Hydrogen Bonds in Crystalline Imidazoles Studied by ^{15}N NMR and *ab initio* MO Calculations

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Intermolecular hydrogen bonds of the type N–H…N in crystals of imidazole and its 4-substituted and 4,5-disubstituted derivatives were studied by ^{15}N CP/MAS NMR and an *ab initio* molecular orbital (MO) calculation. In the ^{15}N CP/MAS NMR spectrum of each of the imidazole derivatives, two peaks due to the two different functional groups, >NH and =N-, were observed. The value of the ^{15}N isotropic chemical shift for each nitrogen atom depends on both the length of the intermolecular hydrogen bond and the kind of the substituent or substituents. It was found that the difference between the experimental chemical shifts of >NH and =N– varies predominantly with the hydrogen bond length but does not show any systematic dependence on the kind of substituent. The *ab initio* MO calculations suggest that the hydrogen bond formation influences the ^{15}N isotropic chemical shift predominantly, and that the difference between the ^{15}N isotropic chemical shift of >NH and =N– varies linearly with the hydrogen bond length.

Key words: ^{15}N CP/MAS NMR; Imidazoles; Hydrogen Bond; ^{15}N Chemical Shift; *ab initio* MO Calculation.

1. Introduction

Imidazole is a basic unit in biologically active molecules such as histamine, histidine, α-chymotrypsin, ribonuclease A, and many metalloenzyme systems. In such systems the imidazole residue plays an important role in biologically active processes; it works as proton donor and/or acceptor, a ligand coordinated to metals and enables charge-transfer processes.

In order to clarify the biological function of imidazole, many imidazole derivatives and their metal complexes have extensively been investigated from the biological as well as the physical and chemical points of view. The electronic and molecular structure of imidazole in the gas phase was studied by electronic absorption spectra and theoretical calculations [1]. The crystal structure of imidazole and its several derivatives has been studied by X-ray and neutron diffraction experiments [2–9]. The biological function of imidazoles is considered to be closely related to the acidity and/or basicity of the nitrogen atoms in the imidazole ring. The acidity or basicity is dominated by the electronic structure of the nitrogens and is reflected by the strength of the hydrogen bonding. The hydrogen bonding in some imidazole derivatives has been studied by means of ^{1}H and ^{15}N high resolution NMR in solutions [10, 11] and by ^{2}H and ^{14}N NQR in the solid state [12, 13].

Garcia et al. have performed systematic investigations of various derivatives and metal-complexes of imidazole by means of ^{14}N and ^{2}H quadrupole double resonance, asserting that the ^{14}N electric field gradient (EFG) tensor of the amide nitrogen atom (>NH) is dominated by the hydrogen bonding environments [13]. They suggested that the direction of the principal z-axis of the ^{14}N EFG varies with the p-orbital population on the nitrogen atoms on the basis of the Towns-Daily theory for the EFG in molecules, and they concluded that the formation of the hydrogen bond changes the electron populations of both the N–H orbital and the π-lone pair orbital [13]. However, they did not discuss fully the dependence of the imidazole rings on the intermolecular hydrogen bond lengths, although they studied systematically the elctronic charge distribution as a function of the substituents on the imidazoles and of the type of the coordination to central metals in the complexes.

The crystals of imidazole and some of its derivatives form a one-dimensional molecular network linked by

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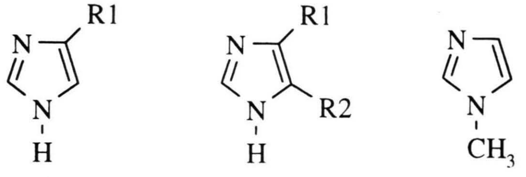
intermolecular hydrogen bonds [2–9]. Therefore, a deep insight into the proton dynamics as well as the static structure of the hydrogen bond is very important to understand the proton-transfer reactions in, *e.g.*, the biological systems. Electric conductivity [14] and ^{1}H NMR measurements [15] suggested that proton transfer takes place in the imidazole crystals. On the other hand, structural studies such as X-ray and neutron diffraction measurements [4, 5] indicated that the hydrogen atom is localized at one site and does not show any transfer to other sites. Thus, the possibility of the proton transfer in the hydrogen bond network has not clearly been confirmed yet.

