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Conformational Flexibility in Hydrated Sugars: the Glycolaldehyde−Water Complex

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Abstract: Conformational flexibility in the smallest hydrated sugar, the glycolaldehyde−water complex, has been investigated in the gas phase by means of a combination of a microwave Fourier transform spectroscopy experiment in a supersonic molecular beam and ab initio quantum chemistry calculations. The water molecule inserts into glycolaldehyde using H-bonding selectivity: the two lowest energy conformations are stabilized by two intermolecular hydrogen bonds, and the next two by one intra- plus one intermolecular hydrogen bond. A dynamical flexibility associated with the two lowest energy conformations has been experimentally observed and accurately modeled with a two-dimensional potential energy surface involving the hydroxyl group and the free OH water group coordinates. The conclusions drawn from the role played in the conformational flexibility by the hydroxyl and carbonyl groups are extended to other carbohydrates and biomolecules.

Introduction

Carbohydrates form one of the four major classes of biomolecules and play a considerable role in several forms of life, building up most of the bioorganic matter. Glycolaldehyde is the simplest sugar, a diose with a structural formula of CH_2-OHCHO. Its structure has been experimentally characterized in the gas phase in the microwave and millimeterwave ranges.[1−3] It is a significant compound in atmospheric chemistry (it can be emitted by biomass fires or formed in oxidation of volatile organic compounds),[4−6] and the presence of glycolaldehyde and its isomers (methyl formate and acetic acid) in the interstellar medium has been recently reported.[7−10] To our knowledge there is no published crystallographic data on glycolaldehyde, and most information on the dimer solid phases comes from Raman and infrared spectroscopies.[11] Water solutions of sugars have been studied in earlier multipulse NMR spectroscopy.[12]

Most hydrated biomolecules have a permanent electric dipole moment and exhibit a pure rotation spectrum. Supersonic gas expansions can easily form a 1:1 complex on any site of the parent molecule available for hydration. Therefore our strategy was to study hydrated sugars in the microwave range because their structure may be determined more accurately with the help of high level ab initio calculations. In addition microwave spectroscopy is a recognized tool for studying the nature of the hydrogen bond with water in the gas phase.[13] In this paper we report the first observation of the glycolaldehyde−water complex in the gas phase, using microwave Fourier transform spectroscopy coupled to a supersonic molecular beam. The dynamical flexibility of glycolaldehyde−water was investigated with the help of ab initio calculations. The results obtained on the smallest hydrated sugar are shown to be of general interest for several hydrated complexes and bring complementary information to the mass-selected resonantly enhanced two-photon ionization (MS-R2PI) experiments, namely for the C6 hydrated sugars in the gas phase recently investigated in the group of Simons.[14−17]

Methods

Microwave Fourier Transform Spectroscopy. Rotational spectra of the glycolaldehyde−water complex were recorded in the 6−20 GHz region using a molecular beam Fourier transform microwave spectrometer.[18,19] Glycolaldehyde dimer was purchased from Sigma-Aldrich

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10.1021/ja062312t CCC: $33.50

as a crystalline mixture of stereoisomers (purity ≥ 98%) and used without further purification. The powder was placed in a nozzle heated at 363 K. The neon carrier gas was seeded with water vapor and mixed with the powder at a stagnation pressure of 3.0 bar (1 bar = 1013.25 hPa). Gas is then introduced into the vacuum tank by means of a pulsed nozzle at a rate of 1.5 Hz to create a supersonic beam expansion with $T_{\mathrm{rot}} = 0.5-1$ K. To amplify the electromagnetic signals, the cell consists of a high finesse Fabry−Perot cavity of adjustable length. The molecules are polarized with 2 μs pulses of tunable microwave radiation, and the free-induction decay occurring at each resonance frequency is detected and processed. As the nozzle is inserted in the center of the fixed mirror of the Fabry−Perot cavity, the supersonic expansion is parallel to the optical axis of the cavity, and each transition is divided into two Doppler components separated by about 100 kHz. The central frequency of the lines are determined by averaging the frequencies of the two Doppler components (10 kHz full width at half-maximum, fwhm) after transformation of 4096 data points of the time domain signal, leading to a digital resolution and accuracy of 2.4 kHz. This operation is then automatically repeated every 0.4 MHz, which corresponds to the bandwidth of the Fabry−Perot cavity mode, to cover step-by-step the whole desired frequency region. By optimizing the temperature in order to minimize the transformation or the decomposition of the sugar, spectra were left with strong signals associated with the parent molecule (the CC conformer, see below),[1] and weak signals associated with both the water dimer[20] and the glycolaldehyde−water complex. Only very few weak features could not be assigned. The energy structure of the glycolaldehyde−water complex was studied with a standard Watsonian model. The Hamiltonian contains the operators for a semirigid rotor. The rigid asymmetric rotor is described in the I^{r} representation by the $\hat{\mathrm{H}}_R$ Hamiltonian:[21]

$$\hat{\mathrm{H}}_R = A\hat{\mathrm{J}}_z^{\,2} + B\hat{\mathrm{J}}_x^{\,2} + C\hat{\mathrm{J}}_y^{\,2} \tag{1}$$

with A, B, and C as the principal rotational constants and $\hat{\mathrm{J}}_g$ ($g = x, y, z$) as the components of the rotational angular momentum operator. The asymmetry parameter $\kappa = (2B - A - C)/(A - C)$ being equal to −0.28, the centrifugal distortion corrections were accounted for by the Watson’s A-reduced $\hat{\mathrm{H}}_{CD}$ Hamiltonian: [22]

