Neutron and X-ray Diffraction, Inelastic Neutron Scattering, and Solid-State ^{13}C NMR Investigations of Polymorphic *p*-Chlorophenylformamide: Absence of Proton Transfer along the Intermolecular N−H···O Hydrogen Bond

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Neutron and X-ray crystal structures of *p*-chlorophenylformamide (ClC_6H_4NHCHO, **1**) have been determined after recrystallization from methanol and acetone solvents. Acetone and methanol grown samples are polymorphic, where the central layer of a three layer asymmetric unit is partially (0.37:0.63) reversed within the acetone grown crystal. All structures reveal that the formamide group is essentially coplanar with the chlorophenyl ring. The possibility of hydrogen atom transfer between amide and iminol tautomers has been ruled out on the basis of crystallographic results and additional ^{13}C CPMAS NMR and inelastic neutron scattering investigations. Only infinite chains of hydrogen-bonded formamide units are found in the crystal. Compound **1** crystallizes from methanol in the orthorhombic space group $P2_12_12_1$ (Mo Kα radiation; 173 K; $Z = 4$; $a = 6.1356(2)$ Å, $b = 9.5362(3)$ Å, $c = 11.8990(4)$ Å; $V = 696.2$ Å^3) and (neutron radiation; 20 K; $Z = 4$; $a = 6.0873(10)$ Å, $b = 9.5095(15)$ Å, $c = 11.814(5)$ Å; $V = 683.9$ Å^3). From acetone, a supercell is observed for crystalline **1**, where $3a = c$ ($P2_12_12_1$; Mo Kα radiation; 173 K; $Z = 12$; $a = 9.5704(2)$ Å, $b = 11.9479(1)$ Å, $c = 18.4555(2)$ Å; $V = 2110.3$ Å^3).

Introduction

Hydrogen bonding can account for the unique physical properties of H_2O, promote stereochemistry in synthetic reactions, and control the structures of a vast multitude of biomolecules, host−guest complexes, and supramolecular assemblies. The amide N−H···O═C hydrogen bond is of paramount importance to molecular structure in biological and chemical systems.[1] A fundamental question remains whether hydrogen has two nondegenerate configurations within the amide hydrogen bond in the solid state. If there are indeed two minima, proton transfer can occur between the nitrogen and oxygen atoms, producing two tautomeric amide and iminol structures, as represented in Figure 1. A double minimum involving proton transfer is a proposed mechanism in protein-mediated proton transport and proton exchange.[2,3]

Infrared,[4] isotopic perturbation nuclear magnetic resonance,[5] vibrational spectroscopy with inelastic neutron scattering,[6] and picosecond-infrared-excitation experiments[7] all support the existence of double minima in hydrogen bonds; however, none of these techniques can as yet determine exact locations of minima, for which additional diffraction data must be collected. Acetanilide is usually used as a simple analogue of proteins because of infinite, single chains of hydrogen-bonded amide groups that form within the crystal. The crystal structures of acetanilide using both X-ray[8−10] and neutron[11] diffraction at room temperature and low temperature (113 K for X-ray and 15 K for neutron) have not revealed evidence for proton transfer along the N−H···O hydrogen bond.

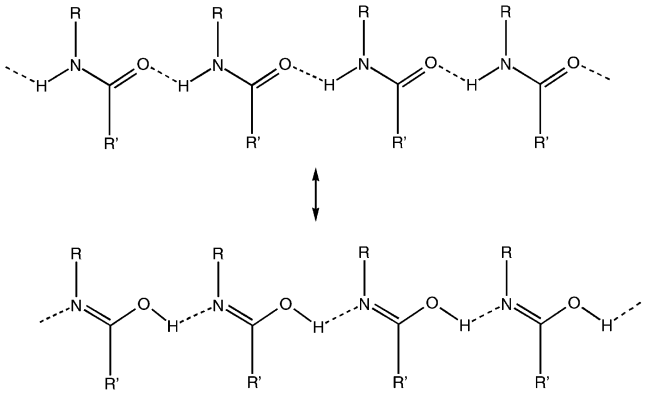

Figure 1. Schematic representation of the proton transfer interconverting amide and iminol forms.

Previously we have investigated the high-yield synthesis of a series of aryl *N*-monosubstituted formamides.[12] These compounds are produced in one step by the reduction of an aryl nitro group with tin in the presence of toluene/formic acid that traps the generated amine as the formamide. N-Monosubstituted formamides have found utility in the synthesis of biologically active compounds,[13] in the catalytic generation of *N*,*N*′-diarylureas,[14] as candidates for cancer chemotherapeutic agents,[15] as well as important precursors in the synthesis of isocyanides (R−NC).[16] This paper focuses on the use of single-crystal neutron and X-ray diffraction, solid-state ^{13}C NMR, and inelastic neutron scattering (INS) to study polymorphic forms of **1** and the possibility of proton transfer along the intermolecular N−H···O hydrogen bond.

