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Annual Review of Physical Chemistry Demystifying the Diffuse Vibrational Spectrum of Aqueous Protons Through Cold Cluster Spectroscopy

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Abstract

The ease with which the pH is routinely determined for aqueous solutions masks the fact that the cationic product of Arrhenius acid dissolution, the hydrated proton, or H⁺(aq), is a remarkably complex species. Here, we review how results obtained over the past 30 years in the study of H⁺ \cdot (H₂O)_n cluster ions isolated in the gas phase shed light on the chemical nature of H⁺(aq). This effort has also revealed molecular-level aspects of the Grotthuss relay mechanism for positive-charge translocation in water. Recently developed methods involving cryogenic cooling in radiofrequency ion traps and the application of two-color, infrared–infrared (IR–IR) double-resonance spectroscopy have established a clear picture of how local hydrogen-bond topology drives the diverse spectral signatures of the excess proton. This information now enables a new generation of cluster studies designed to unravel the microscopic mechanics underlying the ultrafast relaxation dynamics displayed by H⁺(aq).

EIGEN, ZUNDEL, AND THE INFRARED PROTON-CONTINUUM SPECTRUM OF H⁺(aq)

Introductory chemistry textbooks typically state that hydronium (H₃O⁺, n = 1 in **Figure 1**), a molecular ion that is isoelectronic with ammonia, is the charge carrier created by aqueous dissolution (1) of Arrhenius acids:



$$HA \rightarrow H^+(aq) + A^-(aq)$$

Figure 1

Minimum energy structures for selected $H^+ \cdot (H_2 O)_n$ clusters. The Eigen cation at n = 4 consists of the first hydration shell around the H_3O^+ ion. Asymmetric solvation of H_3O^+ occurs at n = 3 and 5. The equally shared proton characteristic of the n = 2 Zundel ion is the persistent motif in the Ar-tagged n = 6-8 clusters. Isomers of n = 6 and 7 exist in Zundel (Z) and Eigen (E) forms. Specifically, 7Z represents the lowest-energy isomer that adopts a five-membered ring structure with a Zundel-type core, while the next three low-energy isomers are all Eigen-type cores and are labeled as $7E_{4R}$ (four-membered ring), $7E_{5R}$ (five-membered ring), and $7E_C$ (noncyclic chains). Structures for n = 6 adapted with permission from Reference 27, and n = 7 adapted with permission from Reference 28; copyright 2013 and 2015, respectively, American Chemical Society. Three-dimensional cage-like morphologies begin at $n \approx 10$, in which the H_3O^+ is integrated into the surface of a cage structure. The n = 21 cluster is color coded to indicate the hydrogen-bonding motifs: hydronium (*red*), first hydration shell around the ion (ADD) (*dark blue*), remote ADD (*light blue*), AADD (*pink*), and AAD (*orange*). A and D denote H-bond acceptor and donor configurations, respectively. The H_3O^+ moiety is located at the top of the n = 10 and 21 structures. Structures for n = 1-5, 8, 10, and 21 adapted with permission from Reference 29; copyright 2015 American Chemical Society.

However, this clearly cannot be the whole story, because the transport of charge through water is about 3.5 times faster than is this process for other ions of similar size, such as ammonium (NH₄⁺) (2). This behavior is rationalized by invoking so-called water wires that support a relay mechanism for charge transport. This hypothesis posits that protons are sequentially passed between two water molecules, constantly creating new H₃O⁺ charge centers that migrate though solution while the arrangement of oxygen atoms remains essentially intact (3). A primitive version of this proton-relay phenomenon was originally suggested in 1806 by Grotthuss (4), almost 50 years before the composition of water was settled in 1860 (5). Charge transduction through water as well as other hydrogen-bonded networks is ubiquitous in biology, with an archetypal example being the mechanism of mammalian vision (6, 7). The relay motif is also central to the proton-transfer membranes that compensate for the flow of electrons in fuel cells (8, 9).

An important clue highlighting the complex speciation of the excess proton in water is the fact that, although the vibrational band pattern of isolated H_3O^+ is indeed very similar to that of NH₃ (10), the spectral response traced to H⁺(aq) in dilute acids is remarkably diffuse (see **Figure 2**). The difference spectrum depicting the changes in absorption arising from the cationic species (**Supplemental Figure 1**) appears as a continuous distribution covering the range from 1,000–3,700 cm⁻¹ (11, 12). The barrier for charge transport is only about one-third that of the typical OH-stretching vibrational quantum in water (13, 14), which means that vibrational excitations can easily access highly anharmonic regions of the free energy landscape available to the charge defect. This diffuse spectral signature has made it very difficult to extract a molecular description of the charge carrier (11, 15–22). One currently debated question, for example, is exactly how many water molecules directly participate in the accommodation of the excess proton (23, 24). In the 1950s, Eigen and colleagues (25) proposed that this speciation involved the tricordinated hydronium ion, $H_3O^+ \cdot (H_2O)_3$, now called the Eigen cation [denoted hereafter as $H^+ \cdot (H_2O)_4$ or, more simply, as n = 4], depicted in **Figure 1**. This corresponds to a completed hydration shell around H_3O^+ because its oxygen atom is a relatively poor hydrogen-bond acceptor (26–29).

Unfortunately, H⁺(aq) speciation in the Eigen cation form does not explain its diffuse spectrum. In the 1960s, Zundel & Metzger (30) postulated that a configuration in which the excess proton is trapped between two water molecules, $H_2O\cdots H^+\cdots OH_2$, would have the properties needed to explain the spectrum (often now called the Zundel continuum in his honor) (31–35). The calculated structure of $H^+ \cdot (H_2O)_2$ (the Zundel cation, n = 2, highlighted at the top of **Figure 1**) features proton accommodation at the midpoint between the two oxygen atoms. The exterior water molecules are oriented at roughly 90° to each other with pyramidal distortions relative to the O–O axis (36–38). Importantly, the Zundel ion structure is calculated to be remarkably responsive to external electric fields through the displacement of the shared proton (30–32, 35, 39, 40). This effect is manifest as the wide range of frequencies associated with the bridging proton because the OH-bond length, R_{OH} , is strongly correlated with its frequency (41). The quasi-linear dependence of the OH frequency on R_{OH} is known as Badger's rule and has been invoked in the context of hydrated protons (29, 42). At the most basic level, the thermal motion of the water molecules in the liquid gives rise to fluctuations in the electric field that in turn modulate the configuration of the O··· H⁺···O moiety and thus its frequency (11, 15–22, 43).

