Hydration of Pyridine Bases in Benzene

Katsumi HIROSE and Motoharu TANAKA*

Laboratory of Analytical Chemistry, Faculty of Science, Nagoya University, Nagoya 464

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Hydration of pyridine bases in benzene has been studied by partition at 25 °C, the total concentration of pyridine bases being less than 1.0 M in benzene. The studied pyridine bases include pyridine, 2-methylpyridine, 4-methylpyridine, 2,6-dimethylpyridine, 3,5-dimethylpyridine, 2,4,6-trimethylpyridine, 2-chloropyridine, 2-bromopyridine, 3-bromopyridine and 2,6-dibromopyridine. Hydrated species with different composition are formed: the composition of the hydrated species (base to water ratio) is as follows: (1: 2) for 2,6-dibromopyridine, (1: 1) and (1: 2) for 2-chloro- and 2-bromopyridine, (1: 1) and (2: 1) for 3-bromopyridine, (1: 1), (1: 2) and (2: 1) for 4-methylpyridine and pyridine itself, and (1: 1), (1: 2), (2: 1) and (2: 2) or (2: 3) for the other methyl derivatives. A linear free energy relationship has been observed between the hydration in benzene for the monomer monohydrate and the protonation in water of the corresponding base.

There have been numerous investigations on the hydrogen-bonded complex of polar organic compounds in nonpolar solvents. Studies on hydration are of importance among them because of the unique ability of water to act as a bridge binding two base molecules. Christian *et al.* have studied the hydration of various organic compounds in nonpolar solvents[1–4] and reviewed on the interaction of polar solutes with water.[5]

In order to study in detail the extraction mechanism, it should be important to determine the hydration equilibrium of extractants and/or synergists in the organic solvents. A study along this line has been carried out by Li *et al.*,[6] who determined the hydration of TBP in the organic solvent. In many cases, however, little attention has been paid to the hydration of extractants and synergists in the organic solvents.

Among various organic bases the hydration of pyridine in nonpolar solvents has been extensively studied by infrared spectroscopy and partition technique.[7–10] An analysis of pyridine water hydrogen-bonded system using Hückel theory has been published recently by Adam *et al.*[11] In the present paper, we shall describe the hydration of several pyridine bases with special reference to the effect of substituents.

Experimental

Materials. All pyridine bases, *i.e.* pyridine, 2-methylpyridine, 4-methylpyridine, 2,6-dimethylpyridine, 3,5-dimethylpyridine, 2,4,6-trimethylpyridine 2-chloropyridine, 2-bromopyridine, 3-bromopyridine and 2,6-dibromopyridine, were of G. R. grade. Pyridine bases except for 2,6-dibromopyridine were purified by distilling and by collecting a fraction distilled at constant temperature. 2,6-Dibromopyridine was purified by twice recrystallization in alcohol. Benzene (G. R.) washed successively with sodium hydroxide, sulfuric acid and water was finally distilled. Calcium chloride of G. R. grade was purified by recrystallization.

Procedure. The method of Christian *et al.*[12] was used for equilibrating the organic phase with solutions of known water activity. 50 ml Centrifuge tubes were utilized for the partition. Equilibrium is known to be reached within less than 12 h.[12] The water activity was controlled by $CaCl_2$–H_2O mixtures of known water activity.[13] It was confirmed that no calcium ion was extracted in the organic phase: 15 ml of 1 M solution of a pyridine base in benzene was equilibrated with the same volume of 5.5 M aqueous calcium chloride. The organic phase was separated and then shaken with 10 ml of distilled water, in which we were not able to detect calcium ion with 3,3′-bis[*N*,*N*-di(carboxymethyl)aminomethyl]-*o*-cresolphthalein. The partition was carried out at 25±0.1 °C. After standing for at least 24 h for complete phase separation, the total concentration of water in the organic phase was determined by the Karl-Fischer method with the Coulometric generation of iodine. The method allows to determine the water content with an error of less than 1%. The total concentration of pyridine base in the organic phase was determined by the colorimetry for the halogen derivatives of pyridine, while for the other pyridine bases it was determined by the acid-base titration in glacial acetic acid with Crystal Violet as an indicator.

