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Molecular dynamics and simulations study on the vibrational and electronic solvatochromism of benzophenone

Venkatraman Ravi Kumar,¹ Chandra Verma,^{2,3,4,a)} and Siva Umapathy^{1,a)}

¹Inorganic and Physical Chemistry Department, Indian Institute of Science, Bangalore 560012, India

²Bioinformatics Institute (A*STAR), 30 Biopolis Street, # 07-01 Matrix, Singapore 138671

³School of Biological Sciences, Nanyang Technological University, 60 Nanyang Drive, Singapore 637551

⁴Department of Biological Sciences, National University of Singapore, 14 Science Drive 4, Singapore 117543

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Solvent plays a key role in diverse physico-chemical and biological processes. Therefore, understanding solute-solvent interactions at the molecular level of detail is of utmost importance. A comprehensive solvatochromic analysis of benzophenone (Bzp) was carried out in various solvents using Raman and electronic spectroscopy, in conjunction with Density Functional Theory (DFT) calculations of supramolecular solute-solvent clusters generated using classical Molecular Dynamics Simulations (c-MDSs). The $>\text{C}=\text{O}$ stretching frequency undergoes a bathochromic shift with solvent polarity. Interestingly, in protic solvents this peak appears as a doublet: c-MDS and *ad hoc* explicit solvent *ab initio* calculations suggest that the lower and higher frequency peaks are associated with the hydrogen bonded and dangling carbonyl group of Bzp, respectively. Additionally, the dangling carbonyl in methanol (MeOH) solvent is 4 cm^{-1} blue-shifted relative to acetonitrile solvent, despite their similar dipolarity/polarizability. This suggests that the cybotactic region of the dangling carbonyl group in MeOH is very different from its bulk solvent structure. Therefore, we propose that this blue-shift of the dangling carbonyl originates in the hydrophobic solvation shell around it resulting from extended hydrogen bonding network of the protic solvents. Furthermore, the $1^1\text{n}\pi^*$ (band I) and $1^1\pi\pi^*$ (band II) electronic transitions show a hypsochromic and bathochromic shift, respectively. In particular, these shifts in protic solvents are due to differences in their excited state-hydrogen bonding mechanisms. Additionally, a linear relationship is obtained for band I and the $>\text{C}=\text{O}$ stretching frequency (cm^{-1}), which suggests that the different excitation wavelengths in band I correspond to different solvation states. Therefore, we hypothesize that the variation in excitation wavelengths in band I could arise from different solvation states leading to varying solvation dynamics. This will have implications for ultrafast processes associated with electron-transfer, charge transfer, and also the photophysical aspects of excited states. © 2016 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4941058>]

I. INTRODUCTION

Solvent effects play a key role in determining the rate of chemical reactions and equilibria,^{1–7} electron transfer reactions,^{8–12} and various photophysical and photochemical processes.^{13–18} The influence of the solvent on the solute can be described in terms of various solvent properties, such as polarity and viscosity. The solute-solvent interactions can be broadly classified into two types: (i) non-specific interactions (Coulombic and van der Waals interactions) and (ii) specific interactions (hydrogen bonding, hydrophobic/solvophobic interactions, etc.).¹⁹ The overall ability of the solvent to solvate the solute through these solute-solvent interactions is collectively referred to as “solvent polarity.”^{2,4,19} In particular, hydrogen bonding²⁰ has been the subject of many experimental and theoretical studies since its inception²¹ because of its fundamental importance in modulating the various molecular and supramolecular structures.^{22–24} Furthermore, the solvent can solvate the solute differently in the ground and excited

electronic states. This is manifested in steady-state electronic absorption and luminescence spectroscopy as solvent polarity dependent changes in the position of the band and in the associated intensity and bandwidth and is known as “electronic solvatochromism.”^{25–27} Thus, it is apparent that the solvent electric field perturbs the electronic structure of the solute leading to concomitant changes in the geometric structure which can be monitored by vibrational spectroscopic techniques. Changes in the vibrational band positions, the associated intensity, and peak-width as a function of solvent polarity are termed as “vibrational solvatochromism.”²⁸

The presence of a solute in a solvent leads to a preferential arrangement of the solvent molecules around the solute at the microscopic level that is very different from the bulk solvent structure; the solvation shell structure corresponding to the region neighboring the solute is called the cybotactic region¹⁴ (which may include multiple solvation shells; the extent of the solute influence on the solvent molecules and hence the extent of the solvation shell are subjective). Macroscopic solvent properties, such as dielectric constant, refractive index, dipole moment, have been used to describe solute-solvent interactions but they have failed to provide detailed

^{a)}Authors to whom correspondence should be addressed. Electronic addresses: umapathy@ipc.iisc.ernet.in and chandra@bii.a-star.edu.sg

insights at the molecular level.¹⁶ Since the solute properties are influenced by the solvation shell structure corresponding to the cybotactic region, understanding of solute-solvent interactions at the microscopic level is of fundamental importance. More recently, several empirical solvent polarity parameters like the Kosower Z-scale, Gutmann's acceptor and donor number, Kamlet-Taft's π^* , α , and β scales, Catalán's Solvent Polarity/Polarizability (SPP), Solvent Basicity (SB), and Solvent Acidity (SA) scales, and Reichardt $E_T(30)$ scale have been used to describe the solute-solvent interactions within the cybotactic region.^{26,27}

