How Many Water Molecules in the Hydration Shell of 18-Crown-6? Monte Carlo Simulations Based on ab Initio-Derived Potential Energy Surface

3 AUTHORS:

Sriprajak Krongsuk
Khon Kaen University
8 PUBLICATIONS 20 CITATIONS

SEE PROFILE

Teerakiat Kerdcharoen
Mahidol University
149 PUBLICATIONS 1,401 CITATIONS

SEE PROFILE

Supot Hannongbua
Chulalongkorn University
124 PUBLICATIONS 1,284 CITATIONS

SEE PROFILE

How Many Water Molecules in the Hydration Shell of 18-Crown-6? Monte Carlo Simulations Based on ab Initio-Derived Potential Energy Surface

Sriprajak Krongsuk,[†] Teerakiat Kerdcharoen,[†] and Supot Hannongbua*,[‡]

Physics Department, Faculty of Science, Mahidol University, Bangkok 10400, Thailand, and Chemistry Department, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

The solvation structure of 1,4,7,10,13,16-hexaoxacyclooctadecane (18-crown-6) in aqueous solution has been investigated using the Metropolis Monte Carlo scheme. Simulations have been performed for a system containing one 18-crown-6 molecule and 500 water molecules. An intermolecular potential function between 18-crown-6 and water has been newly developed, on the basis of ab initio calculations. The MCY potential model was employed to describe water−water interactions. Two water molecules were found in the first hydration shell of the ligand: one molecule was above the ligand plane and another was below it. Each water molecule forms mobile hydrogen bonds with the 18-crown-6 molecule; i.e., the O atom of the water molecule is localized above the ligand cavity, whereas the two H atoms were found to coordinate nonlocally to two of the three O atoms lying on each side of the ligand. In addition, precise orientation and detailed characteristics of the solvation have been comprehensively investigated and displayed.

1. Introduction

The crown ethers have received increasing attention from experimental and theoretical researchers since Pedersen first discovered them in 1967.[1] They show a remarkable range of selectivity for binding various cations, depending on the size of the crown ether, the type of the donor atom, and the polarity of the solvent.[2] Because of these characteristics, there is a wide range of applications for the crown ethers. They have been proposed as separation agents for removing metal ions (i.e., Cs^+ and Sr^{2+}) from mixed nuclear and chemical waste.[1−4] There is also growing interest in the use of crown ethers for radio-immunotherapy treatment of carcinomas[4] and for the development of sensors.[2]

The 1,4,7,10,13,16-hexaoxacyclooctadecane (18-crown-6) molecule is not only the archetype of the crown ether family, but it also is the most extensively characterized crown system. It has a simple but very flexible structure. The flexibility of the 18-crown-6 molecule is very important to facilitate the capture and release of ions in the process of transport at membrane interfaces.[5] It also represents the simplest model to mimic other, larger, supramolecular cavities.[6] Consequently, there have been numerous theoretical,[2,4] experimental,[20−27] and computer simulation studies[3,5−19] of 18-crown-6 and its complexes with various cations. It is well-known that solvation, or more specifically hydration, plays a major role in the stabilization of 18-crown-6 complexes. The solvation and conformation of 18-crown-6 in aqueous solutions have been investigated using several experimental techniques, including Raman spectroscopy,[20,25] infrared spectroscopy,[21,24,26] X-ray diffraction,[22] quasielastic neutron scattering,[21] and ultrasonic velocity measurement.[23] On the theoretical side, molecular mechanics (MM), combined quantum mechanics/molecular mechanics

(QM/MM)[3,14] calculations, and computer simulations (including molecular dynamics (MD)[7−13,15,18,19] and Monte Carlo (MC)[5,17] studies) have become important tools to obtain microscopic details of such phenomena. In general, these studies have indicated that the D_{3d} conformation is the predominant form in aqueous solution and the most favorable conformation for complexes with cations. However, the hydration number is an issue that is still under heavy debate. Reported hydration numbers vary from 1 to 11, depending on the method employed.

Despite the large amount of data regarding 18-crown-6, the hydration structure of the uncomplexed 18-crown-6 molecule has not been fully understood. In the computational study by Ranghino et al.,[6] MC simulations of rigid C_i, D_{3d}, and C_1 conformations of 18-crown-6 in aqueous solution have been performed. The results reveal that there are four water molecules in the first hydration shell for the D_{3d} form of 18-crown-6, with two water molecules on each face of the ring. Kowall and Geiger[15] subsequently used the MD method to investigate the structure and dynamics of the hydration shell of the D_{3d} form. It was found that, among the two water molecules on each face, only one is strongly bound by two crown O atoms. Other work by Thompson,[14] which was based on a semiempirical QM/MM method, also agrees well with the previously mentioned work.

To the best of our knowledge, all simulations of 18-crown-6 in water so far have relied on the use of an intermolecular potential based on MM parametrization. As a matter of fact, this type of potential is constructed to preserve transferability for a wide range of systems. Parametrization by fitting to much of the empirical and/or quantum mechanical data of a large number of representative molecules (typically more than 100) usually leads to the loss of some specific details. For this reason, some doubts arise when the MM potential is used to represent the interaction between the 18-crown-6 molecule and water molecules, in which hydrogen bonding could be very important and better represented by ab initio-derived potentials, as employed in this study.