$$\begin{aligned}\hat{\mathrm{H}}_{CD} = {} & -\Delta_J\hat{\mathrm{J}}^4 - \Delta_{JK}\hat{\mathrm{J}}^2\hat{\mathrm{J}}_z^{\,2} - \Delta_K\hat{\mathrm{J}}_z^{\,4} - \\ & \delta_K[\hat{\mathrm{J}}_z^{\,2},\hat{\mathrm{J}}_x^{\,2} - \hat{\mathrm{J}}_y^{\,2}]_+ - 2\delta_J\hat{\mathrm{J}}^2(\hat{\mathrm{J}}_x^{\,2} - \hat{\mathrm{J}}_y^{\,2})\end{aligned} \tag{2}$$

with Δ_J, Δ_{JK}, Δ_K, δ_J, and δ_K as the quartic centrifugal distortion constants. The energy levels are assigned with the usual J, K_{a}, and K_{c} quantum numbers associated with an asymmetric rotor.

Theoretical Calculations

The potential energy surface of glycolaldehyde has recently been investigated[23] at the frozen-core second-order Møller−Plesset (MP2) level of the theory, using the augmented correlation-consistent basis set aug-cc-pVTZ of Dunning and co-workers.[24,25] Four local minima were found; they are denoted CC (most stable), TT (14.63 kJ/mol), TG (15.39 kJ/mol), and CT (21.72 kJ/mol), where C, T, and G represent cis, trans, and gauche conformations, respectively, around the C−C and C−O bonds. The CC conformer is stabilized by an intramolecular H-bond between the hydrogen atom of the hydroxyl group and the oxygen atom from the carbonyl group. The central bond torsion and the OH torsion have been subsequently studied at the MP4/cc-pVQZ level of the theory, and the relative energies of the four conformers were confirmed within 1 kJ/mol.[26]

For the study of the hydrated complex, all the calculations of the present work were conducted using the Gaussian03 software package.[27] We used the density functional theory with the Becke[28] three-parameter hybrid exchange functional and the Lee−Yang−Parr correlation functional[29] (B3LYP) with different split-valence basis sets as implemented in Gaussian. Our strategy was to optimize first the structure of the four conformers of the parent molecule, at the B3LYP/6-311++G(d,p) level of theory, and then to calculate all the configurations associated with the hydrated complex, at the HF/3-21G* and B3LYP/6-311++G(d,p) levels of theory. Seventeen conformers have been identified. The structures of the nine most stable ones have then been optimized at the B3LYP/6-311++G(2df,p) level of theory, and the Gaussian-3 (G3) compound method was used in its G3MP2B3 version as implemented in Gaussian 03 to calculate the relative energies (MP2 means that the MP2 method is used instead of MP4 for the basis set extension correction, and B3 means that the B3LYP structures and frequencies were used). This method is known to give accurate energies.[30]

Then the two lowest experimentally accessible energy structures were also optimized using the B3LYP/aug-cc-pVTZ level of the theory. Finally harmonic vibrational frequencies were also calculated at the optimized structures for these two conformers at the B3LYP/aug-cc-pVTZ level of the theory.

The conformational flexibility was investigated through a two-dimensional potential energy surface calculated along the hydroxyl group (i.e., the 7H−4O−3C−2C dihedral angle; see Figure 1) and the free OH water group (i.e., the 11H−10O−1O−2C dihedral angle; see Figure 1) coordinates and associated with the two most stable conformers (see below). The grid was built by steps of 5°, as a function of the energy by optimizing the structure of the 1440 grid points at the B3LYP/6-31G* level of theory. The structure of all the maxima and minima was also optimized at the B3LYP/6-311++G(2df,p) level. Finally the energies of the maxima and minima were calculated at the MP2/cc-pVQZ level of theory because the MP2 method is generally more reliable than the B3LYP one to calculate transition state energies.[31]

Results

The glycolaldehyde−water complex MWFT spectrum, one transition of which is shown in Figure 2, displays the typical signature of an asymmetric rotor. The high-resolution spectrum reveals that all the lines are formed by a pair of doublets of the same intensity, separated by a few tens of kHz. The two series of lines were associated with two vibrational sublevels denoted 0^+ (ground state) and 0^- (first excited state) and were fitted separately using a least-squares procedure (program SPFIT, developed by H. Pickett, Jet Propulsion Laboratory). All the lines were assigned to *a*-type and *b*-type transitions, and no *c*-type transition was observed. The frequencies of the assigned microwave lines, along with the observed-minus calculated values are given in Table 1. The spectroscopic parameters are presented in Table 2. They reproduce the observed lines with a standard deviation of 4 kHz, close to the experimental accuracy.

