New Insights into a Hydrogen Bond: Hyper-Raman Spectroscopy of DMSO-Water Solution

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ARTICLE

New Insights into a Hydrogen Bond: Hyper-Raman Spectroscopy of DMSO-Water Solution

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Hydrogen bonding plays an essential role in biological processes by stabilizing proteins and lipid structures as well as controlling the speed of enzyme catalyzed reactions. Dimethyl sulfoxide-water (DMSO-H_2O) solution serves as a classical model system by which the direct and indirect effects of hydrogen bonding between water hydrogens and the sulfoxide functional group can be explored. The complex transition from self-bonding to heterogeneous bonding is important, and multiple spectroscopic approaches are needed to provide a detailed assessment of those interactions. In this report, for the first time, hyper-Raman scattering was successfully employed to investigate molecular interactions in DMSO-H_2O system. We measured the improper blueshift of the C-S and C-H stretching modes of DMSO caused by partial charge transfer and enhanced bond polarization. By detecting differences in the frequency shifts of C-S and C-H modes for low DMSO concentrations (< 33 mol %) we find evidence of the intermolecular bonds between water and the DMSO methyl groups. We exploit the high sensitivity of hyper-Raman scattering to the low frequency librations of H_2O to observe a change in librational mode population providing insight into existing questions about the coordination of H_2O around DMSO molecules and the formation of the H_2O shell around DMSO molecules proposed in prior simulation studies. These results demonstrate that hyper-Raman spectroscopy can be a practical spectroscopic technique to study the intermolecular bonding of model systems and test claims about model system bonding generated by theoretical calculations.

Introduction

Hydrogen bonding is recognized for its role in giving water unusual properties including its ability to solvate an extremely broad range of ionic and polar molecules.[1] Aqueous solution chemistry and biochemistry are dependent on hydrogen bonding.[1] Molecular self-assembly in living organisms such as protein folding and stabilizing lipid bilayers exploits hydrogen bonding.[1–3] The combination of strength and flexibility allow for the existence of large, flexible supramolecular structures such as the DNA helix.[4] Developing a precise understanding of the mechanisms of hydrogen bonding in aqueous solutions is one of the most important problems in organic chemistry.[5–7]

The need to develop increasingly precise understandings of hydrogen bonding has led to the study of simple “model systems” that allow for the controlled study of hydrogen bonding behavior in solution. As a model system, dimethyl sulfoxide (DMSO) and water (H_2O) solutions has been studied for decades as DMSO-H_2O solution displays many nonideal behaviors such as an extremely low eutectic temperature (-70 °C). The eutectic point occurs at a molar ratio (X) of 1DMSO:2H_2O (X = 0.333)[8] as does maxima or minima of other physical properties including viscosity, and density.[9] This molar ratio corresponds to the stoichiometric ratio where two water molecules are present to hydrogen bond to every DMSO oxygen. The strong deviations of the physical properties of the liquid from the ones of an “ideal liquid” speaks to the high enthalpy of the heterogeneous intermolecular bonds compared to the homogeneous bond enthalpies.[10] Applications of the nonideal liquid behavior of DMSO-H_2O include cryoprotection of tissues,[11] denaturing proteins,[12] and enhancing drug permeation.[13]

It is generally accepted that the structure of DMSO-H_2O solutions is due to hydrogen bonding (HB) between the DMSO-H_2O system resulting in enhanced molecular polarization. Different theoretical models have attempted to understand and explain this dual solvation.[14,15] Most models agree that solvation begins by hydrogen bonding between the DMSO oxygen and the H_2O hydrogen atoms whose bond enthalpy is greater than the self-bonding interactions (Fig. 1a).[10,16,17] This hydrogen bonding polarizes the DMSO S=O bond. Less well understood is to the extent this results in partial charge transfer and partial polarization of the methyl group’s C-H bonds and how significant this partial polarization is to the chemistry of the solution (Fig. 1b).[14,15,18] Two major points of contention remain in dispute. The first is how much interaction