ISOLATION AND CHARACTERIZATION OF PROTON ACCOMMODATION IN SIZE-SELECTED CLUSTER IONS, H⁺ · (H₂O)_n

Although Zundel's model provides a compelling explanation for the observed $H^+(aq)$ spectral behavior, assessing whether it indeed captures the essential physics of the system has been difficult precisely because of the diffuse nature of the vibrational signature. This situation has recently

become clearer, however, as ultrafast methods have provided a window into the correlations between different features at various frequencies (23, 24). This new information supports the scenario in which the proton defect is mostly associated with two water molecules (23, 44). In the meantime, however, a complementary effort has been underway that has involved obtaining the



(Caption appears on following page)

Figure 2 (Figure appears on preceding page)

Vibrational predissociation spectra of $H^+ (H_2O)_n$ clusters obtained using the tagging method with Ar (n = 1, 3, 5, 6, 8, and 10) (data from References 51 and 60, respectively), Ne (n = 2) (data from Reference 74), or D₂ (n = 4, 21, and 28) (data from Reference 61). For the smaller clusters between n = 2 and 8, the accommodation of the excess proton switches between the Zundel ($\nu_{par}, 1,000 \text{ cm}^{-1}$) and Eigen ($\nu_{H_3O^+}^{asym}, 2,600 \text{ cm}^{-1}$) motifs. Three-dimensional cage structures begin at n = 10. The position and breadth of the excess proton signature in n = 28 are similar to those seen in bulk dilute acid. Bands in the cluster spectra that are attributed to the excess proton are colored in red; the diffuse spectral response traced to H⁺(aq) in dilute acids is shown by the lower red trace. Fourier-transform infrared spectra of water and dilute acid data adapted from Reference 11 with permission; copyright 2002 AIP Publishing LLC. Figure adapted with permission from Reference 29; copyright 2015 American Chemical Society. Abbreviations: aq, aqueous; asym, asymmetric; ℓ , liquid; par, parallel; sym, symmetric; umb, umbrella.

spectra of isolated ionic clusters, $H^+ \cdot (H_2O)_n$, in the gas phase using temperature-controlled, sizeselected photofragmentation mass spectrometry (45, 46). One of the main advantages of this approach is that when these clusters are frozen close to their vibrational zero-point energies (~10 K), one can follow how specific arrangements of a precisely determined number of water molecules accommodate the extra proton. Moreover, the potential energy landscape is very complex and allows for the formation and isolation of many isomeric structures. As such, the clusters provide a diverse set of structural arrangements that would only occur in solution as transient or unstable configurations in liquid water. Thus, cluster spectra provide exquisite spectroscopic snapshots of how small changes in local environments are manifest in the spectra. Another advantage of the clusters is that they are small enough to be subjected to accurate, high-level theoretical calculations. This can be done by treating the entire assembly as a supermolecule from the point of view of its electronic structure and vibrational spectrum. This capability is crucial because the proton speciation issue directly involves the partial formation of covalent bonds. In addition, the floppy nature of the system demands the explicit inclusion of both electrical and mechanical anharmonicities to extract structural information from the complex vibrational spectra (13, 14, 47, 48).

The calculated structures for various cluster sizes are included in **Figure 1**. Qualitatively, the effect of introducing an extra proton into a neutral water cluster is to break up compact 3D structures in the smaller size range (n = 5-10) into sheet- or weblike arrangements that then form cage-like structures for $n \ge 10$ (49–51). This review highlights some of the insights gained by studying the cluster systems over the past 20 years, first as static, structurally rigid systems and more recently as dynamic ensembles at elevated temperatures (52).

SIZE-DEPENDENT VIBRATIONAL SIGNATURES OF THE EXCESS PROTON, $\sigma_{pr}(\omega)$

Following early, heroic spectroscopic efforts by Schwarz (53) and Begemann & Saykally (54) in the 1970s that were carried out by monitoring IR absorption, all subsequent vibrational spectra of protonated water clusters have been recorded using photofragmentation mass spectrometry (55). This most often exploits the messenger-tagging approach in which a weakly bound adduct (rare gas or H_2 molecule) is attached to the cluster ion hydrate and dissociated upon resonant excitation of a single photon (55). Single-color infrared (IR) multiple photon dissociation (IRMPD) spectra have also been reported for most clusters (45, 49, 50, 56), and while these are often very similar to those obtained by tagging (13, 57), large differences are observed when the excited states reached by the first photon have highly structured absorption spectra that do not include the fixed laser frequency (the so-called IR transparency regime) (58, 59). The spectra of cold, bare cluster ions have also been reported in a few cases (2, 3, 4) using selective photodissociation of clusters excited at a vibrational resonance followed by dissociative excitation with a second IR laser tuned off the resonances associated with these cold clusters (11, 13, 29, 45, 51, 57, 58, 60, 61). An overview of the tagged spectra (using a combination of Ar, Ne, and D₂) of the first 28 water molecules is presented in **Figure 2**. The bands that are not expected to be associated with neutral water networks are highlighted in red and hereafter denoted $\sigma_{\rm pr}(\omega)$. Because these bands are often broad and/or occur with multiplet substructure, this value is taken to be the centroid of the absorption traced to the proton defect (62). Most importantly, these absorptions appear scattered throughout the region below 3,000 cm⁻¹ in a manner that strongly depends on the number of attached water molecules. In fact, in the size range from n = 2 to 4, $\sigma_{\rm pr}(\omega)$ undergoes a very large excursion from 1,000 cm⁻¹ to 2,600 cm⁻¹ that is approximately retraced from n = 4 to 6, where it returns to ~1,000 cm⁻¹. A second wave also occurs over a larger size range in which the $\sigma_{\rm pr}(\omega)$ maximum occurs again near 2,600 cm⁻¹ at n = 10 and falls back to around 2,000 cm⁻¹ at n = 21.

