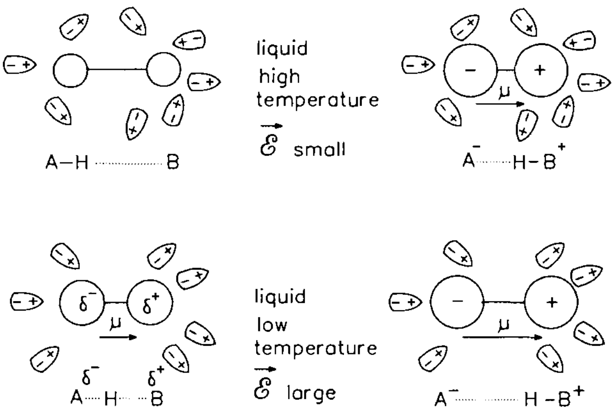

Fig. 2. Model for the observed temperature induced solvent effects on the geometry of a dissolved hydrogen bonded system. For further explanation see text.

These findings can be explained in terms of the scenario illustrated in Fig. 2. The electric dipoles of the individual solvent molecules create a temperature dependent effective electric field at the solute site. This field is large if the dipoles are ordered and small if they are disordered. Due to enthalpy-entropy compensation the local order parameter decreases with increasing temperature; therefore, the electric field at the solute site increases monotonously with decreasing temperature as long as a complete order is not yet reached. As a consequence, the temperature dependent electric field leads to a dipole moment variation in the solute. The dipole moment monotonously decreases when the temperature is lowered. It depends on the polarizability of the complex, which consists of two contributions. The electronic contribution is associated with a reorganization of the electrons under the action of the electric field. The nuclear part which is also called "nuclear" or "vibrational" polarizability [14, 15] is associated with changes of the nuclear geometry. The polarizability of quasi-symmetric hydrogen bonds is especially large and leads to extremely broad absorption bands in the IR spectra [15].

In a molecular complex A-H···B exhibiting a relatively small permanent electric dipole moment the latter can only be enhanced by charge transfer from B to AH. The energy for the charge separation is provided by the electric field; this energy is minimized by a contraction of the hydrogen bond as illustrated in Fig. 2. In other words, a molecular complex A-H····B contracts in the presence of an electric field. This hydrogen bond contraction is accompanied by a displacement of the proton towards the base B, i.e. by an increase of the distance r_1 between A and H and by a decrease of the distance r_2 between H and B. This conclusion follows from a detailed discussion of H/D isotope effects on the proton chemical shifts of these systems [10]. Correlations between r_1 and r_2 have also been well established by neutron diffraction [17], solid state NMR and *ab initio* calculations [18].

By contrast, in the case of a zwitterionic complex $A^-\cdots H\text{-}B^+$ where charge separation has already occurred, the dipole moment is easily increased under the action of the solvent electric field by increasing the heavy atom distance $r(A...B) = r_1 + r_2$ as indicated in Fig. 2. Therefore, the observation of the high field shift of the hydrogen bond proton signal with decreasing temperature, i.e. the associated lengthening of the zwitterionic hydrogen bond is plausible.

The complex of mono-chloroacetic acid with pyridine (Fig. 1b) represents the missing piece of the puzzle. A molecular complex $A\text{-}H\cdots B$ is formed above 150 K. When the temperature is decreased, the proton signal is shifted to low field because of the hydrogen bond contraction and the displacement of the proton to the hydrogen bond center as discussed above in the case of the acetic acid/pyridine complex. At around 140 K, the quasi-symmetric hydrogen bonded structure $A^{\delta-}\cdots H\cdots B^{\delta+}$ is reached as indicated by the maximum proton chemical shift of 21 ppm. The proton is then further displaced towards B leading to the zwitterionic structure $A^-\cdots H{-}B^+$ as is manifest in the increase of $^1J_{^1H\text{-}^{15}N}$. At the same time, the proton signal is again shifted to high field indicating that the hydrogen bond once more lengthens.

