

Protonic Conduction in Imidazole: A Solid-State  $^{15}\text{N}$  NMR Study

Benjamin S. Hickman, Mark Mascall,\* Jeremy J. Titman,\* and Ian G. Wood

Contribution from the Department of Chemistry, University of Nottingham, Nottingham NG7 2RD, U.K.

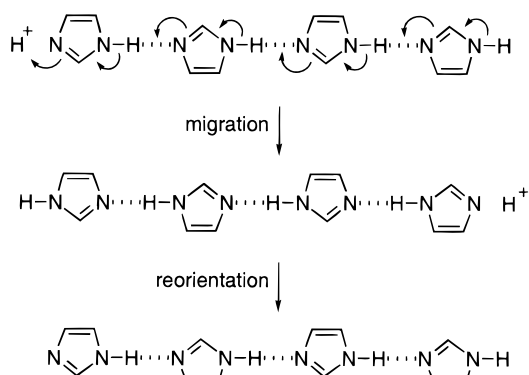
Received April 28, 1999. Revised Manuscript Received July 15, 1999

**Abstract:** Reports of protonic conductivity in crystalline imidazole describe a pronounced anisotropy in the transport of  $\text{H}^+$  with respect to crystallographic direction. Since charge is carried mainly along imidazole's hydrogen bonding axis (*c*), it has long been hypothesized that the phenomenon involves the tunneling of protons through hydrogen bonds. A two-dimensional nitrogen-15 exchange NMR study of  $^{15}\text{N}$ -labeled imidazole, however, demonstrates that the conduction mechanism does not involve the reorientation of the imidazole ring invoked in current models.

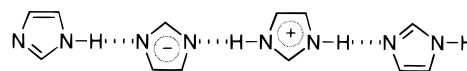
## Introduction

More than a century after the discovery of conductivity in ice,<sup>1</sup> the nature of protonic conduction through crystalline molecular solids is still a matter of debate,<sup>2</sup> and much attention has focused on imidazole (**1**),<sup>3</sup> whose conductivity has been reported to show a pronounced angular dependence in the crystal. The discussion has been fueled by the recognition that the imidazole-containing amino acid histidine is commonly associated with the active sites of transmembrane charge pumping proteins,<sup>4</sup> in addition to being a component of H-bond relays in a number of key hydrolases.<sup>5</sup> Most recently, interest has centered on potential applications of ionic conductors in high-performance solid-state electrochemical devices.<sup>2,6</sup>

Ever since a significant drop in resistivity in the [001] crystallographic direction of imidazole was reported,<sup>3d,e</sup> interpretations of this phenomenon have seized on the fact that the *c* axis is also the direction of infinite hydrogen bonded chains of **1**. Accordingly, two mechanisms have been put forward which involve proton transport through the H-bonds, either in a cooperative Grotthuss process (Figure 1)<sup>7</sup> or by invoking charge defects (Figure 2)<sup>3e</sup> which then migrate toward the electrodes. To sustain a current, however, both of these models require a complete reorientation of the molecules of **1** after delivery of the first proton from the end of the chain (Figure 1). This involves the coherent rotation of all the molecules in the chain, with attendant lattice deformation and the concerted



**Figure 1.** The Grotthuss mechanism in solid **1**, involving a single migration event along the hydrogen-bonded chain followed by a planar rotation of all the imidazole molecules prior to further proton transfer.



**Figure 2.** Formation of charged species in **1**.

breaking of each short, strong hydrogen bond, which, it has been suggested, is consistent with the large activation energy of 1.7 eV.<sup>3e,f</sup> In 1968 Daycock et al. attempted to correlate the proton NMR spin–lattice relaxation time of solid imidazole to the reported conductivity<sup>7a</sup> and derived a molecular rotation rate of ca.  $1 \text{ s}^{-1}$  at 295 K. Calling on a series of assumptions, it was demonstrated that this slow reorientation was nevertheless sufficient to account for the conduction phenomenon. Such proton NMR measurements, however, do not give unambiguous conclusions about the nature and geometry of the dynamic processes they probe. On the other hand, the time scale observed by Daycock suggests that the dynamics responsible for conduction in imidazole might be studied in a more direct fashion by solid-state nitrogen-15 two-dimensional exchange NMR. Variants of this technique measure magnetization transfer via both the interchange of chemical shifts for distinct environments undergoing slow exchange and the reorientation of shift tensors due to rotations of molecular fragments.<sup>8</sup> Extremely slow

