Solvent effect on acid–base clustering between acetic acid and pyridine

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The solvent effect on the acid–base interaction between acetic acid and pyridine has been studied by the mass spectrometric analysis of clusters isolated from liquid droplets. The clusters resulting from the acetic acid–pyridine, acid–base, interaction in water are quite different from those in acetonitrile solvent. In water (acetic acid : pyridine : water = 1 : 1 : 10) the acid–base interaction occurs through the intercluster interaction between acetic acid and pyridine clusters. On the other hand, in acetonitrile (acetic acid : pyridine : acetonitrile = 1 : 1 : 10), the acid–base interaction proceeds through an intermonomer interaction between an acetic acid molecule and pyridine molecule, and the clusters are produced through the aggregation of a polar (acetic acid)$^{\delta-}$(pyridine)$^{\delta+}$ complex. This solvent effect is mainly attributed to the cluster structure of acetic acid and pyridine in water and acetonitrile solvent.

An electron and/or proton transfer reaction, namely an acid–base interaction, occurs easily in a solution, but occurs less readily in the gas phase due to the large activation energy of the reaction. The role of the solvent in the acid–base interaction is very important; however, the discussions are linked to the dielectric continuum model for the substrates in solution. In order to provide an insight into this subject, we have studied the clustering structure of an acid–base interaction in solution. As a typical example, the clustering structure of the acetic acid–pyridine (acid–base) system was studied by a specially designed mass spectrometry experiment. From the mass spectrometric analysis of clusters isolated from liquid droplets, the microscopic structure of solution was examined. The preferential solvation[1] and the molecular self-assembling[2] in solution have previously been discussed on the basis of the cluster structure observed through this mass spectrometry.

The acetic acid–pyridine system and its related acid–base systems have been studied, especially their hydrogen bonding and/or proton transfer interactions.[3–11] Particular attention has been paid to the hydrogen-bonding complex B · · · HA and the proton transfer complex $B^+H \cdots A^-$ formation in solution.[3–7] In this study, the solvent effect on this acid–base interaction was of particular interest, however, IR and NMR spectroscopy, which were used to observe the complexes, limited possible solvents to dichloromethane, benzene, cyclohexanol, *etc.*, although aqueous solution would be the most useful for studying acid–base interactions.

It has already been found, from mass spectrometric analysis of clusters isolated from solution, that clusters of acetic acid larger than a dimer exist in aqueous solution.[12,13] Furthermore, by studying acetic acid in an aprotic solvent through low temperature NMR spectroscopy, it has already been shown that acidity, or rather the proton-donating power of acetic acid, increases with the cluster size.[11]

From these experimental results, it can be suggested that acid–base interactions between acetic acid and pyridine will show an obvious solvent effect, related to the clustering structure. The difference in the acid–base clustering between aqueous and non-aqueous solution is therefore highlighted in this paper.

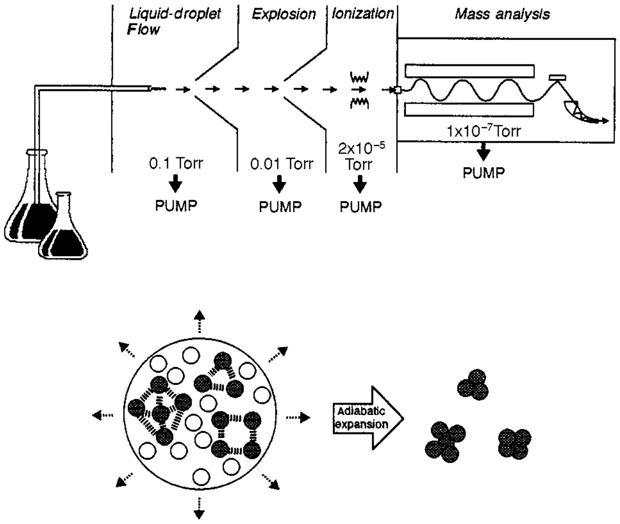

Fig. 1 Schematic diagram of the specially designed mass spectrometer for clusters isolated from liquid droplets through vacuum adiabatic expansion

