Spectroscopic and Structural Signature of the CH−O Hydrogen Bond

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It has been observed that the vibrational stretching frequency of a C−H covalent bond commonly shifts to the blue and suffers intensity loss, when the CH engages in a hydrogen bond. However, the shift does not always occur in this direction, and there are cases when a CH blue shift may be present even in the absence of a CH···O interaction. Ab initio quantum calculations are used to analyze the structure, and vibrational and NMR spectra of small model systems containing both conventional and CH···O H-bonds, and thereby identify patterns that unambiguously signal the presence of a CH···O interaction.

Introduction

Hydrogen bonds are understood to be one of the most important sorts of molecular interactions in both chemistry and biology. Over the decades, there has developed a well recognized set of characteristics that are associated with such bonds.[1−4] The covalent O−H bond of a OH···X interaction typically undergoes a small stretch. From a spectroscopic perspective, the O−H stretching vibrational mode generally shifts to the red, whereas the band is strengthened and broadened. NMR spectra reveal a downfield shift of the bridging proton's chemical shift by several parts per million upon formation of the hydrogen bond. In fact, many of these characteristics are quantitatively correlated with the strength of the hydrogen bond, in that larger changes are commonly associated with a stronger and more attractive interaction.

In recent years, attention has intensified on unconventional hydrogen bonds,[5−10] wherein the donor XH group does not necessarily involve a very electronegative X atom like oxygen or nitrogen. In particular, the CH donor has won increasing consideration as a participant in hydrogen bonds of surprising strength and importance.[11−17] As data have accumulated concerning such CH···X hydrogen bonds, a number of facets of their behavior have gained some notoriety. In particular, in some instances the C−H stretching vibration has been found to shift to the blue,[18−28] rather than to the red, as is essentially always the case with conventional OH···X or NH···X interactions. Moreover, the corresponding C−H stretching band can lose, rather than gain intensity. However, at the same time, such effects are not universal, as CH···X bonds do not always shift to the blue nor lose intensity.[29−38] Whereas some patterns are beginning to emerge, there is not yet any widely accepted set of rules that allow one to confidently predict whether a given CH···X will shift to red or blue. When coupled with the observation that the shifts of CH bond frequencies, whether to the blue or to the red, are typically fairly small in magnitude, this lack of predictability has complicated attempts to use the vibrational frequency of the CH bond as an unambiguous marker of the presence of a CH···X hydrogen bond. Moreover, the intensity changes, whether plus or minus, are not necessarily correlated with the shift of the frequency.[39]

Another very important consideration arises from the fact that when two molecules interact with one another so as to form a hydrogen bond, it is not only the atoms and bonds that directly participate in the intermolecular hydrogen bond that are affected. The nature of the hydrogen bond interaction is such that its influence is felt even at some distance from the site of the actual attachment. For this reason, the simple observation that the stretching frequency of a given CH bond has shifted to the blue, or has lost intensity, cannot in and of itself be taken as compelling evidence that this proton serves as a bridge in a bona fide hydrogen bond. The literature is replete with examples of CH shifts that do not result from the participation of this group in a hydrogen bond.[24,40−42] Even when there is no intermolecular interaction at all, for example, interactions of CH bonds with nitrogen lone pairs on the same molecule can result in CH shifts,[43] as can Fermi resonance effects or the appearance of Bohlmann bands due to overtones.[44] Another factor originates in hyperconjugation,[45] as for example when the entire CH stretching region of dimethyl ether is blue-shifted when it acts as proton acceptor to water.[46] Likewise, CH blue shifts arise in formate, acetates, and carboxylic acids when their carboxylic group accepts a proton,[47,48] and the methyl CH stretches shift to the blue when the oxygen of dimethylformamide acts[49] as a proton acceptor. As yet another example, when triethylamine is paired with $HCCl_3$, it is not at all clear[50] whether the blue shift of the ethyl CH stretches are due to their direct interaction with chlorine atoms on the partner molecule or are a secondary, remote effect arising from the proton acceptance by the nitrogen atom. One proposal[51] attributes these peripheral blue shifts, and attendant bond shortenings, in certain fluoro-substituted hydrocarbons [52,53] to the stretching of the C−F bonds that are themselves engaged in hydrogen bonds.