The important aspect of the cluster spectra is that, while the range of these spectral excursions spans that of the Zundel continuum, the $\sigma_{\rm pr}(\omega)$ bands are themselves rather sharp, especially at the smaller cluster sizes. Cluster spectra therefore encode how the surrounding shapes of the water networks drive the local frequencies associated with the excess proton. Note that large-amplitude motions at elevated temperature wash out this fine structure, leaving diffuse bands quite similar to those displayed by dilute acids in water (**Supplemental Figure 1**, blue trace).

GENERIC FEATURES OF THE INTERMOLECULAR PROTON BOND: TUNING THE PROTON AFFINITY OF THE OXYGEN LONE PAIR OF ELECTRONS

The dramatic changes in the $\sigma_{\rm pr}(\omega)$ maxima with cluster size raise the question of how such large changes are possible, given that the natural frequency of the OH oscillator is about 3,700 cm⁻¹. Recall that in liquid water and ice, which mostly feature tetracoordinated water molecules, the OH stretch occurs in the range 3,000–3,700 cm⁻¹. The location of the OH frequency within this range is often traced to the local electric field, which is modified according to the specific H-bonding configurations of the water molecules in the first and second hydration shells (63–69).

In the case of the Zundel ion, the strong doublet near 1,000 cm⁻¹ (n = 2 spectrum in **Figure 2**) has been analyzed in explicit detail by Meyer and colleagues (37), who traced the dominant oscillator strength to the parallel stretch of the proton between the two oxygen atoms, v_{par} . Interestingly, this ~1,000 cm⁻¹ frequency appears to be a general feature of a proton that is bound equally to the lone pairs of electrons on equivalent oxygen atoms. Note that this binding motif is a partially covalent interaction and arises from the fact that the potential energy curve describing parallel displacement of the bridging proton is broad and roughly quartic in shape. This gives rise both to a low-energy IR fundamental and to vibrational hot bands that appear higher in energy than the fundamental, like the spectrum of an electron in a 1D box. Interestingly, this 1,000 cm⁻¹ characteristic frequency of the equally shared proton in the homogeneous binary complexes is similar to that found in the FHF⁻ anion (1,331 cm⁻¹) (70), which is an archetypal molecule displaying a so-called three-center-two-electron bond (71–73).

To better understand how the low-frequency parallel stretch displayed by the Zundel ion evolves into the $\sigma_{pr}(\omega)$ absorptions that range over 1,600 cm⁻¹, it is useful to first consider the situation in which a single proton is trapped between two oxygen atoms in a variety of different chemical contexts. This expands the class of systems for which the Zundel ion is the simplest member. These variations are readily accessed by studying the spectra of the mixed binary complexes based on proton-bound alcohols and ethers. A survey of these complexes, along with a few heteroatom systems, is presented in **Figure 3** (62), with the ν_{par} bands highlighted in red. The key point here is that, although the symmetric systems [R₁R₂O···H⁺···OR₁R₂ (R_i = H, CH₃)]



Vibrational predissociation spectra of the [A·H⁺·B]·Ar complexes for the following combinations: (*a*) Et₂O·H⁺·Xe, (*b*) MeOH·H⁺·CO₂, (*c*) NH₃·H⁺·H₂O, (*d*) Me₂O·H⁺·H₂O, (*e*) Me₂O·H⁺·MeOH, and (*f*) Et₂O·H⁺·Et₂O. The traces are presented in order of decreasing difference in proton affinities of the A and B molecules (ΔPA) (67) of the [A·H⁺·B] complexes. Regions associated with vibrations more localized on the flanking molecules are indicated by v_i^j labels, where *i* is the molecular moiety and *j* describes the characteristic motions involved in the vibrational mode. The v_{par} bands associated with the parallel stretch of the trapped proton are highlighted in red. In panel *c*, bands indicated by asterisks are due to an (H₂O)₂⁺ impurity. In panels *c*–*e*, the vertical dashed gray lines track features that persist over several complexes. In panel *f*, the gray spectrum overlying the trace corresponds to the solution-phase spectrum, and the blue dashed lines indicate the Gaussian fits used to extract the v_{par} -based transition energies reported for this complex. Panel *f* data from References 68 and 69. Figure adapted from Reference 62 with permission; copyright 2007 American Association for the Advancement of Science. Abbreviations: asym, asymmetric; sym, symmetric.

all display strong multiplet structure in the 900–1,000 cm⁻¹ region, breaking this symmetry by trapping the proton between molecules with different basicities introduces very large blue shifts in the v_{par} band. In fact, the v_{par} values are well correlated to the difference in proton affinities, ΔPA , of the two flanking molecules, as illustrated by the plot in **Figure 4**. This relationship is one of the keys to unlocking the rules that govern the spectral behavior of the excess proton in water. In homogeneous water clusters, these spectral excursions are driven by the hydrogen-bonding topologies of the two water molecules closest to the proton. The heterogeneous proton-bound dimers allow us to mimic this effect by varying the chemical nature of the oxygen atoms.



Dependence of the v_{par} -derived band locations on the difference in proton affinities (ΔPA) for various systems. (*a–c*) The calculated potential curves (using the MP2/aug-cc-pVDZ level of theory) shown here were generated by scanning the shared proton between the heavy atoms while fixing the structures of the molecules at their equilibrium geometries in the complex. Energy levels were derived by solving the 1D Schrödinger equation for the first two vibrational eigenstates. The potential curves are color coded to match points on the graph. Proton affinity values obtained from Reference 67. Figure adapted with permission from Reference 62; copyright 2007 American Association for the Advancement of Science.

The dependence of v_{par} on ΔPA is readily explained by considering the changes in the potential energy curves describing the parallel displacement of the bridging proton. A few calculated curves are included in **Figure 4**. The important point is that when ΔPA increases, the potential distorts so as to exhibit a bulge, or so-called shelf, as the proton migrates closer to the O atom with a greater *PA*. This shelf is the calling card of the emergent, endothermic intracluster protontransfer reaction (also called the frustrated intracluster proton transfer) (38, 62, 74–76). As this asymptote retreats to a higher energy with increasing ΔPA , the potential recovers the narrower Morse shape of the natural OH group, and consequently its v_{par} value increases in energy. This behavior reveals a key mechanical aspect of the hydrated proton: Structural changes in the surrounding water network mimic variations in the relative *PAs* of the electron lone pairs trapping an excess proton. Understanding the physics underlying this behavior is a central goal for the international community working to establish the structure-frequency correlations encoded in the cluster spectra.