* Author to whom correspondence should be addressed. E-mail: supot.h@ chula.ac.th.
† Mahidol University.
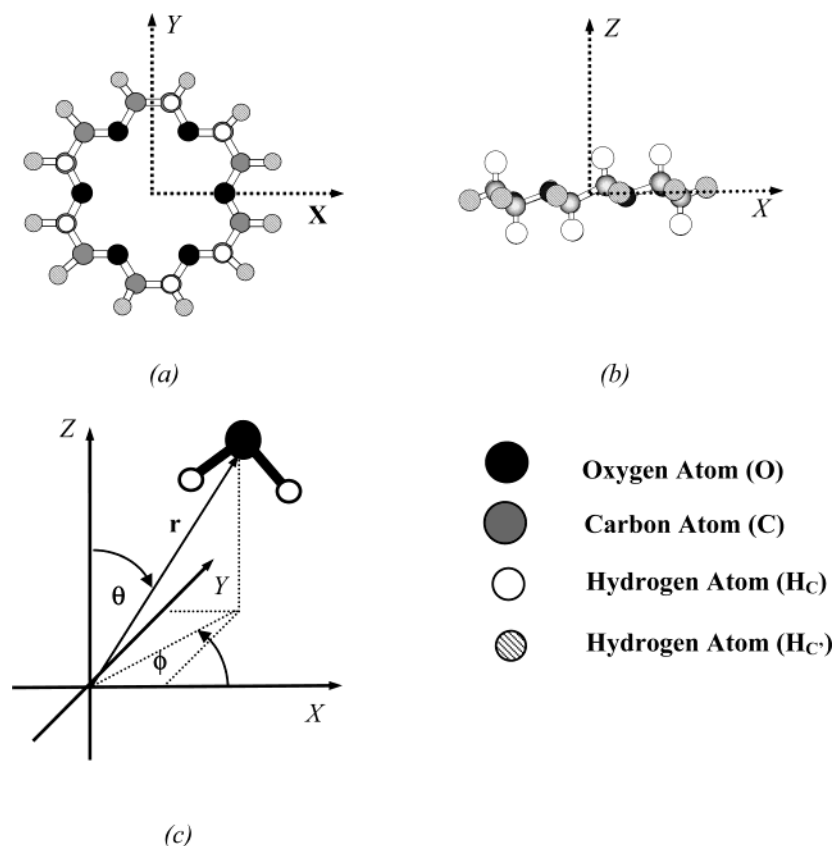‡ Chulalongkorn University.

Figure 1. Orientation of the 18-crown-6 molecule in the coordinate system (panels a and b) and definition of water orientation around the 18-crown-6 molecule (panel c).

2. Details of the Calculations

2.1. 18-Crown-6−Water Potential Function. To develop an intermolecular potential representing the interaction at all configurations and distances, numerous coordinations of a water molecule around the 18-crown-6 molecule have been generated. The D_{3d} form of the 18-crown-6 molecule[2] (Figure 1), which is found to be the most stable conformation in a polar solvent, and the gas-phase geometry of the water molecule[29] have been used and kept constant throughout. Because of the D_{3d} symmetry, the water molecule was positioned only in 1/12 of the entire space around the 18-crown-6 molecule. This volume is identified by $0° \leq \theta \leq 180°$, $0° \leq \phi \leq 30°$, and $1 \text{ Å} \leq r \leq 20$ Å (see Figure 1). Ab initio self-consistent field (SCF) calculations were then performed, with and without correction for basis-set superposition error (BSSE),[28] using the following default basis sets of the Gaussian 98 program:[30] STO-3G, 3-21G, 6-31G, 6-31G**, DZV, and DZP. The DZP basis set was finally selected. (Detailed discussion is given in section 3.1.)

The obtained SCF data points were then fitted to an analytical function of the form

$$\Delta E(L,w) = \sum_{i=1}^{3}\sum_{j=1}^{42} \frac{A_{ij}^{ab}}{r_{ij}^{6}} + \frac{B_{ij}^{ab}}{r_{ij}^{12}} + \frac{C_{ij}^{ab}}{r_{ij}^{4}} + \left[\frac{q_i q_j}{r_{ij}}\right] \quad (1)$$

where 3 and 42 are the number of atoms in the water (w) and 18-crown-6 (L) molecules, respectively, A_{ij}, B_{ij}, and C_{ij} are fitting parameters, and r_{ij} is the distance between an atom i of water and an atom j of 18-crown-6. Also, q_i and q_j are the net charges of atoms i and j (in atomic units, a.u.), as obtained from the population analysis[31] of the isolated molecules in the quantum chemical calculations. The superscripts a and b on the fitting parameters have been used to classify atoms of equal atomic

number but different environmental conditions, for example, H_C and $H_{C'}$ (see Figure 1).

The fitting procedure starts with 300 SCF energy points. The resulting analytical potential function with the best fit for this set of data was tested using an additional 100 randomly chosen points, outside the first set. The test points were then included into the fit. Another 100 points were, again, tested and then included. This procedure was repeated until consistency of the fitting parameters was obtained, leading to a total amount of 500 energy points of 18-crown-6−water interactions.

2.2. Monte Carlo Simulations. MC simulations were performed for the 18-crown-6 molecule in aqueous solution. The system contained 501 rigid particles, including one 18-crown-6 molecule, which was fixed at the center of the cube, and 500 water molecules. The volume of the 500 water molecules at a density of 1 g·cm⁻³ at 298 K and 1 atm, plus additional space occupied by the 18-crown-6 molecule, yielded a periodic cubic volume with a side length of 25.00 Å. A spherical cutoff of the site−site interaction potentials at half of this length, as well as a periodic boundary condition, was applied. The starting configuration of the water molecules was randomly generated. The MCY[32] potential was employed to describe water−water interactions. After equilibration, 30×10^6 configurations were generated and 1 of every 1000 configurations was stored for subsequent analyses.