(1) Ayrton, W. E.; Perry, J. *Proc. Phys. Soc.* **1877**, 2, 171.  
 (2) Colombari, P., Ed. *Proton Conductors: Solids, Membranes, and Gels – Materials and Devices*; Cambridge University Press: Cambridge, 1992.  
 (3) (a) Zimmermann, H. *Z. Elektrochem.* **1961**, 65, 821. (b) Brown, G. P.; Aftergut, S. *J. Chem. Phys.* **1962**, 38, 1356. (c) Joop, N.; Zimmermann, H. *Z. Elektrochem.* **1962**, 66, 541. (d) Pigon, K.; Chojnacki, H. *Acta Phys. Pol.* **1967**, 31, 1069. (e) Kawada, A.; McGhie, A. R.; Labes, M. M. *J. Chem. Phys.* **1970**, 52, 3121. (f) Brédas, J. L.; Poskin, M. P.; Delhalle, J.; André, J. M.; Chojnacki, H. *J. Phys. Chem.* **1984**, 88, 5882. Scheiner, S.; Yi, M. *Phys. Chem.* **1996**, 100, 9235.  
 (4) Cain, B. D.; Simoni, R. D. *J. Biol. Chem.* **1989**, 264, 3292.  
 (5) (a) Silverman, D. N.; Lindskog, S. *Acc. Chem. Res.* **1988**, 21, 30. (b) Meyer, E. *Protein Sci.* **1992**, 1, 1543. (c) Zhong, S.; Haghjoo, K.; Kettner, C.; Jordan, F. *J. Am. Chem. Soc.* **1995**, 117, 7048. (d) Lesburg, C. A.; Christianson, D. W. *J. Am. Chem. Soc.* **1995**, 117, 6838.  
 (6) Recent reviews: (a) Bermudez, V. D.; Poinsignon, C.; Armand, M. *B. J. Mater. Chem.* **1997**, 7, 1677. (b) Kreuer, K. D. *Solid State Ionics* **1997**, 97, 1.  
 (7) (a) Daycock, J. T.; Jones, G. P.; Evans, J. R. N.; Thomas, J. M. *Nature* **1968**, 218, 672. (b) For a modern discussion of the Grotthuss mechanism, see: Agmon, N. *Chem. Phys. Lett.* **1995**, 244, 456.

(8) (a) Schmidt-Rohr K.; Spiess H. W. *Multidimensional Solid-state NMR and Polymers*; Academic Press: London, 1994. (b) de Jong A. F.; Kentgens, A. P. M.; Veeman W. S. *Chem. Phys. Lett.* **1984**, 109, 337. (c) Kentgens, A. P. M.; de Boer, E.; Veeman, W. S. *J. Chem. Phys.* **1987**, 87, 6859. (d) Titman, J. J.; Luz, Z.; Spiess, H. W. *J. Am. Chem. Soc.* **1992**, 114, 3756.

dynamic processes can be studied with correlation times ranging from 10 ms to ca. 10 s, the upper limit being determined by interference from magnetization transfer due to spin diffusion. The resulting two-dimensional spectra give detailed and unambiguous information about the rate and geometry of molecular reorientations.

### Conductivity and Correlation Time

The correlation time for the molecular reorientation of imidazole measured via nitrogen-15 exchange NMR can be related to the conductivity by treating protonic conduction as a diffusive process by analogy with vacancy or interstitial ionic conductors. Conductivity can be expressed in terms of the number density of the charge carriers  $n$  (in this case the NH protons), their charge  $q$ , and their mobility  $\mu$  as

$$\sigma = nq\mu$$

Mobility can be related to the diffusion coefficient  $D$  by the relation

$$\mu = \frac{qD}{kT}$$

where  $k$  is the Boltzmann constant and  $T$  is temperature, while the diffusion coefficient gives the mean time between jumps  $\tau$  for the one-dimensional case appropriate for imidazole as

$$D = \frac{\lambda^2}{2\tau}$$

where  $\lambda$  is the mean distance jumped in each step. We identify  $\tau$  with the correlation time of the imidazole ring reorientation and  $\lambda$  with the distance between NH lattice sites. While this approach avoids mechanistic considerations, the processes described in Figure 1 couple diffusion to the rate-limiting reorientation of **1**. This leads to an expression for the conductivity in terms of the reorientation correlation time:

$$\sigma = \frac{nq^2\lambda^2}{2\tau kT}$$

Using this argument, correlation times in the range 0.1 to 10 s would imply conductivities of  $10^{-7}$  to  $10^{-9}$  S m $^{-1}$ , which are similar to those (up to  $10^{-7}$  S m $^{-1}$ ) measured by Kawada et al. between 300 and 350 K.<sup>3e</sup> Hence, direct observation of molecular reorientations occurring on a ca. 1 s time scale by nitrogen-15 exchange NMR would support the mechanisms proposed for charge translocation in imidazole.

