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A molecular dynamics study of nitric oxide in water: Diffusion and structure

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We present molecular dynamics simulations of the diffusion coefficients and structure of water-nitric oxide mixtures at ambient (298 K) and *in vivo* (310 K) conditions. A two-site rigid-body molecular model with partial charges and a Lennard-Jones potential on both sites is proposed for nitric oxide and used in conjunction with the extended simple point-charge model for liquid water in our simulations. The diffusion coefficients obtained from the simulations are in good agreement with experimental data. The results from intermolecular partial pair functions show that under these thermodynamic conditions, the existence of nitric oxide in liquid water has little impact on the structure of water and the tendency to form H bonds between water molecules. We also find that it is unlikely that H bonds form between the hydrogen atoms in water and either the nitrogen or the oxygen atom on the nitric oxide at the temperatures and densities examined in this study. This study suggests that in low concentrations nitric oxide molecules exist as free molecules in liquid water rather than forming complexes with water molecules. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1992482]

I. INTRODUCTION

Nitric oxide (NO) is one of the most important signal molecules in a living cell. As a typical free radical it had been mainly considered as an atmospheric pollutant and bacterial metabolite until the middle of the 1980s.[1] The discovery of NO's role in physiological processes in the middle 1980s has expanded the interest in nitric oxide into biology, making it the target of many studies. It appears that a simple molecule such as NO can play a key bioregulatory function in a number of physiological responses,[2] for example, NO is regarded as a signal molecule playing an important role in intracellular and intercellular communications.[3] The biological role of NO as an intracellular messenger molecule will be greatly dependent on the diffusion of NO, which determines its effective concentration in the active sites. Despite its well-documented importance, the mechanism for nitric oxide transport *in vivo* is still unclear. The transport of NO from the producing cell to the target cell is not well understood. It has been proposed that NO is transported from endothelial cells through diffusion and that cell membranes are readily permeable to NO.[4]

The neutrally charged NO molecule is hydrophobic with respect to aqueous solutions, which facilitates its free diffusibility. A number of experimental studies of the diffusion coefficient of NO in water have been attempted. Using fluorescence quenching techniques, Denicola *et al.*[5] experimentally measured the diffusion coefficient of NO in buffer solution to be 4.5×10^{-9} m^2/s at 20 °C. Malinski *et al.*[4] employed a porphyrinic microsensor to measure the diffusion coefficient of NO at 37 °C and obtained a value of 3.3×10^{-9} m^2/s. Wise and Houghton[6] reported diffusion coefficients of 2.07×10^{-9} and 5.1×10^{-9} m^2/s in water for temperatures of 20 and 40 °C, respectively. In addition, there are some modeling studies on NO diffusion *in vivo* and *in vitro*, essentially based on Fickian diffusion and reaction diffusion models.[7–9] However, to the best of our knowledge, there has been no molecular dynamics (MD) study on the diffusion of NO in water. In this paper we report the results of a molecular dynamics study, mainly concentrating on the diffusion and structure of NO in water and on the establishment of the NO−H$_2$O potential interactions for future work. Under the conditions described here, the chemical reaction between NO and water can be safely neglected.

Water is very well known and has been studied extensively by computer simulations. We chose the extended simple point-charge (SPC/E) model of Berendsen *et al.*[10] to mimic water due to its simplicity and good prediction of liquid water properties, particularly the diffusion coefficient.[11] There are only few NO potential models proposed or used in previous studies.[12,13] Elert *et al.*[12] used a two-site model for NO in a MD study of the detonation of

nitric oxide. In this model the Morse potential was used for the bonding potential of the NO bond and a potential similar to the Buckingham potential, with the signs of the exponential and r^{-6} terms being reversed, was used for computing nonbonded interactions. Another proposed model consists of two atomic sites with a Lennard-Jones 9-6 potential and point charges.[13] As the most effective water potential models use a Lennard-Jones 12-6 potential for nonbonded interactions, these two functional forms make it difficult to apply the potentials to the mixed system with water. In this study, we will propose a rigid two-site model with the Lennard-Jones 12-6 potential and partial charges. We will also parameterize the model for the mixed system of $NO-H_2O$.

