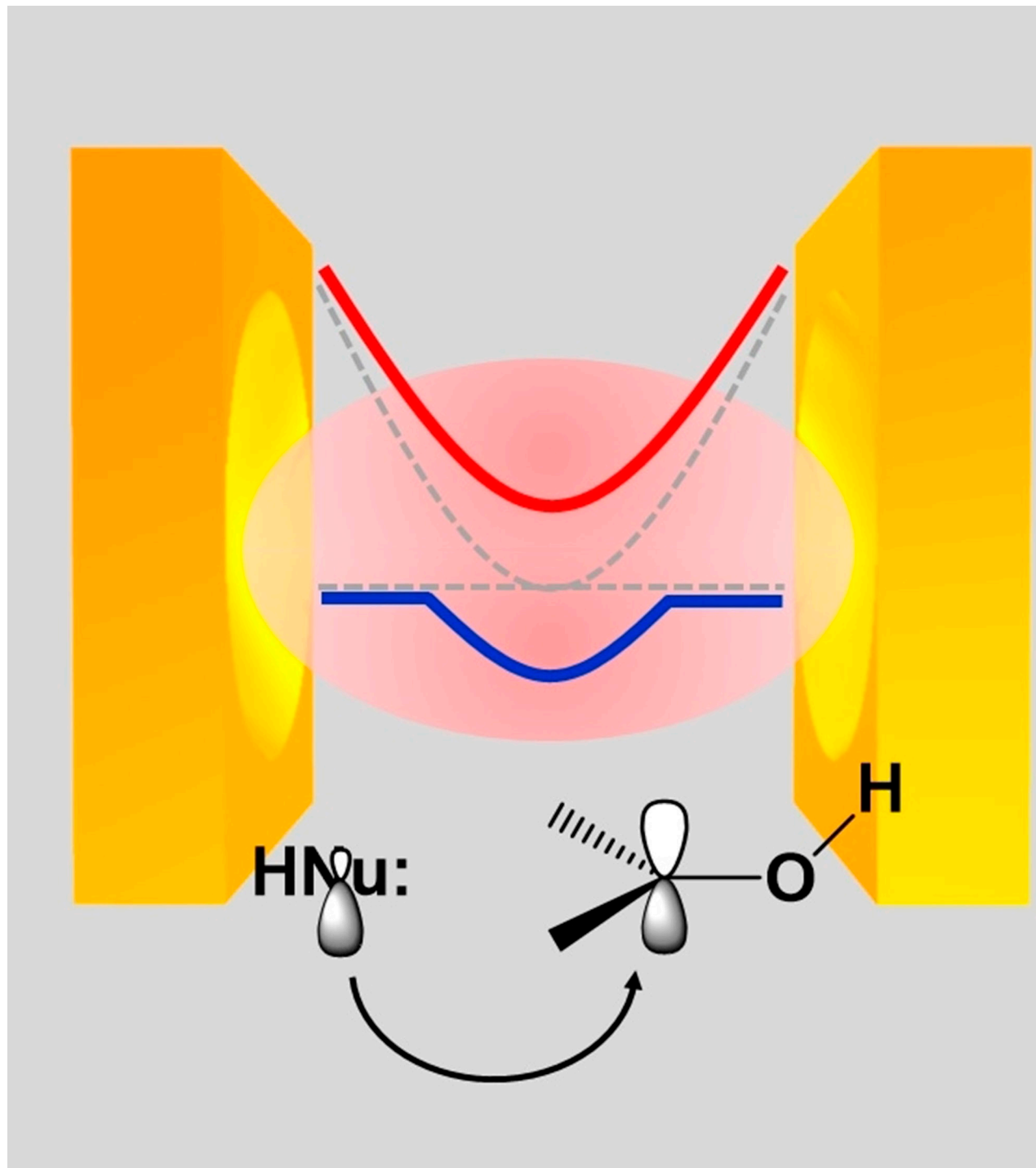VIP *Very Important Paper*

Recent Progress in Vibropolaritonic Chemistry

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Vibrational polaritonic chemistry is emerging as an exciting new sub-field of chemistry, one in which strong interactions with optical cavity vacuum fields are another degree of freedom alongside temperature, solvent, catalyst, and so on to modify thermochemical reactivity. The field stands at a fascinating juncture with experimental works on a variety of organic reactions continuing to blossom, just as many theoretical works appear which diverge significantly in their predictions compared to experiments. The outlook for the field is no doubt an exciting one as it seeks to unify the observed novel optical cavity-induced chemical phenomena with satisfying accompanying physical theory. In this minireview we highlight experimental works on vibrational polaritonic chemistry that have appeared most recently, focusing on the chemistry of the rate-limiting steps to provide mechanistic insight. We hope this review will encourage synthetic chemists to enter the field and we discuss the opportunities and challenges that lie ahead as polaritonic chemistry grows into the future.

