Vibrational Solvatochromism of Alkyne-Derivatized Infrared Probe

Youna Kim and Minhaeng Cho*

Center for Molecular Spectroscopy and Dynamics, Institute for Basic Science (IBS), Korea University, Seoul 02841, Republic of Korea

Department of Chemistry, Korea University, Seoul 02841, Republic of Korea

**E-mail: mcho@korea.ac.kr*

Abstract

Vibrational spectroscopy is effective and useful for studying molecular conformations in condensed phases. Especially useful when small probes are site specifically bound to biomolecular systems. We have analyzed linear IR spectroscopic data and further studied the possibility of interpreting Raman data in terms of specific intermolecular interactions between the probe and its environment. It is important to understand the solvatochromism of Raman imaging, because it can be used to observe small molecules by detecting molecular vibrations and has better spatial resolution than IR imaging. To observe the small molecules, recent Raman imaging experiments attach labels to target molecules, which is called Raman tag imaging. This method can be used to observe the Raman spectra of molecules in the silent region. The silent region is 1800 to 2800 cm^{-1} and certain functional groups show the Raman band in this region. Among the various functional groups, alkyne vibrations provide clear and strong Raman spectra in silent region. In Raman imaging, the alkyne probe can be used to explore the surrounding environment of the molecule through frequency shifts according to solvatochromism.

Vibrational Spectroscopy

IR Absorption Spectroscopy

The IR spectra can be calculated using the cumulant expansion method.

$$I(\omega) \sim \int_{-\infty}^{\infty} dt\, e^{i(\omega-\bar{\omega}_{10})t} \exp[-g(t) - t/2T_1]$$

T_1 : the vibrationally excited state lifetime
g(t) : the line broadening function

$$g(t) = \frac{1}{\pi}\int_0^{\infty} d\omega \coth\left(\frac{\hbar\omega}{2k_BT}\right)\tilde{\xi}_I(\omega)\frac{1-\cos\omega t}{\omega^2} + \frac{i}{\pi}\int_0^{\infty} d\omega\, \tilde{\xi}_I(\omega)\frac{\sin(\omega t)-\omega t}{\omega^2}.$$

An approximate formula based on the linear absorption spectrum of a localized vibrational chromophore can be used to interpret IR spectra of changes in structure and dynamics of a portion of a molecule.

$$I(\omega) \propto \mathrm{Re}\int_{-\infty}^{\infty} e^{i(\omega-\langle\omega_{01}\rangle)t}\langle\exp[-i\int_0^t \delta\omega(\tau)d\tau]\rangle dt$$

From the perspective of interacting with the surrounding environment, it is important to study the absorption line shapes of widely used IR probes. This will help you experiment and analyze vibrational spectroscopic data, frequency shifts, and line shape changes in complex chemical and biological environments.

Raman Scattering Spectroscopy

Raman imaging has a broader range of observations than IR imaging and better spatial resolution. Therefore, it is important to understand the solvatochromism phenomenon, which has a strong and unique Raman signal.
Figure is a solvent-dependent spontaneous Raman spectrum for propargyl alcohol that can be recombined into proteins.

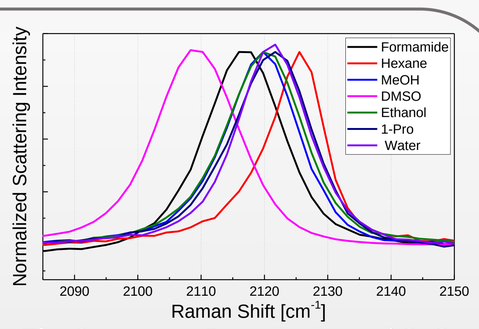
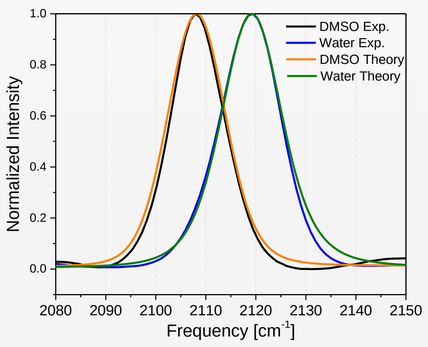


Fig. *Spontaneous Raman spectrum of C≡C stretching of propargyl alcohol.*

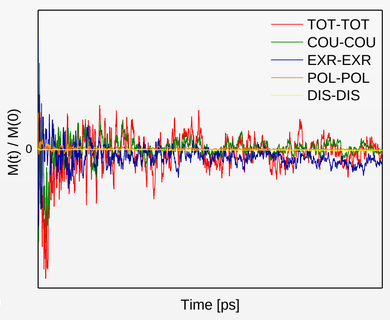
The experiment in Figure shows that alkyne has a wide solvatochromic frequency range. For Raman imaging, probes can be used to determine the immediate molecular environment through spatial changes in complex systems, such as cells or tissues, and solvatochromism changes in frequency.

