Effect of Basicity and Structure on the Hydration of Protonated Molecules and Cluster Formation: An Ion Mobility-Time of Flight Mass Spectrometry and Theoretical Study

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Abstract

Protonation, hydration and cluster formation of ammonia, formaldehyde, formic acid, acetone, butanone, 2-octanone, 2-nonanone, acetophenone, ethanol, pyridine and its derivatives were studied by IMS-TOFMS technique equipped with a corona discharge ion source. It was found that tendency of the protonated molecules, MH^+ , to participate in hydration or cluster formation depends on the basicity of M. The molecules with higher basicity were hydrated less than those with lower basicity. The mass spectra of the low basic molecules such as formaldehyde exhibited larger clusters of $M_nH^+(H_2O)_n$ while for compounds with high basicity such as pyridine only MH^+ and MH^+M peaks were observed. The results of DFT calculations confirm that enthalpies of hydrations and cluster formation decrease as basicities of the molecules increases. Using comparison of mass spectra of formic acid, formaldehyde, and ethanol, effect of structure on the cluster formation was investigated. Formation of symmetric (MH^+M) and asymmetric proton-bound dimers (MH^+N) was studied by ion mobility and mass spectrometry techniques. Both theoretical and experimental results shows that asymmetric dimers are formed more easily between molecules (M and N) with comparable basicity. As the basicity difference between M and N increases, the enthalpy of MH^+N formation decreases.

Keywords: Proton affinity; Clustering; Hydration; Proton-bound dimer; Mass spectrometry.

1. Introduction

Ion-molecules reactions play crucial roles in many phenomena occurring in atmosphere and living systems [1-4]. Among these reactions, proton transfer has been well studied and more considered [5-8] because of its importance and applications in biology, environmental sciences, and chemistry.

Theoretical and experimental studies show that proton can be hydrated to form hydronium clusters $(\text{H}_2\text{O})_n\text{H}_3\text{O}^+$, with different numbers of water molecules [9-11]. König and Fales [9] studied hydronium ions with up to 222 water molecule using quadrupole mass spectrometry. They showed that for medium-size clusters, those with 21 and 28 water molecules have more stability. A theoretical study on the hydronium ions with 21 H_2O molecule revealed that the H_3O^+ ion tends to be located in the surface of the clusters [11]. Protonated molecules, MH^+ , are also hydrated in the presence of water, or form ionic clusters with other neutral molecules [12,13]. In the $\text{M}_n(\text{H}_2\text{O})_m\text{H}^+$ clusters with large numbers of water molecules, the proton tends to remain on the H_3O^+ , even if M has high basicity [8,14-16]. In the $\text{MH}^+(\text{H}_2\text{O})_n$ clusters with 1 or 2 water molecules, the proton usually remains on the M [17,18]. Hydration of protonated molecules influences their stability, and structural and thermodynamic properties [19,20]. Hydration of alkyl diammonium cations influences their structures so that the linear alkyl chain is folded to form a bent structure [19,21].

In mass spectrometers equipped with electrospray or corona discharge ionization sources the protonated molecules are often hydrated and they are observed as $\text{MH}^+(\text{H}_2\text{O})_n$ [22-24]. Amount of hydration is affected by temperature and water vapor content of the systems; so that lower temperature and higher water concentration increase hydration [25]. On the other hand, the hydration of different molecules at the same temperature and the same water pressure is different

[18]. Therefore, other than temperature and water concentration, amount of hydration depends on the nature of the molecule, which is discussed in this paper.

Protonated molecules, MH^+ , also form proton-bound dimers in the presence of excess amount of the neutral molecule, M [26,27],

In the presence of extra amount of M , reaction (1) may proceed to form proton-bound trimers [28]. However, it is reported that the proton-bound trimers are not stable and have short lifetime so that they are observed at lower temperatures in the presence of higher vapor concentration of the sample [29]. Many researchers have reported that the proton-bound dimers are rarely hydrated or hydration destroys these dimers [25,30,31]. Asymmetric proton-bound dimers are also observed in ion mobility (IMS) and mass spectrometry (MS) studies [28]

However, formation of asymmetric proton-bound dimers, MHN^+ , is not as easily as that of symmetric proton-bound dimers, MHM^+ [32-34], so that the former are formed with only some special M and N molecules.

