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Properties of microsolvated ions: From the microenvironment of chromophore and alkali metal ions in proteins to negative ions in water clusters

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Abstract

Here we discuss the fascinating chemistry and physics of microsolvated ions that bridge the transition from bare ions in gas phase to ions in solution. Such ions occur in many situations in biochemistry and are crucial for several functions; metal ions, for example, must remove their water shell to pass through ion pumps in membranes. Furthermore, only a few water molecules are buried in the hydrophobic pockets of proteins where they are bound to charged amino acid residues or ionic chromophores. Another aspect is the reactivity of microsolvated ions and the importance in atmospheric, organic and inorganic chemistry. We close by a discussion of the stability of molecular dianions, and how hydration affects the electronic binding energy. There is a vast literature on microsolvated ions, and in this review we are far from being comprehensive, rather we mainly bring examples of our own work.

Keywords: Microenvironment of protein chromophores; Alkali metal ion solvation; Structural organization of water around halide ions; Internal vs. surface solvation; Reactivity of microsolvated ions; Hydration of molecular dianions

1. Introduction

Microsolvated ions are bare ions that are ligated by one or more solvent molecules. They occur in diverse areas in physics and chemistry such as biochemistry/physics, surface chemistry, and atmospheric chemistry. Indeed, microsolvated ions are highly abundant in the Earth's atmosphere and play a major role for the ion chemistry [1]. Another issue is the environment of protein chromophores, which is far from bulk solution since only a limited number of water molecules have access to the chromophore. Importantly, the electronic absorption spectrum of a chromophore depends strongly on the surrounding chemical environment [2], e.g., a solvent or amino acid residues when the chromophore is located in the interior of a protein. Likewise, the water content inside DNA is limited, about 2.5 water molecules per base pair [3], and only during DNA replication where part of the DNA helix is unwinded, there is large exposure to water. In ion transport through membranes mediated by proteins, the physics of microsolvation is important as well [2]. Ions have to shed their solvation shell of water, but to lower the energy cost, the membrane protein mimics the solvation shell by replacing the water by e.g. amide groups or alcohol groups of amino acid residues. It is amazing how nature is optimized to discriminate between closely related metal ions as Na^+ and K^+, and a thorough understanding relies on a detailed description of the properties of microsolvated ions. The physics of doubly charged negative ions is another area where microsolvation has been a topic of intense research within the last 10 years. When an unsolvated molecular dianion becomes too small, it will stabilize itself by spontaneous emission of an electron (autodetachment) [4] or dissociate into two singly charged ions (charge dissociation) with the release of kinetic energy into translational energy of the fragments [5]. Dianions that are well known to exist in aqueous solution, such as SO_4^{2-} and $C_2O_4^{2-}$ are too small to exist in the gas phase, at least on a time scale (>picoseconds) required to be of importance in chemical reactions with other ions or molecules. Finally, microsolvated ions also serve as

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benchmark systems for theoretical calculations, e.g. for the calculation of bond energies [6].

Microsolvated ions can be formed by solvent addition to bare ions in clustering reactions or by the removal of solvent from large clusters/droplets [7]. A method commonly used today is electrospray ionization where ions in solution are gently brought into the gas phase [8]. A careful control of ion source conditions allows one to end up with bare or microsolvated ions under harsh and soft ion source conditions, respectively. This technique is especially useful for the study of fragile biomolecular ions.

Considerable work has been done to determine thermodynamic data for the gradual built-up of solvation shells around anions and cations, and the issue of competitive solvation by different solvents has been addressed. Thermodynamic properties such as ligand binding energies can be determined by (i) high pressure mass spectrometry (HPMS) at equilibrium conditions [9], (ii) threshold measurements using guided ion-beam instruments in which ions are dissociated in collisions with noble gases, and the fragmentation yield is sampled as a function of collision energy [10], (iii) blackbody infrared radiative dissociation experiments carried out with Fourier Transform Ion Cyclotron Resonance (FT-ICR) instruments where rate constants for dissociation are measured as a function of temperature to obtain Arrhenius plots [11], (iv) bracketing experiments which are based on the competition between binding of two molecules to an ion [12], (v) lifetime measurements in storage rings after photoexcitation based on modeling the decay with a microcanonical statistical rate law [13], and (vi) high-level theoretical calculations [14], often density functional theory and Møller-Plesset perturbation theory. Rate constants for clustering and the reactivity of microsolvated ions are typically measured by FT-ICR instruments [11], HPMS [9], flowing afterglow apparatus [15], ion traps [16] or triple quadrupole instruments [17].