In binary liquids the mutual diffusion, also called chemical diffusion, describing the transport of mass driven by gradients in chemical potential is of more significance than self-diffusion in describing and analyzing the diffusion process of binary systems, particularly in evaluating Fick's law. Mutual and self-diffusivities are related to the velocity correlation functions of collective motions of the system and of single-particle motions, respectively.[14] The mutual diffusion coefficient can be expressed as a combination of self- and distinct diffusion coefficients. Self-diffusion is a measure of mobility of each component in the mixture, while distinct diffusion represents the sum effect of all dynamic cross correlations, which arise from momentum exchange between particles of unlike species.[15] Due to the low solubility of NO in water, in this study we will only examine the diffusivities for systems of low NO concentrations, which is similar to tracer diffusion of individual molecules in equilibrium mixtures. For the low solute concentrations studied in this work, the contribution to the mutual diffusivities due to cross correlations should be either very small or negligible. Therefore, we mainly examined self-diffusivities and assumed the mutual diffusion coefficient to be equal or close to the self-diffusion coefficient of the solute in the mixture. To validate this point, we will also provide comparison results between the self-diffusion and mutual diffusion coefficients for mixtures of the highest solute concentration studied.

II. THEORETICAL FORMALISM FOR DIFFUSION COEFFICIENTS

In a binary mixture of species 1 and 2, the self-diffusion and mutual diffusion coefficients[16] can be written in terms of either the mean-square displacement (MSD) or Green-Kubo (GK) relations through the velocity autocorrelation function (VACF). For self-diffusion coefficients in the mixture these relationships are

$$D_{ii} = \frac{1}{6}\lim_{t\to\infty}\frac{d}{dt}\langle[\mathbf{r}_{ij}(0) - \mathbf{r}_{ij}(t)]^2\rangle \quad (i = 1 \text{ or } 2) \tag{1}$$

$$D_{ii} = \frac{1}{3}\int_0^\infty \langle\mathbf{v}_{ij}(0)\cdot\mathbf{v}_{ij}(t)\rangle dt \quad (i = 1 \text{ or } 2), \tag{2}$$

respectively. Here $\mathbf{v}_{ij}$ is the velocity and $\mathbf{r}_{ij}$ is the position of the center of mass of particle j of species i. The angular brackets denote an ensemble average. Mutual diffusivities are related to the collective motions of the system. In a bi-

nary mixture there is only one independent mutual diffusion coefficient[17] (which follows due to the relations between the component forces and fluxes), which we shall denote D_{12}. The mutual diffusion coefficient can be determined from the mean-square displacement of the center of mass of particles of species 1 or the solute,[16]

$$D_{12} = \frac{Q}{6Nx_1x_2}\left(\frac{m_1}{m_2}x_1 + x_2\right)^2$$
$$\times \lim_{t\to\infty}\frac{d}{dt}\left\langle\left[\sum_{k=1}^{N_1}\mathbf{r}_k(0) - \sum_{k=1}^{N_1}\mathbf{r}_k(t)\right]^2\right\rangle, \tag{3}$$

or from the Green-Kubo expressions for the velocity correlation function of the center of mass of particles of species 1,

$$D_{12} = \frac{Q}{6Nx_1x_2}\left(\frac{m_1}{m_2}x_1 + x_2\right)^2\int_0^\infty\left\langle\sum_{i=1}^{N_1}\mathbf{v}_i(t)\cdot\sum_{i=1}^{N_1}\mathbf{v}_i(0)\right\rangle dt. \tag{4}$$

By changing the reference velocity to one defined with respect to the center of mass of the entire system (barycentric velocity or barycentric frame), it can easily be shown that Eq. (4) may be rewritten as

$$D_{12} = \frac{Q}{3Nx_1x_2}\int_0^\infty\langle\mathbf{J}_{12}(0)\cdot\mathbf{J}_{12}(t)\rangle dt, \tag{5}$$

where

$$\mathbf{J}_{12}(t) = x_2\sum_{k=1}^{N_1}\mathbf{v}_k(t) - x_1\sum_{l=1}^{N_2}\mathbf{v}_1(t) \tag{6}$$

and N is the total number of particles, $x_1 = N_1/N$ and $x_2 = N_2/N$ are the mole fractions of species 1 and 2, where N_1 and N_2 are the number of particles of type 1 and 2, respectively. m_1 and m_2 are the masses of the two different types of particles, $\mathbf{r}_k(t)$ is the position and $\mathbf{v}_k(t)$ is the velocity of particle k of species 1 at time t while $\mathbf{v}_l(t)$ is the velocity of particle l of species 2. Q is a thermodynamic factor which is defined by

$$Q = [1 + x_1x_2\rho(\Gamma_{11} + \Gamma_{22} - 2\Gamma_{12})]^{-1} \tag{7}$$

with

$$\Gamma_{ij} = 4\pi\int_0^\infty r^2[g_{ij}(r) - 1]dr. \tag{8}$$

In the above equations ρ is the number density and g_{ij} is the radial distribution function for the pair of species ij. For thermodynamically ideal binary mixtures (i.e., an ideal solution) it follows that $Q=1$ and from Eq. (7) that $\Gamma_{11} + \Gamma_{22} - 2\Gamma_{12} = 0$. When $Q=1$ the mutual diffusion coefficient is equivalent to the Maxwell-Stefan diffusion coefficient.