1. Introduction

In contrast to classical mechanics, quantum systems constantly fluctuate in their lowest energy state as described by Heisenberg's uncertainty principle. Inside an optical cavity, and in the absence of external light excitation, electromagnetic fields in their lowest energy state, i.e., vacuum fields or vacuum fluctuations, can be spectrally isolated. These cavity fields can exchange energy with the electronic or vibrational transitions of molecules placed inside the cavity. When conditions allow this energy exchange to happen repeatedly, the so-called strong coupling regime is reached, hybridizing the molecular and photonic wavefunctions and generating new polaritonic states for the system Figure 1.[1] Thomas Ebbesen's contention that these polaritonic states could influence the reactivity of molecules and materials inside the cavity has seen 'Polariton Chemistry' grow into a vibrant new field over the past decade.[2]

From a practical perspective polaritonic organic chemistry is most conveniently achieved by placing solutions of reactants inside a Fabry-Pérot (FP) cavity, two reflective surfaces separated by a distance of the order of the wavelength of light being coupled. The focus here is the coupling of molecular vibrational transitions to optical cavities, requiring mirror separations of 10 s of microns and thus being amenable to microfluidic configurations. One of the more fascinating aspects of polariton states is that they are collective, being delocalized over the ensemble of reactants within the FP cavity optical mode volume.[2–4] Polaritonic organic chemistry should also be

achievable with other photonic structures, including surface plasmons propagating on films,[5] localized surface plasmons,[6] whispering gallery cavities,[7] and photonic crystals.[8]

The hybridization of molecular electronic transitions to cavity optical fields has a long history and continues to reveal fascinating phenomena including polariton lasing,[9] room temperature polariton condensation,[10] and the modification of photochemical landscapes.[11] The strong coupling of vibrational modes of molecules to cavities (vibrational strong coupling, VSC) was first reported in 2014, that report also predicting that VSC might be used to influence organic thermochemistry.[12] Particularly in the last year, such reports have proliferated to the point where they can be reviewed and trends identified.[13–20]

To date, VSC has been shown to both accelerate and suppress the chemical reactions of molecules whose vibrational modes are strongly coupled to optical cavities. The suppression
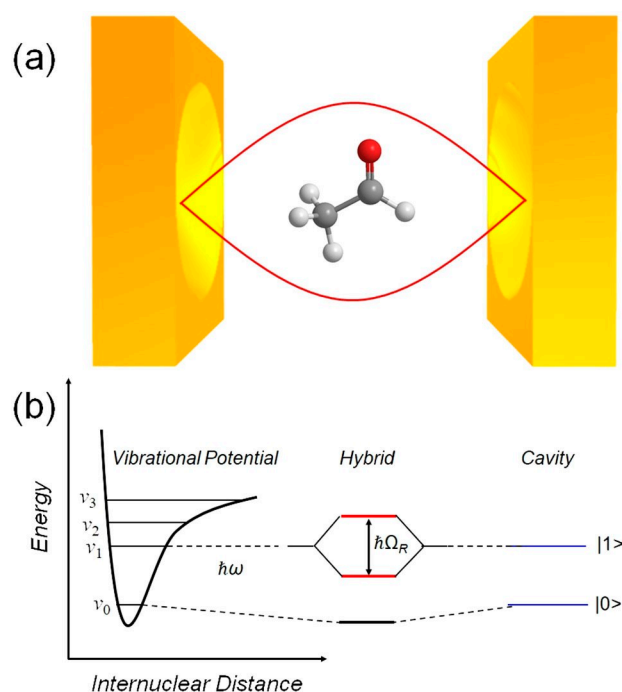
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Figure 1. (a) Schematic illustration of molecules located in a Fabry–Pérot (FP) cavity composed of two reflective mirrors. The red line is an intensity profile of a cavity optical field (fundamental mode) (b) Energy levels of vibro-polaritonic states formed from the coupling of a molecular vibrational transition and a FP cavity mode ($\hbar\Omega_R$ the energy gap between them, is the Rabi splitting).

