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Molecular Dynamics Simulation Study of Hydrogen Bonding in Aqueous Poly(Ethylene Oxide) Solutions

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A molecular dynamics simulation study of hydrogen bonding in poly(ethylene oxide) (PEO)/water solutions was performed. PEO-water and water-water hydrogen bonding manifested complex dependence on both composition and temperature. Strong water clustering in concentrated solutions was seen. Saturation of hydrogen bonding at $w_p \approx 0.5$ and a dramatic decrease in PEO-water hydrogen bonding with increasing temperature, consistent with experimentally observed closed-loop phase behavior, were observed. Little tendency toward intermolecular bridging of PEO chains by water molecules was seen.

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Poly(ethylene oxide) (PEO) is the quintessential synthetic water-soluble polymer due to the extremely wide variety of applications it enjoys as well as the great amount of fundamental study it has engendered. PEO is typical of many water-soluble polymers in that it exhibits a negative heat and entropy of mixing [1] and at sufficiently high molecular weight manifests lower critical solution temperature (LCST) behavior [2]. Understanding the influence of solution composition and temperature on local conformations, hydrogen bonding, and hydration is key to the understanding of the properties of water-soluble polymers. Several mean-field models have been proposed for the closed-loop phase behavior of PEO solutions that have associated LCST behavior with either the composition and temperature dependence of PEO-water hydrogen bonding [3] or the population of hydrophilic conformers [4]. While these models can describe reasonably well the phase behavior of PEO/water solutions, much of the fundamental physical insight yielded by the models, e.g., the influence of temperature and composition on hydrogen bonding or conformer populations, are fit parameters. Since these models, which differ in their fundamental assumptions about the driving force for LCST behavior, can provide similar quality descriptions of PEO/water phase behavior, the ability of the models to reproduce the closed-loop phase behavior is insufficient to validate the fundamental assumptions of the models and the subsequent physical picture of PEO/water interactions. Our hope is that in addition to providing the first detailed picture of hydrogen bonding in PEO/water solutions, this work will contribute structural and thermodynamic data that can be used to critically test, and as necessary, revise, mean-field models of PEO/water solutions.

Previously, we reported on the influence of temperature and composition on conformations of PEO in aqueous solution [5] as determined from molecular dynamics (MD) simulations. Here, we consider in detail PEO-water and water-water hydrogen bonding in these solutions. MD simulations were performed on aqueous solutions of PEO $H\text{-}[—CH_2—O—CH_2—]_{12}\text{-}H$ (530 Da) for compositions (polymer weight fraction) $0.025 \leq w_p \leq 0.90$ over a temperature range $298 \leq T \leq 450$ K. Simulations were performed on systems consisting of approximately 4000 atoms with at least 8 polymer chains for each system. The linear size of the periodic simulation box ranged from 26 to 35 Å depending upon concentration. Quantum chemistry based atomistic potentials for PEO [6] and PEO/water interactions [7] and the TIP4P [8] model for water were used in the simulations. The Ewald summation method was used to calculate long-range electrostatic interactions. $N\text{-}P\text{-}T$ simulations over 2–3 ns were conducted to establish the equilibrium densities at atmospheric pressure for each solution. The production runs were performed in an $N\text{-}V\text{-}T$ ensemble over 10–50 ns. The details of initialization, equilibration, and simulation methodologies are described in our previous work [5,7].

We based our definition of hydrogen bonding on positional order, in particular O-H separations. Representative ether oxygen/water hydrogen (EO-H_w) and water oxygen/water hydrogen (O_w-H_w) intermolecular pair distribution functions are given in Fig. 1. We define each occurrence of an EO-H_w approach within 2.675 Å and each occurrence of an O_w-H_w approach within 2.475 Å (the radii of the first hydrogen atom coordination shell for ether and water oxygen atoms, respectively, as denoted in Fig. 1) as a PEO-water (EO-W) and water-water (W-W) hydrogen bond, respectively. Applying this definition, the number of EO-W hydrogen bonds per ether oxygen (EO) and the number of W-W hydrogen bonds per water oxygen [9] were determined for each composition and temperature investigated, and are shown in Fig. 2(a). Note that while the absolute number of hydrogen bonds for any composition and temperature depends somewhat upon definition, changing the radial cutoff and/or introducing orientational restrictions, e.g., requiring the O—H-O angle to be linear to within some arbitrary criterion (20°, 40°, etc), were found to have almost no effect on the relative extent of hydrogen bonding as a function of temperature and