Another important issue is structure since the organization of water around atomic and molecular ions plays a major role in chemistry and biology. The structure of an ion-solvent cluster is elucidated by infrared spectroscopy with a technique coined 'action spectroscopy' [18]: The concentration of ions in gas phase experiments is too small to cause a measurable reduction in the photon flux, and instead absorption is determined from ionic dissociation. Also computational chemistry contributes largely to an understanding of solvent organization [14].

The electronic structure of ions is determined from photoelectron spectroscopy [9d,19] and absorption spectroscopy [18d,20], techniques that reveal information on the electron binding energy and the energy levels, respectively. Electronic states of dianions in the continuum located behind the Coulomb barrier can be identified from electron scattering experiments on monoanions using storage rings [21]. Resonances in the detachment cross section are signatures of the formation of very short-lived dianions, their lifetime being determined by the electron tunneling rate (cf., the similar case of α-particle decay of unstable nuclei).

This paper is organized in the following way: First we concentrate on the electronic properties of isolated protein chromophores revealed by absorption spectroscopy and compare absorption spectra with those of the proteins and those that are obtained when the chromophore is fully solvated. Next, we turn to competitive solvation of metal ions by water and methanol, a topic that may be of some relevance to ion channeling through membranes though permeation energetics and selectivity are primarily determined by the backbone carbonyl groups according to molecular dynamics simulations [22]. Surface solvation vs. internal solvation of halide ions will then be addressed followed by a discussion on the reactivity of microsolvated ions, which provides details about reaction mechanisms. Finally, we present recent results on dianions and how the electronic binding energy is influenced by hydration.

2. The influence of water on the electronic structure of protein chromophore ions. An example: the Green Fluorescent Protein

We have developed a technique to obtain absorption spectra of biomolecular chromophore ions [23]. It is based on the combination of an electrospray ion source with an electrostatic ion storage ring (Fig. 1) and can be considered a gas phase optical cell. The ions are accumulated in an ion trap for 100 ms before they are accelerated to a kinetic energy of 22 keV, mass-to-charge selected, and injected into the ring where they are stored. The pressure in the ring is a few times 10^{-11} mbar allowing storage times of several seconds. After storage in several milliseconds to ascertain the decay of vibrationally hot ions, the ion bunch is irradiated with laser light at one side of the ring. A pulsed tunable laser, synchronized with the trapping and injection scheme is used. If the ions absorb one or more photons, they increase their internal energy and will dissociate if the internal energy is above the activation energy. Dissociation of singly charged ions leads to neutral fragments that will not be influenced by the electric fields in the ring, and therefore such

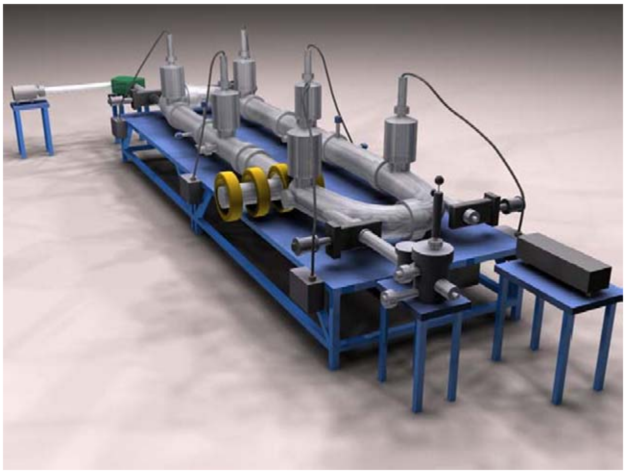

Fig. 1. The electrostatic ion storage ring ELISA equipped with an electrospray ion source, a pulsed laser and detector for the production of neutrals. A typical revolution time in the ring is 100 µs, and it therefore takes about 50 µs before the decay of ions photoexcited on one side of the ring is sampled on the other side. More information can be found on this homepage: http://www.isa.au.dk/facilities/elisa/elisa.html.

neutral fragments continue in the direction of their parent ions at the time of their decay. When the dissociation occurs on the opposite side of the laser interaction region, the neutrals hit a detector positioned at the end of the track. An absorption spectrum is obtained by the measurement of neutrals yield as a function of wavelength (cf., action spectroscopy). More details can be found in refs. [23].