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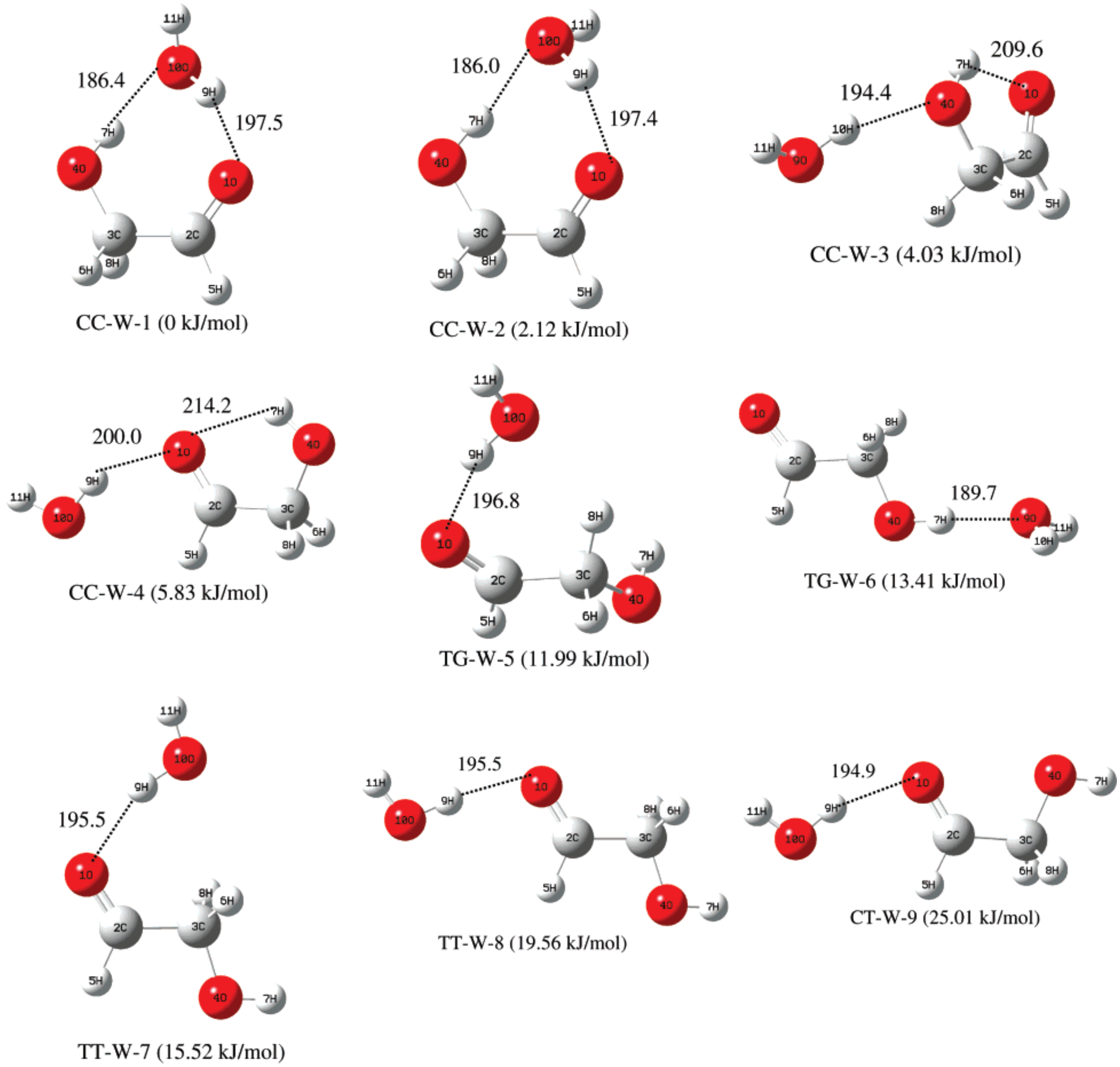

CC-W-1 (0 kJ/mol) CC-W-2 (2.12 kJ/mol) CC-W-3 (4.03 kJ/mol) CC-W-4 (5.83 kJ/mol) TG-W-5 (11.99 kJ/mol) TG-W-6 (13.41 kJ/mol) TT-W-7 (15.52 kJ/mol) TT-W-8 (19.56 kJ/mol) CT-W-9 (25.01 kJ/mol)

Figure 1. Ab initio calculated structure (B3LYP/6-311++G(2df,p)) and energy (G3MP2B3) of the most stable conformers of glycolaldehyde−water. The bond lengths are in picometers.

The very close values of the *A*, *B*, and *C* rotational constants indicate that the 0^+ and 0^- levels are probably close in energy and are the two tunneling sublevels associated with two equivalent positions of the same conformer. Meanwhile in the absence of perturbation we do not have access, by microwave Fourier transform spectroscopy, to the energy difference between the 0^+ and 0^- sublevels.

The conformational assignment was based on ab initio results. Figure 1 displays the nine most stable conformers of the glycolaldehyde−water complex. The notation that is employed combines the label of the parent molecule (CC, TT, TG, and CT) with the W letter for water and a number indicating the energy position relative to the most stable form. This figure deserves a few comments. At first, the four most stable conformers, i.e., CC−W-1 (0 kJ/mol), CC−W-2 (2.12 kJ/mol), CC−W-3 (4.03 kJ/mol), and CC−W-4 (5.83 kJ/mol), are associated with the CC conformer of the parent molecule. Second, these four conformers are stabilized by two hydrogen bonds, indicated by dashed lines, while, in the next five, i.e., TG−W-5 (11.99 kJ/mol), TG−W-6 (13.41 kJ/mol), TT−W-7 (15.52 kJ/mol), TT−W-8 (19.56 kJ/mol), and CT−W-9 (25.01 kJ/mol), only one hydrogen bond is present. Finally, the two lowest energy conformations (CC−W-1 and CC−W-2) are stabilized by two *inter*molecular hydrogen bonds, and the next two (CC−W-3 and CC−W-4), by one *intra*- plus one *inter*-molecular hydrogen bond. We observed that the intramolecular H-bond of the CC parent molecule is replaced by two intermolecular hydrogen bonds in CC−W-1 and CC−W-2. The structures of the four most stable conformers are available in the Supporting Information.