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Electronic Supplementary Information (ESI) available: [Experimental procedures, including materials, data collection, and data processing. Results including pure spectra peak identification, overview of red/blueshifts in DMSO and additional figures for measured vibrational modes]. See DOI: 10.1039/x0xx00000x occurs between H_2O and the DMSO methyl hydrogen atoms due to the partial polarization?[16,19] The second is what is the geometrical arrangement of H_2O around DMSO and can it be viewed as a long term DMSO-H_2O complex?[19] Some models propose this "hydrophobic hydration" between the methyl hydrogens and H_2O is significant and occurs at low H_2O concentrations such as the "push ball" model by Mizuno et al.[14] If so, this process could play a role in the hydration of other organic molecules even in H_2O poor environments such as the lipid membrane of cells. Other models such as Mrazkova and Hobza's "progressive hydration" model claim that the first H_2O molecules hydrogen bond with the DMSO oxygen atom and that hydrogen bonding between the methyl hydrogens and the H_2O molecules occurs later in the final steps of a hydration shell forming around the DMSO molecule.[15]

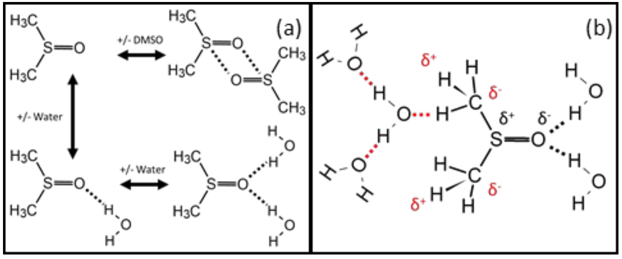

Fig. 1. (a) A DMSO molecule transitioning between bonding with DMSO and H_2O. (b) An expanded view of a DMSO molecule bonding with H_2O with the hypothetical methyl polarization (red text and lines).

The geometrical arrangement of H_2O around DMSO was extensively studied using measurements of physical properties,[20] enthalpy of mixing,[21] nuclear magnetic resonance (NMR),[14] inelastic neutron scattering and x-ray scattering,[22,23] IR absorption,[9,14,16,24] and Raman scattering.[25-27] The vibrational modes of DMSO, deuterated DMSO (DMSO-d_6), H_2O and D_2O are well known.[28-30] Previous IR and Raman studies of DMSO- H_2O have demonstrated that when the liquids were mixed there were detectable redshifts and/or blueshifts of DMSO and H_2O bond vibrations. For our interpretation, we compare our results against previous IR and Raman studies of the DMSO-H_2O system including the S=O response,[9,10] the C-S responses,[31,32] and the C-H responses.[16,33] We additionally rely on previous measurements of the effect of negative ions on the librations of water.[34-36] As our detection method is insensitive to the time dynamics of hydrogen bonding in solution, we refer the reader to other studies that address those observations.[32,37,38]

In this work we, for the first time, analyze the hyper-Raman spectrum of DMSO-H_2O binary systems to provide new insights into the dual solvation processes that occur by studying the responses of modes that are strong in hyper-Raman scattering (HRS). The hyper-Raman selection rules for liquid solutions require all IR active vibrational modes be present in HRS spectra; however, mode intensities may differ drastically.[39] HRS offers insight into low wavenumber signals that are difficult to detect with Raman scattering techniques and allows for probing symmetries in the molecule.[40] We exploit these facts to take measurement of the redshifts and blueshifts of vibrational modes of DMSO, some of which to our knowledge have never been studied. Furthermore, HRS provides opportunities to probe the effect of DMSO on the librational modes of water which have not been studied via Raman or IR spectroscopy. The Raman approach is impractical as H_2O librations are very weak Raman modes easily concealed by the solution background while far-IR absorption measurements would be greatly complicated by the modes' strong absorption. Korepanov et al. demonstrated the librations and rotations of H_2O and D_2O are strong HRS modes.[41] This makes HRS the ideal tool for studying the behavior of these low wavenumber modes in solution. These librations are caused by hydrogen bonding between H_2O molecules that temporarily holds molecules in a semirigid structure. Since the librations are dependent on the strength and probability of H_2O molecules being hydrogen bonded to each other, the librations are sensitive to the formation of hydration shells around ions.[34-36] Having intense librational modes in the mixed solution spectra would allow us to discriminate the water librations from background noise and the wings of the low frequency DMSO modes and probe the hydration shell dynamics of this model system.