Experimental

The clusters in solution were isolated from the liquid droplets through vacuum adiabatic expansion.[2,14] Fig. 1 shows a schematic picture of this experimental setup. A sample solution was injected into a four-stage differentially pumped vacuum system with a flow of 0.1 ml min^{-1} through a heated nozzle (made of a Hamilton syringe needle: N731, id 0.125 mm). A gas–liquid mixture was generated inside the nozzle with heating, which gave the liquid-droplet flow in the first chamber. The temperature of the liquid droplets should be much lower than the nozzle temperature. This temperature difference was

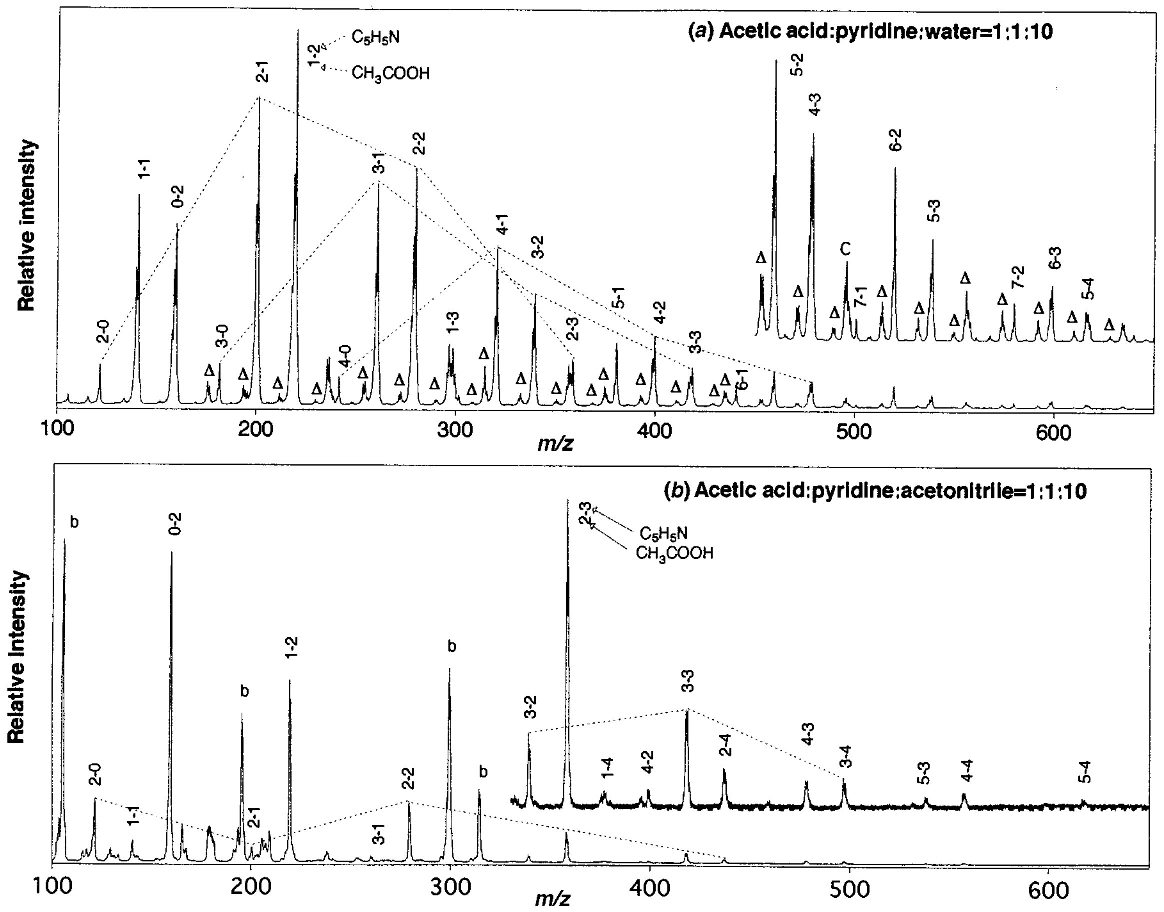

Fig. 2 Mass spectra of clusters generated from solutions containing (*a*) acetic acid–pyridine–water (molar ratio 1 : 1 : 10) and (*b*) acetic acid–pyridine–acetonitrile (molar ratio 1 : 1 : 10). Temperatures of the nozzle are (*a*) 220 °C and (*b*) 130 °C. The paired numbers in (*a*) and (*b*) represent *p*-*q* for $(CH_3COOH)_p(C_5H_5N)_q$. The clusters containing the same number of acetic acid molecules are connected by dotted lines. The peaks marked by Δ in (*a*) correspond to the hydrates of the acetic acid–pyridine clusters, and the peaks marked by 'b' represent background peaks.

estimated to be 70–90 °C.[14] The resulting liquid droplets were transferred into the second and the third chamber by pressure difference (first chamber: 0.1 Torr, second chamber: 0.01 Torr, third chamber: 2×10^{-5} Torr), and during this transfer, the liquid droplets exploded due to adiabatic expansion. As a result of the explosion, the strongly interacting molecules in the liquid droplets formed clusters, but weakly interacting molecules were vapourized as monomeric molecules. The species generated by the explosion of the liquid droplets were ionized by electron impact at 30 eV and analyzed by a quadrupole mass spectrometer (EXTREL C50-4000).

Results and discussion

Solvent effect on the acetic acid–pyridine interaction in water and acetonitrile