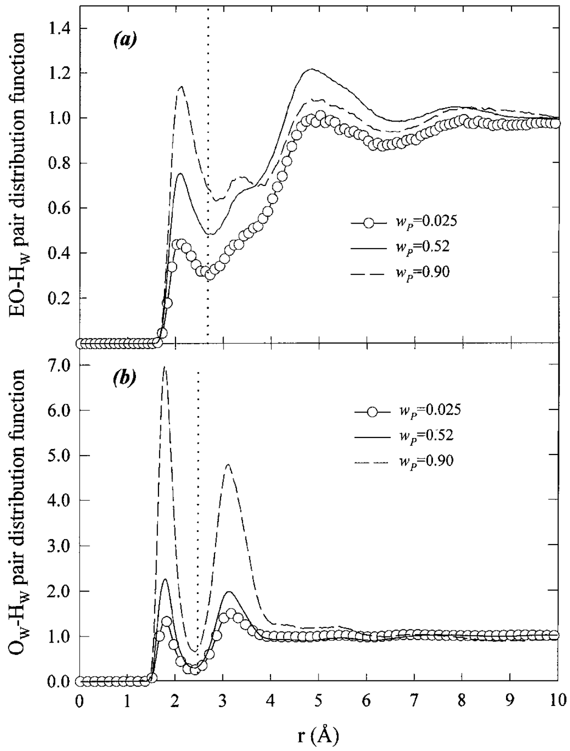

FIG. 1. Pair distribution functions from selected solution compositions at 318 K. Vertical lines denote the O-H separations used to define hydrogen bonding.

composition. Hence, we found no reason to employ a more complex definition of hydrogen bonds as the analysis and conclusions presented here based upon our simple definition are equally valid for any reasonable definition.

Figure 2(a) reveals that W-W hydrogen bonding sets in very rapidly as water is added to the pure polymer. At 10 wt % water ($w_p = 0.90$), the number of W-W hydrogen bonds per water molecule is already 50% or more of that in pure water. This nonrandom mixing behavior reflects strong water clustering in solutions with low water content that is manifested, for example, in the very strong composition dependence of the O_w-H_w pair distribution functions (Fig. 1). As an illustration of the extent of water clustering, in the $w_p = 0.90$ solution at 318 K the number of nearest-neighbor water molecules to any given water molecule is 2.8 times that expected from the average water density in solution [10]. To date, water clustering has not been incorporated in mean-field models of PEO/water solutions. EO-W hydrogen bonding increases rapidly with dilution until $w_p \approx 0.5$, at which point EO-W hydrogen bonding is nearly saturated, exhibiting relatively little increase with increasing dilution. This is in contrast with previous modeling predictions [3] where increasing EO-W hydrogen bonding with dilution over the entire composition range was found. Additional water either participates in perfecting the hydration shell of the polymer without forming additional EO-W hydrogen bonds, or becomes free water not directly involved in polymer hydration [11] (note that there is essentially no free water for solutions $w_p > 0.5$). Issues of PEO hydration will be considered in detail in a future manuscript.