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of reactivity of specific functional groups over others has enabled site-selective reactions.[15] In conventional organic chemistry, site-selective reactions are achieved through protecting groups to retard the formation of undesired products.[21] Using VSC instead brings with it the possibility to eliminate onerous protection/deprotection steps, saving time and reducing waste.

The mechanism by which VSC influences chemical reactivity remains a question under vigorous debate. To gain some mechanistic insight into the effect of VSC on chemical reactions, the dynamics of vibro-polaritonic states have begun to be investigated.[22–27] In addition, a number of theoretical studies have been developed[28–32] since the first observation of the VSC-modified reaction kinetics. Many theoretical works continue to appear which do not predict appreciable reactivity change in experimentally relevant scenarios.[20,33–35] Much work lies ahead before routine prediction of VSC-modulated chemistry is possible.

Here we will introduce the typical experimental setups for undertaking vibrational polaritonic chemistry in liquid samples. Secondly, we will discuss recent studies characterizing vibro-polaritonic states. Thirdly, we will highlight the reaction mechanisms for the known examples of reaction modification under VSC, focusing particularly on the rate-limiting steps in each case. This comprehensive summary will provide insights that will help further the understanding of VSC chemistry.

2. Microcavities for Vibrational Polaritonic Chemistry

FP cavities are the most extensively used tool for exploring polaritonic chemistry. A FP cavity is composed of two parallel mirrors, initially prepared on an infrared-transparent substrate (e.g., CaF_2, BaF_2, and $ZnSe$). In the early reports on strong coupling with organic materials, distributed Bragg reflector (DBR) mirrors were employed in view of the high quality (high reflectivity) of the formed cavities.[36] However, the fabrication of DBR mirrors requires advanced deposition methods, such as chemical vapor/atomic layer deposition, which are both expensive and time consuming. In contrast, metallic mirrors can be easily deposited on substrates by sputtering or evaporation, with gold, silver, and aluminum being popular. Matallic films ca. 10 nm thick allow sufficient reflectivity (Q factors ~50 in the mid-IR) to maintain relatively high quality cavity modes while still allowing optical probing of the system to follow reactions.

For the investigation of chemical reactions, the metal mirror is usually coated with an inert layer, such as silicon dioxide, silicon resin, or an organic polymer, to prevent direct contact with the molecules. A thin protective layer is crucial for avoiding chemical effects from the metal mirrors. Plasmonic effects close to the metal surface are also reduced but are unlikely to play a large role in any case. The two inert mirrors are arranged such that they face each other in parallel. Commercially available films (e.g. Kapton or Mylar films) are used as a spacer between the two mirrors, with the thickness of the spacer roughly determining mirror separation and the resonance frequency of the cavity. For fine adjustment of the cavity optical resonances to the targeted vibrational band energy, standard liquid cells for IR spectroscopy can be employed with screws to gently compress the polymer spacers. Liquid solutions of reactants are then introduced into the FP cavity (Figure 2).

When the vibrational modes of molecules couple strongly to the vacuum electric fields (zero-point energy) of a FP cavity, new vibro-polaritonic states, denoted P+ and P−, are formed and are separated at resonance by the vacuum Rabi splitting energy ($\hbar\Omega_R$: as shown in Figure 1b). This energy splitting can

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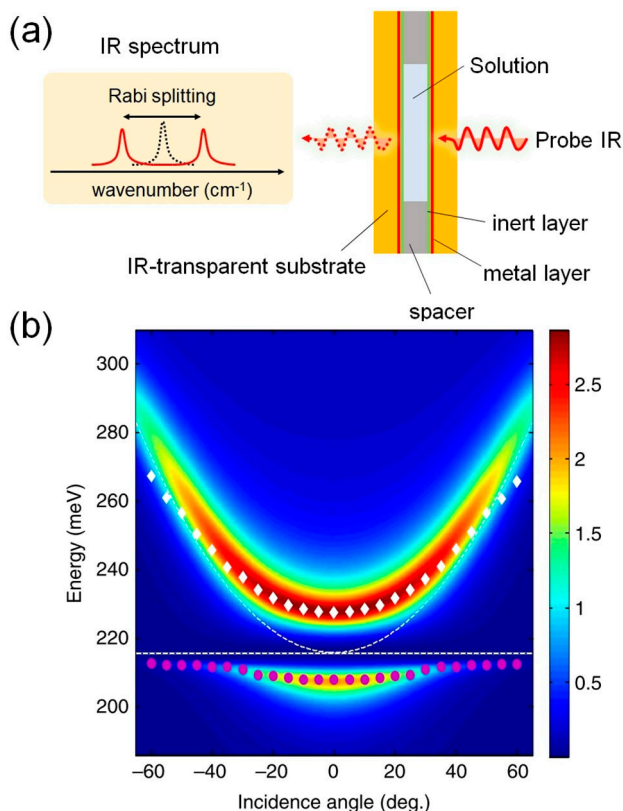
Figure 2. (a) Schematic illustration of a FP cavity for VSC of liquid samples and observation of peak splitting of the vibrational absorption due to polariton formation as observed by IR spectroscopy. (b) Calculated energy vs. probe angle (in-plane momentum) dispersion map of FP cavity transmission. The dashed parabolic and horizontal lines are the dispersive optical mode and (carbonyl) molecular vibration energy, respectively. White diamonds and purple dots indicate the upper (P+) and lower (P−) polaritons, respectively, due to strong coupling, the energy gap between them at normal incidence is the Rabi splitting (20 meV). Reproduced from ref. [38] with permission from Springer Nature.