THE FIRST HYDRATION SHELL: HYDROGEN BOND ANTICOOPERATIVITY AND PROTON POLARIZABILITY OF THE ZUNDEL IONS $H_5O_2^+$ AND $OH^- \cdot (H_2O)$

The strongest size-dependent shifts in $\sigma_{pr}(\omega)$ occur over the first three water molecules that fill the first hydration shell around the hydronium ion. Interestingly, the anionic analog of the proton defect, the hydroxide ion (OH⁻), follows a remarkably similar trend; a comparison between the two systems is presented in **Figure 5** (77). In both cases, the n = 2 clusters are quasi-symmetric,



Comparison of the vibrational spectra displayed by (a-c) H₃O⁺ · (H₂O)_{n = 3,2,1} and (d-f) OH⁻ · (H₂O)_{n = 1,2,3} clusters. These spectra show the surprising similarities in the stepwise hydration of hydroxide and hydronium leading to the completion of their hydration shells. Note that in the protonated clusters, the $\sigma_{pr}(\omega)$ features tracked in the spectra are associated with the central H₃O⁺ ion, while for the hydrated OH⁻ clusters, this feature is associated with the water molecules that donate H bonds to hydroxide in its first hydration shell. In panel *f*, the H atom on the central hydroxide ion is out of the plane of the figure. Figure adapted with permission from Reference 77; copyright 2016 AIP Publishing.

with very low values of v_{par} [900 versus 670 cm⁻¹ for H₅O₂⁺ and OH⁻·(H₂O), respectively], and exhibit very large solvatochromic blue shifts in the bands derived from the proton defects (excess or deficient for cations and anions, respectively), $\sigma_{pr}(\omega)$, upon addition of the next two water molecules. Perhaps surprisingly, the trihydrates of both hydroxide and hydronium yield broad $\sigma_{pr}(\omega)$ bands peaking near 2,500 cm⁻¹ (Figure 5*a*,*f*).

The charge-delocalized nature of the two proton-bound dimers $(H_2O\cdots H^+\cdots OH_2$ and $OH^-\cdots H^+\cdots OH^-)$ is evident in their structures, which both feature out-of-plane orientations of the OH groups that avoid one another [e.g., $HO^- \cdot (H_2O)$ is reminiscent of hydrogen peroxide] (38, 74, 75, 77–79). The Zundel ion is particularly interesting in that both H_2O moieties are bent toward the pyramidal structure of H_3O^+ . The $H_5O_2^+$ system has been studied at length, and its vibrational pattern indicates that the average structure in the vibrational zero-point level is actually far from that of the calculated equilibrium geometry (which is 12-fold degenerate!) (80). The difference arises because of the large-amplitude motion of the shared proton in the vibrational zero-point level. As a result, the effective vibrationally averaged structure is more like

the D_{2d} geometry of an allene. Another clue that the Zundel ion has a covalent character is that its bending fundamental occurs near 1,750 cm⁻¹, about 150 cm⁻¹ above that in isolated H₂O (78, 81). This effect is strongly isotope dependent and has been traced to very strong mixing between the parallel stretch of the bridging proton and the intramolecular bends of the flanking water molecules at the harmonic level (82). In essence, the nominal ν_{par} band near 1,000 cm⁻¹ is actually a complex motion in which the parallel displacement of the proton toward a water molecule occurs in phase with the bending motion of that water molecule, bringing its local structure closer to that of H₃O⁺. The nominal bending motion is also a mixed mode, but this time the ν_{par} displacement is out of phase with the bends of the flanking water molecules, effectively stiffening the potential for proton motion. Interestingly, this effect is also in play in the case of the n =3 cluster but inverted because the nominal location of the bound proton stretch lies above the isolated bend fundamentals. This explains the fact that the HOH intramolecular bend in H₇O₃⁺ lies at 1,534 cm⁻¹ (13), about 60 cm⁻¹ below that in isolated water. Thus, for both n = 2 and 3, the bend and ν_{par} bands appear to repel one another (14).

Supplemental Material >

For the $H_3O_2^-$ Zundel anion, the potential describing the displacement of the bridging proton is calculated to be a double minimum (blue curve in **Supplemental Figure 2**) (77). Here again, the observed vibrational pattern is consistent with a symmetric structure featuring proton accommodation at the midpoint between oxygen atoms, this time due to the delocalization of the $\nu =$ 0 vibrational wave function above the low barrier (calculated to be 75 ± 25 cm⁻¹) (83). Similar vibrational averaging was also found to occur in the protonated ammonia dimer (72).

An important feature of the quasi-symmetric Zundel ions $H_5O_2^+$ and $H_3O_2^-$ is that they are extremely sensitive to external electric fields. This feature was, in fact, identified by Zundel early on (32, 39). This effect is illustrated by the calculated potential curves in **Supplemental Figure 2**, which correspond to two values of the electric field with the OH⁻ ·(H₂O) core held fixed. These fields were chosen based on the expected fields arising from the addition of one and two water molecules in the arrangements indicated in **Figure 5***ef*. The actions of these water molecules strongly distort this potential, first with the introduction of a shelf (see **Supplemental Figure 2**) and then by narrowing the shape until it is closer to that of an isolated OH oscillator. Note that these shapes are remarkably similar to those that account for the strong shifts in v_{par} for the proton dimers (insets in **Figure 4**).