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TABLE 1: X-ray and Neutron Crystallographic and Structure Refinement Data of 1 Grown from Different Solvents

crystallization solvent	methanol	methanol	acetone
radiation type	X-ray	neutron	X-ray
temperature (K)	173	20	173
composition	C_7H_6ClNO	C_7H_6ClNO	C_7H_6ClNO
crystal size (mm)	$0.20 \times 0.16 \times 0.14$	$5 \times 4 \times 0.7$	$0.32 \times 0.21 \times 0.11$
formula wt	155.58	155.58	155.58
crystal system	orthorhombic	orthorhombic	orthorhombic
space group	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$
wavelength (Å)	0.71073 Å	0.7−4.2 Å	0.71073 Å
a (Å)	6.1356(2)	6.0873(10)	9.5704(2)
b (Å)	9.5362(3)	9.5095(16)	11.9479(1)
c (Å)	11.8990(4)	11.814(5)	18.4555(2)
V (Å^3)	696.21(4)	683.89	2110.32(5)
Z	4	4	12
d_{calcd} (g cm^{-3})	1.484	1.484	1.469
θ range	2.74°−25.05°		2.03°−25.03°
index ranges	$-7 \le h \le 7$	$-13 \le h \le 13$	$-11 \le h \le 11$
	$0 \le k \le 11$	$-20 \le k \le 10$	$0 \le k \le 14$
	$0 \le l \le 14$	$-26 \le l \le 1$	$0 \le l \le 21$
reflections collected	3560	6642	9760
independent reflections	1235 ($R_{int} = 0.0345$)	2366	3627 ($R_{int} = 0.0227$)
parameters/restraints	91/0	174/0	315/300
μ (cm^{-1})	4.68	$1.14 + 0.79\lambda$	4.63
F(000)	320		960
R	0.0531	0.094	0.0451
wR	0.1495	0.096	0.1184

Experimental Section

p-Chlorophenylformamide (**1**) was synthesized according to ref 12 and recrystallized from acetone before further crystallization in other solvents. MS *m*/*e* found 155, calcd 155.58. *E* isomer: 40% abundance. ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.65 (1 H, d, −CHO), 8.61 (1 H, broad doublet, −NH−), 7.50 (2 H, d, 2 and 6-H), 7.29 (2 H, d, 3 and 5-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 162.79 −CHO, 135.57 C_4, 130.95 C_1, 129.30 C_3 and C_5, 121.41 C_2 and C_6. *Z* isomer: 60% abundance. ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.36 (1 H, s, −CHO), 7.66 (1 H, broad singlet, −NH−), 7.30 (2 H, d, 3 and 5-H), 7.05 (2 H, d, 2 and 6-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.29 −CHO, 135.46 C_4, 130.04 C_1, 130.01 C_3 and C_5, 120.24 C_2 and C_6. Solid State ^{13}C NMR (*Z* isomer, vide infra) (75 MHz, peaks ∼170 Hz fwhm): δ 161.6 −CHO, 139.5 C_4, 129.4 C_1 (d, $J_{13C-14N} = 570$ Hz), 131.8 and 130.6 C_3 and C_5, 122.0 C_2 and C_6. For single crystals grown by slow evaporation of acetone, mp = 102−104 °C. Elem Anal. Found: C, 54.30; H, 4.00; N, 9.05; Cl, 22.96. Calcd: C, 54.04; H, 3.89; N, 9.00; Cl, 22.79.

N-Deuterated samples for INS spectra were synthesized by successive isotopic substitution using CH_3OD (Aldrich). Subsequent analysis by proton NMR showed almost complete loss of the amide proton signal. Solid-state ^{13}C NMR spectra were acquired at 75.4 MHz with a Chemagnetics CMX-300 solid-state NMR spectrometer on samples packed in zirconia rotors and spun at the magic angle (5.2 kHz).

X-ray Diffraction. Single crystals of **1** were grown either by slow evaporation from methanol or acetone. The crystals were attached to a glass fiber and mounted on the Siemens SMART system for data collection at 173(2) K. An initial set of cell constants was calculated from reflections harvested from three sets of 20 frames. These initial sets of frames are oriented such that orthogonal wedges of reciprocal space are surveyed. This produced initial orientation matrixes determined from ∼100 reflections. Final cell constants were calculated from a large set of strong reflections from the actual data collection. A summary of data collection and refinement information is given in Table 1.

