Computational and Theoretical Chemistry 1049 (2014) 28–34

Contents lists available at ScienceDirect

Computational and Theoretical Chemistry

journal homepage: www.elsevier.com/locate/comptc

Intermolecular hydrogen bonding of N-methylformamide in aqueous environment: A theoretical study

Yun Wang [a], Mingxing Guo [b], Shufang Wei [a,c], Shuhui Yin [a,*], Yaochuan Wang [a], Zhe Song [c], Mark R. Hoffmann [d,*]

[a] Department of Physics, Dalian Maritime University, Dalian 116026, China
[b] Environmental Science and Engineering College, Dalian Maritime University, Dalian 116026, Liaoning, China
[c] Department of Physics, Liaoning Normal University, Dalian 116026, China
[d] Chemistry Department, University of North Dakota, Grand Forks, ND 58202, USA

ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 2 September 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
Time-dependent density functional theory (TDDFT)
Excited state hydrogen bonding
Absorption spectrum
Electronic excitation

ABSTRACT

The intermolecular hydrogen bonding of N-methylformamide (NMF) in water is investigated. Ground-state geometry optimizations and binding energies were calculated with density functional theory (DFT). Electronic transition energies, and corresponding oscillator strengths of low-lying electronically excited states of free NMF monomers and hydrogen-bonded NMF–$(H_2O)_{2,3}$ complexes were calculated with time-dependent density functional theory (TDDFT). Electronic absorption spectra red-shift occurs due to the formation of the intermolecular hydrogen bonds $O_{NMF}\cdots H{-}O_{water}$ and $N{-}H\cdots O_{water}$. Larger electronic absorption spectrum red-shift in *trans*-NMF–$(H_2O)_{2,3}$ than in *cis*-NMF–$(H_2O)_{2,3}$ can be attributed to stronger excited state hydrogen bond strengthening in *trans*-NMF–$(H_2O)_n$ complexes.

1. Introduction

Water is a ubiquitous chemical substance in nature and a critical component in many processes, in fields as diverse as biology, chemistry and geology [1]. Water is an important polar solvent that is often in contact with organic molecules to form hydrogen bonds (HB), in which water can function as a very good hydrogen-donor or hydrogen-acceptor. It has been found that water prefers to form hydrogen bonds with oxygen atoms of peptide bonds in proteins [2,3]. Studies of the interactions between water and other molecules are important to understand more fully the role played by water in the biochemical behavior of the molecules [4–6].

To understand the structural properties as well as biological functions of amides and proteins, it is important to know how they interact with solvents, particularly water. N-methylformamide (NMF) is one of the simplest molecules that include the OCNH peptide bond in its structure, and the prototype to research proton transfer in proteins and the hydrolysis of the peptide bond of biological significance. NMF is itself of considerable medical interest since it possesses antitumor activity [7,8]. So far, a growing number of properties of NMF have been investigated by experimental techniques such as electron diffraction [9], neutron diffraction [10], synchrotron radiation [11], X-ray diffraction [12], nuclear magnetic resonance (NMR) [13,14], and IR spectroscopy [15]. In addition, classical ensemble treatments, such as molecular dynamics simulations [16] and Monte Carlo statistical investigations [17–19] have been performed for NMF. The pure liquid and aqueous solutions of NMF have been the subject of studies in recent years, both theoretically [20–29] and experimentally [30–33]. A structural investigation of liquid NMF by X-ray scattering at 298 K found that the hydrogen bond network occurs in NMF between $C{=}O$ and $N{-}H$ groups, which contributes to the origin of its unusual dielectric and thermodynamics properties [33]. The NMF molecules are, on average, bonded to two others, which agrees with the fact that the molecules can act as both H-bond donor and acceptor [23].