The response of a molecular system to an electric field is generally encoded in its polarizability, α :

$$\mu_{\rm in} = \alpha E$$
,

that relates the induced electric dipole moment, μ_{in} , to the applied electric field. In many molecules, α is derived mostly from the displacement of the electron cloud relative to the nuclei, with relatively little effect on the molecular equilibrium structure. The unique feature of Zundel scaffolds, however, is that this polarizability response mostly comes from the displacement of the bridging proton relative to the two O atoms. In fact, this proton polarizability is about 100 times larger than that arising from the electronic contribution. In a nutshell, this aspect of the Zundel ion lies at the heart of the pathological spectral signatures of the hydrated proton: This structure is hypersensitive to the strong local electric fields at play when embedded in water networks. Not surprisingly, this effect is most significant in the first hydration shell where fields are the strongest. The net effect is that the addition of the next two water molecules to the Zundel structure acts to incrementally reduce the field at a particular OHO moiety (84–86). This in turn reduces the strength of the hydrogen bonds and is therefore an extreme example of hydrogen bonding anticooperativity, the general phenomenon in which formation of a new H bond to the same oxygen center weakens those already in effect (87). The situation in the n = 3 cluster is particularly complex because adding the second water molecule to the Zundel scaffold pushes the $\sigma_{pr}(\omega)$ band to about 1,600 cm⁻¹, close to the energy of the HOH bending fundamental. In addition, the displacements of the OH stretches in the $\nu = 1$ level, which are nominally associated with the hydronium ion, lie close to the shelf in the potential in which the system evolves from the more charge-localized configuration near the equilibrium geometry to the region at larger OH displacements that corresponds to partial proton transfer. This results in large changes in electronic structure upon OH excitation that provide a strong coupling mechanism to the soft modes of the cluster as well as the proximal bend. These interactions were ultimately disentangled using a combination of isotopomer-selective spectroscopy to isolate the role of an isolated OH group combined with fully anharmonic calculations that explicitly treated the coupled motions of all 18 vibrations on an extended potential energy surface (14, 41, 88). The factors that drive the widths of the bound OH stretches in the Eigen cation have been considered in the context of a vibrationally adiabatic picture that is especially clear in the case of hydronium trapped in a crown ether (89). In essence, the widths are traced to the displacements of the soft modes of the Eigen scaffold and are a direct reflection of strong nuclear quantum effects.

SHAPE MATTERS: SYMMETRY BREAKING IN THE ZUNDEL CORE ION BY ITS SECOND SOLVATION SHELL

The serpentine way that $\sigma_{pr}(\omega)$ evolves with cluster size (**Figure 2**) is closely related to the symmetry of the network surrounding the charge center. For example, the $\sigma_{pr}(\omega)$ band in the Eigen cation lies highest in energy and has three equivalent donor H bonds to the water molecules in the first hydration shell, thus distributing the excess charge among the four oxygen atoms in the Eigen structure. Removing or adding one water molecule yields many more red-shifted $\sigma_{pr}(\omega)$ absorptions in the *n* = 3 and 5 clusters as the excess proton is increasingly localized between two and three oxygen atom centers, respectively. Qualitatively, the smaller the number of O atoms that accommodate the excess charge, the lower is the $\sigma_{pr}(\omega)$ frequency.

One isomeric form of the n = 6 cluster adopts a structure in which the Zundel ion is symmetrically solvated by four water molecules attached to the two water molecules bound to the central proton. When this happens, its v_{par} band occurs in essentially the same location as that found in the Zundel ion near 1,000 cm⁻¹. Not accidentally, that band location was also found in the proton-bound dimer of diethyl ether (Figure 3f). Expanding on this theme, the series depicted in **Figure 6** compares how v_{par} evolves when each exterior H atom on the Zundel ion scaffold is sequentially replaced by CH_3 groups (green line in Figure 6) with the case in which an adduct is attached to each of these OH groups [black (Ar) and red (H_2O) lines in Figure 6] (87). The trend is similar in all three cases. In particular, attaching a water molecule to a free OH group on the Zundel scaffold clearly induces a shift in v_{par} that is surprisingly similar to that caused by the replacement of the H atom by a methyl group. The location of the v_{par} band can then be regarded as the consequence of the tug of war that occurs when two oxygen atoms compete for an excess proton. The largest blue shift of v_{par} occurs in cases with the greatest asymmetry (two water molecules solvating the same water molecule in the Zundel core ion or the proton-bound complex between dimethyl ether and water). Systems in which both partners are the same yield the characteristic band near 1,000 cm⁻¹, while the intermediate cases fall in between these extremes.

These considerations indicate that the topology of the water network beyond the immediate charge center is a critical factor controlling the $\sigma_{pr}(\omega)$ location in the spectrum. This effect was clearly expressed in a detailed study of the n = 6 cluster, which can be generated in two different isomeric forms. One isomer corresponds to the fully hydrated Zundel (6Z), as depicted in **Figure 6**, but there is another, lower-symmetry structure based on a distorted hydronium core



Position of the v_{par} frequency determined by Ne/Ar predissociation as a function of the numbers of Ar atoms (*black filled squares*), methyl groups (green open triangles), and solvent H₂O molecules (red filled circles). The v_{par} frequency for the H₅O₂⁺·Ne adduct was determined by Ne predissociation spectroscopy. Figure adapted with permission from Reference 87; copyright 2011 Elsevier.

Supplemental Material >

ion (6E). Thus, even for the same number of water molecules, the nature of the proton defect is quite different. The spectra associated with each isomer have been isolated using two-color, IR–IR photobleaching, requiring two stages of mass separation (IR²MS²) (58), by Asmis and coworkers (**Supplemental Figure 3**) (27), which revealed that the telltale $\sigma_{pr}(\omega)$ band near 1,000 cm⁻¹ that dominates the Zundel-core isomer is missing in the form that occurs with two water molecules in the second hydration shell around the hydronium core ion. In this broken-symmetry arrangement, $\sigma_{pr}(\omega)$ now appears around 2,000 cm⁻¹, about two-thirds of the way back to the $\sigma_{pr}(\omega)$ position (~2,600 cm⁻¹) in the tricoordinated Eigen cation. The n = 7 cluster provides an even richer landscape upon which to express the shape dependence of $\sigma_{pr}(\omega)$, because it is observed to adopt four different structural isomers, each with distinct band patterns (28).