As described and successfully applied in our previous works,[33−35] long-range interactions between the ligand and the solvent molecules were carefully checked during the development of the intermolecular pair potential. It was found that all 500 energy points of 18-crown-6−water interactions change smoothly, as a function of separations, and approach zero before the cutoff distances employed in this simulation. Therefore, long-

TABLE 1: Total Energy (E), Optimal Binding Energy with and without BSSE Correction (ΔE_{BSSE} and ΔE, Respectively), Corresponding Distance from the O Atom of the Water Molecule to the Center of the Cavity of the 18-Crown-6 Molecule with and without BSSE Correction (r_{BSSE} and r, Respectively), and CPU Time Required (for the 18-Crown-6–Water System), Calculated from Various Basis Sets

basis set	E (a.u.)		18-crown-6–water				
	water	18-crown-6	r (Å)	ΔE (kcal·mol^{-1})	r_{BSSE} (Å)	ΔE_{BSSE} (kcal·mol^{-1})	CPU time (min)
STO-3G	−74.96290	−905.84640	1.51	−8.124	2.05	−5.434	2
3-21G	−75.58537	−912.31591	1.53	−20.684	1.85	−12.569	9
6-31G	−75.98399	−916.98796	1.77	−17.306	1.89	−14.251	16
6-31G**	−76.02317	−917.45382	1.92	−12.154	1.97	−9.297	34
DZV	−75.00922	−917.15074	1.79	−17.057	1.89	−14.945	36
DZP	−76.04652	−917.63862	1.92	−11.419	1.99	−9.629	144

TABLE 2: Final Optimization Parameters for the ith Atom of 1,4,7,10,13,16-Hexaoxacyclooctadecane (18-Crown-6) Interacting with the jth Atom of Water^a

$i-j$	A (Å^6·kcal·mol^{-1})	B (Å^{12}·kcal·mol^{-1})	C (Å^4·kcal·mol^{-1})
C−O	−0.114442 × 10^4	0.415121 × 10^6	0.130539 × 10^3
O−O	0.485408 × 10^4	0.212068 × 10^6	−0.111766 × 10^4
H$_{C'}$−O	−0.387956 × 10^3	0.102313 × 10^5	0.207011 × 10^3
H$_C$−O	0.115591 × 10^4	0.398515 × 10^2	−0.153702 × 10^3
C−H	−0.201256 × 10^4	0.164338 × 10^6	0.194903 × 10^3
O−H	−0.677922 × 10^3	0.256119 × 10^4	0.324232 × 10^3
H$_{C'}$−H	0.528242 × 10^3	0.168671 × 10^1	−0.153322 × 10^3
H$_C$−H	0.102546 × 10^2	0.445778 × 10^0	0.129768 × 10^2

^{a} For water, $q_O = -0.662$ a.u. and $q_H = 0.331$ a.u. For 18-crown-6, $q_C = 0.049$ a.u., $q_O = -0.429$ a.u., $q_{H_C} = 0.095$ a.u., and $q_{H_{C'}} = 0.070$ a.u.

range interactions were neglected and the shifted potential function with a cutoff at the half box length was applied.

3. Results and Discussion

3.1. 18-Crown-6–Water Potential Function. Results of the Hartree–Fock calculations for the 18-crown-6–water system with the STO-3G, 3-21G, 6-31G, 6-31G**, DZV, and DZP basis sets are compared in Table 1. It can be seen from this table that nonpolarized basis sets, except for STO-3G, yield binding energies that are too high, in comparison with those from polarized basis sets. Among the polarized basis sets, 6-31G** and DZP give similar results but DZP seems to give a slightly lower BSSE. The computer processing unit (CPU) time required

for the bigger basis set, DZP, is within our effort; therefore, we ultimately decided to use this basis set with the BSSE corrections in the calculations of all data points.

The fitting parameters are summarized in Table 2. Some comments can be made concerning the assignment of a negative or positive value to the fitting parameters. It is not always possible to force the A/r^6 and B/r^{12} terms to represent attractive and repulsive interactions of the pair, respectively. For this study, physically meaningful parameters are not achieved. However, the B/r^{12} term for all atomic pairs was forced to be positive, to avoid unwanted negative holes at short distances, because of the much higher slope of the B/r^{12} term than that of the A/r^6 and C/r^4 terms. Here, the last two terms were freely optimized.

To examine the quality of the newly developed function, the fitted and SCF energies in the configuration where the minimum of the pair interaction takes place (the water molecule lies on the z-axis and points two H atoms toward the cavity of the 18-crown-6 molecule, as shown in Figure 1) were compared in Figure 2. The plot shows good agreement between the energies obtained from the two sources, especially in the area around the minimum. In addition, all data points with a standard deviation of the fit of 0.79 kcal·mol^{-1} were compared in the inset of Figure 2. The quality of the function is also certified by this plot, especially for the attractive region, which is important for the predictions based on the simulation results.

3.2. Solvent Structure and Hydration Shell. The structure of the solvent can be extracted from the simulation, in terms of
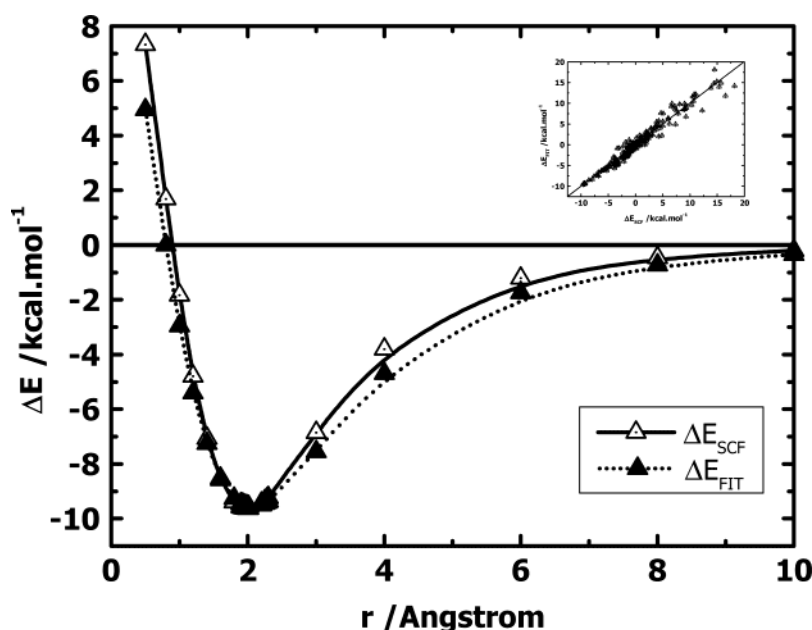