Structures were solved and refined using SHELX-86 and SHELX-97. The space group $P2_12_12_1$ was determined in all cases on the basis of systematic absences and intensity statistics.[17] All non-hydrogen atoms were refined with anisotropic displacement parameters unless stated otherwise. All hydrogen atoms, except the amide proton, were placed in ideal positions and refined as riding atoms with relative isotropic displacement parameters.

For the acetone-crystallized structure the specimen is racemically twinned in a 0.37:0.63(1) ratio. The C−H and N−H bond distances are set for X-ray refinements, and numerous restraints were employed to differentiate the disordered *p*-chlorophenylformamide groups. *p*-Chlorophenylformamide groups were used as templates in conjunction with the SHELXTL SAME restraint. In addition, the SHELXL FLAT, ISOR, and EADP restraints were used with 288 restraints in total. The central layer of a three-layer asymmetric unit was found to be disordered and attempts to move the disorder to each of the other two layers met with no success. Unless the disorder was localized on the central layer, the *R* value was about twice as large. Also creating a subcell by keeping *a* and *b* the same and dividing *c* by 3, which eliminated all of the reflections where the *l* index was not a multiple of three, gave about the same *R* value and the same amount of disorder found in the good solution. This is the original cell found with the crystal grown from methanol, which was not found to be disordered (Table 1).

Neutron Diffraction. Neutron diffraction data were collected at the Intense Pulsed Neutron Source (IPNS), Argonne National Laboratory. A colorless platelike crystal of approximate dimensions $5 \times 4 \times 0.7$ mm^3 and with a mass of 25.3 mg was mounted on the SCD.[18] Data were collected at 20 K using a pulsed neutron beam with a wavelength range of 0.7−4.2 Å. The crystal was mounted in an aluminum foil heat shield within the SCD aluminum vacuum chamber at 10^{-7} Torr. In all, 28 histograms were collected, 10 of which for 5 h each and 18 of which for 3.25 h each. Integrated intensities were corrected for the wavelength dependence of the incident spectrum measured with a vanadium standard, the detector efficiency, a Lorentz factor, and a face-indexed absorption correction [μ (cm^{-1}) = $1.14 + 0.79\lambda$, maximum transmission = 0.82, and minimum transmission = 0.26]. Of 6642 possible measured reflections,

4953 (75%) had intensity greater than $3\sigma(I)$ and 2629 (40%) above 10, where $\sigma(I)$ is the standard deviation derived from counting statistics. Symmetry-related reflections were not averaged since, being measured at different wavelength, different extinction correction factors were applicable to each reflection.

On refinement of the data it became obvious that the structure was disordered with hydrogen-bonded chains in the crystal occasionally running in the opposite direction. Evidence for a $3a \times b \times c$ supercell that was observed in the X-ray diffraction experiments (below) conducted on the acetone-grown sample was also seen for this crystal. However, the supercell intensities are very weak in comparison to the normal cell, and therefore, a disordered model was used to fit the data.

A mirror image of the molecule was created with the atomic coordinates constrained to $x = x'$, $y = -y'$, and $z = z'$. In addition, the fractional occupations of the molecules were constrained to add up to one and the isotropic thermal parameters were constrained so that for atom n and its mirror image n', $U_{iso}(n) = U_{iso}(n')$. The coordinates, the fractional occupations, and the isotropic thermal parameters were then refined. Upon convergence the thermal parameters of the minor component were fixed and anisotropic thermal parameters were refined for the major component. The fractional occupation of the minor component refined to 13.2(5)%. This refinement procedure resulted in more agreeable *R*-factors and anisotropic thermal parameters, although the atomic displacements are still extended along the [010] direction. The refinement was based upon F^2 using the GSAS software package for the structural analysis.[19] Weights were assigned as $wF_o=1/\sigma_c^2(F_o^2)$, where $\sigma_c^2(F_o^2)$ is the variance based on counting statistics. The unit cell, experimental parameters, and refinement data are given in Table 1.

INS Spectra. Inelastic neutron scattering spectra were recorded using the CHEX inelastic neutron spectrometer at IPNS also located at Argonne National Laboratory. The CHEX spectrometer utilizes a fixed final energy, with the time-correlation of the pulsed source providing the energy transfer determination. The spectrometer incorporates a time focusing design to achieve an energy resolution ($\Delta\nu/\nu$) of <2% for frequencies below 2000 cm^{-1}. All spectra were collected at 173 K, the same temperature at which the X-ray crystal structures were determined. Additional experimental INS parameters have previously been published.[20]

Results and Discussion

^{1}H NMR of **1** indicates that two isomers coexist in solution, attributed to hindered rotation about the amide N−C bond on the NMR time scale. In $CDCl_3$, The *E* and *Z* isomers (*E* represents the cis isomer, where the aldehyde proton and the phenyl ring are located on the same side of the amide N−C bond) exist in 40:60 relative abundance. In MeOH-d_4, this ratio changes to 15:85, and with acetone-d_6 only the *Z* isomer is observed. Elemental analyses obtained for crystalline material of **1** grown from acetone closely match predicted values and indicate that solvent is not trapped within the lattice of these crystals.

