

On–Off Infrared Absorption of the S=O Vibrational Probe of Dimethyl Sulfoxide

Suranjana Chakrabarty,^{||} Samadhan H. Deshmukh,^{||} Anjan Barman, Sayan Bagchi,* and Anup Ghosh*



Cite This: *J. Phys. Chem. B* 2022, 126, 4501–4508



Read Online

ACCESS |



Metrics & More

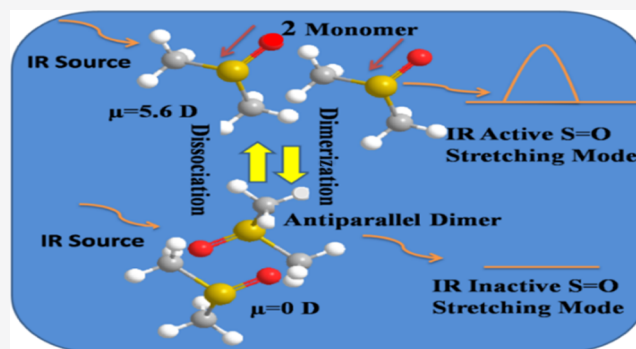


Article Recommendations



Supporting Information

ABSTRACT: Dimethyl sulfoxide (DMSO), a polar solvent molecule, is used in a wide range of therapeutic and pharmacological applications. Different intermolecular interactions, such as dimerization and hydrogen bonding with water, are crucial to understanding the role of DMSO in applications. Herein, we study DMSO in various solvation environments to decipher the environment-dependent dimerization and hydrogen-bonding propensity. We use a combination of infrared spectroscopy, quantum mechanical calculations, and molecular dynamics simulations to reach our conclusions. Although DMSO can exist in a dynamic equilibrium between monomers and dimers, our results show that the relative intensity of the S=O stretch and the CH₃ rocking modes is a spectroscopic indicator of the extent of DMSO dimerization in solution. The dimerization (self-association) is seen to be maximum in neat DMSO. When dissolved in different solvents, the dimerization propensity decreases with increasing solvent polarity. In the presence of a protic solvent, such as water, DMSO forms a hydrogen bond with the solvent molecules, thereby reducing the extent of dimerization. Further, we estimate the hydrogen-bond occupancy of DMSO. Our results show that DMSO predominantly exists as doubly hydrogen-bonded in water.



INTRODUCTION

Dimethyl sulfoxide (DMSO) is one of the polar aprotic molecules with a large dipole moment.¹ In the field of pharmacology, toxicology, biochemistry, and other analytical applications, DMSO is extensively used as a prospective cosolvent in various chemical reactions.^{1,2} Being a cryoprotective agent, DMSO averts the development of intracellular and extracellular crystals during the cell and tissue freezing processes.^{3–7} In addition, DMSO has various therapeutic and pharmaceutical uses, such as anti-inflammatory, analgesic, antibacterial, antifungal, antiviral, and membrane penetration enhancement properties that remain underexplored by pharmaceutical developers and ophthalmologists.⁸ In biochemical and biophysical assays, it is reported that DMSO concentrations influence protein aggregation and stability.^{9,10} Experimental and computational studies revealed that DMSO induces structural and conformational changes in proteins.^{11–13} These wide ranges of applications have generated a profound interest in the structural behavior of DMSO, either neat or in the solution state, in recent years.^{14–25}

The structural properties and the dimerization strategies of DMSO have been previously reported.^{25–30} The intermolecular geometry of DMSO in the liquid state, determined from X-ray and neutron diffraction studies, showed that DMSO mostly prefers to arrange in the antiparallel ordering of S=O dipoles in the liquid state.¹⁴ The formation of hydrogen bonds between DMSO and water molecules has been shown to

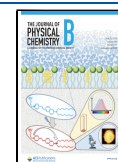
dictate molecular behaviors, enhancing polarizability in the molecules.^{15–17} Having the propensity toward intermolecular associations, either with itself or with other molecules (such as water), DMSO occasionally exhibits abnormal physicochemical properties and can form DMSO–water aggregates with various stoichiometries.^{18–21} At a higher DMSO concentration, the hydrogen-bond network of water is ruptured and stable water–DMSO complexes are formed.^{22–24} For a detailed exploration of the structures of DMSO, infrared (IR) absorption and Raman scattering spectroscopies were employed.^{25–30} These experiments revealed that DMSO can form antiparallel dimers and chain-like associations both in the pure liquid state and in solutions.^{25–31}

Although several vibrational spectroscopic reports on DMSO have been published, a consensus regarding the peak assignments has yet to be reached.^{26,30} The band at 1027 cm⁻¹ is assigned to the S=O stretch arising from parallel chain-like molecular associations. For antiparallel cyclic associations, the bands at 1058 and 1044 cm⁻¹ are attributed to the out-of-

Received: December 14, 2021

Revised: May 24, 2022

Published: June 8, 2022



phase and in-phase S=O stretch modes, respectively.³¹ The out-of-phase S=O stretch of the cyclic dimer is detected at 1063 cm⁻¹ in the IR spectra.³⁰ Toshiyuki Shikata et al. reported that associations of DMSO dimers are formed in the pure liquid and also in the presence of nonpolar solvents.³² When dissolved in CCl₄, antiparallel cyclic dimers of DMSO are formed due to limited self-interaction,³³ with peaks at 1060 and 1000 cm⁻¹ arising from the S=O stretch of monomers and dimers, respectively.³³ Recently, it has been reported that DMSO dimerization happens even at low DMSO concentrations.³⁴ Gajda and Katrusiak used single-crystal XRD at high pressure to study the detailed dimeric structure of DMSO.³⁵ The calculated electrostatic potentials revealed a large positive partial charge on the “S” atom and a negative partial charge on the “O” atom, through which a variety of intermolecular electrostatic interactions can occur.³⁶ Natarajan et al. investigated the structure and stability of DMSO molecules using molecular electrostatic potential and atoms-in-molecules (AIM) analysis with the employment of density functional theory (DFT) studies.³⁷