RATIONAL MANIPULATION OF THE SECOND SOLVATION SHELL TO REVEAL THE SPECTROSCOPIC SIGNATURES OF THE ELEMENTARY INTERMOLECULAR PROTON-TRANSFER PROCESS IN WATER

The fact that attaching a water molecule to an OH group near the charge center acts to attract the excess proton toward the oxygen atom of the acceptor creates an opportunity to use this effect to rationally control the distortion of a water scaffold. Although the addition of a water molecule is a very large perturbation, for example causing incremental shifts in $\sigma_{pr}(\omega)$ of ~1,000 cm⁻¹ in the range n = 1-6, more weakly binding adducts can be placed in this position and thus allow the distortions to be followed with much finer resolution. This strategy was applied to systematically distort the Eigen scaffold into the Zundel-based isomer of n = 6 in the scheme depicted in **Figure 7**.

Recall that $\sigma_{pr}(\omega)$ occurs at high energy (~2,600 cm⁻¹) in the Eigen cation, consistent with charge localization largely on the hydronium core with three equally shared protons to the three



Experimental frequencies of the five OD stretches associated with the transfer of a deuteron of tagged $D_9O_4^+$ (*inset structure at lower right*). The adducts (X = D₂, N₂, CO, and D₂O) cause the red-colored hydrogen atom of the D₃O⁺ core to be attracted toward the tagged D₂O molecule and so reduce the corresponding O–O distance, R_{OO} . The extent of the reaction is indexed by the computed O–O distances (using MP2/aug-cc-pVDZ) for a series of D⁺ \cdot (D₂O)₄ \cdot X adducts that systematically transform the scaffold from the Eigen to the Zundel accommodation motifs. IDB denotes a donor H bond from an OD group on the positively charged center. Abbreviations: A, acceptor; D, donor. Figure adapted with permission from Reference 3; copyright 2016 American Association for the Advancement of Science.

water molecules. However, in the Zundel-based n = 6 cluster, $\sigma_{pr}(\omega)$ lies near 1,000 cm⁻¹, the common feature when charge resides mostly on a single proton equally shared between two oxygen atoms. This equally shared arrangement can be considered to be a transition state for proton transfer between water molecules. The evolution of charge accommodation from the Eigen to the Zundel motifs is the essential feature of the Grotthuss proton-relay mechanism for charge translocation. By gradually increasing the basicity of a library of adducts (X = H₂, N₂, CO, and D₂O in **Figure 7**) attached to one of the water molecules in the second hydration shell, one can spectroscopically characterize the collective reaction coordinate underlying intermolecular proton transfer in water. In essence, this yields a type of stop-action movie of how the assembly flexes during the process of intermolecular proton transfer. The most important outcome of this effort is the determination of the correlations across the vibrational spectra that are associated with the proton-transfer event. **Figure 7** presents a map of how the energies of five OD-stretching fundamentals associated with the indicated groups evolve as a function of the distance, R_{OO} , between

the two oxygen atoms directly involved in the transfer. The most striking aspect of this map is the dramatic splitting between the nearly degenerate bound OH stretches on the Eigen structure (blue and red lines) as the excess charge becomes increasingly associated with the proton trapped between the two most closely spaced oxygen atoms. Experimental evidence is mounting (23, 24) that the speciation of the hydrated proton in liquid water is best described as a charge delocalized over the special pair of closely spaced water molecules (90–92). Indeed, the spectral properties of the isolated clusters have played an important role in clarifying the assignments of features recovered in ultrafast IR studies of $H^+(aq)$ (24).

The basic strategy of employing a library of increasingly strongly binding tag molecules to slowly morph a particular water cluster toward the structure of the next larger size has also proven to be a powerful method to disentangle the assignments of complex band structures (93). That method was particularly useful in the analysis of the n = 3 spectrum, which, as noted earlier, was challenging because the oscillator strength associated with the excess proton was distributed into many states that are themselves large admixtures of states in the normal mode basis (14).

UNRAVELING THE SPECTRAL CHARACTER OF THE PROTON DEFECT IN LARGER (THREE-DIMENSIONAL) WATER CLUSTERS

Mass spectra of the protonated water clusters in the size range n = 1-30 or so were reported in 1974 by Searcy & Fenn (94), who noted the intensity enhancement or so-called magic number character of the n = 21 cluster. These authors prophetically remarked on the fact that 20 water molecules are known to form cages in condensed-phase clathrates that encapsulate small hydrophobic molecules such as methane at high pressure. The thermodynamics associated with the intensity discontinuity were further investigated in a temperature-dependent study in the 1990s by Castleman and colleagues (95), who reported that entropy was a primary driving force leading to the discontinuity in the population distribution at n = 21. That group also used a chemical probe of structure that involved titrating the number of free OH groups by coordinating them to the nitrogen atom lone pair of electrons in the trimethylamine (TMA) molecule (96). That study concluded that 10 TMA molecules are strongly bound to the n = 21 cluster. A more recent variation on that theme involved the sequential replacement of water molecules in the n = 21cluster by tert-butanol molecules (97) to effectively count the number of AAD sites. The idea is that the hydroxyl head groups can replace the bound OH groups on the AAD water molecules and leave the number of oxygen atoms in the enhanced (magic) cluster size intact, as their alkyl groups are likely to point outward. They found that nine alcohol molecules can be incorporated into the cluster while maintaining the magic number in the cluster distribution, thus revising the number of ADD molecules in the n = 21 structure to nine. That number is consistent with the current calculated structure of this species (98).