be observed via infrared (IR) spectroscopy and is proportional to the strength of the coupling. When this splitting is greater than the spectral widths of the material absorption and optical modes in isolation, the strong coupling regime has been attained. In the Fourier-transformed temporal picture, this indicates the reversible exchange of a photon between the molecules and the cavity occurring faster than any loss process. Since the dominant loss process is the photon leaking from the cavity, a high absorption coefficient vibrational absorption and a large concentration of molecules is the primary driver for moving into the strong coupling regime. These ensure reabsorption of photons before they leak from the cavity. The Rabi splitting increases with the concentration of coupled molecules, $\hbar\Omega_R \propto \sqrt{N/\nu} = \sqrt{C}$ (ν: volume of an electromagnetic mode of the microcavity, N: number of molecules, C: concentration). Due to this requirement, the vibrations of highly concentrated solutes or of host solvent molecules are often chosen to couple with the cavity modes. The reversible energy exchange that drives VSC occurs between the cavity field and the super-position of all the resonant molecular vibrations with some material polarization component co-linear with the field

polarization, resulting in oscillators vibrating in phase despite separation over microns (i.e. long-range vibrational coherence).[37] In this way the polariton states average over the differing degrees of coupling of individual molecules to the cavity which are position- and orientation-dependent (the optical field is polarized parallel to the mirrors).

Tuning the optical mode to resonance with the molecular absorber may be achieved not only by tuning mirror separation as already discussed, but also via tuning the angle of probe light incident on the cavity. The angular dispersion of a FP cavity mode's energy is indicated by the parabolic white dashed line in Figure 2b (probe angle is more often plotted in terms of in-plane momentum, k_x or $k_{||}$). In the typical VSC chemistry experiment however, the probe IR beam is normal to the mirrors ($k_{||} = 0$) and cavity thickness is tuned so that the vibrational absorption band (horizontal dashed line in Figure 2b) is resonant at normal incidence. This results in an anti-crossing where the dashed lines would intersect at zero in-plane momentum. The Rabi splitting is then defined by the minimum energy gap between the new polariton states, i.e. the energy gap between P+ (white diamonds) and P− (purple dots) at normal incidence in Figure 2b. Perhaps one of the most surprising aspects of VSC for chemists is that the dispersive property of light is transferred to the hybrid polariton states after strong coupling with molecules. At higher incident angles (i.e. angle-tuning away from resonance), P+ and P− become more purely photonic- and molecule-like, respectively, and the effects of VSC chemistry should reduce. The latter is a highly important 'off-resonance' control experiment for VSC.

3. Vibrational Strong Coupling

3.1. Vibro-Polaritonic States

Vibrational strong coupling (VSC) has now been observed for a wide variety of molecules and materials, including polymers,[38,39] organic molecules,[40] organometallic complexes,[41] proteins,[42] liquid crystals,[43] and solvent molecules.[44]

As was the case for electronic strong coupling of organic materials, transient spectroscopy has been invaluable for understanding the dynamics of vibro-polaritonic states. Transient absorption spectroscopy was used to investigate the excited state dynamics of a vibration-cavity polariton[23–25] of $W(CO)_6$ in hexane with vibrational strong coupling of the carbonyl stretch. Pump-probe spectroscopy showed that the upper polariton relaxes much more quickly than the lower polariton and uncoupled reservoir ($\nu = 1$) states. In the first few picoseconds after excitation, Rabi oscillation – coherent energy transfer between the polariton branches – was also observed.