Another interesting aspect of DMSO is the structural and physicochemical behavior difference in aprotic and protic solvents. To this end, similar behavioral changes can be found in molecules containing a carbonyl (C=O) moiety where the less polarizable C atom replaces the S atom. Furthermore, studies on hydrogen-bond occupancy have shown that S=O- and C=O-containing molecules can form one or more hydrogen bonds in a protic solvent.^{38–49} Recently, a temperature- and concentration-dependent study on DMSO/water mixtures indicated the presence of four distinct forms of DMSO, namely self-associated (aggregated), free-monomer (0HB), singly hydrogen-bonded (1HB), and doubly hydrogen-bonded (2HB) species.^{38,39} On the contrary, a recent study has shown that C=O-containing esters are exclusively doubly hydrogen-bonded in water.⁴⁰ The reported differences in structures' hydrogen-bond occupancies upon changing the C atom in C=O to the S atom in S=O warrants a detailed study of DMSO in the solution state. Moreover, a significant S=O IR absorbance signature for DMSO dimers, either neat or in the solution state, has been surmised in the previous studies.^{25–38} Such an observation cannot be explained based on the symmetric structure of the DMSO dimer.

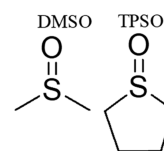
To identify the structural conformers underlying the overlapping DMSO vibrational spectra and to determine their structural details and hydrogen-bonding nature in water, we performed a detailed investigation using IR absorption measurements, DFT calculations, and MD simulations on neat DMSO and DMSO dissolved in various solvents, namely carbon tetrachloride (CCl₄), dichloromethane (DCM), and water (D₂O). We combined IR spectroscopy with *ab initio* quantum mechanical calculations to analyze the monomer–dimer equilibrium in different solvents to show that the relative intensity of the S=O stretch and the CH₃ rocking modes provide an estimate of the DMSO dimer present in the solution. Furthermore, in the presence of a protic solvent like water, we showed that the extent of dimerization is drastically reduced due to the formation of DMSO–water hydrogen bonds. We subsequently analyzed the hydrogen-bonded conformations of DMSO in water. Interestingly, we observed that DMSO interacts predominantly with two water molecules to form a double hydrogen-bonded conformer. Such conformations are well known for molecules containing the C=O moiety.⁴⁰ Overall, our findings suggest an efficient

spectroscopic approach to elucidate the details of the microsolvation environment of DMSO despite the complexity of overlapping bands in the spectra.

MATERIALS AND METHODS

Sample Preparation. Dimethyl sulfoxide (DMSO 99.9%), thiophene oxide (TPSO, 99.9%), and all solvents (99.9%) were bought from Sigma Aldrich. The chemical structure of DMSO and TPSO are shown in Scheme 1. Karl Fischer titration

Scheme 1. Chemical Structure of the Sulfoxide Compound



(coulometric) was performed to quantify the moisture present in used solvents. These titrations indicated negligible water content. Solutions of DMSO and TPSO at a 0.1M concentration in all solvents were prepared for IR absorption measurements.

IR Spectroscopy. All IR absorption spectra were collected on a Bruker 70S FTIR spectrometer equipped with a DTGS detector at 2 cm⁻¹ resolutions. A 50 μL volume of each solution was placed between two CaF₂ windows separated by a 64 μm Teflon spacer, housed in a homemade sample cell. Along with the S=O stretch region, the OH stretch region was also monitored to identify any small amount of water contamination. A flat baseline in the OH stretch region indicated that the samples were not contaminated by water.

DFT Calculations. All initial geometries of DMSO, TPSO, and their water complexes were optimized preliminarily by density functional theory and B3LYP/6-311G(d) calculations using the Gaussian 09 suite of programs to estimate the dipole moments of the DMSO monomer and the dimer.^{50,51} Further, to expose the dissociation energies of one hydrogen bond and two hydrogen bond complexes of DMSO in water, the “scan” analyses were performed on the B3LYP/6-311G(d) optimized structures.⁵²

MD Simulations. Classical molecular dynamics simulation was conducted on the GROMACS 2016.5 package.⁵³ Parameters for DMSO were derived from quantum chemical calculation followed by RESP charge fitting by ANTECHAMBER software to produce the general AMBER force field.⁵⁴ Simulation box was prepared by adding 7 DMSO molecules with 4000 water molecules. Here, water molecules were modeled using the TIP4P-EW model. For short-range electrostatic interactions, a periodic boundary condition with a cutoff distance of 16 Å was used. Before the simulation, an energy minimization using a steepest-descent algorithm was performed, followed by equilibrium in the NVT ensemble at 300 K for 1 ns using a velocity rescale thermostat and equilibrium for the NPT ensemble at 300 K and 1 bar using a Parrinello–Rahman barostat for 5 ns. LINCS was used to constrain all covalently bonded hydrogen atoms. MD run was carried out for 10 ns. A hydrogen-bond analysis was performed on GROMACS with the last 5 ns of the trajectory where a cutoff distance of 3.5 Å and an angle cutoff of 30° were used.

RESULTS AND DISCUSSION

The delicate balance in the noncovalent (solute–solute and solute–solvent) interactions drives the formation and disruption of intermolecular interactions of DMSO dissolved in different solvents. To resolve the detailed molecular structure of DMSO, in both neat and solution states, we performed a series of infrared absorption experiments on 0.1 M DMSO in different solvents (Figures 1 and 2). The second derivatives of

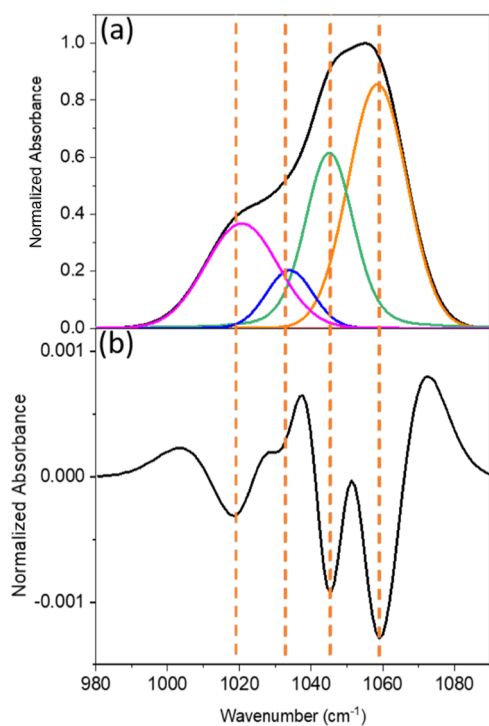


Figure 1. (a) IR absorption spectrum of neat DMSO (black). The experimental spectrum was fitted to four peaks corresponding to the S=O stretch (orange) and the CH₃ rocking modes (green, blue, and magenta) using Voigt line shape functions. During the fitting protocol, the peak positions are assigned based on the (b) second derivative spectrum.