The ^{15}N chemical shift is a highly sensitive probe for the electronic structure around the nitrogen atoms and the strength of the hydrogen bond; for example, a good correlation between the observed ^{15}N chemical shifts and the total charge densities on the nitrogen atoms were revealed in a series of N-methyl and N-aminoazoles including imidazole in $CDCl_3$ solution [10, 11]. The isotope effect on the N–H/D...N type hydrogen bond, which may bring about a variation in the geometry of the hydrogen bonding, has been successfully studied both experimentally and theoretically by probing the ^{15}N chemical shift [16–18]. The structure of the hydrogen bond and the effect of substituents on the ^{15}N chemical shift in NH-pyrazoles, whose molecular structure is similar to imidazole, were studied in detail in solution as well as in the solid state [19, 20]. Thus, it is expected that close examination of the ^{15}N chemical shift provides us with fruitful and quantitative information on the electronic structure of the N–H...N type hydrogen bond in the imidazole family. However, a hydrogen bond study by the use of the ^{15}N chemical shift in the solid state has not extensively been carried out because of the very poor sensitivity of the ^{15}N resonance. Munowitz et al. [21] reported ^{15}N CP/MAS NMR data for imidazole and histidine and discussed the spectra in relation to the acidity and/or basicity of the imidazole group in the histidine, but they did not mention the effect of the hydrogen bond on the ^{15}N NMR spectrum.

In our previous work [9] we refined the crystal structure of 4,5-dichloroimidazole and solved the crystal structure of 4,5-dicyanoimidazole. In addition, we measured infrared (IR) spectra and natural abundance ^{15}N cross polarization/magic angle spinning (CP/MAS) NMR spectra to characterize the hydrogen bonds in those compounds.

The present work deals with the structure and the property of the N–H...N type hydrogen bond in crystals of the five 4-substituted and two 4,5-substituted imidazoles shown in Figure 1. The crystal structure of these substances except the 4-methyl derivative has been determined, and it has been pointed out that the molecules form a one-dimensional hydrogen bond network in the crystal of the materials except 4,5-dicyano imidazole, in which the amide, >NH, group forms bifurcated hydrogen bonds with both =N– and CN. We determined the ^{15}N chemical shifts by measuring the natural abundance ^{15}N CP/MAS NMR spectra for these substances. Next we carried out *ab initio* molecular orbital calculations for those compounds to elucidate the theoretical background for the probable correlation between the ^{15}N chemical shifts and the properties of the hydrogen bond.



1 **2** **3**

1a :R1=H
1b :R1=Cl
1c :R1=Br
1d :R1=NO_2
1e :R1=CH_3

2a :R1=Cl, R2=Cl
2b :R1=CN, R2=CN

Fig. 1. Imidazole derivatives. 4-substituted, 4,5-disubstituted and 1-substituted substances are denoted by **1**, **2**, and **3**, respectively.

2. Experimental

Imidazole and its derivatives, except 4-Chloroimidazole (**1b**) and 4-bromoimidazole (**1c**), were purchased from Aldrich Chemical Company, Inc., and ^{15}N enriched imidazole (99 atom%) was purchased from ICON Inc. (U.S.A.). All the substances were purified by recrystallization and/or by sublimation under reduced pressure. 4-Chloroimidazole (**1b**) and 4-bromoimidazole (**1c**) were synthesized and purified according to [22]. X-ray powder diffraction was measured on the purified specimens to confirm the morphology and the quality of the crystals. The ^{15}N CP/MAS NMR spectra at room temperature were measured by Bruker MSL200, DSX200, DSX300, and/or MSL400 spectrometers operating at the Larmor frequencies of 20.3, 20.3, 30.4, and 40.6 MHz, respectively. The contact time between ^{1}H and ^{15}N spin

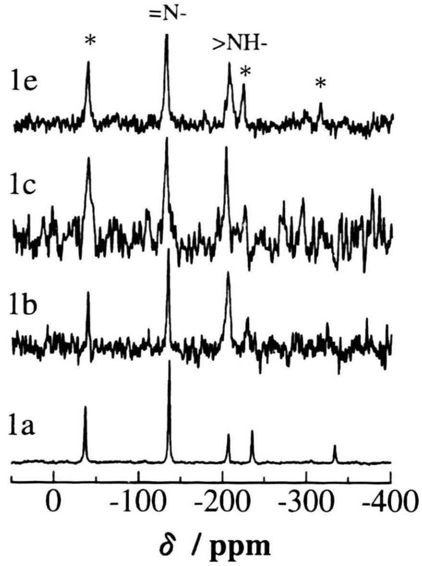


Fig. 2. ^{15}N CP/MAS NMR spectra of 4-substituted imidazoles with reference to ^{15}N in nitromethane as an external reference at room temperature. Asterisks indicate the spinning side band.