The calculated spectroscopic parameters (rotational constants and components of the electric dipole moment) are presented in Table 3. Only those conformers were considered that have a small enough energy difference from the lowest-energy conformer to be observed at the low temperature of the expansion; i.e., the four lowest-energy conformers have been considered.[32] The comparison with the experimental rotational constants (Table 2) leaves us with the conformers CC−W-1 or CC−W-2

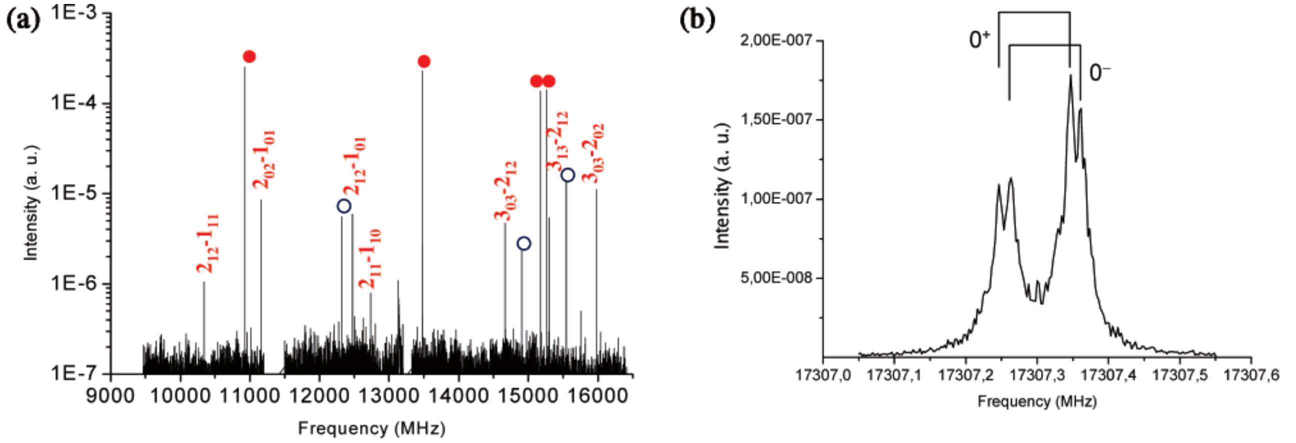

Figure 2. (a) Low resolution frequency scan showing the pure rotation spectra of glycolaldehyde (dot), water dimer (circle), and glycolaldehyde−water (J_{KaKc} assigned lines); (b) High-resolution spectrum of the $J_{KaKc} = 3_{22}$-2_{21} transition of glycolaldehyde−water evidencing a large amplitude motion associated with the two equivalent positions of the CC−W-1 conformer.

Table 1. Frequencies of the Rotational Transitions of Glycolaldehyde−Water Associated with the Tunneling States 0^+ and 0^- (the Observed Minus Calculated Value Is between Parentheses)

lines[a]	0^+/MHz	0^-/MHz	$\Delta\nu$[b]/kHz
$1_{01} - 0_{00}$	5769.196 (4)	5769.203 (3)	7
$1_{11} - 0_{00}$	7902.383 (−5)	7902.405 (5)	22
$2_{02} - 1_{11}$	9024.577 (−1)	9024.594 (6)	17
$2_{12} - 1_{11}$	10340.735 (−1)	10340.752 (5)	17
$2_{02} - 1_{01}$	11157.783 (9)	11157.783 (−6)	0
$3_{22} - 3_{13}$	11998.265 (−5)	11998.308 (1)	43
$2_{12} - 1_{01}$	12473.926 (−6)	12473.943 (−5)	17
$2_{11} - 1_{10}$	12735.837 (0)	12735.852 (−2)	15
$3_{31} - 3_{22}$	13868.933 (−1)	13869.008 (0)	75
$3_{03} - 2_{12}$	14668.326 (−2)	14668.349 (0)	23
$4_{23} - 4_{14}$	14669.140 (3)	14669.199 (4)	59
$3_{13} - 2_{12}$	15301.268 (−2)	15301.292 (3)	24
$3_{03} - 2_{02}$	15984.486 (−0)	15984.512 (4)	26
$3_{13} - 2_{02}$	16617.428 (0)	16617.452 (4)	24
$3_{22} - 2_{21}$	17307.297 (−3)	17307.313 (−11)	16
$3_{21} - 2_{20}$	18629.775 (4)	18629.796 (3)	21
$3_{12} - 2_{11}$	18813.426 (−7)	18813.464 (−1)	38
$2_{21} - 1_{10}$	19135.388 (8)	19135.417 (−3)	29
$4_{13} - 3_{22}$	19552.352 (1)	19552.389 (1)	37
$4_{04} - 3_{13}$	19848.391 (2)	19848.420 (1)	29

[a] The lines are assigned as $(J_{KaKc})' \leftarrow (J_{KaKc})''$. [b] $\Delta\nu$ is the difference between the 0^+ and 0^- line frequencies.

Table 2. Experimental Rotational and Quartic Centrifugal Distortion Constants of Glycolaldehyde−Water in the 0^+ and 0^- Tunneling States[a]

constants	0^+	0^-
A/MHz	5616.5972(13)	5616.6051(13)
B/MHz	3483.4258(14)	3483.4321(14)
C/MHz	2285.7921(8)	2285.7929(8)
Δ_J/kHz	6.45(4)	6.47(4)
Δ_{JK}/kHz	−14.24(14)	−14.50(14)
Δ_K/kHz	21.94(11)	21.31(11)
δ_J/kHz	1.958(20)	1.934(20)
δ_K/kHz	5.16(25)	6.00(25)
Std/kHz	4.1	4.3
Δ/amu.Å^2	−13.9648(2)	−13.9645(2)

[a] The values of the inertial defect (Δ) and of the standard deviation of the fit are also reported.