Reorganizing Eq. (5), the mutual diffusion coefficient can be written as a linear combination of the self-diffusion coefficients D_{11} and D_{22} of the mixture and the distinct diffusion coefficient[18] D_{12}^d,

$$D_{12} = Q(x_2 D_{11} + x_1 D_{22} + x_1 x_2 D_{12}^d). \tag{9}$$

The distinct diffusion coefficient D_{12}^d corresponds to the dynamical cross velocity correlation function $C_{12}^d(t)$ and is given by

$$D_{12}^d = \int_0^\infty C_{12}^d(t) dt, \tag{10}$$

where $C_{12}^d(t)$ can be written as the sum of three correlation functions:

$$C_{12}^d(t) = \frac{1}{3Nx_1^2} \left\langle \sum_{k=1}^{N_1} \sum_{k' \neq k}^{N_1} \mathbf{v}_k(t) \cdot \mathbf{v}_{k'}(0) \right\rangle$$
$$+ \frac{1}{3Nx_2^2} \left\langle \sum_{l=1}^{N_2} \sum_{l' \neq l}^{N_2} \mathbf{v}_l(t) \cdot \mathbf{v}_{l'}(0) \right\rangle$$
$$- \frac{2}{3Nx_1 x_2} \left\langle \sum_{k=1}^{N_1} \sum_{l=1}^{N_2} \mathbf{v}_k(t) \cdot \mathbf{v}_l(0) \right\rangle. \tag{11}$$

In the above equation, the first two terms are the cross-correlation functions of the velocities of particles of species 1 and 2, respectively, while the third term is the cross-correlation function of the velocities between the two different types of particles. The deviation of distinct diffusion from zero implies that correlations between the distinct particles of the system depend on microscopic details. For a thermodynamically (where $Q=1$) and dynamically (where $D_{12}^d=0$) ideal mixture Eq. (9) reduces to

$$D_{12} = x_2 D_{11} + x_1 D_{22}, \tag{12}$$

which suggests that all velocity cross correlations do not contribute to the mutual diffusion coefficient. This model is the so-called Darken model and has found applications in nonelectrolyte solutions.[19] It is worth noting that the self-diffusion coefficients in above equations are those of the mixture and are composition dependent. As suggested by Eq. (7), for dilute solutions studied in this paper, the thermodynamic factor will differ very little from unity.

III. INTERMOLECULAR POTENTIALS AND SIMULATION DETAILS

A. Intermolecular potentials

The SPC/E model of Berendsen *et al.*[10] has been used to represent water. In this model the water molecule is assumed to be rigid. The model consists of partial charges on all the three atom sites and a Lennard-Jones potential on the oxygen site. The potential parameters and geometry parameters are given in Tables I and II, respectively.

Nitric oxide is modeled as a two-site rigid body with partial charges and a Lennard-Jones potential on both sites. The experimental dipole moment (μ), together with the equilibrium bond length, was used to determine the atomic partial charges for nitric oxide (NO). The Lennard-Jones parameters were optimized based on molecular dynamics simulations of the liquid. The equilibrium density (ρ) and the heat of vaporization[13] were used to determine the parameters and N-V-T simulations were carried out during the param-

TABLE I. Potential parameters used for the water/NO interactions.

Site	ε_0 (kJ/mol)	σ_0 (Å)	$q(e)$
H(H$_2$O)	$\cdots$	$\cdots$	0.4238
O(H$_2$O)	0.6502	3.166	-0.8476
N (NO)	0.661	3.014	0.0288
O (NO)	0.806	2.875	-0.0288

eterization stage to optimize the Lennard-Jones (LJ) parameters so that the heat of vaporization obtained from the simulation agrees with the experimental value. To compute the LJ potential between nitrogen and oxygen atoms, Lorentz-Berthelot (LB) combining rules are used, i.e., $\varepsilon_{ij} = \sqrt{\varepsilon_{ii}\varepsilon_{jj}}$ and $\sigma_{ij} = (\sigma_{ii} + \sigma_{jj})/2$. The density and heat of vaporization of NO liquid at the boiling point (T_b) are 1.269 g/cm^3 and 13.85 kJ/mol, respectively. For nitric oxide, four parameters for two atom types need to be parameterized. We used the method adapted by Yang *et al.*,[13] where two scaling factors (for ε_0 and σ_0, respectively) were used to optimize the parameters for each of the atom types. The initially estimated Lennard-Jones parameters of NO used for parameterization were also taken from Yang *et al.*[13] The finally obtained parameters for NO are listed in Table I. With these parameters we obtained a value of 13.71 kJ/mol for the heat of vaporization from our simulations. We also obtained a value of $(1.46 \pm 0.03) \times 10^{-9}$ m^2/s for the self-diffusion coefficient of liquid NO. However, we could not find corresponding experimental data for comparison purposes.