Further studies on the dynamics of the vibro-polaritonic states of $W(CO)_6$ were realized through the application of two-dimensional (2D) IR spectroscopy.[24–27] Strong coupling of N molecules and a cavity mode generates N+1 collective states, of which two can couple radiatively and are observable (P+ and P−) and the other N-1 linear combinations are collective dark

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states. Another fraction of dark states are localized states of uncoupled molecules which are outside the field mode volume or have their transition dipole moment orthogonal to the mode polarization. These dark state populations are not observable via normal IR transmission spectra. The application of 2D IR spectroscopy allows study of these dark states in isolation from the radiative (bright) vibro-polaritonic states. The 2D spectra showed that dark and bright polariton mode dynamics were inter-dependent. When one set (e.g. the dark states) were excited, the response of the radiative vibro-polaritons was influenced, and vice versa. Once again in close parallel with electronic strong coupling of organic systems, dark and uncoupled populations must be understood and disentangled from radiative ones in VSC systems, and their presence included in theory,[28] to fully understand the effect of VSC on chemical reactivity.

Finally in this section we mention that the IR emission properties of vibro-polaritonic states have only just begun to be explored.[45] The comparative ease with which emission spectra can be taken in the visible spectrum has meant that in stark contrast, fluorescence spectroscopy has played a dominant role in the investigation of electronic strong coupling of organic molecules. We believe the further development of IR emission spectroscopy is important for a deeper understanding of VSC.

3.2. Vibrational Strong Coupling in Chemical Reactions

In this section we focus on recent breakthroughs related to the modulation of chemical reactivity by VSC. The first example of VSC applied to chemical reactions involved the deprotection of an alkynylsilane (Figure 3a and Table 1a).[13] VSC was achieved by placing the reactant into a FP cavity with an optical mode resonant with the reactant Si–C vibrational stretching mode. The specific deprotection reaction chosen involved 1-phenyl-2-trimethylsilylacetylene and its reaction with tetra-*n*-butylammonium fluoride. The reaction was convenient as the starting material is a pure liquid and the reaction occurred in facile conditions over ~20 minutes. The reaction rate decreased by a factor of up to 5.5 under VSC of the Si–C bond. Eyring plots of reactions with and without VSC suggested a change in reaction pathways. This reaction typically proceeds through an associative reaction pathway whereby the initial step is a fluorine attack on the silicon atom to form an intermediate with pentavalent coordination, i.e., an S_N2 reaction. For such reaction mechanisms, the activation entropy ($\Delta S^{\ddagger}$) is typically negative, and the activation barrier is low, which is observed in the reaction without the cavity. In contrast, a higher energy barrier ($\Delta H^{\ddagger}$) and a positive $\Delta S^{\ddagger}$ value, such as were observed under VSC, are characteristics of a dissociative transition state, that is, the C–Si bond starts breaking before the silicon center is attacked by the fluorine, i.e., an S_N1 reaction.

Deacceleration of the Si–C deprotection reaction has been further developed to realize site-selective deprotection involving Si–O and Si–C bonds.[14,15] Specifically, the reactivity of a compound bearing two possible silyl bond cleavage sites, Si–C and Si–O bonds, was investigated under the VSC of three
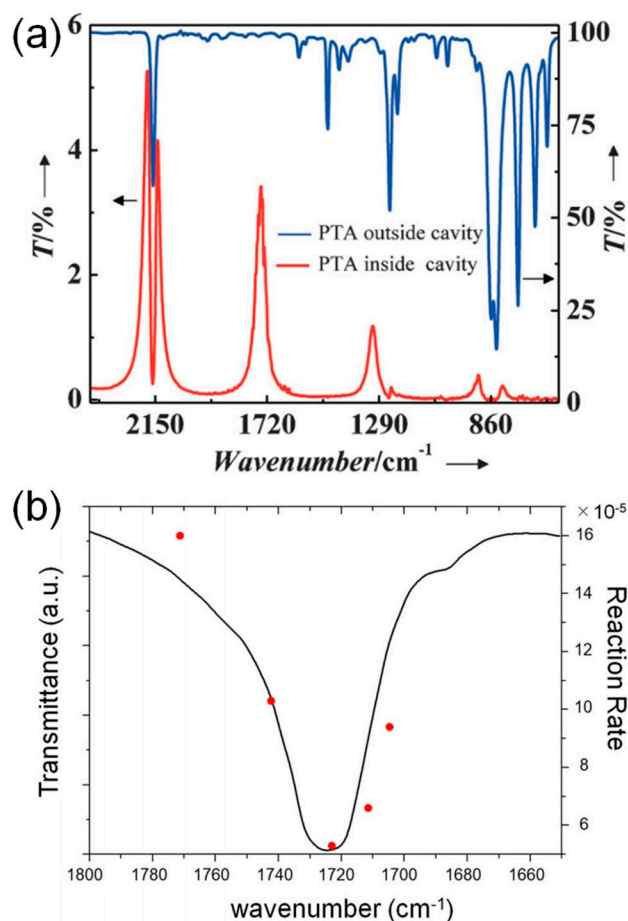