Figure 2. Plot of the 18-crown-6–water stabilization energies obtained from the DZP basis set with BSSE corrections (ΔE_{SCF}), and from the potential function (ΔE_{FIT}) with the fitting parameters given in Table 2, where the water molecule lies along the z-axis and points two H atoms toward the cavity of the 18-crown-6 molecule (see Figure 1c). All ΔE_{SCF} and ΔE_{FIT} data points are compared in the inset.
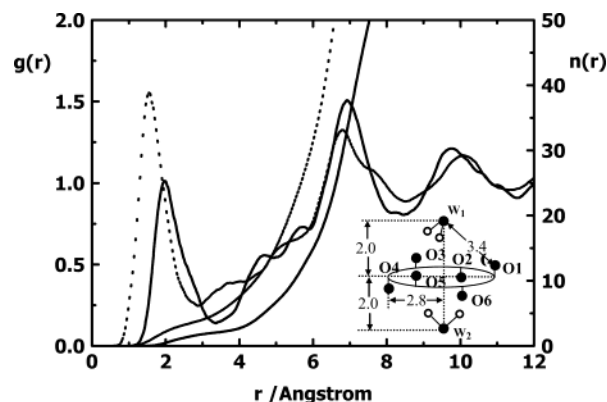
Figure 3. Radial distribution functions, $g(r)$, and corresponding running integration numbers, $n(r)$, from the center of mass of the 18-crown-6 molecule to the O (solid line) and H (dashed line) atoms of water molecules. Inset shows a schematic representation of the 18-crown-6 molecule with six donor atoms (O1, O3, and O5 point upward, whereas O2, O4, and O6 point downward) and the two nearest water molecules (w_1 and w_2), with estimated distances (given in angstroms) between the related atoms indicated.
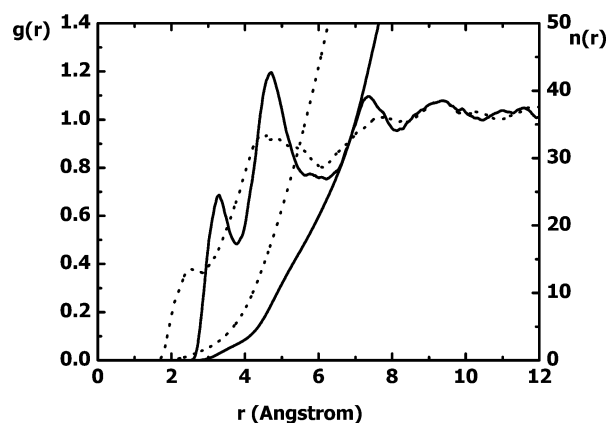

Figure 4. Radial distribution functions, $g(r)$, and corresponding running integration numbers, $n(r)$, from the O atoms of the 18-crown-6 molecule to the O (solid line) and H (dashed line) atoms of water molecules.

Figure 5. Projection of coordinates of the two O atoms of the two nearest water molecules, which lie (a) above and (b) below the molecular plane of the 18-crown-6 molecule, onto the $x{-}y$ plane.

the atom−atom radial distribution function (RDF), $g_{xy}(r)$, which represents the probability of finding an atom of type y in the spherical volume of radius r around the central atom of type x. Characteristics of the $g_{OO}(r)$, $g_{OH}(r)$, and $g_{HH}(r)$ RDFs of water obtained from this study are identical with those of pure water.[33] This means that the presence of the 18-crown-6 molecule in the solution does not influence the structure of the bulk solvent.

The RDFs from the center of the cavity of the 18-crown-6 molecule to the O and H atoms of water, $g_{EO}(r)$ and $g_{EH}(r)$, as well as the corresponding running integration numbers, $n(r)$, are depicted in Figure 3. The $g_{EO}(r)$ plot shows three sharp peaks, positioned at 2.0, 6.9, and 9.8 Å, and two pronounced shoulders, at 4.7 and 5.7 Å. Integration of the RDF up to the minima of the first five peaks at 3.3, 4.8, 5.9, 8.5, and 11.5 Å corresponds to 2, 6, 14, 72, and 201 water molecules, respectively. A sharp and pronounced first peak indicates that two water molecules bind strongly to the cavity of the 18-crown-6 molecule: one above the ligand plane (w_1) and the other one below it (w_2). An appearance of the first $g_{EH}(r)$ peak in the range from 0.7 to 2.8 Å with the coordination number of 4 means that each of the two water molecules lying under the first $g_{EO}(r)$ peak points two of its H atoms toward the cavity of the 18-crown-6 molecule. The geometry of the two nearest neighbors is tentatively sketched in the inset of Figure 3.
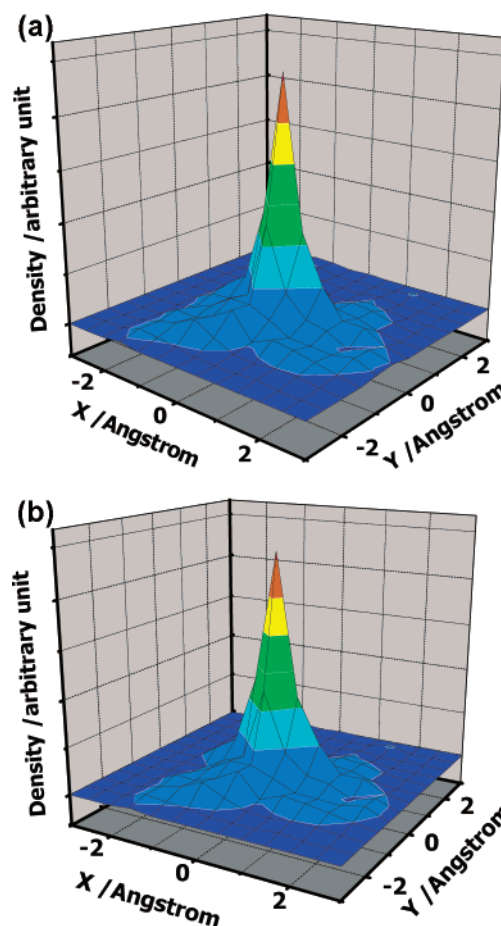
Although the 18-crown-6−water interaction is rather weak, five layers of hydration shells around the 18-crown-6 molecule can be clearly observed (Figure 3). This effect is observed up to a distance of 12.0 Å from the molecular center. A clear picture of the ligand solvation, in connection with these layers, is proposed in the conclusion and is displayed in Figure 9.