To gain insight into the solute-solvent interactions at the microscopic level, computational, and theoretical analyses have become indispensable to complement the experimental observations.^{14,15,23,29,30} Since Onsager and Kirkwood's seminal papers on classical solvation models,³¹ the development of theoretical models to incorporate solvent effects on solute properties has attracted several chemical physicists and theoreticians; since most of the physico-chemical and biological processes of technological and fundamental importance are carried out in the solution phase. Implicit continuum solvation models, particularly those employing quantum mechanics, have satisfactorily reproduced the long-range electrostatic interactions of the solvent with the solute, especially when the macroscopic parameters of the solvent (viz., dielectric constant, refractive index, etc.) are included.³² However, these methods fail dramatically at short distances, when specific solute-solvent interactions like hydrogen bonding, etc., need to be taken into account. In addition, the often used continuum approaches are based on macroscopic solvent parameters and thus fail to provide insight into the detailed atomistic solute-solvent interactions within the cybotactic region. The discrete-continuum solvent model (supramolecule-continuum) approach has been used to describe the solvent effects in which a solute and cybotactic region of the solvent shell structure were embedded in an implicit polarizable continuum solvent model (PCM) and together treated by *ab initio* methods.³³ This model did succeed in accounting for the short-range specific solute-solvent interactions like hydrogen bonding, etc. A major disadvantage of this approach is that the solute-solvent configurations generated by the quantum mechanical energy minimization techniques correspond to energy minima.³⁰ Real liquid solutions are characterized by the fluctuations of the solute-solvent configurations leading to inhomogeneous broadening of the peaks/bands observed with various spectroscopic techniques.³⁴ Therefore, statistical sampling of different solute-solvent configurations using either classical/*ab initio* molecular dynamics simulations (MDSs) or hybrid Quantum Mechanics/Molecular Mechanics (QM/MM) methods is necessary for computer simulations of liquid solutions.^{35–37} In this paper, we demonstrate the applicability of latter mentioned approach using classical molecular dynamics and simulations in understanding the microscopic solvation structure with benzophenone (Bzp) solvatochromism as an example.

Vibrational and electronic solvatochromism of organic molecules containing carbonyl group have attracted various experimental and theoretical investigations owing to its importance in both fundamental and technological relevant

FIG. 1. Molecular structure of benzophenone (Bzp) with atomic numbering.

applications.³⁸ *N*-methyl acetamide a simplest model for a peptide bond has been subjected to enormous solvatochromic studies because of its various biophysical applications.³⁹ Bzp is one such organic molecule containing carbonyl group (an aromatic ketone) with molecular structure as shown in Fig. 1. It has been studied extensively owing to its central importance in understanding the photophysics and photochemistry of organic molecules.⁴⁰ The carbonyl group ($>C=O$) of Bzp is sensitive to the type of electronic transitions and the solvent environment.⁴¹ Therefore, the $>C=O$ stretching frequency has been used as a marker to monitor the reaction dynamics of Bzp in the triplet manifolds.⁴² Recently, Hackett and co-workers have utilized the $>C=O$ stretching frequency as a solvent polarity marker using Raman spectroscopy in conjunction with Density Functional Theory (DFT) calculations and discussed its application as an electrostatic probe for protein and complex environments.⁴³

In this study, we have utilized Raman spectroscopy and computer simulations invoking a supramolecule embedded in a polarizable-continuum solvent model to gain insight into the solute-solvent interactions at the microscopic level. The supramolecule configurations were generated by classical molecular dynamics simulations (c-MDSs), adopting the Optimized Potentials for Liquid Simulation-All Atoms (OPLS-AA) force fields developed by Jorgensen and co-workers.^{44,45} To our knowledge, this is the first report on the use of a discrete solvent model approach to explain the vibrational solvatochromism and solvation structure of Bzp at the molecular level. The main objectives of this study are to understand: (i) the solute-solvent interactions at the microscopic level; (ii) the molecular origin of the solvatochromic shifts observed in electronic and vibrational spectroscopy. We use steady-state electronic absorption and Raman experiments in conjunction with a supramolecule-PCM theoretical approach generated by c-MDS to gain a fundamental understanding of the solvatochromic behavior and solvation structure of Bzp.

II. METHODS

A. Experimental method

Raman spectra were recorded by an upright Raman microscope (Invia Raman Microscope, Renishaw) with a 785

nm laser (HPNIR, Renishaw) and a 20× long working distance objective (Leica). The power at the sample was kept <100 mW. All the Raman spectra shown are solvent subtracted and calibrated with the solvent bands and the precision of the Raman peaks was found to be $\pm 1\text{ cm}^{-1}$. The absorption studies were carried out with a UV-VIS-NIR (UV-Visible-Near Infrared) spectrometer (Lambda 750, Perkin Elmer) with suprasil cuvette (Hellma Analytics) of 1 cm path length. All the Raman and absorption studies were carried out at room temperature (23 °C). Benzophenone (>99%) used in the experiments was obtained from Sigma-Aldrich and was used as received. The following solvents were used in the experiments: n-hexane (HEX), carbon tetrachloride (CCL), methyl acetate (MeAc), acetonitrile (ACN), dichloromethane (DCM), chloroform (CHL), iso-propanol (iPrOH), ethanol (EtOH), methanol (MeOH), chloroethanol (ClEtOH), and trifluoroethanol (TFEtOH). The solvents used in this study were purchased from Merck Millipore and Sigma-Aldrich and were used as received.

B. Computational method

1. Single molecule calculations

All single molecule calculations were carried out with the B3LYP/cc-pVDZ functional in Integral Equation Formalism-Polarizable Continuum solvent Model⁴⁶ (IEF-PCM) as employed in the Gaussian 09 (G09) suite.⁴⁷ Frequency analysis (harmonic approximation) was performed for all optimized geometries and the frequencies are scaled⁴⁸ to account for anharmonicity, etc.; the frequencies were found to be real, indicating that the optimized geometries correspond to local minima. The Potential Energy Distribution (PED) for the normal mode frequency was carried out by VEDA 4.0 software.⁴⁹ PED analysis presents the normal mode co-ordinates as a linear combination of linearly independent 3N-6 internal (local mode) co-ordinates of a non-linear polyatomic molecule.⁴⁹ It is very useful in interpreting the contributions of various functional groups (local modes), e.g., C=C stretching, rocking motions, etc., towards a particular normal mode.¹⁴ The vertical excitation energies were obtained using the Time Dependent (TD)-DFT method with B3LYP functional (in the linear response approach) as implemented in G09.⁵⁰ Natural population analysis was computed on the optimized geometry of Bzp in ground and excited electronic states using the NBO program as implemented in the G09 suite.⁵¹

2. Ad hoc explicit solvent calculations

To understand the hydrogen bonding influence on Bzp, a solvent was added explicitly in an *ad hoc* (supramolecule) approach, which is embedded in an implicit IEFPCM solvent model to account for bulk solvent effects. The number of solvent molecules used in the explicit solvent calculations is one. All the calculations were carried out with the B3LYP/cc-pVDZ method. The vertical excitation calculations of the supramolecule were carried out using the TD-DFT/cc-pVDZ method with B3LYP functional (in the linear response approach) embedded in an implicit IEFPCM solvent model.