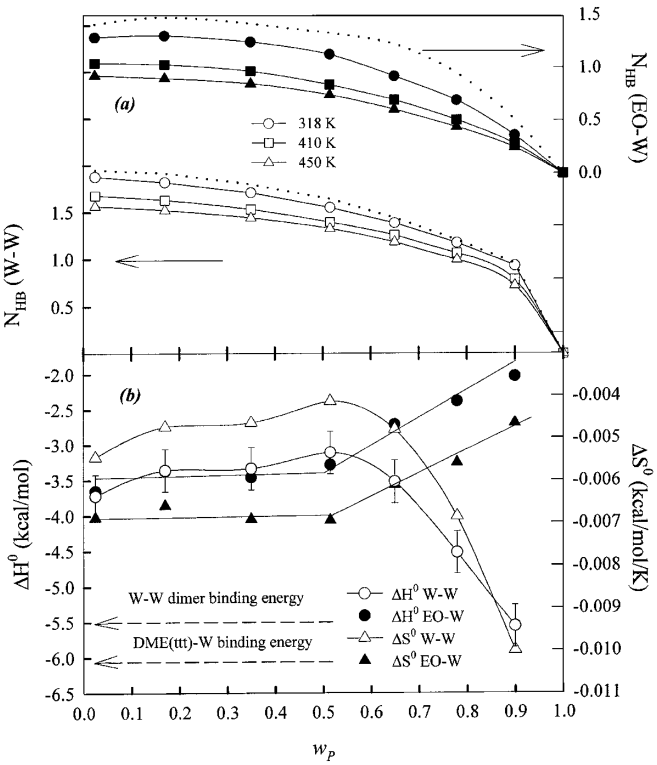

FIG. 2. (a) Number of PEO-water hydrogen bonds per ether oxygen and the number of water-water hydrogen bonds per water oxygen in PEO/water solutions as a function of solution composition. Also shown (dotted lines) are the numbers of hydrogen bonding sites (N^0_{HB}) from Eq. (3). (b) Enthalpy and entropy of PEO-water and water-water hydrogen bond formation as a function of solution composition from Eq. (3). Water dimer and dimethoxyethane (DME)-water dimer binding energies from quantum chemistry (Ref. [7]) are also shown. Error bars are based on uncertainties in the number of hydrogen bonds as determined from simulation. Solid lines serve to guide the eye.

Knowledge of the temperature dependence of the extent of W-W and EO-W hydrogen bonding allows us to extract important thermodynamic information about the formation of hydrogen bonds in PEO/water solutions. If we consider the polymer as providing hydrogen bonding sites (e.g., ether oxygen atoms) for water binding, we can express hydrogen bonding equilibrium according to the expression

$$\mathrm{EO}_f + W \Leftrightarrow \mathrm{EO}_{\text{H-bond}}\,, \tag{1}$$

where EO_f is a free ether oxygen and $\mathrm{EO}_{\text{H-bond}}$ is a hydrogen bonded EO. If it is assumed that the activity of a hydrogen bonding site is given by its fractional occupancy, then the equilibrium condition for a given composition and temperature is expressed as

$$\Delta G^\circ(T) = -RT\ln\{X_0(T)/[1 - X_0(T)]\}, \tag{2}$$

where $X_0(T)$ is the fraction of occupied hydrogen bonding sites at temperature T and $\Delta G°(T)$ is the temperature dependent free energy difference between an occupied site (hydrogen bond) and an unoccupied site (no hydrogen bond) plus a water molecule at equilibrium activity. In order to determine $X_0(T)$, we must know the number of EO-W hydrogen bonds per EO as a function of temperature and composition, which we determined from simulation (Fig. 2). We must also know the number of available hydrogen bonding sites per EO, i.e., the number of hydrogen bonds per EO at low temperature where configurational entropy contributions are negligible (100% occupation). A similar treatment can be applied to W-W hydrogen bonding.

For a given composition, let $N_{\mathrm{HB}}(T)$ be the number of hydrogen bonds (per EO or W) (Fig. 2), N^0_{HB} be the number of hydrogen bonding sites (per EO or W), ΔH^0 the enthalpy of EO-W or W-W hydrogen bond formation, and ΔS^0 the entropy of EO-W or W-W hydrogen bond formation. If we assume for a given solution composition that ΔH^0 and ΔS^0 are independent of temperature, Eq. (2) becomes

$$\Delta H^0 - T\Delta S^0 = -RT \ln \frac{N_{\mathrm{HB}}(T)/N^0_{\mathrm{HB}}}{1 - N_{\mathrm{HB}}(T)/N^0_{\mathrm{HB}}}. \qquad (3)$$

We determined values of ΔH^0, ΔS^0, and N^0_{HB} that gave the best fit of Eq. (3) to the hydrogen bonding data [$N_{\mathrm{HB}}(T)$ for EO-W and W-W] for each composition. Once ΔH^0, ΔS^0, and N^0_{HB} (shown in Fig. 2) have been established for a given composition, the extent of hydrogen bonding (X_0) can be predicted at any temperature using Eq. (2), as shown in Fig. 3(a). Good agreement with simulation can be seen. Figure 3(a) reveals that the extent of EO-W hydrogen bonding decreases much more rapidly than W-W hydrogen bonding with increasing temperature, consistent with the experimentally observed LCTS behavior in higher molecular weight PEO solutions. At temperatures corresponding to the immiscible region for PEO/water solution (≈450 K), around 50% of EO-W hydrogen bonds have broken up, in agreement with the predictions of the model of Pincus *et al.* [3].

