Molecular Dynamics

Isotopomeric Conformational Change in Anisole–Water**

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Isotopic substitution is generally considered not to perturb the structure of a molecular system. It affects, however, the molecular spectroscopy of the system, especially the frequencies of rotational transitions, which depend on moments of inertia. Differences in moments of inertia among isotopomers represent, in turn, the best tool for the determination of molecular structure.[1] Furthermore, changes in chemical properties, such as kinetics[2] and equilibrium constants,[3] are well known, and it has been observed that the temperature of spontaneous phase transitions can vary,[4] sometimes by as much as 25 K.[5] A smaller modification (relative to that described herein) of the structure of a system through the so-called geometric isotope effect was outlined by Ichikawa.[6] However, when isotopically labeled substances are used, the usually justified assumption is made that they do not alter the fundamental nature of the material under study. Reasonable information on the geometry of molecular complexes, for example of complexes of water with ethers, has been obtained upon deuteration of the water moiety. Limitations to this assumption are due to a remarkable shrinking (Ubbelohde effect[7]) of the distance between the two heavy atoms involved in the hydrogen bond upon deuteration. Such an effect has been observed both in crystals[7] and in the gas phase.[8] Zhou et al. showed very recently that this assumption is unjustified for the complex of pentachlorophenol with 4-methylpyridine, because the substitution of a single hydrogen atom for a deuterium atom leads to the thermodynamic stability of an entirely different crystal polymorph. [9] We show herein that a similar large effect is observed for the gas-phase configuration of the molecular complex anisole–water (ANI$\cdots$water; see Figure 1).

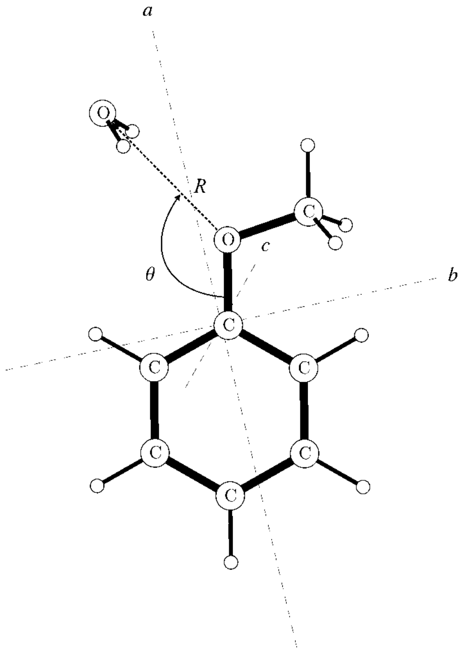

Figure 1. Conformation, relevant structural parameters, and principal axes of ANI$\cdots$water.

Two recent publications have appeared on spectroscopic and quantum-chemical investigations of ANI$\cdots$water. The first, based on resonant two-photon ionization and IR–UV double-resonance vibrational spectroscopy in the region of the OH stretches, and on MP2/6-31G* ab initio calculations, suggests that the minimum conformation includes an OH–O H bond and a "free" water hydrogen atom.[10] In the second the authors suggest a conformation of the complex with the water oxygen atom coplanar to the ring based on the results of vibronically and rotationally resolved spectroscopy and molecular-mechanics calculations.[11]

We measured the molecular-beam Fourier transform microwave spectra of six isotopomers of ANI$\cdots$water, namely, ANI$\cdots$H$_2$O, ANI$\cdots$D$_2$O, ANI$\cdots$DOH, ANI$\cdots$H$_2{}^{18}$O, ANI$\cdots$D$_2{}^{18}$O, and ANI$\cdots$D^{18}OH. We first assigned the rotational spectrum of the normal species, ANI$\cdots$H$_2$O. Each rotational transition was split into two component lines with an intensity ratio of 1:3, as expected for the tunneling states of a vibrational motion inverting two equivalent hydrogen atoms, and with two equivalent minima describing the potential-energy surface. Similar spectra were observed for phenol–water[12] and indole–water.[13] In these molecular complexes the water moiety acts as a proton acceptor, and the two hydrogen atoms of the water molecule are therefore equivalent to each other, located one above and one below the plane of symmetry of the partner molecule. After measuring the spectrum of ANI$\cdots$H$_2$O and performing a partial fitting (based on the spectroscopic constants of the