Table 1. ^{15}N chemical shifts and lengths of the intermolecular hydrogen bond in imidazole and its 4-substituted and 4,5-disubstituted derivatives in the solid state; the experimental isotropic shift, $\delta_{\mathrm{Exp.}}$, and the calculated isotropic shift, $\delta_{\mathrm{Calc.}}$.

Substance	Type	$\delta_{\mathrm{Exp.}}$/ ppm	$\delta_{\mathrm{Calc.}}$/ppm			$R_{\mathrm{N...N}}$/ nm
			Free	Dimer	Trimer	
Imidazole	>NH	−207±1	−344.6	−327.5	−323.4	0.286[b]
(**1a**)	=N−	−136±1	−196.7	−219.3	−224.1	
4-Chloro-	>NH	−205±3	−358.7	−343.4	–	0.2847,
(**1b**)	=N−	−133±1	−186.7	−209.0	–	0.2882[c]
4-Bromo-	>NH	−202±2	−353.4	−335.4	–	0.2834[c]
(**1c**)	=N−	−131±2	−182.8	−201.7	–	
4-Nitro-	>NH	−200±1	−351.6	−337.4	–	0.2871[d]
(**1d**)	=N−	−143±1	−192.0	−213.1	–	
4-Methyl-	>NH	−204±3	–	–	–	–
(**1e**)	=N−	−129±2	–	–	–	
4,5-Dichloro-	>NH	−200±2	−353.0	−339.1	–	0.2800[e]
(**2a**)	=N−	−133±2	−189.5	−211.3	–	
4,5-Dicyano-	>NH	−211±2	−342.3	–	–	0.3051[e]
(**2b**)	=N−	−118±2	−189.6	–	–	
1-Methyl-	>NMe	−219.2	–	–	–	–
(**3**)[a]	=N−	−119.1	–	–	–	

[a] Chemical shift values in dimethylsulfoxide solution. [b] [5]. [c] S. Nagatomo, unpublished results. [d] [7]. [e] [9].

systems to enhance the polarization of ^{15}N magnetization was between 1 and 5 ms. The free induction decay (FID) signal of ^{15}N nuclei after a contact pulse was recorded under ^{1}H decoupling with a field strength between 30 kHz and 45 kHz. The repetition time was between 100 and 1000 s, depending on the ^{1}H spin-lattice relaxation times (T_1), and the number of accumulations was 8 for ^{15}N enriched imidazole and 1024 for other specimens. Sample spinning was carried out using a ZrO_2 rotor (7 mm $\phi \times 18$ mm) with a spinning rate of 3 ~ 4 kHz. Powdered samples of ^{15}N-enriched glycine (–347.5 ppm from nitromethane) and $^{15}NH_4Cl$ (–341.2 ppm) were used as the external standards for the ^{15}N chemical shift [23].

The principal values of the ^{15}N chemical shift tensors σ and their anisotropies for each compound were calculated using the GAUSSIAN 94 molecular orbital program package [24] with 6-311G(df, p) basis set under the GIAO condition [25]. The details and the theoretical background of the calculation of the principal values of the chemical shift tensor are described in [26]. Each computation was carried out on the actual molecular geometry, which has been determined by the structure analysis. The contribution of the hydrogen bond to the ^{15}N chemical shift was evaluated by comparing the calculated values for the free single molecule and the dimer (or trimer in the case of imidazole crystal). The value of the calculated chemical shift δ was scaled by referring to that for an isolated nitromethane molecule.

3. Results and Discussion

3.1. ^{15}N CP/MAS NMR Spectra and ^{15}N Chemical Shift

Figure 2 shows the ^{15}N CP/MAS NMR spectra of 4-substituted imidazole derivatives at room temperature. Two peaks due to >NH and =N– are observed at ca. –200 ppm and ca. –135 ppm, respectively. For ^{15}N enriched imidazole (99 atom%), the spectrum was observed with a high *S*/*N* ratio, whereas the other substances gave poor *S*/*N* ratios because of the very low natural abundance of ^{15}N. Although the observed spectra except for imidazole were very poor in the *S*/*N* ratio, the resolution of the spectra is sufficiently high for the determination of the isotropic chemical shift values for >NH and =N– groups. The spectral analyses using Lorentzian gave the ^{15}N isotropic chemical shifts $\delta_{\mathrm{Exp.}}$, which are listed in Table 1 together with the hydrogen bonded intermolecular N...N lengths, $R_{\mathrm{N...N}}$.