the broad overlapping IR absorption spectra (Figures 1b, and 2b,2d,2f) in the 950–1100 cm⁻¹ region indicate four underlying peaks. Each spectrum is fitted with four peaks using Voigt line shape functions. The fits are shown in Figures S1 and S2. The peak positions are fixed to the frequencies corresponding to the minima in the second derivative spectra (Table S1). The fitted peaks in Figures 1 and 2 are assigned to the S=O symmetric stretching mode and three CH₃ rocking modes based on previous reports.^{31–34,38,39} In neat DMSO (Figure 1), three rocking modes and the symmetric S=O mode are observed at ~1019, 1030, 1045, and 1059 cm⁻¹, respectively. Interestingly, the intensity of the S=O mode is comparable to that of the CH₃ rocking modes even though the transition dipole moment of S=O is larger than those of the rocking modes. One plausible explanation for the comparable intensities in Figure 1 can be that neat DMSO predominantly exists as symmetric dimers even at low concentrations, as reported previously.³⁴ Theoretical calculations (discussed later) suggest that the S=O mode of antiparallel dimers is not IR active. However, when dissolved in another solvent, the dimers should not be formed at a low DMSO concentration. Indeed, the IR absorption spectra of a dilute solution of

DMSO in different solvents show that the intensity of the S=O stretch band is distinctly larger than those of the CH₃ rocking modes (Figure 2).

We performed DFT calculations at the B3LYP/6-311G(d) level of theory^{50,51} to estimate the dipole moments of the DMSO monomer and the dimer. Our calculations suggest that the dipole moment is zero for an antiparallel DMSO dimer, whereas a considerable dipole moment (5.6D) is estimated for the monomer. We surmise that the S=O peak in the IR spectrum (Figure 1) arises from the monomeric species, which are in equilibrium with DMSO dimers in neat DMSO. The self-association of the monomers to form antiparallel dimers is quite likely due to the high polarity of the S=O bond. In addition, the dynamic monomer–dimer equilibrium happens due to the intrinsic molecular fluctuations.

We further evaluated the ratios of S=O peak areas to the integrated peak areas of the rest of the bands in the 950–1100 cm⁻¹ region (Figure 3a). The ratio has a minimum value for neat DMSO and subsequently increases with the polarity of the solvent. In water, the ratio is remarkably enhanced by a factor of ~6 from that in neat DMSO. The polarity and the hydrogen-bonding capacity of the solvent play a key role in the monomer–dimer equilibrium of DMSO. A nonpolar aprotic solvent like CCl₄ or DCM weakly interacts with the solute (DMSO), but a polar protic solvent like water can form hydrogen bonds with the S=O moiety of DMSO (see Figure S3 in the Supporting Information). Therefore, the propensity of the monomeric species is higher in water than in other organic solvents. In neat DMSO, two polar DMSO molecules can form the antiparallel dimer, giving rise to an increase in the dimeric species. This effect is corroborated by the ratios shown in Figure 3. The trend remains the almost same if the area of one of the rocking modes is considered (Figure 3a) instead of the integrated area (Figure 3b). The small discrepancy in the ratios for CCl₄ and DCM solvents (Figure 3b) most plausibly arises due to the effect of the coupling between the S=O stretch and the CH₃ rocking modes (see the Supporting Information). However, the overall trend remains the same.

To elucidate this phenomenon, we calculated the dimerization energy of DMSO and compared it with solvation energy in organic and aqueous solvents (Figure 4). When compared to aprotic solvents, Figure 4 clearly shows that the stability obtained from the dimerization of DMSO is much smaller than that obtained from the solvation of DMSO by water molecules, thereby increasing the ratio in water (Figure 3).

To confirm our arguments, we performed control IR absorption experiments and DFT calculations on TPSO. The DFT calculations suggest that the bulky five-membered ring of TPSO provided steric hindrance when two TPSO monomers approached one another, making the dimerization unfeasible even in neat TPSO. We performed a series of IR absorption experiments of TPSO and analyzed the 950–1100 cm⁻¹ spectral region (same frequency range as DMSO). The IR spectra of neat TPSO show three peaks (Figure 5a), one arising from the S=O stretch and the other two arising from CH₂ rocking modes. Interestingly the absorption of the S=O mode was stronger than that of the rocking modes. Similar results are obtained when TPSO was dissolved at a low concentration in other solvents (Figure 5b–d). Herein, we fitted TPSO IR absorption spectra based on the quality (Figure S4) and second-order derivative spectra (Figure S5). Figure 6 shows the ratios of the S=O peak area to that of the rocking mode (~990 cm⁻¹). The similar ratios in TPSO, CCl₄, and

