Aqueous Proton Transfer

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Base-Induced Solvent Switches in Acid–Base Reactions**

Omar F. Mohammed, Dina Pines, Erik T. J. Nibbering, and Ehud Pines**

Proton-transfer reactions in aqueous environments have been the subject of numerous studies in solution chemistry as they play a central role in many chemical[1–8] and biochemical processes.[9–12] Modern discussions of acid–base reactions that involve proton transfer between Brønsted acids and Brønsted bases[13] have evolved from the seminal studies of Eigen[14,15] and Weller.[16] Eigen's review of the field[14] outlined the general kinetic approach for acid–base reactions in aqueous solution (Figure 1 a). Eigen discussed three reaction branches that lead to proton transfer and ultimately resulting in chemical equilibrium, namely direct proton exchange between acid and base, acid dissociation to solvent with subsequent proton scavenging by the base (protolysis), and water hydrolysis by the base with subsequent neutralization of the acid by the hydroxide anion. This model proved to be extremely useful for analysis of the relaxation kinetics of acid–base reactions that occur on the micro- to millisecond timescale.[14–16]

More refined details of the mechanisms of acid–base reactions have been determined in more recent studies with the advance of temporal resolution to the pico- and femtosecond timescales.[17–19] With sufficient time-resolution the two lower reaction branches of Figure 1 a directly are usually probed directly. The third branch, namely the hydrolysis reaction by the base, is too slow to affect proton-transfer reactions that occur on the picosecond timescale.

Recently, we have used ultrafast mid-infrared spectroscopy to probe the proton-transfer reaction between an electronically excited photoacid (pyranine; 8-hydroxypyrene-1,3,6-trisulfonic acid trisodium salt), abbreviated as HPTS) and several carboxylate bases at molar concentrations[20–23] and have been able to follow the proton-transfer reaction, for the first time, by monitoring all three reactive species involved in the ultrafast reaction, namely the acid, the base, and the hydrated proton while "in flight" between the acid and the base. We have also been able to identify a hierarchy of lifetimes for the proton transfer between acid and base depending on the reaction conditions. The shortest lifetime (below 150 fs) was observed for directly linked acid and base pairs (tight complexes), an intermediate lifetime (from 6 ps to several tens of picoseconds) was observed for acids and bases that form solvent-separated (loose) complexes, and the longest lifetime (in the pico- to nanosecond range) was observed for the diffusion-limited reaction between acid and base molecules that are initially separated by bulk water.

These studies have opened the way to monitoring the encounter complex in acid–base reactions directly. Judging by the magnitude of the reaction radius in typical (diffusion-controlled) acid–base reactions, it has been estimated that two

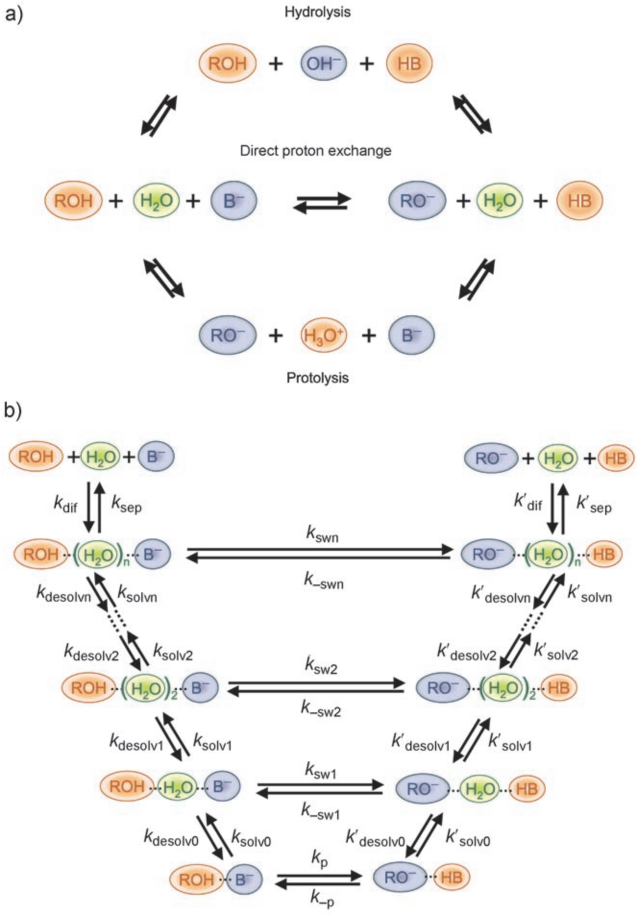

Figure 1. a) Eigen's original general scheme for aqueous acid–base neutralization reactions (ROH = acid, B = base); b) the direct proton-transfer reaction can be represented in a different way that shows the sequential desolvation and solvation pathways as well as the possible proton shuttling channels.

