

Viewpoint

Ion-induced long-range orientational correlations in water: Strong or weak, physiologically relevant or unimportant, and unique to water or not?

Pavel Jungwirth¹ and Damien Laage²

¹*Institute of Organic Chemistry and Biochemistry, Academy of Sciences of the Czech Republic,
Flemingovo nam. 2, 16610 Prague 6, Czech Republic, pavel.jungwirth@uochb.cas.cz*

²*PASTEUR, Département de Chimie, École Normale Supérieure, PSL University, Sorbonne
Université, CNRS, 75005 Paris, France, damien.laage@ens.fr*

There is an ongoing discussion in the literature about the spatial extent of the influence of dissolved ions on the structure and dynamics of the surrounding water molecules in solution.^{1–12} This is not just a narrow academic issue, since it has a strong influence on how we perceive the role of the aqueous solvent in biological processes, where salt ions are ubiquitous^{13, 14}. The three key questions pertinent to this issue may be formulated as follows: How strong is the influence of dissolved ions on water structure beyond the short-range solvation shell effects? What is the effect of increasing salt concentration, particularly when approaching physiological conditions? And, finally, how special in this respect is water as a solvent?

A recent paper published in this Journal¹⁵ brings a much-needed fresh look at these questions. The authors show how reviving well-established theories of liquids and electrolytes developed more than 40 years ago can provide a valuable contribution to this debate. The effect induced by a solute – e.g. an ion – on the structure of an aqueous solvent can be usefully

characterized by its influence on the water-water pair distribution function^{16, 17}. The angular part of this correlation can be expanded on spherical harmonics, with the leading term reporting on the mean value of $\cos(\phi)$ – where ϕ is the angle between the dipole moment vectors of a pair of water molecules¹⁸ – which is accessible experimentally⁹, theoretically^{12, 15} and numerically^{9, 11}. The authors opportunely remind us that long-range limiting laws for this orientational correlation can be obtained by a diagrammatic expansion of the pair function, where the total correlation between two solvent molecules is decomposed into a direct correlation and a sum of indirect correlations propagated via chains of intermediate particles¹⁷. This approach shows¹⁵ that the long-range water-water orientational correlation measured by $\langle \cos[\phi(R)] \rangle$ scales with the distance R between the water molecules as $\exp(-\kappa_D R)/R$. Here, $1/\kappa_D$ is the Debye screening length, which amounts to approximately 10 nm at a 1 mM ionic strength, but shortens to about 0.8 nm at physiological conditions of 150 mM¹⁹. At long distances, the presence of ions thus replaces the direct dipole-dipole interaction in $1/R^3$ with the screened electrostatic interaction in $\exp(-\kappa_D R)/R$.

With this brief introduction, the three questions posed in the first paragraph can now be answered. We see from the above expression that the range of the salt-induced water-water correlations is due to a combination of two factors – a concentration-independent $1/R$ decay, together with a concentration-dependent $\exp(-\kappa_D R)$ exponential attenuation. This immediately addresses the question about the influence of the salt concentration. Namely, at physiological (and higher) concentrations the strongly attenuating exponential term $\exp(-\kappa_D R)$ dominates at distances above ~ 1 nm, effectively making all long-range water-water correlations vanish. Only at significantly lower (millimolar) concentrations, where the Debye screening length $1/\kappa_D$ extends to ~ 10 nm, does the more slowly decaying term proportional to $1/R$ dominate the correlations in the longer-range region of several nanometers, i.e., beyond the immediate ionic solvent shells.

Nevertheless, if one takes into account the amplitude of the orientational correlation function ¹⁵, the correlations in this region still remain orders of magnitude smaller than the short-range correlation in the immediate solvation shells of the ions at sub-nanometer separations ^{9, 11, 15}.

Measuring these very weak long-range correlations present in dilute salt solutions is thus challenging, but it was recently done in a tour de force second harmonic scattering experiment⁹. In this technique, the signal is *summed* over all pairs of water molecules. This means that the contribution from individual solvent pairs at large separations R is drastically amplified by the Jacobian factor pertinent to spherical coordinates, proportional to R^2 , leading eventually to a detectable experimental signal. However, this changes little on the fact that *locally* the long-range ion-induced water-water correlations remain very weak even in dilute solutions. Note that the deviation of $\langle \cos[\phi(R)] \rangle$ with respect to the zero value expected in absence of correlations can be interpreted as resulting from an effective potential biasing the water molecules' orientation, whose amplitude is on the order of $\langle \cos[\phi(R)] \rangle$ times the thermal energy, i.e. $\sim 10^{-4} k_B T$ at separations of several nanometers ¹¹. Due to random thermal motions of water molecules such a negligible bias can hardly induce any significant long-range order and structuring of the solvent. This is also manifested in numerical simulations¹¹, where extensive averaging is required before the residual correlation can be distinguished from statistical noise.