### Solid-State Nitrogen-15 NMR Experiments

Solid-state nitrogen-15 NMR spectra of **1** were measured at a resonance frequency of 30.4 MHz. Three versions of the basic nitrogen-15 two-dimensional exchange NMR technique were used to investigate molecular reorientations. Nonspinning exchange NMR experiments were performed as described by Schmidt-Rohr and Spiess<sup>8a</sup> at temperatures between 293 and 348 K with mixing times of up to 5 s. This method is particularly useful for detecting slow reorientations of shift tensors and results in spectra which exhibit two-dimensional variants of the powder pattern NMR line shapes characteristic of isotropic samples. Since the principal axis system of the shift tensor has a fixed orientation with respect to the local bonding framework these patterns can be inverted to give information about molecular rotations. For discrete jump motions, as opposed to

**Table 1.** Principal Components of the Nitrogen-15 Shift Tensor<sup>a</sup> (ppm) for Both Sites in **1**<sup>9</sup>

site	$\sigma_{11}$	$\sigma_{22}$	$\sigma_{33}$	$\sigma_{\text{iso}}$
N	19	-55	-359	-132
NH	-118	-186	-320	-208

<sup>a</sup> Referenced to nitromethane.  $\sigma_{\text{iso}}$  is the average of the principal components.

rotational diffusion, elliptical features away from the diagonal ( $\omega_1 = \omega_2$ ) result.

Rotor-synchronized MAS exchange experiments<sup>8b,c</sup> were also carried out under similar conditions at a spinning rate of 1.5 kHz. This method detects the same reorientations of shift tensors via the appearance of “cross-peaks” which link the MAS rotational sidebands observed along the diagonal in the two-dimensional spectrum. MAS exchange experiments have the advantage over their nonspinning counterparts that chemical exchange processes which occur in concert with molecular reorientations are easier to identify.<sup>8d</sup> In the experiments described here the mixing period was constrained to be an integral number of MAS periods and the “anti-echo” component of the two-dimensional exchange spectrum was acquired. These precautions have been shown to eliminate spurious cross-peaks arising from macroscopic reorientation of the whole sample due to the spinning.

Unsynchronized exchange experiments were performed at the relatively rapid MAS rate of 5 kHz for which the rotational sidebands of the nitrogen-15 resonances are small. These experiments allow the rates of chemical exchange processes to be determined but do not give any information about the geometry of molecular reorientations. They were also used here to assess the rates of intra- and intermolecular spin diffusion in **1** and so to determine the upper limit for the correlation times which can be measured.

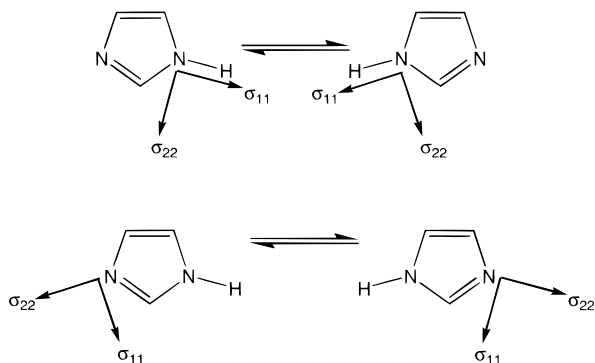
In all cases cross polarization with a contact time of 5 ms was used to increase the sensitivity of the nitrogen-15 resonances. A relaxation delay of 120 s was used for proton  $T_1$  relaxation between scans which required experiment times of up to 40 h. Further experimental details are given in the figure captions.