Table 3. Ab Initio Spectroscopic Parameters (Rotational Constants A, B, C, Inertial Defect Δ, and Electric Dipole Moment Component μ_a, μ_b, μ_c) Derived at the Equilibrium Structures of the Most Stable Conformers, and Calculated at the B3LYP/aug-cc-pVTZ and B3LYP/6-311++G(2df,p) Levels

		CC–W-1		CC–W-2		CC–W-3	CC–W-4
	expt	VTZ	(2df,p)	VTZ	(2df,p)	(2df,p)	(2df,p)
A/MHz	5616.6	5551.8	5545.0.	5577.8	5559.2	9883.4	17731.3
B/MHz	3483.4	3595.6	3592.4	3553.6	3562.5	1887.4	1675.5
C/MHz	2285.8	2309.4	2309.1	2277.1	2283.4	1877.9	1545.3
Δ/amu.Å^2	−13.96	−12.75	−12.96	−10.88	−11.44	−49.78	−3.09
μ_a/D		−1.2	−1.1	−1.6	−1.5	−0.5	0.1
μ_b/D		0.6	0.7	1.2	1.3	1.5	0.6
μ_c/D		0.2	0.2	2.4	2.5	1.4	0.0

as possible candidates. The experimental optimized microwave power, indicating that $\mu_b < \mu_a$, is in favor of CC−W-1. Also the value of the inertial defect Δ ($\Delta = (1/C - 1/B - 1/A) \times 505379.07$ amu Å^2) confirms the identity of the experimentally detected conformer as being CC−W-1, in agreement with our ab initio calculations. The absence of any *c*-type transition on the spectrum, which is associated with a very weak dipole moment along the *c* inertial axis, could also be in favor of CC−W-1. However the dipole moment value along the *c* axis is not discriminating. Indeed, in the presence of tunneling, it is well-known that a low *effective* dipole moment component results from the average of two opposite components associated with the two equivalent positions. Therefore, the same observation would have been made if the CC−W-2 conformer spectrum had been observed.

It should be noted that the difference between the CC−W-1 and the CC−W-2 conformers is mainly related to the position of the free H-atom from water (see Figure 1), as detailed with the main structural parameters presented in Table 4. Indeed in both cases the structure of the parent molecule is unchanged. Compared with the isolated CC glycolaldehyde conformer, the most striking features are the torsion of the C−C bond (the 1O−2C−3C−4O dihedral angle moves from 0° in CC to −10.5° in CC−W-1, and to 10.8° in CC−W-2) and the reorientation of the 4O−7H hydroxyl group, moving from the 4O−3C−2C plane into the direction of water to form a dihedral angle (7H−4O−3C−2C) of about 46.9° in CC−W-1 (44.1° in CC−W-2). Among CC−W-1 and CC−W-2, the positions of the free 10O−11H water group with respect to 1O−2C (dihedral angle 11H−10O−1O−2C, equal to 135.5° and 255.2°, respectively) are separated by an angle of 119.7°, the 10O water atom being closer to the parent molecule in the CC−W-2 conformer

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Table 4. Principal Bond Lengths, Bond Angles, and Dihedral Angles of Glycolaldehyde−Water in the Two Most Stable Conformations (CC−W-1 and CC−W-2) and in Their Associated Two Lowest Transition States (TS2 and TS3), Calculated at the B3LYP/aug-cc-pVTZ and B3LYP/6-311++G(2df,p) Levels

	CC–W-1[a]	CC–W-2[a]	TS2[b]	TS3[b]
GA Skeleton:				
4O−7H/pm	97.6	97.5	97.6	97.7
3C−4O−7H/deg	110.88	111.49	111.00	113.20
1O−2C−3C−4O/deg	−10.5	10.8	−10.8	−2.7
7H−4O−3C−2C/deg	46.9	44.1	52.5	7.3
Water Skeleton:				
9H−10O/pm	97.2	97.1	96.9	97.0
11H−10O/pm	96.2	96.1	96.0	96.2
9H−10O−11H/deg	106.42	106.57	110.64	106.85
GA−W:				
7H−10O/pm	186.5	186.6	186.1	186.6
9H−1O/pm	195.4	195.2	200.4	198.4
10O−9H−3C−2C/deg	161.1	169.6	163.0	−178.2
11H−10O−1O−2C[c]/deg	135.5	255.5	225.0	248.6

[a] B3LYP/aug-cc-pVTZ level of theory. [b] B3LYP/6-311++G(2df,p) level of theory. [c] Values reported on a 360° scale, as in Figure 3. On a 180° scale, the corresponding values are 135.5° (CC−W-1), −104.8° (CC−W-2), −135.0° (TS2), and −111.6° (TS3).

than in the CC−W-1 one. In each conformer the hydroxyl group of the parent molecule lies along the axis of one of the nonbonding electron pairs of the water oxygen. Therefore the two free OH water group positions are clearly related to the two possibilities of having one or the other free electronic orbital of the water oxygen linked to the hydroxyl group. The structure of the parent molecule in CC−W-1 and CC−W-2 is comparable with the conformation of glycolaldehyde in particules.[33] Indeed, in the particules, monomers with a 1O−2C−3C−4O dihedral angle of 0° and 7H−4O−3C−2C dihedral angle around 50° are strongly preferred. The intramolecular hydrogen bond observed in the gas phase is partly replaced by intermolecular hydrogen bonds.