Results and Discussion

Equilibrium Treatment. Hydrates of pyridine base, $B_m(H_2O)_n$, being assumed to be formed in benzene, the hydration equilibrium of a pyridine base B is written as follows:

$$m\mathrm{B}_o + n(\mathrm{H_2O})_o \rightleftharpoons (\mathrm{B}_m(\mathrm{H_2O})_n)_o \qquad (1)$$

where the subscript o denotes the organic phase. Under the experimental conditions, Henry's law is assumed to be valid for both hydrated and non-hydrated species. The vapor pressure measurement has revealed the ideal behavior of non-hydrated pyridine and 2-methylpyridine in benzene at least up to 0.1 mole fraction (1 M).[14] The concentration equilibrium constant, $\beta_{m,n}$, for hydrated species $(\mathrm{B}_m(\mathrm{H_2O})_n)_o$ remains constant.

$$\beta_{m,n} = [\mathrm{B}_m(\mathrm{H_2O})_n]_o/[\mathrm{B}]_o^m[\mathrm{H_2O}]_o^n \qquad (2)$$

Water in the organic solvent may be present as monomeric and/or polymeric species, such as dimer, trimer and so on.[15–18] It is known, however, that only monomeric water is present in benzene. Therefore, the partition equilibrium of water is given as follows:

$$(\mathrm{H_2O})_w \rightleftharpoons (\mathrm{H_2O})_o$$

$$K_{\mathrm{D,H_2O}} = [\mathrm{H_2O}]_o/a_w$$

where a_w is the activity of water in the aqueous phase and the subscript w denotes the aqueous phase.

When a pyridine base is partitioned between the aqueous and organic phases, the total concentration

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* To whom correspondence should be addressed.

of the pyridine base in the organic phase, $C_{B,o}$, is given as follows:

$$C_{B,o} = \sum_{m=0}\sum_{n=1} m[B_m(H_2O)_n]_o \qquad (3)$$

Since the increase in the formal solubility of water in the presence of the pyridine base in the organic phase at a given water activity is due to the formation of hydrated pyridine bases, the total concentration of water in the organic phase, $C_{H_2O,o}$, is given as follows:

$$C_{H_2O,o} = \sum_{m=0}\sum_{n=1} n[B_m(H_2O)_n]_o \qquad (4)$$

The composition of the hydrated species and the hydration equilibrium are determined on the basis of Eqs. (2), (3), and (4).

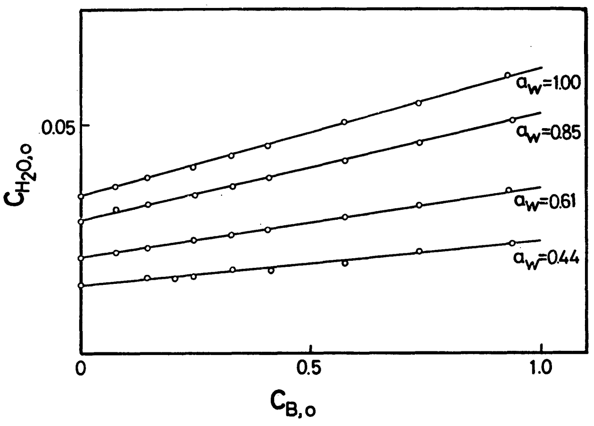

Fig. 1. The total concentration of water as a function of the total concentration of pyridine base in benzene for 2-bromopyridine. Curves are calculated with the constants given in Table 1.

Determination of the Composition of the Hydrated Species. In order to determine the composition of the hydrated species, the total concentration of water, $C_{H_2O,o}$, was plotted against the total concentration of pyridine base $C_{B,o}$ at various water activities. The result for 2-bromopyridine is shown in Fig. 1 as an example. Similar plots were obtained for 2-chloropyridine and 2,6-dibromopyridine. The linear relationship between $C_{B,o}$ and $C_{H_2O,o}$ points to the fact that the hydrated species are monomeric in the organic phase. Then the following expression is obtained from Eqs. (2), (3), and (4).

$$C_{H_2O,o} = \left(\sum_{n=1} n\beta_{1,n}[H_2O]_o^n\right)\left(1+\sum_{n=1}\beta_{1,n}[H_2O]_o^n\right)^{-1}C_{B,o} + [H_2O]_o \qquad (5)$$

The composition of the hydrated species is determined from the relation between the water concentration in benzene and the slope of the plot of $C_{B,o}$ *vs.* $C_{H_2O,o}$. Monomer monohydrate and monomer dihydrate are both present in benzene for 2-chloropyridine and 2-bromopyridine, while monomer monohydrate was hardly detected for 2,6-dibromopyridine, that is, $\beta_{1,1}<0.1$. The hydration constants thus obtained are given in Table 1. The plot of $C_{H_2O,o}$ against $C_{B,o}$ for pyridine is different from these halogen derivatives as shown in Fig. 2. Similar plots were obtained for the other pyridine bases. Non-linearity of the plot points to the presence of the hydrated species involving more than one molecule of pyridine base in benzene for 3-bromopyridine, pyridine and its methyl derivatives. If the number of pyridines involved in the hydrated species is two or less, the total concentration of the pyridine base is given by Eq. (6) and the increment of water in the organic phase due to the presence of the pyridine base, $\Delta C_{H_2O,o}$, is given by Eq. (7).