Methanol-Crystallized X-ray Structure Determination. An initial low-temperature X-ray structure determination of **1** grown from methanol was conducted and a structure obtained. No solvent was found in the crystal and the ClC_6H_4 fragment is found to be pseudosymmetric. In all cases, the Cl, N, and two aromatic ring carbon atoms lay close to the plane $y = 1/2$ and the other two pairs of ring carbon atoms are approximately related by reflection across this plane. The remainder of the atoms in the formamide break this pseudosymmetry, and the amide fragment adopts the *Z* (trans) geometry. It appears that the methanol-crystallized specimen is nearly 100% ordered; however, the difference Fourier does contain one 1.0 e $Å^{-3}$ peak midway between the nitrogen of one group and the oxygen in the hydrogen bond. This was converted into an amide proton and refined in a separate model. It refined to a position midway between these atoms, but the isotropic temperature factor became nonpositive definite. It is possible this difference Fourier peak is due to a small percentage of disordered formamide groups as observed in the neutron structure and acetone-grown supercell structure presented below. A hydrogen bond between infinite chains of unique *p*-chlorophenylformamide groups links N−H···O (2.908(5) Å) fragments, and another hydrogen bond links C(7)−H···Cl (3.781(4) Å) fragments in adjacent chains. The amide N−C(7) bond distance (1.334(5) Å) and the O−C(7) bond distance (1.218(5) Å) are typical of normal amide linkages.

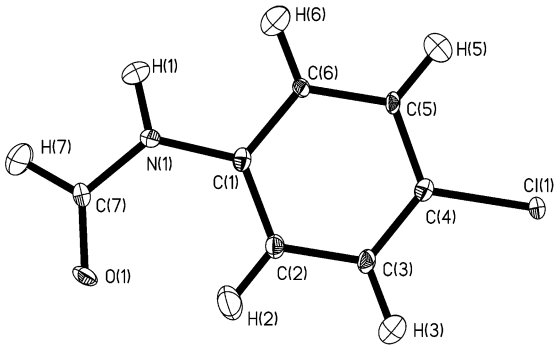

Figure 2. Thermal ellipsoid diagram (50% probability) of **1** crystallized from methanol (neutron data, 20 K). Cl−C(4) = 1.7424(16) Å; C(1)−N = 1.4118(19) Å. Other significant distances and angles are listed in Table 2.

TABLE 2: Significant Interatomic Distances (Å) and Angles (deg) of 1

distance or angle	methanol		acetone, 173 K (av or range)	other formamides[20−22]
	X-ray, 173 K	neutron, 20 K		
N-C(7)	1.334(5)	1.352(3)	1.357(5)	1.34(1)
C(7)−O	1.218(5)	1.221(4)	1.223(3)	1.21(1)
N−H		1.018(5)		
N−H···O	2.908(5)	2.866(3)	2.89−2.93(1)	
N−H···O angle		170.1(4)		
Cl···H(7)−C(7)	3.781(4)	3.780(2)	3.77−3.83(1)	
C1−N1−C7−O1 torsion angle	7.9(6)	6.6(3)	5.3(6)	35−84

Methanol-Crystallized Neutron Structure Determination. Due to the uncertainty of the amide-iminol hydrogen position in the above X-ray structure, a data set at 20 K was collected at the Intense Pulsed Neutron Source at Argonne Laboratory, Argonne, IL. A thermal ellipsoid diagram with atom labels is given in Figure 2, and selected bond distances are provided in the figure caption and Table 2. These results clearly establish that the H(1) atom is covalently bonded to N(1) and has not transferred to O(1). The N(1)−H(1)···O(1) hydrogen bond has distances of N(1)···O(1) = 2.866(3) Å and H(1)···O(1) = 1.857(5) Å and an angle of N(1)−H(1)···O(1) = 170.1(4)°. Examination of the final Fourier and difference Fourier does not show any evidence of proton transfer. Figure 3 also shows the infinite linear chains of hydrogen-bonded formamide units formed within the crystal.