3. Molecular dynamics simulations

All c-MDSs were carried out using the Gromacs-4.6 software⁵² utilizing the all-atom optimized potential for liquid simulations (hereafter will be mentioned as OPLS) force field. For the solvents (ACN, MeOH, and EtOH), the OPLS force field parameters were used as implemented in the Gromacs-4.6 software. For the Bzp molecule, the force field parameters were developed by *ab initio* calculations using RHF/6-31G(d) method *in vacuo* as recommended by Jorgensen and co-workers.^{44,45} The partial charges for Bzp were obtained by using the Charges from Electrostatic Potentials using a Grid (CHELPG)⁵³ based method as implemented in the G09 suite and are shown in Table SI in the supplementary material.⁵⁴ The van der Waals (vdW) parameters were obtained from the OPLS force field of corresponding atom types and are listed in Table SII.⁵⁴ The bond stretching and angle bending force constants were obtained using the *antechamber* program⁵⁵ of ambertools12 software and are given in Table SIII.⁵⁴ The torsional parameters for the benzene ring were obtained from the OPLS force field. For the phenyl rotation with respect to the carbonyl group, the torsional parameters were obtained using the *ab initio* RHF/6-31G(d) method *in vacuo* by carrying out a relaxed scan along the torsional angle as depicted in Fig. S1⁵⁴ and the torsional parameters of C—C—C and C—C—C—O dihedral angles are listed in Table SIV.⁵⁴

A cubic box of 1000 solvent (ACN, MeOH, and EtOH) molecules was subject to equilibration simulations over 50 ps under NVT conditions at 298.15 K and was followed by a 200 ps NpT simulation at 298.15 K and 1 atmospheric pressure. The system was coupled to velocity-rescale thermostat and Berendsen barostat⁵⁶ and a 2 fs integration step was carried out with a velocity Verlet integrator.⁵⁷ A Bzp molecule was placed at the center of the pre-equilibrated solvent box and energy minimization by steepest descent was employed to avoid any bad contacts of Bzp with solvent molecules. The energy minimized Bzp-solvent systems were equilibrated by canonical NVT and isothermal-isobaric (Gibb's) NpT simulations as mentioned above. The equilibrated Bzp-solvent systems were then subjected to isothermal-isobaric NpT simulations for 2-3 ns production run at 298.15 K and 1 atmospheric pressure by coupling to a Nose-Hoover thermostat and a Parrinello-Rahman barostat,⁵⁸ respectively, and were used for subsequent analysis. Velocity-rescale thermostat and Berendsen barostat does not sample the canonical ensemble properly but can be used for equilibrium run because it can achieve required thermodynamical parameters at a faster time scales. The production run was carried out with Nose-Hoover thermostat and a Parrinello-Rahman barostat to ensure a proper sampling of the canonical ensemble. In all the simulations, the cutoff for vdW and electrostatic interactions was 1.10 nm (a switching function was applied to the vdW term at 1.05 nm) and 1.40 nm, respectively. The energy and pressure term for long range dispersion beyond the vdW cut-off radii were corrected and the particle mesh Ewald (PME) method⁵⁹ was used to account for long range electrostatic interactions. Since we were using a 2 fs integration step for all the simulations, all X—H bonds were constrained by LINCS constraint algorithm as implemented

in Gromacs.⁶⁰ The neighbor group list was updated every 5 integration steps (10 fs) by the grid method as implemented in Gromacs.

4. Extraction of solute-solvent clusters and their optimization

Radial distribution functions (RDFs) of the solvents relative to Bzp were obtained using the Gromacs post-processing tool and are shown in Fig. S2.⁵⁴ All RDFs were obtained with respect to the center of mass of both solute and solvents. Since we are interested in hydrogen bonding interactions only, solute-solvent clusters up to the first solvation shell were chosen for DFT calculations. To this end, cluster size was truncated at the first minimum of RDFs for solvents, viz., 6.4, 6.2, and 6.6 Å for ACN, MeOH, and EtOH solvents respectively, as shown in Fig. S2⁵⁴ and these correspond to 7, 10, and 8 solvent molecules, respectively. Structures that are correlated do not provide new information and since quantum mechanical calculations are computationally expensive for supramolecular clusters, there is a need for choosing only the clusters that are statistically uncorrelated. The dipole-dipole autocorrelation functions (ACFs) were obtained for ACN, MeOH, and EtOH solvents and the decay of ACFs (τ) was found to be 4.2, 6.8, and 28.4 ps, respectively. Therefore, 50 snapshots of the NPT production run for each solvent were chosen at an interval of 8.4, 13.6, and 56.8 ps, respectively (please note that twice the τ value is generally considered to contain statistically uncorrelated states³⁵), and was used for subsequent DFT calculations. The hydrogen bonding criteria used in all c-MDS analysis are $r(\text{A}—\text{H}—\text{D})$ of 3.5 Å and $\angle\text{ADH}$ of 30°.