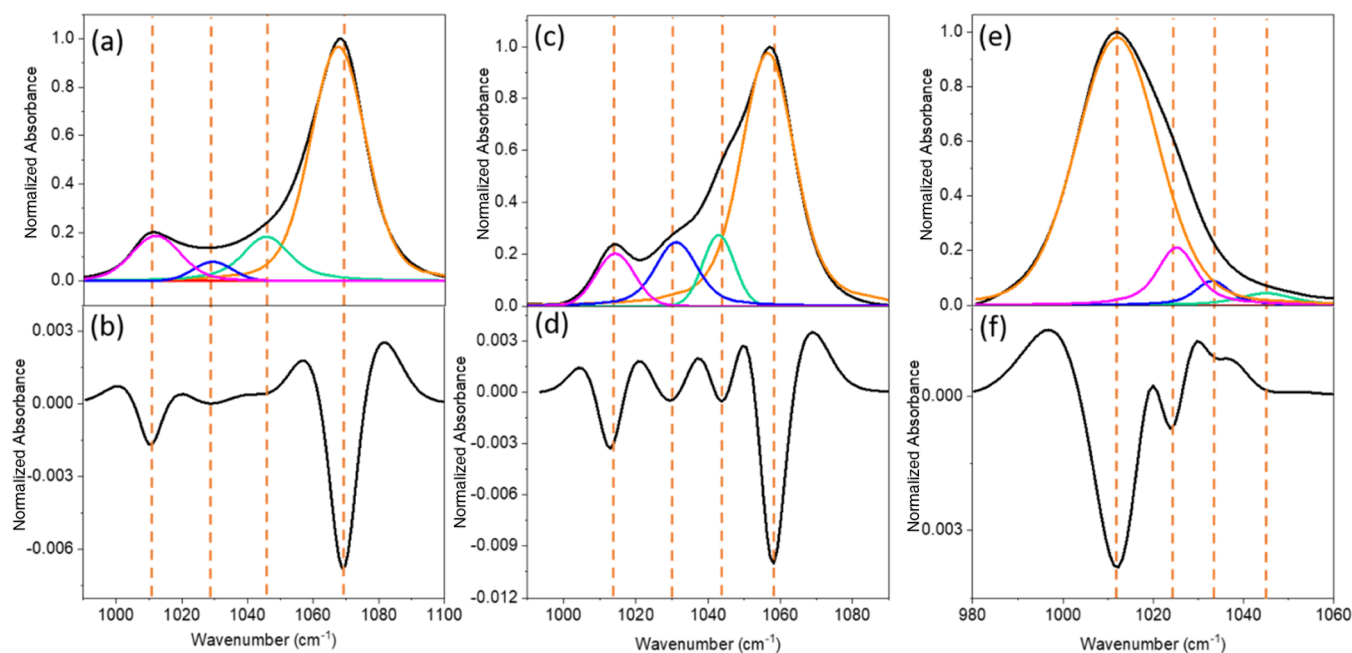


Figure 2. Black curves denote the IR absorption spectra of DMSO in (a) CCl_4 , (c) DCM, and (e) D_2O . The experimental IR spectra are fitted to four peaks using Voigt line shape functions. The orange peaks correspond to the S=O stretch, and the green, blue, and magenta peaks correspond to the CH_3 rocking modes. The peak positions during the fitting protocol are obtained from the second derivative spectra of DMSO in (b) CCl_4 , (d) DCM, and (f) D_2O .

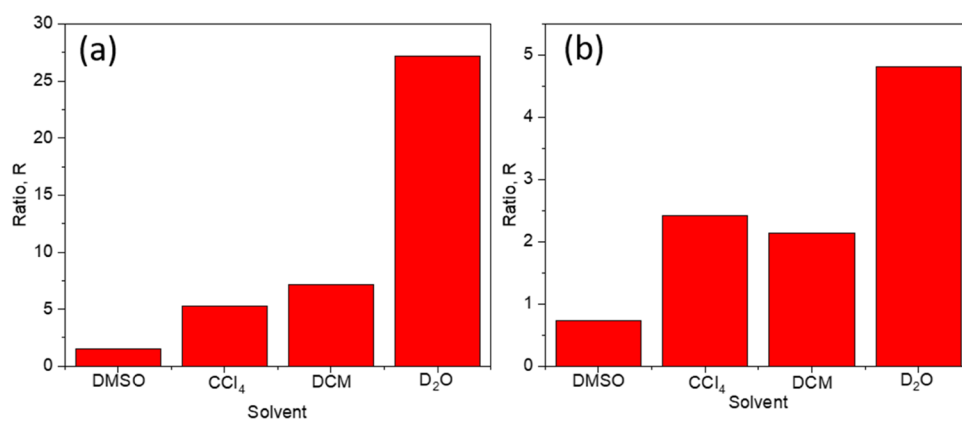


Figure 3. (a) Ratio (R) of the IR absorption area of the S=O stretching mode and the integrated area of the rocking mode at around 1045 cm^{-1} . (b) Ratio (R) of the integrated IR absorption area of the S=O stretching mode and the integrated area of all overlapping rocking modes.

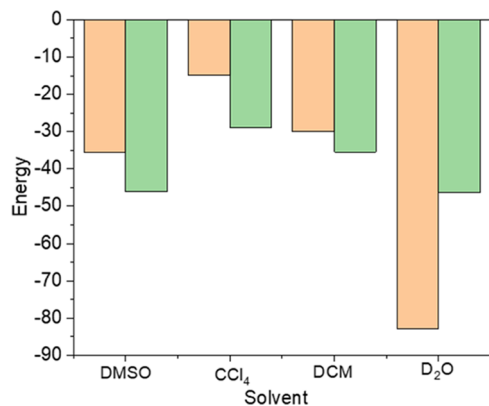


Figure 4. Solvation energy (orange) and dimerization energy (green) of DMSO in different solvents.

DCM corroborate the DFT prediction of the dimerization infeasibility in neat TPSO. The lower polarity of TPSO when compared with DMSO, along with the steric hindrance in TPSO to the formation of hydrogen bonds might have resulted in a lower ratio in water. However, the control experiments in TPSO provide additional support for the formation of an antiparallel DMSO dimer in a neat solution.