The Green Fluorescent Protein (GFP) found in the jellyfish *Aequorea victoria* is a highly important photoactive protein that converts blue light to green light [24]. It is used in molecular biology to image cells and monitor movements of, e.g., proteins within the cell. We have investigated how the microenvironment of the protein chromophore perturbs its electronic structure by carrying out absorption spectroscopy of the isolated chromophore in vacuum [23c].

The spectrum of the isolated chromophore anion of GFP is shown in Fig. 2 together with the spectra of the chromophore anion in water solution and of the protein itself. The band maximum of the chromophore anion in vacuo is at 479 nm, which blueshifts to 426 nm when the chromophore is dissolved in water. This shift of more than 50 nm clearly demonstrates that the electronic structure depends strongly on the chemical environment. The hydrogen-bonding interaction between a water molecule and the phenolate anion oxygen lowers the energy of the electronic ground state more than that of the excited state since the negative charge of the oxygen is reduced after photoexcitation.

The protein itself displays two band maxima at 395 nm (major band) and 477 nm (minor band), which are due to a neutral and an anionic form of the chromophore, respectively. Our data reveal that the band maximum of the isolated chromophore anion is essentially identical to that of the protein when the chromophore is on its anionic form. Hence, the electronic structure of the anion within the protein is similar to that of the chromophore in vacuo. This is not to say that the chromophore in the interior of the protein is in a pure vacuum cavity but that the local interactions from the amino acid residues or buried water molecules are of little importance or they counteract each other in such a way that the electronic structure is unperturbed compared to the vacuum situation. For other chromophores such as those in the DsRed and PYP proteins, we have obtained similar results [25]. It seems that treating the environment as being vacuum-like provides the best approximation to the protein pocket, at least much better than bulk water solution. This picture is also in agreement with the fact that strong salt bridges form in hydrophobic pockets where the electrostatic interactions are maximal because of low water content. Indeed, the dielectric constant inside proteins is often assumed to be about 4, which is much less than that of water being ~80 at room temperature.

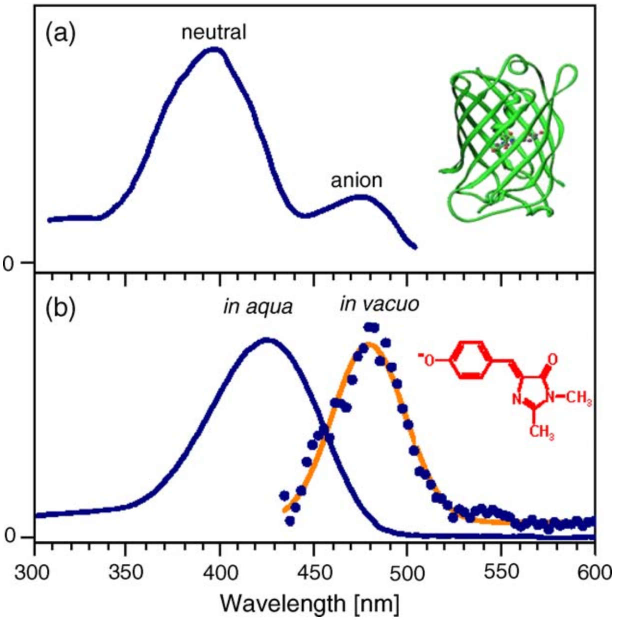

Fig. 2. (a) Absorption spectrum of the wild-type *Aequorea victoria* GFP. The two peaks are due to the absorption of a neutral and an anionic form of the chromophore. (b) Absorption spectra of the model GFP chromophore anion in aqua and in vacuo.