Whatever their origin, it should not be assumed that all shifts of nonbonding CH stretching frequencies are consistently to the blue. For example, the methylene CH stretches of triethylamine[54] shift toward the red when its nitrogen atom acts as proton acceptor. Likewise, the CH stretching frequency of dimethylformamide shifts downward when its oxygen atom is engaged as a proton acceptor.[49] When proton acceptors are added to 1,2,4,5-tetrafluorobenzene, the CH bond of the donor shifts to the red.[55] A recent set of calculations[56] indicated that when complexed with an anion, the CH bonds of the donor will shift to the red if a single, linear hydrogen bond is formed, but in the opposite direction when two protons are donated in a

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bifurcated arrangement. On the other hand, other researchers note a blue shift in trifurcated arrangements.[57,58]

With regard to NMR spectra, it appears that the chemical shifts of bridging protons are shifted downfield, whether OH, NH, or CH.[59−61] Calculations have indicated there may be a correlation between the direction of the stretching frequency shift and the change of the chemical shift.[62] Moreover, a shift of as much as 2 ppm was observed in a series of bindone analogues, where the degree of the shift was correlated with the length of the hydrogen bond.[63] On the other hand, solid-state NMR spectroscopic studies combined with DFT calculations of other systems[64] have indicated a poor correlation between $\Delta\delta$ and the CH bond length. More importantly, these shifts may not signify a hydrogen bond at all but might be due simply to proximity to a C═O bond.[65] The chemical shift may also be affected by the hybridization of the carbon atom.[66]

In summary, then, it would appear that at this point in time, in contrast to the cases of conventional OH···X and NH···X hydrogen bonds, there are no consistent patterns in vibrational or NMR spectra that offer strong evidence of the presence of a CH···X hydrogen bond in a given system. This situation is unfortunate, as such interactions have shown that they can be surprisingly strong contributors to the collection of various factors that govern the structure and function of a plethora of different systems. The present work represents the beginning of a strategy to rectify this situation. Through the use of accurate quantum chemical calculations, a set of small model systems are constructed and carefully scrutinized. These systems are chosen so as to minimize complicating factors and allow unambiguous analysis of the effects of hydrogen bonds at various locations on each molecule upon the properties of both bridging and nonbridging atoms. The ensuing contrast permits the elucidation of the fingerprint of a CH···X hydrogen bond from spectroscopic and any available structural information. Whereas it is understood that the results pertain directly only to the model systems under scrutiny, the patterns should represent a solid starting point for treatment of larger and more complex systems.

Computational Methods

All calculations were performed at the correlated MP2 level[67,68] (inner-shells excluded from the correlation) using the *Gaussian 03* code.[69] A split-valence double-ζ quality 6−31+G(d,p) basis set was used for all calculations, including Cartesian d-polarization and diffuse functions for non-hydrogen atoms, and p-polarization functions for hydrogen. (The extension of basis set to triple-ζ quality (6−311+G**) was not found to change the results significantly.) Geometries were fully optimized with BSSE correction added directly to the potential energy surface[70] and without any symmetry constraints, with the following exceptions. Those structures containing a single CH···O interaction were optimized subject to the restriction that θ(CH···O) = 180°, to prevent cyclization and formation of additional hydrogen bonds that would complicate the analysis.

Interaction energies were computed as the difference in energy between the complex and the sum of isolated monomers, with basis set superposition error (BSSE)[71,72] corrected by the counterpoise procedure of Boys and Bernardi.[73] Unscaled vibrational frequencies are reported for all cases. (In certain cases, additional frequency calculations were performed via monodeuterium substitution to more clearly identify each individual O−H stretch of the participating water molecule.) NMR chemical shifts were computed using the gauge-including atomic orbital (GIAO) approach at the MP2 level, which has been shown to produce rather accurate data for hydrogen bonds.[74]

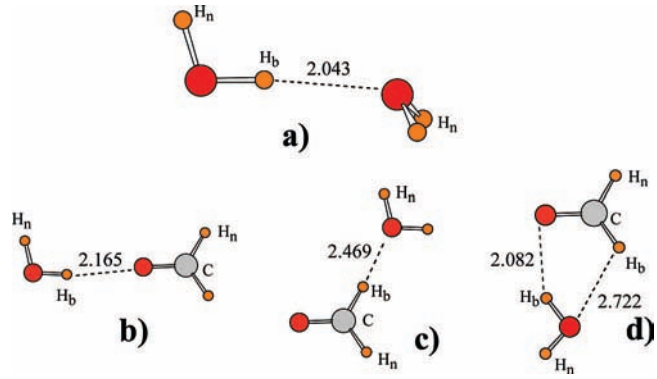

Figure 1. Molecular arrangements and atomic labeling of complexes containing HOH and H_2CO.