To resolve the hydrogen-bonded populations of DMSO, we further performed MD simulation with GROMACS (version 4.6.5) in neat water. The hydrogen-bond occupancy of DMSO has been explored by keeping the angle of H-donor–acceptor (H–O–O) between 0 and 30° and the O (donor)–O (acceptor) distance was below 3.5 \AA .⁴⁰ The force-field parameters for DMSO were obtained from virtualchemistry.org.⁴¹ The TIP4P-Ew model was used for water.⁴² The simulations reveal the hydrogen-bond formation and breaking mechanisms of DMSO in neat water. The hydrogen-bond analysis from the MD simulation trajectories demonstrates that

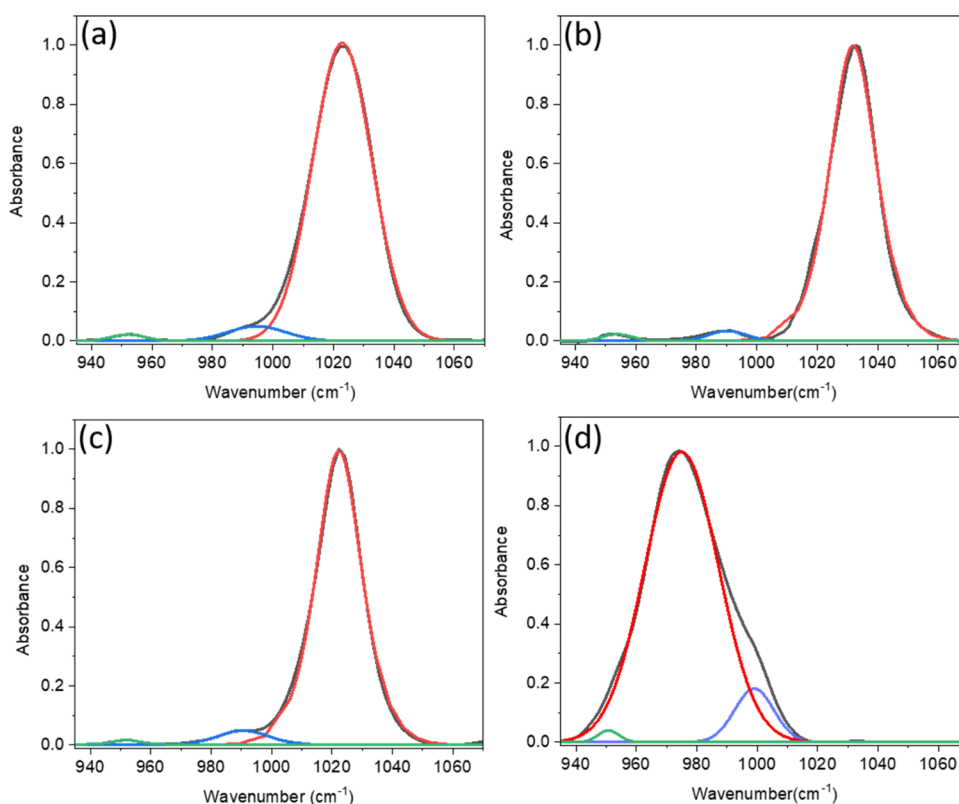


Figure 5. IR absorption spectra (a) of neat TPSO (black) and TPSO in (b) CCl_4 (c) DCM, and (d) D_2O . The experimental spectra were fitted to three peaks corresponding to the S=O stretch (red) and the CH_2 rocking modes (green, blue) using Voigt line shape functions. During the fitting protocol, the peak positions are assigned based on the second derivative spectrum shown in Figure S5.

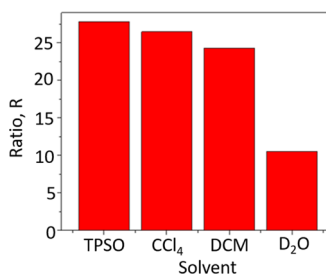


Figure 6. IR absorption ratio of the S=O stretching frequency and the CH_2 rocking mode ($\approx 990 \text{ cm}^{-1}$) of TPSO.

S=O can form zero, one, or two HB complexes with the surrounding water molecules.^{44–48} Interestingly, the free DMSO (0.35%) and 1HB complexes (3.5%) are found to be negligibly small in comparison to 2HB (96.15%) populations. Similarly, TPSO predominantly forms 2HB populations (92%) compared to 1HB (8%) and 0HB (0%) in neat water. These results support our experimental results wherein we mentioned only one S=O stretching IR absorption peak for both DMSO (Figure 2e) and TPSO (Figure 5d) in neat water.

To further understand the stability of HB complexes of DMSO in neat water, we performed density functional theory (DFT) calculations by employing Gaussian 09 software.^{50,51} The hydrogen-bond energies of 1HB and 2HB complexes are obtained from the B3LYP-6-311G-optimized structures. To calculate the hydrogen-bond dissociation energies of 1HB and 2HB bonds, we used the Morse potential energy calculation method (eq 1)⁵²

$$V = D_e(1 - e^{-a(r-r_e)})^2 \quad (1)$$

where r is the distance between the atoms, r_e is the equilibrium hydrogen-bond distance, and D_e is the dissociation energy. The Morse potential diagrams show that the HB dissociation energies of 1HB and 2HB of DMSO are almost comparable (Figure 7), which signifies that DMSO can form 1HB and 2HB

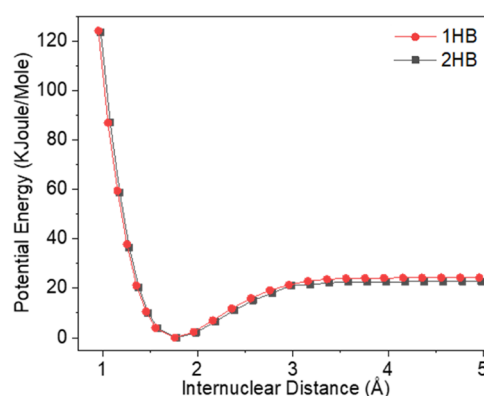


Figure 7. Morse potential diagram of one hydrogen bond and two hydrogen bond complexes of DMSO in water.

with equivalent probability, as the estimated energy difference is almost negligibly small. The calculated formation energy values of 1HB and 2HB complexes are -24.33 and -22.72 kJ/mol, respectively. The similar values of formation energy indicate the equal probability of 1HB and 2HB formation. We calculated the change of Gibbs free energy of both the hydrogen-bond formation from DFT calculations and finally,

used it to calculate the equilibrium constants. Subsequently, after calculation of K_1 and K_2 (7942.63 and 718.38/mol, respectively), we calculated the ratio of C_{1HB}/C_{2HB} from the eqs 1–6 of Scheme S1. The negligible ratio (2.50×10^{-5}) of C_{1HB}/C_{2HB} is the indication of negligible 1HB populations compared to 2HB (Table 1). Quantitative S=O H-bond

