Localization of Hydrogen Bond Deuterons in Proton Sponges by Dipolar Solid State ^{15}N NMR Spectroscopy

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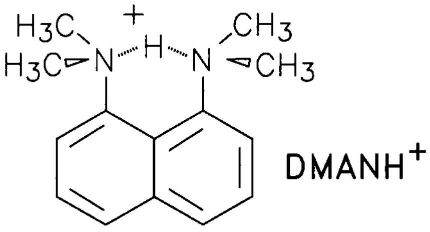
It is shown that dipolar solid state ^{15}N NMR spectroscopy can be employed in order to estimate the positions of hydrogen bond deuterons in polycrystalline ^{15}N labeled proton sponges containing an intramolecular N...H...N hydrogen bond. For singly ^{15}N labeled 1,8-bis(dimethylamino)naphtalene$\cdot$ LPF_6 (**1**-h: L = H, **1**-d: L = D), an asymmetric hydrogen bond with cubic average distances between the two nitrogen atoms and the hydrogen bond deuteron of 1.19 Å and 1.47 Å are obtained. These values are in accordance with the N...H distances of 1.19(7) Å and 1.43(6) Å, obtained previously by x-ray diffraction at 150 K.

1. Introduction

The great basicity of proton sponges containing two close nitrogen atoms has been rationalized in terms of a low-barrier $[N\cdot\cdot H\cdot\cdot N]^+$-hydrogen bond in the conjugate acid [1–10]. The symmetry and geometry of the hydrogen bond depend greatly on the molecular environment. For the most prominent system, i.e. 1,8-bis(dimethylamino) naphthalene-H^+ ($DMANH^+$, Scheme 1) two non-equivalent nitrogen atoms were observed by ESCA-spectroscopy in the gas phase [2]. This asymmetry is supported by *ab initio* quantum chemical calculations [3]. A discussion of scalar $^1J(^{15}N...H)$ coupling constants determined by natural abundance ^{15}N NMR is compatible with a fast equilibrium between two asymmetric forms [4]. On the other hand, x-ray diffraction (XRD) of various salts indicates either proton ordering as expected for a single asymmetric form or a dynamic or static proton disorder, depending on the counteranion [5–8]. Due to the known problems of XRD to localize protons [9], several neutron diffraction structures have been reported [6]. This method can, however, not always be applied as relatively large crystals are required. Solid state natural abundance ^{13}C and ^{15}N CPMAS NMR techniques (CP ≡ cross polarization, MAS ≡ magic angle spinning) were therefore applied to this problem [6–8, 10], but unfortunately, the chemical shielding of the sp^3-nitrogen atoms in solid protonated sponges are not very sensitive to the proton locations; ^{13}C chemical shifts [6, 8, 11] and in sponges containing phosphor, ^{31}P chemical shifts [7] exhibit larger variations but may not easily be related to the hydrogen bond geometries. Recently, ^1H chemical shifts of solid sponges were obtained using MAS techniques which revealed typical proton chemical shifts around 17 ppm and indicated a strong hydrogen bond [6h]. On the other hand, some of us have proposed to use dipolar ^{15}N-D interactions in ^{15}N enriched compounds in order to characterize hydrogen bond geometries by solid state ^{15}N NMR [12]. As this method appeared to be also very useful for the study of proton sponges, we have prepared singly ^{15}N labeled $DMANH^+PF_6^-$ (1) whose x-ray crystal structure was determined recently [8]. Both, the synthesis of this compound as well as the determination of the dipolar ^{15}N-D interaction is reported in this paper.



Scheme 1

2. Experimental

2.1 Synthesis of 1[1-^{15}N],8-bis(dimethylamino) naphthalene

Naphthalene and the unlabeled materials-1-nitronaphthalene, 1,8-dinitronaphthalene, 1,8-diaminonaphthalene and 1,8-bis(dimethylamino)naphthalene- employed were commercial products purchased from Aldrich, Germany. Potassium nitrate-^{15}N, 95 atom% ^{15}N was obtained from Chemotrade, Germany.