To ascertain more information concerning the hydration around the six donor atoms of the 18-crown-6 molecule, the RDFs centered on the O atoms of the ligand to the O and H atoms of water ($g_{OC−O}(r)$ and $g_{OC−H}(r)$, respectively) have been calculated and plotted in Figure 4. The first two peaks of $g_{OC−O}(r)$ appear at 3.28 and 4.76 Å, and their coordination numbers are 2.1 and 17.5 O atoms, respectively. Interest is focused on the appearance of the 2.1 water molecules, which are located at a distance of 3.28 Å from each O atom of the 18-crown-6 molecule. This distance is within the ranges of those from w_1 to O1, O3, and O5 above the ligand plane and from w_2 to O2, O4, and O6 below the ligand plane (see inset of Figure 3). This indicates that the first $g_{OC−O}(r)$ peak centered at 3.28 Å is the contribution from w_1 and w_2. Therefore, it can be concluded clearly that the six O atoms of the 18-crown-6 molecule are solvated by these two molecules only. The corresponding $g_{OC−H}(r)$ shows a first pronounced shoulder at 2.64 Å, accumulating four H atoms of the two water molecules that belong to the $g_{OC−O}(r)$ first peak.

3.3. Mobility and Flexibility of the Two Nearest Neighbors of 18-Crown-6. The two tightly solvated water molecules have been investigated in an effort to gather more information. Coordinates of the O and H atoms of w_1 and w_2 have been

Water Molecules in the Hydration Shell of 18-Crown-6

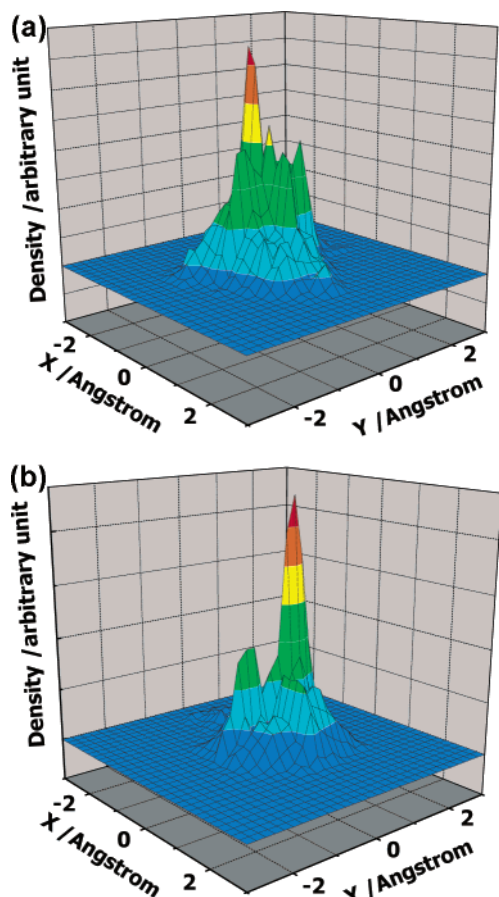*J. Phys. Chem. B, Vol. 107, No. 17, 2003* **4179**

Figure 6. Projection of coordinates of the four H atoms of the two water molecules, which lie (a) above and (b) below the molecular plane of the 18-crown-6 molecule, onto the $x-y$ plane.

projected onto the $x-y$ plane and are plotted in Figures 5 and 6, respectively. The base of the plot denotes the molecular plane of the ligand. The density represents the probability of finding the O or H atoms of w_1 above the molecular plane (Figure 5a) and those of w_2 below the molecular plane (Figure 5b). The sharp peaks at the center of each plot in panels a and b in Figure 5 lead to a clear conclusion that the O atoms of w_1 and w_2 are located exactly above and beneath the center of the 18-crown-6 cavity. Flexibility of the two O atoms is indicated in the three-dimensional (3D) plots by the broad distribution at the base around the central sharp peak.

The behavior of the two nearest neighbors, in terms of flexibility and their orientations, can be extracted from the distribution plots of their H atoms shown in Figure 6. The 3D plots show a broad distribution, covering a large region. This indicates high mobility of the H atoms of w_1 (Figure 6a) and w_2 (Figure 6b).

