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| Journal: | *Physical Chemistry Chemical Physics* |
| Manuscript ID | CP-ART-09-2018-005552.R1 |
| Article Type: | Paper |
| Date Submitted by the Author: | 31-Oct-2018 |
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Physical Chemistry Chemical Physics

ARTICLE

# Water Induces the Same Crown Shapes as $Li^+$ or $Na^+$ in 15-Crown-5 Ether: a Broadband Rotational Study†

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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15-crown-5 ether (15C5) and its complexes with water have been studied using broadband Fourier transform microwave spectroscopy in a supersonic jet. A new conformer of 15C5 has been observed and established as the new global minimum out of a total of nine isolated structures. In addition, two 15C5-$H_2O$ and two 15C5-$(H_2O)_2$ clusters have been observed. The cluster structures have been unambiguously identified through the observation of water $^{18}O$ isotopologue spectra. In all the clusters, at least one water molecule, located close to the axis of the 15C5 ring, interacts through two simultaneous hydrogen bonds to the endocyclic oxygen atoms. This interaction reshapes the 15C5 ring to reduce its rich conformational landscape to only two open structures, related to those found in complexes with $Li^+$ or $Na^+$ ions. In the most abundant 15C5-$(H_2O)_2$ form, the two water molecules repeat the same interaction scheme while binding to opposite sides of the ring. In the second most abundant dihydrated form the two water molecules lie on the same side of the ring. This finding is exceptionally rare because water-water interactions typically prevail over the formation of additional solute-water contacts, and it showcases the particular binding features of crown ethers.

## Introduction

Crown ethers (CE) are macro-heterocycles that in their simplest form are cyclic oligomers of dioxane. These were discovered by Pedersen[1] in the 1960s, and their chemistry contributed to the introduction of host-guest supramolecular chemistry owing to their exceptional structural features and applications.[2] One of their most important attributes is the specificity with which they form complexes with metal cations.[2,3] Other cationic[4,5] and neutral molecules[6–14] have been also identified as possible guests.

The conformational behavior of small cycles, usually reduced to a few conformers, is related to the potential energy surface associated to the out-of-plane ring motions[15], of which there are N-3 for an N-membered ring. For crown ethers the number of such skeletal motions increases to 9, 12 or 15 for 12-crown-4 (12C4), 15-crown-5 (15C5) or 18-crown-6 (18C6) ethers, respectively. This gives rise to many low energy conformers as the eight observed for 15C5 from rotational spectroscopy.[16,17] The coupling between skeletal modes make the interconversion between conformers through reasonably low barriers possible.[13] In fact, the potential energy surfaces (PES) of CEs contain multiple energy minima with low interconversion barriers,[16–18] resulting in a high flexibility and giving rise to a rich conformational landscape. This flexibility enables transformation mechanisms to maximize host-guest interactions in the formation of complexes. The amphiphilic character of CEs is usually exploited to form host-guest complexes in hydrophilic solvent phases, which are then transferred to hydrophobic phases. In this context, investigating the role of water and host-water interactions to facilitate complex formation mechanisms in solution is an enlightening endeavor.[7–13]

An advantageous way to quantify host-water interactions is to isolate the clusters formed in a supersonic jet. This isolation allows one to obtain their conformation and intrinsic properties in an environment free of other intermolecular interactions such as liquid phase solvent effects. Microwave (MW) spectroscopy in supersonic jets is a very powerful experimental method to investigate the structure of an isolated molecule or cluster. Its most advanced form, Chirped-pulse Fourier transform microwave spectroscopy (CP-FTMW),[19] also becoming known as Molecular Rotational Resonance (MRR), is able to record broad sections of a rotational spectrum in a single acquisition with the usual high resolution and sensitivity of MW spectroscopy, thus permitting the observation of low concentration species. These features make it particularly adequate to investigate CEs and their clusters. Apart from the need of a permanent dipole moment, the size of the molecule poses restrictions because the molecules need to be brought

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†Electronic Supplementary Information (ESI) available: Rotational constants of all the observed species; figures and results of *ab initio* calculations on 15C5 and its complexes with water; results from Kraitchman analysis, and line list of the experimental transitions. See DOI: 10.1039/x0xx00000x

into the gas phase and since the rotational lines of relatively heavy systems tend to collapse at low frequencies. Nevertheless, the structure and properties of molecules and adducts of increasing size investigated using CP-FTMW is an active field of research. [13,20–23]

Only a limited number of gas-phase studies of crown ethers[7,16–18] or their complexes with water[7–13] or other solvents[14] can be found in the literature. The first gas phase works on CE-water complexes were done by Ebata and co-workers[7–11] on benzo-18-crown ether-$(H_2O)_n$ and dibenzo-18-crown ether-$(H_2O)_n$ and Shubert et al.[12] on benzo-15-crown ether-$(H_2O)_n$ and 4'-amino-benzo-15-crown ether-$(H_2O)_n$, all of them bearing a chromophore group that enabled the use of laser spectroscopy techniques in supersonic jets. However, there is not much gas phase information about the structure or interaction with water of common crown ethers without a chromophore. Such studies would offer insight into the influence of the chromophore on the molecule's shape and its clusters with water. MW spectroscopy provides access to molecules without chromophore groups, thus widening the range of molecules accessible to study. The only two systems studied by MW spectroscopy are 15-crown-5 ether (15C5)[16,17] and 12-crown-4 ether-$(H_2O)_n$.[13] In the previous microwave work on the 15C5 monomer[16,17] performed with a narrowband molecular-beam FTMW spectrometer (MB-FTMW) based on a Fabry-Pérot type resonator design, the spectra of eight different conformers of 15C5 crown ether were observed following the guide of formerly reported ab initio calculations.[24] In contrast, in the study of the CP-FTMW spectrum of 12-crown-4 ether (12C4) only clusters with one and two water molecules were observed. This result is due to the fact that the most populated forms of the 12C4 monomer have no dipole moment. Here we present the study of the microwave spectrum of 15C5 and its microsolvated clusters using CP-FTMW spectroscopy, which allows the observation of a full conformational landscape of the species under study. We also compare the results with related systems, such as 15C5-$Na^+$ and 12C4-$H_2O$ clusters.