We first report HRS observations of S=O and confirm they are qualitatively similar to previous IR observations.[9,10] We then compare the wavenumber shifts and hyperpolarizability enhancements of C-S, and C-H vibrations to search of methyl hydrogen - H_2O interactions. Finally, we detect substantial changes in the intense HRS librational modes of H_2O as DMSO is added and observe that these changes can be explained by the transition between homogeneous and heterogeneous hydrogen bonding.

Results and Discussion

As polar bonding between sulfoxide groups of DMSO molecules plays a dominant role in the formation of aggregated DMSO clusters and the hydrogen bonding of DMSO-H_2O,[27] we show in Fig. 2 the HRS spectra of this region as a function of DMSO concentration (X). The spectral features in Fig. 2 closely resemble Oh *et al.*'s IR study and can be explained by their analysis.[9,10] Dilution of DMSO with H_2O resulted in the rapid reduction of the "free" DMSO response at ~1058 cm^{-1} with an initial rise in the concentration of the "aggregate" state at ~1044 cm^{-1} (X = 1.00 to X = 0.75). Further dilution resulted in suppression of the S=O aggregate state and in increase in the 1 HB state at ~1022 cm^{-1} (X = 0.75 to X = 0.33). At very low DMSO concentrations the further redshifted 2 HB state at ~1012 cm^{-1} can be observed (X = 0.10). We note that the lower two frequencies, 1 HB and 2 HB, overlap a pair of methyl rocking modes which greatly complicates quantitative analysis of the peak amplitudes.[16]

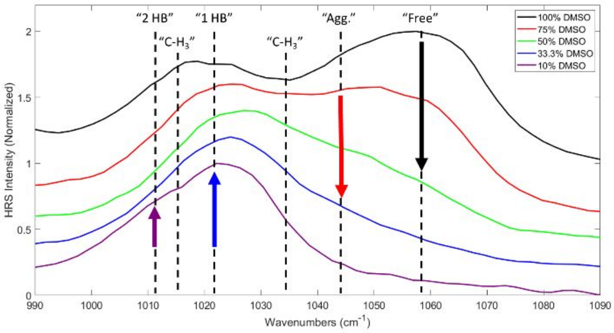

Fig. 2. HRS spectra of sulfoxide and methyl group response in DMSO-H_2O solution. The proposed vibrational modes and their responses to the addition of H_2O are shown with colored arrows.

Next, we consider the indirect effects of hydrogen bonding on the DMSO molecule by detecting a shift in wavenumber of the stretch modes of C-S and C-H bonds. For both bonds the symmetric and asymmetric stretch modes are blueshifted as H_2O is added suggesting the bonds are strengthened. This is in agreement with the blueshifts seen in Refs. 16 and 33 (IR) and Refs. 25, 31, and 32 (Raman). Linear regression of the C-S stretch mode displays two regimes ($X = 1.00$ to $X = 0.70$) and ($X = 0.65$ to $X = 0.01$) as shown in Fig. 3. We compare this to the C-H stretch modes. We observe a transition at $X = 0.70$ similar to the C-S bond. However, we observe a second transition near $X = 0.33$ for both symmetric and asymmetric modes and a possible third transition around $X = 0.05$ for the symmetric mode shown in Fig. 3 (See supporting information for asymmetric modes). The observed multi-transition of the C-H is in good agreement with Ref. 16 and supports the claim of multiple transitions over the single transition around $X = 0.6$ reported by Ref. 25.Both C-S and C-H bonds are strengthened via charge redistribution caused by hydrogen bonding between H_2O and the DMSO oxygen. The change in blueshift slope we observe in Fig. 3 around $X = 0.70$ could be explained by the existence of two states of DMSO in solution (free and aggregate) with the transition occurring because the free DMSO in solution is exhausted leading to H_2O disrupting and hydrogen bonding with aggregate DMSO. C-H shows additional transitions that C-S does not. Since both bonds were affected by enhanced charge polarization of hydrogen bonding to the S=O group, we conclude the enhanced blueshift we see for $X < 0.33$ for C-H was the result of weak hydrogen bonding between the methyl group with H_2O.

