

# Understanding the Microsolvation of Salts in Molecular Clusters

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The solvation of salts in water and salt–water interactions are important for understanding a large variety of chemical, biological, and atmospheric processes. In this perspective, we summarize our recent studies on the theoretical modeling of salt–water clusters. In these studies, the integrated tempering sampling method was used for structure search and density functional theory was used to optimize the low-

energy configurations. The microsolvation mechanisms of three alkali–halide ion pairs in clusters are discussed. We also discuss the implications of these studies to our understanding of corresponding bulk solutions. © 2014 Wiley Periodicals, Inc.

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## Introduction

Understanding the microscopic mechanism of salt dissolution is of fundamental importance in solution chemistry, atmospheric chemistry, and biology. Although the microsolvation model derived from salt–water clusters is not expected to quantitatively predict the liquid-phase solvation of the salts, it can be used to provide valuable insights into the interactions between the solvent and the solute ions. A large number of experimental<sup>[1–5]</sup> and theoretical<sup>[2–13]</sup> studies were performed to provide detailed information on the structural and thermodynamic properties of the clusters, and hints on molecular level explanations for corresponding liquid-phase systems. Important questions remain challenging: does the ion cooperativity shown in bulk solutions also exist in clusters? How easily do different ion pairs become solvated by water molecules? Does the pairing between anions and cations follow the well-known “matching water affinity” rule? In this perspective, we will summarize our recent work that was aimed at tackling the above questions, where the integrated tempering sampling (ITS)<sup>[14,15]</sup> method was used to overcome the sampling difficulty in molecular clusters consisting of relatively large number of degrees of freedom. The minimal energy structures optimized using the density functional theory (DFT) and the thermodynamics and structural information obtained from molecular dynamics (MD) trajectories of ITS simulations are used to illustrate the microsolvation of three alkali–halide ion pairs. Finally, implications to the bulk solutions and the future development on this topic will also be described.

## ITS Sampling Method Combined with DFT Calculations

It is well known that for large systems consisting of, for example, dozens of atoms, the high dimensional potential energy surface (PES) normally becomes very complex. As a result, it remains a challenge to locate most, not to say all, of the low-energy configurations of large-size molecular clusters. There exist several methods focusing on structure search, such as

basin-hopping<sup>[16]</sup> and modified genetic algorithm<sup>[17]</sup> methods. In our studies, we utilized the recently established ITS method. Briefly, to accelerate sampling in configuration space, in ITS simulation, [see Eq. (1)]

$$U' = -\frac{1}{\beta_0} \ln \sum_{k=1}^N n_k e^{-\beta_k U} \quad (1)$$

A modified potential energy  $U'$  is obtained from a summation of Boltzmann factors over a series of temperatures  $\beta_k$ . In Eq. (1),  $U$  is the potential energy of the system;  $\beta_0 = 1/k_B T$ , with  $k_B$  being the Boltzmann constant and  $T$  being temperature;  $n_k$  is the weighting factor of a series Boltzmann factors. The thermodynamic properties can be calculated through the following reweighting factors, shown in Eq. (2)

$$e^{-\beta_0(U-U')} = \frac{e^{-\beta_0 U}}{\sum_{k=1}^N n_k e^{-\beta_k U}} \quad (2)$$

This method achieves efficient sampling of cluster structures by allowing fast transitions between different structures on the PES and at the same time identification of low-energy

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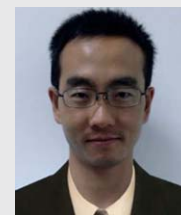
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This work is dedicated to Prof. Lemin Li on the occasion of his 80th birthday

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ones. ITS was shown to be efficient in the studies of complex molecular systems, for example, protein folding<sup>[18–20]</sup> and aggregation.<sup>[21]</sup> In our approach for studying molecular clusters, the configurations obtained from ITS classical MD simulations are optimized using both empirical force fields and DFT functionals, as well as other *ab initio* methods.<sup>[22]</sup>

The effectiveness of this “ITS-MD/DFT” procedure was first validated by the success on searching for the low-energy structures for (H<sub>2</sub>O)<sub>12</sub> and (H<sub>2</sub>O)<sub>20</sub> clusters.<sup>[22]</sup> Specifically, through ITS simulations, we identified a new minimum structure for (H<sub>2</sub>O)<sub>20</sub> (fused-like structure in Fig. 1), which, to the best of our knowledge, had not been reported before. Interestingly, this new structure is lower in energy than the previously reported global minimum (edge-sharing structure in Fig. 1) according to the energies from all four different functionals tested (see Ref. [22]). The computational framework was then applied to systematically investigate the microsolvation of alkali-halide ion pairs in water.