The solvent effect on an acid–base interaction is a particularly interesting subject, especially the comparison between aqueous and non-aqueous systems, which is expected to afford contrasting results. However, it was difficult to study this due to the limitations of the IR and NMR spectroscopy. Using our specially designed mass spectrometer, the acid–base interaction could be observed even in aqueous solution. Here, the acid–base clustering of acetic acid–pyridine in water and in acetonitrile was investigated. In general, acetonitrile is used as a polar solvent, but the acid–base interaction was found to be quite different in water and in acetonitrile.

Fig. 2(*a*) and (*b*) shows the mass spectra of clusters generated from an acetic acid–pyridine–water mixture (molar ratio 1 : 1 : 10) and an acetic acid–pyridine–acetonitrile mixture (molar ratio 1 : 1 : 10), respectively. The paired numbers in Fig. 2(*a*) and (*b*) represent *p*-*q* for $(CH_3COOH)_p(C_5H_5N)_q$. To show how the acetic acid clusters interact with the pyridine molecule, the clusters with the same number of acetic acid molecules are connected by dotted lines. In the spectrum of the acetic acid–pyridine aqueous solution [Fig. 2(*a*)], each series of clusters connected by dotted lines shows maximum distribution. Of the relatively small clusters, 2-1, 3-1, 4-1 and 5-1 clusters are found to predominate. For relatively large clusters, the favourable number of pyridine molecules interacting with the acetic acid clusters increases slightly, such as 6-2, 7-2, *etc.* In addition to these acetic acid–pyridine clusters, their hydrated clusters are also observed in Fig. 2(*a*).

In the mass spectrum of the acetonitrile solution [Fig. 2(*b*)], the resulting acid–base clusters are obviously different from those in the aqueous solution. For relatively small clusters, 0-2 and 1-2 clusters predominate, which indicates that the stable pyridine dimer is formed and interacts with a monomeric acid to form cluster 1-2. Of the relatively larger clusters, 2-2, 2-3, 3-3, 4-3, 4-4, *etc.* are predominant. This shows that all these relatively large clusters are composed of nearly equal numbers of acetic acid and pyridine molecules. The acid–base clusters that are predominant in aqueous solution (2-1, 3-1, 4-1, 5-1, *etc.*) were minor species in acetonitrile. Furthermore, the peak intensities for the observed clusters in acetonitrile [Fig. 2(*b*)] are much lower than those in water [Fig. 2(*a*)], so the background peaks for Fig. 2(*b*) are relatively stronger than those for Fig. 2(*a*).