Figure 3. (a) IR transmission spectrum of 1-phenyl-2-trimethylsilylacetylene inside (red trace) and outside (blue trace) the ON resonance cavity.[13] Reproduced from ref. [13] with permission from Wiley-VCH. Copyright Wiley-VCH. (b) The reaction rate as a function of the FP cavity tuning for the reactions occurring within (red dots). The solid black line represents the IR transmission spectrum of the carbonyl stretching vibration of acetaldehyde.[16] Reproduced from ref. [16] with permission from Wiley-VCH.

distinct vibrational modes: Si–C, SiO, and Si–CH$_3$ bonds (Table 1b-c). A molecule with two distinct sites for prospective silyl bond cleavage, tert-butyldimethyl{[4-(trimethylsilyl)but-3-yn-1-yl]oxy}silane, was used to realize selective deprotection. Nucleophilic attack by a fluoride ion on either Si atom can result in cleavage of the respective bonds, which for attack at Si–C bond yields (but-3-yn-1-yloxy)(tert-butyl)dimethylsilane (**1**), while attack at the Si–O bond yields 4-(trimethylsilyl)but-3-yn-1-ol (**2**). The production of (**1**) was suppressed under the VSC of the Si–C, Si–O, and Si–CH$_3$ vibration modes. The variation of thermodynamic parameters was in the same direction as the previous report.[13] The increase of $\Delta H^{\ddagger}$ and decrease of $\Delta S^{\ddagger}$ value suggests a more dissociative transition state. In the S_N2 reaction the three CH$_3$ groups flip over as the trimethylsilane leaves, resulting in an inversion of the configuration. This is perhaps the reason why the VSC of Si–CH$_3$ bonds also influences reactivity in this case.

The effect of VSC on a series of aldehydes and ketones undergoing Prins cyclization has also been investigated (Table 1d).[16] In the simplest case, the reaction of a homoallylic

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Table 1. The chemical reactions modulated by VSC.[a–l]

Entry	Reaction	Vibration	Effect	Thermodynamic parameters				Ref.
				$\Delta H^{\ddagger[1]}$ [kJmol⁻¹]	$\Delta H^{\ddagger}_{VSC}$[2] [kJmol⁻¹]	$\Delta S^{\ddagger[3]}$ [JK⁻¹mol⁻¹]	$\Delta S^{\ddagger}_{VSC}$[4] [JK⁻¹mol⁻¹]	
[a]		Si–C	deaccelerated	39	96	−171	7.4	[13]
[b]		Si–CH₃ Si–C Si–O	deaccelerated	34	60 (Si–C) 57 (Si–O)	−173	−95 (Si–C) −106 (Si–O)	[14] [15]
[c]		Si–CH₃ Si–C Si–O	deaccelerated	23	85 (Si–C) 76 (Si–O)	−214	−6 (Si–C) −39 (Si–O)	[14] [15]
[d]		C=O	deaccelerated	1: 19.2 2: 23.4 3: 25.0 4: 27.1	1: 30.9 2: 37.6 3: 36.8 4: 38.8	1: −251.1 2: −240.7 3: −236.5 4: −231.7	1: −222.7 2: −204.7 3: −209.9 4: −205.6	[16]
[e]	$2H_2O + OCN^- \rightarrow CO_3^{2-} + NH_4^+$ $2D_2O + OCN^- \rightarrow CO_3^{2-} + ND_4^+$	O–H O–D	accelerated	–	–	–	–	[17]
[f]	$2H_2O + NH_3BH_3 \rightarrow NH_4^+ + BO_2^-\ 3H_2$	O–H	accelerated	–	–	–	–	[17]
[g]		N=C=O	accelerated	–	–	–	–	[17]
[h]	$K^+[O=C=N^-] + NH_4Cl \rightarrow (H_2N_2)CO + KCl$	O=C=N	accelerated	–	–	–	–	[17]
[i]		C=O C=C=O	accelerated	–	–	–	–	[17]
[j]		S=C=S C=C=O	accelerated	–	–	–	–	[17]
[k]		C=O	accelerated	53.2	7.9	−70.9	−206.2	[18]
[l]	$R_1NHCOR_2 \rightarrow R_1NH_3^+ + R_2COOH$	O–H	deaccelerated	–	–	–	–	[19]

