The Base-catalyzed Tautomerization of Acetylacetone in Organic Solvents. The Correlation of the Catalytic Coefficient with the Partition Coefficient

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The keto-enol tautomerization rate of acetylacetone catalyzed by triethylamine or tributylamine was observed in eight organic solvents, and the catalytic coefficient for each process of the ketonization and enolization was obtained. A remarkable solvent effect on the catalysis was discussed following the linear free-energy relationship between the catalytic coefficient and the liquid-liquid partition coefficients of the keto and enol forms. It was concluded that, in the homogeneous base-catalysis, the solvent affects the free-energy change of the transition state more greatly than those of the keto and enol forms. On the contrary, in the heterogeneous catalysis by the silica surface, the free-energy change of the keto and enol forms was suggested to be the main factor governing the kinetic solvent effect.

In the course of our study of the kinetic behavior of acetylacetone, a well-known extractant,[1)] in a liquid-liquid partition system, we found that the keto-enol tautomerization rate in an organic phase is very slow and that the addition of a base, such as amine, trialkyl phosphate and trialkylphosphine oxide, which are often used in synergic extractions,[1)] remarkably enhances the tautomerization rate in an organic phase. Those catalytic effects strongly depend on the nature of the solvent.

From the standpoint of the transition-state theory,[2)] a kinetic solvent effect is thought to be due to the difference in solvent effects on the reactant and on the transition state. Many kinetic studies of the solvent effect, however, have dealt with the solvent effect only on a rate constant, which reflects the free-energy difference between the reactant and the transition state. We think that the experimental resolution of an activation free energy into two parts is more worthwhile than a qualitative and conventional discussion of the relationship between an activation energy and the solvent property. Previously, we reported the utility of a liquid-liquid partition coefficient in evaluating the contribution of the free-energy change of the reactant to the activation free energy.[3,4)] In the present study, we will show a further application of the rate-partition approach to the solvent effect on the base-catalyzed tautomerization rate of acetylacetone in organic solvents.

Experimental

Materials. The acetylacetone was used after the distillation of a commercially purchased reagent (Nakarai, G. R.). The triethylamine (TEA) and tributylamine (TBA) used as catalysts were purified by double distillation over sodium and kept in a darkened desiccator. The organic solvents were distilled after drying over sodium or phosphorus pentaoxide. The purity of the amines and the solvents were checked by GLC. Redistilled water was used throughout. The preparation of a nonaqueous solution was carried out in a gloved box desiccated by silica gel.

Kinetic Measurements. Although the keto-enol equilibrium of acetylacetone in an inert solvent is not attained even after one week, the addition of an amine at a concentration of 10^{-3} M (1 M=1 mol dm^{-3}) remarkably accelerates the tautomerization rate. The measurement of the rate of the catalysis has been carried out by means of a Hitachi 356 spectrophotometer at 290 nm for aromatic-solvent systems and at 271 nm, the absorption maximum of acetylacetone, for the other systems. The catalysis was initiated by one of the following two methods, depending on the solvent used: when the enol fraction at equilibrium in a given solvent was below 0.8, the vapor injection method[5)] was employed, while in a solvent in which the enol fraction was over 0.8, an alternative method was employed since the vapor injection method does not produce a sufficient absorbance difference between that at the initial time and at equilibrium; *ca.* 1 ml of the pure liquid of acetylacetone was heated for one hour at 100 °C, cooled to room temperature rapidly, and diluted with an organic solvent in a Teflon flask, and then a 50-μl portion of this solution was spiked into 4 ml of the solution of a catalyst in an optical cell which was thermostated with circulating water at 25±0.1 °C. By the heating procedure, the enol fraction of 0.82 at room temperature decreases to 0.66. From the absorbance change, as recorded on a Hitachi 056 recorder, an observed rate constant k_{obsd}(s^{-1}) was obtained within an error of ±3%. The rate constants obtained by the two different initiation methods were confirmed to coincide in the benzene system.

It was noted in a preliminary experiment that the surface of the quartz cell acts as an effective catalyst on the tautomerization. The catalytic activity of the surface depends on the solvent and increases in an inert solvent such as hexane. Hence, it was necessary to make the surface inert by treating the cell and all of the volumetric glassware with a 1% benzene solution of dichlorodimethylsilane.[6)]

An increase in the TEA concentration up to 0.2 M shows no influence on either the apparent absorption coefficient or on the shape of the spectrum of acetylacetone, so that the amine is confirmed to participate only in a kinetic process as a catalyst in the tautomerization process. The catalytic experiment was carried out in 8—10×10^{-5} M for acetylacetone, in 10^{-5}–10^{-1} M for TEA, and in 10^{-5}–0.15 M for TBA.