### Exchange NMR Simulations

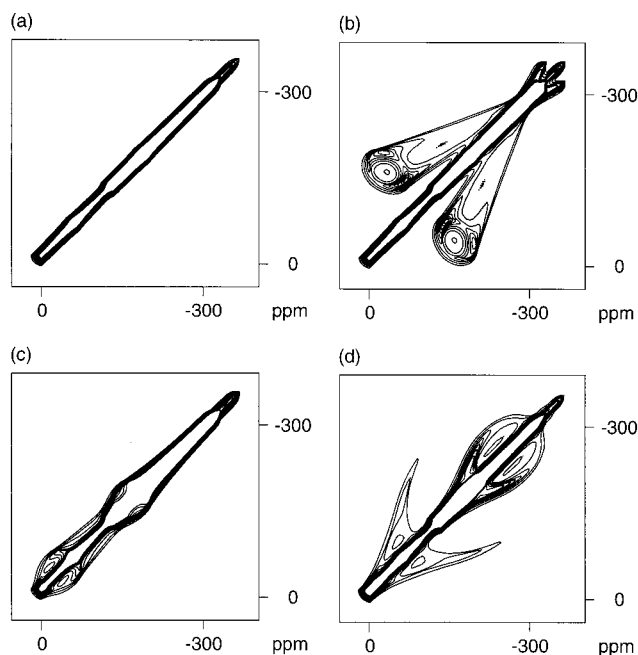
Simulations of the expected nitrogen-15 exchange NMR intensities for **1** were carried out, assuming a planar flip of the shift tensor for the “reorientation” step common to the proposed H<sup>+</sup> transfer mechanisms. The principal values of the two nitrogen-15 shift tensors (see Table 1) and the orientations of their principal axis systems relative to the ring were taken from Solum et al.<sup>9</sup> The proton “migration” step (Figure 1) involves chemical exchange of the two nitrogen sites, while the subsequent flip corresponds to a 36° reorientation of the two least shielded principal components of both shift tensors (see Figure 3), but does not affect the most shielded components which are perpendicular to the ring.

Simulations of the two-dimensional powder patterns produced by nonspinning exchange experiments are shown in Figure 4 for (a) no reorientation, (b) proton migration followed by reorientation (Figure 1), and (c and d) isolated 36° planar reorientations around different shift tensor principal axes without prior proton migration. In all four cases equal populations in

(9) Solum, M. S.; Altmann, K. L.; Strohmeier, M.; Berges, D. A.; Zhang, Y. L.; Facelli, J. C.; Pugmire, R. J.; Grant D. M. *J. Am. Chem. Soc.* **1997**, *119*, 9804.



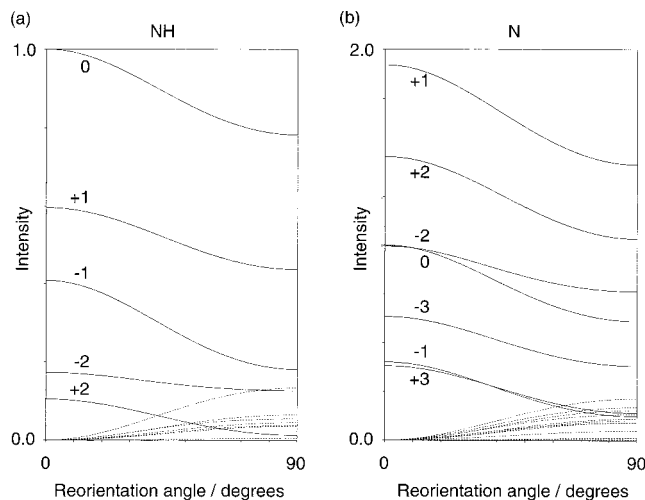
**Figure 3.** Orientation of nitrogen-15 shift tensor principal values with respect to **1** and their reorientation during a planar rotation of the ring.



**Figure 4.** Simulated two-dimensional expected nitrogen-15 exchange NMR spectra for **1** for (a) no reorientation, (b) proton migration followed by reorientation (as in Figure 1), and isolated  $36^\circ$  planar reorientations around the (c) 3 and (d) 1 shift tensor principal axes without prior proton migration. In all spectra nine contours are plotted at equal intervals between 4 and 20% of maximum intensity. The simulated spectra were convoluted with a Gaussian line broadening function to aid comparison with experimental results. Note the significant elliptical features away from the diagonal in all cases except part a.

the initial and final orientations were assumed, and nine contours are plotted at equal intervals between 4 and 20% of maximum intensity. All the simulated spectra were convoluted with a Gaussian line broadening function to aid comparison with experimental results. The elliptical features, which are clear in spectra b, c, and d, are characteristic of discrete molecular reorientations, coupled in the case of spectrum b with chemical exchange. Significant off-diagonal features appear in all cases at high-intensity levels (up to 20%), suggesting that if any of these dynamic processes were to occur in **1** they would be detectable by nonspinning exchange NMR experiments.