Whereas little disorder was observed in the previous X-ray structure, hydrogen-bonded chains were found to occasionally run in the opposite direction in this sample. A mirror image of the molecule was created with the atomic coordinates con-

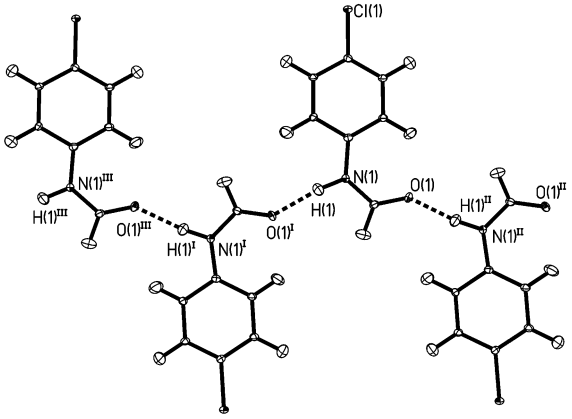

Figure 3. The chain of hydrogen-bonded formamide units in the neutron structure of **1**.

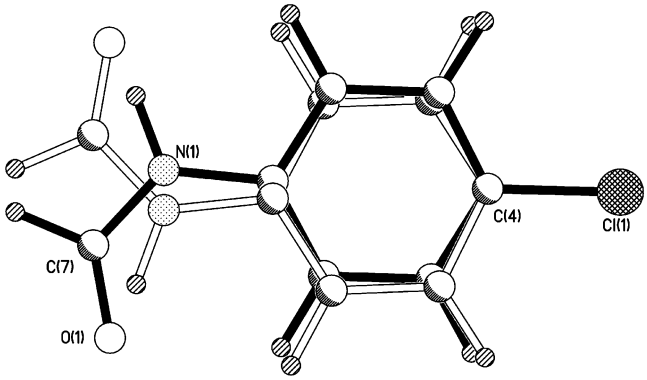

Figure 4. The disordered model. The minor component (~13%) has been draw with hollow bonds; atoms C(4) and Cl(1) are not disordered.

strained to $x = x'$, $y = -y'$, and $z = z'$, and the fractional occupations of the molecules were constrained to add up to 1. Both the major and minor components representing the modeled disorder are shown in Figure 4. The minor component is ~13% occupied and improved the overall residual. Additional evidence for a $3a \times b \times c$ supercell was also observed; however, the supercell intensities are very weak in comparison to the normal cell, and therefore, a disordered model was used to fit the data. This supercell has been further characterized in samples of **1** crystallized from acetone.

Acetone-Crystallized X-ray Structure Determination. A low-temperature X-ray structure analysis of single crystals of **1** grown by slow evaporation from acetone was also completed. Cell constants indicate that this structure is essentially a superlattice of the previously determined structures where the *a* lattice constant has tripled in length (now the *c* lattice constant in the acetone structure). The superlattice is caused by a disorder in the orientation of **1** in the central layer of a three layer asymmetric unit. Figure 5A shows the minor component where the amide fragment of the central layer is aligned in the same direction. In Figure 5B, the amide fragment of the central layer is reversed. A and B are found in a 0.37:0.63 ratio, respectively. Notably, however, the molecule is always found in the *Z* configuration. The amide N−C(7) bond distance (1.357(5) Å, av) and the O−C(7) bond distance (1.223(3) Å, av) are typical of regular amide distances.

Common with all the structures, the formamide group is almost coplanar with the rest of the molecule. The carbonyl group is twisted out of the plane of the phenyl ring by 5.3(6)° compared to the range of 35°−84° for five other formamide crystal structures previously determined.[22−24] Similarly, the least-squares plane composed of Cl, C(1),C(2), C(3), C(4), C(5), C(6), and N(1) (mean deviation = 0.0135 Å) has a dihedral angle of 7.6° with the least squares plane of N(1), C(7), and O(1). Two types of hydrogen bonds exist: (1) between infinite chains of unique *p*-chlorophenylformamide groups linking N−H···O−C(7) fragments and (2) between C(7)−H···Cl−C(4) fragments of adjacent chains. These range between 2.89−2.93(1) Å (N−H···O) and 3.77−3.83(1) Å (C(7)−H···Cl), respectively. Sufficient single-crystal neutron diffraction data were also obtained on crystals grown from acetone that confirms the supercell found in the X-ray analysis; however, modeling the layered disorder of this structure was not successful using either GSAS or SHELX.

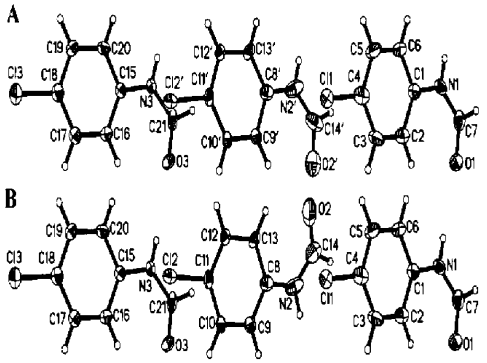

Figure 5. Diagram of minor (A, 37%) and major (B, 63%) disorder of the center layer (formamide groups in the central layer point in opposite directions).