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[*] Dr. O. F. Mohammed, Dr. E. T. J. Nibbering
Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie
Max-Born-Strasse 2A, 12489 Berlin (Germany)
Fax: (+49) 30-6392-1409
E-mail: nibberin@mbi-berlin.de

Dr. D. Pines, Prof. Dr. E. Pines
Department of Chemistry
Ben-Gurion University of the Negev
P.O. Box 653, Beer-Sheva 84125 (Israel)
Fax: (+972) 8-6472-943
E-mail: epines@bgumail.bgu.ac.il

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to three water molecules separate between acid and base when they exchange a proton.[16] In reality, however, this value is likely to be an averaged result of several encounter complexes (with *n* rearrangement steps) that lead to proton transfer (Figure 1 b).

We have identified two innermost types of encounter complexes (tight and loose) that result in a sub-150-fs proton-dissociation lifetime of the photoacid.[20,21,23] The proton transfer in both encounter complexes is reversible and in loose complexes it occurs in a stepwise manner.[2,3] The first step, namely sub-150-fs dissociation of the photoacid, involves a H_3O^+-like cation that resembles the proton solvation core in the Eigen cation $H_9O_4^+$.[24] The second and final reaction stage, namely proton transfer to the base, is much slower than the first one and takes place on a picosecond timescale. The stability of the hydrated proton in the loose complex increases with a decrease in the reactivity (basicity) of the carboxylate base, as measured in bulk water. Stepwise proton shuttling through water[2,3,12] provides a route for proton transfer that circumvents the further desolvation of the acidic and basic groups that is necessary for direct transfer. Proton transfer through one water molecule bridge constitutes the simplest case of short-circuiting a bottleneck in the direct proton-transfer reaction.

Herein, we report on the proton-transfer reaction between electronically excited HPTS (ROH) and the trichloroacetate anion ($^-OOCCCl_3$), which is a relatively weak and relatively bulky proton base (relative to acetate and chloroacetate bases[20,21,23]). Both electronically excited HPTS and trichloroacetic acid are strong acids with comparable pK_a values in H_2O solution (0.5 for excited HPTS[16,17] and 0.6 for trichloroacetic acid[25]). Figures 2 and 3 show the time evolution of the deuteron transfer as determined by monitoring the characteristic IR bands of the conjugate photobase of the photoacid (RO^-), of D_3O^+, and of the conjugate acid of trichloroacetate. Sensitivity factors impose limitations on our detection ability that are reflected by the fact that not all the expected bands are present in Figure 3, especially the weak signal for the deuterated deuteron at 1 M and the photobase band at 3 M base concentration owing to limited IR transmission. The much faster rise in the RO^- population compared to the rise in the population of trichloroacetic acid at 1 M base concentration is clearly noticeable (Figure 3 c). This situation is the result of photoacid dissociation, which means that the protons reside in the solvent for a relatively long time before arriving at the base.

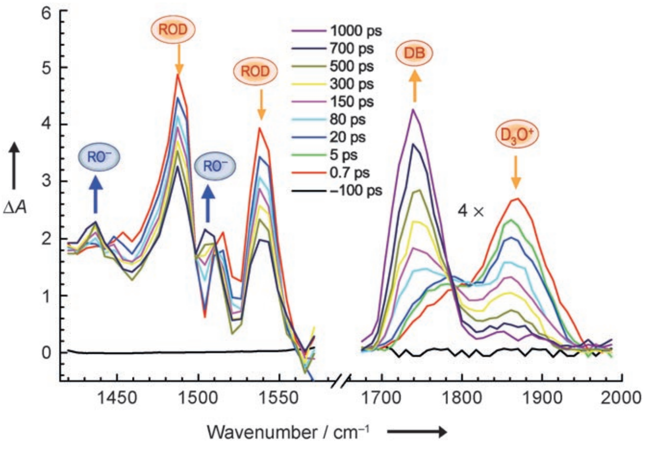

Figure 2. IR absorbance difference (ΔA) spectra measured at specific pulse delays after electronic excitation of HPTS (ROD) in the S_1 state, which converts it into the $HPTS^-$ photobase (RO^-), in D_2O with 2 M $^-OOCCCl_3$. The deuteron-transfer dynamics was derived from the $HPTS^-$ band at 1435 cm^{-1}, the deuterated-deuteron band at 1860 cm^{-1} (D_3O^+), and the C=O stretching band of trichloroacetic acid (DB) at 1740 cm^{-1}. The signals obtained for the latter two bands have been multiplied by a factor of four for clarity. (The negative time indicates that the probe pulse arrives at the sample before the pump pulse.)