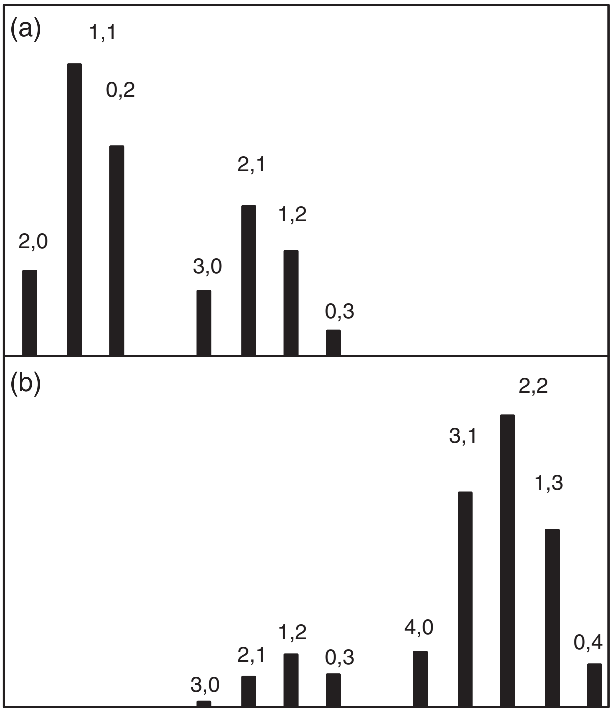

Fig. 3. $Li^+(H_2O)_x(CH_3OH)_y$ intensity distributions obtained when methanol complexes of Li^+ are supplied to the reaction chamber which contains H_2O and CH_3OH at a constant partial pressure ratio (5.6). x,y: $Li^+(H_2O)_x(CH_3OH)_y$. Temperature of the reaction chamber: 436 K (a) and 303 K (b). Reproduced with permission from Ref. [27]. Copyright 1999 Am. Chem. Soc.

3. Competitive solvation of metal ions by water and methanol and the importance to the K^+ ion channel protein

In high pressure mass spectrometry experiments, ions are thermalized in a high-pressure chamber (about 10 Torr nitrogen bath gas), typically made of copper [26]. Gases are led into the chamber, and if the ion residence time in the chamber is large enough (about 100 μs), ion equilibria establish, which implies that classical thermodynamic relations can be used. Ions escape through a small orifice in the chamber due to a small electric

Table 1
Enthalpy changes (in kcal mol^{-1}) for the substitution of water with methanol in $M^+(H_2O)_x(CH_3OH)_y$, *n* is the total number of ligands ($x+y$)

n	*x*,*y*	*x*−1,*y*	Li^+	Na^+	K^+	Rb^+	Cs^+
1	1,0	0,1	−4.0	−2.6	−2.1	−1.8	−1.7
2	2,0	1,1	−3.1	−2.1	−1.5	−1.5	−1.4
	1,1	0,2	−3.0	−2.2	−1.6	−1.8	−1.6
3	3,0	2,1	−2.4	−1.7	−1.3		
	2,1	1,2	−2.4	−1.7	−1.4		
	1,2	0,3	−2.4	−1.8	−1.4		
4	4,0	3,1	−1.8	−1.4			
	3,1	2,2	−1.8	−1.4			
	2,2	1,3	−1.9	−1.4			
	1,3	0,4	−2.0	−1.6			

The uncertainty is estimated at 0.2 kcal mol^{-1}.

field and are measured by a mass spectrometer, e.g. a quadrupole analyzer. From the ion distributions and the known partial pressures of the gases, equilibrium constants are determined. These lead directly to Gibbs free energies since the temperature is known. Enthalpies and entropies are often obtained from measurements of the equilibria at different temperatures, cf. van't Hoff plots.

In this way, the free energy was determined for substitution of water with methanol in $M^+(H_2O)_x(CH_3OH)_y$ complexes containing from one to four ligands and for $M^+=Li^+$, Na^+, K^+, Rb^+, and Cs^+ [27]. Ion distributions at two different temperatures are shown in Fig. 3 for complexes of Li^+. At the high temperature, the complexes are, not surprisingly, smallest. The entropy change of the ligand exchange reaction is modest (0–4 cal mol^{-1} K^{-1}) and is mainly due to the different number of pathways for loss of water and methanol from the intermediate complex, $M^+(H_2O)_x(CH_3OH)_y(CH_3OH)$, and the change in translational entropy. The first contribution is easily evaluated from $R\ \ln(x/y+1)$, where R is the gas constant, and the second from the Sackur Tetrode equation that only depends on the masses of the reactants and products. From these entropies, enthalpies were obtained (Table 1). It appears that methanol binds stronger than water to alkali metal ions but less so for larger complexes. Furthermore, the exothermicity of the exchange reaction is independent of the number of exchanges for a given number of ligands, and it decreases with the ionic radius of the alkali metal ion. These findings reflect the larger polarizability of methanol (3.3 Å^3) [28] relative to water (1.45 Å^3) [28], which is more important at close distance than the larger dipole moment of water (1.85 D) [28] compared to that of methanol (1.70 D) [28].