In this work, hydration of different protonated molecules is studied using IMS and MS techniques and DFT methods. The amount of hydration of the protonated molecules, MH^+ , is discussed based on the basicity and structure of the neutral molecule M . In addition, the required criteria for successful formation of symmetric and asymmetric proton-bound dimers are determined and discussed.

2.1 Instrumentation

The experiments were performed with an IMS-TOFMS equipped with a corona discharge (CD) ionization source operating in positive mode. The IMS-TOFMS was a homemade instrument constructed in Department of Experimental Physics of Comenius University in Slovakia. A detailed description of the instrument can be found elsewhere [35]. The IMS operated at sub-ambient pressure (0.75 bar) so that the sample could be sucked into the ionization region with adjustable flow rate of 20 ml/min. The flow rate of the drift gas was 500 ml/min. The drift tube temperature was set to 110 °C. A voltage of 8 kV was applied to the whole cell of IMS (12.5 cm) to provide a drift field of 640 V/cm. The CD was supplied by potential difference of 3 kV between the electrodes. The length of the linear time-of-flight mass spectrometer (TOF-MS) was 54.7 cm with internal pressure of 10^{-5} mbar. A multichannel plate (MCP) was used as a detector for TOF-MS.

2.2 Materials and method

Pyridine, 2,6-dimethyl pyridine, 2,6-di-tertbutyl pyridine (DTBP), and ammonium carbonate were Sigma-Aldrich products and acetone, formic acid, formaldehyde, ethanol, 2-butanone, 2-octanone, 2-nonanone, and acetophenone were purchased from Fluka. The head space vapor of each sample at ambient temperature (~20 °C) was injected to the ionization region by a syringe. The head space vapor of ammonium carbonate, $(\text{NH}_4)_2\text{CO}_3$, was injected to the ionization region to study ionization and hydration of NH_3 . The experiments were carried out at drift tube temperature of 110 °C.

2.3 Computational details

The structures of all molecules and clusters including neutral and protonated molecules and their hydrated forms were optimized by density functional theory (DFT) and B3LYP functional. The 6-

311++G(d,p) basis which includes both polarization and diffuse functions for hydrogen and heavy atoms was used for the calculations. Frequency calculations were performed at the same level of theory to obtain the thermodynamic quantities including proton affinities (PA), enthalpy (ΔH) and Gibbs free energy (ΔG) of hydration or cluster formation. The charge distributions were computed using natural bond orbital (NBO) method. The calculations were carried out at 298.15 K and in gas phase using Gaussian 09 software [36].

3. Results and discussion

3.1 Effect of basicity on the hydration and proton-bound dimer formation

Figure 1 shows the mass spectra of formaldehyde, acetone, 2-butanone, 2-octanone, 2-nonanone, acetophenone, pyridine, 2,6-dimethyl pyridine (DMP), and 2,6-di-tertbutyl pyridine (DTBP). Amount of hydration and cluster formation decrease from formaldehyde to DTBP. Formaldehyde and acetone form clusters with up to three H_2O molecules; the protonated butanone is di-hydrated; other larger ketones and pyridine and DMP are only mono-hydrated while DTBP is not hydrated. Also, we observed a proton-bound trimer (M_3H^+) peak for formaldehyde, a proton-bound dimer (MH^+M) for ketones while DMP and DTBP do not form any dimer or trimer. Since the water concentration and drift cell temperature were the same for the all experiments, the difference in the amount of hydration is attributed to the basicity of the molecules. The calculated values of proton affinities (PA) and gas phase basicities (GB) are summarized in Table 1. The calculated enthalpies (ΔH) and Gibbs free energies (ΔG) of mono-hydration and proton-bound dimer formation are also included in Table 1. The ΔH and ΔG values for di-, tri- and tetra-hydration as well as trimer formation have been provided in Tables S1 and S2 (Supplementary Materials). The data in Table 1 show that the basicity increases from formaldehyde to DTBP while ΔH and ΔG

values of hydration and dimer formation decrease. In other words, the protonated forms (MH^+) of molecules with higher basicity are less hydrated.

Figure 1. The MS spectra of (a) formaldehyde, (b) acetone, (c) 2-butanone, (d) 2-octanone, (e) 2-nonanone, (f) acetophenone, (g) pyridine, (h) 2,6-dimethyl pyridine, and (i) 2,6-di-tert-butyl pyridine. The basicity increases from (a) to (i).