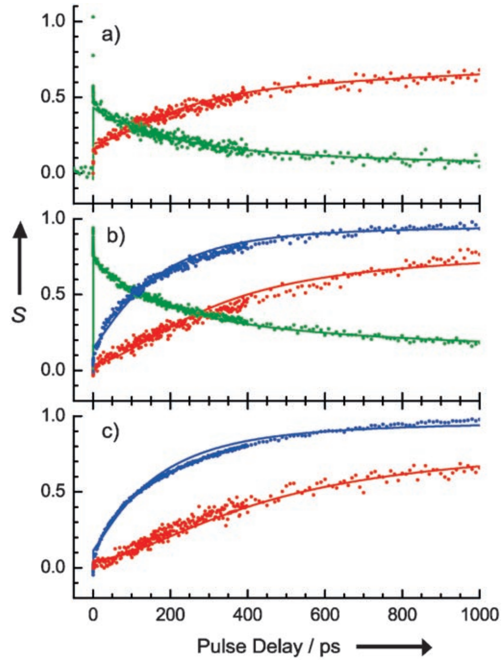

Figure 3. The time evolution (dots) of the deuteron transfer as monitored by following the normalized signal intensity, *S*, of the IR-active marker modes belonging to $HPTS^-$ (blue), the deuterated-deuteron band (green), and the C=O stretching band of trichloroacetic acid (red) for base concentrations of 3 M (a), 2 M (b), and 1 M (c). The fits obtained from the dynamic reaction model given in Figure 4 are shown as solid lines.

Figure 3 b shows the deuteron-transfer reaction of ROD at a trichloroacetate base concentration of 2 M. Under these conditions the absorption of the deuterated deuteron in loose complexes is clearly noticeable (see Figure 2). Each of the three IR bands shown in Figure 3 b exhibits complex population kinetics, and about 18 % of the RO^- population appears within the time resolution (less than 150 fs). This immediate rise is then followed by a much slower multi-exponential rise of the rest of the RO^- population. The immediate rise in the deuterated-deuteron band correlates with the immediate rise of the sub-population of the RO^- band and is in contrast to the slow rise in the trichloroacetic acid signal, which is not fully completed even after 700 ps. This situation shows that the first dissociation stage of the photoacid is insensitive to the base strength. The slower component of the rise of the signal for the RO^- ion does not fit with the immediate rise of the signal for the D_3O^+ ion because the deuterated deuteron (D_3O^+) is almost exclusively generated by the loose-complex ($n=1$) pathway, whereas the RO^- signal is caused by proton dissociation over all pathways. The decay of the D_3O^+ signal does not fit with the rise in the trichloroacetic acid signal, which points to multiple protonation pathways for the trichloroacetate base.

We have found previously that the rate of the overall proton transfer from the photoacid to the trichloroacetate base conforms to a free-energy relationship.[8,17] However, the time evolution of the various reactive populations diverges from that of stronger carboxylate bases. Consequently, we consider below an extended kinetic scheme to account for proton transfer to a less-reactive proton acceptor (Figure 4; see the Supporting Information for details of the fits). The complexity of the kinetic system makes a best fit by a unique set of reaction parameters practically impossible. However, each closed reaction loop obeys detailed balancing and the proton-transfer reactions to and from the bulk solvent conform to the equilibrium constant of deuterated HPTS and trichloroacetic acid. Below we analyze the numerical outcome of our generalized kinetic model when applied to the reaction between HPTS and trichloroacetate in D_2O:

a) Desolvation or insertion of water molecules when the acid and base are in close contact is a relatively slow process that occurs on the pico- to nanosecond timescale. This situation means that strong and medium-strong acids are likely to transfer the proton by dissociating to the solvent and not by direct proton transfer to the base. Only weak acids[3] are likely to transfer the proton to a stronger-than-water base after full desolvation.
b) Proton transfer by a short solvent switch, where the acid in close proximity to the base first dissociates to the solvent and then the proton diffuses and reacts with the base, occurs when proton dissociation to the solvent is faster than further desolvation of the acid and base. For HPTS and trichloroacetate we find that the bulk of the proton-transfer reactions occur through $n>1$ solvent switches.
c) We observe base-induced acid dissociation that results in a moderate increase in the bulk dissociation rate of HPTS for loose complexes, even for the weak trichloroacetate base, which implies an effect that is mainly driven by electrostatic long-range interactions.
d) The trichloroacetate base has a tendency to form a contact ion-pair with H_3O^+. The relatively slow rate of proton transfer to the carboxylate base in loose HPTS–trichloroacetate complexes is due to the back proton transfer being more favorable than the forward reaction.
e) We observe a mild increase in the proton-dissociation rate of the photoacid (k_{sw}) when the acid and base are within a distance of a few water molecules. This situation implies a base-induced dissociation of the photoacid at longer separations than the formal encounter (loose) complex distance.
f) When the scheme shown in Figure 4 is applied to stronger, more agile carboxylate bases (acetate and chloroacetate), the kinetic data in these experiments can be reproduced without a solvent switch, thus confirming our previous reports using less general kinetic models.[20–23] Apparently, as we will report shortly,[26] desolvation down to a well-defined encounter (loose) complex and subsequent rapid (sequential) proton transfer to the base is the most efficient process in these reactions.