Jiang, Lee, and coworkers (56) reported the first vibrational spectra in the n = 2-10 size range in 2000. These spectra were measured in the OH-stretching region using IRMPD. Although the envelopes in the hydrogen-bonding region from 3,000 cm⁻¹ to 3,700 cm⁻¹ were too broad to directly encode structural information, the activity of the sharper bands associated with dangling, or free, OH groups was useful. Specifically, small shifts in this transition frequency reveal the local hydrogen-bonding environments of these molecules; a more recent series of spectra (49, 50) highlighting the free OH bands is presented in **Figure 8. Figure 8a** displays the evolution of the bands in the smaller size range, where the outer two features (v_{sym} and v_{asym}) arise from the symmetric and asymmetric OH stretches on water molecules that accept a single H bond (the A motif). The bands between v_{sym} and v_{asym} are associated with the single OH stretches on water molecules that have both acceptor (A) and donor (D) H bonds. The interior doublet is assigned to



An expanded view of the vibrational predissociation spectra of (*a*) $H^+ \cdot (H_2O)_n = _{6-11}$ and (*b*) $H^+ \cdot (H_2O)_n = _{18-24}$ clusters showing the size-dependent evolution of the four telltale bands in the free OH region, with the spectrum of $H^+ \cdot (H_2O)_{21}$ highlighted in yellow. Abbreviations: A, acceptor; D, donor. Figure adapted with permission from Reference 50; copyright 2004 American Association for the Advancement of Science.

tricoordinated AAD and bicoordinated AD sites as indicated. The loss of the A water signatures with increasing cluster size is clearly evident in **Figure 8***a*, as all molecules donate at least one H bond to the network by n = 11. This is consistent with the formation of ring motifs, which are calculated to wrap into cage-like structures in the n = 10-20 range (49).

The evolution of the free OH doublet around the magic number n = 21 cluster was reported by Fujii and colleagues (49) and Johnson and colleagues (50) in 2004, and several of the key spectra are presented in **Figure 8b**. The collapse of the AAD/AD doublet into a single AAD feature at n = 21is exactly the behavior expected for the formation of a water cage structure with 12 five-membered rings on the surface of a strongly distorted pentagonal dodecahedron (PD). Consistent with the results of the cluster size distribution study (97), this structure indeed has nine AAD sites along with six ADD and five AADD sites, as illustrated by the structure in **Figure 9b**. More symmetric PD structures of this type are well known to form around the Cs⁺ cation, which occurs with a representative topology depicted in **Supplemental Figure 4**. This cluster also yields a locally sharp AAD band at n = 20.

These first reports of the larger cluster spectra left key questions unanswered regarding the local, molecular-level speciation of the charge defect and whether it is located inside the cage or is embedded in its surface. Calculations indicated that the lowest-energy isomer featured surface accommodation of the excess charge in an arrangement in which tricoordinated hydronium, reminiscent of the n = 4 Eigen cation, is integrated into the cage surface with a neutral water molecule inside it (50). Unfortunately, the key bands near 2,600 cm⁻¹ calculated to signal this motif were conspicuously absent in the IRMPD spectrum, while tagging, which is necessary to explore the lower-energy region with tabletop lasers, was not possible in that era. In the early 2010s, Mizuse & Fujii (99, 100) succeeded in H₂-tagging the n = 21 spectrum using a supersonic jet ion source, and although the lower-energy region of the diffuse OH-stretching envelope was enhanced, the key predicted bands of the embedded Eigen core were absent. Moreover, the AD shoulder above the dominant AAD OH stretching band was evident, suggesting that many isomers may have been kinetically trapped in the strong quenching regime required to generate tags in the jet.



Composite vibrational predissociation spectra of D₂-tagged ions taken with the Berlin infrared free-electron laser (<1,000 cm⁻¹) and the Yale tabletop system (1,000–3,800 cm⁻¹) for (*a*) H₃O⁺ \cdot (H₂O)₃ and (*b*) H₃O⁺ \cdot (H₂O)₂₀. The inset structure in panel *a* presents the bare H₃O⁺ \cdot (H₂O)₃ ion, which yields a simple doublet in the free OH region, for comparison. Panel *a* dapted from References 57 and 109 for the ranges 1,000–3,800 cm⁻¹ and <1,000 cm⁻¹, respectively; copyright 2018 American Chemical Society. The inset in panel *b* shows the structure in which the Eigen motif is embedded in the surface of a distorted pentagonal dodecahedron cage. Panel *b* adapted from Reference 108; copyright 2014 National Academy of Sciences. Abbreviations: A, acceptor; D, donor.

The spectroscopic situation improved dramatically with the application of cryogenic, radiofrequency ion traps (101–107), which allow much better control of the cooling kinetics. These traps achieve this enhanced control because they operate at lower pressure (millitorr versus atmospheres) and cool the ions over a much longer time scale (tens of milliseconds versus microseconds), which together suppress kinetic trapping by small barriers. In 2014, Fournier, Asmis, and coworkers (108) obtained the H₂-tagged spectrum of n = 21 over the range 200–4,000 cm⁻¹ using a combination of tabletop IR and the IR free-electron laser at the Fritz Haber Institute in Berlin. The composite spectra of the n = 4 Eigen cation (57, 109) and that of n = 21 are compared in Figure 9. The key observation is that the bands traced to the OH-stretching vibrations associated with the charge defect, $\sigma_{\rm pr}(\omega)$, exhibit a ~660 cm⁻¹ red shift when hydronium is tricoordinated in the Eigen cation and an additional 680 cm⁻¹ red shift in going from n = 4 to 21. This effect was predicted for the structure in which the Eigen motif is embedded in the surface of a distorted PD cage, which is depicted in Figure 9b. Specifically, in 2011 Torrent-Sucarrat & Anglada (110) carried out anharmonic calculations on the surface structure, accounting for why the earlier estimates based on harmonic calculations anticipated $\sigma_{\rm pr}(\omega)$ to have a value near that $(\sim 2,600 \text{ cm}^{-1})$ found for n = 4.



Evolution of the potential energy curves calculated for the translation of a proton away from the oxygen atom in H₃O⁺ in the bare ion, the first hydration shell (Eigen), the distorted Eigen motif within the n = 21 cage, the second solvation shell (n = 10), and n = 21. The potentials show large increases in anharmonicity upon the addition of both the first and second solvation shell water molecules around the embedded hydronium ion. The potentials have been shifted so that their minima are at the origin. Figure adapted from Reference 29; copyright 2015 American Chemical Society.