The ^{15}N $\delta_{\mathrm{Exp.}}$ values in the solid state are certainly related to both the nature of the intermolecular hydrogen bond and the sort of the substituents. The substitution of the hydrogen at the 4-position of imidazole brings about the low-field shift of both nitrogen atoms (=N– and >NH) except for 4-nitro-imidazole. This tendency is independent of $R_{\mathrm{N...N}}$. The maximum shifts with reference to imidazole are 5 ppm in **1c** for >NH and 7 ppm in **1e** for =N–.

In order to distinguish the effect of the possible formation of the intermolecular hydrogen bond on the ^{15}N $\delta_{\mathrm{Exp.}}$ value from the substituent effect, we will refer the values of the ^{15}N chemical shift in each material to the δ value in 1-methyl-imidazole (**3**), which cannot form any intermolecular hydrogen bond. The ^{15}N δ values in this substance were determined to be –219.2 ppm for >NH and –119.1 ppm for =N– in dimethylsulfoxide solution [27]. The intermolecular hydrogen bond in 4,5-dicyanoimidazole (**2b**) is considered to be very week because $R_{\mathrm{N...N}}$ in this crystal is longest among the materials in Table 1. The ^{15}N $\delta_{\mathrm{Exp.}}$ value in **2b** is –211 ppm for >NH and –118 ppm for =N–, corresponding to the relative shift of +8.2 ppm for >NH and of +1.1 ppm for =N– with reference to **3**. On contrast, 4,5-dichloro-imidazole (**2a**), which has the smallest $R_{\mathrm{N...N}}$ among the compounds in Table 1, gives relative ^{15}N $\delta_{\mathrm{Exp.}}$ values of +19.2 ppm for >NH and –13.9 ppm for =N- to **3**. It should be noted that the effect of the hydrogen bond lengths on the $\delta_{\mathrm{Exp.}}$ for both nitrogen atoms is larger than that of the 4-substitutions.

Recent ^{15}N CP/MAS solid state NMR experiments on the N-H...N type hydrogen bond in solid 3,5-disubstituted pyrazoles revealed that the effect of the hydrogen bond on the ^{15}N δ value is larger than that of the substituents [19, 20]. Benedict et al. demonstrated that the difference in the chemical-shifts, $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ between the protonated and unprotonated nitrogen atoms decreases with increase in the strength of the hydrogen bond, that is, with decrease in $R_{\mathrm{N...N}}$ in the hydrogen bonded system $[\mathrm{M{-}C{\equiv}N...H...N{\equiv}C{-}M}]^{-}\mathrm{X}^{+}$ (M = $\mathrm{Cr(CO)_5}$, X = $\mathrm{AsPh_4}$, $\mathrm{NnPr_4}$) [16]. Thus, $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ between >NH and =N– is considered to be a useful measure for the strength of the hydrogen bond. In imidazole and its derivatives in Table 1 $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ is distributed in the range between –93 ppm (for **2b**) and –67 ppm (for **2a**). Figure 3(a) shows the experimental $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ values against $R_{\mathrm{N...N}}$. The experimental $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ value in the series of the imidazole derivatives, except for the 4-nitro derivative (**1d**), trends to increase linearly with the $R_{\mathrm{N...N}}$. As $R_{\mathrm{N...N}}$ decreases, the shielding of the ^{15}N nuclei in the >NH group decreases, while that in =N– increases, leading to a decrease in $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ with decrease in $R_{\mathrm{N...N}}$. This fact implies that the formation of the intermolecular hydrogen bond causes a partial mixing of the two extreme electronic structures, >NH and =N–. The extent of the mixing varies with the reciprocal of the hydrogen bond length, which reflects directly the strength of the hydrogen bond. However, the theoretical interpretation of any relationship between $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ and $R_{\mathrm{N...N}}$ has not been established yet. So, in the next section we attempt to shed light on the theoretical aspect of the relation between $\Delta(\delta_{=\mathrm{N-}}-\delta_{>\mathrm{NH}})$ and $R_{\mathrm{N...N}}$ by using an *ab initio* MO calculation.