Figure 3(b) reveals that ΔG^0 for both EO-W and W-W hydrogen bond formation depends on both solution composition and temperature. This is further illustrated in Fig. 2(b), where ΔH^0 and ΔS^0 are shown as a function of composition. Note that the ΔH^0 values are comparable to the optimal water-ether or water-water interaction energy as determined from quantum chemistry calculations on two molecule complexes [7]. ΔH^0 and ΔS^0 for EO-W hydrogen bonds indicate strengthening or perfecting (i.e., more favorable enthalpy and less favorable entropy of formation) with dilution up to $w_p \approx 0.5$. For W-W hydrogen bonds, the inverse behavior for ΔH^0 and ΔS^0 is observed in this composition range ($0.5 < W_P < 1.0$), with a rapid decrease in favorable enthalpy and unfavorable entropy effects with dilution. With further dilution ($w_p < 0.5$) ΔH^0 and ΔS^0 for both EO-W and W-W hydrogen bonds are nearly independent of composition. For compositions $w_p \leq 0.5$ W-W hydrogen bonds are energetically less favorable but also entropically less penalized in comparison with more concentrated solutions. Consequently, as shown in Figs. 3(a) and 3(b), at low temperatures W-W hydrogen bonds for the more concentrated solutions are relatively stable, but at higher temperatures (e.g., corresponding to the miscibility gap), the large entropic penalty resulting from water clustering effects becomes dominant and W-W hydrogen bonds in the more concentrated solutions are relatively unfavorable. The composition $w_p \approx 0.5$ corresponds to the onset of free water and saturation of EO-W hydrogen bonds (see above) and is also the composition of the polymer-rich phase for most of the temperature range between the LCST and the UCST for PEO/water solutions that show closed-loop phase behavior [2].

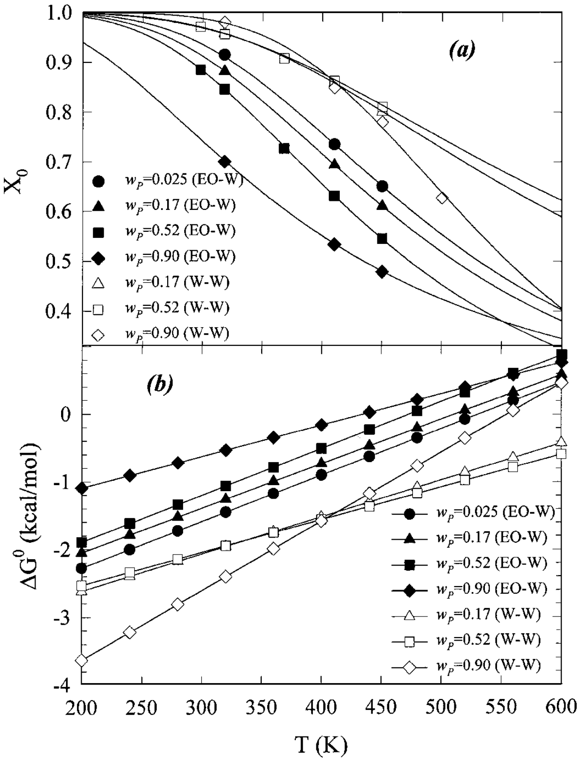

FIG. 3. (a) Extent of PEO-water and water-water hydrogen bonding for selected compositions as a function of temperature. Solid lines are from Eq. (2), symbols are from simulation. (b) Free energy of PEO-water and water-water hydrogen bond formation for selected compositions as a function of temperature from Eq. (3).