Cross-peak intensities for rotor-synchronized exchange experiments were also calculated for the same dynamic processes. Figure 5 shows the expected intensity of diagonal (solid lines) and cross-peaks (dotted lines) for an isolated flip, as a function of planar reorientation angle for (a) the NH and (b) the N site in **1**. Diagonal peaks corresponding to the centerband and



**Figure 5.** Calculated intensity of diagonal (solid lines) and cross-peaks (dotted lines) in two-dimensional rotor-synchronized experiments as a function of planar reorientation angle for (a) the NH and (b) the N site in **1**. Diagonal peaks corresponding to the centerband and sidebands out to  $\pm 3\omega_R$  ( $\pm 2\omega_R$  for NH) are shown as well as cross-peaks linking these in the two-dimensional spectrum. In each case the peak intensities are normalized to the intensity of the corresponding centerband diagonal peak. The curves for the diagonal peak are labeled with the sideband order  $N$  where  $N = 0$  corresponds to the centerband. The different cross-peak curves have not been labeled. Note the relative scaling of the plots which allows easy comparison of the diagonal intensities with the one-dimensional MAS spectrum of Figure 6. The calculations suggest that for a  $36^\circ$  reorientation angle the cross-peaks are small, and that the largest cross-peaks (at  $(\omega_1, \omega_2) = (-\omega_R, 0)$  and  $(0, -\omega_R)$  for the NH site) rise to less than 5% of the intensity of the NH centerband diagonal peak.

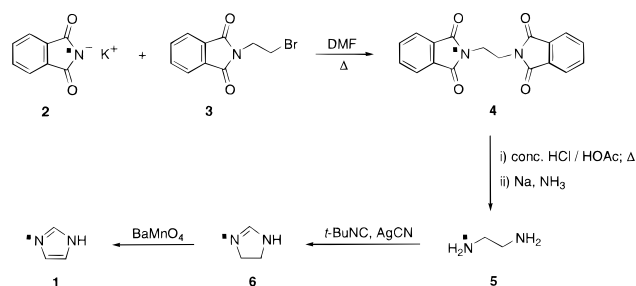
sidebands out to  $\pm 3\omega_R$  ( $\pm 2\omega_R$  for NH) are shown as well as cross-peaks linking these in the two-dimensional spectrum. In each case the peak intensities are normalized to the intensity of the corresponding centerband diagonal peak. The curves for the diagonal peak are labeled with the sideband order  $N$  where  $N = 0$  corresponds to the centerband. Note that while the most intense line for the NH site is the centerband, for the N site it is the sideband at  $+\omega_R$ . The relative scaling of the plots for the two sites will facilitate later comparison with experimental intensities. The simulations suggest that for a  $36^\circ$  reorientation angle the cross-peaks are small, and that the largest cross-peaks (at  $(\omega_1, \omega_2) = (-\omega_R, 0)$  and  $(0, -\omega_R)$  for the NH site) rise to 5% of the intensity of the NH centerband diagonal peak. Calculations for a flip preceded by proton migration result in similar exchange intensities with cross-peaks linking sidebands of the two nitrogen sites.

## Results and Discussion

The low natural abundance and magnetogyric ratio of nitrogen-15 necessitated the preparation of labeled imidazole ( $^{15}\text{N}_2\text{-1}$ ), which was conveniently done using a literature procedure.<sup>10</sup> The solid-state nitrogen-15 CP MAS NMR spectrum of  $^{15}\text{N}_2\text{-1}$  showed two isotropic chemical shifts corresponding to the two nitrogen sites at  $\delta -133$  (N) and  $-205$  (NH) ppm relative to  $\text{CH}_3\text{NO}_2$ . This is in contrast to the solution-state NMR spectrum that shows a single nitrogen-15 line at  $\delta -173$  ppm, which is close to the average of the two solid-state shifts. The spectrum indicates that the tautomeric exchange of **1** which occurs rapidly in solution is not observed on the NMR

(10) Alei, M., Jr.; Morgan, L. O.; Wageman, W. E.; Whaley, T. W. *J. Am. Chem. Soc.* **1980**, *102*, 2881.

## Scheme 1

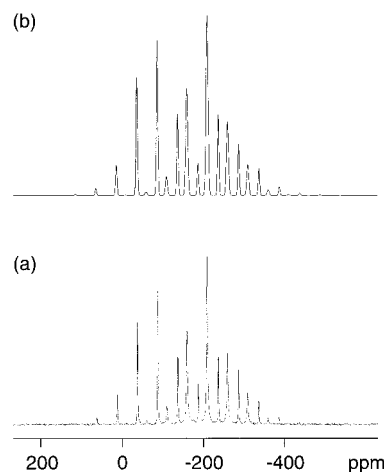


time scale in the solid. This conclusion has been drawn previously from both carbon-13<sup>11a</sup> and nitrogen-15<sup>11b</sup> CP MAS NMR spectra.