## Experimental

For the experiments, the Hamburg CP-FTMW spectrometer COMPACT[25] was used. 15C5 was placed at 145 ºC in a heatable reservoir close to the orifice of a pulse valve. The molecules were supersonically expanded into vacuum using neon as a carrier gas to provide low rotational temperatures (1-2 K). The molecules were excited using a low-frequency 2-8 GHz microwave chirp of 4 μs duration. This low-frequency range is particularly suited for larger and heavier molecular systems like CEs that have large moments of inertia and thus small rotational constants. After the excitation pulse was over, the free-induction decay (FID) molecular response was recorded in the time domain for 40μs. In order to increase data acquisition speed and reduce sample consumption, each valve pulse was followed by 8 excitation pulses using the "fast frame" option of the digitizer, which are coadded and averaged in the time domain.[26] A Fast Fourier transformation to the frequency domain yielded the rotational spectrum of all polar species sufficiently populated in our jet, such as conformers, clusters with different amounts of water molecules attached, or isotopologues.

## Results and discussion

In the CP-FTMW broadband spectrum of 15C5, recorded without the addition of water (see Figure S1 of the supplementary material), we first identified the individual rotational spectra of the eight previously observed conformers.[16,17] The new sets of rotational constants obtained from an updated fit of all observed transitions are compiled in Table S1. For these forms, we used the same labeling, I, II, III, IV, V, VI, VIII and IX as in Ref. 13 (see Figures S2). The most intense spectra correspond to forms I to IV. As discussed later, conformer VII (see predicted parameters in Table S2) was neither observed in the MB-FTMW spectroscopy work[17] nor in the present one. After removing the lines assigned to the eight known 15C5 conformers, the cleaned spectrum shows very intense unassigned lines. The observation of different recognizable transition patterns (see Figure S3) allowed for the identification of five new species, initially labelled with the capital letters A, B, C, D, and E, which approximately follow the order of decreasing intensity. The cleaned CP-FTMW spectrum is compared in Figure 1 with those calculated for these species from the experimentally determined parameters (see Tables 1 and 2). All of them were characterized by groups of intense $\mu_c$-type R-branch lines approximately spaced by A+B. This pattern is characteristic of a near oblate asymmetric top. The analysis of the spectra using the A-reduced semirigid Hamiltonian of Watson[27] in the $I^r$ representation yielded the rotational parameters given in Tables 1 and 2.

As recently shown for the 12C4 ether,[13] a first insight into the nature of the observed species was based on a property of the

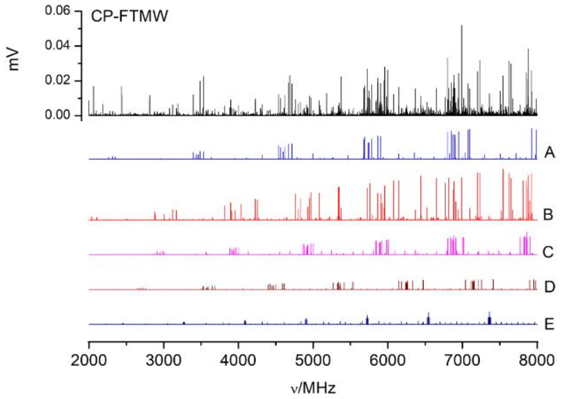
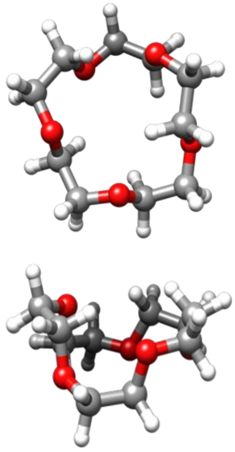


Figure 1. Comparison of the CP-FTMW spectrum of 15C5 (upper trace) cleaned from lines of the eight known forms with the spectra calculated from the observed parameters (see Tables 1 and 2) of the newly assigned species labelled with the capital letters A, B, C, D, and E. The intensities of the calculated lines (T= 1 K) have been set to reproduce approximately the observed spectra.

**Table 1.** Rotational parameters obtained from the analysis of the spectrum (A-reduction[27], I$^r$ representation) of the most abundant species (A) of 15-crown-5 ether and its comparison with the MP2/6-311++G(d,p) ab initio values for the global minimum conformer 15C5-0.

| Param.[a] | Species A | 15C5-0 |
|---|---|---|
| $A$/MHz | 599.41652(16)[b] | 606.5 |
| $B$/MHz | 554.06562(19) | 556.8 |
| $C$/MHz | 339.94984(20) | 344.4 |
| $\kappa$ | 0.65 | 0.6 |
| $P_{aa}$/uÅ$^2$ | 777.81918(71) | 771.0 |
| $P_{bb}$/uÅ$^2$ | 708.80899(59) | 696.5 |
| $P_{cc}$/uÅ$^2$ | 134.30926(44) | 136.7 |
| $\Delta$J /kHz | 0.0458(14) | 0.09 |
| $\Delta$JK /kHz | [0.]c | 0.08 |
| $\Delta$K /kHz | [0.] | -0.16 |
| $\delta$J /kHz | 0.01830(74) | 0.006 |
| $\delta$k /kHz | 0.0590(44) | -0.04 |
| $\sigma$/kHz | 5.1 | |
| n | 98 | |
| $\mu_a$/D | weak | 0.4 |
| $\mu_b$/D | no | 0.2 |
| $\mu_c$/D | intense | 1.2 |