Both the molecular composition and the peak intensities of the resulting acetic acid–pyridine acid–base clusters were found to be remarkably influenced by the solvents, water and acetonitrile. In water, the acetic acid clusters seem to form the main part of acid–base clusters; while in acetonitrile, the acid–base clusters, especially larger ones, seem to be constructed

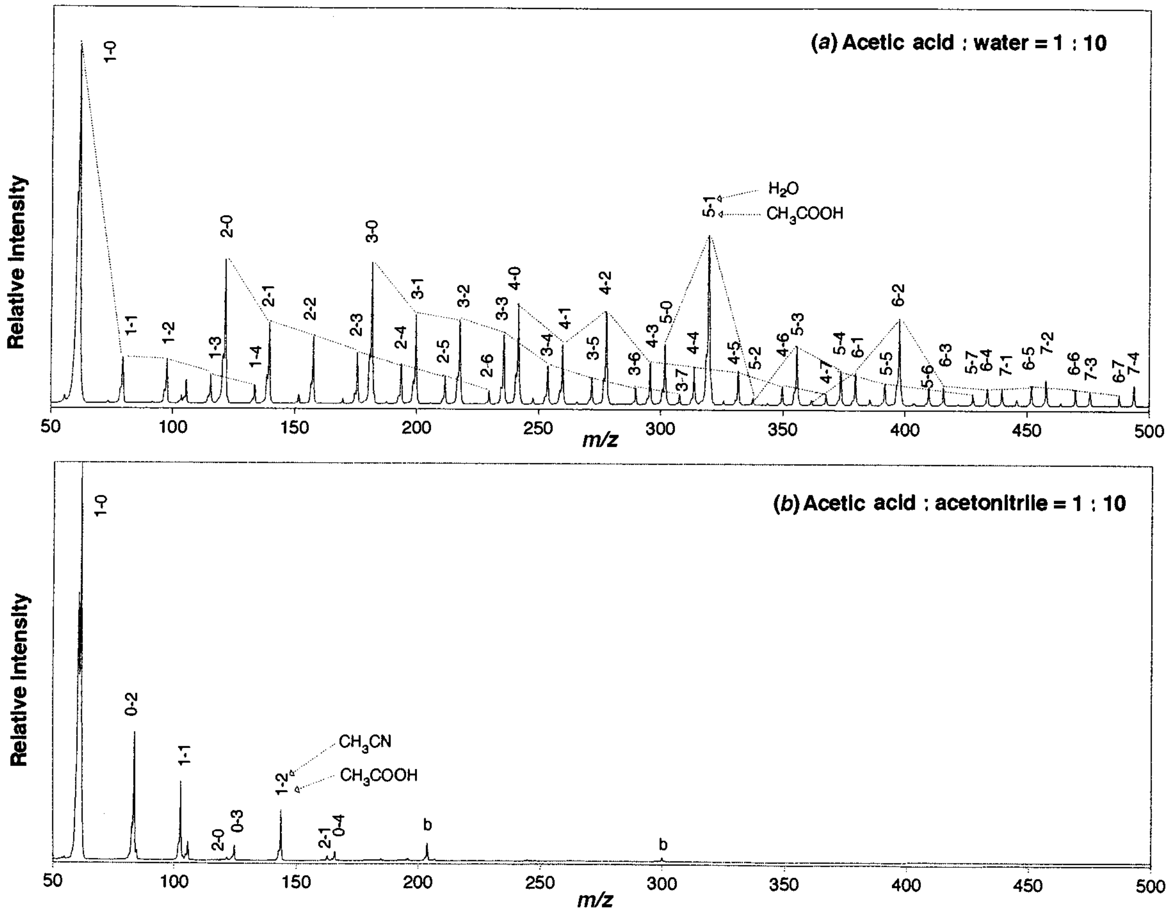

Fig. 3 Mass spectra of clusters generated from solutions containing (*a*) acetic acid–water (molar ratio 1 : 10) and (*b*) acetic acid–acetonitrile (molar ratio 1 : 10). Temperatures of the nozzle are (*a*) 220 °C and (*b*) 130 °C. The paired numbers in (*a*) and (*b*) represent *m*-*n* for $(CH_3COOH)_m(H_2O)_n$ and *r*-*s* for $(CH_3COOH)_r(CH_3CN)_s$ clusters, respectively. The clusters containing the same number of acetic acid molecules are connected by dotted lines. The peaks marked 'b' correspond to background peaks.

through the interaction of acid and base molecules or dimers. These differences are related to the cluster structures of acetic acid and pyridine in water and in acetonitrile. In order to confirm this, the clustering of acetic acid in water and acetonitrile, and the clustering of pyridine in water and in acetonitrile were studied by the same mass spectrometry technique.

Clustering of acetic acid and pyridine in water and acetonitrile

To see the clustering of acetic acid in water and acetonitrile solvents, the mass spectra of acetic acid in these solvents were recorded under the same conditions as those for Fig. 2 except for the absence of pyridine. Fig. 3(*a*) and (*b*) shows the mass spectra of clusters generated from acetic acid in water and in acetonitrile, respectively. The paired numbers in Fig. 3(*a*) and (*b*) represent *m*-*n* for $(CH_3COOH)_m(H_2O)_n$ and *r*-*s* for $(CH_3COOH)_r(CH_3CN)_s$ clusters, respectively. Fig. 3 indicates clearly that the clustering of acetic acid molecules is quite different in water and in acetonitrile. In aqueous solution [Fig. 3(*a*)], acetic acid clusters and their hydrated clusters such as 2-1, 2-2, 2-3 *etc.