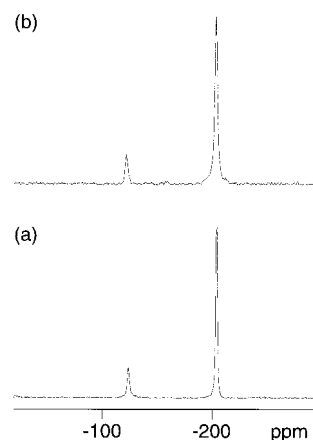
Significant cross-peaks linking the two nitrogen-15 resonances were observed in two-dimensional exchange spectra (not shown) recorded at a MAS rate of 5 kHz with mixing times as short as 100 ms. Their intensities were found to be independent of temperature over the range studied (293 to 348 K), and therefore their appearance was attributed to intramolecular spin diffusion in the doubly labeled sample. To minimize this effect, which severely limits the time scale over which molecular reorientations can be investigated, mono-<sup>15</sup>N-labeled imidazole was required. The one reported synthesis of <sup>15</sup>N-**1** was not preparative<sup>12</sup> and thus an alternative approach was devised as shown in Scheme 1.

Commercial potassium <sup>15</sup>N-phthalimide **2** reacts with *N*-(2-bromoethyl)phthalimide **3** to give the singly labeled diphthaloyl ethylenediamine derivative **4**. Acid hydrolysis gives the diamine salt that was treated with sodium and liquid ammonia to give the anhydrous free base **5**. Condensation of **5** with *tert*-butylisocyanide in the presence of a silver catalyst<sup>13</sup> gave 2-imidazoline **6** in 70% yield. Finally, dehydrogenation of **6** using barium permanganate<sup>14</sup> gave the target material <sup>15</sup>N-**1**, which was doubly sublimed for the NMR study.

Figure 6 shows (a) the experimental nitrogen-15 CP MAS NMR spectrum of <sup>15</sup>N-**1** at a spinning rate of 1.5 kHz and (b) a simulation based on the shift tensors of Solum et al.<sup>9</sup> As for <sup>15</sup>N<sub>2</sub>-**1**, two nitrogen-15 lines are observed at  $\delta$  -133 (N) and -205 (NH), and the two nitrogen-15 resonances of <sup>15</sup>N-**1** show temperature-independent cross-peaks in the exchange spectrum due to spin diffusion, but at much longer mixing times (less than 2% of maximum diagonal intensity at 0.5 s and less than 20% at 5 s). This reflects the greater N-N separation in neighboring molecules of at least 2.85 Å (NH...N), depending on which nitrogen sites are labeled, vs a fixed 2.21 Å separation in <sup>15</sup>N<sub>2</sub>-**1**.<sup>15</sup> Figure 7 shows cross sections through the 5 kHz MAS two-dimensional exchange spectrum parallel to  $\omega_2$  at the  $\omega_1$  frequency of the NH site recorded at (a) 293 and (b) 348 K with a mixing time of 5 s. Proton migration followed by a molecular flip (Figure 1) would be expected to produce temperature-dependent cross-peaks rising to intensities comparable to the diagonal peaks at mixing times equal to the correlation time. The lack of such cross-peaks in Figure 7 which



**Figure 6.** (a) One-dimensional nitrogen-15 CP MAS spectrum of **1**. Note the two sites centered at -133 and -205 ppm, each with a corresponding sideband manifold. Experimental details (where relevant for one-dimensional acquisition) were as for Figure 8. (b) Simulated spectrum.



**Figure 7.** Cross sections parallel to  $\omega_2$  through 5 kHz MAS two-dimensional nitrogen-15 exchange spectra at the  $\omega_1$  frequency of the NH site recorded at (a) 293 and (b) 348 K. The mixing time was 5 s, and the integrated intensity ratio of diagonal to cross-peaks was measured as 1:0.19 in each case.

would indicate an activated chemical exchange process rules out the occurrence of the proton "migration" step of Figure 1 on time scales up to several seconds.

To determine whether other dynamic processes occur in **1**, such as a planar reorientation without a proton "migration" step, nonspinning and slow MAS nitrogen-15 exchange NMR experiments were also carried out. Figure 8 shows two-dimensional nonspinning nitrogen-15 exchange NMR spectra recorded with mixing times of 0.5 s at (a) 293 and (b) 348 K. Nine equally spaced contour levels are plotted from 4% of the level of the maximum spectral intensity. The lowest level is well below that at which the elliptical features appear in the simulated spectra shown in Figure 4. The lack of off-diagonal intensity at these long mixing times indicates that any reorientation of imidazole molecules occurs with correlation times of several seconds, if at all. Similar spectra have been recorded with 5 s mixing times, and the ellipses are not observed even under these conditions, although the effect of spin diffusion obscures the results somewhat. Finally, two-dimensional rotor-synchronized nitrogen-15 exchange NMR spectra recorded at temperatures up to 348 K with mixing times of 0.5 s and MAS at 1.5 kHz do not show any cross-peaks. Hence, this new evidence drawn from a more direct NMR measurement of molecular dynamics suggests that