As a result, the decrease of temperature leads to an increased electric field at the molecular hydrogen bonded complex resulting in the transformation $A\text{-}H\cdots B \leftrightarrow A^{\delta-}\cdots H\cdots B^{\delta+} \leftrightarrow A^-\cdots H\text{-}B^+$, assisted by an intermediate hydrogen bond contraction at the midpoint where the two heavy atom – proton distances r_1 and r_2 are almost equal and the sum $r_1 + r_2$ minimal, as illustrated schematically in Fig. 3. One can thus conclude that this transformation will occur for every hydrogen bonded acid-base complex where the electric field of the solvent is strong enough. One could, therefore, measure the acidity or proton donating power of AH in $A\text{-}H\cdots B$ qualitatively by the temperature where the maximum chemical shift is reached, assuming a monotonous increase of the local electric field, i.e. neglecting saturation effects arising from maximum solvent dipole ordering. In order to reach the inversion temperature for acetic acid one would have to move to lower temperatures than can actually by realized, and for HCl this temperature is so high that the condition of slow hydrogen bond and proton exchange can no longer be maintained. As a consequence, one could compare the acidities and basicities of isolated proton donors and acceptors via *ab initio* calculations of complexes $A\text{-}H\cdots B...Li^+ \leftrightarrow A^{\delta-}\cdots H\cdots B^{\delta+}...Li^+ \leftrightarrow A^-\cdots H\text{-}B^+...Li^+$ where Li^+ ion models the electric field created in condensed matter at a hydrogen bonded site by the surroundings. This approach has been successfully employed recently in the case of quasi-symmetric hydrogen bonds perturbed by an external electric field [18].

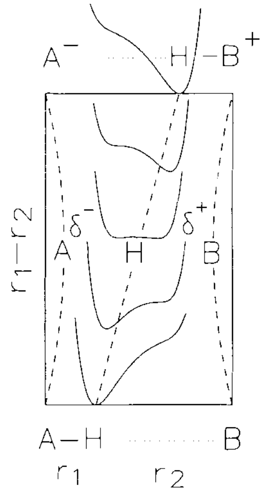

Fig. 3. Average nuclear positions and proton potentials (schematically) in 1:1 hydrogen bonded complexes AHB as a function of the proton donating power of the acid AH, or the electric field created as a function of temperature at the complex site. The proton transfer coordinate depends on the average distances r_1 and r_2.

It is interesting to note that recently in the case of a Mannich base containing an intramolecular hydrogen bond a reversal of hydrogen/deuterium isotope effects on the ^{13}C chemical shifts was observed at a given temperature indicating similarly the dominance of a zwitterionic structure at low and of a molecular complex at high temperature [19].

The above-mentioned findings can not easily be explained in terms of the usual two-state reaction scheme [19–23] as indicated in Fig. 4a. Taking the difference $r_1 - r_2$ as being the reaction coordinate, the probability $P(r_1 - r_2)$ of a certain nuclear geometry is then represented by two sharp gaussian peaks. This situation can therefore be described in terms of a single equilibrium constant K characterizing the proton transfer and two average values of $r_1 - r_2$ characterizing the nuclear geometries.

The finding of gradual displacements of the average proton positions associated with a substantial hydrogen bond contraction is not in agreement with Fig. 3a, but indicates a very broad distribution of complexes with different structures $A\text{-}H\cdots B \leftrightarrow A^{\delta-}\cdots H\cdots B^{\delta+} \leftrightarrow A^{-}\cdots H\text{-}B^{+}$, which change with temperature. This situation is visualized in Figures 4b to 4d, characterized by very broad proton density distribution functions $P(r_1 - r_2)$. Fig. 4b exhibits two broadened maxima whose intensity ratio is dependent on temperature. This situation still resembles that of Fig. 4a. In Fig. 4d, there is only one maximum shifting through the center as a function of temperature. Finally, Fig. 4c represents a combination of Figures 4b and 4c: two maxima