It is interesting to note that in a mixed water-methanol solution, it seems that the first solvation shell is primarily made of water molecules [29]. The reason is that water molecules in the first shell permit a more extensive hydrogen bond network between first and second shells.

Metal ions have low permeability through biological membranes. This problem is solved in nature by membrane proteins that work as channels selective for particular metal ions. One such example is the K^+ membrane channel protein that is able to discriminate between K^+ and Na^+. K^+ ions are dehydrated, transferred through the channel and rehydrated in a time of 10 ns, which is close to being diffusion limited [30]. X-ray crystallography by the MacKinnons group revealed that the protein mimics the solvation shell of K^+ by replacing water with amide carbonyl of amino acid residues and the alcohol group of the threonine side-chain. According to our measurements for binding of water and methanol to alkali metal ions, such an exchange reaction is expected to be exothermic for the threonine alcohol groups. Exchange of water for amide carbonyl in small clusters is even more exothermic; the enthalpy change of the $K^+(H_2O)+CH_3C(O)NH_2 \rightarrow K^+(CH_3C(O)NH_2)+H_2O$ reaction is −12.6 kcal mol^{-1}) [6c,31]. This is in agreement with an even larger polarizability of acetamide (5.67 Å^3) [28] compared to that of methanol.

4. Surface vs. internal solvation of anions

Vibrational predissociation spectroscopy has been used with great success to obtain infrared spectra of microsolvated ions [18]. Importantly, the argon tagging technique developed by Johnson et al. [18f] has enabled the study of vibrationally cold ions. Ions are, so to speak, frozen down in a nanomatrix and as such the technique bears strong resemblance to the spectroscopy done on molecules or ions in solid rare gas matrixes [32]. The technique builds upon the 'messenger' technique pioneered by Okumura et al. [33], where H_2 was weakly bound to protonated water clusters and lost after IR absorption.

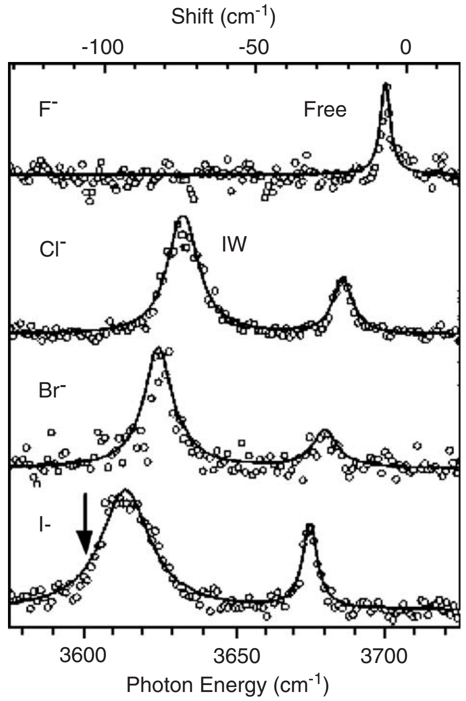

Fig. 4. Expanded view of the $X^-(H_2O)_2$ higher energy vibrational modes. The arrow indicates the position of the interwater H-bonded OH stretch fundamental observed in the neutral water dimer. Band labels correspond to IW = interwater H-bonded, and Free = free OH stretches. Reproduced with permission from Ref. [34]. Copyright 1999 Am. Chem. Soc.

Much work has been devoted to the understanding of halide microhydration [18f], and in the following we discuss, as an example, the halide dihydrates. Infrared spectra of $X^-(H_2O)_2 \cdot Ar_2$ in the OH stretch region from 3580 to 3720 cm^{-1} are shown in Fig. 4 for $X^- = F^-$, Cl^-, Br^-, and I^- [34]. Spectra were recorded by monitoring the loss of argons as a function of photon energy. The strong bands from the ionic hydrogen bonds are much lower in energy and therefore do not appear in the region depicted. It is evident that when $X^- = Cl^-$, Br^- and I^- a band is present between 3600 and 3650 cm^{-1} due to interwater hydrogen bonding. The band for $I^-(H_2O)_2$ is close to that of the free water dimer, but the band blueshifts from I^- to Cl^-, which reflects the stronger binding of smaller halide ions to water and a weakening of the interwater hydrogen bond. In the case of F^-, the band is completely absent and only a band from the free OH stretch is observed. Hence the interwater hydrogen bond is completely broken in $F^-(H_2O)_2$.