For the reason mentioned in the Introduction, the solute-solvent clusters were partially optimized (using the normal mode optimization method)⁶¹ such that the solute-solvent intermolecular conformations obtained from MDS were subjected to minimal changes while relaxing the higher frequency necessary for further analysis. The partial optimization of clusters obtained from MDS was performed with the B3LYP/cc-pVDZ functional embedded in an implicit IEFPCM solvent model to treat the bulk solvent polarization. The modes within 250i -250 cm⁻¹ were kept constant during the DFT calculations using QGRAD^{61,62} interfaced to the G09 program. The frequency calculations were performed on the partially optimized clusters as mentioned above under the harmonic approximation. The simulated Raman spectra were obtained using the following equation:⁶³

$$I_{\text{Raman}}^{\text{Simulated}} = \left(\frac{2^4 \pi^4}{45} \right) \left\{ \frac{(\tilde{\nu}_{\text{exc}} - \tilde{\nu}_j)^3 \tilde{\nu}_{\text{exc}}}{1 - \exp\left(-\frac{hc\tilde{\nu}_j}{k_B T}\right)} \right\} \times S_J \left(\frac{h}{8\pi^2 c \tilde{\nu}_j} \right) \left\{ 4 \left(\frac{\tilde{\nu}_j - \tilde{\nu}_{\text{max}}}{\Delta\tilde{\nu}_{\text{FWHM}}} \right)^2 + 1 \right\}, \quad (1)$$

where $\tilde{\nu}_{\text{exc}}$ and $\tilde{\nu}_j$ are the laser excitation frequency and the vibrational frequency of the j -th mode (cm⁻¹), respectively; k_B , h , and c are the Boltzmann constant, Planck's constants, and velocity of light, respectively; the last term in Eq. (1) is the Lorentzian line shape function, where $\tilde{\nu}_{\text{max}}$ and $\Delta\tilde{\nu}_{\text{FWHM}}$

are obtained from the average and standard deviation of the histogram plot of the vibrational frequencies obtained from the DFT calculations. Simulated Raman spectra of Bzp in different solvents were scaled by a factor such that they match the experimental Raman spectra of the corresponding solvents.

III. RESULTS

Benzophenone shows intriguing solvatochromic behavior when interrogated using both vibrational and electronic spectroscopies. Hence, a detailed solvatochromic analysis of Bzp was carried out using electronic and Raman spectroscopy experiments. These results are corroborated and rationalized with extensive *ab initio* calculations of solute-solvent supramolecular clusters generated by full atomistic classical molecular dynamics and simulations and the results are presented in Secs. III A–III C.

A. Raman spectra

Bzp has 24 atoms and therefore it has 66 normal vibrational modes. The crystal structure of Bzp has approximate C₂ symmetry with both benzene rings having a planar structure.⁶⁴ The computed C=O bond length of Bzp is found to be 1.23 Å, which is in agreement with the X-ray crystal structure.⁶⁴ The other computed and experimental bond lengths of Bzp are listed in Table SV⁵⁴ and are in very good agreement.

To assign the peaks observed in the Raman spectra of Bzp in ACN solvent, normal mode analysis was carried out on the optimized geometry of Bzp with C₂ symmetry; there are 33 A and 33 B symmetry vibrational normal modes. The computational (implicit solvent model) and experimental Raman spectra of Bzp in ACN solvent are shown in Fig. 2 and are in very good agreement with each other in terms of relative intensities and positions. Some of the representative peaks are indicated in Fig. 2 and the complete vibrational assignments of Bzp are given in Table SVI.⁵⁴ The PED analysis of the ν_{6a} mode demonstrates that it has a dominant contribution from the C=O stretching mode. Similarly, ν_{7a} , ν_{15a} , and ν_{19a} modes are assigned to an aromatic C=C stretching mode, C—H bending mode, and in-phase symmetric ring breathing mode of both phenyl groups, respectively; the assignments of other vibrational modes are given in Table SVI.⁵⁴

To examine the solvent effect on the structure of Bzp in the ground electronic state, we have carried out Raman experiments in selected solvents of diverse solvent polarity as shown in Fig. S3.⁵⁴ The C=O stretching frequency is sensitive to the solvent polarity and shows a red-shift with increasing polarity. Interestingly, in protic solvents this peak appears as a doublet and coalesces into a single broad peak for stronger hydrogen bond donating (HBD) solvents such as TFEOH, as seen in Fig. 3, while other peaks in the fingerprint region show no dependence on the solvent polarity. These observations are in very good agreement with previous work by Hackett and co-workers.⁴³ The C=O stretching frequency in different solvents of varying polarity and their various solvatochromic

FIG. 2. (a) Computational and (b) experimental Raman spectra of Bzp in ACN solvent under off-resonance conditions, λ_{exc} : 785 nm. Some of the representative Raman peaks are indicated. Refer to Table SVI⁵⁴ for the assignments.

parameters are tabulated in Table I. Hereafter, C=O stretching in aprotic solvents will be indicated as ν_{6a} , while the lower and higher C=O stretching frequencies in protic solvents will be indicated as ν'_{6a} and ν''_{6a} , respectively. A plot of the >C=O stretching frequency in different solvents of varying polarity and their corresponding Gutmann's acceptor number (AN) is shown in Fig. 4. A very good linear correlation was obtained for the ν_{6a} and ν'_{6a} peaks with polarity. The ν''_{6a} peak in protic solvents followed a distinct straight line (not shown).

To understand the origin of the two peaks in protic solvents, *ab initio* calculations were carried out using two methods, viz., (i) with implicit solvent model; and (ii) with engineered single explicit protic solvent embedded in a corresponding implicit solvent model (supramolecule approach). For the latter method, the hydrogen bond between the Bzp and protic solvents was confirmed by the second-order perturbative NBO analysis which indicates a charge transfer from the lone pair orbital of the oxygen atom of the Bzp to the anti-bonding orbital of the O—H bond of the protic solvents as given in Table SVIIa.⁵⁴ The C=O stretching frequency obtained by the supramolecule approach was found to be red-shifted from the implicit solvent model calculation as indicated in Table SVIIb.⁵⁴ Therefore, the lower and higher

FIG. 3. Solvatochromic shift of >C=O stretching frequency of Bzp. The vertical dashed-dotted line is used as a reference line to visualize the >C=O peak shift with respect to CCL solvent.

frequency peaks seen in protic solvents were assigned to the hydrogen bonded and dangling (free) carbonyl stretching vibrations respectively.