A more detailed description of the conformational landscape is necessary to quantitatively understand the tunneling effect resulting in the presence of pairs of doublets in the spectrum of the CC−W-1 conformer. First, the two equivalent positions are the mirror images one from the other through the 4O−3C−2C plane: the water molecule goes from one side of the parent molecule to the opposite one, keeping the two intermolecular hydrogen bonds. The two paths through which the tunneling can proceed are identified on a two-dimensional potential energy surface, along the glycolaldehyde hydroxyl (7H−4O−3C−2C dihedral angle) and the free OH water group (11H−10O−1O−2C dihedral angle) coordinates; see Figure 3 (note that the potential energy surface was computed at a low level of the theory, and the energy of the extrema was optimized at the MP2/cc-pVQZ level). For the first path the two global minima are linked through the diagonal path, which involves a "planar" transition state TS1: the water molecule lies in the 7H−4O−3C−2C−1O plane. Meanwhile it is a high energy path, the relative energy, and barrier, associated with the global maximum being equal to 17.72 kJ/mol. Clearly this barrier is too high to produce a splitting of a few tens of kHz on a microwave spectrum, knowing that the potential surface does not present any shallow feature.[34−36] The second path involves the conformer CC−W-2 (2.36 kJ/mol) which is associated with the local minimum shown in Figure 3. The equivalent positions of CC−W-1 can be reached via a path along the free OH water 11H−10O−1O−2C dihedral angle, through a first barrier (TS2, 4.36 kJ/mol), followed by a path along the hydroxyl group 7H−4O−3C−2C dihedral angle, through a second barrier (TS3, 4.98 kJ/mol). This pathway is very interesting and evidences the conformational flexibility within the glycolaldehyde−water complex. Indeed the transition state TS2 associated with the first local maximum (saddle point) puts the plane of the water molecule into the direction of the hydroxyl group. Then the motion along the hydroxyl coordinate involves a transition state TS3 associated with the second local maximum (saddle point), i.e., with the hydroxyl group close to the 1O−2C−3C−4O plane. Finally the water molecule basically moves from one side of the molecule to the other one. The energy associated with the conformational temperature (about 3.0 kJ/mol) indicates that the CC−W-2 conformer can relax to the CC−W-1 conformer, leaving us only with the spectroscopic signature of the most stable conformer. If we estimate that the separation between the 0^+ and 0^- sublevels is of the order of 1 cm^{-1} (30 GHz), the conformational flexibility occurs in the time scale of the picosecond. It should be noted that the observed line splittings (Table 1) are now in agreement with the calculated height of the barrier. Indeed in benzonitrile−water, a transition splitting was also observed in the microwave range (10 kHz at 10 GHz and a few MHz at 60 GHz).[37] It was assumed to be due to the "pure" rotation of water because of the observation of a 3:1 intensity ratio. Due to the presence of a perturbation it was possible to determine the barrier to the internal rotation of water. It was found equal to 287(20) cm^{-1} (3.43(24) kJ/mol). Although the dynamics in benzonitrile−water and in glycolaldehyde−water are not exactly the same, the large amplitude motions of the OH group in both molecules are hindered by a barrier of the same order of magnitude. Therefore we believe that the dynamical path suggested for glycolaldehyde−water gives observed splittings which are in qualitative agreement with the height of the barriers. Finally ab initio quantum chemistry calculations indicate that the fingerprint vibrational signatures, which permit distinction between CC−W-1 and CC−W-2, lie in the mid-infrared region. In particular strong resolved bands appear in the vicinity of 500 cm^{-1}, as illustrated in Figure 4. They are associated with the localized bending deformations of the 4O−7H hydroxyl group and 10O−9H water bond. For the sake of completeness, the unscaled harmonic frequencies of the 27 normal modes of CC−W-1 and CC−W-2, along with the associated line strengths, are presented in the Supporting Information.

Discussion

It is the high symmetry of the parent molecule which allowed us to see a tunneling effect through two equivalent positions of glycolaldehyde−water. This effect was already observed in formic acid−water, the most simple carboxylic acid containing both carbonyl and hydroxyl groups.[38] Obviously this effect can only be observed in carbohydrates where the pseudorotation

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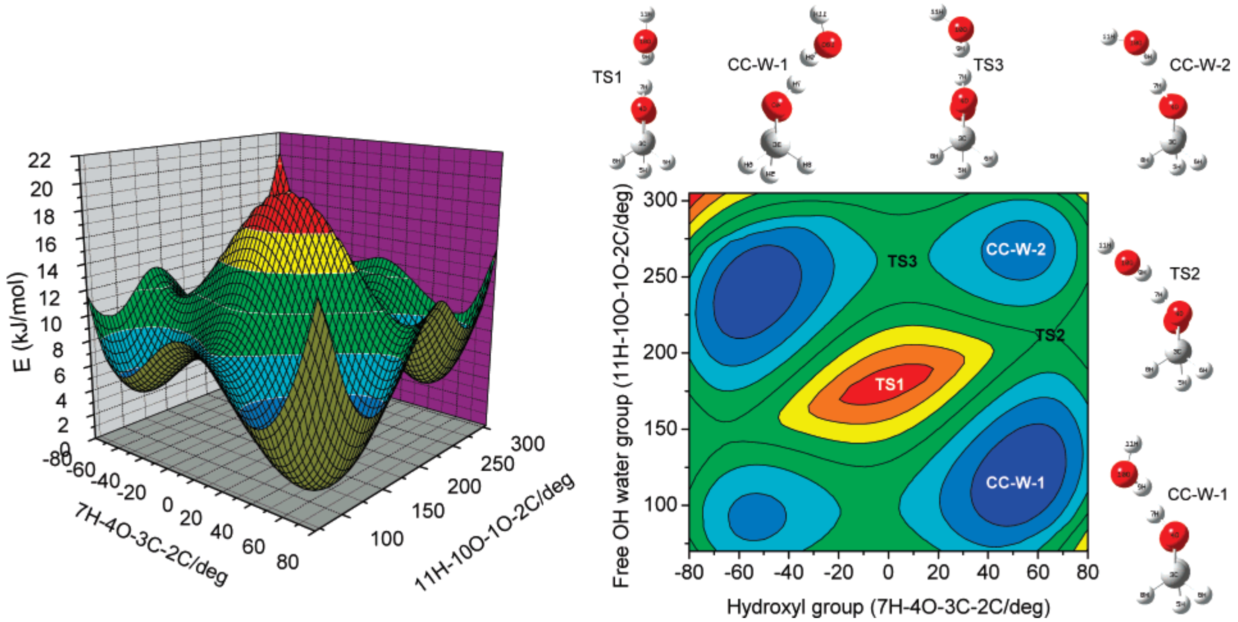