Table 1. Thermodynamical Data Obtained from DFT Calculations

complexes	formation energy (kJ/mol)	change of Gibbs free energy (kJ/mol)	equilibrium constant (mol)	populations (%)
1HB	−24.33	−22.25	7942.63	0.0025
2HB	−22.72	−16.29	718.38	99.9975

populations in water are extracted for 1HB and 2HB complexes with values of 0.0025 and 99.9975%, respectively. Thus, the DFT analysis made our assessment a concrete conclusion. From our experimental and theoretical studies, a clear parity of H-bond populations is undoubtedly recognized. Subsequently, we confirmed conclusive 2HB populations of DMSO in neat water, which is also logically explained in Scheme S1. Especially, in the mixing process, hydrogen bonding is simply transferred from water–water interactions (18.5 kJ/mol) to water–DMSO interactions as the H-bond interaction of water–water is lower than the H-bond interaction of water–DMSO in neat water (22.72 kJ/mol).

CONCLUSIONS

In this work, we inspected the structural arrangements of DMSO molecules in the neat form and in solution. We showed that the presence of dimeric associations in neat DMSO decreases the IR intensity of the S=O stretch, making the intensity comparable with the CH₃ rocking modes. We demonstrated that the zero net dipole moment of the antiparallel dimer, in contrast to that of the monomer, can affect the overall intensity of the S=O peak arising from monomer–dimer equilibrium. We showed that the dimeric configurations are disrupted with the increase in solvent polarity and therefore the S=O absorbance enhances when compared to that of the rocking mode. The relative intensity of the S=O stretch and the rocking mode reaches the highest in water as all dimeric structures of DMSO are disrupted by the formation of hydrogen-bonded complexes. A single HB conformation (i.e., 2HB) is found to be present in neat water from MD simulations. This result is in contrast with the previously published reports.^{25–39,44,45} Our experiments provide a detailed molecular understanding of the structure of neat DMSO and DMSO–water binary mixtures. Finally, our results provided an overview of the influence of solvent polarity in the dissociation of DMSO dimers. We envisage that our findings will help in future studies based on the solvent effects on dynamical configurations of biomolecules in DMSO–water mixtures.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.jpcb.1c10558>.

Fitted linear IR spectra of neat DMSO, fitted linear IR spectra of DMSO in different solvents, table of linear IR absorption peak positions of DMSO and TPSO, fitted

linear IR spectra of DMSO in DCM and D₂O mixtures, fitted linear IR spectra of TPSO, second-order derivative spectra of TPSO, details of coupling, and mathematical calculations of H-bond populations (PDF)

AUTHOR INFORMATION

Corresponding Authors

Sayan Bagchi – Physical and Materials Chemistry Division, CSIR-National Chemical Laboratory, Pune 411008, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India; orcid.org/0000-0001-6932-3113; Email: s.bagchi@ncl.res.in

Anup Ghosh – Department of Condensed Matter Physics and Materials Sciences, S. N. Bose National Centre for Basic Sciences, Kolkata 700106, India; Physical and Materials Chemistry Division, CSIR-National Chemical Laboratory, Pune 411008, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India; orcid.org/0000-0002-1442-8740; Email: anupg86@gmail.com

Authors

Suranjana Chakrabarty – Department of Condensed Matter Physics and Materials Sciences, S. N. Bose National Centre for Basic Sciences, Kolkata 700106, India

Samadhan H. Deshmukh – Physical and Materials Chemistry Division, CSIR-National Chemical Laboratory, Pune 411008, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

Anjan Barman – Department of Condensed Matter Physics and Materials Sciences, S. N. Bose National Centre for Basic Sciences, Kolkata 700106, India; orcid.org/0000-0002-4106-5658

Complete contact information is available at: <https://pubs.acs.org/10.1021/acs.jpcb.1c10558>

Author Contributions

[†]S.C. and S.H.D. contributed equally.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

A.G. thanks SNBNCBS, Kolkata, for instrumental facilities and financial support from the DST, India. S.B. thanks CSIR-NCL and SERB, India, (SR/S2/RJN-142/2012 and EMR/2016/000576) for financial support.

REFERENCES

- Vaisman, I. I.; Berkowitz, M. L. J. Local structural order and molecular associations in water–DMSO mixtures. *Molecular dynamics study. J. Am. Chem. Soc.* **1992**, *114*, 7889–7896.
- Chalaris, M.; Marinakis, S.; Dellis, D. Temperature effects on the structure and dynamics of liquid dimethyl sulfoxide: A molecular dynamics study. *Fluid Phase Equilib.* **2008**, *267*, 47–60.
- Lovelock, J. E.; Bishop, M. W. H. Prevention of Freezing Damage to Living Cells by Dimethyl Sulphoxide. *Nature* **1959**, *183*, 1394–1395.
- Rall, W. F.; Fahy, G. M. Ice-free cryopreservation of mouse embryos at -196 °C by vitrification. *Nature* **1985**, *313*, 573–575.
- Fahy, G. M. Cryoprotectant toxicity neutralization. *Cryobiology* **2010**, *60*, S45–53.
- Rammler, D. H.; Zaffaroni, A. Biological implications of DMSO based on a review of its chemical properties. *Ann. N. Y. Acad. Sci.* **1967**, *141*, 13–23.