[a] $A$, $B$ and $C$ are the rotational constants; $\kappa$ is Ray's asymmetry parameter ($-1 < \kappa = (2B-A-C)/(A-C) < 1$); $P_{\alpha\alpha}$ ($\alpha = a$, $b$ or $c$) are the planar moments of inertia derived from the inertial moments $I_\alpha$ ($P_{cc}=(I_a+I_b-I_c)/2$); $\Delta_J$, $\Delta_{JK}$, $\Delta_K$, $\delta_J$ and $\delta_K$ are the quartic centrifugal distortion constants; $\sigma$ is the rms deviation of the fit; n is the number of lines fitted. [b] Standard errors are given in parentheses in units of the last digit. [c] Values in square brackets were kept fixed.

rotational parameters of ring-shaped molecules. The values of the planar moment $P_{cc}$ and the C rotational constant present a linear correlation as shown in Figure 2 for the observed forms of 15C5. Since the c inertial axis is almost perpendicular to the average ring plane, the rotational constant C (or the $I_c$ principal moment of inertia, which are inversely proportional to each other) measures the average diameter of the ring. The $P_{cc}$ planar moment of inertia, which gives the mass extension out of the *ab* plane, measures the ring thickness. For example, forcing the ring to pucker means reducing its radius and increasing the thickness, so both C and $P_{cc}$ have to increase. On the contrary an extended ring would have lower values of C and $P_{cc}$ so a positive slope for their correlation is expected as shown in Figure 2. When the corresponding values for the new species are plotted, the species with the most intense spectrum, labelled A, falls close to the correlation line of bare 15C5 conformers, while the other lie far apart and can be identified as 15C5-water complexes.

Species A is thus a previously unobserved conformer of the 15C5 monomer. Its rotational constants are close to those of form II, but it has a dominant $\mu_c$ electric dipole component instead of $\mu_a$. A new quantum-chemical search (MP2/6-311++G(d,p))[28] for the low energy conformers of 15C5 found a new global minimum, labeled 15C5-0. The spectroscopic parameters calculated for this form are in good agreement with the observations for the species A as can be seen in Table 1. The newly observed conformer was not observed in the previous narrow-band molecular beam FTMW spectroscopy study,[16,17] and was also missed in the theory paper. This result demonstrates one of the advantages of broadband CP-FTMW spectroscopy over narrowband techniques: The ability to record broad sections of the spectrum significantly reduces the risk of missing important species in the spectrum as well as reducing the need of having highly accurate quantum-chemical calculation results at hand. The *ab initio* results for all the low energy 15C5 forms are given in Table S2. This table also includes conformer XX with a relative energy rather high compared to other forms. This form, which has a significant crown-shaped open structure, is relevant in the formation of complexes (see below).

The remaining observed species were identified as complexes with water (w) that were initially labelled as 15C5-w-B, 15C5-w-C, 15C5-w$_2$-D and 15C5-w$_2$-E. The observation of these complexes from the sample of 15C5 alone was attributed to the presence of water in the sample as water "contamination", which has been detected in related compounds.[12,13] The intensity of their spectra increased when water vapor was allowed to flow into the supersonic expansion. A definitive identification of the complexes was achieved from the observation of complexes with $H_2{}^{18}O$ using a 1:1 $H_2{}^{18}O$/ $H_2O$ mixture. Only one $^{18}O$ isotopologue was observed for 15C5-w-B and 15C5-w-C, confirming that these are 15C5 monohydrated complexes. For complex 15C5-w$_2$-D, two isotopologues with spectra weaker than that of the parent species were observed. For the weak species 15C5-w$_2$-E, a quasi-oblate symmetric top that was identified thanks to its sharp c-type R-branch group patterns (see bottom trace of Figure 1), only one $^{18}O$ isotopologue has been identified from a very weak c-type spectrum. The rotational parameters for the observed $^{18}O$ species are given in Tables S3 and S4 in the supporting information. All the observed frequencies are collected in Tables S11-S28.

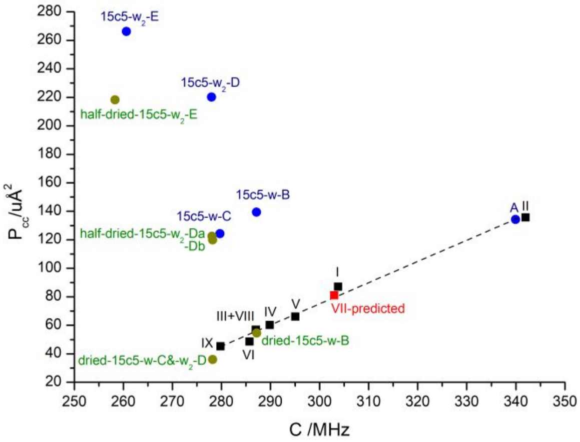


Figure 2. Scatter plot showing the correlation between the values of the planar moment $\boldsymbol{P_{cc} = (I_a + I_b - I_c)/2 = \sum_i m_i c_i^2}$ and the C rotational constant ($\boldsymbol{C = h/8\pi^2 I_c;\quad I_c = \sum_i m_i(a_i^2 + b_i^2) = \sum_i m_i r_{ci}^2}$) for the previously observed 15C5 forms (■). This plot allows to classify the species observed in this work (●) as bare 15C5 forms like A or 15c5-water species as 15C5-w-B, 15C5-w-C, 15C5-w$_2$-D and 15C5-w$_2$-E. The estimated values for dried 15C5-w-B, 15C5-w-C; 15C5-w$_2$-D, and for half-dried 15C5-w$_2$-D and 15C5-w$_2$-E (●) are also plotted.