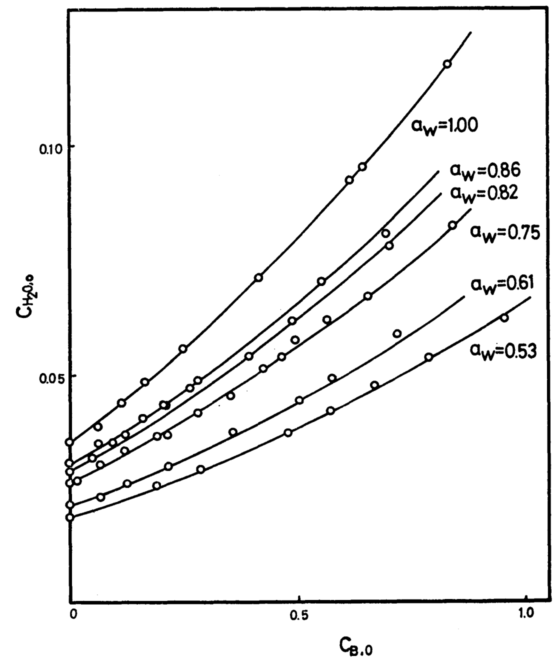

Fig. 2. The total concentration of water as a function of the total concentration of pyridine base in benzene for pyridine. Curves are calculated with the constants given in Table 1.

$$C_{B,o} = \alpha_1[B]_o + \alpha_2[B]_o^2 \qquad (6)$$

$$\Delta C_{H_2O,o} = \alpha_3[B]_o + \alpha_4[B]_o^2 \qquad (7)$$

with

$$\alpha_1 = 1 + \sum_{n=1}\beta_{1,n}[H_2O]_o^n$$

$$\alpha_2 = \sum_{n=1} 2\beta_{2,n}[H_2O]_o^n$$

$$\alpha_3 = \sum_{n=1} n\beta_{1,n}[H_2O]_o^n$$

$$\alpha_4 = \sum_{n=1} n\beta_{2,n}[H_2O]_o^n$$

where $\Delta C_{H_2O,o}=C_{H_2O,o}-[H_2O]_o$, and α_1, α_2, α_3 and α_4 are constant when the activity of water is kept constant. The composition of hydrated species and these hydration constants are determined from Eqs. (6) and (7). This calculation was carried out on a computer, FACOM 230-60, by use of the least squares method. The result is given in Table 1. For 3-bromopyridine we have monomer monohydrate and dimer monohydrate, although we have hardly detected monomer dihydrate. For pyridine and 4-methylpyridine we have monomer monohydrate, dimer monohydrate and monomer dihydrate, while for the other methyl derivatives we should take into account dimer dihydrate or dimer trihydrate in addition. Thus the following equilibria are relevant to the hydration of pyridine bases in benzene:

$$B_o + (H_2O)_o \rightleftharpoons (BH_2O)_o$$

$$B_o + 2(H_2O)_o \rightleftharpoons (B(H_2O)_2)_o$$

TABLE 1. HYDRATION CONSTANTS OF PYRIDINE DERIVATIVES IN BENZENE

Pyridine derivatives	$\beta_{1,1}$ M^{-1}	$\beta_{1,2}$ M^{-2}	$\beta_{2,1}$ M^{-2}	$\beta_{2,2}$ M^{-3}	$\beta_{2,3}$ M^{-4}	sd[a)]
Pyridine	1.0_1	19	1.1			0.0008
	1.2[b)]	6.4[b)]	1.6[b)]			
2-Methylpyridine[c)]	1.9_4	7.7	0.4_5	19		0.0011
	2.0_4	8.6	0.7_3		2.7×10^2	0.0019
4-Methylpyridine	1.6_3	17	1.6			0.0012
3,5-Dimethylpyridine	1.5_9	17	0.7_0	24		0.0011
	1.5_9	17	1.3		3.2×10^2	0.0011
2,6-Dimethylpyridine[c)]	1.0_7	26	1.1	12		0.0009
	1.8_5	13	0.7_7		3.7×10^2	0.0008
2,4,6-Trimethylpyridine[c)]	1.8_6	33	1.3	17		0.0010
	1.9_5	33	1.8		2.3×10^2	0.0010
2-Chloropyridine	0.39	9.0				0.0003
2-Bromopyridine	0.51	4.3				0.0003
3-Bromopyridine	1.1_1		0.4_0			0.0006
2,6-Dibromopyridine		5.1				0.0003

a) Standard deviation. b) Ref. 10. c) Dimer dihydrate and dimer trihydrate interpret the experimental results equally well.