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[**] We thank the University of Bologna and the MIUR for financial support.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

DOI: 10.1002/ange.200461860

normal species) of the r_0 structure, limited to the R and θ parameters of the H bond in Figure 1, we planned to measure the spectrum of ANI···D_2O. However, we were unable to locate the rotational lines for this isotopomer based on the hypothesis made about the conformation of the two water hydrogen atoms in the normal species. In contrast, the assignment of the lines in the spectrum of ANI···$H_2{}^{18}O$ after the above-mentioned structural adjustment was straightforward. We then returned to the search for the dideuterated species, and were finally able to assign a spectrum that was not in agreement with the geometry of the normal species. We also assigned the spectrum of the complex with partially deuterated water, with features intermediate between those of the H_2O and D_2O adducts. The spectrum of this isotopomer displayed only one set of lines, doubly intense with respect to the overall intensity of the H_2O or D_2O doublets, thus confirming that the two water hydrogen atoms are quantum-mechanically equivalent in the complex. Finally, we measured the spectra of the ANI···$D_2{}^{18}O$ and ANI···$D^{18}OH$ isotopomers in a mixture containing all six (H/D, $^{16}O/^{18}O$) isotopic species. The line frequencies (μ_a- and μ_b-type rotational transitions) for all isotopomers (available as Supporting Information) were fitted with a standard "S"-reduced Watson semirigid-rotor Hamiltonian[14] to yield the spectroscopic parameters given in Table 1. The two tunneling states of the ANI···H_2O and ANI···D_2O species were fitted separately.

It is well known that rotational constants, which are proportional to the reciprocal of the moments of inertia, should decrease upon substitution with heavier isotopes. In the case of ANI···water, the rotational constants decrease when ^{16}O is substituted for ^{18}O, but not when H is substituted for D. The rotational constant B increases in going from ANI···H_2O to ANI···HOD to ANI···D_2O (Table 1). The increase in B corresponds to a decrease, rather than an increase, in the mass extensions along the direction of the a axis, as indicated by the related changes in the M_{aa} planar moments of inertia, also reported in Table 1. This effect can be explained only if the O_{water}···O–C_{Ph} angle (θ in Figure 1) decreases by about 10° in going from ANI···H_2O to ANI···D_2O. This argument is shown graphically in Figure 2.

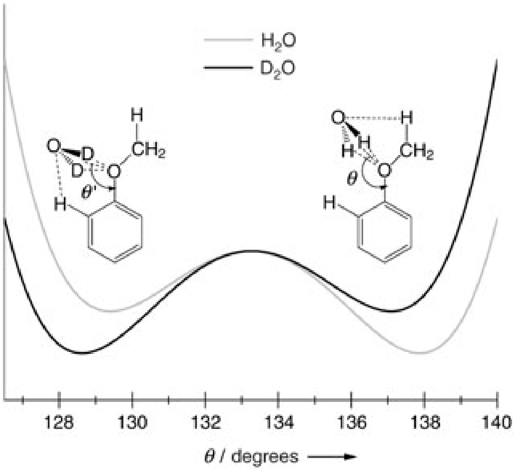

Figure 2. A qualitative hypothesis to explain the change in conformation of ANI···water upon H→D isotopic substitution: a slight variation in the potential-energy function, $E(\theta)$.

It was also possible, for each of the pairs ANI···H_2O/ANI···$H_2{}^{18}O$, ANI···HOD/ANI···$H^{18}OD$ and ANI···D_2O/ANI···$D_2{}^{18}O$, to obtain the substitution coordinates[15] of the oxygen atom of the water molecule. We believe the data are reliable because for each pair the hydrogen-bonding interactions and the molecular vibrations are the same. Based on the assumption that the geometries of isolated anisole[16] and water[17] remain unaltered in the adduct, we could estimate the local r_0 structure at the H bond, that is, the parameters R and θ in Figure 1. To estimate these values we needed to

Table 1: Spectroscopic constants for the isotopomers of the anisole–water complex.