The NMF–water mixture has been studied theoretically [34–36] and experimentally [37,38]. The studies of Mu et al. [34] and Cordeiro et al. [19] showed that hydrogen bonds are formed between NMF and water. The thermodynamic measurements presented by Zaichikov et al. found that different water molar fractions will produce different $(NMF)_m$–$(H_2O)_n$ complexes [36]. The higher the water molar fraction is, the more the water molecules

---

[*] Corresponding authors.
E-mail addresses: yinsh@dlmu.edu.cn (S. Yin), mark.hoffmann@email.und.edu (M.R. Hoffmann).

http://dx.doi.org/10.1016/j.comptc.2014.09.006
2210-271X/

are involved in the complexes. In addition, Nasr et al. studied the hydrogen-bond interactions in NMF–water mixtures with X-ray scattering measurements in combination with density functional theory (DFT) calculations [37,38]. They performed the investigations with three water molar fractions, 1.0, [37] 0.66 and 0.75 [38]. Their results showed that H-bond network are preferentially formed between one NMF and three water molecules. A tetramer involving one $N{-}H\cdots O_{water}$ and two $O{-}H\cdots O_{NMF}$ hydrogen bonds is the more probable model describing the local order in these systems.

Although enormous effort has been made to characterize the NMF–water hydrogen-bond interactions, a detailed picture of the intermolecular hydrogen bond of NMF and water remains an elusive goal. Studies on the hydration of NMF are interesting because NMF has the OCNH structure of peptide bonds and are models classically employed of proteins. In particular, the investigation of the intermolecular hydrogen bonding interactions can provide an important contribution in the stability of hydrogen-bonded complexes as proteins and polypeptides. X-ray scattering measurements indicated that NMF preferentially forms hydrogen bonds with more than one water molecule [37,38]. Therefore, investigations on the intermolecular hydrogen bonding of NMF with two and three water monomers would shed more light on the intermolecular interaction of NMF–H_2O clusters. In this work, we study the intermolecular hydrogen bonding of NMF–$(H_2O)_{2,3}$ complexes using time-dependent density functional theory (TDDFT) and DFT. The ground state geometric structures of free NMF monomers and the NMF–$(H_2O)_{2,3}$ clusters are optimized using DFT. The electronic excitation energies and the corresponding oscillator strengths are calculated using TDDFT. The combination of DFT and TDDFT has been used successfully to study weak interactions in many molecular systems. Zhao et al. [39,40] have studied intramolecular and intermolecular hydrogen bonding dynamics of both the ground and electronically excited states using DFT and TDDFT. This paper is organized as follows. In Section 2, the methodology used in the study is described. The results are presented and discussed in Section 3. That section is followed by the conclusions in Section 4.

2. Theoretical methods

The ground state geometric optimizations of free NMF and NMF–$(H_2O)_{2,3}$ clusters were performed using DFT, and the electronic excitation energies and corresponding oscillator strengths of the hydrogen-bonded NMF–$(H_2O)_{2,3}$ complexes, as well as the isolated NMF monomers were calculated using TDDFT. Specifically, for both the DFT and TDDFT calculations, Becke's three-parameter hybrid exchange function with Lee–Yang–Parr gradient-corrected correlation functional (B3LYP hybrid functional) [41] were used with the 6-311++G(d,p) basis sets throughout [42]. Frequencies were composed for all structures and confirmed the presence of local minima.

The binding energies (*BE*) of the hydrogen-bonded complexes in ground state of all species were calculated at B3LYP level by using geometries optimized at the same level. *BE* is computed as:

$$BE = E_{\text{complex}} - \sum_{i=1}^{n} E_{\text{im}},$$

where E_{complex} is the energy of the hydrogen-bonded complexes NMF–$(H_2O)_{2,3}$, and E_{im} represents the monomer energy computed with the monomer basis at the optimum monomer geometry. Here, n is 3 for NMF–$(H_2O)_2$ and 4 for NMF–$(H_2O)_3$ complexes, respectively. The *BE* was corrected for basis set superposition error (BSSE) by means of the counterpoise correction of Boys and Benardi [43]. *CPC* denotes the counterpoise correction,

$$CPC = \sum_{i=1}^{n} [E(i,m) - E(i,c)].$$

$E(i, m)$ and $E(i, c)$ are energies of monomer i computed at the optimum geometry in the NMF–$(H_2O)_{2,3}$ complexes using the monomer basis (m) and complex basis (c), respectively. Then, the counterpoise corrected binding energy (BE^{CP}) is $BE^{CP} = BE + CPC$ [44,45]. The optimized geometry energy of hydrogen-bonded complexes NMF–$(H_2O)_{2,3}$ with counterpoise correction can also be obtained by $E_{CPC} = E_{\text{complex}} + CPC$. All calculations were carried out using the Gaussian 09 program suite.