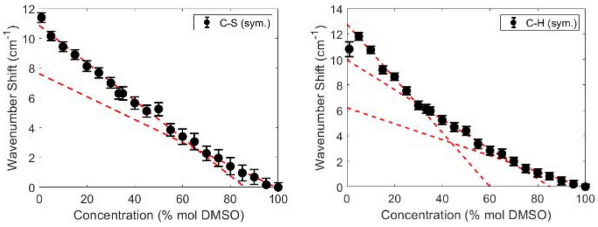

Fig. 3. The wavenumber shift of the C-S symmetric stretch mode (left) and C-H symmetric stretch mode (right). Dashed lines show linear fits of selected regions.

In addition to blueshift, hydrogen bonding caused the intensities of the C-S and C-H stretch modes of DMSO diluted in H_2O not to obey a linear combination of pure DMSO and H_2O responses ($\text{Signal} = X*\text{Signal}_{DMSO} + (1-X)*\text{Signal}_{H2O}$).[16,31] In Fig. 4 top, the deviation of the HRS signal was plotted against concentration for the reduced power of 1.0 W (chosen to mitigate changes in intensity caused by self-focusing in the sample). The C-S and C-H bonds experience hyperpolarizability enhancement for all mixtures with a rapid decrease in signal for $X < 0.4$ (Fig. 4 top). This was reflected in the hyperpolarizability enhancement plots (Fig. 4 bottom), that showed HRS signal enhancement was of a factor of 2x near the eutectic point ($X = 0.33$), the transition of two regimes around the eutectic point for the C-S and C-H modes and that the slope of the C-H mode is dramatically smaller than the slope of the C-S mode for $X < 0.33$. From this we conclude our HRS results supports the claim that H_2O-methyl hydrogen bonding occurs at concentrations up to the eutectic and stress the importance of this information in testing competing models of hydrogen bonding. For example, the credibility of a model would be enhanced if the model could replicate the wavenumber shifts seen in Fig. 2 and the S.I. and/or demonstrate that the dipole moment of the C-S bonds are weakened,[16] the C-S polarizabilities enhanced,[31] and the C-S hyperpolarizabilities enhanced in solution.

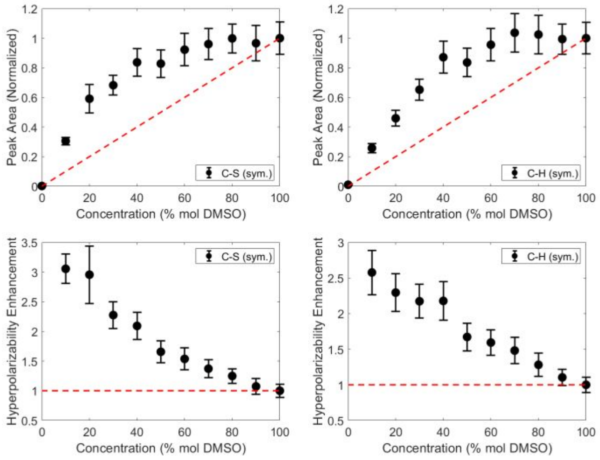

Fig. 4. Integrated signal of the C-S symmetric stretch mode (top left) and C-H symmetric stretch mode (top right). The hyperpolarizability enhancement of the C-S symmetric stretch mode (bottom left) and C-H symmetric stretch mode (bottom right). The red dashed lines show the linear combination of pure signals.