## Microsolvation of Alkali-Halide Ion Pairs in Water Clusters

The microsolvation characteristics of three different alkali-halide ion pairs, LiI, and CsI and NaCl, will be illustrated making use of the detailed analysis of the DFT optimized minimal energy structures. Further information is obtained on the cation–anion distance distribution over a range of temperatures, which is readily available from the ITS classical MD simulations.

### Microsolvation based on the DFT-optimized minimal structures

Generally, with more water molecules added to the cluster to interact with ions, the initial bare ion pair is expected to change from contact ion pair (CIP) to solvent separated ion pair (SSIP), and then eventually double-solvent-separated ion pair (2SIP).<sup>[12,23]</sup> In Figure 2a, we show how the cation–anion

distance evolves as a function of the number of water molecules in the most stable cluster structures. It is seen that with the Li–I distance increases, Li<sup>+</sup> and I<sup>−</sup> undergo the changes from CIP to SSIP and finally to 2SIP; In contrast, Cs<sup>+</sup> and I<sup>−</sup> remain in close contact even for *n* up to 20. This result is consistent with the matching water affinity rule. The more similar Cs<sup>+</sup>/I<sup>−</sup> ion pair is more difficult to be separated. Conversely, if only electrostatic interaction were considered, one would conclude that it is more difficult to separate Li<sup>+</sup> and I<sup>−</sup>. Our preliminary results show that, for Na<sup>+</sup> and Cl<sup>−</sup>, at least 10 water molecules are needed to separate a Na–Cl pair, which is consistent with previous theoretical study.<sup>[3]</sup>

The geometries of the clusters are shown in Figure 2b. It is seen that in LiI(H<sub>2</sub>O)<sub>*n*</sub> clusters, the strong interaction of lithium ion with water molecules dictates the cluster structure, which is also consistent with the previous study on lithium–water clusters.<sup>[24]</sup> Whereas in CsI(H<sub>2</sub>O)<sub>*n*</sub> clusters, due to the weak interactions of both cesium and iodide ions with water, the most stable structures of CsI(H<sub>2</sub>O)<sub>10</sub> and CsI(H<sub>2</sub>O)<sub>18</sub> resemble well the low-energy structures of (H<sub>2</sub>O)<sub>12</sub> and (H<sub>2</sub>O)<sub>20</sub>, respectively.<sup>[22]</sup> Namely, introduction of CsI only causes a small perturbation to water–water interactions. A common feature in

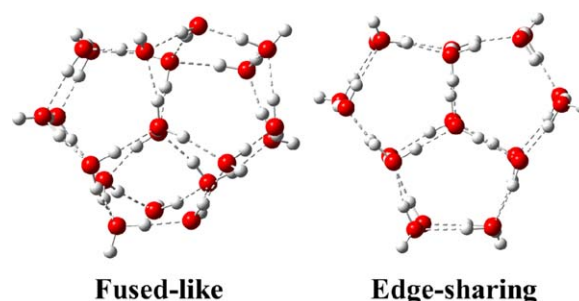
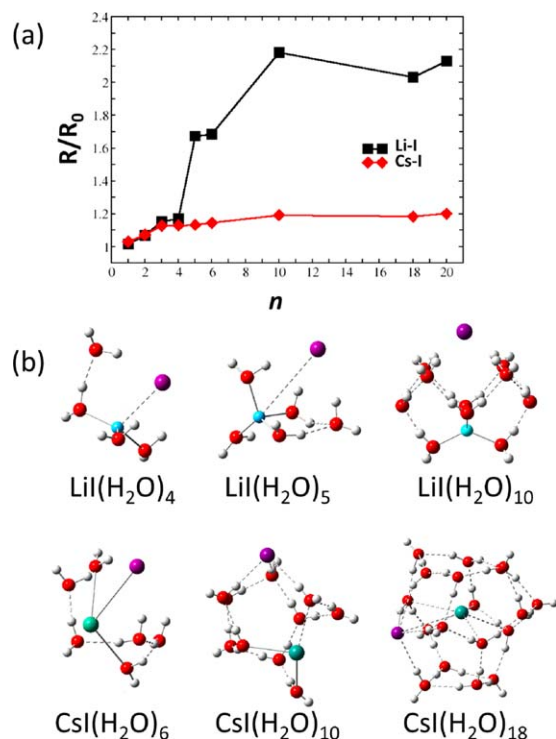