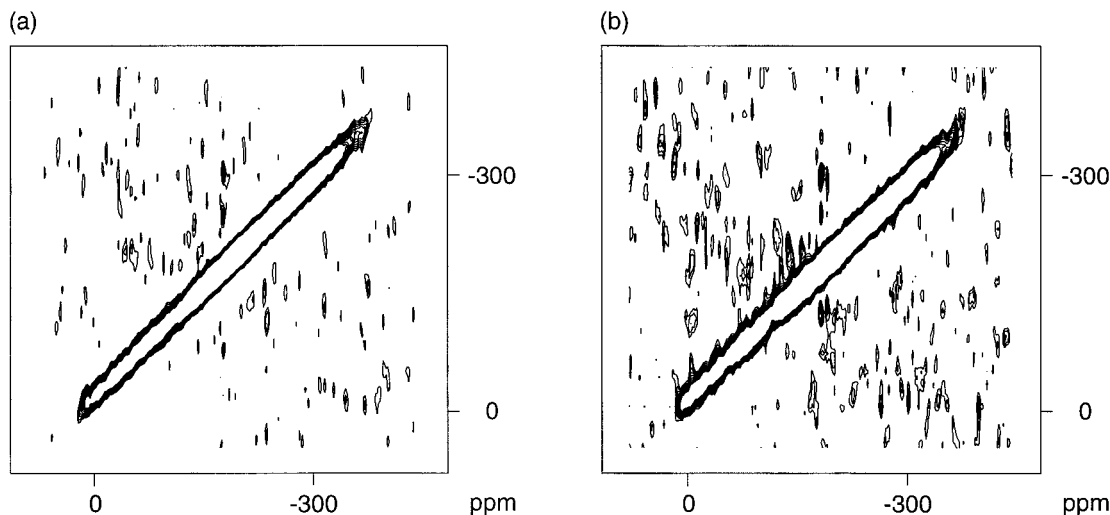
(11) (a) Elgeuro, J.; Fruchier, A.; Pellegrin, V. *J. Chem. Soc., Chem Commun.* **1981**, 1207. (b) Munowitz, M.; Bachovchin, W. W.; Herzfeld, J.; Dobson, C. M.; Griffin, R. G. *J. Am. Chem. Soc.* **1982**, *104*, 1192.

(12) Lont, P. J.; Van Der Plas, H. C.; Bosma, E. *Recl. Trav. Chim. Pays-Bas* **1972**, *91*, 1352.

(13) Method of Ito et al.: Ito, Y.; Inubushi, Y.; Zenbayashi, M.; Tomita, S.; Saegusa, T. *J. Am. Chem. Soc.* **1973**, *95*, 4447.

(14) Method of Hughey et al.: Hughey, J. L., IV; Knapp, S.; Schugar, H. *Synthesis* **1980**, 489.

(15) Craven, B. M.; McMullan, R. K.; Bell, J. D.; Freeman, H. C. *Acta Crystallogr., Sect. B* **1977**, *33*, 2585.



**Figure 8.** Part of the two-dimensional nonspinning nitrogen-15 exchange NMR spectra recorded with mixing times of 0.5 s at (a) 293 and (b) 348 K. Nine equally spaced contour levels are plotted from 4% of the level of the maximum spectral intensity. Note that the lowest level is well below that at which the elliptical features appear in the simulated spectra shown in Figure 4. No elliptical features appear in the experimental spectra away from the sharp diagonal ridge expected for the case of no reorientation (Figure 4a). The framing box and scales are drawn slightly outside the plotted region, and only positive contour levels are shown for clarity, since there was only noise at the corresponding negative level. Typical experimental details were as follows: relaxation delay 120 s, cross polarization time 5 ms, nitrogen-15 Larmor frequency 30.4 MHz, mixing time 0.5 s, spectral width in both dimensions 60 kHz, proton and nitrogen-15  $90^\circ$  pulses 4 and 5  $\mu$ s respectively, acquisition time 17 ms, datasets zero-filled to  $1024 \times 256$  points and Gaussian broadened prior to Fourier transform.

the  $1 \text{ s}^{-1}$  relaxation process apparently measured by Daycock<sup>7a</sup> is not associated with an imidazole ring reorientation.