A key advantage of HRS over IR spectroscopy is the ease of detecting the two low frequency librations of H_2O over a range of concentrations. In this experiment, the changes seen in the two librational modes were diametrically opposed. The 750 cm^{-1} libration redshifts to 690 - 700 cm^{-1} and the FWHM narrows from 300 cm^{-1} to 150 cm^{-1} (see Fig. 5) At the same time, the 500 cm^{-1} libration blueshifts to ~540 cm^{-1} and the FWHM broadens from ~220 cm^{-1} to 300 - 400 cm^{-1} (see Fig. 5). The frequency shifts and FWHM changes stabilize at higher DMSO concentrations $X > 0.35$ suggesting that the final values were indicative of the librations of water molecules hydrogen bonded to DMSO. For this system, DMSO appears to act like a large negative anion (such as I^-) as negative ions at molar concentrations are known[34-36] to redshift of the 750 cm^{-1} libration due to the formation of a hydrations shell encompassing the ion. From this study, it appears the changes seen in Fig. 5 between $X = 0.0$ to $X = 0.33$ can be explained as a linear combination of the librations of DMSO hydrogen bonded H_2O molecules and a pure H_2O mode ($\nu = 3X*\nu_{DMSO-H2O} + (1-3X)*\nu_{PureH2O}$ and $\text{FWHM} = 3X*\text{FWHM}_{DMSO-H2O} + (1-3X)*\text{FWHM}_{PureH2O}$).

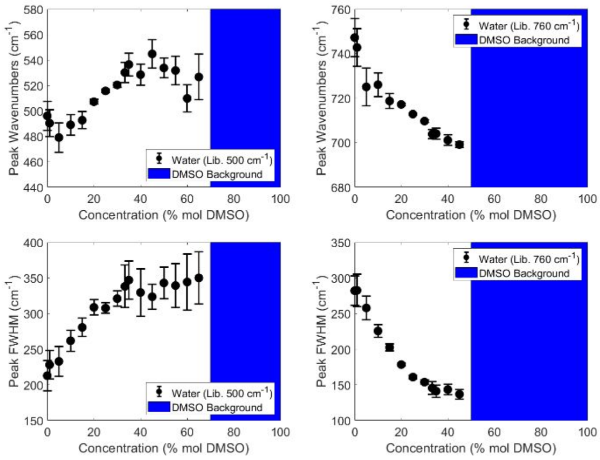

Fig. 5. The wavenumber shifts of the 500 cm^{-1} libration (top left) and 750 cm^{-1} libration (top right). The FWHM of the 500 cm^{-1} libration (bottom left) and 750 cm^{-1} libration (bottom right). In the solid blue regions, the DMSO background reduced the accuracy and precision of the peak fitting algorithm.

Conclusion

DMSO-H_2O solutions are an essential model system to test our understanding of hydrogen bonding. In this report, hyper-Raman scattering is applied for the first time to probe the complex dynamics of DMSO-H_2O solutions over a range of molar ratios. First, we apply HRS to measure the well-studied direct effect of hydrogen bonding of the S=O modes and verify our results were consistent with prior experiments.[9] By comparing the blueshifts of the C-S and C-H stretch modes we found evidence of weak hydrogen bonding of the DMSO methyl hydrogens at DMSO concentrations up to the eutectic (X = 0.33). Finally, we exploited the strong liberational response of H_2O under HRS excitation to report, for the first time, the effect of DMSO addition on H_2O liberation. The addition of DMSO results in a population shift from the 750 cm^{-1} mode similar to the addition of molar concentrations of heavy anions such as I$^-$. These observations provide (1) new experimental results that contribute to our understanding of the DMSO-H_2O model system, (2) provide experimental benchmarks for future computer simulation of hydrogen bonding. and (3) demonstrate the utility of HRS in understanding hydrogen bonding dynamics of model systems.

Conflicts of interest

There are no conflicts to declare.

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