Table 1 The calculated values of proton affinities (PA), gas phase basicities (GB), enthalpies (ΔH) and Gibbs free energies (ΔG) of mono-hydration and proton-bound dimer formation. The energies are in kJ/mol

Molecule (M)	Basicity		Hydration of MH^+		Dimer formation	
	PA	GB	ΔH	ΔG	ΔH	ΔG
H ₂ O	687.8 (691) ^a	659.5 (660) ^a	-154.8	-116.7	-154.8	-116.7
Formaldehyde	705.1 (712) ^a	673.7 (683.3) ^a	-134.4	-95.7	-136.1	-96.3
Formic acid	740.8 (743.9) ^b	709.1 (710.3) ^a	-113.8	-77.6	-129.7	-91.3
Ethanol	779.2 (776.4) ^a	748.9 (746) ^a	-108.2	-71.1	-136.9	-99.2
Acetone	816.2 (812) ^a	784.8 (782.1) ^a	-91.9	-56.6	-129.8	-96.9
2-Butanone	831.1 (827.3) ^a	797.7 (795.5) ^a	-85.6	-47.2	-126.4	-84.0
2-Octanone	840.9	814.8	-74.1	-35.9	-112.4	-72.3
2-Nonanone	841.5	815.8	-74.0	-35.4	-112.5	-69.7
NH ₃	852.7 (853.6) ^a	824.5 (819.0) ^a	-89.5	-50.1	-118.9	-78.1
Acetophenone	869.3 (861.1) ^a	838.8 (829.3) ^a	-76.6	-37.6	-117.5	-75.4
Pyridine	934.4 (930) ^a	902.5 (898.1) ^a	-66.5	-31.8	-102.3	-62.2
2,6-Dimethyl pyridine	968.9 (963) ^a	947.0 (931.1) ^a	-54.37	-8.3	-75.8	-23.4
2,6-Di- <i>t</i> -buthyl pyridine	990.8 (982.9) ^a	959.7 (951) ^a	-30.2	+7.8	-6.3	+19.9

^aRef.[37] ^bcalculated by W1BD from Ref [38].

Figure 2 shows the optimized structures of the clusters observed in the MS spectra of Fig. 1. Comparison of the $MH^+ \dots OH_2$ bond lengths reveals that this distance is shorter for molecules (M) with lower basicity and longer for molecules with higher basicity which is in agreement with hydration enthalpies. The same trend is observed for the bond lengths in the proton-bound dimers, $MH^+ \dots M$. The relationship between basicity of M and $MH^+ \dots M$ distance has been recently predicted theoretically [39]. Figure S1 (Supplementary Materials) shows the variations of $MH^+ \dots OH_2$ and $MH^+ \dots M$ distances versus PA of M. These plots show that there is a linear

relationship between these hydrogen bond distances and PA so that as PA increases the hydrogen bonds are lengthened. The more basic molecules has more ability to delocalize the positive charge of the entering proton, therefore, it is expected that the partial charge on the proton in MH^+ is smaller for more basic molecules. Figure S2 (Supplementary Materials) shows the NBO charge distributions for the protonated molecules studied in this work. As PA of M increases the main part of the positive charge of H^+ is transferred to M so that the partial charge (q) on the H atom of MH^+ decreases. Hence, the MH^+/H_2O or MH^+/M interactions become weaker and the ΔH values of hydration or dimer formation decrease.

Some part of low tendency of $DTBPH^+$ to hydration or dimer formation is due to steric hindrance of bulky butyl groups adjacent to the proton acceptor site, N. To investigate this effect, hydration enthalpy of a molecule with strong basicity (PA=1020 kJ/mol) [40] without any steric hindrance was calculated (Fig. S3 in Supplementary Materials). The calculated hydration enthalpy for this molecule is -50 kJ/mol which is smaller than those for all molecules studied in this work except DTBP. Therefore, although steric hindrance may influence the hydration enthalpy, basicity has a determinant effect on the hydration.