Figure 1. The fused-like and edge-sharing structures for (H<sub>2</sub>O)<sub>20</sub> cluster. The former is lower in energy than the previously reported global minimum structure (the latter) under different functionals (see the relative energetics in Ref. [22]).



**Figure 2.** a) The cation–anion distance (normalized by the corresponding bare ion distance  $R_0$ ) evolution as a function of cluster size and b) the representative structures are also presented. Cations (Li and Cs) are in purple sphere and iodide ion is in light blue sphere. a) is adapted with permission from Ref. [22] (Copyright [2014] American Chemical Society).

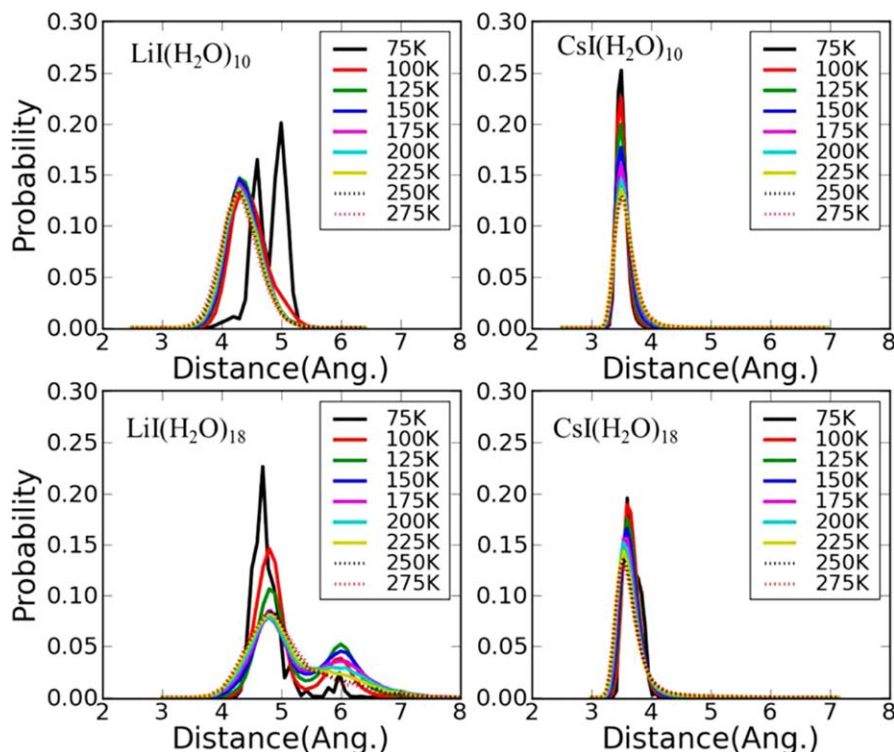
these salt–water clusters is that anions, but not cations, tend to reside on the surface of the clusters.

### The balance between the CIPs and SSIPs are temperature dependent

From the above discussions, it can be concluded that the formation of CIPs and SSIPs is resulted from the balance among the cation–anion, cation–water, anion–water, and water–water interactions. Therefore, with a given number of water molecules whether the cluster is in the CIP or SSIP form is ion pair specific, depending on both cation and anion. Such an observation reflects the importance of ion cooperativity.<sup>[25]</sup> We present in Figure 3 the cation–anion distance distribution over a broad range of temperatures, calculated from the classical ITS MD simulation data. It can be seen that in  $\text{LiI}(\text{H}_2\text{O})_n$  ( $n = 10$  and  $18$ ), both CIPs and SSIPs exist in the low temperature ranges, and the balance between them is temperature dependent. In contrast, the Cs-I distance remains largely constant in either  $\text{CsI}(\text{H}_2\text{O})_{10}$  or  $\text{CsI}(\text{H}_2\text{O})_{18}$  in the temperature range of 75–275 K.