SolEFP Calculation Results

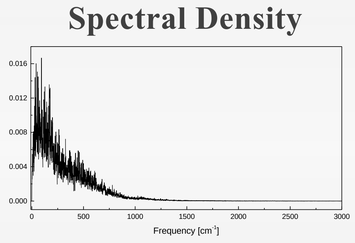
Absorption Spectrum



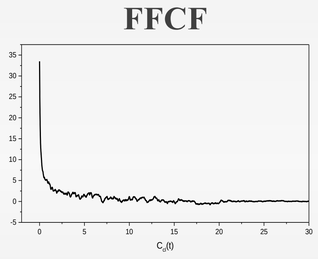
Time Correlation Functions



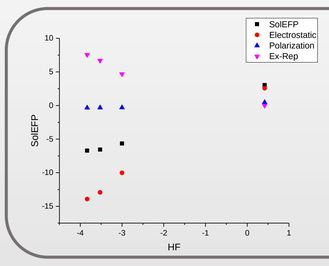
Spectral Density



FFCF



To simulate the IR spectrum, we used a second-order cumulant expansion method based on spectral density calculations. If the static distribution of frequency shifts is approximately Gaussian and the time-dependent third-order cumulant term is negligible, the line shape and width can be obtained using the frequency-frequency autocorrelation function (FFCF). FFCF is defined as $M(t) = \langle\delta\omega(t)\,\delta\omega(0)\rangle$.



Propargyl alcohol and water clusters

The C≡C stretching mode frequency shifts components that were computed for few clusters. Comparison of SolEFP frequency shifts with Hartree-Fock calculations. The frequency shifts are calculated for various Propargyl alcohol-$(Water)_n$ (n=1~4) clusters using both HF method (with 6-311++G** basis set) and SolEFP methods. The frequencies are calculated by HF method, so no dispersion interaction induced frequency shifts contribute to the total frequency shifts in this graph.

Intermolecular Interactions

Intermolecular interactions play an important role in most of the molecular and biological processes that exist in nature. One of the spectroscopic phenomena caused by intermolecular interactions is the frequency shifts of molecular vibrations in solution.

$$\Delta\omega_j = -\frac{1}{2M_j\omega_j}\left[\sum_i \frac{f_i g_{ijj}}{M_i\omega_i^2} - K_{jj}\right] \quad f_i = \left(\frac{\partial U}{\partial Q_i}\right)_{\mathbf{Q}_0} \quad K_{ij} = \left(\frac{\partial^2 U}{\partial Q_i \partial Q_j}\right)_{\mathbf{Q}_0} \quad g_{ijk} = \left(\frac{\partial^3 V}{\partial Q_i \partial Q_j \partial Q_k}\right)_{\mathbf{Q}_0}$$

The vibrational frequency shift of the solute molecule of the *j*th IR active normal mode induced by the interaction with the surrounding solvent molecules is shown in equation.

We will use the effective fragment potential(EFP) method to partition the intermolecular interaction potential and calculate the intermolecular interaction energy(*U*). This will explain the origin of the vibrational frequency shifts caused by solute-solvent interactions.

$$U^{\mathrm{SolEFP}} = U^{\mathrm{Coul}} + U^{\mathrm{Rep}} + U^{\mathrm{Pol}} + U^{\mathrm{Disp}} + U^{\mathrm{CT}}$$