B. Simulation details

The MD simulations have been conducted in the N-V-T ensemble with a total of 500 molecules. For binary mixtures the number of NO molecules varies from 2 to 12. We ran the simulations at two temperatures, 25 and 37 °C. These temperatures correspond to ambient and *in vivo* conditions, respectively. Six different concentrations were examined at each temperature. This allowed us to extrapolate the results to the infinite dilute solution. The densities of mixtures are calculated from the water and liquid NO densities for each concentration. The water densities are 0.9973 and 0.9942 g/ml, respectively, for temperatures 25 and 37 °C and the density of liquid NO is 1.269 g/ml. As the NO concentration changes, the dimension of the unit cell changes from 24.683 to 24.809 Å. The equations of motion were integrated by the leap-frog method with a 2 fs time step. The molecular temperature was controlled with velocity rescaling and was conducted every 20 fs. The SHAKE (Refs. 20,21) constraint algorithm was used to keep both the water and nitric oxide molecules rigid. Independent simulations using a Gear predictor-corrector integrator, combined with a

TABLE II. Geometry parameters for water and NO molecules.

b_0^{OH} (Å)	θ_0^{HOH} (°)	b_0^{NO} (Å)
1.0	109.47	1.15

Gaussian thermostat, were conducted on binary mixtures of 12 NO and 488 water molecules. These simulations produced the same results within statistical uncertainties as that obtained by using the simulation methods described above. Long-range electrostatic interactions were evaluated using an Ewald sum method with the convergence parameter α $=5.0/L$ (Ref. 22) and summation over $5 \times 5 \times 5$ reciprocal-lattice vectors, where L is the side length of the simulation box. A cutoff of $0.5L$ was used for the evaluation of the Lennard-Jones and real-space electrostatic terms. Periodic boundary conditions were used to construct an infinite lattice that replicates the cubic simulation box through space.

Molecules of each mixture were first placed at face-centered-cubic (fcc) lattice sites and then a simulation was run for 100 000 steps to melt the lattice and generate initial configurations for further MD runs. All the MD runs were performed for 100 ps simulation times for equilibrium configurations before statistical averages were taken. For the calculation of the water diffusion coefficient we obtained reproducible results for 200-ps production runs (with variation smaller than 1.4%), averaging over molecules in the unit cell and all time origins. The interval between two time origins was 0.04 ps. To calculate the mean-squared displacements, in addition to the atom positions to which standard periodic boundary conditions are applied, another copy of true atom positions (i.e., without applied periodic boundary conditions) was also maintained in our program. For the calculation of the nitric oxide diffusion coefficient in water, production runs of up to 1 ns were performed. We typically conducted six to ten runs at each individual concentration for improved statistics. For the multiple runs at each individual concentration, the simulations were started from the same initial coordinates. The initial velocities for different runs were randomly generated with different seeds so that all initial velocity distributions follow a Maxwell-Boltzmann distribution. We found that different seeds had little impact on the simulation results of the majority of water molecules but do have an impact on the NO molecules in the mixtures. Multiple runs are necessary for better statistics for the mixtures examined in this paper.