### Implications to the Bulk Solutions and Future Work on this Topic

Although it is questionable to directly compare the results from molecular clusters to those of corresponding solutions, the former may provide useful information for understanding the corresponding bulk solutions. For example, we, as well as



**Figure 3.** The cation–anion distance distribution for LiI-water and CsI-water clusters. This figure is reproduced with permission from Ref. [22] (Copyright [2014] American Chemical Society).

other researchers,<sup>[3,5]</sup> have noticed that the number of water molecules needed to separate one ion pair is coincident with the solvent/solute ratio in corresponding saturated aqueous solutions for some of these salts. A very recent AIMD simulation work<sup>[26]</sup> reported that Na<sup>+</sup>, Cl<sup>-</sup>, Cs<sup>+</sup>, and I<sup>-</sup> take the role of water molecules in the network participating in directed ring structures with similar “network rules” present in neat water. This finding agrees very well with our results on the corresponding clusters. Additionally, in near-edge spectra studies,<sup>[27,28]</sup> it is found that the formation of prenucleation clusters is responsible for the spectra features. It would be helpful to simplify the model systems as clusters to investigate the molecular details. To summarize, studies using molecular clusters as models not only provide detailed interaction information between ions and water, but also can be used to understand and predict the properties of corresponding solutions.

For its simplicity and significant role in our daily life, much attention has been paid to sodium chloride. We have also conducted studies on NaCl–water clusters, in which the clusters consist of one, two, three, or four NaCl and a varied number of water molecules. For example, we found that in (NaCl)<sub>3</sub>(H<sub>2</sub>O)<sub>*n*</sub>, the water-doped cuboid structures, with two water molecules substituting the roles of Na<sup>+</sup> or Cl<sup>-</sup>, are energetically favored.<sup>[29]</sup> In addition, atmospheric aerosol systems including multicomponent species, such as ions, water, and organic acids are very important in understanding air pollution. For example, it is known that mixing of *cis*-pinonic acid with H<sub>2</sub>SO<sub>4</sub> and water vapors causes a marked increase in the aerosol particle concentration.<sup>[30]</sup> Studies are also being performed in our group on salts containing complex anions such as nitrates and sulfates, with the hope to understand of the particle formation thermodynamics and kinetics in the atmosphere.

We want to note here that the thermodynamic properties from ITS simulation trajectories at low temperatures are in good accordance with the quantum ones, which validates the reliability of the classical force fields. Quantum calculations are certainly desired for studies of clusters as well as bulk solutions. Therefore, one future direction of further development is the direct application of ITS method in *ab initio* molecular dynamics (AIMD) simulations. In our recent efforts, ITS method has been successfully embedded into QM/MM MD simulations to study organic and biocatalytic reactions. Such development will be helpful in studies of chemical reactions in complex environment, such as those occur at surfaces or in the solution phase, and is expected to provide an alternative for the enhanced sampling simulation study of aqueous solution properties besides classical force fields.

## Conclusions

In this short perspective, we summarized mainly our recent studies on the microsolvation of alkali–halide ion pairs. The “ITS-MD/DFT” procedure was shown to be efficient in the studies of relatively large-size clusters, largely overcoming the computational bottleneck in the sampling of their structures. The

solvation characteristics of the three ion pairs discussed here are distinctively different from each other, indicating the importance of the ion pair specific effect and ion cooperativity. We hope that information obtained from such studies will finally help us understand the molecular properties of bulk electrolyte solutions. We expect that the “ITS-MD/DFT” framework will allow us to reveal the structure and interaction information of many more interesting systems.