	ANI···H_2O[a]		ANI···D_2O		ANI···HOD	ANI···$H_2{}^{18}O$		ANI···$D_2{}^{18}O$		ANI···$H^{18}OD$
	v = 0	v = 1	v = 0	v = 1		v = 0	v = 1	v = 0	v = 1	
A[b]	2943.058(2)[c]	2943.578(2)	2660.639(1)	2660.657(2)	2847.47(1)	2912.223(8)	2912.769(6)	2621.694(9)	2621.80(3)	2813.57(1)
B[b]	900.1885(9)	900.0276(8)	914.1605(5)	914.1581(6)	907.4638(6)	857.1386(9)	856.9846(7)	876.3307(6)	876.3222(6)	866.2243(2)
C[b]	694.1488(9)	694.1155(8)	687.0905(3)	687.0900(4)	692.5413(8)	666.5972(7)	666.5624(5)	662.9146(2)	662.9170(9)	666.2012(1)
D_J[d]	4.25(2)	4.22(2)	4.509(3)	4.510(4)	5.73(1)	4.054(5)	4.029(4)	4.419(7)	4.39(2)	5.789(2)
D_{JK}[d]	−54.0(1)	−53.8(1)	−54.4(6)	−54.36(5)	−72.3(2)	−52.4(2)	−52.3(1)	−54.6(2)	−56.(1)	−75.5(2)
D_K[d]	219.0(2)	218.3(2)	202.3(2)	203.5(2)	200(10)	218(1)	218(1)	271(5)	317(9)	196(3)
d_1[d]	−1.760(2)	−1.751(2)	−1.843(2)	−1.845(3)	−2.394(3)	−1.644(4)	−1.638(3)	−1.802(4)	[−1.845][e]	[−2.394]
d_2[d]	−0.108(2)	−0.106(1)	−0.065(2)	−0.064(2)	−0.086(6)	−0.105(3)	−0.106(2)	[−0.065]	[−0.064]	[−0.086]
H_J[f]	0.7(2)	0.6(1)			0.14(4)	[0.7]	[0.6]			[0.14]
H_{JK}[f]	−15.0(1)	−14.0(9)				−12(2)	−13(2)			
H_{KJ}[f]	85(10)	83(9)				80(10)	78(10)			
M_{aa}[g]	558.8757(8)	558.9585(7)	549.2111(5)	549.2128(5)	554.5879(9)	587.1110(9)	587.2001(7)	573.1450(6)	573.150(2)	581.2018(4)
M_{bb}[g]	169.1800(8)	169.1322(7)	186.3237(5)	186.3226(5)	175.1577(9)	171.0365(9)	170.9870(7)	189.2141(6)	189.206(2)	177.3964(4)
M_{cc}[g]	2.5390(8)	2.5565(7)	3.6228(5)	3.6226(5)	2.3258(9)	2.5007(9)	2.5176(7)	3.5540(6)	3.554(2)	2.2256(4)
σ[f]	5	5	6	6	5	5	5	1	4	3
N[h]	42	42	40	42	35	30	31	12	10	13

[a] The rotational constants for the normal species from reference [11] are $A = 2941.4(2)$, $B = 899.65(6)$, $C = 693.93(4)$ MHz. [b] MHz. [c] Standard errors in units of the last digit are given in parentheses. [d] kHz. [e] Parameters in square brackets were fixed to those of the corresponding $H_2{}^{16}O$ species. [f] Hz. [g] uÅ^2. [h] Number of fitted transitions.

predict the positions of the hydrogen atoms of the water molecule. Since the statistical weight indicates that they are equivalent to one other, we assumed that they point towards the oxygen atom of anisole, thus forming a bifurcated H bond. All these structural data are reported in Table 2. The discrepancies between the experimental and calculated values of the $|b|$ coordinates might result from the fact that the hydrogen atoms of the water molecule do not point, as we assumed, exactly towards the ether oxygen atom for the three isotopomers. We also calculated the $O_{water}\cdots H_{Me}$ and $O_{water}\cdots H_{Ph}$ distances (Table 2), which are relevant for secondary interactions (weak H bonds[18]). These distances change from 2.73 and 3.74 Å, respectively, in ANI···H_2O to 3.43 and 3.17 Å in ANI···D_2O. The H→D substitution destroys the weak H bond $O_{water}\cdots H_{Me}$ and seems to lead to the formation of the weak H bond $O_{water}\cdots H_{Ph}$.