TABLE 3: ^{13}C NMR Chemical Shifts of 1[a]

	$CDCl_3$		solid-state
assignment	*E* (40%)[b]	*Z* (60%)[b]	*Z* (100%)[b]
C1	130.95	130.04	129.4 ($J_{^{13}C-^{14}N}$ = 570 Hz)
C2 and C6	121.41	120.24	122.0
C3 and C5	129.30	130.01	131.8 and 130.6
C4	135.57	135.46	139.5
C7	162.79	159.29	161.6

[a] Labeling is the same as in Figure 2. [b] Isomer abundance.

Solid-State ^{13}C NMR. In the present case, solid-state ^{13}C NMR may assist in observing similarities between solution and solid-state forms of **1**, differentiating between geometric *E* and *Z* isomers, and possibly distinguishing between polymorphic forms in crystalline solids.[25,26]

Due to the broadness of the solid-state ^{13}C resonances (~170 Hz fwhm), precise assignment of the solid-state structure of **1** as the *Z* isomer (vide ante, crystallographic results) is difficult, although overall chemical shifts do correlate well with those observed in $CDCl_3$ solvent (Table 3). Using interrupted decoupling methods where only the quaternary carbons are observed, C_1 appears as a doublet split by the quadrupolar ^{14}N nucleus of the pendent amide group ($J_{^{13}C-^{14}N}$ = 570 Hz), previously observed in other amides, and assists in assignment of this resonance.[27] Also, in the solid-state spectrum, C_4 has shifted ~5 ppm downfield, compared to the same resonance in solution, which is likely due to deshielding of C_4 caused by hydrogen bonding between the chlorine atom of a *p*-chlorophenylformamide group of an adjacent chain and the hydrogen on C_7. Finally, no significant change in chemical shift of the formyl carbon (C_7) is observed between solution and solid-state spectra, indicating that the structure of the formamide is relatively unchanged upon crystallization. Polymorphism could not be observed by solid-state ^{13}C NMR, since the resonances of methanol- and acetone-grown materials are essentially the same, except for small differences in peak width.

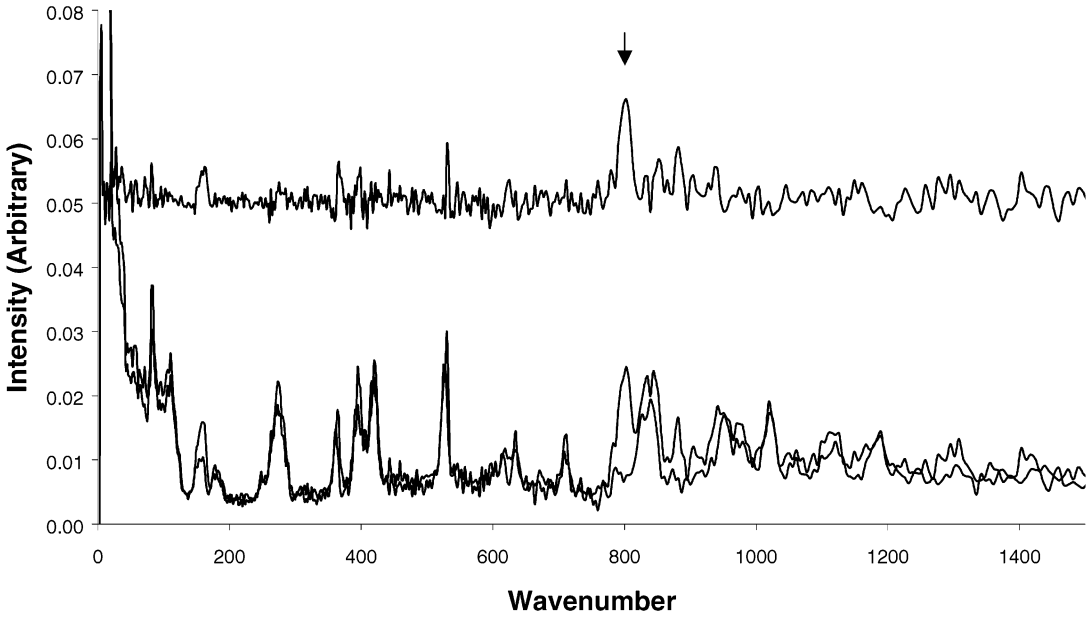

Figure 6. Experimental INS spectra of **1**, N-deuterated **1**, and the resulting difference spectrum. The cursor marks the NH wagging frequency in the difference spectrum.