Figure 3. Ab initio potential energy surface of glycolaldehyde−water along the free OH water group and along the hydroxyl group coordinates, calculated at the B3LYP/6-31G* level. Pathways between the equivalent positions of CC−W-1 involve either TS1 or TS2, TS3, and CC−W-2.

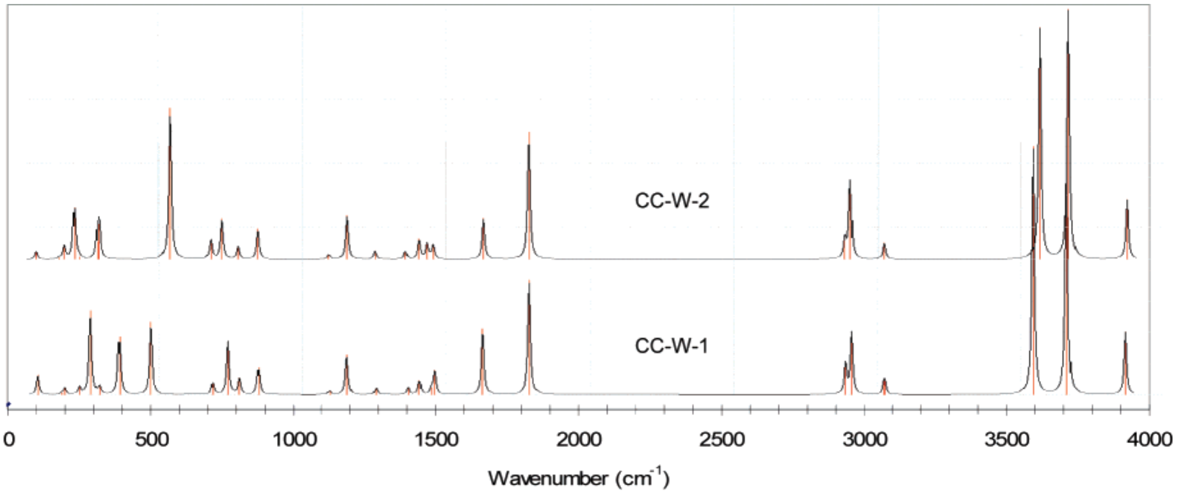

Figure 4. Ab initio IR spectrum of CC−W-1 and CC−W-2, the most stable conformers of glycolaldehyde−water, calculated at the B3LYP/aug-cc-pVTZ level of theory. The vibrational fingerprint region which permits distinguishing between the two conformers is located below 600 cm^{-1}.

motion of water between two equivalent positions does not change the structural parameters of both minima. Meanwhile, we believe that the conformational flexibility landscape investigated in glycolaldehyde−water is of general interest, not only for other carbohydrates but also for several water complexes, as those already studied by microwave Fourier transform spectroscopy. The reason is that most of the water complexes presenting two intermolecular hydrogen bonds will often be associated with two conformers close in energy, and the isolated species investigated in a supersonic expansion will experience the same type of two-dimensional energy surface (the two coordinates are the OH free water group and an OH or a NH group from the parent molecule, linked to water through an H-bond).

Among the hydrogen-bonded complexes, 3-hydroxytetrahydrofuran−water [36] has a weak intramolecular hydrogen bond in the parent molecule which is replaced by two stronger intermolecular hydrogen bonds in the complex with water: water (H_f−O_w−H_b) is accepting a hydrogen bond from the hydroxyl and is donating one, through H_b, to the furanose oxygen O_r. The free O_wH_f water group is roughly oriented in the direction of the hydroxyl (structure I in ref 36). Meanwhile there should be another low energy structure with two intermolecular hydrogen bonds for which the only difference is the orientation of the free O_wH_f water group. Indeed Figure 4 of ref 36 presents the potential energy curve along the wagging motion of water (H_f−O_w−H_b−O_r), calculated at the MP2/6-31G** level. This curve has a global minimum, associated with structure I, and suggests the presence of a local minimum at 500 cm^{-1} (6 kJ/mol; this point was not optimized at a higher level probably because of the high computational cost), presumably associated with another orientation of the O_wH_f water group. Another interesting case is the alaninamide−water van der Waals complex.[34] Water (H_f−O_w−H_b) binds to alaninamide by two intermolecular H-bonds, O_w−H_{amino} and H_b−$O_{carbonyl}$, the O_wH_f water group being oriented 75° below the amide plane. Again the size of the molecule makes high level ab initio calculations costly. Meanwhile the potential energy curve along the $H_f-O_w-H_{amino}-N$ dihedral angle (Figure 4 of ref 34) clearly evidenced, at the MP2/6-31+G** level, two minima associated with the possible positions of the O_wH_f water group below and above the amide plane. The minima are separated by a barrier of approximately 240 cm^{-1} (2.9 kJ/mol) and a relative energy of 90 cm^{-1} (1.1 kJ/mol). We believe that for these two molecules already studied in the literature the conformational flexibility can be modeled with a two-dimensional landscape as in glycolaldehyde−water. Of course depending on the symmetry of the molecule, the presence of two equivalent minima will not be always observed.