**Keywords:** integrated tempering sampling · quantum calculation · alkali–halide ion pairs · salt–water clusters · microsolvation mechanisms

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- [1] Y. Feng, M. Cheng, X.-Y. Kong, H.-G. Xu, W.-J. Zheng, *Phys. Chem. Chem. Phys.* **2011**, *13*, 15865.
- [2] R.-Z. Li, C.-W. Liu, Y. Q. Gao, H. Jiang, H.-G. Xu, W.-J. Zheng, *J. Am. Chem. Soc.* **2013**, *135*, 5190.
- [3] V. E. Bondybey, M. K. Beyer, *Int. Rev. Phys. Chem.* **2002**, *21*, 277.
- [4] D. Schröder, L. Ducháčková, J. Tarábek, M. Karwowska, K. J. Fijalkowski, M. Ončák, P. Slaviček, *J. Am. Chem. Soc.* **2011**, *133*, 2444.
- [5] F.-F. Xia, D. Zeng, H.-B. Yi, C. Fang, *J. Phys. Chem. A* **2013**, *117*, 8468.
- [6] D. E. Woon, T. H. Dunning, Jr. *J. Am. Chem. Soc.* **1995**, *117*, 1090.
- [7] M. Sudolská, L. Cantrel, I. Černušák, *J. Mol. Model.* **2014**, *20*, 1.
- [8] S. M. Ali, S. De, D. K. Maity, *J. Chem. Phys.* **2007**, *127*, 044303.
- [9] L. X. Dang, *J. Chem. Phys.* **1992**, *97*, 1919.
- [10] A. Sen, B. Ganguly, *J. Comput. Chem.* **2010**, *31*, 2948.
- [11] A. C. Olleta, H. M. Lee, K. S. Kim, *J. Chem. Phys.* **2007**, *126*, 144311.
- [12] M. K. Ghosh, S. Re, M. Feig, Y. Sugita, C. H. Choi, *J. Phys. Chem. B* **2013**, *117*, 289.
- [13] C.-K. Siu, B. S. Fox-Beyer, M. K. Beyer, V. E. Bondybey, *Chem. Eur. J.* **2006**, *12*, 6382.
- [14] Y. Q. Gao, *J. Chem. Phys.* **2008**, *128*, 064105.
- [15] Y. Q. Gao, L. Yang, Y. Fan, Q. Shao, *Int. Rev. Phys. Chem.* **2008**, *27*, 201.
- [16] D. J. Wales, J. P. K. Doye, *J. Phys. Chem. A* **1997**, *101*, 5111.
- [17] O. Oña, V. E. Bazterra, M. C. Caputo, J. C. Facelli, P. Fuentealba, M. B. Ferraro *Phys. Rev. A* **2006**, *73*, 053203.
- [18] Q. Shao, H. Wei, Y. Q. Gao, *J. Mol. Biol.* **2010**, *402*, 595.
- [19] Q. Shao, Y. Q. Gao, *J. Chem. Theor. Comput.* **2010**, *6*, 3750.
- [20] Q. Shao, Y. Q. Gao, *J. Chem. Phys.* **2011**, *135*, 135102.
- [21] Y. I. Yang, Y. Q. Gao, *J. Phys. Chem. B* (in press). DOI: 10.1021/jp502169b.
- [22] C.-W. Liu, F. Wang, L. Yang, X.-Z. Li, W.-J. Zheng, Y. Q. Gao, *J. Phys. Chem. B* **2014**, *118*, 743.
- [23] M. J. Blandamer, M. F. Fox, *Chem. Rev.* **1970**, *70*, 59.
- [24] X. Li, Z.-Z. Yang, *J. Phys. Chem. A* **2005**, *109*, 4102.
- [25] Y. Q. Gao, *J. Phys. Chem. B* **2011**, *115*, 12466.
- [26] Y. Ding, A. A. Hassanali, M. Parrinello, *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3310.
- [27] R. Demichelis, P. Raiteri, J. D. Gale, D. Quigley, D. Gebauer, *Nat Commun* **2011**, *2*, 590.
- [28] Y. Zhang, I. R. Türkmen, B. Wassermann, A. Erko, E. Rühl, *J. Chem. Phys.* **2013**, *139*, 134506.
- [29] C.-W. Liu, G.-L. Hou, W.-J. Zheng, Y. Q. Gao, *Theor. Chem. Acc.* **2014**, *133*, 1.
- [30] R. Zhang, A. Khalizov, L. Wang, M. Hu, W. Xu, *Chem. Rev.* **2012**, *112*, 1957.

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