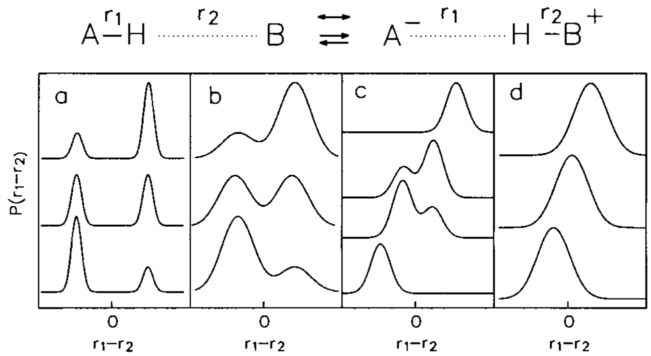

Fig. 4. Equilibrium vs. distribution models for proton transfer in AHB complexes dissolved in organic liquids. $P(r_1 - r_2)$ is the probability of finding a configuration characterized by $r_1 - r_2$. For further explanation see text.

are only present in the quasisymmetric case but in the asymmetric cases, single maxima which shift strongly with temperature are realized. Unfortunately, by liquid state NMR only average configurations can be observed each representing a point on the pathway of Fig. 3. In order to distinguish between the various possibilities of Fig. 4, combined studies of the systems described here by NMR and by "faster" techniques such as IR or UV spectroscopy would be fruitful, carried out under the same experimental conditions. By NMR the average complex structures are then determined as function of temperature and by IR/UV the interaction of the complexes with the solvent. Such experiments seem quite promising, as Kreevoy *et al.* have obtained UV spectra of p-nitrophenate/acid complexes where a change of the acid leads to UV spectra exhibiting features of Fig. 4c [24].

5. Conclusions

We have described the temperature dependent NMR spectra of neutral 1:1 complexes between acids AH and bases B in the regime of slow hydrogen bond exchange. As the temperature is lowered, the transformation A-H····B $\leftrightarrow$ $A^{\delta-}$···H····$B^{\delta+}$ $\leftrightarrow$ A^-···H−B^+ is observed assisted by a hydrogen bond contraction in the quasisymmetric intermediate stage. The hydrogen bond length of molecular complexes A-H···B therefore decreases and those of zwitterionic complexes A^-···H-B^+ increase as the temperature is lowered. These results have been modeled in terms of an increase of the electric field created by ordering of the solvent dipoles at low temperatures around the solutes. This field induces electric dipoles in the acid base complexes associated with a hydrogen bond contraction in A-H····B and a lengthening in A^-···H-B^+. In other words, the acidity of a proton donor AH towards a base increases as the temperature is lowered. Strong acids transfer the proton already at higher temperatures where the effective electric field created by ordering of the solvent dipoles is small. These findings could have some effect on biological systems because the lengthening of a neutral hydrogen bonded complex and the contraction of a zwitterionic hydrogen bridge could, with increasing temperature, be associated to changes of the enzymatic structure and activity. Currently, we are modeling the effects of temperature mediated solvent polarity on the hydrogen bond length in terms of the Buckingham theory [25, 26] combined with the Onsager-Butcher solute-solvent interaction potential. The results of this study will be presented elsewhere [27–29]. Moreover, *ab initio* calculations are carried out on AHB..Li^+ complexes where the Li^+ ion models the solvent electric field.

Acknowledgements

The authors express their thanks to Professor L. Sobczyk, University of Wroclaw, for stimulating discussions and for drawing our attention to the results of Ref. [19]. Furthermore, grants from the Stiftung Volkswagenwerk, Hannover, the Fonds der Chemischen Industrie, Frankfurt, as well as from the Russian Foundation for Fundamental Research, grant numbers 93-03-5664 and 94-03-08533 are gratefully acknowledged.