$$2B_o + (H_2O)_o \rightleftarrows (B_2(H_2O))_o$$
$$2B_o + n(H_2O)_o \rightleftarrows (B_2(H_2O)_n)_o$$
$$n = 2 \text{ or } 3$$

The hydrated species obtained for pyridine are in accord with the results reported by Christian *et al.*[10)] except for monomer trihydrate which was not found in our case. The presence of the monomer monohydrate and dimer monohydrate are consistent with the results by the infrared spectroscopy for pyridine.[7–9)] On the basis of our results and others, the fundamental types of the hydrated organic base are the monomer monohydrate B···H–O–H and thedime r monohydrate B···H–O–H···B in a nonpolar solvent as pointed out by Josien[19)] when any specific effect such as steric hindrance is not present. Monomer dihydrate and dimer monohydrate are formed as a result of a competition of water with pyridine base for the monomer monohydrate.

For the *o*-halogen derivatives of pyridine, dimer monohydrate cannot be detected under the experimental conditions, and the sequence of the hydration constant for monomer dihydrate is not parallel with the basicity of pyridine bases. Very low basicity and the steric effect of the *o*-halogen should prevent the formation of dimer monohydrate, whereas the hydogen-bond formation with *o*-halogen favors the formation of monomer dihydrate.

The hydration of pyridine bases is considered as an acid-base reaction in benzene. Recently the formation of molecular complexes involving phenol, alcohol, and so on, in inert solvents has been reported.[20–22)] The formation constant of the hydrogen-bonded complex is linearly related with the basicity of bases involved. In Fig. 3 the hydration constant $\beta_{1,1}$ for monomer monohydrate is plotted against pK_a of corresponding pyridinium. This figure includes the plot of the hydration constant of triethylamine in benzene.[4)] The correlation is obviously good: the stronger the base, the more extensive the hydration. The following two Hammett equations (8) and (9) may be written[23)] for the hydration of pyridines in benzene and the dissociation of pyridinium ion in water, respectively:

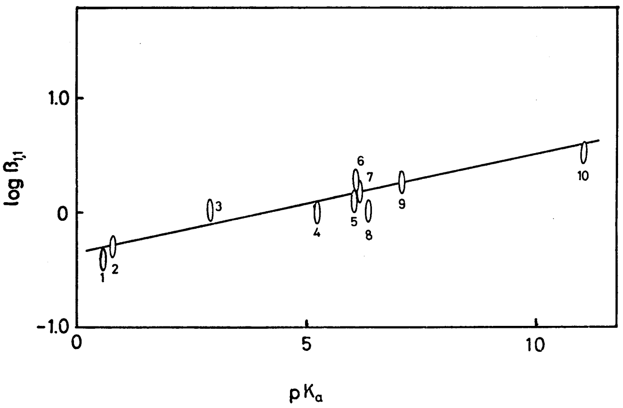

Fig. 3. Correlation of hydration constant $\beta_{1,1}$ with the basicity. 1) 2-chloropyridine, 2) 2-bromopyridine, 3) 3-bromopyridine, 4) pyridine, 5) 4-methylpyridine, 6) 2-methylpyridine, 7) 3,5-dimethylpyridine, 8) 2,6-dimethylpyridine, 9) 2,4,6-trimethylpyridine, 10) triethylamine. Data of pK_a's taken from Refs. 24 and 25.

$$\log \beta_{1,1} = \log \beta^{\circ}_{1,1} + \rho\textstyle\sum\sigma_x \quad (8)$$

$$\mathrm{p}K_a = \mathrm{p}K_a^{\circ} + \rho'\textstyle\sum\sigma_x \quad (9)$$

where $\beta_{1,1}$ and $\beta^{\circ}_{1,1}$ refer to the formation constants of the 1 : 1 hydrates of substituted and non-substituted pyridines, respectively, pK_a and pK_a° denote the acid dissociation constants of the substituted and non-substituted pyridiniums, respectively. σ_x is the substituent constant for x in pyridines and ρ and ρ' are the reaction constants for the hydration and the acid dissociation, respectively. From Eq. (8) and (9), we have immediately

$$\log \beta_{1,1} = \frac{\rho}{\rho'}\mathrm{p}K_a + \text{constant.} \quad (10)$$

This is a linear free energy relationship as shown in Fig. 3. Water, being a very week acid, discriminates the basicity of these pyridines to an extent much smaller than proton does: ρ' is much greater than ρ. Thus the hydration constant is not very sensitive to the basicity as seen from Fig. 3.

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