TABLE 1: Complexation Energy (kcal/mol) and Changes in Internal Bond Length (mÅ) of Complexes in Figure 1

	$-\Delta E^c$	OH_b	CH_b	OH_n	CH_n	C═O
a) HOH···OH_2	4.9	5.6		−0.9[d], 0.6[a]		
b) HOH···OCH_2	3.3	2.6		−0.7[d]	−1.5[a]	0.6[a]
c) HOCH···OH_2	2.0		−3.1	0.6[a]	1.4[d]	3.1[d]
d) HOCH···OH_2 (cyc)	4.8	5.4	−1.9	−1.0[b]	−1.9[b]	3.7

[a] Acceptor. [b] Both donor and acceptor properties in cyclic structure. [c] Corrected for BSSE by counterpoise method. [d] Donor.

Results

1. HOH and H_2CO. The optimized water dimer complex is illustrated in part a of Figure 1 wherein the bridging hydrogen is labeled H_b and H_n is used to denote nonbridging hydrogen atoms. Complexes pairing water with H_2CO are also depicted in Figure 1. Water acts as proton donor in part b of Figure 1, and its oxygen atom accepts a CH proton from H_2CO in part c of Figure 1. A cyclic complex is shown in part d of Figure 1 wherein both the HOH and H_2CO molecules act simultaneously as both donor and acceptor. The intermolecular R(H···O) distances reported in Figure 1 are consistent with the notion that OH···O hydrogen bonds are stronger, and also shorter, than their CH···O counterparts. The relative weakness of the latter is supported by the value of 2.0 kcal/mol for the CH···O interaction energy in part c of Figure 1 that is listed in the first column of data in Table 1.

The next two columns of Table 1 display the stretches and/or contractions undergone by the OH or CH covalent bonds that directly participate in the hydrogen bonds. It is immediately obvious that the hydrogen bond causes the OH bonds to stretch, whereas the CH bond contracts. The latter effect is not necessarily small; in fact the CH contraction in **1c** is larger in magnitude than the OH stretch in **1b**.

The next three columns of Table 1 report the bond length changes associated with the other covalent bonds of each monomer. First, in terms of the water molecule, the nonbridging OH bond contracts when HOH acts as proton donor, that is, it changes in the opposite direction from the bridging OH bond. On the other hand, when water serves as proton acceptor, its OH bonds undergo a small stretch. It is worth stressing that the changes in the nonbridging OH bonds, less than 1 mÅ, are considerably smaller than those in the bridging OH bond. Just as the CH and OH bonds behave in opposite fashion from one another when they participate in a hydrogen bond, so too are

TABLE 2: Vibrational Frequency Shifts Relative to Monomers (cm^{-1}) of Complexes in Figure 1

	OH_b[e]	CH_b	OH_n	CH_n	C═O
a) HOH···OH_2	−106		10[d], (−3,−8) [a,c]		
b) HOH···OCH_2	−34		8[d]	(18,26) [a,c]	3[a]
c) HOCH···OH_2		52	(−6,−9) [a,c]	−16[d]	−5[d]
d) HOCH···OH_2 (cyc)	−104	43	12[b]	27[b]	−9[a]

[a] Acceptor. [b] Both donor and acceptor properties in cyclic structure. [c] (sym,asym). [d] Donor. [e] Computed via monodeuterium substitution, so as to more clearly identify each individual O−H stretch.

TABLE 3: Intensification of Vibrational Modes Relative to Monomers, I/I_o of Complexes in Figure 1.

	OH_b	CH_b	OH_n	CH_n	C═O
a) HOH···OH_2	6.9		0.9[d],(1.6,1.3) [a,c]		
b) HOH···OCH_2	4.7		0.9[d]	(0.9,0.8) [a,c]	1.2[a]
c) HOCH···OH_2		0.2	(1.2,1.2) [a,c]	1.2[d]	1.0[d]
d) HOCH···OH_2 (cyc)	5.0	0.4	1.1[b]	0.9[b]	0.7[a]

[a] Acceptor. [b] Both donor and acceptor properties in cyclic structure. [c] sym,asym. [d] Donor.

they opposite when nonbridging. More specifically, the nonparticipating CH bond of H_2CO stretches as the bridging CH bond contracts when H_2CO acts as proton donor. It is interesting also that the changes undergone by the peripheral CH bonds, about 1.5 mÅ, are larger in magnitude than those of their OH analogues. The final column of Table 1 shows that the C═O bond of H_2CO stretches whether this molecule serves as proton donor or acceptor, although the stretch is much larger when a donor, notable in that the C═O bond is not itself directly involved in the hydrogen bond in the latter case.