IV. RESULTS AND DISCUSSIONS

A. Comparison between self- and mutual diffusion coefficients

As indicated by Eq. (9), the deviation between the self-diffusion and mutual diffusion coefficients happens in the case of increased solute concentration and non-negligible distinct diffusion coefficient. To begin, we computed the velocity auto- and cross-correlation functions for the NO–water mixture of 12 nitric oxide and 488 water molecules, which is the highest solute concentration examined in this study. A typical set of VACF and relative velocity correlation function (RVCF) data are shown in Fig. 1. It is seen that the VACF data of the self-diffusion quickly decay to zero within 2 ps. There are very slight oscillations for NO molecules (dotted line) due to the small sampling space for statistics. However, RVCF data show greater amplitude and long-time fluctuations. RVCFs are collective quantities and therefore show
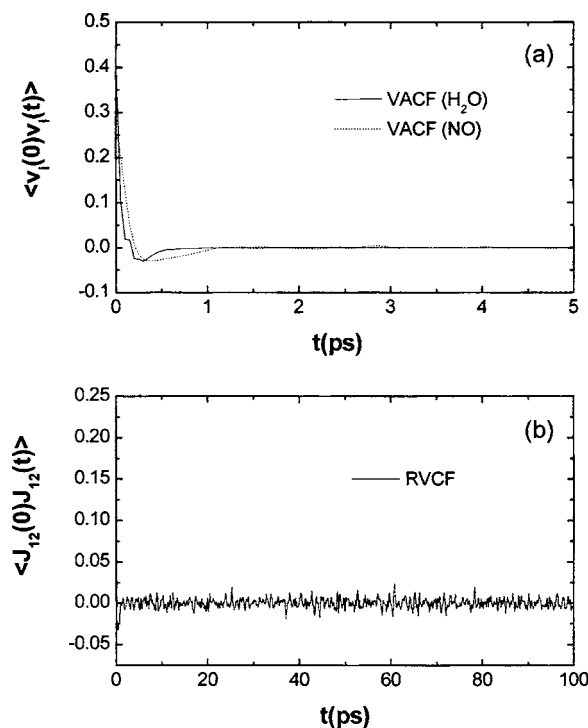

FIG. 1. (a) Velocity autocorrelation function for water and NO at 310 K. (b) Relative velocity correlation function for the binary mixture.

larger fluctuations in comparison to the VACFs, which are averaged over all particles of each species. The accuracy of the mutual and distinct diffusion coefficients, which can be obtained from the RVCF, is therefore lower. To obtain more accurate estimates eight runs were performed, and the mutual diffusion coefficient D_{12} calculated from the integration of RVCF data of individual runs (doted lines) and D_{12} averaged over eight runs (solid lines) are shown in Fig. 2. It can be seen that there are significant variations in the mutual diffusion coefficient D_{12} with time for each individual run. Even after averaging over eight runs there are still slight variations in the mean of D_{12}. Comparing to the mutual diffusion coefficient, the self-diffusion coefficients obtained from integration of VACF data are much better.

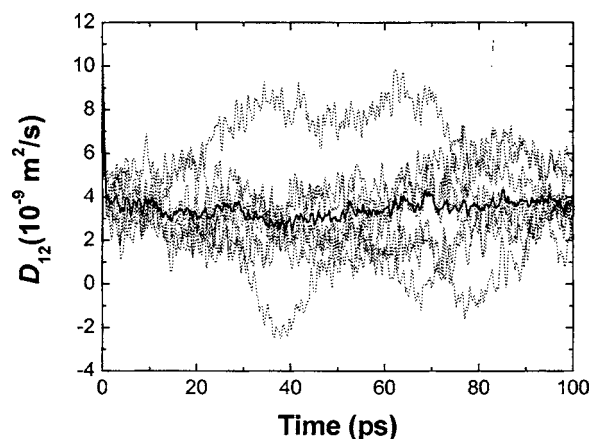To assess the error associated with the computed values

FIG. 2. Mutual diffusion D_{12} from individual runs (dotted lines) and D_{12} (solid line) averaged over eight simulation runs at 310 K for a mixture of 12 NO and 488 water molecules.

TABLE III. The self-diffusion, mutual diffusion, and distinct diffusion coefficients (in units of 10^{-9} m^2/s) and their variations for a mixture of 12 nitric oxide and 488 water molecules at 310 K.

D_{11}	D_{22}	D_{12}	D_{12}^d	D_{11}[a]	D_{22}[a]	D_{12}[a]
3.40(0.14)	2.98(0.04)	3.46(0.51)	2.8(21.6)	3.45(0.21)	2.95(0.03)	3.58(0.40)

[a]Diffusion coefficient computed using the MSD method; others computed using the Green-Kubo relations.