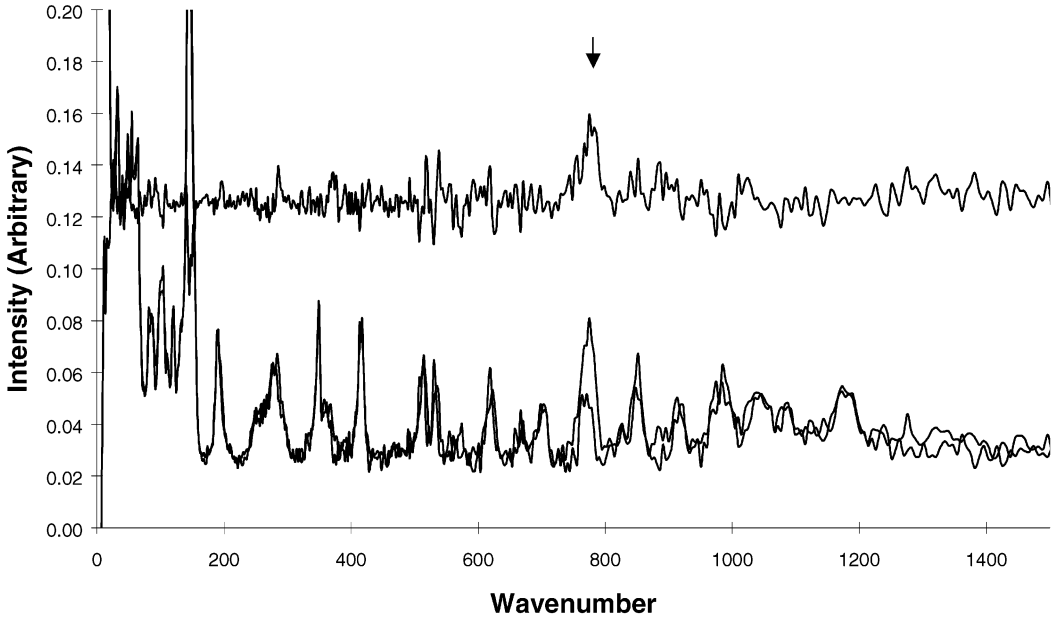

Figure 7. Experimental INS spectra of acetanilide, N-deuterated acetanilide, and the resulting difference spectrum. The cursor marks the NH wagging frequency in the difference spectrum.

INS Spectroscopy. INS is an attractive technique for studying hydrogen-bonded systems. This is because the low-frequency region, of interest for slow biological processes (often obscured by vibrational motions of other heavier atoms), is not accessible by conventional optical techniques. Specifically, INS has a preferential sensitivity for proton movements, since hydrogen has a high incoherent scattering cross section and all vibrational modes can be observed due to the lack of the symmetry selection rules necessary for other optical techniques. Large shifts in NH wagging frequencies have been previously observed between free and hydrogen-bonded amides molecules as compared to NH in-plane bending or NH stretching frequencies, which generally produce changes of less than 5%.[20,21] With successive isotopic exchange, deuterium can replace acidic hydrogens, which, by comparison, lends for easy identification of hydrogen-related vibrational motion.

Figure 6 shows the INS spectra at 173 K for acetone-crystallized **1** and its deuterium substituted (−NDCHO) analogue. The major feature of the difference spectrum is the peak centered at 802 cm^{-1}. This same feature has previously been observed in solid formamide itself ($HCONH_2$) at 841 cm^{-1} and in *N*-methylformamide ($HCONHCH_3$) at 824 cm^{-1}, also at low temperature.[20,21] These features are assigned to the NH wagging motions of an amide hydrogen and are supported by ab initio calculations of hydrogen-bonded networks of formamides in close agreement with the experimental results. Additionally, no appreciable differences in the INS spectra were found with the methanol-crystallized material as compared with the acetone-crystallized sample.

Because previous neutron and X-ray diffraction results do not support proton transfer in crystalline acetanilide ($CH_3CONHC_6H_5$),[11] INS spectroscopy of this material provides

an excellent opportunity for comparison with **1**. Figure 7 shows the INS spectra at 173 K for hydrogen- and deuterium-substituted ($CH_3CONDC_6H_5$) acetanilide with the NH wag in this case appearing at 775 cm^{-1} in the difference spectrum. This resonance is again consistent with a normal amide proton. Acetanilide likely has a lower stretching frequency due to the increased donating ability of the methyl group attached to the carbonyl carbon.

Conclusions

Crystallographic results show that the chlorophenyl ring and formamide substituent in **1** are coplanar, affording the possibility of proton transfer between amide and iminol tautomers. The heavy atom positions in single-crystal X-ray diffraction results and the location of the proton by neutron diffraction quite definitively indicate that proton transfer between amides fragments in infinite chains of *p*-chlorophenylformamide has not occurred. However, methanol- vs acetone-grown crystals do produce polymorphic structures that can contribute to confusion in the crystallographic results about the exact location of the amide proton in the intermolecular N−H···O hydrogen bond.