- (7) Jacob, S. W.; Herschler, R. Pharmacology of DMSO. *Cryobiology* **1986**, *23*, 14–27.
- (8) Hoang, C.; Nguyen, A. K.; Nguyen, T. Q.; Fang, W.; Han, B.; Hoang, B. X.; Tran, H. D. Application of Dimethyl Sulfoxide as a Therapeutic Agent and Drug Vehicle for Eye Diseases. *J. Ocul. Pharmacol. Ther.* **2021**, *37*, 441–451.
- (9) Chan, D.-H.; Madeline, E. K.; Kirsty, J. M.; Andrew, W. M.; Dijana, M. V.; Anthony, G. C.; Chris, A. Effect of DMSO on Protein Structure and Interactions Assessed By Collision-induced Dissociation and Unfolding. *Anal. Chem.* **2017**, *89*, 9976–9983.
- (10) Tjernberg, A.; Markova, N.; Griffiths, W. J.; Hallén, D. DMSO-Related Effects in Protein Characterization. *SLAS Discovery* **2006**, *11*, 131–137.
- (11) Ghosh, S.; Chatteraj, S.; Chowdhury, R.; Bhattacharyya, K. Structure and dynamics of lysozyme in DMSO–water binary mixture: fluorescence correlation spectroscopy. *RSC Adv.* **2014**, *4*, 14378–14384.
- (12) Roy, S.; Jana, B.; Bagchi, B. Dimethyl sulfoxide induced structural transformations and non-monotonic concentration dependence of conformational fluctuation around active site of lysozyme. *J. Chem. Phys.* **2012**, *136*, No. 115103.
- (13) Sterling, H. J.; Prell, J. S.; Cassou, C. A.; Williams, E. R. Protein conformation and supercharging with DMSO from aqueous solution. *J. Am. Soc. Mass Spectrom.* **2011**, *22*, 1178–1186.
- (14) Onthong, U.; Megyes, T.; Bakó, I.; Radnai, T.; Grósz, T.; Hermansson, K.; Probst, M. X-ray and neutron diffraction studies and molecular dynamics simulation of liquid DMSO. *Phys. Chem. Chem. Phys.* **2004**, *6*, 2136–2144.
- (15) Soper, A. K.; Luzar, A. Orientation of Water Molecules around Small Polar and Nonpolar Groups in Solution: A Neutron Diffraction and Computer Simulation Study. *J. Phys. Chem. A* **1996**, *100*, 1357–1367.
- (16) Mancera, R. L.; Chalaris, M.; Samios, J. The Concentration Effect on the ‘Hydrophobic’ and ‘Hydrophilic’ Behaviour around DMSO in Dilute Aqueous DMSO Solutions. A Computer Simulation Study. *J. Mol. Liq.* **2004**, *110*, 147–153.
- (17) Kirchner, B.; Hutter, J. Solvent Effects on Electronic Properties from Wannier Functions in a Dimethyl Sulfoxide/Water Mixture. *J. Chem. Phys.* **2004**, *121*, 5133–5142.
- (18) Borin, I. A.; Skaf, M. S. Molecular association between water and dimethyl sulfoxide in solution: A molecular dynamics simulation study. *J. Chem. Phys.* **1999**, *110*, 6412–6420.
- (19) Luzar, A.; Chandler, D. Structure and hydrogen bond dynamics of water dimethyl sulfoxide mixtures by computer simulations. *J. Chem. Phys.* **1993**, *98*, 8160–8173.
- (20) Vishnyakov, A.; Lyubartsev, A. P.; Laaksonen, A. Molecular Dynamics Simulations of Dimethyl Sulfoxide and Dimethyl Sulfoxide–Water Mixture. *J. Phys. Chem. A* **2001**, *105*, 1702–1710.
- (21) Kirchner, B.; Reiher, M. The Secret of Dimethyl Sulfoxide–Water Mixtures. A Quantum Chemical Study of 1DMSO–*n*Water Clusters. *J. Am. Chem. Soc.* **2002**, *124*, 6206–6215.
- (22) Baker, E. S.; Jonas, J. Transport and relaxation properties of dimethyl sulfoxide–water mixtures at high pressure. *J. Phys. Chem. B* **1985**, *89*, 1730–1735.
- (23) Chowdhuri, S.; Pattanayak, S. K. Pressure dependence on the single-particle dynamics and hydrogen bond structural relaxation of water–DMSO mixtures under ambient and cold conditions. *Mol. Phys.* **2013**, *111*, 135–146.
- (24) Kirchner, B.; Hutter, J. The Structure of a DMSO–Water Mixture from Car–Parrinello Simulations. *Chem. Phys. Lett.* **2002**, *364*, 497–502.
- (25) Forel, M. -T.; Tranquille, M. Spectres de vibration du diméthylsulfoxyde et dn diméthylsulfoxyde-d6. *Spectrochim. Acta, Part A* **1970**, *26*, 1023–1034.
- (26) Fawcett, W. R.; Kloss, A. A. Attenuated total reflection fourier-transform IR spectroscopic study of dimethyl sulfoxide self-association in acetonitrile solutions. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 3333–3337.
- (27) Fawcett, W. R.; Kloss, A. A. Solvent-Induced Frequency Shifts in the Infrared Spectrum of Dimethyl Sulfoxide in Organic Solvents. *J. Phys. Chem. C* **1996**, *100*, 2019–2024.
- (28) Fine, G.; Mirone, P. Short-range orientation effects in dipolar aprotic liquids–HI. Intermolecular coupling of vibrations in sulfoxides, sulfones, nitriles and other compounds. *Spectrochim. Acta, Part A* **1976**, *32A*, 625–629.
- (29) Sastry, M. I. S.; Singh, S. J. Self-association of dimethyl sulfoxide and its dipolar interactions with water: Raman spectral studies. *J. Raman Spectrosc.* **1984**, *15*, 80–85.
- (30) Skripkin, M. Y.; Lindqvist-Reis, P.; Abbasi, A.; Mink, J.; Persson, I.; Sandstrom, M. Basic materials physics of transparent conducting oxides. *Dalton Trans.* **2004**, 4038–4049.
- (31) Perelygin, I. S.; Itkulov, I. G.; Krauze, A. S. Temperature dependence of associative equilibria of DMSO according to Raman scattering spectra. *Russ. J. Phys. Chem.* **1991**, *65*, 410–414.
- (32) Shikata, T.; Sugimoto, N. Dimeric Molecular Association of Dimethyl Sulfoxide in Solutions of Nonpolar Liquids. *J. Phys. Chem. A* **2012**, *116*, 990–999.
- (33) Figueroa, R. H.; Roig, E.; Szmant, H. H. Infrared study on the self-association of dimethyl sulfoxide. *Spectrochim. Acta, Part A* **1966**, *22*, 587–592.
- (34) Singh, S.; Srivastava, S. K.; Singh, D. K. Raman scattering and DFT calculations used for analyzing the structural features of DMSO in water and methanol. *RSC Adv.* **2013**, *3*, 4381–4390.
- (35) Gajda, R.; Katrusiak, A. Electrostatic matching versus close-packing molecular arrangement in compressed dimethyl sulfoxide (DMSO) polymorphs. *J. Phys. Chem. B* **2009**, *113*, 2436–2442.
- (36) Clark, T.; Murray, J. S.; Lane, P.; Politzer, P. Why are dimethyl sulfoxide and dimethyl sulfone such good solvents? *J. Mol. Model.* **2008**, *14*, 689–697.
- (37) Venkataramanan, N. S.; Suvithaa, A.; Kawazoea, Y. Density functional theory study on the dihydrogen bond cooperativity in the growth behavior of dimethyl sulfoxide clusters. *J. Mol. Liq.* **2018**, *249*, 454–462.
- (38) Oh, K. I.; Rajesh, K.; Stanton, J. F.; Baiz, C. R. Quantifying hydrogen-bond populations in DMSO/water mixtures. *Angew. Chem. Int. Ed.* **2017**, *56*, 11375–11379.
- (39) Oh, K. I.; Baiz, C. R. Crowding Stabilizes DMSO–Water Hydrogen-Bonding Interactions. *J. Phys. Chem. B* **2018**, *122*, 5984–5990.
- (40) Ghosh, A.; Cohn, B.; Prasad, A. K.; Chuntunov, L. Quantifying conformations of ester vibrational probes with hydrogen-bond-induced Fermi resonances. *J. Chem. Phys.* **2018**, *149*, 184501–184511.
- (41) Ghosh, A. Vibrational Coupling on Stepwise Hydrogen Bond Formation of Amide I. *J. Phys. Chem. B* **2019**, *123*, 7771–7776.
- (42) Kashid, S. M.; Jin, G. Y.; Chakrabarty, S.; Bagchi, S.; Kim, Y. S. Two-Dimensional Infrared Spectroscopy Reveals Cosolvent Composition-Dependent Crossover in Intermolecular Hydrogen Bond. *J. Phys. Chem. Lett.* **2017**, *8*, 1604–1609.
- (43) Kashid, S. M.; Jin, G. Y.; Bagchi, S.; Kim, Y. S. Cosolvent Effects on Solute–Solvent Hydrogen-Bond Dynamics: Ultrafast 2D IR Investigations. *J. Phys. Chem. B* **2015**, *119*, 15334–15343.
- (44) Borin, I. A.; Skaf, M. S. Molecular Association between Water and Dimethyl Sulfoxide in Solution: The Librational Dynamics of Water. *Chem. Phys. Lett.* **1998**, *296*, 125–130.
- (45) Luzar, A.; Chandler, D. Structure and Hydrogen-Bond Dynamics of Water–Dimethyl Sulfoxide Mixtures by Computer-Simulations. *J. Chem. Phys.* **1993**, *98*, 8160–8173.
- (46) Kashid, S. M.; Singh, R. K.; Kwon, H.; Kim, Y. S.; Mukherjee, A.; Bagchi, S. Arresting an Unusual Amide Tautomer Using Divalent Cations. *J. Phys. Chem. B* **2019**, *123*, 8419–8424.
- (47) Kashid, S. M.; Singh, R. K.; Kwon, H.; Seol, J. G.; Kim, Y. S.; Mukherjee, A.; Bagchi, S. Reply to “Comment on ‘Arresting an Unusual Amide Tautomer Using Divalent Cations’”. *J. Phys. Chem. B* **2021**, *125*, 479–483.
- (48) Wulf, A.; Ludwig, R. Structure and Dynamics of Water Confined in Dimethyl Sulfoxide. *ChemPhysChem.* **2006**, *7*, 266–272.