**Table 2.** Rotational parameters obtained from the analysis of the spectrum of the 15-crown-5 ether···$(H_2O)_n$ (n=1,2) clusters and its comparison with the ab initio values for the identified forms.

| Param.[a] | 15c5-w-B | 15c5-w-1 | 15c5-w-C | 15c5-w-3 | 15c5-w2-D | 15c5-w2-1 | 15c5-w2-E | 15c5-w2-6 |
|---|---|---|---|---|---|---|---|---|
| $A$/MHz | 550.48306(17) [b] | 561.3 | 506.27482(12) | 516.8 | 468.67292(21)b | 474.1 | 411.00203(38) | 417.9 |
| $B$/MHz | 450.93827(12) | 452.3 | 478.08872(15) | 480.5 | 428.35788(10) | 434.8 | 406.94503(37) | 410.9 |
| $C$/MHz | 287.15720(11) | 290.0 | 279.72069(12) | 281.9 | 278.01562(11) | 280.0 | 260.63832(19) | 262.3 |
| $\kappa$ | 0.24 | 0.20 | 0.75 | 0.69 | 0.58 | 0.60 | 0.94 | 0.91 |
| $P_{aa}$/uÅ$^2$ | 981.30079(63) | 979.5 | 932.78939(67) | 933.7 | 959.64716(74) | 950.7 | 975.6318(18) | 973.7 |
| $P_{bb}$/uÅ$^2$ | 778.63770(49) | 763.3 | 873.93792(55) | 859.7 | 858.16080(50) | 854.4 | 963.3732(13) | 953.1 |
| $P_{cc}$/uÅ$^2$ | 139.42690(34) | 137.0 | 124.29267(39) | 118.2 | 220.15840(36) | 211.6 | 266.25337(71) | 256.1 |
| $\Delta$J /kHz | 0.03298(72) |  | 0.02546(80) |  | [0.] |  | 0.0329(10) |  |
| $\Delta$JK /kHz | -0.0552(27) |  | [0.]c |  | 0.0445(25) |  | -0.0303(11) |  |
| $\Delta$K /kHz | 0.1267(37) |  | [0.] |  | [0.] |  | [ 0.] |  |
| $\delta$J /kHz | 0.01531(33) |  | 0.01154(42) |  | [0.] |  | -0.0455(21) |  |
| $\delta$k /kHz | 0.0287(18) |  | 0.0344(20) |  | -0.0030(18) |  | [ 0.] |  |
| $\sigma$/kHz | 5.2 |  | 4.9 |  | 5.4 |  | 7.0 |  |
| n | 67 |  | 164 |  | 134 |  | 156 |  |
| $\mu_a$/D | weak | 0.7 | no | 0.2 | no | 0.3 | very weak | -0.8 |
| $\mu_b$/D | weak | 1.0 | weak | -0.6 | no | 0.2 | weak | 2.4 |
| $\mu_c$/D | intense | 2.9 | intense | 1.5 | intense | 1.3 | moderate | 2.9 |
| $\Delta E$/kJ/mol |  | 0.0 |  | 1.1 |  | 0.0 |  | 12.5 |

[a] $A$, $B$ and $C$ are the rotational constants; $\kappa$ is Ray's asymmetry parameter ($-1 < \kappa = (2B-A-C)/(A-C) < 1$); $P_{\alpha\alpha}$ ($\alpha$ = $a$, $b$ or $c$) are the planar moments of inertia derived from the inertial moments $I_\alpha$ ($P_{cc}=(I_a+I_b-I_c)/2$); $\Delta_J$, $\Delta_{JK}$, $\Delta_K$, $\delta_J$ and $\delta_K$ are the quartic centrifugal distortion constants; $\sigma$ is the rms deviation of the fit; n is the number of lines fitted. [b] Standard errors are given in parentheses in units of the last digit. [c] Values in square brackets were kept fixed.

The observation of monosubstituted isotopologue spectra is a prerequisite to determine the structure of a molecular system in microwave spectroscopy. In the present case it provides interesting conclusions about the structure of the complexes prior to using any ab initio results. In the case of microsolvated molecules, the location of the water molecule(s) can be obtained from the investigation of $^{18}O$ spectra. The additional set of rotational constants allowed us to determine the position of the oxygen atom(s) with respect to the center of mass of the complex. The first remarkable fact is that in all cases the $C$ rotational constant and the planar moments $P_{aa}$ and $P_{bb}$ have nearly the same values for the parent and $^{18}O$ substituted species, a proof that the water oxygen atom lies on or very near to the $c$ inertial axis of the complexes.

The rotational constants are the basis of the substitution method, $r_s$, that uses the Kraitchman equations,[29,30] to give the absolute values of the coordinates of the isotopically substituted atoms in the principal inertial axis system of the parent species. The signs of the coordinates can be chosen from a reasonable *ab initio* structure. The $r_s$ coordinates of the water oxygen atoms are given in Table 3. In fact, the $^{18}O$ atoms are located near the $c$ axis in all cases, and the $a$ and $b$ coordinates are close to zero. The limitations of this method to determine the position of atoms lying near the principal axes are evident from the $a$ and $b$ coordinates of 15C5-w-B and the $b$ coordinate of one of the water oxygen atoms of 15C5-$w_2$-D, for which the result is an imaginary number.