Equilibrium Measurements. The apparent partition coefficient of acetylacetone (P) between water (10^{-3} M perchloric acid) and heptane, chlorobenzene, or 1,2-dichloroethane was determined spectrophotometrically within a precision of ±3% by the batch method. Similarly, P in the nonaqueous two-phase system of heptane/acetonitrile was determined. Each solvent of heptane and acetonitrile was mutually saturated before the partition experiment, since the mutual solubility is not negligible, it is determined by GLC to be 2.8 wt % acetonitrile in heptane and 10.1 wt % heptane in acetonitrile at 25 °C. The enol fractions of acetylacetone in the organic solvents were determined within a precision of ±0.01 by the NMR method[7] using a Varian A-60 NMR apparatus at 25 ±1.5 °C.

Results

The Catalytic Coefficients of TEA and TBA. The observed tautomerization rate constant was proportional to the concentration of amine, [B], in all the systems investigated;

$$k_{\mathrm{obsd}} = k_{\mathrm{B}}[\mathrm{B}] \tag{1}$$

where $k_{\mathrm{B}}(\mathrm{M}^{-1}\,\mathrm{s}^{-1})$ refers to a catalytic coefficient. Some typical examples of the plot of k_{obsd} *vs.* [B] in heptane and benzene systems are shown in Fig. 1. The slopes of Fig. 1 give the catalytic coefficients. The catalytic coefficients for the eight solvent systems are tabulated in Table 1. It appeares that the catalytic coefficient increases with the increase in the dielectric constant of the solvent. TEA is more effective than TBA in every solvent. A linear correlation between the logarithmic values of the catalytic coefficients of TEA and TBA appeared.

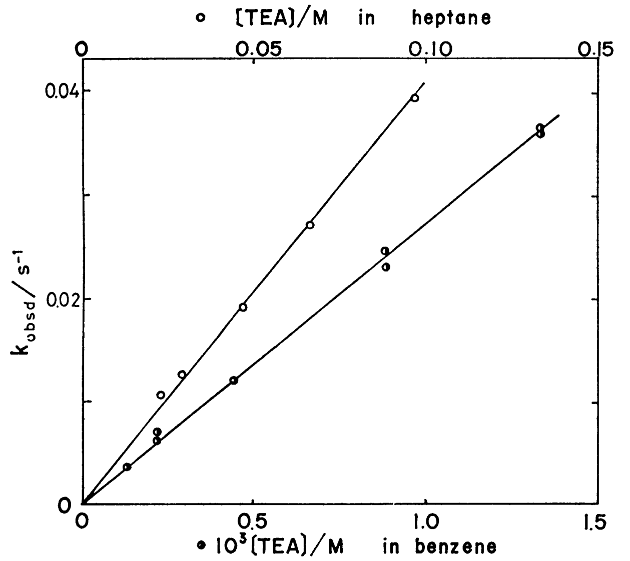

Fig. 1. The effect of TEA on the keto-enol tautomerization rate of acetylacetone in heptane and in benzene.

Table 1. The catalytic coefficients of the amines in relation to the tautomerization rate, the apparent partition coefficients (P) between water and organic solvent, and the enol fraction (f_0) in organic solvents of acetylacetone

No. Solvent	$k_{\mathrm{B}}/\mathrm{M}^{-1}\,\mathrm{s}^{-1}$ TEA	$k_{\mathrm{B}}/\mathrm{M}^{-1}\,\mathrm{s}^{-1}$ TBA	P	f_0
1. Heptane	4.17×10^{-1}	2.00×10^{-1}	0.887	0.97
2. Cyclohexane	5.25×10^{-1}	2.37×10^{-1}	1.03[a)]	0.95[b)]
3. Toluene	2.10×10	3.27	4.57[a)]	0.91
4. Benzene	2.73×10	4.22	5.93[a)]	0.88
5. Chlorobenzene	8.67×10	1.98×10	5.27	0.91
6. 1,2-Dichloroethane	3.62×10^{2}	9.83×10	11.5	0.79
7. Dichloromethane	4.42×10^{2}	1.97×10^{2}	22.5[a)]	0.78
8. Acetonitrile	5.88×10^{2}	2.02×10^{2}	7.85[c)]	0.60

a) Quoted value; H. Johansson and J. Rydberg, *Acta Chem. Scand.*, **23**, 2797 (1969). b) Quoted value; R. A. Dwek and G. Allen, *J. Chem. Soc., B,* **1966**, 161. c) Estimated value; see text.

