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Ab initio molecular dynamics simulation of liquid water and water–vapor interface

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The results of ab initio molecular dynamics simulations of liquid water and liquid water–vapor interface using the Perdew-Wang 91 (PW91) exchange-correlation functional are presented. The structural and transport properties of liquid water are comparable to the previous results using Becke-Lee-Yang-Parr (BLYP) functional and experimental data. The shape and the position of the first peak in the oxygen–oxygen radial distribution function is in good agreement with the most recent neutron diffraction data. The ab initio molecular dynamics simulation of liquid water–vapor interface, which is the first of its kind, suggests a preferred orientation of the surface water dipole towards the bulk region. © 2001 American Institute of Physics. [DOI: 10.1063/1.1413515]

I. INTRODUCTION

The structure and dynamics of liquid water have been the subject of many theoretical and experimental investigations.1–13 Still there is a continued interest in the interpretation of the experimental results and in using various simulation methods at different levels of theory. Most of the empirical potentials used in “classical” molecular dynamics (MD) simulations are essentially optimized to reproduce the experimentally observed bulk properties. However, the interpretation of the experimental results (see Ref. 2 and references therein) may lead to quite distinct pair radial distribution functions (RDF).

An alternative to the MD simulations using classical interaction potentials are ab initio molecular dynamics methods, which do not require any input from experiments or previous theoretical calculations. Recent publications of ab initio MD simulations have shown a good prediction of the structural and dynamical properties of bulk liquid water (Refs. 9–13 and references therein). One of the main conclusions9 is that the BLYP exchange-correlation (XC) functional14,15 gives the best description for bulk water. In another work13 the results for HCTH/120 exchange-correlation functional were also reported to well estimate the experimental observations. The comparison between the density functionals reported by Sprik et al.9 and Boese et al.13 does not include the PW91 density functional.16 Furthermore, recent work of Hamman17 showed that both PW91 and PBE18 density functionals give a good agreement with experiment for the sublimation energy and the volume of hexagonal ice Ih. The PW91 exchange-correlation functional is commonly used for modeling adsorption processes on transition metal surfaces. Since our interest is in the application of density functional theory methods for description of metal–liquid water interfaces, the purpose of the present work is to assess the accuracy of the PW91 functional for simulation of liquid water.

In this work density functional theory (DFT) simulations of single water molecule, water dimer and bulk water are presented. The water monomer and dimer have been studied by means of geometry optimizations, whereas molecular dynamics simulations have been performed to model liquid water at ambient conditions.

We present also the first results of a self-consistent ab initio molecular dynamics simulation of a thin water layer as a model for liquid water–vapor interface. The structure of liquid water–vapor interface has been studied quite intensively using experimental19 or theoretical20–26 methods. These studies, however, lead to different conclusions regarding the orientational distributions of the surface water dipole moments. In this work we study the orientational distribution at the water/vapor interface using ab initio MD methods.

II. COMPUTATIONAL METHOD

The ab initio MD simulations in this paper have been carried out using Vienna Ab Initio Simulation Package (VASP) which is a DFT-based code for systems with periodic boundary conditions. The forces acting on the atomic nuclei are computed from a self-consistent solution of the Kohn-Sham equations.29 The interactions between the ions and the electrons are described using Vanderbilt-type ultrasoft pseudopotentials provided by Kresse and Hafner.31 The code uses a plane-wave (PW) basis set and for the exchange-correlation part of the energy functional, we used the generalized gradient approximation proposed by Perdew and Wang32 (PW91). An essential difference of the molecular dynamics method implemented in VASP with the Car-Parrinello MD32 is that the electronic wave functions are not included in the equations of motion of the system. The electronic ground state is computed self-consistently at each MD step.

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The initial configuration for the ab initio simulation was taken from an equilibrated run performed with the MD package MOLDY. 33

A number of input parameters of the VASP program, such as the energy cutoff for the PW basis set, the size of periodic unit cell, the number of k-points sampled in the Brillouin zone, are of importance for the accuracy of the calculation. In the next section we will first present several tests of the accuracy using simple systems containing one water molecule and a water dimer in a cubic box. Sections III B. and III C. concern ab initio MD simulations of bulk liquid water and a thin water layer which are discussed in relation to previous MD results. For comparison, additional classical MD simulations were performed for systems containing 32, 64 and 128 water molecules using the SPC/E potential. 34