The formation of each hydrogen bond induces changes into the stretching frequencies of each monomer. These shifts, displayed in Table 2, are consistent with numerous reports in the literature that bridging OH bonds shift to the red and CH shift toward higher frequency. The nonbridging bonds behave in an interesting fashion. When part of the donor molecule, the OH bonds shift to lower frequency, albeit by a small amount, less than 10 cm^{-1}. If part of the acceptor molecule, a small blue shift is observed, opposite to the large red shift of the bridging OH bond. Once again, the behavior of the CH bonds is opposite to their OH cousins: a fairly large blue shift occurs in the CH bonds when H_2CO acts as proton acceptor, and the nonbridging CH bond of the H_2CO donor shifts to the red. Changes in the C═O frequency are small, less than 10 cm^{-1}.

The changes in vibrational band intensity are illustrated in Table 3, wherein they are reported as the ratio between the value in the complex versus that in the optimized monomer. One may note a clear correspondence with the frequency shifts of OH and CH bonds in Table 2 in that red shifts lead to intensity enhancements ($I/I_o > 1$), and the reverse occurs for blue shifts. There is also a rough correlation between the magnitudes of these two effects.

The effects of complexation upon the NMR chemical shifts are documented in Table 4. Focusing first upon the bridging hydrogen atoms in the first two columns of data, the chemical shifts move downfield, OH more than CH. When the OH proton is not engaged in a hydrogen bond, the next column indicates a drastic lowering of any effect by about an order of magnitude. Likewise, the CH proton's shift is about 5 times smaller when it is peripheral rather than an active participant. The carbonyl oxygen atom in the next column undergoes a positive shift of 12−20 ppm as a proton acceptor atom, but a much smaller, and negative, shift when peripheral to the CH donor group. The

TABLE 4: Change in Isotropic NMR Chemical Shifts (ppm) of Complexes in Figure 1

	(O)H_b	(C)H_b	(O)H_n	(C)H_n	$O_{C=O}$	C
a) HOH···OH_2	−2.6		0.3[c],−0.5[a]			
b) HOH···OCH_2	−2.3		0.0[c]	0.1[a]	11.8[a]	−2.6[a]
c) HOCH···OH_2		−0.5	−0.2[a]	−0.1[c]	−0.9[c]	−5.2[c]
d) HOCH···OH_2 (cyc)	−2.4	−0.0	0.1[b]	−0.0[b]	19.9[a]	−5.3[b]

[a] Acceptor. [b] Both donor and acceptor properties in cyclic structure. [c] Donor.

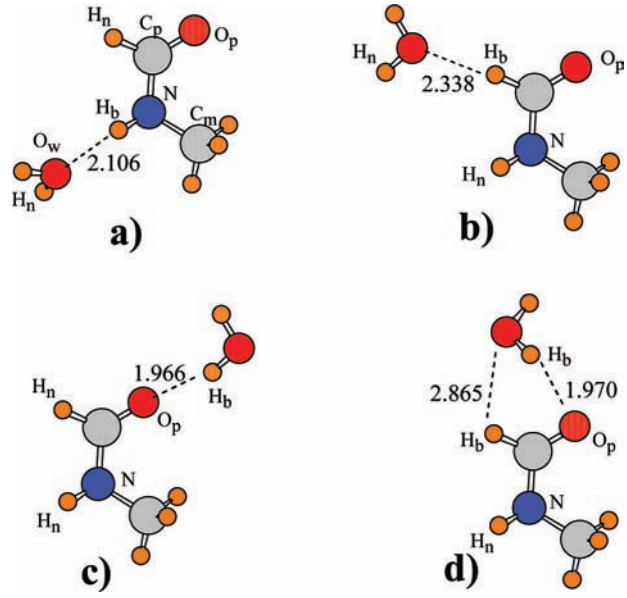

Figure 2. Molecular arrangements and atomic labeling of complexes containing *N*-methylformamide.

carbonyl carbon atom shifts in the negative direction in all cases but more so when it is involved in proton donation in the last two rows of Table 4.

In terms of distinguishing the presence of a CH···O hydrogen bond, this interaction is marked by a contraction of its covalent CH bond, and a blue shift of its stretching frequency, coupled with a diminution of the intensity of the latter. When the CH bond is not directly involved in a hydrogen bond, it may shift either to the blue or red, depending on whether the molecule on which it lies acts as proton donor or acceptor. However, in either case, the magnitude of the nonbridging shift will be considerably smaller than the blue shift when the CH bond itself participates in the hydrogen bond. The intensities offer a second indicator, in that the fairly strong reduction of the CH stretching band intensity is much more obvious than any small changes in intensity when the CH is not so engaged. The hydrogen atom undergoes a larger downfield NMR shift when participating in a hydrogen bond than when not, and the associated carbon atom a fairly large downfield shift as well.