The Partition Coefficients and the Enol Fractions. The apparent partition coefficients (P) and the enol fraction (f_0) are listed in Table 1. The partition coefficient in the system of acetonitrile-water was estimated from the results in the systems of heptane/water and heptane/acetonitrile. It appears that the organic solvent with a smaller f_0 shows a larger value of P.

Discussion

Correlation between the Catalytic Coefficient and the Partition Coefficient. The catalytic coefficients for the ketonization ($k_{\mathrm{B,k}}$) and the enolization ($k_{\mathrm{B,e}}$) were estimated by the following equations, neglecting any spontaneous process:

$$\begin{aligned} k_{\mathrm{B,k}} &= (1-f_0)k_{\mathrm{B}} \\ k_{\mathrm{B,e}} &= f_0 k_{\mathrm{B}} \end{aligned} \tag{2}$$

The calculated results are listed in Table 2, together with the partition coefficients of the keto (P_{K}) and enol (P_{E}) forms of acetylacetone calculated using the values of P, f_0, and the enol fraction in the aqueous phase, $f=0.15$.[5)]

In order to examine the free-energy relationship between the two processes, *i.e.*, the base catalysis in an organic solvent and the transfer of acetylacetone from water to the solvent, log $k_{\mathrm{B,k}}$ and log $k_{\mathrm{B,e}}$ were plotted against log P_{E} and log P_{K} respectively. The results are shown in Figs. 2 and 3. In the catalyses by both TEA and TBA, satisfactory linear correlations are obtained.

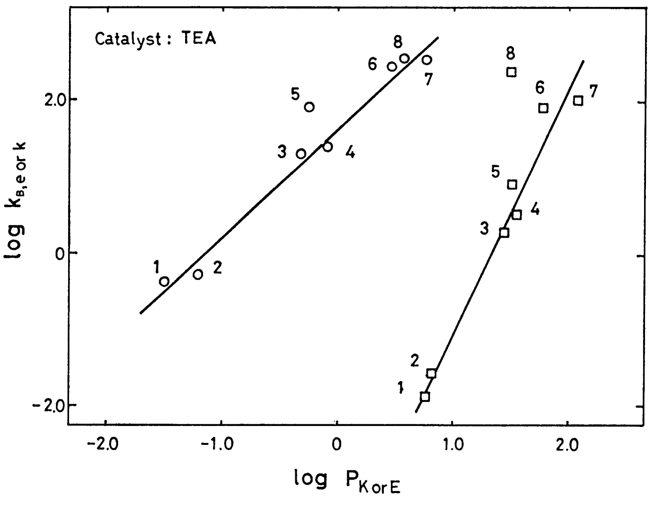

Fig. 2. The correlation between the catalytic coefficient of TEA and the partition coefficient of acetylacetone. The numbers in this figure correspond to those in Table 1.

○: log $k_{\mathrm{B,e}}$ *vs.* log P_{K}, $r=0.974$; □: log $k_{\mathrm{B,k}}$ *vs.* log P_{E}, $r=0.983$ except for acetonitrile.

TABLE 2. THE CATALYTIC COEFFICIENTS IN RELATION TO THE KETONIZATION ($k_{B,k}$)$^{a)}$ AND ENOLIZATION ($k_{B,e}$)$^{a)}$ REACTIONS AND THE PARTITION COEFFICIENTS OF THE KETO (P_K) AND ENOL (P_E) FORMS OF ACETYLACETONE AT 25 °C

No. Solvent	TEA		TBA		log P_K	log P_E
	log $k_{B,k}$	log $k_{B,e}$	log $k_{B,k}$	log $k_{B,e}$		
1. Heptane	−1.90	−0.39	−2.22	−0.71	−1.51	0.76
2. Cyclohexane	−1.58	−0.30	−1.93	−0.65	−1.21	0.82
3. Toluene	0.28	1.28	−0.53	0.47	−0.32	1.44
4. Benzene	0.52	1.38	−0.30	0.57	−0.08	1.54
5. Chlorobenzene	0.89	1.90	0.25	1.26	−0.25	1.51
6. 1,2-Dichloroethane	1.88	2.46	1.31	1.89	0.46	1.78
7. Dichloromethane	1.99	2.54	1.64	2.19	0.77	2.07
8. Acetonitrile	2.37	2.55	1.91	2.08	0.54	1.47

a) $M^{-1}s^{-1}$.