3.4. Orientation of the Two Nearest Neighbors of the 18-Crown-6 Molecule. Comprehensive investigation has been made to seek the precise orientation of the two water molecules in the nearest shell of the 18-crown-6 molecule. The distribution of the β-angle, which is defined as the angle between the vector linking the two H atoms of w_1 (or w_2) and the vector pointing from the O atom of w_1 (or w_2) to the center of the ligand, has been calculated and is displayed in Figure 7a. A pronounced peak with a maximum of 90° indicates that the vector linking the two H atoms of w_1 (or w_2) is parallel to the ligand plane.

Another angle, defined by the antidipole vector of w_1 (or w_2) and the vector pointing from the O atom of w_1 (or w_2) to the
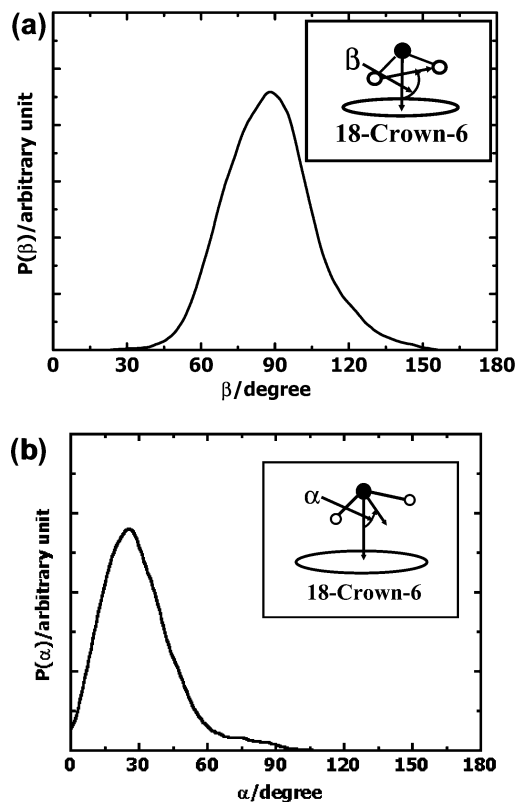

Figure 7. Distribution of the angles (a) β and (b) α (each is defined in the respective inset; see text for more details) for the two nearest water molecules of the 18-crown-6 molecule lying above and below the ligand plane.

center of the 18-crown-6 molecule, has been evaluated and drawn in Figure 7b. The distribution plot shows a pronounced peak centered at 30°. This indicates that the two nearest neighbors do not point their antidipole vectors toward the center of the ligand. In other words, the two O−H bonds of each water molecule, w_1 or w_2, form H bonds with two of the three O atoms of the 18-crown-6 molecule, lying above (O1, O3, and O5) or below (O2, O4, and O6) the ligand plane.

Taking into account the data related to the two nearest neighbors shown in Figures 5 (where the O atoms of w_1 and w_2 lie above the center of the cavity of the ligand), 6 (where H atoms of these water molecules are highly mobile), 7a (where the vector linking the two H atoms of each water molecule is parallel to the ligand plane ($\beta = 90°$)), and 7b (where the two H atoms of each water molecule do not point toward the center of the cavity but rather point toward two of the three O atoms of the 18-crown-6 ($\alpha = 30°$)), the following conclusions can be made: (i) each nearest neighbor forms two hydrogen bonds with the O atoms of the ligand in the configuration shown in Figure 8a, and (ii) the observed hydrogen bond is a mobile type of bond in which the O atom of water is localized above the ligand cavity, whereas the two H atoms were found to coordinate to and move between two of the three O atoms lying on each side of the ligand (e.g., the H atoms of w_1 can bind to O1 and O3, to O3 and O5, or to O5 and O1 (see inset of Figure 3)). A schematic representation of the mobile hydrogen bond is depicted in Figure 8b.

The above-mentioned results disagree somewhat with the MD simulation results reported by Kowal and Geiger,[15] who used a MM potential; those results indicated that both water molecules point their hydrogen atoms toward the center of the cavity of the 18-crown-6 molecule. Other work by Thompson,[14] which was based on semiempirical QM/MM simulations, confirms that
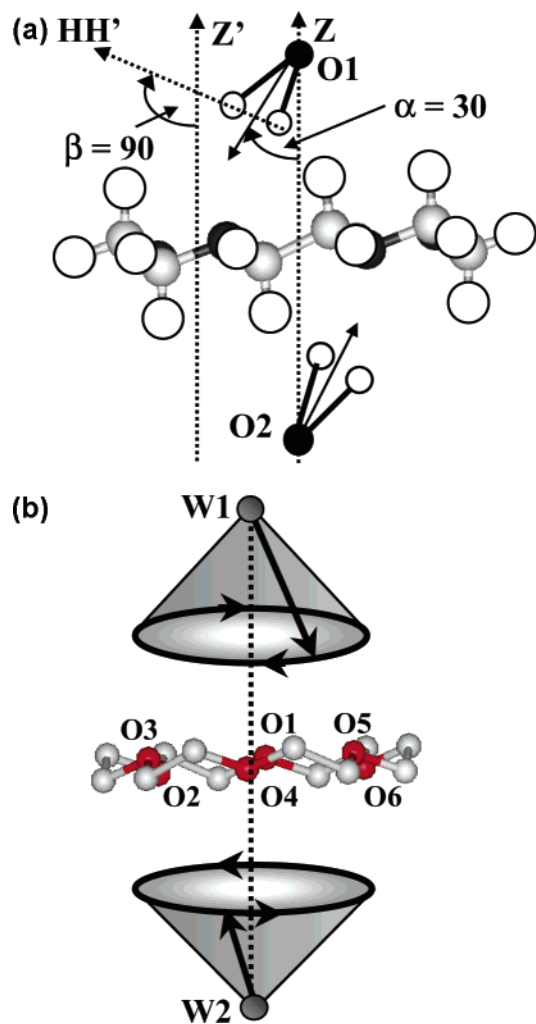
Figure 8. (a) Orientation of the two nearest water molecules in the solvation shell of the 18-crown-6 molecule; the definitions and optimal values of the angles β and α are taken from Figure 7. (b) Schematic representation of the mobile hydrogen bonds between the two nearest water molecules (above and below the ligand plane) and two of the three O atoms of the ligand (O1, O3, and O5, or O2, O4, and O6, as shown in the inset of Figure 3); the arrow denotes the antidipole vector of the water molecule.