Figure 2. The optimized structures of the clusters observed in the MS spectra of Fig. 1. The bond lengths are in Å. Ac: Acetone; But: 2-Butanone; Oct: 2-Octanone; Non: 2-Nonanone; AcPh: Acetophenone; Pyr: Pyridine; DMP: 2,6-Dimethyl pyridine; DTBP: Di-tertbutyl pyridine

It has been reported that moisture can destroy the proton-bound dimers or proton-bound dimers are rarely hydrated [25,30,31]. Comparison of the enthalpies of hydration and dimer formation (Table 1) shows that formation of proton-bound dimers from MH^+ and M is thermodynamically more favorable than hydration of MH^+ . However, in the presence of high amount of water vapor, according to the Le Chatelier's principle, the reaction $M_2H^+ + H_2O \rightarrow MH^+(H_2O) + M$ may be occurred resulting in dimer destruction. Hydration of proton-bound dimers depends on the structures of M and MH^+ which is discussed in the next section.

3.3 Effect of size and structure on the hydration and proton-bound dimer formation

Other than basicity, size and structure of a molecule affect its hydration and cluster formation enthalpies. Figure 3a and 3b compares the MS spectra of NH_3 and H_2O with PA difference of about 60 kJ/mol. Hydration of ammonium ion proceeds to tri-hydration, $NH_4^+(H_2O)_3$, while octanone- H^+ , nonanone- H^+ , and acetophenone- H^+ with comparable PA are mono-hydrated in the same condition. H_3O^+ and NH_4^+ are small ions with comparable size, therefore, we can attribute their large amount of hydrations to their large surface density of the positive charge leading in strong interactions with water molecules. However, comparison of the hydration enthalpies of H_3O^+ and NH_4^+ (Table S1) shows that hydration enthalpies of NH_4^+ are noticeably smaller than those of H_3O^+ . Another factor influencing the hydration of NH_4^+ is four identical hydrogen atoms which can participate in hydrogen bonding interactions with water molecules (Fig. S4 in Supplementary Materials).

Figure 3. MS spectra for (a) water clusters, (b) hydrated ammonium, (c) ethanol, and (d) formic acid

To investigate effect of structure in more details, hydration and clustering of ethanol and formic acid with the same molecular weights, comparable PAs, and different structures were studied. Figures 3c and 3d compare the MS spectra of ethanol and formic acid. Both $C_2H_5OH_2^+$ and $HC(OH)_2^+$, the protonated forms of ethanol and formic acid, have two hydrogen atoms which can participate in hydration or cluster formation. However, Fig. 3 exhibits two different patterns of hydration and clustering for ethanol and formic acid. $C_2H_5OH_2^+$ mainly participates in hydration

reactions while HC(OH)_2^+ tends to be both hydrated and clustered. The optimized structures of different clusters of ethanol and formic acid have been provided in Supplementary Materials (Figs. S5, S6 and S7). Neutral formic acid, HC=O(OH) , has a carbonyl groups, C=O , whose oxygen atom acts as a hydrogen bond acceptor without any steric hindrance while, at the same time, the OH group is involved in another hydrogen bonding interaction. Therefore, each formic acid molecule plays the role of a ring or a chain in a hydrogen bonding network (Fig S7). On the other hand, ethanol, $\text{C}_2\text{H}_5\text{OH}$ has only one OH group; when it interacts via its H atom, the O atom cannot freely form another hydrogen bond with other molecules. It should be mentioned that the more tendency of formic acid to be clustered compared to ethanol is not due to higher concentration of formic acid in the ionization region because we injected the head space vapor of the compounds and vapor pressure of ethanol is more than that of formic acid.

Figure 1 shows that, similar to formic acid, aldehyde also forms a proton-bound trimer, $(\text{H}_2\text{CO})_3\text{H}^+$. Because of small size of formaldehyde and the high charge density of its protonated form, $\text{H}_2\text{C=OH}^+$, the hydrogen of CH group also participates in cluster formation (Fig. 2). Another reason for formation of formaldehyde trimer is its higher concentration in the ionization region due to its high vapor pressure. However, enthalpy of trimer formation, $\text{M}_2\text{H}^+ + \text{M} \rightarrow \text{M}_3\text{H}^+$, for formaldehyde is about 23 kJ/mol smaller than that for formic acid (Table S2 in Supplementary Materials). H_2O molecules can act as bridges between the formaldehyde molecules and form more stable cluster of $(\text{H}_2\text{CO})_3\text{H}^+(\text{H}_2\text{O})_3$ whose peak is more intense than the $(\text{H}_2\text{CO})_3\text{H}^+$ peak (Fig. 1a). However, in the case of formic acid the $(\text{HCOOH})_3\text{H}^+$ peak is more intense compared to the $(\text{HCOOH})_3\text{H}^+(\text{H}_2\text{O})_3$ peak. Comparison of the formation enthalpies in Tables S2 and S3 shows that although $(\text{HCOOH})_3\text{H}^+$ is more stable than $(\text{H}_2\text{CO})_3\text{H}^+$, the stability for the tri-hydrated clusters is reverse so that $(\text{H}_2\text{CO})_3\text{H}^+(\text{H}_2\text{O})_3$ is more stable than $(\text{HCOOH})_3\text{H}^+(\text{H}_2\text{O})_3$. This