of diffusion coefficients, we computed their means and the standard deviation of the means. The mean values of diffusivities for each of the eight runs were computed by averaging over all time steps in either the Green-Kubo or MSD methods, and then the mean value of D_{12} is obtained by averaging over the eight runs. Table III lists the mean diffusion coefficients averaged from eight runs together with the standard errors of the means as included in the brackets. The values include the results computed from both Green-Kubo relations and the mean-square displacement method with Eqs. (1)–(5) and (10), respectively. D_{11} and D_{22} are the self-diffusivities of nitric oxide and water in the mixture, respectively, D_{12} the mutual diffusion coefficient, and D_{12}^d the distinct diffusion coefficient. As shown in Table III, the self-diffusion coefficients, as calculated from the Green-Kubo relations, agree well with those obtained from the mean-square displacement. The value of D_{12}^d given in Table III indicates that the distinct diffusion coefficient is of the same magnitude as the self-diffusion coefficients of water and nitric oxide. However, the error in the distinct diffusion coefficient is very large. The distinct diffusion is an important indicator of the associative tendency of a mixture. A positive value suggests that the mixture is demixing or dissociative in nature thereby enhancing the mutual diffusivity. As the solute concentration is low in our study, the contribution from both the distinct diffusivity and the self-diffusivity of the solvent to the mutual diffusivity of our mixture system is actually low and the mutual diffusion coefficient is very close to the self-diffusion coefficient of the solute in the mixture. As the solute concentration further decreases, the contribution of the distinct diffusivity and the self-diffusivity of the solvent to the mutual diffusivity should diminish to become negligible. However, as indicated in Table III, the variations of distinct and mutual diffusivities are quite large. The large error in the distinct diffusion coefficient means that the results on the mutual diffusion coefficients are less accurate for mixtures of low solute concentration. Therefore, in what follows, we mainly focus on the self-diffusion results of mixtures.

B. NO diffusion in water at different solute concentrations

The self-diffusion coefficients of NO and water in mixtures of various solute concentrations were measured by the mean-square displacement method at two different temperatures. With a mixture of eight NO in 492 water molecules, typical mean-square displacements for each individual nitric oxide molecule, calculated from a 1000-ps run, are plotted in Fig. 3 as dashed lines while the mean-square displacement of all eight NO molecules is shown as the solid line in the same figure. We observed a significant scatter in the individual

mean-square displacements, although the average mean-square displacements over the eight NO molecules show a good linearity. To improve the statistical accuracy of our results, typically six to ten long runs were performed at each individual concentration. The diffusion coefficients were first obtained by averaging all the individual mean-square displacements and then averaging all the runs. Figure 4 shows the self-diffusion coefficients for NO and water molecules in mixtures as functions of solute concentration. It can be seen that both solute and solvent diffusion coefficients approach a constant value, within statistical errors, when the solute concentration is below 0.015, suggesting that the infinite dilution limit diffusion coefficient is reached below this concentration. For pure water we obtained a value of (2.54 ± 0.03) $\times 10^{-9}$ and $(3.08 \pm 0.04) \times 10^{-9}$ m^2/s for temperatures of 298 and 310 K, respectively. These results agree well with the results from other simulation studies on SPC/E water, such as a value of 2.7×10^{-9} m^2/s at a temperature of 301 K.[11] For nitric oxide our results agree satisfactorily with the observed experimental diffusion coefficients of NO in water. At 298 K, we obtained a value of $(3.07 \pm 0.47) \times 10^{-9}$ m^2/s compared to the experimental value[5,6] in the range of $(2.07 - 4.5)$ m^2/s at 293 K, and a value of $(3.59 \pm 0.32) \times 10^{-9}$ m^2/s compared to the experimental value[4,6] in the range of $(3.3 - 5.1) \times 10^{-9}$ m^2/s for a temperature of 310 K. The nearly neutrally charged NO molecule is hydrophobic with respect to aqueous solutions, which facilitates its mobility in the mixture system, and hence gives a higher diffusion coefficient than water in the mixtures.

C. Structure

For liquid water at 298 K the intermolecular partial pair-correlation functions or the radial distribution functions,[20] $g_{OO}(r)$, $g_{OH}(r)$, and $g_{HH}(r)$, have been extensively deter-
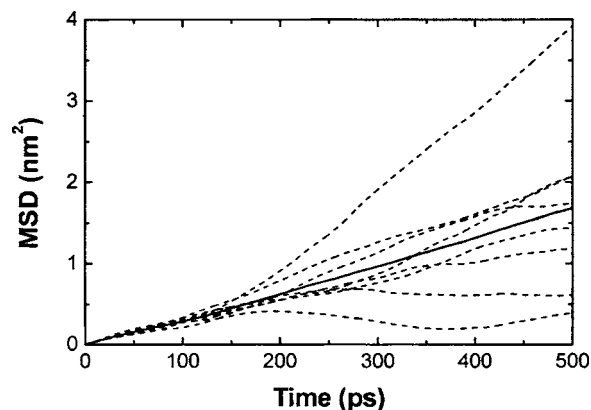

FIG. 3. Mean-squared displacements of nitric oxide molecules in water at 310 K. The dashed lines are for each of the eight individual NO molecules and the solid line represents the average over all eight NO molecules.