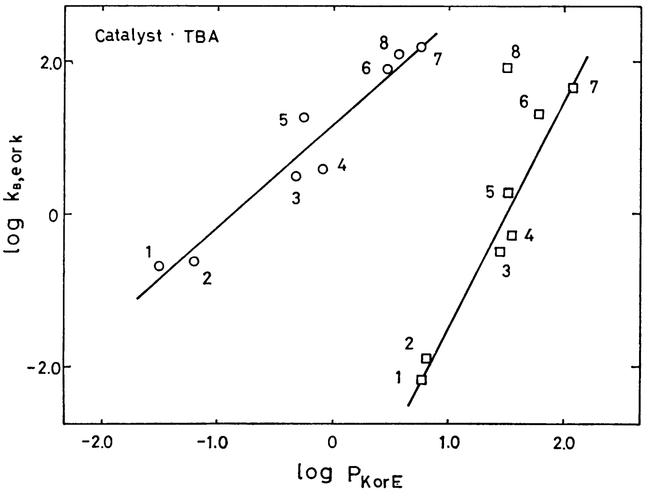

Fig. 3. The correlation between the catalytic coefficient of TBA and the partition coefficient of acetylacetone. The numbers in this figure correspond to those in Table 1.
○: log $k_{B,e}$ *vs.* log P_K, r=0.968; □: log $k_{B,k}$ *vs.* log P_E, r=0.977 except for acetonitrile.

A free-energy consideration of the base catalysis leads to the following equation;

$$\Delta G^{\neq} - \Delta G^{\neq\circ} = \delta\Delta G_X - \sum_i \delta\Delta G_i \tag{3}$$

where $\Delta G^{\neq}$ and $\Delta G^{\neq\circ}$ are, respectively, the activation free energies in a given solvent and in the hypothetical standard solvent and where $\delta\Delta G_X$ and $\delta\Delta G_i$ are the respective transfer free energies of the transition state and the reactant, i, from the standard solvent to the other solvent. For the ketonization and the enolization reactions, Eq. 3 leads to;

$$\begin{aligned}\Delta G_k^{\neq} - \Delta G_k^{\neq\circ} &= \delta\Delta G_X - \delta\Delta G_E - \delta\Delta G_B,\\ \Delta G_e^{\neq} - \Delta G_e^{\neq\circ} &= \delta\Delta G_X - \delta\Delta G_K - \delta\Delta G_B,\end{aligned} \tag{4}$$

where the subscripts X, E, K, and B correspond to the transition state, the enol form, the keto form, and the base catalyst respectively. Equation 4 can be rewritten by introducing the catalytic coefficient and the partition coefficient;

$$\begin{aligned}RT\ln(k_{B,k}/k^\circ_{B,k}) &= \delta\Delta G_B - \delta\Delta G_X - RT\ln(P_E/P_E^\circ),\\ RT\ln(k_{B,e}/k^\circ_{B,e}) &= \delta\Delta G_B - \delta\Delta G_X - RT\ln(P_K/P_K^\circ),\end{aligned} \tag{5}$$

where the superscript ○ denotes the standard solvent. The linear relationships obtained in Figs. 2 and 3 for the seven inert solvents prove that the term of $\delta\Delta G_B - \delta\Delta G_X$ is proportional to both $RT\ln(P_E/P_E^\circ)$ and $RT\ln(P_K/P_K^\circ)$.