observation reveals that the structure of formic acid with both hydrogen bond donor and acceptor sites compared to formaldehyde with only one proton bond acceptor site is more capable for clustering so that the formic acid forms more stable trimers without any water bridge. The structures of $(\text{H}_2\text{CO})_3\text{H}^+(\text{H}_2\text{O})_3$ and $(\text{HCOOH})_3\text{H}^+(\text{H}_2\text{O})_3$ are shown in Figs. 2 and S7, respectively. $(\text{H}_2\text{CO})_3\text{H}^+(\text{H}_2\text{O})_3$ has only one stable structure while different isomers were predicted for $(\text{HCOOH})_3\text{H}^+(\text{H}_2\text{O})_3$.

Clustering of formic acid proceeds up to tetramer with three water molecules, $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$. The eight possible structures for the $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$ are shown in Fig. 4. Comparison of the relative stabilities of the $(\text{HCOOH})_3\text{H}^+(\text{H}_2\text{O})_3$ (Fig. S7) and $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$ isomers (Fig. 4) shows that the structures in which the proton remains on the water and H_3O^+ is the core center of the cluster are more stable. These results are in accordance with those previously reported [14-16]. The isomers **a** and **b** of $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$ in which the water and formic acid molecules have been positioned alternatively, are the less stable structures. The isomers **c** and **f** with a water cluster of $\text{H}_3\text{O}^+(\text{H}_2\text{O})_2$ are the most stable structures, however, the isomer **c** in which the $\text{H}_3\text{O}^+(\text{H}_2\text{O})_2$ group is located in the center of the $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$ is more stable.

Figure 4. The optimized structures of different isomers of $(\text{HCOOH})_4\text{H}^+(\text{H}_2\text{O})_3$ cluster. The relative energies and bond lengths are in kJ/mol and Å, respectively

3.2 Effect of basicity on the asymmetric proton-bound dimer formation

The MS spectra of Figs. 1 and 3 show that although the chance of formation of the symmetric proton-bound dimers (MH^+M) decreases with increase in the basicity of the molecule M, these symmetric dimers are readily formed. Figures 5a compares the IMS spectra of 2-octanone, acetophenone and their mixtures. The IMS spectra of 2-octanone and acetophenone show only the monomer, (MH^+) and dimer (MH^+M) peaks of these molecules. In the IMS spectrum of their

mixture a new peak with high intensity appears between the symmetric dimers. The MS spectrum of this mixture (Fig. 5b) confirms that the new peak is due to formation of the asymmetric dimer of octanone–H⁺–acetophenone. When a mixture of pyridine and 2-octanone was injected into IMS, a small peak was hardly observed between the dimer peaks of pyridine and 2-octanone (Fig. 5c). The experiment was repeated with several mixtures with different ratios of 2-octanone/pyridine. The MS spectrum of the octanone/pyridine mixture shows that the new peak is due to the asymmetric dimer of octanone–H⁺–pyridine (Fig. 5d).

Figure 5. (a) IMS spectra for 2-octanone, acetophenone, and their mixture; (b) MS spectrum for 2-octanone/acetophenone mixture; (c) IMS spectra for 2-octanone, pyridine, and their mixture; and (d) MS spectrum of the 2-octanone/pyridine mixture. The peaks of the asymmetric proton-

bound dimers have been shown by purple color. Oct: 2-octanone; AcPh: acetophenone; Pyr: pyridine

The calculated values of ΔH and ΔG for formation of the symmetric (MH^+M) and asymmetric dimers (MH^+N) are tabulated in Table 2. Furthermore, PA differences (ΔPA) of the molecules participating in the dimer formation are also included in Table 2. For the symmetric dimer the ΔPA values are zero and the enthalpies of dimer formation are about -102 to -117 kJ/mol. For the asymmetric dimer octanone- H^+ -acetophenone, the basicities of octanone and acetophenone are not so different ($\Delta PA=28$ kJ/mol), therefore, this asymmetric dimer is easily formed with enthalpy of -106 kJ/mol. The difference of basicity between octanone and pyridine is considerable ($\Delta PA=94$ kJ/mol) resulting in lower enthalpy of asymmetric dimer formation ($\Delta H=-85$ kJ/mol). In summary, the asymmetric dimers are formed more easily between the molecules with comparable basicity.