FIG. 5. Plot of the radial distribution functions for water with and without nitric oxide. Solid line: pure water; dashed line: mixture of five NO and 495 water molecules; dotted line: mixture of 12 NO and 488 water molecules.
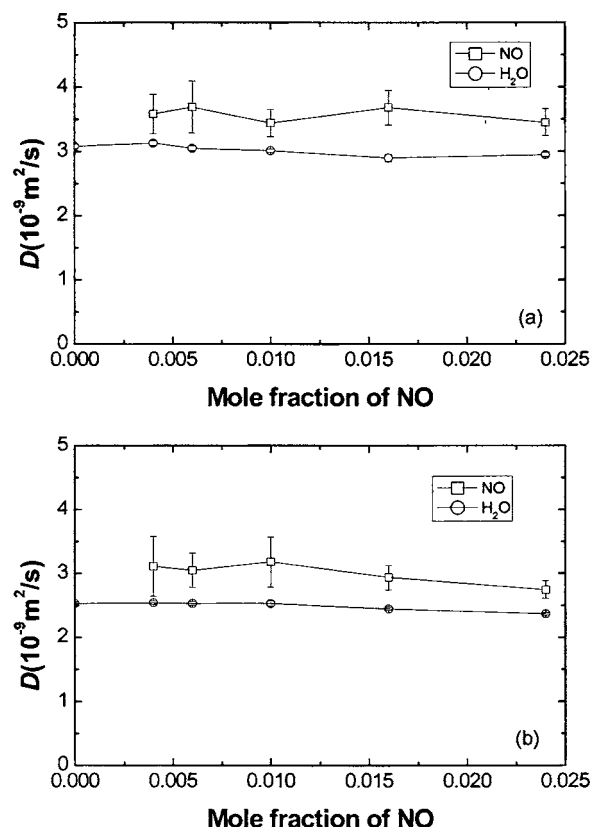
FIG. 4. Self-diffusion coefficients of NO and water at various solute mole fractions. (a) 310 K, (b) 298 K.

mined by simulations and experiments, such as from neutron-diffraction data and x-ray diffraction methods. However, to the best of our knowledge, there is neither experimental data nor simulation results for the structural properties of binary mixtures of water and nitric oxide.

The radial distribution functions for pure water and water mixture systems are shown in Fig. 5. Water has the strong tendency to form linear H bonds. $g_{OH}(r)$ shows the first peak at around 0.179 nm, which corresponds to the average length of the hydrogen bonds between water molecules. The experimental H bond[23] between two water molecules is 0.185 nm, which is considerably less than the intermolecular distance expected from the van der Waals radii for O and H, while greater than the O–H bond length of 0.1 nm. It can be seen from Fig. 5 that the resulting partial pair-correlation functions, $g_{OH}(r)$, $g_{OO}(r)$, and $g_{HH}(r)$, are barely distinguishable from the pure water system to the two water and nitric oxide mixtures of different concentrations. This suggests that the structures obtained from pure water and mixtures are almost equivalent. Thus, the existence of low-concentration nitric oxide in water has little impact on the structure and the tendency to form H bonds between water molecules.