It is interesting to note that the presence of water can stabilize the structure of the parent molecule, in particular in the presence of an amino group or a free hydroxyl group. That cannot be clearly observed for alaninamide−water because of the presence of two amino groups and one methyl group. However this is well illustrated in the case of formamide. The vibration−rotation data of formamide indicate that, as the amino group inverts, the molecule twists about the CN bond,[39] while no such effect has been reported in the spectrum of formamide−water.[40]

The conformation of hydrated phenyl-substituted sugars has recently been investigated by means of a combination of mass selected, conformer specific ultraviolet and infrared double resonance hole burning spectroscopy experiments and ab initio quantum chemistry calculations.[15] Much information has been obtained on mannose−, galactose−, and glucose−water complexes. Meanwhile the IR−UV hole burning double resonance spectra recorded in the 3 microns region cannot always be assigned unambiguously because of the experimental resolution and/or the precision of the ab initio calculations (relative energy and vibrational frequencies). This is especially true for all the conformers with water linked to the hydroxyl and the ether groups of the sugar through two intermolecular H-bonds, as discussed hereafter (for the notation see ref 41). Indeed, in βpGal−W, both the A_ins6a (0 kJ/mol) and A_ins6b (1.5 kJ/mol) conformers match the observed spectrum U, and both the C_ins6a (0.9 kJ/mol) and C_ins6b (0.3 kJ/mol) conformers match the observed spectrum P. In each case the *a* and *b* conformer structures mainly differ by the position of the free water OH group as in the glycolaldehyde−water CC−W-1 and CC−W-2 conformers. In βpGlc−W only the A_ins6a (1.1 kJ/mol) conformer was considered, probably because two structures (cG-g+_ins4 and A_ins2) associated with other localization sites for water are energetically more stable. The same situation occurs in αpMan−W. In light of our results, we believe that dynamical relaxation probably occurs between these close-lying conformers. Indeed all the gas-phase experiments used supersonic expansion, and the energy barriers between the conformers must be of the same order as in glycolaldehyde−water (4.36 kJ/mol along the free OH water coordinate; 4.98 kJ/mol along the hydroxyl group coordinate). To answer this suggestion in more detail, investigation of either the “conformational flexibility” fingerprint region or the “structural” fingerprint microwave region is needed.

Conclusions

We have conducted the first spectroscopic study of the smallest hydrated sugar by combining microwave spectroscopy and ab initio calculations. The very high resolution (10 kHz) and sensitivity (10^{-10} cm^{-1}) of our spectrometer, together with the small size of the system, resulted in experimental evidence of a conformational flexibility process. High level ab initio calculations (B3LYP/aug-cc-pVTZ) explained quantitatively this flexibility in terms of a two-dimensional potential energy surface involving the free OH water (11H−10O−1O−2C) and the hydroxyl sugar (7H−4O−3C−2C) dihedral angles. No interchange of water hydrogen atoms through an internal rotation was observed. Reviewing the literature data we have shown that this conformational flexibility process can occur in several hydrated molecules involving two intermolecular H-bonds. We believe that our strategy to study sugars in the microwave range to enlighten the hydration processes is highly complementary to the infrared studies. Finally we discussed the vibrational fingerprint signature, which could be investigated using a synchrotron facility. For this purpose the beamline AILES (Advanced Infrared Line Exploited for Spectroscopy) of the new generation synchrotron radiation facility SOLEIL (located in France near Paris) will offer a new powerful spectroscopic tool, especially in the terahertz and mid-infrared region, and will be available at the beginning of 2007.[42]

Acknowledgment. This work was supported by the Institut du Développement des Ressources en Informatique Scientifique (Contract IDRIS 51715) and by the Programme National de Physico-Chimie du Milieu Interstellaire (PCMI). Prof. D. Petitprez (Université Lille 1) is thanked for useful discussions in the early stage of the study.

Supporting Information Available: Complete ref 27 (p S1). Ab initio structure of the four most stable conformers of glycolaldehyde−water, as reported in Figure 1 (p S2). Ab initio harmonic frequencies of the 27 normal modes of the CC−W-1 and CC−W-2 conformers and the associated line strengths (pp S3−S7). This material is available free of charge via the Internet at http://pubs.acs.org.

JA062312T

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(41) Briefly, the carbon atoms of the sugar ring are numbered 1−6, starting from the anomeric carbon, C1, and finishing with the exocyclic hydroxymethyl group. Ins*n* means that water is bound to the H-bond acceptor of the OH*n* group. Conformer A and C are associated with the sugar and are assigned to ccG+g- and cG-g+, respectively. The notation indicates that the ring OH groups are linked in a clockwise (c) or counterclockwise (cc) sense; they may be oriented in a gauche conformation: g+ (g−) means that the $H_n-O_n-C_n-C_{n+1}$, $n = 2-4$, dihedral angles are lying between 240° and 360° (0° and 120°), and G+ (G−) is related to the exocyclic hydroxymethyl group position. For details concerning the notation, see ref 14.

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