* were observed as predominant species. In the observed hydrated clusters, 5-1 and 6-2 cluster peaks stand out, and this is in good agreement with the magic-number species reported previously.[13] Acetic acid clusters larger than a pentamer are found to be stabilized by including water molecules. However, in acetonitrile solution [Fig. 3(*b*)], larger acetic acid clusters like those formed in water could not be observed except for the presence of a small amount of acetic acid dimer.

It was found that the acetic acid molecules easily form clusters in aqueous solution but exist as monomeric molecules in acetonitrile. The clear solvent effect on the clustering of acetic acid reflects the difference in solvation structure for acetic acid. The clustering of acetic acid is promoted by hydrophobicity of the molecule in water,[12,13] but in acetonitrile each acetic acid molecule is separated.

It has been suggested by NMR experiments that the acidity of acetic acid increases with the increase in cluster size.[11] When deprotonation of acetic acid takes place, positive and negative charges are generated. In aqueous solution, water clusters and acetic acid have positive and negative charges, respectively, which promotes the dissociation of a proton from the acetic acid [reaction (1)]. However, this kind of charge-delocalization

$$(CH_3COOH)_a + (H_2O)_b \longrightarrow (CH_3COOH)_{a-1}(CH_3COO^-) + H^+(H_2O)_b \quad (1)$$

effect is much smaller for unimolecular acetic acid in acetonitrile. Under the experimental conditions used, the clustered and the unimolecular acetic acid must work as an acid in water and in acetonitrile, respectively, which will result in a large difference in the resulting acid–base interaction.