Fournier et al. (29) considered the origin of the large anharmonic shift (29, 108) in the n = 21PD structure in 2015 with particular attention to the relative contributions of the local electric field and charge delocalization into outer hydration shells on the cage surface. Analysis of electronic structure calculations indicated that most of the shift is due to the electric field, like the situation with $OH^ (H_2O)_n$ discussed earlier (Supplemental Figure 2). Specifically, the charge distribution using Bader analysis (111) indicated that +0.72e is associated with the hydronium core ion with about +0.02e on each of the three water molecules in the first hydration shell and the remainder distributed onto the second hydration shell (29). This observation then raises the question of how many water molecules are required to establish this local electric field. That information is encoded in the shape of the potential describing the OH displacement in the core H_3O^+ moiety. The calculated potentials for OH-bond displacement in the H₃O⁺ and H₉O₄⁺ molecules as well as in a $H_{21}O_{10}^+$ cluster cut out of the n = 21 cage structure are compared in Figure 10. These curves adopt a shelf shape very similar to that observed in the $A \cdot H^+ \cdot B$ (A and B = Brønstedbase) systems (Figure 4) that is significantly lowered from n = 4 to 10, which corresponds to the filling of the second hydration shell around H₃O⁺. The latter curve was calculated for the artificial situation in which the n = 4 and 10 cluster structures are those adopted in the n = 21 PD cage and carved out of the network to isolate the contributions of each local configuration. Note that the shapes of the potentials are essentially the same for n = 10 and 21, which reveals that most of the spectral response of the surface charge defect is accounted for by the action of the first two hydration shells (52).

Although this review is primarily focused on the spectral signatures of the proton defect, recent extension of IR photodissociation spectroscopy to the D_2 -tagged $D_3O^+ \cdot (HDO)(D_2O)_{19}$ isotopologue has yielded important clues about the structure of the neutral water network that accommodates the charge defect on the surface (52). Because this isotopologue has only one OH



Nonselective spectra of D_2 -tagged D_3O^+ ·(HDO)(D_2O)₁₉ (top trace) and the isotopomer-selective photobleaching scans (*lower traces* with downward peaks) obtained with certain probe laser positions (*colored arrows*). The bands are colored according to the contributions from each type of water molecule as indicated in the structure and key at the right. A combination band with a soft mode is labeled with a gray bracket above the OH-stretching fundamental at ~3,400 cm⁻¹ (*magenta*). Abbreviations: A, acceptor; D, donor. Figure adapted from Reference 52; copyright 2020 Springer Nature Publishing AG.

Supplemental Material >

group, the coupling between OH oscillators present in the all-H isotopologue is suppressed. As a result, the spectrum in the OH-stretching region, presented in Figure 11, displays only six wellresolved bands compared to the continuum pedestal that appears in the $H_3O^+ \cdot (H_2O)_{20}$ spectrum (Figure 9) and in the OD region of the same ion (Supplemental Figure 5). The presence of many peaks, even though only one OH group is present, suggests that these bands are associated with the OH group that occupies many different spectroscopically distinct sites in the PD structure. Interestingly, the OH group was found to occupy all of the available sites with about the same probability, so each isotopomer corresponds to OH occupation of one of the spectroscopically distinct sites in the PD cage. At low temperatures, the isotopomers that arise from OH occupation are structurally distinct because the barriers to interconversion are rather high. As such, the spectral behavior of each site could be isolated using the same two-color, IR-IR photobleaching method used to obtain the spectra of the structural isomers in the n = 6 system (Supplemental Figure 3) (27). The isotopomer-selective spectra of the $D_3O^+ \cdot (HDO)(D_2O)_{19}$ isotopologue are presented as the negative-trending dip spectra in Figure 11. The pattern of colored OH bands in the nonselective spectrum of the ensemble of ions is thus revealed to arise from the contributions of distinct species. In almost all cases, the spectral signatures associated with each site are localized to a single transition, with the only exception being the observation of a $\sim 100 \text{ cm}^{-1}$ combination band (bracket under magenta peak) that occurs upon excitation of the transition near 3,400 cm⁻¹.

Having identified specific frequencies for the various sites, comparison with theoretical patterns allows a tentative assignment of these local absorptions to OH groups in specific sites

relative to the proton defect on the surface. These assignments are color coded in **Figure 11**. The main point is that the PD structure originally suggested on the basis of a single observation of the free OH quartet (**Figure 8**) is now being subjected to much more quantitative spectroscopic characterization. The photobleaching spectra also reveal the strong correlation between the intrinsic, homogeneous line widths of the various sites and their locations in the spectrum (52). This sets an upper bound, for example, of ~75 fs for the coherence lifetime of an embedded OH oscillator at ~3,100 cm⁻¹.

OUTLOOK: CHALLENGES AND OPPORTUNITIES

The advances in both theory and instrumentation in this area over the past 15 years have been dramatic. Qualitative structural hypotheses based on limited spectral data in 2004 have now been replaced by fully anharmonic theoretical analyses of spectroscopic results obtained using sophisticated multiple-resonance laser schemes combined with isotopic labeling and cryogenic cooling. The next phase of this endeavor will likely determine the evolution of spectroscopic features as a function of temperature and increasing size and complexity of the cluster systems. We list the following specific opportunities, while being fully aware that new plot twists will undoubtedly emerge as connections to other fields continue to unfold:

- Measure the barriers to proton transport as a function of temperature and network topology to provide quantitative benchmarks for theoretical simulations of bulk behavior.
- Experimentally access much larger systems.
- Determine the temperature dependence of surface versus internal charge accommodation.
- Monitor the kinetics of acid-base reactions within clusters, using them as microscopic test tubes for aqueous chemistry in a regime in which every atom counts.
- Find ways to carry out 2D coherent spectroscopy to follow H⁺(aq) dynamics in the sizeselected cluster regime, thus anchoring the molecular-level interpretation of results obtained by ultrafast experiments on liquid water (23, 24, 112).

An overarching goal for cluster studies is to provide well-defined, finite systems that are sufficiently large to yield observables that accurately reproduce bulk behavior but are small enough that they can be accurately modeled by theoretical methods that explicitly include all atoms. A particularly exciting possibility on the horizon is to exploit clusters as a venue in which to follow chemical reactions mediated by the thermal exchange of energy between reactant and solvent molecules. In this way, processes usually considered to be in the domain of statistical mechanics can be treated as properties of the cluster supermolecule, in which the reactant and solvent molecules are treated on an equal footing. An aspirational target to guide such efforts might be to extend the size range so that well-defined cluster systems can be used to understand the microscopic origin of the accelerated reaction rates that have been reported in 100–1,000 nm water droplets (113–117).

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