Figure 6 shows the radial distribution functions between the solute and solvent molecules, including $g_{OO'}(r)$, $g_{O'H}(r)$, $g_{NH}(r)$, and $g_{ON}(r)$, where O and O′ denote the oxygen on water and nitric oxide molecules, respectively. These intermolecular partial pair-correlation functions may be used to gain some insight into the interaction and possible complex structure between water and nitric oxide molecules. Comparing to the water $g_{OH}(r)$, as shown in Fig. 5, the first peaks of
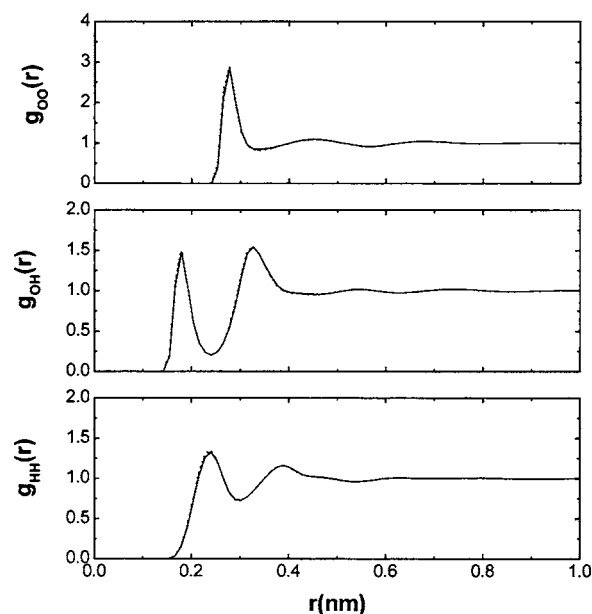
$g_{O'H}(r)$ and $g_{NH}(r)$ are broad and flat and are observed at 0.38 and 0.35 nm with peak heights of 1.23 and 1.26, respectively. There are no peaks at the position around 0.18 nm. These results indicate that there is no tendency to form H bonds between the water hydrogen and either the nitrogen or the oxygen atom of the nitric oxide molecule at the temperatures and densities studied here. The first peaks of the radial distribution functions [$g_{OO'}(r)$ and $g_{ON}(r)$] between the water oxygen with the nitrogen and the oxygen atom on the nitric
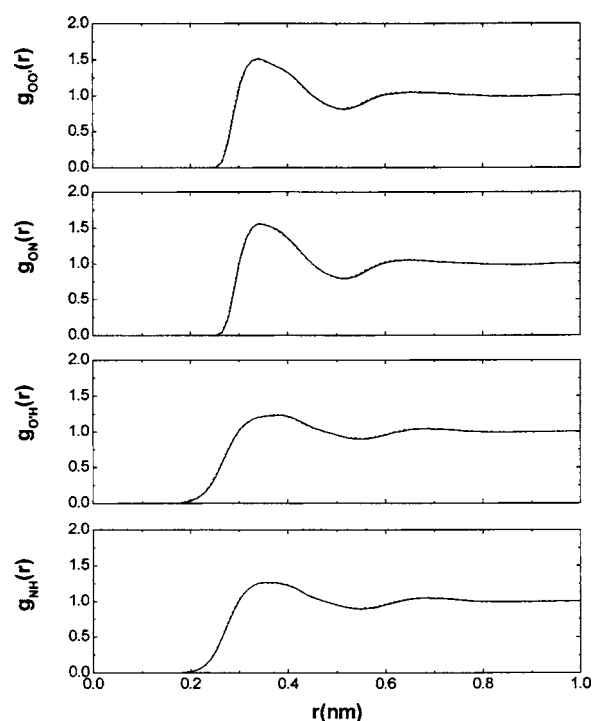

FIG. 6. Plot of the radial distribution functions between the solute and solvent. Solid line: mixture of five NO and 495 water molecules; dashed line: mixture of 12 NO and 488 water molecules.

oxide molecule are observed at 0.34 nm, slightly larger than the intermolecular distance expected from the van der Waals radii between them. The heights of these two peaks are about 1.52 and 1.56, respectively, which are much lower than the value of 2.85 for the peak height of $g_{OO}(r)$ between water oxygen atoms. This result suggests that the interaction between the water molecules is stronger than that between two different kinds of molecules. An *ab initio* study[24] had examined four possible interactions and complexes between individual NO and water molecules. The four complexes are possibly formed through O′–H, N–H, O–O′, and O–N bonds. The calculated bond distance for the two H-bonded complexes is about 0.266 nm, 0.274 nm for the O–N bond, and 0.309 nm for the O–O′ bond. However, the *ab initio* calculation indicates that all four complexes are higher in energy with respect to the isolated molecules at 298 K. Therefore, at 298 K the free molecules are more stable than the four possible complexes. Our results support this point of view.

V. CONCLUSIONS

We have proposed a model for the interaction of molecular nitric oxide with water and conducted the first molecular dynamics simulations of water-nitric oxide mixtures at various NO concentrations and temperatures to investigate the diffusion coefficients and the structure of the mixtures. Using our potential model, the self-diffusion coefficients determined from molecular dynamics simulations are in good agreement with experimental data. We also calculated the mutual and distinct diffusion coefficients for a mixture of 12 NO and 488 water molecules. The computed mutual diffusion coefficient is very close to the self-diffusion coefficient of the solute for the dilute solution. A positive value of the distinct diffusion coefficient determined from the dynamic cross velocity correlation functions would indicate a demixing behavior of the mixture. However, significant variations in the mutual and distinct diffusion coefficients are observed with respect to the self-diffusion coefficients. This limited accuracy restricts a detailed and reliable check of the collective dynamical properties for dilute binary solutions.

It was found that the radial distribution functions of the solvent were insensitive to the presence of nitric oxide in the binary systems for our low-concentration systems. This suggests that at low concentrations the existence of nitric oxide in water has little impact on the water structure and the tendency to form H bonds between water molecules. The first peaks of the radial distribution functions between the solute and solvent are broad and flat and positioned at longer distances than the bond distances of those possible NO–H_2O complexes. This suggests that there is little tendency to form H bonds between the water hydrogen and either the nitrogen or the oxygen atom on the nitric oxide in our liquid mixtures. At the given temperatures and concentrations, nitric oxide molecules are free molecules in the mixtures and do not form complexes with water molecules.

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