The C rotational constants for the 15C5-w-C and 15C5-$w_2$-D complexes have similar values indicating a similar mass distribution around the $c$ axis. In order to know if 15C5 takes on the same conformation in both cases we estimated the rotational constants of 15C5 in these complexes by subtracting the inertial contributions of the water molecules from the experimental rotational constants and the $r_s$ data.[31,32] Since only the water oxygen atom coordinates were available, we assumed that these are close to the center of mass of water, and that all the mass of water is located at the oxygen position.[13] The resulting rotational constants are an estimate of the values corresponding to the structure adopted by 15C5 in the complex. The application of this approach to our data is summarized in Table 3 where it can be seen that in fact in both "dried" 15C5-w-C and 15C5-$w_2$-D complexes the crown ether has similar rotational constants, and thus the same 15C5 structure is present in both complexes. On the other hand, the rotational constants for bare 15C5-w-B are different. The points corresponding to the result of this subtraction approach are also represented in the $P_{cc}$ vs. $C$ diagram in Figure 2. The subtraction of the contribution of only one water molecule ("half-dried") from the 15C5-$w_2$-D rotational constants leads to rotational constants close to those of 15C5-w-C (see Table 3).

**Table 3.** Determined $r_s$ coordinates for the water oxygen atoms in the 15C5-w-B, 15C5-w-C and 15C5-$w_2$-D and 15C5-$w_2$-E complexes observed in this work and rotational parameters estimated for the bare 15C5 subunit in the 15C5-w-B, 15C5-w-C and 15C5-$w_2$-D complexes by subtracting the inertial contributions of water from the experimental rotational constants of Table 2. Full-dried means subtraction of contributions from all water molecules and half-dried the subtraction of contributions of one water molecule for a 15C5-$w_2$ complex as for 15C5-$w_2$-E.

| $\|r_s\|$[a] | 15c5-w-B | 15c5-w-C | 15c5-$w_2$-D(a) | 15c5-$w_2$-D(b) | 15c5-$w_2$-E (a) |
|---|---|---|---|---|---|
| $\|a\|$/Å | 0.239i[0.000(6)][b] | 0.3455(50) | 0.1825(90) | 0.2475(64) | 0.13(82) |
| $\|b\|$/Å | 0.156i[0.000(9)][b] | 0.2568(68) | 0.019(86) | 0.09i[0.000(2)] [b] | 0.30(82) |
| $\|c\|$/Å | 2.08816(73) [c] | 2.03291(85) | 2.24482(73) | 2.27481(70) | 1.725(65) |

| Dried 15C5 | 15c5-w-B[c] | 15c5-w-C | 15c5-$w_2$-D[d] | | | 15c5-$w_2$-E half-dried | |
|---|---|---|---|---|---|---|---|
| | | | full-dried | half(a) | half(b) | exp. | ab initio |
| $A$/MHz | 606.6 | 565.2 | 565.2 | 515.3 | 516.5 | 432.0 | 430.6 |
| $B$/MHz | 487.9 | 508.2 | 508.2 | 467.3 | 468.5 | 427.0 | 428.6 |
| $C$/MHz | 287.2 | 278.2 | 278.2 | 278.1 | 278.2 | 260.9 | 258.6 |
| $P_{aa}$/u Å$^2$ | 981.30 | 958.38 | 958.38 | 959.0 | 958.4 | 975.38 | 979.8 |
| $P_{bb}$/u Å$^2$ | 778.64 | 858.16 | 858.16 | 858.3 | 858.2 | 961.68 | 974.2 |
| $P_{cc}$/u Å$^2$ | 54.47 | 36.02 | 36.02 | 122.5 | 120.3 | 208.18 | 199.4 |

[a] Obtained from the application of Kraitchman[29] equations to parent and water $^{18}O$ species. [b] The cartesian coordinates with imaginary values were fixed to zero. [c] The error is given in parenthesis in units of the last digit. This error has been estimated according to Costain rules.[30] [c] Estimated by setting all the imaginary coordinates to zero. [d] Estimated from the following $r_s$ sign combination: ($^{18}O_a$): 0.1825, 0.0, 0.1825, ($^{18}O_b$): −0.2475, 0.0,−2.27481; other possible combinations give the same constants within 0.2 MHz.

The points corresponding to subtraction of both water molecules lie on the line corresponding to the 15C5 monomers "open" cycles with low values of both $C$ rotational constants and $P_{cc}$ planar moments. In the case of 15C5-$w_2$-E, the subtraction of the known water contributions led to a set of constants that do not correspond to a bare 15C5 form, nor are they close to those of other known or predicted species.

The identification of the observed species to the structures shown in Figure 3 was achieved with the help of ab initio computations as described in the supplementary information. A summary of the most relevant results is given in Tables S5 and S6 and Figures S4 and S5. In those tables the conformers are labelled as 15C5-w-$n$ or 15C5-$w_2$-$n$ ($n$ = 1, 2, 3,…) where $n$ refers to the order of increasing energy. In this way the observed complexes 15C5-w-B, 15C5-w-C, 15C5-$w_2$-D and 15C5-$w_2$-E correspond respectively to the optimized forms 15C5-w-1, 15C5-w-3, 15C5-$w_2$-1 and 15C5-$w_2$-6 (see Tables S5 and S6). The experimental and theoretical rotational parameters are compared in Table 2. The calculated electric dipole moment components for each complex are in reasonable agreement with the observed line intensities. The $r_e$ structures of the complexes are compared to the $r_s$ data in Figure 3 and Tables S7-S9.