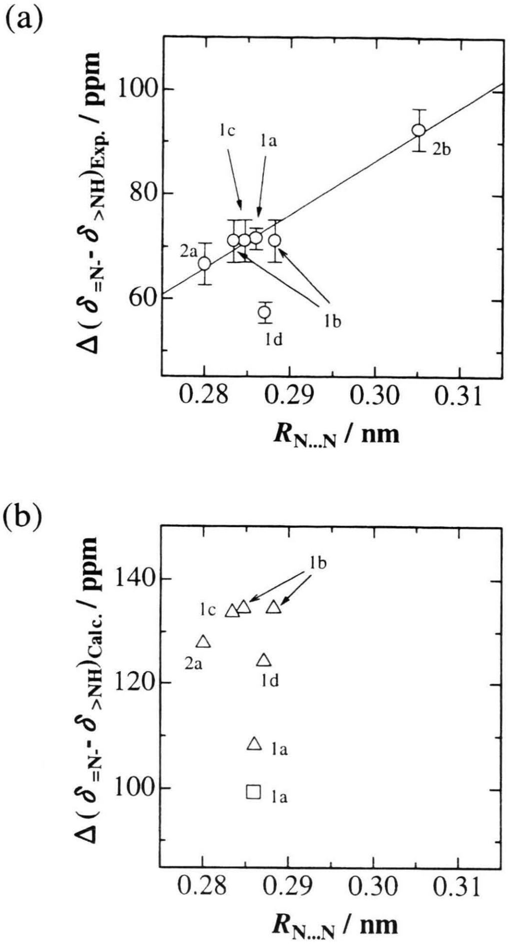


Fig. 3. Difference between ^{15}N chemical-shifts of >NH– and =N– plotted against the hydrogen bond distance; (a) experimental and (b) calculated values (△: dimer, □: trimer).

3.2. *Ab initio MO Calculations*

The *ab initio* molecular orbital calculation gives the principal values (σ_{11}, σ_{22}, and σ_{33}) of the ^{15}N chemical shift shielding tensor. The ^{15}N isotropic chemical shift was defined as the average of the principal values:

$$\sigma^{\text{iso.}} = \frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}) .$$

It is convenient to use the symbol $\delta \equiv (\sigma_{\text{Ref.}} - \sigma_{\text{Sample}})$ to represent the isotropic chemical shift, where $\sigma_{\text{Ref.}}$ is the isotropic value of the shielding tensor in a reference compound and σ_{Sample} is that of the sample. In the present work the ^{15}N chemical shift value was referred to σ of nitromethane, for which the σ value was computed to be –235.09 ppm. Then, the δ values of the imidazole derivatives are calculated by $\delta_{\text{Calc.}} = (-235.09 - \sigma_{\text{Sample}})$. The calculated ^{15}N chemical shifts, $\delta_{\text{Calc.}}$, are listed in Table 1. The values of the calculated and experimental chemical shifts in each compound do not agree with each other. However, the effect of the hydrogen bond on $\delta_{\text{Calc.}}$ can be evaluated by comparing $\delta_{\text{Calc.}}$ values between the hydrogen-bonded molecular dimer and/or trimer and a free single molecule of each substance. The formation of the hydrogen bond brings about more deshielding for >NH to an extent between 14 ppm and 21 ppm, whereas it results in more shielding for =N– to an extent between 19 ppm and 27 ppm with reference to those in the single molecule. On the other hand, the effect of the substituents on $\delta_{\text{Calc.}}$ may be evaluated by comparing the $\delta_{\text{Calc.}}$ values for the free molecules of the mono- or disubstituted compound with those in the free imidazole. It was found that the substitution in the 4-position causes a high field shift of the resonance peak for the >NH group and a low field shift for =N–. The trend of the shifts is hence opposite to the case of hydrogen bond. The maximum shifts in the materials in Table 1 with reference to imidazole are 14.1 ppm for >NH in **1b** and 13.9 ppm for =N– in **1c**. These values are slightly smaller than those for the formation of the hydrogen bond.

The formation of the hydrogen bond brings about a decrease in the shielding for >NH and an increase for =N-, and consequently leads to a decrease in the value of $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})$. The value of $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ is plotted against $R_{\text{N...N}}$ in Figure 3(b). It can be seen that the trend of the variation of $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ with $R_{\text{N...N}}$ is consistent with the experimental one, except for **1**. This implies that the $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})$ value depends strongly on the hydrogen bond length irrespective of the kind of the 4-substituent. The deviation of the $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ value in **1a** deviates significantly from the trend of the variations against $R_{\text{N...N}}$, but it agrees better with the observed $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})$ than the others. It also shows a tendency to approach the observed $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})$ as the number of molecules included in the computation increases from two to three. Therefore it seems that the $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ value approaches the experimental one as the number of the molecules in the hydrogen bonded network increases.