Despite, the macroscopic polarity (Onsager's polarity) of ACN and MeOH solvents is similar (refer to Table II) the dangling carbonyl peak (ν''_{6a}) position of Bzp in MeOH solvent is blue shifted by 4 cm^{-1} relative to the ν_{6a} in ACN solvent. This indicates that the microscopic environment of the dangling carbonyl is very different. The empirical solvent polarity of the dangling carbonyl environment is evaluated from the linear fit obtained from Fig. 4 as seen in Fig. S4.⁵⁴ It indicates that the microscopic solvation structure of the dangling carbonyl in protic solvents resembles more of a non-dipolar environment as shown in Fig. S4.⁵⁴ To understand the microscopic solvation structure of the dangling carbonyl of Bzp in protic solvents, we have carried out extensive

TABLE I. Solvatochromic shifts of $>C=O$ stretching frequencies in different solvents.

Solvent	C=O peak position ^a /cm ⁻¹	Solvatochromic parameters ^b			
		AN	α	π^*	$f(\epsilon_r, n^2)$
HEX	1670	0.0	0.00	-0.04	0.001
CCL	1666	8.6	0.00	0.28	0.022
MeAC	1664	10.7	0.00	0.60	0.439
ACN	1662	18.9	0.19	0.75	0.610
DCM	1660	20.4	0.13	0.82	0.434
CHL	1658	23.1	0.20	0.58	0.296
iPrOH	1655 (1668)	33.5	0.76	0.48	0.553
EtOH	1654 (1667)	37.1	0.86	0.54	0.580
MeOH	1652 (1666)	41.3	0.98	0.60	0.617
ClEtOH	1650 (1662)	...	1.28	0.46	0.525
TFEtOH	1648	53.8	1.51	0.73	0.639

^aExperimental Raman peaks obtained under off-resonant condition with 785 nm excitation wavelength. The value in parentheses is $>C=O$ stretching frequency in the higher wavenumber side (ν''_{6a}).

^bAN—Gutmann's acceptor number; α —Taft hydrogen bond donating of the solvent; π^* —Taft dipolarity/polarizability scale and $f(\epsilon_r, n^2)$ —Ongsager's polarity function. Please refer to Refs. 27 and 14 for further details.

classical molecular dynamics and simulations in conjunction with *ab initio* calculations and the results are presented in Sec. III C.

B. Electronic spectra

The absorption spectrum of Bzp displays an interesting solvatochromism and is more pronounced in protic solvents.^{65–68} In the UV range (>220 nm), the spectra comprises two bands, viz., (i) a weak band (~ 340 nm and $\log \epsilon \sim 2$) hereafter referred to as band I; and (ii) a strong band (~ 250 nm and $\log \epsilon \sim 5$) hereafter called band II. The absorption spectra of Bzp in various solvents of diverse polarity are shown in Fig. S5.⁵⁴ It is seen that bands I and II undergo a blue shift and red shift, respectively, with increasing polarity. The electronic assignments of these bands are given in Table SVIII;⁵⁴ band II involves several electronic transitions, of which the most intense electronic transition was related to the experimentally observed absorption maximum. The Frontier

TABLE II. Solvatochromic shifts of absorption bands I and II of Bzp in different solvents.

Solvent	Band I	Band II	Solvatochromic parameters ^a			
	$\lambda_{\max}/\text{nm}^b$		$E_T(30)$	A	π^*	$f(\epsilon_r, n^2)$
Hex	346.6 (28 852)	248.0 (40 323)	31.0	0.00	-0.04	0.001
CCL	345.0 (28 986)	...	32.4	0.00	0.28	0.022
MeAC	341.8 (29 257)	...	40.0	0.00	0.60	0.439
ACN	339.0 (29 499)	251.0 (39 841)	45.6	0.19	0.75	0.610
DCM	338.8 (29 516)	...	40.7	0.13	0.82	0.434
iPrOH	334.6 (29 886)	252.0 (39 683)	49.2	0.76	0.48	0.553
EtOH	332.8 (30 048)	252.6 (39 588)	51.9	0.86	0.54	0.580
MeOH	331.6 (30 157)	253.0 (39 526)	55.4	0.98	0.60	0.617
TFEtOH	328.0 (30 488)	256.0 (39 063)	59.8	1.51	0.73	0.639

^a $E_T(30)$ —Reichardt's empirical solvent polarity scale; α —Taft hydrogen bond donating ability of the solvent; π^* —Taft solvent polarity scale for dipolarity/polarizability; $f(\epsilon_r, n^2)$ —Ongsager's polarity function which is defined as $f(\epsilon_r) - f(n)$; $f(\epsilon_r) = (2\epsilon_r - 1)/(2\epsilon_r + 1)$ and $f(n^2) = (2n^2 - 1)/(2n^2 + 1)$.

^bThe values in parentheses are in wavenumbers (cm⁻¹). The UV cutoff of MeAC, DCM, and CHL solvents interfere with band II position.

Molecular Orbitals (FMOs) of the corresponding electronic transitions are given in Fig. S6.⁵⁴ Band I involves excitation of an electron from an n to the π^* orbital as shown in Fig. S6⁵⁴ and is assigned to a $1n\pi^*$ transition. Band II involves excitation of an electron from π to π^* orbital as shown in Fig. S6⁵⁴ and is assigned to a $3\pi\pi^*$ transition. The assignments are in excellent agreement with the solvatochromic behavior observed in both experiments and in computations.

Band I in ACN (aprotic dipolar) and MeOH (protic dipolar) solvents undergoes a blue shift of 647 and 1305 cm⁻¹, respectively, relative to HEX (aprotic non-dipolar) solvent. In contrast, band II in ACN and MeOH solvents undergoes a red shift of -482 and -797 cm⁻¹, respectively, relative to HEX solvent. For the solvatochromic shifts of both bands in other solvents with their solvent polarity parameters, please refer to Table II. Additionally, band I shows a vibronic structure in non-dipolar solvents with an average spacing of ~ 1200 cm⁻¹ has been assigned to the carbonyl stretching frequency of Bzp in the S_1 state and it is in close agreement with the calculated frequency of 1251 cm⁻¹ (scaled by 0.9717 factor), while in dipolar solvents it is broadened due to different solvent environments (inhomogeneous broadening). The relative shifts of the C=O stretching frequency (cm⁻¹) and band I (cm⁻¹), respectively, in different solvents with respect to HEX are charted in Fig. S7⁵⁴ and a linear relationship is observed with a high correlation coefficient.