Species 15C5-w-C, 15C5-$w_2$-D and 15C5-$w_2$-E share the same ring conformation. In these complexes the water molecules situated on the ring axis form two simultaneous O-H···O hydrogen bonds with two or three of the endocyclic 15C5 oxygen atoms. For the 15C5-$w_2$-D complex, the two water molecules are on opposite sides of the ring while for the 15C5-$w_2$-E the two water molecules lie on the same side. The central water molecule in conformer 15C5-$w_2$-E is on the opposite side of the 15C5 ring to that observed for 15C5-w-C. The second water molecule lies far from the $c$ axis and establishes a hydrogen bond to the oxygen atom of the central water molecule. It is further stabilized by secondary C-H···O weak contacts with two adjacent methylene groups.

It is a common observation that even a populated conformational landscape is significantly reduced as a result of complex formation with other molecules. This is normally a consequence of the low concentration of complexes compared to that of the corresponding monomers. For 15C5, this behavior is dramatic if we consider the experimental results. Nine conformers of the monomer have been observed experimentally in the supersonic jet. The number of different structures of 15C5 reduces to only two in the water complexes (see Figure 3). These structures differ from those of bare 15C5 observed conformers which is a first indication that 15C5 is

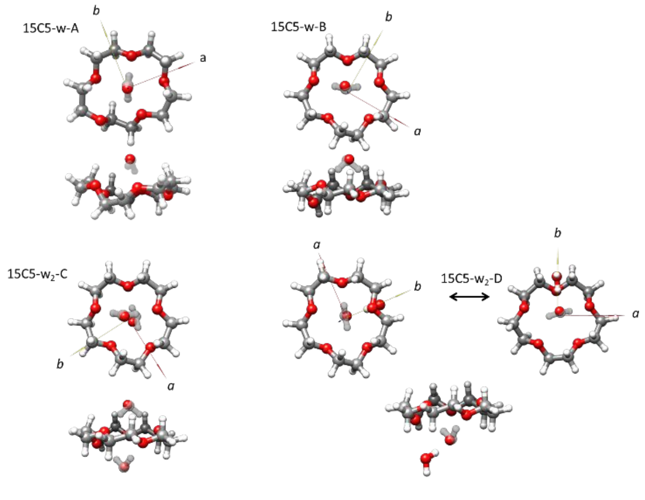


Figure 3. The structures of the observed complexes of the 15C5 crown ether with water showing the location of water molecules. The form adopted by the ring for complexes 15C5-w-C, 15C5-$w_2$-D, and 15C5-$w_2$-E is the same. Two perspectives of 15C5-$w_2$-E from the two sides of the ring are shown.

reshaped upon complexation. Moreover, the observed S/N ratios for the spectra of the complexes (B, C, D) are roughly 3-6 times lower than that of the most abundant monomer species (A), meaning that the complexes are highly populated in the supersonic jet. The first 15C5 complex structure corresponds to 15C5-w-B, which is related to the bare monomer 15C5-VII structure (see Figure S6). *Ab initio* optimizations allowing water to interact perpendicularly on any face of bare 15C5-VII suggests that this interaction reshapes the ring to reach the structure observed in the 15C5-w-B complex. On the other hand, optimization of the monomer structure observed in 15C5-w-B without water gives the 15c5-VII monomer conformer. This correlation raises the question of why the 15c5-VII conformer was not observed, attributed in the previous work to collisional relaxation in the jet to the 15c5-III conformation.[17] However, could it also be due to the 15C5-VII conformer's role in the formation of water complexes? By adding a second water molecule to 15C5-w-B on the opposite side of the ring, the 15C5 structure reshapes further to reach another crown-shaped open ring structure, the 15C5-$w_2$-2 form (see Table S6 and Figures S5 and S6). This conformer preserves the $C_2$ symmetry axis of 15C5-VII and has almost the same energy and rotational constants as the observed 15C5-$w_2$-1 complex. However, 15C5-$w_2$-2 is a non-observable conformer since it is predicted to have an almost zero dipole moment.

A second ring structure was observed for the complexes 15C5-w-C, 15C5-$w_2$-D, and 15C5-$w_2$-E. This crown-shaped open ring structure correlates to a structure of the monomer that we designate as conformer 15C5-XX (see Figures S2) predicted to have an energy of 16.2 kJ/mol relative to the global minimum. This structure is obtained when a geometry optimization of the bare ring is conducted by starting from any of these complexes. Given the high energy (16.2 kJ/mol) of this form its population should be very low compared to the other low energy forms. Thus, the structure of complexes leads us to conclude that the interaction with water involves a significant modification of the crown potential energy surface[13] to reshape the ring from the low energy forms to the open ring crown-shaped configurations observed in the 15C5-water adducts.

The open ring structures observed in this work for the water complexes correspond to those most commonly found in the crystal structures of 15C5 in complexes with $Li^+$ or $Na^+$ as reported in the Cambridge Structure Database.[33] Conformers/structures correlated to 15C5-XX have been found for example in 15C5-NaI[34] or 15C5-dithiooxamine and 15C5-dithiourea[35] in which the guest interacts with 15C5 through N-H···O hydrogen bonds in exactly the same way as in the 15C5-w-C complex. Structures correlated to the 15C5-VII monomer such as 15C5-w-B or the predicted 15C5-$w_2$-2 complexes have been observed in 15C5·Li-In$(CH_3)_3$Cl.[36]