III. RESULTS AND DISCUSSIONS

A. Water molecule and dimer in a cubic box

Water Molecule in a Cubic Box: Computational Parameters. To estimate the proper computational setup, we performed a series of calculations concerning the dependence of the total energy and the optimized geometry of a water molecule on the cell dimensions, the number of k-points, and the quality of the plane-wave basis set. First the unit cell size was varied in the range of 8.0 to 15.5 Å, while keeping the energy cutoff of the PW basis set constant at 500 eV. Only the Γ-point was used for the integration of the band energies. In this range of box sizes there was only a small (\(<0.01\) eV) increase in the computed total energy. The final geometries of the molecule were practically the same — we found differences of less than 0.002 Å and 0.3° for the O–H bond length and H–O–H bond angle, respectively. The convergence with respect to the number of k-points in the Brillouin zone was tested using the same cutoff and a unit cell of side length \(L = 9.861\) Å. (This unit cell size was also used for the simulation of bulk liquid water and will be referred to as the MD unit cell.) Switching from the Γ-point—only to a \(3\times3\times3\) Monkhorst-Pack-type mesh 35 (corresponding to 8 irreducible k-points) — resulted in a difference in the computed total energy of less than \(1\times10^{-5}\) eV. The basis set dependence was evaluated by varying the energy cutoff \(E_{\text{cut}}\) from 300 to 600 eV. The total energy converged to within 0.01 eV for \(E_{\text{cut}}\) greater than 400 eV with no significant changes in the optimized geometry of the molecule for cutoffs above 325 eV.

To conclude, the MD unit cell size, a Γ-point-only sampling of the Brillouin zone, and a cutoff of 400 eV are sufficient for an accurate description of a water molecule. The estimated O–H bond length of 0.973 Å and H–O–H angle of 104° are the same as the results obtained 6 using the BLYP functional and are in a reasonable agreement with the experimental values of 0.958 Å and 104°, respectively. 36 Except for the cutoff of the plane-wave basis set, which was varied, the simulations of the water dimer were therefore performed using the above-mentioned settings.

Water Dimer in a Cubic Box. To obtain the water dimer equilibrium geometry and dissociation energy and their dependence on the computational parameters, two series of calculations were performed using the “accurate” cutoff of 400 eV and a reduced cutoff of 325 eV. The configuration under study corresponds to the trans-configuration with a plane of symmetry, which has been determined experimentally. 37 The dissociation energy of the dimer (Table I) was computed as the difference in the total energy of the dimer and the sum of the total energies of two single water molecules in the same unit cell size using the same cutoff. The energies were corrected for dipole–dipole interactions between periodic images in the neighboring cells as implemented in VASP. The O–O distance (Table I) in the water dimer is shifted to a smaller value compared to experiment 37 or the BLYP result, 9 but compares well to high-level ab initio coupled-cluster results. 38

From the presented results for the water monomer and dimer we conclude that, already for a cutoff of 325 eV, the predicted equilibrium geometries and dissociation energy are in a reasonable agreement with the experimental and other theoretical results. The simulation of bulk liquid water was nevertheless performed using the “accurate” cutoff of 400 eV. The molecular dynamics of the water slab was performed using a reduced cutoff of 325 eV, to improve the computational speed.

B. Molecular dynamics simulation of liquid water

An ab initio MD simulation of liquid water was carried out using a model of 32 molecules placed in a cubic box of size 9.861 Å, corresponding to the density \(\rho = 0.998\) g cm\(^{-3}\) at ambient conditions. All atoms, including the hydrogens, were treated classically with no quantum effects taken into account. The Verlet integration scheme was used with a time step of 0.5 fs and no constraints to the molecular geometries were applied. The starting configuration was obtained from an equilibrated “classical” simulation performed with MOLDY. The system was equilibrated for 1 ps, after which statistical data were collected for 3.5 ps. The average temperature during the microcanonical NVE ensemble simulation was 307 K.

Enthalpy of Vaporization. A thermodynamic property of a molecular liquid that is relatively easy to estimate from our simulations is the enthalpy of vaporization. The enthalpy \(H\) of a thermodynamic system is given by the expression \(H = U + pV\), where \(U\) is the internal energy of the system and \(p\) and \(V\) are the pressure and the volume, respectively. The evaluation of \(U\) from a MD run is straightforward by averaging the total energy of the system. The internal energy of the model liquid state (32 molecules in a box) was calculated in this way. Considering a system of classical particles, the

<table>
<thead>
<tr>
<th>(E_{\text{cut}}) (eV)</th>
<th>(r(O-O)/)Å</th>
<th>(E_{\text{dim}}/)kJ mol(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>2.88</td>
<td>23.5</td>
</tr>
<tr>
<td>400</td>
<td>2.89</td>
<td>23.9</td>
</tr>
<tr>
<td>CCSD(T)</td>
<td>2.91</td>
<td>21.0</td>
</tr>
<tr>
<td>BLYP</td>
<td>2.95</td>
<td>18</td>
</tr>
<tr>
<td>Experiment</td>
<td>2.98</td>
<td>22</td>
</tr>
</tbody>
</table>