For larger clusters, an interesting aspect is whether halide ions are preferentially located at the surface or centrally solvated within the cluster. Photoelectron spectroscopy experiments in combination with molecular dynamics simulations have indicated that halide ions are surface solvated [35,36], in contrast to metal ions [35b]. This is related to the high polarizability of anions. The preferred surface solvation of halide ions in water clusters is important for the surface chemistry of aerosol particles: Cl_2 is produced at the surface in a reaction between Cl^- and OH radicals [36]. The OH radicals are formed when solar UV light photolyzes ozone to O_2 and O followed by hydrogen abstraction from water by the oxygen atom. The reaction between Cl^- and OH occurs with a much larger rate constant than if the halide ions were internally solvated.

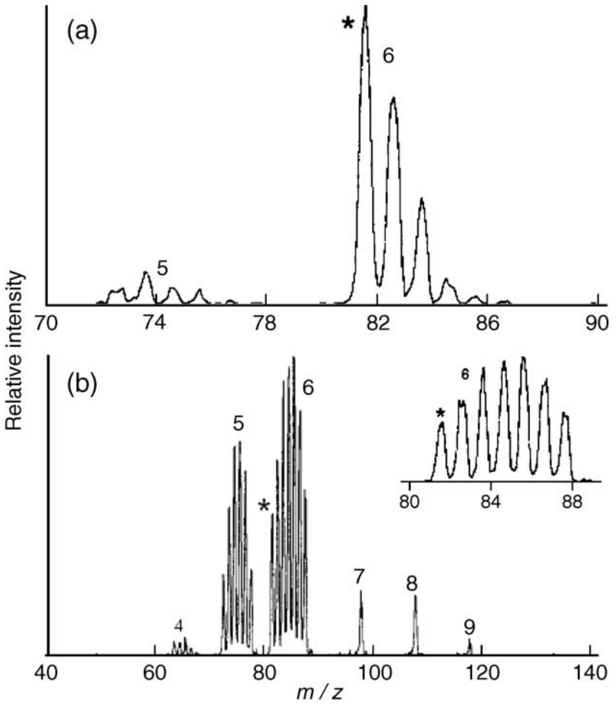

Fig. 6. Spectra obtained from the reaction between $Mn(H_2O)_6^{2+}$ and D_2O at two different pressures: (a) 0.20 mTorr, (b) 0.40 mTorr. The reactant ion is indicated by ∗. The number at each group of peaks indicates the number of aqua ligands in the complex assigned to the peaks. The reactions took place in an octopole between two quadrupole mass analyzers, the first selecting $Mn(H_2O)_6^{2+}$ ions and the second scanning the product ions formed in the octopole. Reproduced from Ref. [39] by permission of The Royal Society of Chemistry.

5. Reactivity of solvated ions

One particularly beautiful example on how solvent molecules affect reactivity is the nitration of arenes. Cacace et al. [37] showed that in the gas-phase reaction between NO_2^+ and benzene, electron transfer or oxygen-atom transfer take place instead of nitration. In contrast, when NO_2^+ is solvated by just one methanol, the classical Wheland complex between NO_2^+ and benzene is formed followed by a rearrangement reaction to give the nitrated product (Fig. 5). Hence even though the methanol molecule does not directly participate in the chemical reaction, it switches off the other channels, allowing nitration to occur.

Aqua complexes are well studied in solution, and they are well known to undergo exchange of intact ligands as well as proton exchange [38]. In contrast, in the gas phase doubly charged aqueous complexes undergo ligand exchange but not proton exchange [39], to be described in the following. The outcome of the reaction between $Mn(H_2O)_6^{2+}$ and D_2O in an octopole collision cell for two different pressures of D_2O was