2. Amide. The amide functionality of *N*-methylformamide (NMF) is an important group, and also contains some of the structural features[75−78] of the polypeptide backbone. This molecule offers both NH and CH as proton donors, as well as a carbonyl C═O acceptor group. NMF was paired with a water molecule in the four arrangements depicted in Figure 2. The NH group serves as proton donor to water in configuration **2a**, the CH is donor in **2b**, and the C═O accepts a water proton in structure **2c**. Configuration **2d** permits the water molecule to engage in a cyclic dimer with NMF wherein it both accepts a proton from the CH group, while simultaneously donating a proton to the C═O group.

TABLE 5: Complexation Energy (kcal/mol) and Changes in Internal Bond Length (mÅ) of Complexes in Figure 2

	$-\Delta E$	XH_b[c]	CH_b	NH_n	CH_n	C═O	NC_p	NC_m
a) NH···O_w	5.1	4.1			2.7	−3.2[d]	2.5	−2.6
b) CH···O_w	1.9		−3.9	0.2[d]		3.5[d]	2.0	−1.4
c) O···HO_w	5.2	5.6		0.5	−1.7	3.2	−7.4	2.1
d) cyclic	6.4	0.9	−2.5	−0.1[b]		6.6[b]	−7.8	0.9

[a] Acceptor. [b] Both donor and acceptor properties in cyclic structure. [c] X═O or N. [d] Donor.

TABLE 6: Vibrational Frequency Shifts Relative to Monomers (cm^{-1}) of Complexes in Figure 2

	XH_b[b]	CH_b	NH_n	CH_n	C═O
a) NH···O_w	−59			−3	−6[d]
b) CH···O_w		64	−1.8		−15[d]
c) O···HO_w	−9		0.9	23	−13
d) cyclic	−183	39	2.6		−11

[a] Acceptor. [b] X═O or N. [d] Donor.

TABLE 7: Intensification of Vibrational Modes Relative to Monomers, I/I_o of Complexes in Figure 2

	XH_b[b]	CH_b	NH_n	CH_n	C═O
a) NH···O_w	6.2			1.1[c]	1.1[c]
b) CH···O_w		0.1	1.0[c]		1.0[c]
c) O···HO_w	41.3		1.3	0.9	1.1
d) cyclic	10.6	0.5	1.9		1.1

[a] Acceptor. [b] X═O or N. [c] Donor.

TABLE 8: Change in Isotropic NMR Chemical Shifts (ppm) of Complexes in Figure 2

	XH_b[b]	CH_b	NH_n	CH_n	N	O_p	C_p	C_m
a) NH···O_w	−2.2			−0.1[c]	−3.1	8.1	−0.6	0.2
b) CH···O_w		−0.9	−0.2		0.7	2.6	−4.0	0.5
c) O···HO_w	−2.9		−0.3	0.1	−3.5	16.0	−0.7	−0.6
d) cyclic	−3.5	0.0	−0.3		−1.6	16.8	−3.1	−0.5

[a] Acceptor. [b] X═O or N. [c] Donor.

The hydrogen bond distances displayed in Figure 2 suggest that the NH···O and OH···O hydrogen bonds of structures **a**, **c**, and **d** are the shortest and presumably strongest, as compared to the CH···O distances, which are considerably longer. This expectation is confirmed by the interaction energies reported in the first column of data in Table 5, which places the CH···O value of ΔE at roughly 40% of the two other sorts of hydrogen bonds. The next two columns of Table 5 show that once again OH (and here also NH) covalent bonds are stretched upon forming a hydrogen bond, whereas the CH bond shortens. The CH contractions of 2.5 to 3.9 mÅ in NMF are consistent with what was found above for the CH bonds contained within the H_2CO molecule. Moving on to the nonbridging hydrogen atoms in the next columns, changes within the NH bond are quite modest. The CH bond, on the other hand, stretches a surprising amount when the neighboring NH group acts as proton donor, and shortens when C═O accepts a proton. The latter contraction is considerably smaller than the similar phenomenon when the CH itself is being donated.