References

1. a) S. N. Vinogradov and R. H. Linnell, *Hydrogen Bonding*, Van Nostrand Reinhold Comp., New York 1971; b) M. D. Joesten and L. J. Schaad, *Hydrogen Bonding*, M. Dekker Inc., New York 1974.
2. A. Novak, Struct. Bonding (Berlin) **18** (1974) 177.
3. E. E. Tucker and E. Lippert, in *The Hydrogen Bond*, Eds. P. Schuster, G. Zundel and C. Sandorfy, North Holland Publ. Comp., Amsterdam 1976, Chapter 17.
4. F. Hibbert and J. Emsley, Adv. Phys. Org. Chem. **26** (1980) 255.
5. H. H. Limbach, in *Aggregation Processes in Solution*, Eds. E. Wyn-Jones and J. Gormally, Elsevier, Amsterdam-Oxford-New York 1983, Chapter 16.
6. H. H. Limbach, "Dynamic NMR Spectroscopy in the Presence of Kinetic Isotope Effects", Chapter 2 in *NMR Basic Principles and Progress*, Vol. 26, Springer, Berlin 1991.
7. N. S. Golubev and G. S. Denisov, Dokl. Akad. Nauk SSSR, 1978.
8. N. S. Golubev and G. S. Denisov, J. Mol. Struct. **270** (1992) 263.
9. N. S. Golubev, S. N. Smirnov, V. A. Gindin, G. S. Denisov, H. Benedict and H. H. Limbach, J. Am. Chem. Soc. **116** (1994) 12055.
10. S. N. Smirnov, N. S. Golubev, G. S. Denisov, H. Benedict, P. Schah-Mohammedi and H. H. Limbach, J. Am. Chem. Soc. **118** (1996) 4094.
11. a) M. Witanowski, L. Stefaniak, G. A. Webb, *Annual Reports on NMR Spectroscopy*, 11 B, Academic Press, New York 1981; b) G. Martin, M. L. Martin and J. P. Gouesnard, NMR-Basic Principles and Progress; Springer: Heidelberg, Germany 1989; Vol. 18, ^{15}N *NMR Spectroscopy* and references cited therein.
12. N. Muller and R. C. Reiter, J. Chem. Phys. **42** (1965) 3265.
13. N. Muller and R. J. Rose, J. Phys. Chem. **69** (1965) 2564.

14. P. M. Borodin, N. S. Golubev, G. S. Denisov and N. A. Safarov, Vestn. Leningr. Univ., Phys. Chem. (1978) 66.
15. R. Janoschek, E. G. Weidemann, H. Pfeiffer and G. Zundel, J. Am. Chem. Soc. **94** (1972) 2387; J. Chem. Soc., Faraday Trans. 2, **69** (1973) 505.
16. D. Borgis, G. Tarjus and H. Azzouz, J. Chem. Phys. **97** (1992) 1390.
17. T. Steiner and W. Saenger, Acta Crystallogr. **B50** (1994) 348; T. Steiner, J. Chem. Soc. Chem. Comm. (1995) 1331.
18. H. Benedict, C. Hoelger, F. Aguilar-Parrilla, W. P. Fehlhammer, M. Wehlan, R. Janoschek and H. H. Limbach, J. Mol. Struct. **378** (1996) 11.
19. L. Sobczyk, personal communication.
20. G. M. Barrow, J. Am. Chem. Soc. **78** (1956) 5802.
21. G. V. Gusakova, G. S. Denisov, A. L. Smolyanski and V. M. Schreiber, Dokl. Akad. Nauk SSSR **193** (1970) 1065.
22. Th. Zeegers-Huyskens and P. Huyskens, in *Molecular Interactions*, 1980, Vol. 2, J. Wiley and Sons, Chichester, p. 1.
23. Z. Dega-Szafran and M. Szafran, Heterocycles **37** (1994) 627.
24. M. M. Kreevoy and T. M. Liang, J. Am. Chem. Soc. **102** (1980) 361.
25. (a) A. D. Buckingham, Proc. R. Soc. London, Ser. A, **248** (1958) 169; (b) I. M. Leclerq, I. M. M. Allavena and Y. Bouteiller, J. Mol. Phys. **78** (1983) 4606.
26. A. C. Legon and D. I. Millen, Chem. Rev. **86** (1986) 6.
27. V. M. Schreiber and D. N. Shchepkin, J. Mol. Struct. **270** (1992) 481.
28. G. S. Denisov, V. A. Gindin, N. S. Golubev, H. H. Limbach, D. N. Shchepkin and S. N. Smirnov, J. Mol. Liquids, 1995, in press.
29. N. S. Golubev, G. S. Denisov, V. A. Gindin, S. M. Melikova, S. N. Smirnov and D. N. Shchepkin, in *The Latest NMR Research in Organic Chemistry*, Ed. A. I. Koltsov, Norell Press, New York 1995, in press.