The 1[1-^{15}N],8-bis(dimethylamino)naphthalene was prepared by a multistep procedure as shown in Scheme 2, starting from naphthalene.

1[1-^{15}N]-Nitronaphthalene **1**

1.94 g (15.14 mmol) of naphthalene, 1.53 g (15.14 mmol) of potassium nitrate-^{15}N, 95 atom% ^{15}N and 7.5 ml

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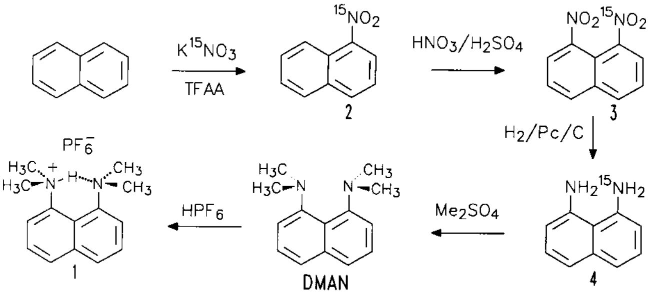

Scheme 2

(53 mmol) of trifluoroacetic anhydride (TFAA) were placed into a 50 ml, single-necked, round bottomed flask provided with a magnetic stirrer and a reflux condenser topped with a drying tube. 15 ml of chloroform were added and the reaction allowed to proceed at room temperature for 20 hours. The yellow crude product was poured into 50 ml of water then extracted with chloroform (3×15 ml). The solvent was evaporated off and the residue purified via column chromatography on silicagel 60 (70–230 mesh) using hexane-ethyl acetate 8:2 as eluent, yielding 1[1-^{15}N]-nitronaphthalene (1.3 g, 50%). The purity was checked by comparison with unlabeled 1-nitronaphthalene.

1[1-^{15}N],8-Dinitronaphthalene **2**

Compound **1** (1 g, 5.74 mmol) was dissolved in 5 ml of concentrated sulphuric acid (d 1.84) and under vigorous stirring, a mixture of sulphuric acid (1 ml, d 1.84) and nitric acid (0.26 ml, d 1.52), 4:1 in volume, was added dropwise while maintaining the temperature at 0 °C. After the addition the reaction mixture was stirred continuously for 2 hours at room temperature, then poured on ice and the formed precipitate collected, washed with water and dried for 24 hour at 55 °C.

The crude product, containing mainly 1[1-^{15}N],8- and 1[1-^{15}N],5-dinitronaphthalene, was chromatographed on an alumina column (Aluminium oxide 90, 70–230 mesh) using benzene as an eluent. The final eluted fractions were of 1[1-^{15}N],8-dinitronaphthalene **2** (0.63 g, 48%).

1[1-^{15}N],8-Diaminonaphthalene **3**

0.613 g (2.8 mmol) of 1[1-^{15}N],8-dinitronaphthalene **2** were dissolved in 250 ml of ethanol and hydrogenated under pressure on a Parr 3911 hydrogenator in the presence of 0.3 g of palladium on activated carbon (Pd 10%). After 3 hours, the catalyst was separated by filtration and the ethanol removed to obtain the 1[1-^{15}N],8-diaminonaphthalene **3** (0.42 g, 95%).

1[1-^{15}N],8-Bis(dimethylamino)naphthalene DMAN and its Ionic Complex with Hexafluorophosphoric Acid DMANH$^+$ PF$_6^-$ **1**

The 1[1-^{15}N],8-diaminonaphthalene was finally permethylated with dimethyl sulphate [16]. The ionic complex of the singly labelled DMAN with hexafluorophosphoric acid was prepared in a similar way as for the unlabeled DMAN [8].