Table 2: Changes in the local structural features of the H bond upon H→D isotopic substitution.

r_0 distances [Å] and angles [°]; see Figure 1.

	ANI···H_2O	ANI···HOD	ANI···D_2O
R	2.90(1)	2.87(1)	2.92(1)
θ	137.4(2)	134.2(2)	128.7(2)
$O\cdots H_{Me}$	2.73(3)	3.22(3)	3.43(3)
$O\cdots H_{Ph}$	3.74(3)	3.34(3)	3.17(3)

r_s coordinates [Å] for the oxygen atom of the water molecule

	ANI···H_2O		ANI···HOD		ANI···D_2O	
	Exptl[a]	Calcd[b]	Exptl	Calcd	Exptl	Calcd
$\|a\|$	3.774	3.714	3.662	3.610	3.469	3.542
$\|b\|$	1.005	1.162	1.102	1.182	1.250	1.227
$\|c\|$	0.0	0.0	0.0	0.0	0.0	0.0

[a] The experimental errors in the substitution coordinates are not given because they are unrealistically small (in the fourth decimal digit): They do not take into account the vibrational contributions. [b] Calculated from the r_0 structure reported above.

It is likely that the water molecule forms a strong hydrogen bridge—probably bifurcated (or effectively bifurcated)—with the ether oxygen atom, and that the hydrogen-bonding interaction of the oxygen atom of the water molecule can oscillate between the methyl and the phenyl hydrogen atoms: The shrinking of the O–H/D distances within the water molecule upon deuteration alters this equilibrium. Two qualitative hypotheses are plausible: 1) a small change, upon deuteration, in the potential-energy surface, as shown qualitatively in Figure 2; 2) a substantial change, upon deuteration, in some of the frequencies of the six low-frequency normal vibrational modes of water with respect to anisole, and therefore in the relative r_0 energies of the two $O_{water}\cdots H_{Me}$ and $O_{water}\cdots H_{Ph}$ conformations, even in the case of two nearly equivalent wells in the potential-energy surface. Quantitative data on this potential-energy surface are difficult to obtain as a result of the complexity and flexibility of the problem, and the scarcity of experimental data.

In summary, we have described a novel isotopic effect: the conformational change of a hydrogen-bonded adduct upon deuteration of the hydrogen atoms involved in the H bond. Rotational resolved spectroscopy again proved to be a powerful tool for obtaining detailed chemical information that would be difficult to obtain by other techniques. However, we have also shown that structural information should only be derived with caution from shifts of moments of inertia in cases of H→D isotopic substitution of a hydrogen atom involved in hydrogen bonding. The results presented herein may also serve as a stimulus for new developments in theoretical calculations, which at present, to our knowledge, can not take into account such isotopomeric effects.

Experimental Section

A commercial sample of anisole (Aldrich) was used without further purification. D_2O (99%) and $H_2{}^{18}O$ (90%) were supplied by Promochem GmbH (Germany).

The MB-FTMW spectrum in the 6–18.5-GHz frequency region was measured by using a COBRA-type[19] molecular-beam Fourier transform microwave (MB-FTMW) spectrometer described elsewhere.[20] He at a pressure of ≈2 bar was blown over a 1:1 (v/v) mixture of water and anisole, and out through the solenoid valve (general valve, series 9, nozzle diameter 0.5 mm) into the Fabry–Pérot cavity, where the mixture reached an estimated rotational temperature of 1–2 K. The frequencies were determined after Fourier transformation of the 8k-data-point time-domain signal, recorded with 100-ns sample intervals. Each rotational transition was split by the Doppler effect as a result of the coaxial arrangement of the supersonic jet and resonator axes. The rest frequency was calculated as the arithmetic mean of the frequencies of the Doppler components. The estimated accuracy of the frequency measurements is better than 3 kHz. Lines separated by more than 7 kHz are resolvable.

Received: September 1, 2004

Keywords: hydrogen bonds · isotope effects · molecular beams · molecular complexes · molecular dynamics

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