The activation enthalpy [1] without VSC [2] and under VSC. The activation entropy [3] without VSC [4] and under VSC.

alcohol with a carbonyl compound under the influence of an acid catalyst, termed Prins cyclization,[46,47] is a powerful method for the synthesis of cyclic moieties. The reaction rate of Prins cyclization was deaccelerated under the VSC of the carbonyl stretching vibrations of the aldehyde/ketone. The plot of reaction kinetics against cavity mode wavelength follows the absorption curve of the carbonyl stretching vibration, confirming the cavity resonance effect (Figure 3b). The activation enthalpy ($\Delta H^{\ddagger}$) increased by approximately 10 kJ.mol⁻¹ under VSC, however the activation entropy ($\Delta S^{\ddagger}$) was not altered much. Plots of $\Delta H^{\ddagger}$ against $\Delta S^{\ddagger}$ showed a linear correlation between $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$, suggesting that the reaction mechanism was unchanged by VSC, but the energy barrier to reaction was increased. The rate-limiting step in this reaction involves protonation of a carbonyl group and the attack of oxygen at a carbonyl carbon. This work suggested that the nucleophilicity of a carbonyl oxygen or the electrophilicity of a carbonyl carbon can be influenced by the VSC of the carbonyl stretching vibration, or in other words, bond polarity may be affected.

Other intriguing VSC-modified chemistry has been reported recently on archival preprint servers. In sharp contrast to the suppression of the chemical reactions mentioned above, the acceleration of reaction kinetics under VSC has been claimed. The hydrolysis of cyanate ions and ammonia borane was accelerated under vibrational ultra-strong coupling (V-USC) of the OH stretching mode of water to a FP cavity mode (Table 1e–f).[17] Ultra-strong coupling indicates the Rabi splitting is a significant fraction (>10%) of the energy of the coupled

transition. In this reaction, water acts as both reactant and solvent and due to the high concentration of water, coupling of the OH stretching mode reaches the regime of V-USC. The V-USC of water reportedly enhanced the hydrolysis reaction rate of cyanate ions by 10²-fold and that of ammonia borane by 10⁴-fold.

The addition reaction of phenyl isocyanate and methanol or isopropanol was explored under the VSC of an N≡C=O stretching vibration (Table 1g).[17] The reaction was initiated by the attack of a hydroxyl group at the carbon of a cyanate group.[48,49] The effect of VSC in this case resembled those that increase the electrophilicity of the carbon in cyanate. The synthesis reaction (Wöhler reaction) of urea from cyanate ions (OCN⁻) and ammonium ions[50] was also accelerated under the VSC of an O=C=N vibration mode (Table 1h). The cyclization of (triphenylphosphoranylidene)ketene (TPPK) and acetone was also accelerated under VSC of the C=O or C=C=O stretches (Table 1i).[17] It can be assumed that the initial step involved a Wittig reaction, which led to the formation of methyleneketene.[51] This reactive intermediate was added rapidly to the TPPK to produce the final cyclobutene product. The reactivity of methyleneketene was influenced by VSC of the C=C=O vibrational mode. The effect of VSC of C=O in this reaction is complicated, with the VSC likely influencing the reactivity of the C=O of TPPK as well as the acetone solvent. The effect of VSC on the solvation properties of acetone is unknown, but solvation of activated complexes is a key factor in determining the reaction kinetics. While the reaction

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mechanism differs from cyclization reactions, the exchange reaction of TPPK with carbon disulfide was also accelerated under the VSC of C=S and C=O vibrational modes (Table 1j).[17] A reaction kinetic model[52] has also been claimed in an archival preprint based on this series of results,[17] wherein the variation of reaction kinetics under VSC is correlated with the Rabi frequency, the energy of the vibrational modes, and the original activation energy.