Figure 9. (a) Proposed model for the solvation of uncomplexed 18-crown-6 in D_{3d} form in aqueous solution where labels L1–L5 represent the solvation layers corresponding to five peaks of $g_{EO}(r)$ (see text for more details). (b) Snapshot of the solvation shell of the 18-crown-6 molecule, consisting of two and six water molecules in layers L1 and L2, respectively.

of Kowal and Geiger. Good agreement between these two simulations is not surprising, because QM calculations have been used only to model the flexibility of the ligand, whereas the MM potential has been applied to represent the ligand−water interaction in the combined QM/MM potentials. In these works, the precise orientation and characteristics of the solvation unfortunately have not been mentioned.

In terms of coordination numbers of the 18-crown-6 molecule in the D_{3d} form, the values of the two water molecules found in our study are between 1 and 11, which is the range that has been reported theoretically[3,5−19] and experimentally[20−26] in the literature.

3.5. The Proposed Solvation Model. To visualize the hydration structure of the 18-crown-6 molecule using the above-mentioned data, the RDF referring to the center of the cavity of the ligand, $g_{EO}(r)$ (Figure 3), was again considered. Here, the hydration layers corresponding to five pronounced peaks of $g_{EO}(r)$ have been proposed and are shown in Figure 9a, whereas the snapshot of the solvation shell of the 18-crown-6 molecule has been given in Figure 9b for comparison.

As described and discussed previously, the nearest layer (L1 in Figure 9) was formed by two water molecules, w_1 and w_2,
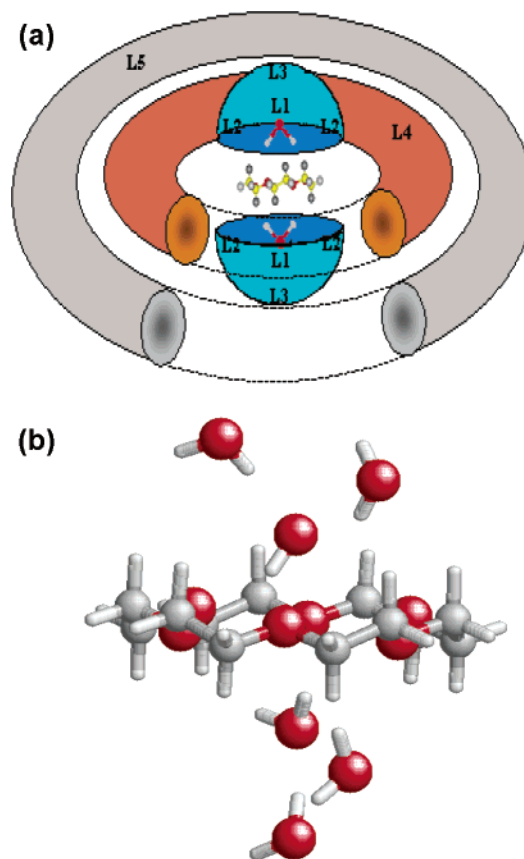
lying under the first $g_{EO}(r)$ peak. The second (L2) and third (L3) layers accumulate water molecules located under the second and third peaks of $g_{EO}(r)$ with distances to the cavity of the ligand of 4.7 and 5.7 Å, respectively. These water molecules are proposed, at the same time, to be the first hydration shell of w_1 and w_2 (see Figure 9). Here, two sets of water molecules lying in equatorial (L2) and axial (L3) positions around w_1 and w_2 lead to the two peaks at 4.7 and 5.7 Å, respectively, in the $g_{EO}(r)$ RDF. The next two layers, L4 and L5, contribute to the fourth and fifth peaks, which are centered at 6.9 and 9.8 Å, respectively, from the ligand cavity. Because of the disklike structure of the 18-crown-6 molecule, these two layers can be considered to be the first and second hydration shells of the ligand, with respect to its molecular plane. The snapshot of the solvation shell of the 18-crown-6 molecule (Figure 9b), which is one of 30×10^6 configurations, consisting of two and six water molecules in layers L1 and L2, respectively, is in good agreement with the solvation model proposed in Figure 9a.

3.6. The Hydration Energy. The hydration energy of the 18-crown-6 molecule contributed from the proposed hydration layers has been calculated and monitored in Figure 10. The plot shows the energy distribution of the first hydration shell water (layer L1) as an isolated peak centered at −8.5 kcal·mol⁻¹. The broad peak between −4.6 and −7.8 kcal·mol⁻¹ represents the energies of the water molecules belonging to layers L2 and L3, whereas the shoulder on the negative side of the main peak is due to the L4 layer. The highest probabilities is found between −2 and 3 kcal·mol⁻¹. This peak contributes from the energies of water molecules at greater distances from the 18-crown-6

Water Molecules in the Hydration Shell of 18-Crown-6

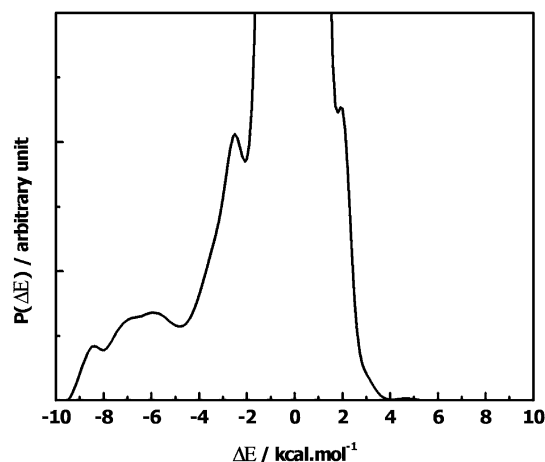*J. Phys. Chem. B, Vol. 107, No. 17, 2003* **4181**

Figure 10. Distribution of the hydration energy of 18-crown-6.

molecule (layer L5) and all other water molecules that are not located in layers L1−L4.