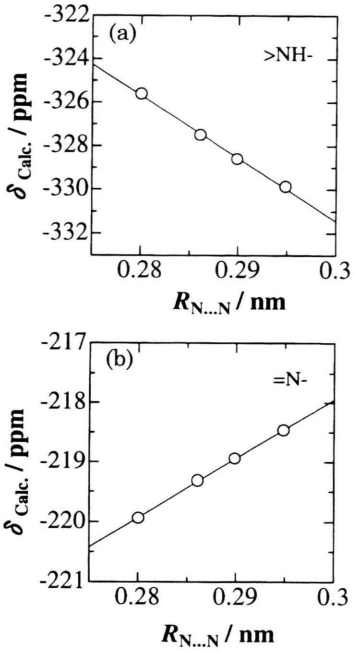


Fig. 4. Calculated isotropic values of the ^{15}N chemical shift tensor vs. hydrogen bond distance in imidazole dimer; (a) for >HN– and (b) for =N–.

We now attempt to establish the relation between $\delta_{\text{Calc.}}$ and $R_{\text{N...N}}$ by computing the δ's for imidazole dimer as a function of the N...N distance between 0.280 nm and 0.295 nm with keeping the shape of each molecule unchanged. The results are shown in Figs. 4(a) and (b). It is found that the $\delta_{\text{Calc.}}$ values for both nitrogen atoms change linearly with $R_{\text{N...N}}$. On an increment of $R_{\text{N...N}}$ from 0.280 nm to 0.295 nm the shielding in the >NH group decreases by 4.3 ppm, whereas the deshielding in =N– is increased by 1.4 ppm. This implies that the $\delta_{\text{Calc.}}$ of >NH is more sensitive to the hydrogen bond than that of =N-. The finding of a linear change of $\delta_{\text{Calc.}}$ with $R_{\text{N...N}}$ for each of the =N– and >NH nitrogen atoms implies that $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ also varies linearly with $R_{\text{N...N}}$. Thus, $\Delta(\delta_{=\text{N}-} - \delta_{>\text{NH}})_{\text{Calc.}}$ increases linearly from 105.7 ppm to 111.4 ppm as $R_{\text{N...N}}$ increases from

0.280 nm to 0.295 nm. This means that the slope of $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})_{\mathrm{Calc.}}$ against $R_{\mathrm{N...N}}$ is 0.380×10^3 ppm/nm. On the other hand, the experimental value of $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$ varies from 67 ppm in **2a** ($R_{\mathrm{N...N}}$ = 0.2800 nm) to 93 ppm in **2b** ($R_{\mathrm{N...N}}$ = 0.3501 nm), giving a slope of 1.04×13^3 ppm/nm. The experimental slope, $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})/R_{\mathrm{N...N}}$, is 2.7 times larger than the calculated one. The discrepancy in both values is caused probably by the incompleteness of the structural model adopted for the theoretical computation. We calculated $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$ for the dimetric unit of imidazole. The actual crystal consists, however, of an infinite molecular chain linked by intermolecular hydrogen bonds. Although it is not certain to what extent the infinitely long chain contributes to $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$, the comparison between $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$'s in dimer and trimer suggests the trend that $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$ decreases as the number of molecules, and so the number of hydrogen bonds increases, and will reach a certain value at infinite chain length. Hence, we can neither discuss the absolute values of $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})_{\mathrm{Calc.}}$ nor its slope against $R_{\mathrm{N...N}}$. We showed only the trend of $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})_{\mathrm{Calc.}}$ with respect to $R_{\mathrm{N...N}}$. Anyway, the $\Delta(\delta_{=\mathrm{N}-}-\delta_{>\mathrm{NH}})$ obtained by the *ab initio* computation can predict its relation to the structure of the N–H...N type hydrogen bond in a semi-quantitative manner in the imidazole family.

In order to advance the quantitative treatment of the hydrogen bond of type N-H...N in the imidazole family, we are now planning to study the chemical shift shielding tensor and its anisotropy both experimentally and computationally for ^{15}N in >NH and =N– groups. In addition, we carried out first experiments on the 1D and 2D ^{15}N exchange CP/MAS NMR to clarify the possible proton dynamics in the intermolecular hydrogen bond. In the ^{15}N 2D exchange NMR spectrum, the cross peaks between two main peaks corresponding to >NH and =N– were observed at room temperature with a mixing time longer than 100 ms. A detailed experiment is in progress to confirm the existence of proton transfer in the intermolecular hydrogen bond network.

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