Finally, the quantitative agreement in the long-range solvent orientational correlations between the recent study based on a general theory of polar liquids and molecular dynamics simulations of specific aqueous salt solutions ^{9, 11, 15} demonstrates that in this respect there is nothing special about water or, as a matter of fact, hydrogen bonding in general. Indeed, the commented study ¹⁵ shows that any dipolar solvent exhibits such ion-induced orientational

correlations, the spatial extent of which is dictated primarily by the salt concentration and the corresponding Debye screening due to the dissolved ions.

Acknowledgment

DL acknowledges support from the European Research Council under the European Union's Seventh Framework Program (FP7/2007-2013)/ERC Grant Agreement No. 279977. PJ thanks the Czech Science Foundation (grant no. 16-01074S) for support.

References

- (1) Omta, A. W.; Kropman, M. F.; Woutersen, S.; Bakker, H. J. *Science* **2003**, *301*, 347-349.
- (2) Collins, K. D.; Neilson, G. W.; Enderby, J. E. *Biophys Chem* **2007**, *128*, 95-104.
- (3) Mancinelli, R.; Botti, A.; Bruni, F.; Ricci, M. A.; Soper, A. K. *Phys Chem Chem Phys* **2007**, *9*, 2959-2967.
- (4) Laage, D.; Hynes, J. T. *Proc Natl Acad Sci USA* **2007**, *104*, 11167-11172.
- (5) Tielrooij, K. J.; Garcia-Araez, N.; Bonn, M.; Bakker, H. J. *Science* **2010**, *328*, 1006-1009.
- (6) Gaffney, K. J.; Ji, M.; Odelius, M.; Park, S.; Sun, Z. *Chem Phys Lett* **2011**, *504*, 1-6.
- (7) Funkner, S.; Niehues, G.; Schmidt, D. A.; Heyden, M.; Schwaab, G.; Callahan, K. M.; Tobias, D. J.; Havenith, M. *J Am Chem Soc* **2012**, *134*, 1030-1035.
- (8) Stirnemann, G.; Wernersson, E.; Jungwirth, P.; Laage, D. *J Am Chem Soc* **2013**, *135*, 11824-11831.
- (9) Chen, Y.; Okur, H. I.; Gomopoulos, N.; Macias-Romero, C.; Cremer, P. S.; Petersen, P. B.; Tocci, G.; Wilkins, D. M.; Liang, C.; Ceriotti, M.; Roke, S. *Sci Adv* **2016**, *2*, e1501891.
- (10) Shalit, A.; Ahmed, S.; Savolainen, J.; Hamm, P. *Nat Chem* **2017**, *9*, 273-278.
- (11) Pluhařová, E.; Laage, D.; Jungwirth, P. *J Phys Chem Lett* **2017**, *8*, 2031-2035.
- (12) Wilkins, D. M.; Manolopoulos, D. E.; Roke, S.; Ceriotti, M. *J Chem Phys* **2017**, *146*, 181103.
- (13) Jungwirth, P. *J. Phys. Chem. Lett.* **2015**, *6*, 2449-2451.
- (14) Qvist, J.; Persson, E.; Mattea, C.; Halle, B. *Faraday Discuss.* **2009**, *141*, 131-144.
- (15) Belloni, L.; Borgis, D.; Levesque, M. *J Phys Chem Lett* **2018**,
- (16) Deutch, J. M. *Annu Rev Phys Chem* **1973**, *24*, 301-323.
- (17) Hoye, J. S.; Stell, G. *J Chem Phys* **1979**, *71*, 1985-1986.
- (18) Hansen, J.-P.; McDonald, I. R. *Theory of simple liquids*; Elsevier Academic Press: London; Burlington, MA, 2006;
- (19) Barthel, J. M. G.; Krienke, H.; Kunz, W. *Physical Chemistry of Electrolyte Solutions: Modern Aspects*; Springer: 1998;