We interpret the composition dependence of the W-W hydrogen bond enthalpy and entropy as follows. Beginning with concentrated solutions, the first added water molecules form clusters. These clusters are highly structured as water tries to form W-W hydrogen bonds, while at the same time maintaining EO-W hydrogen bonds. This is reflected in the highly favorable energy and unfavorable entropy of W-W hydrogen bond formation in concentrated

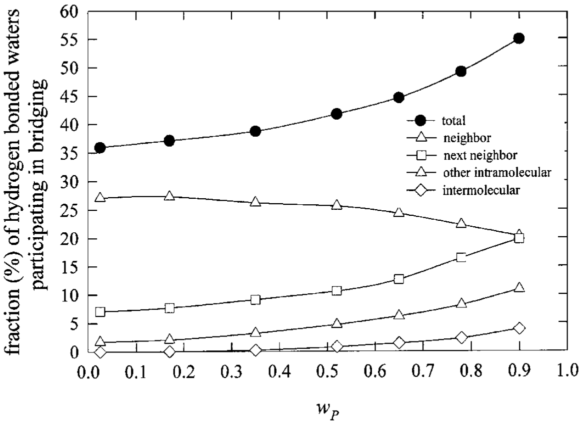

FIG. 4. Fraction of water molecules hydrogen bonded to PEO that participate in hydrogen bonding bridges as a function of solution composition at 318 K.

solutions. With increasing dilution, water is more readily available for forming W-W hydrogen bonds. The continuing need to satisfy EO-W hydrogen bonds results in relatively loose (energetically weak, entropically favorable) W-W hydrogen bonding. At $w_p \approx 0.5$, where EO-W hydrogen bonds are nearly saturated and free water first begins to appear, there is simultaneously plenty of water and plenty of PEO for hydrogen bond formation—water is in a hydrogen bonding opportunity rich environment. With further dilution, the environment appears increasingly waterlike and the role of the polymer on W-W hydrogen bonding diminishes as more water is free, i.e., not involved in PEO hydration. It appears that a slight further perfection of W-W hydrogen bonding occurs with additional dilution ($w_p < 0.5$), resulting in energetically favorable and entropically unfavorable hydrogen bonding compared to the $w_p \approx 0.5$ solutions, but this trend is not definitive given the uncertainties in the ΔH^0 and ΔS^0 values.

The final important issue we wish to address is the concept of water bridging. It has been suggested that in concentrated solutions in response to a plethora of EO-W hydrogen bonding opportunities water will have a strong tendency to form two EO-H_w hydrogen bonds with different PEO molecules, thereby forming hydrogen bonding bridges between PEO molecules [12]. Figure 4 shows the fraction of water molecules hydrogen bonded to PEO that forms bridges. We define a bridge forming water molecule as one that is hydrogen bonded to two EO. In the most concentrated solution approximately 55% of the hydrogen bonded water forms such bridges. However, as shown in Fig. 4, the majority of these bridging water molecules are being shared by neighbor or next-neighbor EO on the same PEO chain. It should also be kept in mind that despite the paucity of water in concentrated solutions there is extensive W-W hydrogen bonding due to water clustering. Figure 4 reveals that very few water molecules participate in intermolecular hydrogen bonding bridges, even in concentrated solutions.

This work clearly illustrates the complex dependence of PEO-water and water-water hydrogen bonding in PEO/water solutions on both composition and temperature. We believe the driving forces for this complex behavior, e.g., water clustering and PEO-water hydrogen bond saturation, must be incorporated into any model that attempts to describe phase behavior in PEO/water solutions. We would also point out that while many aspects of hydrogen bonding in PEO/water solutions observed in our simulations are consistent with experimentally observed phase behavior, it cannot be safely concluded that hydrogen bonding is the only, or even the most important, cause for LCST behavior. Our previous study [5] clearly demonstrated that the population of hydrophilic PEO conformations shows temperature and composition dependence in many ways similar to that seen here for hydrogen bonding.

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[9] The total number of W-W hydrogen bonds per water molecule is obtained by doubling the values shown in Fig. 2.

[10] The first coordination shell of a water consists of the volume within 3.675 Å of the O_w.

[11] We define first hydration shell of PEO to consist of the volume within approximately 4 Å of the heavy atoms.

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