C. Molecular dynamics simulations

To understand the microscopic solvation structure of Bzp, we have carried out c-MDS in conjunction with DFT calculations in the discrete-continuum (supramolecule-continuum) solvent approach. To explain the intriguing aspects of Raman spectra for Bzp in protic solvents as mentioned in the vibrational solvatochromism section, we have performed c-MDS of Bzp in ACN (aprotic dipolar), as well as in MeOH and EtOH (protic dipolar) solvents. All c-MDS analyses were performed on the production runs.

FIG. 4. A plot of Gutmann's Acceptor Number (AN) and $>C=O$ stretching frequency. Refer to the main text for further discussions.

FIG. 5. Radial Distribution Functions (RDFs) of carbonyl oxygen atom of Bzp with hydrogen (solid line) and oxygen (dashed-dotted line) atoms of MeOH. The vertical dashed line is the hydrogen bonding cut-off distance used in this study.

The RDFs of the carbonyl oxygen atom of Bzp with the oxygen (hereafter indicated as $g(r)_{\text{O-O}}$) and hydrogen (hydrogen bond donor of MeOH; hereafter indicated as $g(r)_{\text{O-H}}$) atoms of MeOH, respectively, are shown in Fig. 5. Some of the important features of these RDFs are as follows; (i) a first maximum at ca. 2.94 and 2.06 Å with a shoulder at ca. 4.84 and 5.40 Å for $g(r)_{\text{O-O}}$ and $g(r)_{\text{O-H}}$, respectively; and (ii) a broad second maximum at ca. 8.00 Å for both RDFs. Similar RDFs for Bzp in EtOH solvent were plotted as shown in Fig. S8.⁵⁴ The hydrogen bond lifetimes for MeOH and EtOH with Bzp were calculated and are given in Table SIX.⁵⁴ For all hydrogen bond analyses, a time resolution of 2 ps was used, i.e., hydrogen bonds broken and reformed between the same neighboring molecules within 2 ps are considered as a single hydrogen bond while those that exist for less than 2 ps were not considered in the analysis.⁶⁹ The average hydrogen bond lifetimes for MeOH and EtOH were computed to be 5.3 and 21 ps, respectively, and the number of hydrogen bonded carbonyls in MeOH and EtOH solvents over 2 ns production simulation was found to be 106 and 48, respectively. Therefore, the total hydrogen bond residence time for Bzp in MeOH and EtOH was calculated to be 561.8 and 1008 ps as given in Table SIX, which corresponds to a population of ~28% and 50% hydrogen bonded conformers in MeOH and EtOH solvents, respectively (please refer to Table SIX⁵⁴ for details).

The supramolecule (Bzp molecule with the first solvation shell) obtained from c-MDS snapshots was partially optimized using the DFT method (please refer to Sec. II for details). The selected snapshots of Bzp in ACN, MeOH, and EtOH solvents after partial optimization by the DFT method are shown in Fig. S10.⁵⁴ Interestingly, in protic solvents, both dangling and hydrogen bonded carbonyl solute-solvent conformers were obtained. A histogram plot for the distribution of O—O and O—H distances of hydrogen bonded Bzp clusters in MeOH and EtOH solvents are charted in Fig. S9.⁵⁴ There is a good similarity between the histogram plot (Fig. S9⁵⁴) and the radial distribution functions represented in Figs. 5 and S8,⁵⁴ which indicates that the solute-solvent conformers

are intact after the partial optimization as mentioned in Sec. II B. Furthermore, most of the dangling carbonyls were exposed to the hydrophobic region of the protic solvents as depicted in Figs. S9(b) and S9(c). The simulated Raman spectra of the C=O stretching frequency of Bzp in ACN, MeOH, and EtOH solvents (this vibrational frequency being sensitive to the solvent polarity) are shown in Fig. 6 and were obtained as discussed in Sec. II. Interestingly, in protic solvents two peaks were obtained in remarkable agreement with the experiment, viz., the lower (ν'_{6a}) and the higher (ν''_{6a}) C=O stretching frequency corresponding to hydrogen bonded and dangling carbonyls, respectively. Their relative peak positions and intensities are also in excellent agreement with the experimental observations.

FIG. 6. Simulated Raman spectra of Bzp in ACN, MeOH, and EtOH solvents. Each spectrum is scaled to match the experimentally observed peaks. Please refer to Sec. II for further details on the spectra. The blue, green, and red sticks in protic solvents correspond to zero, one, and two hydrogen bonded carbonyl groups, respectively.

IV. DISCUSSION

We aim to shed light on the microscopic solvation structure of Bzp, to this end we have performed Raman, electronic absorption spectroscopy in conjunction with DFT calculations of supramolecular solute-solvent clusters generated by c-MDS; the experimental and computational results obtained are rationalized in Secs. IV A–IV D.

A. Vibrational solvatochromism

The C=O stretching frequency of Bzp undergoes a red-shift with increasing solvent polarity (bathochromic shift) as shown in Fig. 3. This shift could be interpreted in two ways: (i) either by inspecting the resonance canonical structures of Bzp as depicted in Fig. S11⁵⁴ or (ii) could arise from a change in the dipole moment of the ground and excited vibrational states according to the following equation:

$$\Delta E_{g \rightarrow e} = -\mu_g \cdot \Delta \mu_{eg} a^{-3} \Delta f(\epsilon, n^2), \quad (2)$$

where $\Delta E_{g \rightarrow e}$ is the solvatochromic shift of the vibrational peak as a function of change in the solvent dipolarity/polarizability $\Delta f(\epsilon, n^2)$, μ_g (vector quantity) represents the dipole moment of the ground vibrational state, $\Delta \mu_{eg}$ ($\mu_e - \mu_g$) is the difference in dipole moment between the excited and ground vibrational states, and a^3 is the solute volume (values in CGS units). Therefore, a bathochromic shift occurs when the dipole moment in the excited vibrational state is greater than in the ground state (assuming the dipole moments of both states are in the same directions). According to this equation, a linear relationship should be obtained for the peak shift with solvent polarity, although the above equation fails dramatically when specific solute-solvent interactions also contribute to the observed peak shifts. Therefore, an empirical solvent polarity scale like Gutmann's AN was used in our study to correlate the experimentally observed peak shifts as indicated in Fig. 4. The observed bathochromic shift of C=O stretching frequency suggests that the dipole moment of the excited vibrational state is greater than that of the ground vibrational state and therefore we propose that Bzp has a positive dipole moment derivative ($\partial \mu / \partial Q_{6a} > 0$) for the C=O stretching mode.⁷⁰ The ν''_{6a} peak falls in the non-dipolar region as shown in Fig. 4; this underscores the proposition that the dangling carbonyl group is exposed to the hydrophobic-like environment of the protic solvents. The above proposition is supported by classical molecular dynamics simulation studies as will be discussed in Sec. IV B.