Table 2 The calculated values of ΔH and ΔG for the symmetric and asymmetric dimer formations

Dimer formation ^a	ΔH	ΔG	ΔPA^b
Oct + Oct. $H^+ \rightarrow (Oct)_2H^+$	-112.4	-72.3	0.0
AcPh + AcPh. $H^+ \rightarrow (AcPh)_2H^+$	-117.5	-75.4	0.0
Pyr + Pyr. $H^+ \rightarrow (Pyr)_2H^+$	-102.3	-62.2	0.0
Oct + AcPh. $H^+ \rightarrow (Oct-H-AcPh)^+$	-106.3	-69.5	28.4
Oct + Pyr. $H^+ \rightarrow (Oct-H-Pyr)^+$	-84.7	-54.5	93.5

^aOct: 2-octanone; AcPh: acetophenone; Pyr: pyridine. ^b $\Delta PA(MH^+N)=PA(M)-PA(N)$ of the molecules participating in dimer formation.

The optimized structures of the studied symmetric and asymmetric proton-bound dimers are compared in Fig 6. The $M...H...M$ and $M...H...N$ hydrogen bond lengths are also shown in Å. In the symmetric dimer of acetophenone, with the highest enthalpy of formation, the bond lengths are 1.353 and 1.091 Å and their difference is 0.262 Å. On the other hand, for the asymmetric dimer

of octanone–H⁺–pyridine, with the lowest enthalpy of formation, the difference in the bond lengths is 0.601 Å. It seems there is a direct relationship between the enthalpy of dimer formation and the structure. The plot of variations of enthalpy of dimer formation versus the difference in the hydrogen bond lengths in the dimer structures is shown in Fig. S8 (Supplementary Materials). Observation of this relationship is expectable because difference in the hydrogen bond lengths is due to difference in the basicities of the molecules participating in proton-bound formation which, as mentioned above, it determines the enthalpy of dimer formation.

Figure 6 The optimized structures of the studied symmetric and asymmetric proton-bound dimers. The bond lengths are in Å

4. Conclusion

The thermodynamic and structural criteria for cluster formation and hydration of protonated molecules (MH⁺) were investigated both experimentally and theoretically. Comparison of the MS spectra of a class of compounds with a wide range of basicity (PA=690-990 kJ/mol) showed that

amount of hydration of MH^+ decreases as the PA of M increases so that more basic compounds form smaller $MH^+(H_2O)_n$ clusters. The same trend was observed for formation of proton-bound dimers (M_2H^+), trimers (M_3H^+) and tetramers (M_4H^+) so that the tendency of compounds with lower basicity for dimer, trimer or tetramer formation is more. Generally, the protonated form of a more basic molecule tends to form smaller clusters. Structures of M and MH^+ also influence the amount of hydration or clustering. Although NH_3 has high basicity, its MS spectrum shows that the cluster $NH_4^+(H_2O)_3$ is easily formed because of four identical hydrogen atoms of NH_4^+ acting as hydrogen bond donors. Also, formic acid due to its C=O and OH groups can interact with two hydrogen bond donor and acceptor atoms simultaneously and forms a network or chain cluster. Therefore, despite of its higher basicity compared to H_2O and formaldehyde, it can form larger cluster such as $M_4H^+(H_2O)_3$ in the same condition. Effect of basicity of M and N on the formation of their asymmetric dimer (MH^+N) was investigated. It was found that the enthalpy of MH^+N formation depends on the difference in the basicities of M and N. The asymmetric dimer of 2-octanone and acetophenone with comparable PA is formed easily with ΔH of -106 kJ/mol while the ΔH for formation of asymmetric dimer of 2-octanone and pyridine with ΔPA of 94 kJ/mol is -85 kJ/mol.

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