Changes in the C═O bond length depend upon which segment of the amide is participating in the hydrogen bond. The C═O bond becomes shorter when the NH donates a proton but stretches when the CH acts as donor or the C═O itself serves as a proton acceptor. Its largest change, a stretch of nearly 7 mÅ, is observed in the cyclic structure, where both of the latter processes occur simultaneously. There are two carbon atoms in NMF: C_p refers to the central atom of the CHO group, and C_m represents the terminal methyl group, as illustrated in part a of Figure 2. The two CN bond lengths in the amide also undergo changes, opposite in sign to one another. NH or CH donation causes the N−C_p bond of the COH group to elongate, whereas C═O participation yields an opposite shortening effect, by a larger amount.

As was noted earlier for the H_2O and H_2CO molecules, bridging OH (or here NH as well) bonds undergo a red shift in their stretching frequency upon complexation, whereas CH bonds shift to the blue. The latter quantities, as reported in Table 6, are surprisingly large, as much as 64 cm^{-1} for the CH···O complex **2b**. Shifts in the frequencies of nonbridging atoms are very much smaller, virtually negligible. The only exception to this rule is the 23 cm^{-1} blue shift of the CH bond when the neighboring carbonyl oxygen atom accepts a proton. The C═O stretching frequency consistently shifts to the red, when either NH or CH acts as proton donor, or when C═O is proton acceptor. Also consistent with the data for H_2O and H_2CO, Table 7 shows that OH stretching bands are intensified and CH weakened when engaged in a hydrogen bond. Very little effect is observed in the nonbridging bonds, or in C═O.

Turning finally to the NMR chemical shifts in Table 8, one sees again the downfield (negative) shifts of the OH and NH bridging proton, by 2−3 ppm. The CH_b proton also shifts in this direction, albeit by a smaller amount than OH or NH. The changes in the nonbridging proton's chemical shifts are much smaller, perhaps not even detectable. The nitrogen atom undergoes a downfield shift when NH serves as donor, or when the C═O group accepts a proton, but not when CH acts as donor. The largest shift of all occurs in the oxygen atom of the amide which shifts upfield; this shift is clearly smallest when CH acts as donor. With regard to the two carbon atoms, the C_p that is connected to the hydrogen and oxygen atoms is shifted 4 ppm downfield when its CH acts as donor but undergoes much smaller shifts when not. The other carbon atom, on the terminal methyl group shifts by less than 1 ppm, upfield when the amide is a proton donor, downfield when it is an acceptor.

3. Comparison with Other Results. The results described here are consistent with some earlier calculations. Masella and Flament had paired H_2CO with both HOH and NH_3, in configurations[79] that are very much like the cyclic structure in part d of Figure 1. The binding energy of the HOCH···OH_2 complex at the MP2/6−311+G(2df,2p) level is within 0.1 kcal/mol of that computed here with our smaller basis. Changes in the OH and CH bond lengths reported in the last row of Table 1 were also quite close to those obtained by Masella and Flament, within 1 mÅ. The agreement with respect to the two CH blue shifts of the two CH bonds is nearly perfect, within 1 cm^{-1}. These authors reported neither vibrational intensities nor NMR data so comparison is not possible. It may further be noted that when the HOH molecule in part d of Figure 1 is replaced[79] by NH_3, one still sees the same pattern that both CH stretches of H_2CO are shifted to the blue, and that the bridging CH bond shifts quite a bit more than does the other CH, so this pattern is not limited to the water molecule as partner. The same cyclic HOCH···OH_2 structure was examined also in a 2000 study by Chandra et al.,[80] although they made use of a DFT approach rather than MP2. Nonetheless, blue shifts of both CH bonds were reported as found here, and that of the bridging CH bond was about 20 cm^{-1} greater than that of the peripheral CH, also consistent with our data. Further in agreement with our findings, the intensity of the bridging CH bond stretching mode is cut in

half by the formation of the hydrogen bond, whereas that of the other CH bond is reduced by a much smaller amount of only 10%.

These same authors[80] had also paired water with an amide to form a complex similar to our cyclic structure illustrated in part d of Figure 2. Taking into account both their use of a different amide ($HCONH_2$ vs our $HCONHCH_3$), and the application of B3LYP as opposed to our MP2, the agreement of a blue shift of the bridging CH bond of the amide, and red shift of C═O, is gratifying, as are the quantitative values which are within 10 cm^{-1} of one another. Zhang et al. have also and more recently considered the interaction[81] of the unmethylated formamide with a water molecule, as well as HF, H_2S, and NH_3, with regard to the behavior of the CH and NH bonds of the amide. They found that the nonbridging CH bond of formamide elongates and shifts to the red when the amide NH bond acts as proton donor, consistent with the trends observed here with *N*-methylformamide. Also conforming to our findings, when the amide C═O accepts a proton, both the nonbridging CH and NH bonds of formamide shift to the blue, although the amounts of these shifts vary with molecule type. Importantly, the qualitative trends were insensitive to the nature of the partner molecule, whether HOH or HF, H_2S, or NH_3. This result indicates that the patterns emerging from these model studies may be validly extended to larger systems, more directly relevant to proteins. Unfortunately, the previous workers did not consider vibrational band intensity changes nor NMR chemical shifts, so no comparison is possible here.