Now, we may assume the following proportionality:

$$\begin{aligned}\delta\Delta G_B &= a\delta\Delta G_K = a'\delta\Delta G_E,\\ \delta\Delta G_X &= b\delta\Delta G_K = b'\delta\Delta G_E,\end{aligned} \tag{6}$$

where a, b, a', and b' are proportional constants following the relation of $a'/a = b'/b = c$ (constant). Equation 6 is based on the assumption that the solute-solvent interaction which occurs during the base catalyzed tautomerization process does not include specific interactions, *e.g.*, a strong dipole-dipole interaction and a hydrogen-bonding interaction. The correlation between $\delta\Delta G_K$ and $\delta\Delta G_E$ is shown in Fig. 4, in which the linear correlation between the logarithmic values of the partition coefficients of the keto and enol forms of acetylacetone

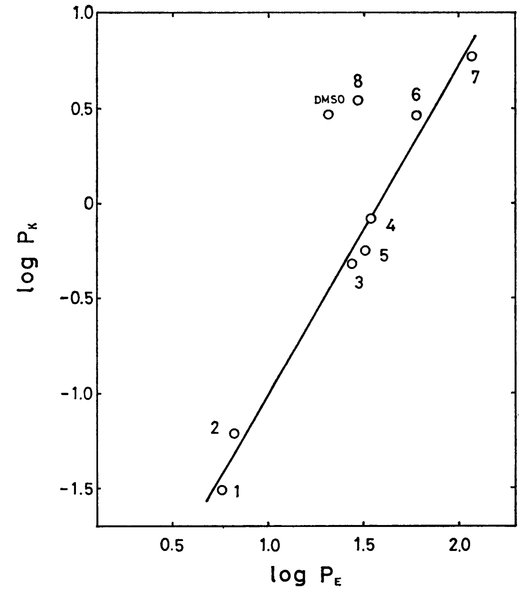

Fig. 4. The correlation between the partition coefficient of the keto (P_K) and the enol (P_E) forms of acetylacetone. The numbers in this figure correspond to those in Table 1.
log P_K=1.71 log P_E+2.73, r=0.993 except for acetonitrole and DMSO[3])

is shown for the seven inert solvents, allowing the estimation of the "c" constant from the slope as 1.71. A linear relationship was observed among the gas solubilities[8] and between the solubilities of bis(acetylacetonato)copper(II) and bis(dipropionylmethanato)-copper(II),[9] also. By the introduction of Eq. 6 into Eq. 5, we obtain the following equations;

$$\begin{aligned} \log k_{\mathrm{B,e}} &= (b-a-1)\log P_{\mathrm{K}} \\ &\quad + \{\log k^{\circ}_{\mathrm{B,e}} - (b-a-1)\log P_{\mathrm{K}}{}^{\circ}\}, \\ \log k_{\mathrm{B,k}} &= (b'-a'-1)\log P_{\mathrm{E}} \\ &\quad + \{\log k^{\circ}_{\mathrm{B,k}} - (b'-a'-1)\log P_{\mathrm{E}}{}^{\circ}\}. \end{aligned} \tag{7}$$

Consequently, the slopes of Figs. 2 and 3 give the set of the proportional constants of $(b-a)$ and $(b'-a')$—2.32 and 4.16 for TEA-catalysis and 2.37 and 4.01 for TBA-catalysis. The deviation observed for the acetonitrile system in Figs. 2 and 3 may be attributed to the destabilization in a polar solvent such as acetonitrile of the enol form, which is less polar than the keto form; this is also suggested by the deviation in Fig. 4.

Relationship among $\delta\Delta G_{\mathrm{X}}$, $\delta\Delta G_{\mathrm{K}}$, and $\delta\Delta G_{\mathrm{E}}$. In the above section, the relationship between the catalytic coefficient and the partition coefficient has been proved in terms of the free energy. The result shows that the lowering of the standard free energy of the tautomers causes a descrease in the activation free energy because of the further lowering of the standard free energy of the transition state compared to those of the tautomers. The values of $\delta\Delta G_{\mathrm{X}}$ are more sensitive to the solvent than those of $\delta\Delta G_{\mathrm{K}}$ and $\delta\Delta G_{\mathrm{E}}$. The transition state is expected to be a complex of an ion-pair or charge-transfer type between the amine and acetylacetone. Then, $\delta\Delta G_{\mathrm{X}}$ can be separated into $\delta\Delta G_{\mathrm{B}}$ and $\delta\Delta G_{\mathrm{X,r}}$,

$$\delta\Delta G_{\mathrm{X}} = \delta\Delta G_{\mathrm{B}} + \delta\Delta G_{\mathrm{X,r}}, \tag{8}$$