2.1 NMR Spectroscopy

All ^{15}N CP NMR measurements were performed at 9.12 MHz (2.1 T cryomagnet) using a Bruker CXP 100 spectrometer equipped with a Doty 7 mm standard CPMAS probe. A standard CP pulse sequence was employed. 6 ms ^{1}H 90° pulse width, 4–12 ms CP time and 5 s recycle delay, 20000 Hz spectral width. All spectra were recorded under high-power ^{1}H decoupling and are referenced to external solid ^{15}NH$_4$Cl (95%).

For the simulations of the static powder ^{15}N CP NMR spectra of **1**, a computer program described previously [12] was employed. The spectra were analyzed and simulated as follows. As **1** was singly ^{15}N labeled and the spin label statistically distributed between the two nitrogen sites N1 and N2, the spectra consist of a superposition of two components arising from N1 and N2 located in different molecules. As a result of the ^{1}H decoupling, dipolar ^{1}H-^{15}N interactions are removed. Therefore, thesubspectra of a given nitrogen site depend in the case of the protonated system only on the values of the three components σ_{11}, σ_{22}, σ_{33} of the nitrogen chemcial shift tensor. These components are related to the isotropic nitrogen chemical shift obtained under MAS-conditions by

$$\sigma_{\text{iso}} = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3 \,. \tag{1}$$

The nitrogen spectra of the deuterated compound **1**-d depend additionally on the dipolar ^{15}N...D coupling constants [12]

$$J_{\text{d}}\,(^{15}\text{N} \ldots \text{D})/\text{Hz} = 1868\, r_{\text{N...D}}^{-3} \,. \tag{2}$$

where $r_{\text{N...D}}$ represents the cubic average N...D distance. The Euler angles α and β relate the N...D vector to the principal axis system of the chemical shift tensor as illustrated in Fig. 1.

3. Results

The superposed experimental and calculated ^{15}N-solid state NMR spectra of polycrystalline powders of singly ^{15}N labeled **1**-h and **1**-d obtained under various conditions are depicted in Figs. 2a and 2d. Single peaks are observed under MAS conditions for **1**-h (Fig. 2a) and for **1**-d (Fig. 2c), where the line is slightly broader and shifted to high field of around 1 ppm. This result does not necessarily indicate that the nitrogen atom sites N1 and N2 are equivalent because chemical shift differences between protonated and non-protonated sp^3-nitrogen atoms are generally small, i.e. only of the order of 10 ppm [14c].

By contrast the spectra obtained for the static powdered samples are very different. In the case of **1**-h (Fig. 2b)

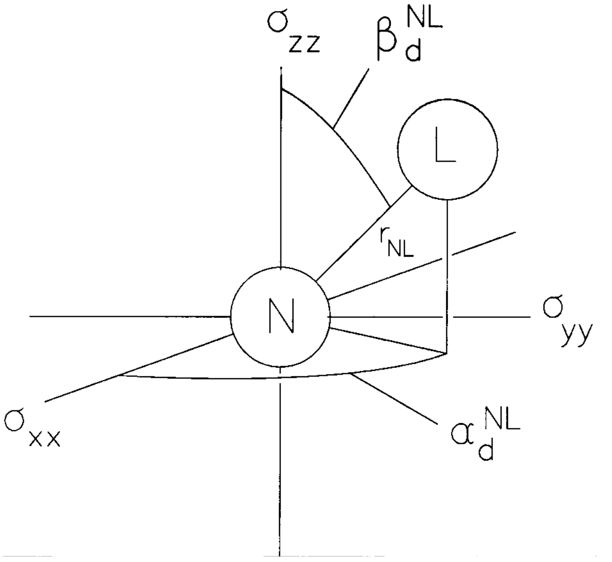

Fig. 1
Orientation of the N-L bond vector in the principal axis system of the tensor for the chemical shift anisotropy (CSA)