Clustering of pyridine in water and acetonitrile

In order to investigate the behaviour of pyridine molecules in water and acetonitrile, the mass spectrum of pyridine in both solvents was measured. Fig. 4(*a*) and (*b*) shows the mass spectra of clusters generated from pyridine in water and in acetonitrile, respectively. The paired numbers in Fig. 4(*a*) and (*b*) represent *v*-*w* for $(C_5H_5N)_v(H_2O)_w$ and *x*-*y* for $(C_5H_5N)_x(CH_3CN)_y$ clusters, respectively. In the pyridine–water system (molar ratio 1 : 10), Fig. 4(*a*), pyridine clusters smaller than the tetramer and their hydrated clusters are observed. By comparing the peak intensities of clusters with the same number of water molecules, such as 1-10, 2-10, 3-10 or 1-14, 2-14, 3-14 *etc*, the number of

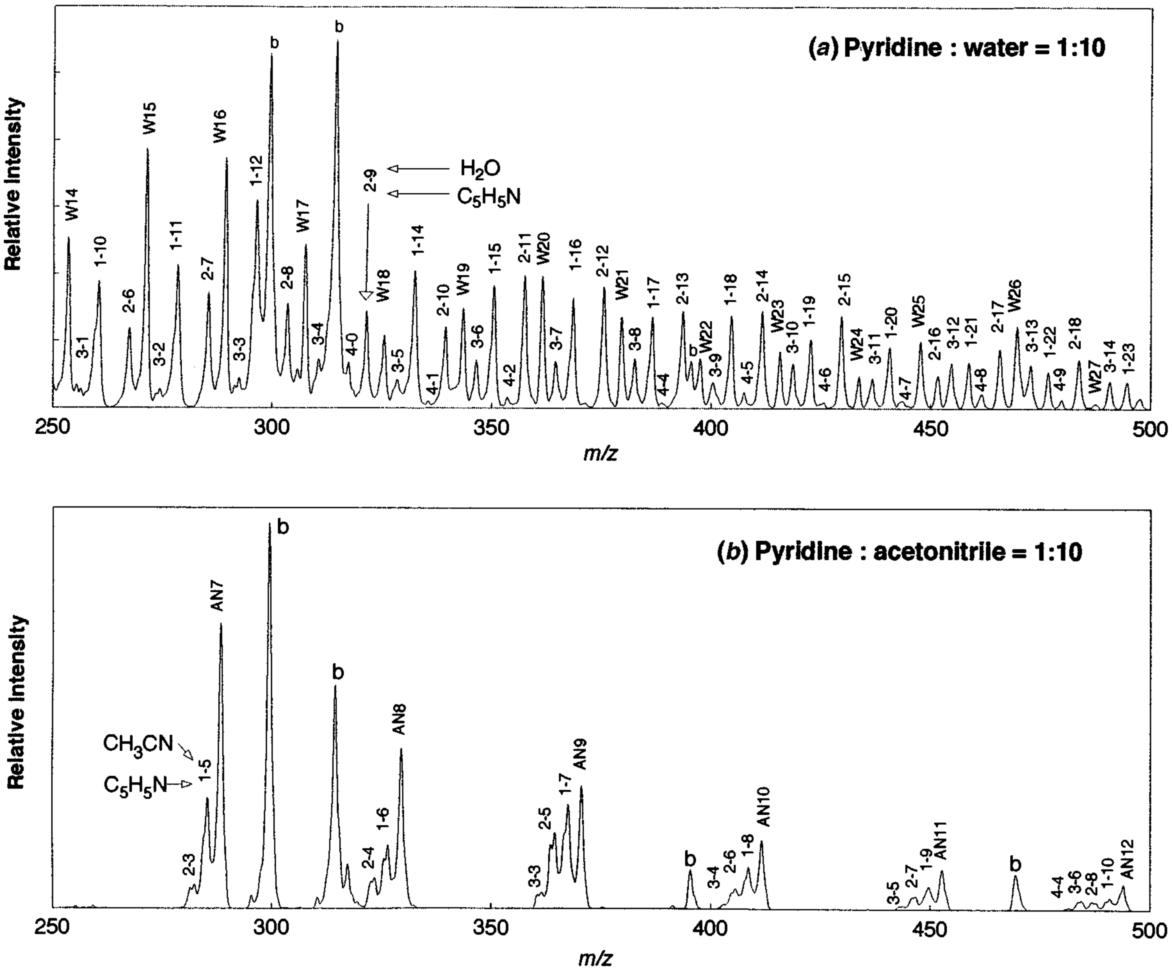

Fig. 4 Mass spectra of clusters generated from solutions containing (*a*) pyridine–water (molar ratio 1:10) and (*b*) pyridine–acetonitrile (molar ratio 1:10). Temperatures of the nozzle are (*a*) 155 °C and (*b*) 115 °C. The paired numbers in (*a*) and (*b*) represent *x*-*y* for $(C_5H_5N)_x(H_2O)_y$ and *v*-*w* for $(C_5H_5N)_v(CH_3CN)_w$ clusters, respectively. The peaks marked W and AN represent water clusters, $H^+(H_2O)_n$, and acetonitrile clusters, $H^+(CH_3CN)_n$, respectively. The peaks marked 'b' correspond to background peaks.

pyridine hydrate clusters are generally found to decrease with an increasing number of pyridine molecules. From these peak intensities, the ratio of pyridine monomer–dimer–trimer–tetramer in water can be roughly estimated as 100:75:25:6. This ratio correlates well with the peak intensity ratio of acetic acid–pyridine clusters generated from aqueous solution, shown in Fig. 2(*a*). For example, the intensity ratio of peaks $(CH_3COOH)_2(C_5H_5N)_1$–$(CH_3COOH)_2(C_5H_5N)_2$–$(CH_3COOH)_2(C_5H_5N)_3$–$(CH_3COOH)_2(C_5H_5N)_4$ in Fig. 2(*a*) is close to the peak intensity ratio of the pyridine clusters, 100:75:25:6. Accordingly, this suggests that the acetic acid–pyridine acid–base interaction proceeds through intercluster interactions in water.