TABLE I. Calculated O–O distance and binding energy of water dimer compared to the results using CCSD(T) 39 and BLYP 9 and experiment. 37,41
internal energy $U$ can be expressed as a sum of the potential energy of the optimized (equilibrium) geometry and the averaged kinetic energy of the thermal movement $E_k$. For the purpose of evaluating the enthalpy of vaporization, the gas phase water is considered a gas of noninteracting molecules with $N=9$ degrees of freedom (including translations). Thus, the total average kinetic energy of a molecule at a temperature $T$ is $E_k=NkT/2$ and the gas occupies a molar volume $V_m$ as an ideal gas. Following this scheme and taking the pressure $p=1$ atm, the computed enthalpy of vaporization of liquid water is 39 kJ·mol$^{-1}$ (307 K) in satisfactory agreement with the experimental value of 43.9 kJ·mol$^{-1}$ (298 K).

Radial Distribution Functions. We have evaluated the radial distribution functions (RDF) of the three atom pairs, i.e., O–O, O–H, and H–H. The comparison with the results from neutron diffraction data is shown on Fig. 1. The determination of the O–O pair distribution function based on neutron diffraction has been subject to a number of revisions due to experimental uncertainties.

Most noticeable is the fact that, the position and the shape of the first peak of the O–O RDF at 2.7Å are in good agreement with the most recent experimental result giving a peak at around 2.75 Å. The pair radial distribution functions using BLYP and HCTH/120 density functionals were found to compare very well with the older experimental data, which are also shown on Fig. 1. It should be noted that the molecular structure in our simulation is more ordered compared to the experiment, resulting in a lower value of the first minimum in the RDF. The computed RDF is in fact quite sensitive to the size of the unit cell. In a recent work Silvestrelli et al. reported a significant improvement in the RDF’s compared to experiment with the increase of the size of the system from 32 to 64 deuterated water molecules. The shape of the O–H distribution function is also influenced by quantum effects of the hydrogen atoms, which are not taken into account in our model (for a quantum mechanical study and the extent of quantum effects on the RDF’s, see for example Ref. 7).

In conclusion, accounting for the limitations of the model, the radial distribution functions for the PW91 density functional compare well with the experimental neutron diffraction data, and are not notably inferior to those obtained with the BLYP functional.

Self-Diffusion Coefficient. An important dynamic characteristic of a liquid is the self-diffusion coefficient $D$. As the oxygen atoms are much heavier than the hydrogen atoms, we considered the movement of the oxygen atoms to be representative for the movement of the center-of-mass of the molecules. The self-diffusion coefficient can be computed using the mean-square displacement (MSD) or the velocity autocorrelation function.

The value for the self-diffusion coefficient is $0.8 \times 10^{-9}$ m$^2$·s$^{-1}$ using the MSD of the oxygen atoms (Fig. 2, $N=3$ directional degrees of freedom) and $1.2 \times 10^{-9}$ m$^2$·s$^{-1}$ from the integration of the oxygen velocity autocorrelation function. The difference in the results for $D$, using the two definitions, is due to the relatively short MD simulation time. It is, however, more important to notice that the value of $D$ and the shape of the MSD function implies a liquid-like behavior of a bulk water. Compared with the experimental result of $2.30 \times 10^{-9}$ m$^2$·s$^{-1}$, the computed value confirms the reduced mobility of the molecules, which is related to the small size of the unit cell. The result for BLYP for a system of the same size, but using 32 deuterated water molecules, was reported as $1.0 \times 10^{-9}$ m$^2$·s$^{-1}$ and $1.3 \times 10^{-9}$ m$^2$·s$^{-1}$.

The influence of the size of the unit cell was demonstrated by Silvestrelli et al., who reported an increase of $D$ by a factor of around 2.5 for a system of 64 deuterated water molecules compared to 32. This result also agrees with the classical MD simulations that we carried out for models containing 32, 64, and 128 water molecules. The computed self–diffusion coefficients are 1.8, 2.7 and $2.7 \times 10^{-9}$ m$^2$·s$^{-1}$, respectively.

Assuming transferability of the results concerning the size of the system, the estimated value for PW91 is not only

FIG. 1. (a) O–O, (b) O–H and (c) H–H radial distribution functions: the computed RDF’s are given by solid lines; dotted and dashed lines represent Soper’s experimental data from 2000 and 1997, respectively.
in the region 400–1000 cm$^{-2}$.