It is interesting to compare the results of this work with those observed for 12C4,[13] benzo-15C5,[12,18] benzo-18C6, and dibenzo-18c6[7–11] crown ethers and their microsolvates. For 12C4 no signals of the isolated monomer were observed in the rotational spectrum because the two most stable species are predicted to have zero dipole moment. They give rise to the observed monohydrated 12C4 complexes. Reshaping was observed in the interaction of the second most stable monohydrate conformer to adopt a structure close to that of the fourth 12C4 conformer in order of energy. In the monohydrated clusters, water interacts through hydrogen bonds with only one oxygen atom of the crown ether, opposite to 15C5, for which forms 15C5-B and 15C5-C were observed. The interaction of water with two oxygen atoms is observed only in the dihydrated 12C4-$w_2$ complexes. For the benzo-15C5 crown ether monomer,[18] only three conformers have been isolated in the gas phase, contrary to nine conformers observed in the case of 15C5. This is particularly notable because benzo-15C5 crown ether was isolated in the LIF experiment using He as carrier gas, which does not lead to significant conformational relaxation. This difference in the number of conformers might be due to the presence of the heavy benzo group, which may influence the out-of-plane ring motions to limit the flexibility of the 15C5 ring as well as introduce the possibility of intramolecular dispersion contacts. Similar behavior is observed for the benzo-18C6 and dibenzo-18C6 crown ethers for which four and two forms have been observed, respectively, in the gas phase.[7–9] Interestingly, the way in which benzo-15C5 crown ether interacts with water is almost identical to that observed for the bare 15C5 crown ether, with the same number and shape of the complexes. In all the conformers, the ring seems to reshape to adopt open "crown" structures. The complexes of benzo-18C6 and dibenzo-18C6 crown ethers with water have been observed in the gas phase for up to four water molecules.[7–11] The monohydrated complexes show similar behavior to that found for 15C5 complexes, where the water molecule interacts in a bidentate way with two ring oxygen atoms. For di-, tri- and tetrahydrates, the water molecules have been found either to interact with two ring oxygen atoms on both sides of the ring or to interact with other water molecules as observed here for 15C5-$w_2$-E complex.

It is also notable that the lowest-energy two-water complexes adopt structures with the two water molecules sitting on opposite sides of the ring. This result is in line with the observations for benzo-15C5 ether, benzo-, and dibenzo-18C6 ethers, but contrary to the results for the smaller crown ether 12C4, where the water molecules form a water dimer structure. Even more notable, these cases together with some sugars[37,38] are indeed among the few where the dominant water-water interactions are overcome. It is well known that water, in the gas phase, is a strong hydrogen bond acceptor so that water self-association is a common feature in most microsolvates. This work shows that the high electron density created inside the ring cavity due to the cooperation of the oxygen atoms' lone pairs of 15C5 crown ether results in proton acceptor sites probably stronger than water. In this way, water interacts with these high electron density regions through two simultaneous hydrogen bonds, that is, offering all of its potential as a donor. In the most stable 15C5-$w_2$ complexes, the separate interaction of the water molecules on each side of the 15C5 ring leads to more stable forms than those showing water self-association. In the most stable 15C5-w 1:2 complexes the separate interaction of the water molecules on each side of the 15C5 ring leads to more stable forms than those showing water self-association.

As with the preferences of different crown ethers to interact with cations of varying size (i.e. $Li^+$, $Na^+$, or $K^+$), the ring size may be the origin for the differences observed in how the 12C4 and 15C5 crown ethers interact with water.

## Conclusions

To summarize, we used CP-FTMW spectroscopy to investigate 15C5 crown ether and the 15C5···water system. We were able to complete the rich conformational landscape of 15C5 by identifying the global minimum observing nine conformers. We have identified a number of different mono and dihydrated 15C5-water clusters for which 15C5 reduces its conformational flexibility to only two different open ring "crown" structures to maximize host–guest interactions. One of these structures associated to the most abundant monohydrated form is correlated to a non-observed bare 15C5 low energy structure. Both ring structures are the same as those observed in many 15C5 complexes with $Na^+$, $Li^+$ or neutral forms. Our results indicate that only a single water molecule is able to drastically alter the conformational landscape of the 15C5 ring structure (i.e. energy of minima and interconversion pathways) in the same way that strong ligands like $Li^+$ or $Na^+$ do.

## Acknowledgements

J.C.L and S.B. acknowledge the Ministerio de Economía y Competitividad (Grant CTQ2016-75253-P) for financial support. M.S. acknowledges financial support from the Deutsche Forschungsgemeinschaft with grant number SCHN1280/4-2 within the priority program 1807 "Control of London dispersion interactions in molecular chemistry". Bucknell University and Furman University provided institutional support for this work. This project is supported in part by NSF grants CHE-1213521 and CHE-1508556. Computational resources were provided by NSF grant CHE-1229354 as part of the MERCURY high- performance computer consortium (http://www. mercuryconsortium.org).

## Conflicts of interest

There are no conflicts to declare.