3. Results and discussions

The electronic ground state geometric conformations of free NMF and six hydrogen-bonded NMF–$(H_2O)_{2,3}$ complexes were fully optimized and are shown in Fig. 1. The methyl and carbonyl moieties can adopt two configurations in NMF, *trans*-NMF and *cis*-NMF (*trans* and *cis* refer to the orientation of C=O and N—H bonds with respect to the C—N bond), [15,20,21,23] as shown in Fig. 1a and b, respectively. *Trans*-NMF is more stable than *cis*-NMF, and is dominant at normal conditions [46,47]. The energy difference between *trans*-NMF and *cis*-NMF has been reported in literature to be between 4.2 and 7.87 kJ/mol [15,20,21,46]. Optimized geometry energies performed at the considered DFT calculation for the two isolated *trans* and *cis* isomers and hydrogen bonded NMF–$(H_2O)_{2,3}$ complexes in this work are presented in Table 1. Our optimization results show that the total energy of *trans*-NMF is 4.54 kJ/mol (1.09 kcal/mol) lower than that of the *cis*-NMF, which is in accordance with the rotational spectrum study of NMF reported by Fantoni and Caminati [46]. The optimized geometric conformations show that the structure of the C=O—N—H group in NMF is planar. To understand better the intermolecular hydrogen bonding between NMF and H_2O molecules, we theoretically study the hydrogen bonded *trans*-NMF–$(H_2O)_{2,3}$ and *cis*-NMF–$(H_2O)_{2,3}$ complexes. Due to the ultrafast time scale of the hydrogen bonding dynamics, only the water molecules in the inner solvation shell were considered in this work without considering the bulk effect of the outer solvation shells.

3.1. Ground-state geometric conformations

First, we present the ground-state geometric conformations involving *trans*-NMF. The optimized conformation of free *trans*-NMF is shown in Fig. 1a. The calculated bond lengths for C1=O1 and N1—H1 are 1.215 Å and 1.008 Å, respectively, which show good agreement with experimental and previous computational results in literature [9,15,16,20]. Two intermolecular hydrogen bonds can be formed between *trans*-NMF and two water monomers in two different ways. The hydrogen bonded complexes are denoted as *trans*-NMF–$(H_2O)_{2c}$ and *trans*-NMF–$(H_2O)_{2d}$, respectively (Fig. 1c and d). For *trans*-NMF–$(H_2O)_{2c}$, the formed intermolecular hydrogen bonds are labeled as HB-I and HB-II. Hydrogen bonds are labeled as HB-III and HB-IV for *trans*-NMF–$(H_2O)_{2d}$. The lengths of the hydrogen bonds (dots denote hydrogen bonds in Fig 1, and $H\cdots O$ distance is defined as the bond length) HB-I, HB-II, HB-III and HB-IV increase in order L(HB-II) < L(HB-IV) < L(HB-III) < L(HB-I). The bond length of HB-II is the shortest, showing the strong hydrogen acceptor ability of C=O group of NMF. Fig. 1e exhibits the hydrogen-bonded complex formed by *trans*-NMF with three water monomers. Two hydrogen bonds $O\cdots H{-}O_{water}$, formed by the O atom of C=O group of NMF and H atoms of water (labeled as HB-V, HB-VI), have similar bond lengths, which are shorter than the hydrogen bond length of $N{-}H\cdots O_{water}$ (labeled as HB-VII) (detailed bond lengths information in ESI†