B. Solvation structure of benzophenone in protic solvents

The sharp maximum for $g(r)_{O-H}$ and $g(r)_{O-O}$ of Bzp in MeOH at 2.06 and 2.94 Å, respectively, as shown in Fig. 4, shows a strong evidence for hydrogen bond formation between them. Similar RDFs were obtained for Bzp in EtOH solvent, indicating hydrogen bond formation for the latter. The hydrogen bonded population of Bzp in MeOH and EtOH solvents indicates that the both dangling and hydrogen bonded sub populations exist. As discussed in Sec. III A that ACN

and MeOH solvents have similar Onsager's polarity (refer to Table II), the ν''_{6a} peak in MeOH is blue shifted by 4 cm⁻¹ compared to ν_{6a} peak in ACN solvent as shown in Figs. 3 and S4.⁵⁴ This suggests that the local solvent structure of the dangling carbonyl in protic solvents is very different from the bulk solvent structure and is supported by inspecting some of the snapshots of Bzp in protic solvents as shown in Figs. S9(b) and S9(c).⁵⁴ The collective fluctuation of the hydrogen bonding network in the second solvation shell requires the hydrogen bonded carbonyl of Bzp also to be dynamic. Whenever the protic solvents are hydrogen bonded to the second solvent shell (due to the collective fluctuation of the hydrogen bonding network), they orient the hydrophobic region towards the carbonyl group, giving its environment a hydrophobic-like character. The snapshots of a part of molecular dynamics simulation clearly depict that initially the MeOH hydrogen bonded to the secondary solvent shell thereby exposing the dangling carbonyl group of Bzp to the hydrophobic-like environment and then switches its hydrogen bond to the carbonyl group of Bzp by undergoing a reorientational motion assisted by MeOH molecules in the first solvent shell as seen in Fig. S12⁵⁴ (a molecular dynamics movie of the trajectory illustrating the above mentioned dynamics is provided in the supplementary material⁵⁴). Therefore, we propose that the blue shift observed for the dangling carbonyl stretching frequency (ν''_{6a}) originates in the microscopic hydrophobic-like solvent structure surrounding the dangling carbonyl group due to the extended hydrogen bonded network of the protic solvents. These observations suggest that the Bzp carbonyl group is very sensitive to the solvent/environment polarity at the molecular level, which explains its suitability as a polarity marker.

C. Electronic solvatochromism

In general, the solvatochromic shifts observed in the electronic absorption spectrum in aprotic dipolar or non-dipolar solvents can be explained by Eq. (2), where the subscripts in the equation correspond to the electronic states. In other words, a bathochromic shift occurs when the excited electronic state dipole moment is greater than that in the ground state and vice versa for the hypsochromic shift. A linear relationship between the solvent polarity function (Δf) and the solvatochromic shifts is expected in aprotic dipolar and non-dipolar solvents, but this equation fails dramatically, when, in addition to electrostatic interactions, specific interactions play a role in the differential solvation of the ground and excited electronic states. Therefore, in order to gain a fundamental understanding of solute-solvent interactions and the relative contributions of non-specific and specific interactions towards differential solvation in the ground and excited states, we have carried out Linear Solvation Energy Relationships (LSERs) of both bands I and II using the Kamlet-Taft (K-T) approach¹³ and using the following equations (using multiple parameter linear regression analysis):

$$XYZ = XYZ_0 + s\pi^* + a\alpha, \quad (3)$$

$$XYZ = XYZ_0 + s(\pi^* + d\delta) + a\alpha, \quad (4)$$

where XYZ is the observed solvatochromic shift from the experiment, XYZ_0 is the intercept, s is the dipolarity/polarizability, d is the polarizability correction term, a is the HBD ability of the solvents and δ , π^* , α are the respective K-T polarity scales. Equations (3) and (4) were used for solvatochromic analysis of bands II and I, respectively. These equations are obtained for the solute Bzp and the solvents used in the present study but for the complete K-T equation and its description please refer to our previous work.¹⁴ The LSERs for Bzp in different solvents of diverse polarity obtained by multiple parameter linear regression analysis are

$$\tilde{\nu}_{\max}^{\text{band II}}(\text{cm}^{-1}) = 40\,320 - 480\pi^* - 570\alpha, \quad (5)$$

$$n = 6; \text{Adj } R^2 = 0.99; sd = 40,$$

$$\tilde{\nu}_{\max}^{\text{band I}}(\text{cm}^{-1}) = 28\,900 + 670(\pi^* - 0.2\delta) + 840\alpha, \quad (6)$$

$$n = 9; \text{Adj } R^2 = 0.99; sd = 50,$$

where Eqs. (5) and (6) are the K-T equations for bands II and I, respectively. The K-T equations predict that the hydrogen bonding interaction is dominant for both bands II (54%) and I (51%). The contributions were calculated from the corresponding K-T Eqs. (5) and (6), e.g., in Eq. (5), the sum of all the contribution of interactions is 1050 and then each contribution is weighted by the sum of all the contributions leading to 46% and 54% of non-specific and hydrogen bonding interactions, respectively, for band II.