Theoretical considerations of various proton-dissociation reactions of weak acids in aqueous solution[2,3,6,12] show collective solvent polarization which induces proton dissociation along the hydrogen-bonding network connecting acid and base. In the present study we find that the formation of either direct or loose encounter complexes between photoacid and base under almost total desolvation is relatively slow. Thus, proton transfer to solvent molecules when acid and base approach each other accelerates the neutralization reaction. The agile hydrated proton is then efficiently transferred to the base by way of the sequential von Grotthuss mechanism[4,7,27,28] through the hydrogen-bonding network of the solvent. (For a historical review of the achievements of von Grotthuss, see reference. [29].) The proton is solvated by several water molecules while shuttling through a water switch and is likely to exist in a fluxional (nonlocalized) form that resembles bulk solvation until it reacts with the base. The transfer of the proton through a solvent switch is either stepwise,[2,3,12] as observed in our experiments, or concerted through water-wires, as found in H_2O dissociation, depending on the chemical

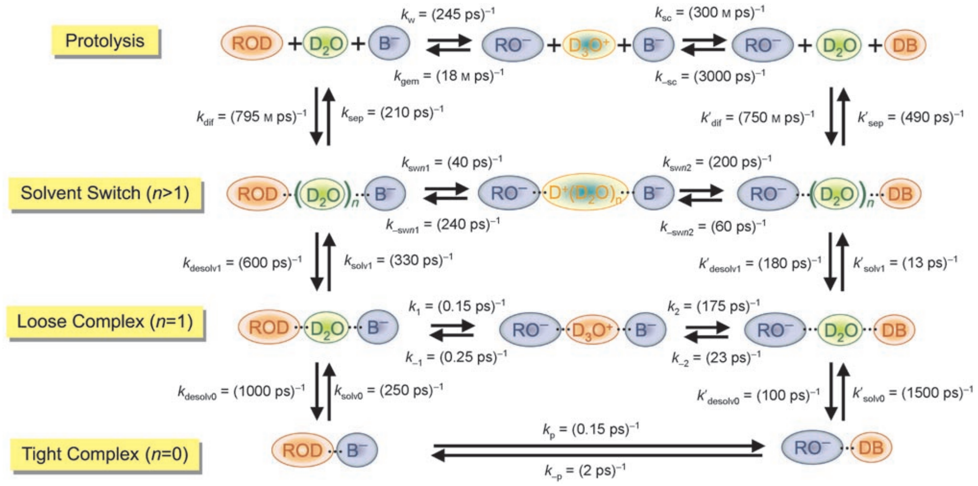

Figure 4. Reaction scheme used to model the experimental results obtained for the photoacid–base pair HPTS–trichloroacetate, with values obtained for a base concentration of 2 M. Abbreviations: gem: geminate recombination; w: proton dissociation; dif: diffusion; sep: separation; sw*n*: switch consisting of *n* water molecules; (de)solv: (de)solvation; sc: proton scavenging.

reactivity and the structure of the solvent connecting the acid and base.

The IR signature of the shuttling proton in a solvent switch having $n>1$ water molecules between the acid and base should resemble that of the IR spectrum of concentrated solutions of strong mineral acids, where the strongest IR feature is a large IR continuum resulting from the spreading out of the absorption of the hydrated proton over a spectral range of about 2000 cm^{-1}.[30–33] A recent computational study of the IR absorption of HF dissociating in water has shown the importance of contact ion-pairs and solvent-separated ion-pairs.[33] In light of this work on diatomic HF and our results on the larger carboxylate acids with at least two binding sites available for the proton, the microscopic details of the bases should also play a decisive role in the nature and kinetic stability of the hydrated protons in contact and solvent-separated ion-pairs.[23] The substantial spectral overlap of different species in the condensed phase makes tracking the diffusing aqueous (bulk) proton by spectroscopic means extremely difficult,[34] therefore global kinetic analysis of acid–base reactions is likely to remain an extremely valuable tool for tracking the reactive path of the proton through bulk water in aqueous environments.

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