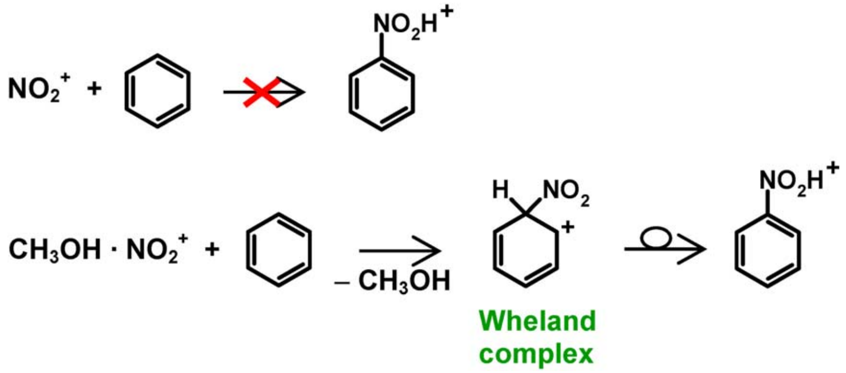

Fig. 5. In the reaction between bare NO_2^+ ions and benzene, no nitration takes place. Solvation by just one methanol, however, leads to nitration.

studied by Brøndsted Nielsen and Bojesen, and product ion spectra are shown in Fig. 6. The parent ions have a mass-to-charge ratio *m*/*z* of 81.5 and the products of consecutive ligand exchange reactions occur at intervals of one *m*/*z* value above the parent ion. The degree of exchange depends on the pressure of D_2O: At the low pressure the unexchanged reactant is the most abundant ion whereas the product of four ligand exchanges is the most abundant at the high pressure. Since the ions are doubly charged, the exchange reaction leads to an increase in the mass of two Daltons, corresponding to the exchange of intact water molecules with D_2O. Importantly, no evidence of hydrogen exchange was observed. An H/D exchange would first involve proton transfer to the incoming water to give an intermediate complex, $Mn(OH)(H_2O)_5^+ \cdots D_2HO^+$. This complex would be shortlived because of the electrostatic repulsion between the two separated charges and dissociate before back exchange of a deuteron had time to occur. These results demonstrate the strong importance of the charge state for processes taking place in vacuum. The spectra also reveal peaks from complexes with other than six ligands, which are due to collision-induced dissociation in the collision cell or clustering processes.

6. Hydration of dianions

Sulfate is a well-known dianion (i.e., divalent anion) that is stable in water, but the bare ion is electronically unstable in the gas phase. Actually, solvation by three water molecules is required for stability as revealed by mass spectrometry [40]. Photoelectron spectroscopy experiments, done by Wang et al. [40], on $SO_4^{2-}(H_2O)_n$ clusters ($n = 3$–40) have shown that the first few water molecules each stabilizes the dianion by about 0.3–0.5 eV. For larger clusters, it was found that the electron binding energy approaches that of water clusters: The spectra change from displaying solute features to bulk features. It was argued that the sulfate is centrally solvated (in contrast to halide ions) and that the photodetached electron from the solute cannot escape; it is trapped within the water cluster.

In the case of electronically unbound dianions where the extra electron is confined behind the Coulomb barrier, the flight time from the ion source to the laser interaction region may be too long (typical tens of microseconds) for the ions to survive, which calls for another technique than photoelectron spectroscopy. Indeed, electron scattering experiments in storage rings [41] have been successful in the study of unbound states of dianions [21]. In such experiments monoanions are bombarded by electrons, and the neutrals yield as a function of electron energy *E* is measured. Electron detachment can be treated by a classical "reaction-zone" model [41] where the detachment cross section σ depends on the threshold for detachment E_{th}, $\sigma = \sigma_0(1 - E_{\mathrm{th}}/E)$, where σ_0 is a constant. The threshold energy is directly related to the vertical detachment energy, VDE, of the anion according to 2.7 eV $(\mathrm{VDE/eV})^{3/4}$. However, at certain energies, the incoming electron may tunnel through the Coulomb barrier and populate dianion states. These states are normally observed at high energy, and the electron will autodetach within a few femtoseconds and may at the same time induce a dissociation of the ion or the removal of an electron, in both cases with the production of detectable neutrals. Such processes are revealed as resonances in the otherwise smooth cross section for neutrals production.

The NO_2^{2-} dianion is formed in an aqueous nitrate solution after pulse radiolysis [42]. It has a lifetime of 1 µs, which is long enough for the ion to participate in reactions with the solvent or other ions. We have studied the physics of this ion in vacuum from electron scattering experiments on NO_2^- in a storage ring and found that the isolated NO_2^{2-} dianion is unstable by 7.2 eV [43a]. The lifetime is much shorter than in solution phase, only a few femtoseconds, being less than any of the vibrational periods. Electron bombardment of NO_2^- solvated by one and two water molecules reveals resonances at 6.4 eV and 5.6 eV, respectively (Fig. 7), which means that each water molecule renders the dianion less unstable by nearly 1 eV [43b].