## Conclusion

Solid-state exchange NMR experiments using mono- $^{15}\text{N}$ -labeled imidazole have shown that neither chemical exchange nor molecular reorientation occur at rates up to and beyond that which would be required to account for the reported conductivity based on the prevailing mechanisms. The findings reported here discount earlier support of these mechanisms based on proton NMR measurements.<sup>7a</sup> Hence two possible conclusions can be drawn: Either (a) the mechanism of conduction does not involve a Grothuss or related process on this time scale, but some other means of charge tunneling, or (b) the anisotropy of the already low conductivity with respect to crystallographic direction is an artifact, and no anomalous charge mobility is present in **1**. The fact that the three published studies of conduction in single crystals of imidazole<sup>3c-e</sup> do not come to a consensus with respect to the magnitude of conductivity is perhaps an indication of the latter.

## Experimental Section

**General.** All compounds described below were identical by melting point (or boiling point) and  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopy (allowing for  $^{15}\text{N}$  couplings) with the corresponding unlabeled compounds already described in the literature. It is important to note that the ethylenediamine **5** must be kept anhydrous as the subsequent reaction with *tert*-butyl isocyanide fails with the monohydrate.

**$^{15}\text{N}$ -ethylenediamine Bis(phthalic acid imide) (4).** A solution of the potassium salt of  $^{15}\text{N}$ -phthalimide **2** (98 atom %  $^{15}\text{N}$ , 4.98 g, 26.7 mmol) and *N*-(2-bromoethyl)phthalimide **3** (6.85 g, 27.0 mmol) in dry DMF (70 mL) was heated at  $90^\circ\text{C}$  for 12 h. The solvent was evaporated under high vacuum to leave a pale yellow solid, which was partitioned between water (20 mL) and ether (50 mL). The layers were separated, the aqueous phase extracted with ether ( $2 \times 20$  mL), and the combined

organic fraction dried over  $\text{MgSO}_4$ . Evaporation of the solvent gave **4** (8.30 g, 97%) as a pale yellow solid.

**$^{15}\text{N}$ -Ethylenediamine (5).** Compound **4** (8.30 g, 25.8 mmol) was added to a mixture of concentrated hydrochloric acid (200 mL) and glacial acetic acid (200 mL) and the reaction was heated at  $80^\circ\text{C}$  for 12 h. The volatiles were evaporated to leave **5**·2 HCl as a white crystalline solid, which was triturated with dry methanol and dried under vacuum. A solution of sodium (1.0 g, 43 mmol) in liquid ammonia (100 mL) was prepared and the above hydrochloride (3.04 g) introduced in small portions over a 10 min period. The mixture was stirred for 20 min and then the cooling bath was removed. The ammonia was evaporated in a stream of dry nitrogen to leave a white solid. The solid was heated under high vacuum in a short-path distillation apparatus and the free base collected in a receiving flask cooled to  $-78^\circ\text{C}$ . On warming to ambient temperature the white solid product **5** was obtained as a colorless oil (1.26 g, 80%).

**4,5-Dihydro-1H- $^{15}\text{N}$ -imidazole (6).** To a neat mixture of **5** (1.26 g, 20.6 mmol) and *tert*-butyl isocyanide (1.81 g, 21.8 mmol) was added catalytic silver cyanide (0.14 g, 1.0 mmol) and the reaction was heated at  $90^\circ\text{C}$  with stirring for 20 h. The reaction mixture was distilled to give **6** (1.03 g, 70%) as a waxy white solid, bp  $96\text{--}98^\circ\text{C}$  at 14 Torr.

**1H- $^{15}\text{N}$ -Imidazole (1).** Imidazoline **6** (1.03 g, 14.5 mmol) was added to a stirred suspension of barium permanganate (20 g) in dry  $\text{CH}_2\text{Cl}_2$  (50 mL) and the mixture heated at vigorous reflux for 40 h. The reaction was filtered through Celite and evaporated to leave the crude product as a waxy, pale purple solid. Sublimation in a vacuum at  $90^\circ\text{C}$  gave white crystals, which were collected and resublimed to give **1** (0.46 g, 46%) as a white crystalline solid.  $^{15}\text{N}$  NMR (50.7 MHz,  $\text{CDCl}_3$ ):  $\delta$   $-173.0$  [lit.<sup>16</sup>  $-172.6$  (natural abundance sample)].

**Acknowledgment.** The authors thank Beat Meier (ETH, Zürich), Ken Packer, and Martin Willis (Nottingham) for helpful discussions and the EPSRC for financial support (Grant No. GR/L26742).

JA991401L

(16) Chen, B. C.; von Philipsborn, W.; Nagarajan, K. *Helv. Chim. Acta* **1983**, *66*, 1537.