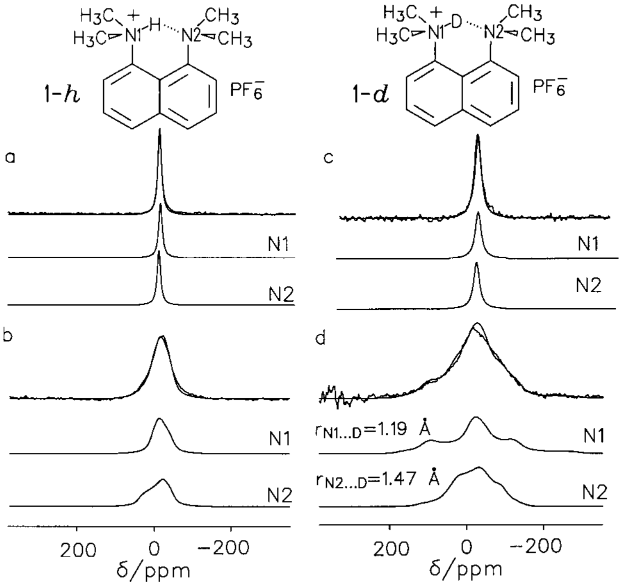

Fig. 2
Superposed experimental and calculated solid state ^{1}H decoupled ^{15}N CP NMR spectra (9.12 MHz, CP$\equiv{}^1$H-^{15}N cross polarization) of polycrystalline singly ^{15}N labeled 1,8-bis(dimethylamino)-naphthaline·LPF$_6$ **1** obtained under various conditions. (a) Sample of **1**-h rotating at the magic angle (MAS); (b) **1**-h, static sample; (c) sample of **1**-d, rotating at the magic angle (MAS); (d) **1**-d, static sample. MAS spectrum of **1**-d. The calculated contributions of the two nitrogen sites are included. Reference: ^{15}NH$_4$Cl [13]. The ^{15}N chemical shifts can be converted into the nitromethane scale using the equation [δ(CH$_3$NO$_2$)$=\delta$(NH$_4$Cl)-352.9 ppm] [14]

the chemical shift anisotropy leads to a somewhat asymmetric line broadening. As isotope effects on chemical shifts are minimal the contribution of the chemical shift anisotropy should be similar in the case of **1**-d. However, because of the dominance of the additional dipolar ^{15}N-D couplings, the spectrum is completely different (Fig. 2d).

The search for a consistent set of parameters capable of satisfying all the spectra in Fig. 2 was difficult. The results are assembled in Table 1. Firstly, the chemical shift anisotropies of N1 and N2 were determined by calculation of the static powder spectrum of **1**-h leading to the calculated subspectra of Fig. 1b. The chemical shift parameters σ_{11}, σ_{22} and σ_{33} for N1 and N2 were chosen assuming that the latter are not chemically equivalent, but that σ_{iso}(N1) and σ_{iso}(N2) so similar that they are not resolved in the MAS spectrum (Fig. 1a). This assumption was required in order to calculate the static powder spectra of **1**-d in Fig. 2d as they cannot be simulated in terms of two equivalent nitrogen atoms exhibiting similar distances, i.e. N1...D and N2...D. Moreover, isotope effects on the ^{15}N chemical shifts of sp^3-nitrogen sites should be minimal. During the first stage of the simulation of the spectra of **1**-d the set of chemical shift parameters of **1**-h were employed and only the two dipolar coupling constants and the Euler angles were varied. In a refinement we allowed for very small variations of the chemical shift parameters of the order of a few ppm. The contribution of N1 exhibiting the smaller N...D distance leads to a larger signal component as compared to N2 (Fig. 2d). The dipolar coupling constants obtained are included in Table 1.