Experimental measurements of ethers and alcohols in aqueous solvent[82] confirm our computational finding that the nonbridging CH bond stretch shifts to the blue when the oxygen atom of the pertinent molecule acts as proton acceptor to water, a result that is confirmed by 2D-FTIR measurements[83] of *N*,*N*-dimethylformamide in water. And with specific regard to the C═O bond, some very recent calculations and infrared measurements of carboxylic acids[84] confirm our own conclusions that the C═O bond elongates, and its stretching frequency shifts to the red, when it accepts a proton, and that this same bond shortens when a different part of the molecule acts as proton donor.

Conclusions and Discussion

In summary, there are certain trends that are characteristic of the HOH, H_2CO, and CH_3NHCHO molecules considered here. As anticipated for conventional hydrogen bonds, the proton-donating O−H and N−H bonds consistently stretch when engaged in a hydrogen bond. Their stretching frequencies shift to the red by a significant amount commonly around 100 cm^{-1}, and the band intensity is amplified several fold. The NMR chemical shift of the bridging hydrogen undergoes a downfield shift of 2−3 ppm. When the OH or NH bond is not itself directly participating in the hydrogen bond, which occurs at a different part of the molecule, changes are much smaller and of variable sign. Bond lengths are constant to within 0.001 Å, and stretching frequency changes are an order of magnitude smaller than when participating directly in a hydrogen bond, with a minimal impact upon the band strength. NMR chemical shifts, too, are scarcely affected by hydrogen bonds to other segments of the molecule, on the order of 0.1−0.2 ppm for the most part.

In clear contrast, the proton-donating C−H bonds shorten, and their stretching frequency shifts to the blue by as much as 40−60 cm^{-1}; the corresponding stretching band is weakened in all cases. The NMR chemical shift of the proton also moves downfield, albeit by a smaller amount than OH protons. These trends generally, but not universally, reverse when CH is peripheral to the hydrogen bond. For example, the bridging CH bond of HCHO shortens by 3.1 mÅ, whereas the other, nonbridging CH bond elongates by half that amount. On the other hand, both of the nonparticipating CH bonds contract when the C═O of HCHO acts as proton acceptor, albeit by only half as much as when the CH serves as a bridge. The vibrational frequency shifts mimic this behavior, with red/blue shifts associated with bond stretches/contractions respectively and of proportional magnitudes. Thus, the bridging CH bond of HCHO shifts to the blue by 52 cm^{-1}, but this same bond shifts to the blue by less than half this amount when HCHO serves as a proton acceptor. In the case of the amide, the bridging CH of NMF contracts by 4 mÅ and its stretch shifts to the blue by 64 cm^{-1}, along with a 10-fold weakening. These changes are similar in sign, but much smaller in magnitude when the C═O accepts a proton. Even more conspicuous, these trends in the CH bond are reversed (and lowered in magnitude) when it is the NH of NMF that donates the proton, rather than CH. NMR chemical shifts are negligible for nonbridging CH bonds, compared to downfield shifts of roughly 1 ppm when engaged directly in a hydrogen bond.

The trademark of the CH···O hydrogen bond in systems such as these would first be the magnitude of the changes. Fairly large blue shifts are characteristic, as well as a marked weakening of the CH stretching band. In the absence of such a hydrogen bond, the shifts might be in either direction, but would be of considerably smaller magnitude. Another clear sign of a CH···O interaction would be a downfield movement of the bridging CH proton's NMR chemical shift of some 0.5−1 ppm. A large upfield shift of the amide's O chemical shift, by as much as 16 ppm, can clearly signal the presence of a C═O···H bond and thereby help disentangle ambiguities arising from the vibrational spectra. It is helpful also that this oxygen shift is much different when the amide's CH donates a proton as compared to NH. Another indicator may be the chemical shift of the carbon atom in the amide. When its CH acts as proton donor, the carbon shift is in the −4 to −5 ppm range, as compared to a much smaller change when the C═O serves as proton donor; an even smaller change occurs when NH acts as proton donor.