In the pyridine–acetonitrile system (molar ratio 1:10) [Fig. 4(*b*)] acetonitrile clusters and pyridine–acetonitrile clusters, $(C_5H_5N)_x(CH_3CN)_y$, were observed. In comparing the peak intensities of the clusters containing pyridine molecules between aqueous [Fig. 4(*a*)] and acetonitrile [Fig. 4(*b*)] solutions, the intensities for clusters in acetonitrile solution are seen to be much weaker than those for the clusters in aqueous solution. Furthermore, with increasing temperature, all the clusters containing pyridine molecules disintegrated as the acetonitrile molecules were vaporized. This indicates that the interpyridine interaction is not as strong as the interacetonitrile interaction. Therefore, it seems that the large pyridine clusters are difficult to form in acetonitrile. Acetic acid also exists as its monomeric form in acetonitrile, as shown in Fig. 3(*b*). Therefore, acetic acid–pyridine interactions in acetonitrile are thought to occur predominantly through the intermonomer interactions.

Conclusions

Acid–base interaction from the viewpoint of cluster structure

We have focused on the acid–base interaction which is controlled by the cluster structure in solvents. Depending on the solute–solvent interactions, the cluster structures of the acid base molecules changed drastically. It is the first experimental result where the solvent effect on the acid–base interaction can be related to the cluster structure.

Fig. 5 illustrates the solvent effect on the acid–base interaction schematically. In water solvent, acetic acid clusters and pyridine clusters are formed favourably, and they are thought to work as acid and base, respectively. The acetic acid–pyridine, acid–base clusters observed in Fig. 2(*a*), can be explained by formation through this intercluster interaction.

On the other hand, in acetonitrile, acetic acid and pyridine exist favourably in the monomeric forms due to solvation; therefore, the monomeric acetic acid and pyridine work as an acid and a base, respectively. Once an acetic acid molecule interacts with a pyridine molecule in acetonitrile, a polarized acid–base complex is formed, and it can grow into larger clusters spontaneously through electrostatic interaction, as shown in Fig. 5.