References and Notes

(1) Pedensen, C. J. *J. Am. Chem. Soc*. **1967**, *89*, 2945.

(2) Glendening, E. D.; Feller, D.; Thompson, M. A. *J. Am. Chem. Soc.* **1994**, *116*, 10657.

(3) Thompson, M. A.; Glendening, E. D.; Feller, D. *J. Phys. Chem.* **1994**, *98*, 10465.

(4) Feller, D. *J. Phys. Chem. A* **1997**, *101*, 2723.

(5) Ranghino, G.; Romano, S.; Lehn, J. M.; Wipff, G. *J. Am. Chem. Soc.* **1985**, *107*, 7873.

(6) Jagannadh, B.; Kunwar, A. C.; Thangavelu, R. P.; Osawa, E. *J. Phys. Chem.* **1996**, *100*, 14339.

(7) Dang, L. X. *J. Am. Chem. Soc*. **1995**, *117*, 6954.

(8) Kowall, T.; Geiger, A. *J. Phys. Chem.* **1995**, *99*, 5240.

(9) Dang, L. X.; Kollman, P. A. *J. Am. Chem. Soc.* **1990**, *112*, 5716.

(10) Eerden, J. V.; Harkema, S.; Feil, D. *J. Phys. Chem.* **1988**, *92*, 5076.

(11) Wipff, G.; Weiner, P.; Kollman, P. A. *J. Am. Chem. Soc.* **1982**, *104*, 3249.

(12) Dang, L. X.; Kollman, P. A. *J. Phys. Chem.* **1995**, *99*, 55.

(13) Ha, Y. L.; Chakraborty, A. K. *J. Phys. Chem.* **1993**, *97*, 11291.

(14) Thompson, M. A. *J. Phys. Chem.* **1995**, *99*, 4794.

(15) Kowall, T.; Geiger, A. *J. Phys. Chem.* **1994**, *98*, 6216.

(16) Guilbaud, P.; Wipff, G. *J. Phys. Chem.* **1993**, *97*, 5685.

(17) Ha, Y. L.; Chakraborty, A. K. *J. Phys. Chem.* **1991**, *95*, 10781.

(18) Leuwerink, F. T. H.; Briels, W. J. *J. Phys. Chem. B* **1997**, *101*, 1024.

(19) Mazor, M. H.; McCammon, J. A.; Lybrand, T. P. *J. Am. Chem. Soc*. **1989**, *111*, 55.

(20) Fukuhara, K.; Tachikake, M.; Matsumoto, S.; Matsuura, H. *J. Phys. Chem.* **1995**, *99*, 8617.

(21) Nickolov, Z. S.; Ohno, K.; Matsuura, H. *J. Phys. Chem. A* **1999**, *103*, 7544.

(22) Ozutsumi, K.; Natsuhara, M.; Ohtaki, H. *Bull. Chem. Soc. Jpn*. **1989**, *62*, 2807.

(23) Miyazaki, Y.; Matsuura, H. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 288.

(24) Bryan, S. A.; Willis, R. R.; Moyer, B. A. *J. Phys. Chem.* **1990**, *94*, 5230.

(25) Fukushima, K.; Ito, M.; Sakurada, K.; Shiraishi, S. *Chem. Lett*. **1988**, 323.

(26) Patil, K.; Pawar, R. *J. Phys. Chem. B* **1999**, *103*, 2256.

(27) Mootz, D.; Albert, A.; Schaefgen, S.; Stäben, D. *J. Am. Chem. Soc*. **1994**, *116*, 12045.

(28) Boys, S. F.; Bernardi, F. *Mol. Phys*. **1970**, *19*, 553.

(29) Benedict, W. S.; Gailar, N.; Plyler, E. K. *J. Chem. Phys*. **1959**, *24*, 1139.

(30) Frisch, M. J.; Trucks, G. W.; Head-Gordon, M.; Gill, P. M. W.; Wong, M. W.; Foresman, J. B.; Johnson, B. G.; Schlegel, H. B.; Robb, M. A.; Replogle, E. S.; Gomperts, R.; Andres, J. L.; Raghavachari, K.; Binkley, J. S.; Gonzalez, C.; Martin, R. L.; Fox, D. J.; Defrees, D. J.; Baker, J.; Stewart, J. J. P.; Pople, J. A. *Gaussian 98*, revision A; Gaussian, Inc.: Pittsburgh, PA, 1998.

(31) Mulliken, R. S. *J. Chem. Phys*. **1955**, *23*, 1833; **1955**, *23*, 2338.

(32) Matsuoka, O.; Clementi, E.; Yoshimine, M. *J. Chem. Phys*. **1976**, *64*, 1351.

(33) Hannongbua, S.; Rode, B. M. *J. Chem. Soc., Faraday Trans*. **1986**, *82*, 1021.

(34) Hannongbua, S. *J. Phys. Chem.* **1996**, *100*, 17655.

(35) Hannongbua, S.; Udomsub, S. *J. Chem. Soc., Faraday Trans. 2* **1997**, *93*, 3045.