The broad peak at 2900–3800 cm$^{-1}$ is attributed to the intramolecular stretching; the bending vibrations are recognized at around 1600 cm$^{-1}$. These results agree well with the experimental infrared and Raman spectral data. The vibrational properties of the system were examined in terms of the vibrational power spectrum, which is defined as the Fourier transformation of the velocity autocorrelation function. The power spectrum (Fig. 3) was computed using the hydrogen velocity autocorrelation. The broad peak at 2900–3800 cm$^{-1}$ corresponds to the intramolecular stretching; the bending vibrations are recognized at around 1600 cm$^{-1}$. The broad peak in the region 400–1000 cm$^{-1}$ represents intermolecular modes. These results agree well with the experimental infrared and Raman spectral data.

C. Molecular dynamics simulation of water–vapor interface

Our model for water–vapor interface is based on a system containing a thin water slab. The model was constructed by taking a configuration from the equilibrated $ab$ initio simulation of bulk water and placing it in a rectangular box obtained by doubling the original size in the $z$-direction. The resulting simulation unit cell is $9.861 \times 9.861 \times 19.723$ Å and contains 32 water molecules in a slab of a thickness 9.861 Å and a vacuum region of the same size. For this simulation we used the $ab$ initio functional. This result therefore appears to point to a mobility of the water molecules, which is too high compared to experiment.

Vibrational Power Spectrum. We also examined the vibrational properties of the system in terms of the vibrational power spectrum, which is defined as the Fourier transformation of the velocity autocorrelation function. The power spectrum (Fig. 3) was computed using the hydrogen velocity autocorrelation. The broad peak at 2900–3800 cm$^{-1}$ corresponds to the intramolecular stretching; the bending vibrations are recognized at around 1600 cm$^{-1}$. The broad peak in the region 400–1000 cm$^{-1}$ represents intermolecular modes. These results agree well with the experimental infrared and Raman spectral data.

Mean-Square Displacement and Self-Diffusion. As can be seen from Fig. 2, which shows the computed $xy$ ($N=2$) and $z$ ($N=1$) components of the MSD of the O atoms, only "cage movement" effects are observed, resulting in the small slope of the curve at longer times. This picture contradicts the findings in earlier (classical) MD simulations, where an increase of the self-diffusion coefficient in the surface

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define an angle variable \( u \) should still be valid.

Qualitative conclusions regarding the dipole orientation obtained from a 4 ps simulation with 32 water molecules, the suggests that in spite of the relatively poor density profile maximum of the angular distribution of around 10°. This result,\(^{21-23,25}\), although two studies reported a water dipole of the "classical" simulations studies also agree with our

20% of the bonds point towards the bulk at an angle of 160–180° with the outward surface normal. Compared to the result for the dipole moment, the O–H orientational distribution is not that symmetric. It should be noted that the used normalization has the effect of over-accentuating the deviations from the homogeneous distribution at angles \( \phi \) around 0° and 180°. This results in a much higher peak in the curve for L1 around \( \phi = 0° \), which only corresponds to a fraction of the O–H bonds. The corresponding peak in the L3-curve is slightly shifted and is around \( \phi = 160° \).

**Vibrational Power Spectrum.** As in the case of bulk liquid water, the vibrational power spectrum was computed using the hydrogen velocity autocorrelation function (Fig. 3). Compared to the bulk water, the peak at 3750–3800 cm\(^{-1}\) is strongly enhanced due to free O–H groups at the surface. This peak is indeed expected on the basis of the preferred orientation illustrated on Fig. 4 and is in agreement with the experimentally observed peak at 3690 cm\(^{-1}\).\(^{40}\)

**IV. SUMMARY AND CONCLUSIONS**

We presented an investigation of (non-deuterated) aqueous systems using DFT-based methods with a self-consistent treatment of the electrons. The Perdew-Wang 91 exchange-correlation functional used in this work gives an acceptable description of the properties of a water molecule, a water dimer, and liquid water. The computed enthalpy of vaporization of 39 kJ mol\(^{-1}\) is in satisfactory agreement with the experimental value of 43.9 kJ mol\(^{-1}\). Taking into account the small system size, the structural results in terms of radial
distribution functions show a reasonable agreement with the most recent neutron diffraction data. The simulated O–O separation is comparable to the result using the BLYP functional and gives a better description of the shape and the position of the first peak than BLYP. The estimated value for the self-diffusion coefficient is also in reasonable agreement with the BLYP results and experiment. The \textit{ab initio} simulation of the liquid water–vapor interface shows a preferred orientation of the water molecule dipole towards the bulk region at an angle of 120° with the outward surface normal. This result agrees qualitatively with most of the previous classical MD simulation results and experimental data.

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