(49) Ludwig, R.; Farrar, T. C. Temperature Dependence of the Deuteron and Oxygen Quadrupole Coupling Constants of Water in the System Wated Dimethyl Sulfoxide. *J. Phys. Chem. D* **1994**, *98*, 6684–6687.

(50) Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. Ab Initio Calculation of Vibrational Absorption and Circular Dichroism Spectra Using Density Functional Force Fields. *J. Phys. Chem. A* **1994**, *98*, 11623–11627.

(51) Becke, A. D. Density-functional thermochemistry. III. The role of exact exchange. *J. Chem. Phys.* **1993**, *98*, 5648–5652.

(52) Chakrabarty, S.; Maity, S.; Yazhini, D.; Ghosh, A. Surface-Directed Disparity in Self-Assembled Structures of Small-Peptide L-Glutathione on Gold and Silver Nanoparticles. *Langmuir* **2020**, *36*, 11255–11261.

(53) Abraham, M. J.; Murtola, T.; Schulz, R.; Pall, S.; Smith, J. C.; Hess, B.; Lindahl, E. GROMACS: High performance molecular simulations through multi-level parallelism from laptops to supercomputers. *SoftwareX* **2015**, *1–2*, 19–25.

(54) Wang, J.; Wolf, R. M.; Caldwell, J. W.; Kollman, P. A.; Case, D. A. Development and testing of a general amber force field. *J. Comput. Chem.* **2004**, *25*, 1157–1174.

Recommended by ACS

Solvent Polarity under Vibrational Strong Coupling

Maciej Piejko, Joseph Moran, *et al.*

JUNE 08, 2023

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

READ 

Exploring the Origins of the Intensity of the OH Stretch-HOH Bend Combination Band in Water

Rachel M. Huchmala and Anne B. McCoy

AUGUST 08, 2023

THE JOURNAL OF PHYSICAL CHEMISTRY A

READ 

Excitation of NH Stretching Modes in Aromatic Molecules: *o*-Toluidine and α -Methylbenzylamine

J. Ree, H. K. Shin, *et al.*

AUGUST 11, 2023

THE JOURNAL OF PHYSICAL CHEMISTRY B

READ 

Direct Determination of the Relationship between the Intramolecular Oxygen–Hydrogen Bond Length and Its Stretching Vibrational Frequency of the Methanol Molecule...

Yasuo Kameda, Toshiya Otomo, *et al.*

SEPTEMBER 06, 2023

THE JOURNAL OF PHYSICAL CHEMISTRY B

READ 

Get More Suggestions >