When the vibrational modes of reactant and solvent molecules overlap, vibrations of the reactant can be strongly coupled to cavity modes even if the reactants themselves are present in low concentrations. This cooperative strong coupling[53] of reactants and solvents was observed in solvolysis reactions. The solvolysis reaction of para-nitrophenyl acetate (PNPA) was carried out under mild basic conditions provided by tetrabutylammonium fluoride (TBAF).[18] TBAF in ethyl acetate (EtOAc) facilitates a base-catalyzed acyl (BAc$_2$) bond-breaking. The cooperative VSC of a carbonyl stretching vibration with PNPA as a reactant and EtOAc as a solvent increases the reaction rate by one order of magnitude (Table 1k). The activation enthalpy (ΔH^+) decreased substantially under VSC, indicating that the transition state is energetically lowered under VSC. The activation entropy (ΔS^+) also decreased, attributed to the transition state being more polar under VSC and thereby re-structuring the solvent cage which also decreases ΔH^+. The interaction of reactants and solvent at the transition state is believed to become stronger under VSC, thus accelerating the reaction.

The VSC of OH stretching modes during enzymatic reactions in water can also be classified as a cooperative strong coupling interaction. The effect of VSC of water on the enzymatic activity of pepsin was investigated under VSC of the OH stretching vibrations of both water molecules and pepsin (Table 1l).[19] The rate constant of pepsin-mediated peptide hydrolysis was found to decrease, while no effect was observed for the strong coupling of the bending vibration. In addition to the general role of water as a solvent, the active sites of pepsin also include hydroxyl groups such that VSC of OH stretches may influence solvation as well as the active sites of pepsin. A change of hydration properties due to VSC of water might induce slight changes in enzyme structures, which may then influence the reactivity of enzyme reactions.

The symmetry of the vibrational modes has recently been considered in order to understand the effects of VSC on reaction rates. In the charge transfer (CT) complex of trimethylated benzene and iodine, the equilibrium constant of the CT complex is changed under VSC, suggesting modification of the Gibbs free energy ($\Delta G°$). The increase or decrease of $\Delta G°$ depends only on the symmetry of the normal mode that is coupled to the FP cavity. This result suggests a role for vibrational symmetry in VSC for the modulation of organic reactions.[54]

4. Summary and Outlook

For the moment it is difficult to draw general conclusions about mechanisms for vibrational polariton-modified organic thermochemistry. As might be expected for an emerging sub-field, as apparent trends emerge, so do counter-examples. Several works have shown an exponential change in reaction rate with Rabi splitting under VSC.[13,18] This suggests, as has been recently demonstrated,[14] a near-linear change in the activation free energy with Rabi splitting. The change in activation free energy at 298 K inside the cavity compared to outside ($\Delta G^+_{VSC} - \Delta G^+ = \Delta\Delta G^+$) can scale with the Rabi splitting even for very different reactions and bonds subjected to VSC. For example, for a desilylation reaction (Table 1a, VSC of Si–C bond with Rabi splitting of 98 cm^{-1}), $\Delta\Delta G^+ = 3.8$ kJ/mol, while for a series of Prins cyclizations (Table 1d, VSC of C=O bond with Rabi splitting of 105 cm^{-1}), $\Delta\Delta G^+ = 3.5$ kJ/mol on average. Many more examples are required to identify a trend here, and indeed to explain why Rabi splittings of 100 cm^{-1} (~1 kJ/mol) can lead to several kJ/mol changes in activation free energy.[14]

Counter-examples to these common threads become particularly apparent when activation entropy is considered. For the desilylation and Prins cyclizations mentioned above, the former shows a significant change in ΔS^+ under VSC while the latter does not. The large acceleration in reaction kinetics observed for solvolysis reactions under VSC of solvent OH[17] and C=O[18] bonds (Table 1e and k) contrasts with the rate suppression observed when only the solute is coupled. In the latter case ΔS^+ was significantly varied under VSC, attributed to modified solvation and a more polar transition state.

Indeed the changes in reactivity observed under vibrational strong coupling in several cases could be accounted for by changes in the polarity of the targeted bond. For example, decreased electrophilicity of Si–C and Si–CH$_3$ bonds[13–15] and of C=O bonds[16] would lead to the reactivity changes observed inside optical cavities. However, this does not explain why reaction rates are decelerated[19] or accelerated[17] elsewhere when vibrational strong coupling includes solvent molecules. For a deeper understanding of vibrational polaritonic chemistry, more reactions need to be investigated in concert with further development of theory and fundamental understanding of vibro-polaritons via IR emission and (ultrafast) transient spectroscopy.

As seen throughout this review however, even though vibrational polaritonic chemistry is still in its infancy in many aspects, momentum in the field is growing. As more researchers enter the field, influx of new viewpoints will ensure rapid development of polaritonic chemistry concepts and further pioneering cross-disciplinary breakthroughs. We anticipate these developments with much excitement.

Conflict of Interest

The authors declare no conflict of interest.

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