4. Discussion

We have estimated for the first time the dipolar ^{15}N-D coupling constants of a ^{15}N labeled proton sponge in the solid state by line shape analysis of the ^{15}N spectra of sta-

Table 1
Parameters of calculated subspectra of the individual nitrogen atoms N1 and N2 for protonated and deuterated substances (**1**-h and **1**-d)

	σ_{11} [ppm]	σ_{22} [ppm]	σ_{33} [ppm]	σ_{iso} [ppm]	α [°]	β [°]	$J_{\mathrm{N...D}}$ [Hz]	$r_{\mathrm{N...D}}$ [Å]	W_0 [Hz]
N1...H	8	–12	–47	–17	–	–	–	–	200
N2...N	40	–23	–48	–10	–	–	–	–	200
N1...D	2	–18	–53	–23	–87.14	11.39	1110±50	1.19±0.01	300
N2...D	35	–30	–55	–17	–12.92	51.49	590±50	1.47±0.01	300

$r_{\mathrm{N...D}}$: cubic average distances N...D obtained from the dipolar coupling constants $J_{\mathrm{N...D}}$ using Eq. (2). σ_{iso}: isotropic ^{15}N chemical shifts; α_{CSA}, β_{CSA}: Euler angles relating the CSA and dipolar ND coupling tensors according to Fig. 1. The margins of error do not include possible systematic errors

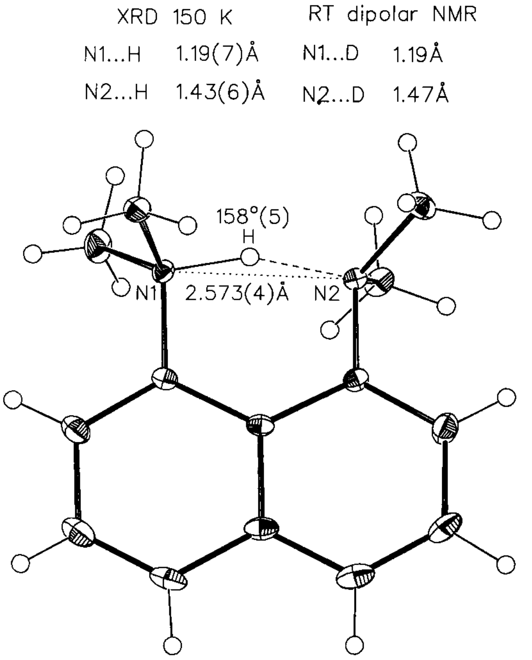

Fig. 3
Comparison of the x-ray crystal structure of **1**-h at 150 K adapted from Ref. [8] with NMR results obtained in this study

tic powdered protonated and deuterated samples. Assuming a harmonic deuteron motion we calculate the average cubic distances $r_{\mathrm{N1}\ldots\mathrm{D}}=1.19$ Å and $r_{\mathrm{N2}\ldots\mathrm{D}}=1.47$ Å, from the dipolar coupling constants obtained, using Eq. (2). These values are consistent with the crystallographic values. 1.19(7) Å and 1.43(6) Å of **1** determined at 150 K [12]. This agreement is visualized in Fig. 3 which shows the crystal structure of the sponge studied. The results are consistent with an interplay of intermolecular and intramolecular interactions leading to a localization of the hydrogen bond protons and deuterons close to the nitrogen site N1. On the other hand, the agreement should not be overestimated, because (i) several parameters of the line shape could not yet be determined precisely and had to be estimated, (ii) **1**-h was studied at 150 K by XRD and **1**-d at room temperature by NMR; (iii) the problems of localizing protons by XRD are well known [9] and (iv) for a strong hydrogen bond the assumption of a harmonic deuteron motion may not be a good approximation.

5. Conclusions

It has been shown that dipolar ^{15}N solid state NMR is a useful method for the determination of deuteron locations in proton sponges. In the case of the DMANH$^+$ consitency is obtained with X-ray diffraction. NMR will, therefore, be especially useful for future applications where the proton locations are still unknown due to apparent static or dynamic proton disorder.

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they are no directly comparable because they have been calculated by using some approximate relationship between chemcial shift references [14].

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