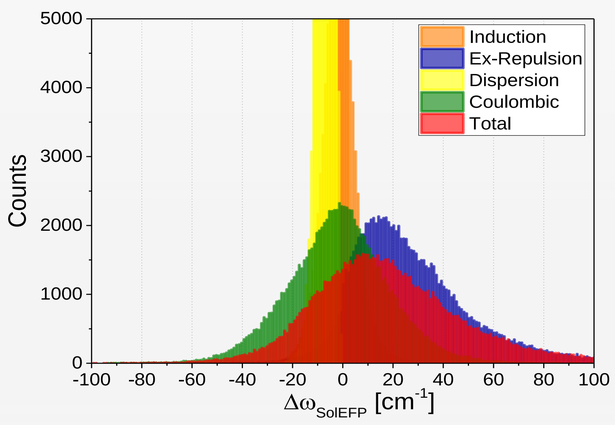
- **Electrostatic** Modeled by the interaction of damped electrostatic distributed multipole moments placed at appropriately selected interaction sites.
- **Exchange-repulsion** Only a single Pauli exchange of electron pairs between monomers is considered when ignoring other multiple exchange effects.
- **Polarization (induction)** Modeled by distributed dipole-dipole static electric polarizations centered on localized molecular orbital centroids for each monomer.
- **Dispersion** Modeled by integrating distributed dipole-dipole dynamic electric polarizations for imaginary frequencies.
- **Charge-transfer** Donor-acceptor interactions between solvent and solute molecules.

$$\Delta\omega_j^{\mathrm{SolEFP}} = \Delta\omega_j^{\mathrm{Coul}} + \Delta\omega_j^{\mathrm{Rep}} + \Delta\omega_j^{\mathrm{Pol}} + \Delta\omega_j^{\mathrm{Disp}} + \Delta\omega_j^{\mathrm{CT}}$$

The corresponding frequency shift obtained from the above equations.

Frequency Shift Distributions

Propargyl alcohol in Water



Propargyl alcohol in DMSO

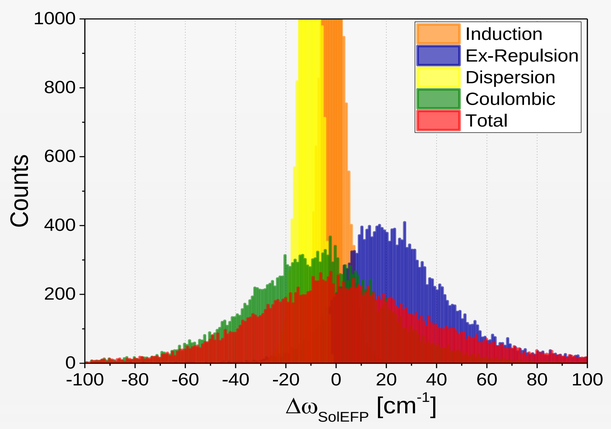


Fig. The frequency shift distributions of C≡C stretching mode of propargyl alcohol dissolved in water and DMSO at 300K, respectively. Obtained by applying the SolEFP method of the C≡C stretching mode in propargyl alcohol to MD simulation trajectories.

$\Delta\omega_{C\equiv C}$ [cm^{-1}]	$\Delta\omega^{SolEFP}$	$\Delta\omega^{Coul}$	$\Delta\omega^{Disp}$	$\Delta\omega^{Rep}$	$\Delta\omega^{Ind}$
Water	18.48	-2.03	-7.10	28.68	-1.06
DMSO	7.32	-9.19	-10.89	28.30	-0.89

Table. The ensemble-averaged values of the frequency shifts.

$\Delta\omega_{C\equiv C}$ [cm^{-1}]	IR Spectrum	$\Delta\omega^{Expt.}$	$\Delta\omega^{SolEFP}$	Error
Gas Phase	2103.5	-	-	-
Water	2119.4	15.9	18.4	**2.5**
DMSO	2107.8	4.3	7.3	**3.0**
Water-DMSO	-	**11.6**	**11.1**	-

Table. The vibrational frequencies of the C≡C of propargyl alcohol in gas phase, Water and DMSO obtained from the experimental data or SolEFP, respectively.

Conclusion

Spectroscopic data is directly related to the locally interacting environment around the probe group. This allows us to identify the unknown topology around the IR probe as well as the equilibrium or dynamic conformation of the biomolecule in the condensed phase, when the average frequency shifts and fluctuation dynamics of a probe incorporated system change as a result of different solvents or structural changes due to target binding or other biologically relevant processes.

Reference

[1] B. Błasiak, M. Cho, *Acc Chem Res* **2017,** *50* (4), 968-976.
[2] B. Błasiak, M. Cho, *J. Chem. Phys*, **2015**, *143*, 164111
[3] M. Cho, *J Chem Phys* **2009,** *130* (9), 094505.

Acknowledgements

This work was supported by IBS-R023-D1