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Supporting Information Available: Neutron and X-ray crystallographic information in CIF format for **1** crystallized from acetone and methanol is available. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Jeffrey, G. A.; Saenger, W. *Hydrogen Bonding in Biological Structures*; Springer: Berlin, 1994.

(2) Krimm, S.; Dwivedi, A. M. *Science* **1982**, *216*, 407.

(3) Tüchsen, E.; Woodward, C. *J. Mol. Biol.* **1985**, *185*, 421.

(4) Careri, G.; Buontempo, U.; Galluzzi, F.; Scott, A. C.; Gratton, E.; Shyamsunder, S. *Phys. Rev. B* **1984**, *30*, 4689.

(5) Perrin, C. L. *Science* **1994**, *266*, 1665.

(6) Kearley, G. J.; Fillaux, F.; Baron, M.-H.; Bennington, S.; Tomkinson, J. *Science* **1994**, *264*, 1285.

(7) Fann, W.; Rothberg, L.; Robertson, M.; Benson, S.; Madey, J.; Etemand, S.; Austin, R. *Phys. Rev. Lett*. **1990**, *64*, 607.

(8) Brown, C. J.; Corbridge, D. E. *Acta Crystallogr*. **1954**, *7*, 711.

(9) Brown, C. J. *Acta Crystallogr*. **1966**, *21*, 442.

(10) Wasserman, H.; Ryan, R.; Layne, S. *Acta Crystallogr. C* **1985**, *41*, 783.

(11) Johnson, S. W.; Eckert, J.; Barthes, M.; McMullan, R. K.; Muller, M. *J. Phys. Chem*. **1995**, *99*, 16253.

(12) Hrvatin, P.; Sykes, A. G. *SynLett.* **1997**, 1069.

(13) Kabayashi, K.; Nagato, S.; Kawakitu, M.; Morikawa, O.; Konishi, H. *Chem. Lett.* **1995**, 575.

(14) Kotachi, S.; Tsuji, Y.; Kondo, T.; Watanabe, Y.*J. Chem. Soc., Chem. Commun*. **1990**, 549.

(15) Petit, G. R.; Kalnins, M. V.; Liu, T. M. H.; Thomas, E. G.; Parent, K. *J. Org. Chem.* **1961**, *26*, 2563.

(16) Ugi, I.; Fetzer, U.; Eholzer, U.; Knupfer, H.; Offermann, K. *Angew. Chem., Int. Ed.* **1965**, *4*, 472.

(17) *SHELXTL-Plus V5.1*; Siemens Industrial Automation, Inc.: Madison, WI.

(18) (a) Schultz, A. J.; Van Derveer, D. G.; Parker, D. W.; Baldwin, J. E. *Acta Crystallogr*. **1990**, *C46*, 276. (b) Schultz, A. J. *Trans. Am. Crystallogr. Assoc*. **1987**, *23*, 61.

(19) Larson, A. C.; Von Dreele R. B. *GSAS General Structural Analysis System*; Los Alamos National Laboratory: Los Alamos, NM, 2000.

(20) Tam, C. N.; Bour, P. Trouw, F. R. *J. Phys. Chem*. **1997**, *101*, 5877.

(21) Bour, P.; Tam, C. N.; Trouw, F. R. *J. Chem. Phys*. **1998**, *108*, 351.

(22) Weeks, C. M.; Rohrer; D. C.; Warner, P. L., Jr. *Cryst. Struct. Commun*. **1978**, *7*, 719.

(23) Boeyens, J. C. A.; Denner, L.; Evans, D. G. *J. Cryst. Spectrosc. Res*. **1988**, *18*, 175.

(24) Salazar, L.; Espada, M.; Sanz, D.; Claramunt, R. M.; Elguero, J.; Garcia-Granda, S.; Diaz, M. R.; Gomez-Beltran, F. *J. Chem. Soc., Perkin Trans. 2* **1993**, 377.

(25) Padden, B. E.; Zell, M. T.; Dong, Z.; Schroeder, S. A.; Grant, D. J. W.; Munson, E. J. *Anal. Chem*. **1999**, *71*, 3325.

(26) Zell, M. T.; Padden, B. E.; Grant, D. J. W. Chapeau, M.-C.; Prakash, I.; Munson, E. J. *J. Am. Chem. Soc*. **1999**, *121*, 1372.

(27) Eichele, K.; Lumsden, M. D.; Wasylishen, R. E. *J. Phys. Chem*. **1993**, *97*, 8908.