The number of water molecules, at which a transition to a bound system occurs, relies on the Coulomb repulsion between the two negative charges (decreases with distance, i.e., cluster radius) and the positive binding energy of an electron to a water cluster (increases with cluster radius [44]). The cluster radius is inversely proportional to the cubic root of the number of water molecules *n* in the cluster. For large cluster sizes the electron binding energy should be a constant and approach that of a $(H_2O)_n^-$ anion (3.30 eV) [44], and a simple equation for

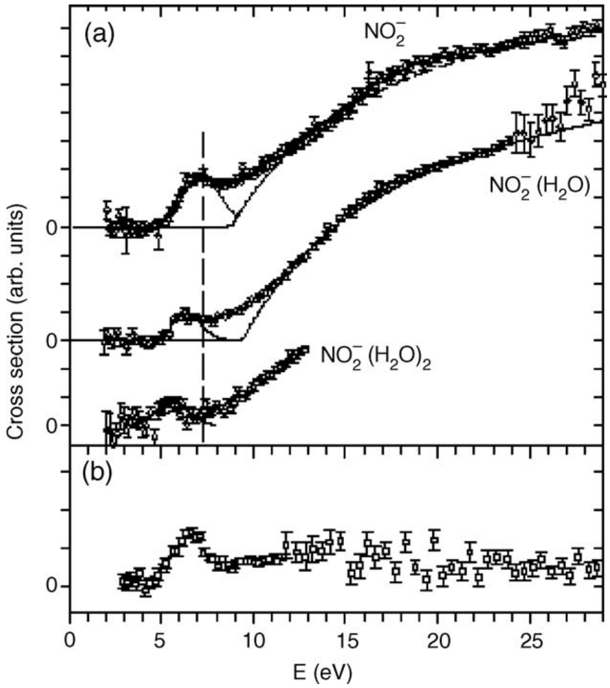

Fig. 7. (a) The cross section for formation of neutrals as a function of the electron kinetic energy for NO_2^- (top), $NO_2^-(H_2O)$ (middle), and $NO_2^-(H_2O)_2$ (bottom). The vertical line is the position of the dianion resonance for NO_2^-. Curves are drawn at the resonance positions to guide the eye. Further, the nonresonant contribution to the cross section is drawn for NO_2^- and $NO_2^-(H_2O)$. (b) The cross section for production of either N, O, OH, or H_2O as the only neutral fragment as obtained at the ASTRID storage ring with $NO_2^-(H_2O)$. The cross section displays a clear low energy resonance. Reproduced with permission from Ref. [43b]. Copyright 2005 American Physical Society.

the electron binding energy in such a cluster is therefore 3.30 eV + $\alpha n^{-1/3}$, where α is a constant. Using the experimental values for the electron binding energies in the small clusters, we predict that the addition of about 100 water molecules would result in an electronically stable dianionic cluster in which the extra electron instead of binding in an antibonding orbital of NO_2^- is dipole-bound to the water cluster.

7. Conclusions

We have presented a broad range of examples where microsolvated ions play a major role, ranging from biophysics to atmospheric chemistry to inorganic and organic chemistry. In summary, gas phase absorption spectra of protein chromophores indicate that the microenvironment of a chromophore within certain photoactive proteins is best approximated by a vacuum cavity. Importantly, the data provide a test and calibration of theoretical models for the calculation of excited states. With better models at hand, computations become a useful means of designing chromophores that have optical propensities for specific applications, such as optical markers in molecular and cell biology. The effect of gradual solvation of the chromophore is an interesting new direction for future examination. The competition between water and methanol binding to alkali metal ions is in favor of methanol because of its larger polarizability and even more so for the amide oxygens of amino acid residues of importance to the K^+ membrane protein. Infrared spectroscopy and photoelectron spectroscopy of halide-water clusters have revealed that in such perturbed water clusters there is an important balance between ion-solvent interactions and solvent–solvent interactions. The reactivity of bare ions can be completely different from that of microsolvated ions, even if limited to a single solvent molecule, as discussed in the case of solvent-driven nitration of arenes. Also the charge state of a microsolvated ion determines its reactivity and what channels are open. Finally, we have demonstrated that the addition of single water molecules to unstable dianions renders the dianions less unstable, and if the cluster becomes large enough the dianion may even become electronically stable.

Acknowledgements

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