It may be noted that the results presented here refer to optimized geometries. In many cases, geometrical restrictions of a larger molecular system may prevent the hydrogen bonds from achieving such ideal structures, resulting in stretched or bent conformations. One would expect the values reported here to be accordingly lessened by these distortions, which do not permit the full potential of each interaction. These situations might cloud certain aspects of the criteria enunciated above to distinguish the presence of a CH···X hydrogen bond.

For example, the blue shift of the CH bond of an amide when engaged in a hydrogen bond is normally 2−3 times larger than the shift that this same bond undergoes when the C═O of the amide acts as proton acceptor. If a CH···X hydrogen bond were present, but the CH blue shift lowered due to a stretch or bend, this interaction might be difficult to distinguish from a C═O···HX bond. In a case such as this, one might resort to other criteria, for example NMR data, to differentiate the two cases. First, the bridging CH proton of CH···X would be expected to shift downfield by as much as 1 ppm, whereas this proton would shift in the opposite direction, and by very little, when it is the C═O group of the amide that engages in the hydrogen bond. The chemical shift of the pertinent oxygen atom would be even more telling. Whereas a CH···X bond would shift the oxygen value upfield by a very small amount (less

than 3 ppm in the optimal geometry, even less if the CH···X is distorted), this atom would move upfield by a much greater amount of as much as 16 ppm in the case when it acts as proton acceptor.

Auguring even more auspiciously for the utility of vibrational data, a CH···X bond of the amide would be very easily distinguished from a NH···X bond, even without the aid of NMR spectra. Even if the 64 cm^{-1} blue shift of the bridging CH bond were reduced by a geometric distortion, it could hardly be confused with the tiny red shift that would be observed in the presence of a NH···X bond; and in any case, even if the distinction could not be made for some reason, any geometric deformation that lowers the C−H blue shift would also reduce the interaction energy contained within the CH···X bond, to the point where its energetic contribution would be quite small and therefore of little interest as a structural factor.

Of course, hydrogen bonds do not always occur singly. A group like an amide, with more than one proton donor site as well as a proton acceptor group, would in many instances engage in several hydrogen bonds simultaneously. One could use the data supplied in the tables contained herein to estimate what might be the effects of multiple hydrogen bonds. For example, because the blue shift of the C−H bond is calculated to be 64 cm^{-1} when it acts as proton donor, but only −3 cm^{-1} when N−H is the donor, one would not expect the NH donation to very much affect the blue shift in the CH···X bond. On the other hand, when the amide C═O accepts a proton, the CH bond of the amide would blue shift by as much as 23 cm^{-1}. Adding this C═O···HX interaction to the mix would likely enhance the blue shift of the C−H by a certain significant amount. In terms of the NMR chemical shifts, that of the CH proton is only affected to a significant degree by a CH···X bond, so other hydrogen bonds are unlikely to play a strong role here.

Further indication of the influence of multiple hydrogen bonds may be gleaned from examination of the final rows of the tables here which pertain to cyclic complexes, that contain more than one hydrogen bond. However, it must be understood as well that the pair of hydrogen bonds that are present in each of these cyclic complexes are both geometrically deformed from the structures that would obtain if only a single hydrogen bond were present at any one time. Table 2, for example, shows that the CH stretching frequency of H_2CO shifts to the blue by 52 cm^{-1} when the CH···O bond is the only one present, and by 18−26 cm^{-1} in the same direction, if the carbonyl of H_2CO accepts a proton. However, when both of these interactions are present simultaneously in the cyclic structure, the total blue shift is only 43 cm^{-1}, smaller than the sum of these two effects, due to the strong angular deformations of both hydrogen bonds in the cyclic geometry. Likewise in the case of the amide in Table 6, where the 39 cm^{-1} blue shift of the CH bond in the cyclic structure is smaller than the sum of the shifts it would experience if the CH···O hydrogen bond were not angularly distorted by the other hydrogen bond. In other words, the additivity of the effects of the two hydrogen bonds upon the CH stretching frequency cannot fully compensate for the reduction caused by the angular distortions.

In conclusion, the results presented here offer some tools that may be useful to discern the presence of a CH···O hydrogen bond within a given system. There are clear differences in behavior between a bridging CH bond and one that is instead perturbed by the presence of hydrogen bonds at other sites of the molecule. Clues may be obtained from vibrational and NMR spectra as well as from details of the molecular structure. If any of these particular quantities are inconclusive on their own, the combination of data extracted by different methods can usually permit a more decisive conclusion to be drawn. Of course, the data extracted from the calculations were derived from small model systems. These trends may alter when larger and more complex molecules are considered. Nonetheless, the patterns observed for these small models serve as a useful starting point to which perturbations introduced by the complexities of larger molecules can be referenced.

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