## Notes and references

1 C. J. Pedersen, *Science*, 1988, **241**, 536–40.
2 G. W. Gokel, W. M. Leevy and M. E. Weber, *Chem. Rev.*, 2004, **104**, 2723–2750.
3 C. J. Pedersen, *J. Am. Chem. Soc.*, 1967, **89**, 7017–7036.
4 X. X. Zhang, J. S. Bradshaw and R. M. Izatt, *Chem. Rev.*, 1997, **97**, 3313–3362.
5 P. Hurtado, F. Gámez, S. Hamad, B. Martínez-Haya, J. D. Steill and J. Oomens, *J. Phys. Chem. A*, 2011, **115**, 7275–7282.
6 C. J. Pedersen, *J. Org. Chem.*, 1971, **36**, 1690–1693.
7 R. Kusaka, Y. Inokuchi and T. Ebata, *Phys. Chem. Chem. Phys.*, 2007, **9**, 4452.
8 R. Kusaka, Y. Inokuchi and T. Ebata, *Phys. Chem. Chem. Phys.*, 2008, **10**, 6238.
9 R. Kusaka, Y. Inokuchi and T. Ebata, *Phys. Chem. Chem. Phys.*, 2009, **11**, 9132.
10 S. Kokubu, R. Kusaka, Y. Inokuchi, T. Haino and T. Ebata, *Phys. Chem. Chem. Phys.*, 2010, **12**, 3559.
11 R. Kusaka, S. Kokubu, Y. Inokuchi, T. Haino and T. Ebata, *Phys. Chem. Chem. Phys.*, 2011, **13**, 6827–36.
12 V. A. Shubert, C. W. Müller and T. S. Zwier, *J. Phys. Chem. A*, 2009, **113**, 8067–79.
13 C. Pérez, J. C. J. C. López, S. Blanco and M. Schnell, *J. Phys. Chem. Lett.*, 2016, **7**, 4053–4058.
14 H.-J. Buschmann, R.-C. Mutihac and E. Schollmeyer, *J. Solution Chem.*, 2010, **39**, 291–299.
15 A. C. Legon, *Chem. Rev.*, 1980, **80**, 231–262.
16 F. Gámez, B. Martínez-Haya, S. Blanco, J. C. López and J. L. Alonso, *J. Phys. Chem. Lett.*, 2012, **3**, 482–485.
17 F. Gámez, B. Martínez-Haya, S. Blanco, J. C. López and J. L. Alonso, *Phys. Chem. Chem. Phys.*, 2012, **14**, 12912.
18 V. A. Shubert, W. H. James and T. S. Zwier, *J. Phys. Chem. A*, 2009, **113**, 8055–66.
19 G. G. Brown, B. C. Dian, K. O. Douglass, S. M. Geyer, S. T. Shipman and B. H. Pate, *Rev. Sci. Instrum.*, 2008, **79**, 4–5.
20 C. Pérez, A. Krin, A. L. A. L. Steber, J. C. J. C. López, Z. Kisiel and M. Schnell, *J. Phys. Chem. Lett.*, 2016, **7**, 154–60.
21 A. A. Fokin, T. S. Zhuk, S. Blomeyer, C. Pérez, L. V. Chernish, A. E. Pashenko, J. Antony, Y. V. Vishnevskiy, R. J. F. Berger, S. Grimme, C. Logemann, M. Schnell, N. W. Mitzel and P. R. Schreiner, *J. Am. Chem. Soc.*, 2017, **139**, 16696–16707.
22 S. R. Domingos, A. Cnossen, W. J. Buma, W. R. Browne, B. L. Feringa and M. Schnell, *Angew. Chemie Int. Ed.*, 2017, **56**, 11209–11212.
23 S. T. Shipman, J. L. Neill, R. D. Suenram, M. T. Muckle and B. H. Pate, *J. Phys. Chem. Lett.*, 2011, **2**, 443–448.
24 S. E. Hill and D. Feller, *Int. J. Mass Spectrom.*, 2000, **201**, 51–58.
25 D. Schmitz, V. Alvin Shubert, T. Betz and M. Schnell, *J. Mol. Spectrosc.*, 2012, **280**, 77–84.
26 C. Pérez, S. Lobsiger, N. a. Seifert, D. P. Zaleski, B. Temelso, G. C. Shields, Z. Kisiel and B. H. Pate, *Chem. Phys. Lett.*, 2013, **571**, 1–15.
27 J. K. G. Watson, in *Vibrational Spectra and Structure a Series of Advances, Vol 6*, ed. J. R. Durig, Elsevier, New York, 1977, pp. 1–89.
28 M. J. Frisch et al, *Gaussian Inc., Wallingford, CT,*.
29 J. Kraitchman, *Am. J. Phys.*, 1953, **21**, 17–24.
30 B. P. van Eijck, *J. Mol. Spectrosc.*, 1982, **91**, 348–362.
31 A. Held and D. W. Pratt, *J. Am. Chem. Soc.*, 1993, **115**, 9708–9717.
32 J. C. Lopez, R. Sanchez, S. Blanco and J. L. Alonso, *Phys. Chem. Chem. Phys.*, 2015, **17**, 2054–2066.
33 C. R. Groom, I. J. Bruno, M. P. Lightfoot, S. C. Ward and IUCr, *Acta Crystallogr. Sect. B*, 2016, **72**, 171–179.
34 G. W. Buchanan, M. Gerzain, C. Bensimon and IUCr, *Acta Crystallogr. Sect. C Cryst. Struct. Commun.*, 1994, **50**, 1016–1019.
35 Y. A. Simonov, M. S. Fonari, M. J. Zaworotko, H.

Abourahma, J. Lipkowski, E. V. Ganin and A. A. Yavolovskii, *Org. Biomol. Chem.*, 2003, **1**, 2922.

36 P. C. Stark, M. Huff, E. A. Babaian, L. M. Barden, D. C. Hrncir, S. G. Bott and J. L. Atwood, *J. Incl. Phenom.*, 1987, **5**, 683–688.

37 N. Mayorkas, S. Rudić, E. J. Cocinero, B. G. Davis and J. P. Simons, *Phys. Chem. Chem. Phys.*, 2011, **13**, 18671.

38 N. Mayorkas, S. Rudić, B. G. Davis and J. P. Simons, *Chem. Sci.*, 2011, **2**, 1128.

TABLE OF CONTENTS ENTRY:

Complexation with water reduces the structural landscape of 15-crown-5 ether to the two forms observed for $Li^+$ or $Na^+$ complexes.