As for the reaction efficiency, the solvation of acetic acid and pyridine by acetonitrile restrains their acid–base interaction. However, the hydrophobicity of acetic acid and pyridine in water promotes their acid–base interaction, that is, both acetic acid and pyridine molecules aggregate and release hydration shells in order to minimize their interface with water, which

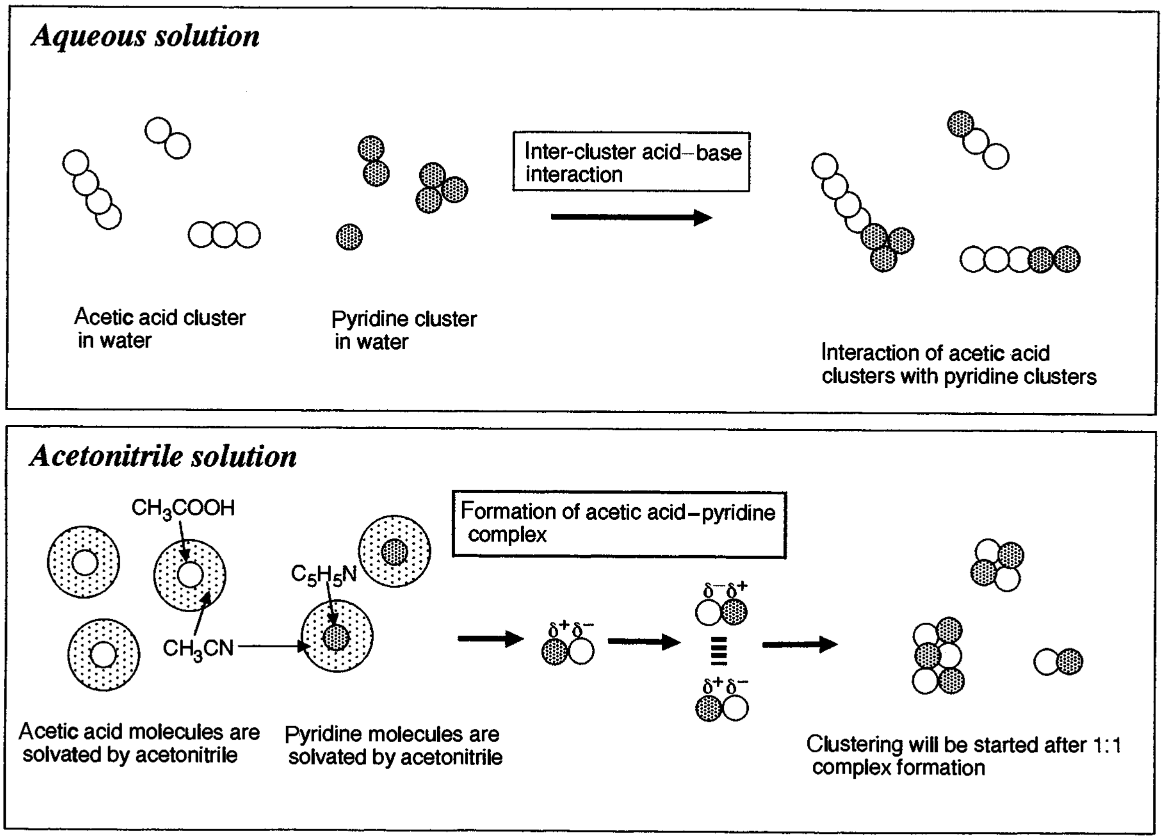

Fig. 5 This picture shows the behaviour of acetic acid and pyridine in forming acid–base clusters in water and acetonitrile. The open and shaded circles represent an acetic acid and a pyridine molecule, respectively. Acetic acid and pyridine molecules form clusters in aqueous solution; however, they exist as monomeric molecules in acetonitrile. Therefore, in water, an intercluster acid–base interaction takes place; on the other hand, in acetonitrile, the monomeric acetic acid molecules interact with monomeric pyridine molecules. The resulting (acetic acid)$^{\delta+}$(pyridine)$^{\delta+}$ complex grows into larger clusters through dipole–dipole interactions.

increases the probability of encountering further acetic acid and pyridine molecules.

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