In light of the above, we propose that the hypsochromic and bathochromic shifts of bands I and II in protic solvents are due to hydrogen bond weakening and strengthening, respectively, in the excited state. This hydrogen bond mechanism in the excited state is also supported by the electron density difference⁷¹ analysis of the respective electronic transitions as shown in Fig. S13.⁵⁴ Band I involves an electronic transition from HOMO (n) to LUMO (π^*) orbitals with a concomitant decrease in the electron density at the carbonyl oxygen atom. In contrast, band II involves an electronic transition from HOMO-3 and HOMO-2 (π) to LUMO (π^*) with a concomitant increase in the electron density at the carbonyl oxygen atom. Therefore, the charge redistribution at the C=O site for electronic transition corresponding to bands I and II may assist in hydrogen bond weakening and strengthening, respectively. This is further corroborated by the vertical excitation calculations of Bzp with *ad hoc* one explicit solvent (MeOH) and the corresponding implicit solvent approach. The Bzp with *ad hoc* one explicit solvent undergoes a blue and red shift for the S_0 - S_1 and S_0 - S_4 electronic transition relative to the implicit solvent method, respectively, as shown in Table SX.⁵⁴ Although, Kamlet-Taft linear solvation energy relationship has some inherent challenges in separating the contribution of dielectric and hydrogen bonding effects⁷² but the vertical excitation energy calculations with implicit and explicit solvent models mentioned above can provide direct evidence for the influence of hydrogen bonding in the excited state.

D. Solvatochromic shifts and solvation dynamics

Interestingly, a linear relationship was obtained for the relative shifts of the $>\text{C}=\text{O}$ stretching frequency and the $1^1n\pi^*$

transition of Bzp in different solvents. This may be explained by the following hypotheses: (i) the blue shift of band I arises predominantly from the ground state stabilization relative to the excited state and (ii) the electronic transition of band I is localized in the carbonyl group. Since the $>\text{C}=\text{O}$ stretching frequency is a measure of the ground state solvation of the carbonyl group, it correlates well with the solvatochromic shift of band I as shown in Fig. S7.⁵⁴ In this study, we have focused on the solvatochromic shifts and the associated hydrogen bonding dynamics. The potential energy curve for intermolecular hydrogen bonding of MeOH with Bzp in the S_0 and the $S_1(n\pi^*)$ states is shown in Fig. 7. Interestingly,

FIG. 7. A scheme for solvation state selective excitation: The band I absorption spectrum (scheme) of Bzp in MeOH solvent in which the red and blue edges of the band correspond to the dangling and the hydrogen bonded carbonyls. On the right and left sides of the absorption spectrum are the proposed solvation structures corresponding to the blue and red edges of the band I. The potential energy curve (scheme) for intermolecular hydrogen bonding of MeOH with Bzp for S_0 and $S_1(n\pi^*)$ states is shown. Please refer to the main text for further details.

in the S_1 state, the charges on the oxygen and carbon atoms of the carbonyl group of Bzp are reversed relative to the S_0 state (photo-umpolung) as shown in Table SXI.⁵⁴ Therefore, in the S_1 state, Bzp undergoes hydrogen bond weakening with respect to the S_0 state and the potential energy curve is dissociative as shown in Fig. 7. It indicates that the blue-edge and red-edge excitations on band I might lead to different solvation dynamics in protic solvents (apart from the intramolecular structural reorganization) as depicted in Fig. 7. Since the $>C=O$ stretching frequency and band I with different solvents provided a linear correlation, we have selected two distinct solvation states of Bzp in MeOH, viz., (i) hydrogen bonded and (ii) non-hydrogen bonded. These states correspond to the peak maxima (ν'_{6a} and ν''_{6a} , respectively) of the simulated Raman spectra; we performed vertical excitation energy calculations on the corresponding clusters as shown in Fig. S14.⁵⁴ The vertical excitation energies of hydrogen bonded and non-hydrogen bonded clusters should correspond to the λ_{max} of the respective clusters and clearly matches the blue and red side of the band I as indicated in Fig. S14.⁵⁴ These excitation wavelength-dependent solvation dynamics could have implications for ultrafast reactions such as photoinduced-electron transfer⁷³ and charge transfer processes and the photophysical aspects of the excited state. A detailed study on the excitation wavelength-dependent solvation states of Bzp in different solvents is in progress.

V. CONCLUSION

A detailed solvatochromic analysis of benzophenone (Bzp) was performed in various solvents of diverse polarity using Raman and electronic spectroscopy, in conjunction with DFT calculations of supramolecular clusters generated using c-MDS. The $>C=O$ stretching frequency undergoes bathochromic shift with solvent polarity and a very good linear relationship was obtained for the solvatochromic shifts with Gutmann's acceptor number. Interestingly, in protic solvents, this peak appears as a doublet: the lower and higher frequency peaks were assigned to the hydrogen bonded and dangling carbonyl group of Bzp, as suggested by c-MDS and *ad hoc* explicit solvent *ab initio* calculations. In addition, the dangling carbonyl in methanol (MeOH) solvent is blue-shifted 4 cm^{-1} from acetonitrile solvent despite their similar dipolarity/polarizability. This suggests that the cybotactic region of dangling carbonyl group in MeOH is very different from its bulk solvent structure. Therefore, we propose that the hydrophobic solvation shell (solvophobic shell) around it due to extended hydrogen bonding network of protic solvents is the molecular-origin for its blue-shift. Furthermore, $1^1\pi\pi^*$ (band I) and $1^1\pi\pi^*$ (band II) electronic transitions show hypsochromic and bathochromic shifts, respectively. The solvatochromic analysis of electronic absorption bands I and II with Kamlet-Taft linear solvation energy relationships indicate that the hydrogen bonding contribution in protic solvents is dominant towards the differential solvation of excited electronic state relative to the ground state: the hypsochromic and the bathochromic shifts were due to excited state hydrogen bond weakening and strengthening, respectively, as corroborated

by DFT calculations and solvatochromic analysis of Bzp. Additionally, a linear relationship was obtained for band I and the $>C=O$ stretching frequency, which suggests that the different excitation wavelengths in band I correspond to different solvation states. Therefore, we hypothesize that the different excitation wavelengths in band I could lead to different solvation dynamics and will have implications for ultrafast processes associated with electron-transfer, charge transfer, and also the photophysical aspects of excited states.

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