where $\delta\Delta G_{\mathrm{X,r}}$ is the residual part which is obtained by substracting $\delta\Delta G_{\mathrm{B}}$ from $\delta\Delta G_{\mathrm{X}}$. $\delta\Delta G_{\mathrm{X,r}}$ can be expected to be the transfer free energy of a state like an ion-pair of the proton and the enolate anion of acetylacetone. Equations 6 and 8 lead to this relation,

$$\delta\Delta G_{\mathrm{X,r}} = (b-a)\delta\Delta G_{\mathrm{K}} = (b'-a')\delta\Delta G_{\mathrm{E}}, \tag{9}$$

or

$$\begin{aligned} \delta\Delta G_{\mathrm{X,r}} &= 2.43\delta\Delta G_{\mathrm{K}} = 4.16\delta\Delta G_{\mathrm{E}} \\ &\qquad \text{for TEA-catalysis,} \\ \delta\Delta G_{\mathrm{X,r}} &= 2.37\delta\Delta G_{\mathrm{K}} = 4.01\delta\Delta G_{\mathrm{E}} \\ &\qquad \text{for TBA-catalysis.} \end{aligned} \tag{10}$$

Equation 10 shows that $\delta\Delta G_{\mathrm{X,r}}$ is most affected by the solvent in the transfer free energies of the three states and that the change in $\delta\Delta G_{\mathrm{X,r}}$ is the main factor governing the solvent effect on the rate of the catalysis. The difference in the solvent effect on the three states is probably due to the difference in the electric property; *e.g.*, the expected order of the delocalization of the electron density is the transition state> the keto form> the enol form.

Although the details of the reaction mechanism of the base-catalyzed tautomerization are still obscure, it can reasonably be expected that the proton transfer will occur *via* an intramolecular process assisted by the amine, rather than by an intermolecular process, as proposed by Baba and Takemura[10] for the base-catalysis of anthrone–anthranol interconversion in nonpolar solvents. This interpretation is supported by the fact that, even in inert solvents, TEA and TBA effectively catalyze the tautomerization of acetylacetone.

Free-energy Consideration of the Effect of the Silica Surface. As was mentioned in the Experimental section, the tautomerization rate is extremely enhanced by the contact with the wall of the quartz cell, depending on the solvent used. In considering the solvent effect in this heterogeneous catalysis, we applied the free-energy treatment developed in this study. It was assumed that the transition state is the adsorbed acetylacetone on the silica surface and that the solvation effects on the transition state and on the silica surface are negligible or compensate each other, *i.e.*, $\delta\Delta G_{\mathrm{B}}-\delta\Delta G_{\mathrm{X}}=\text{const}$ in Eq. 5. Then, Eq. 5 degenerates to;

$$\log k_{\mathrm{obsd}} = -\log f_0(1-f_0)P + \text{const.} \tag{11}$$

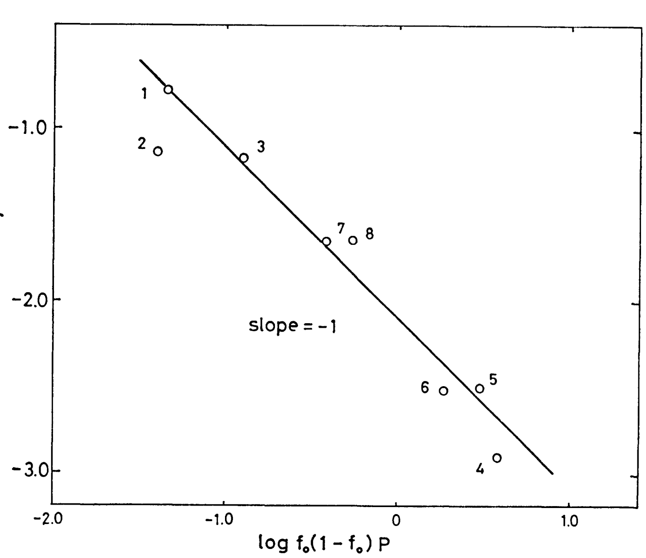

Fig. 5. The solvent effect on the silica surface catalysis. Solvent; 1: hexane, 2: cyclohexane, 3: carbon tetrachloride, 4: dichloromethane, 5: chloroform, 6: 1,2-dichloroethane, 7: benzene, 8: toluene.

According to the above equation, the experimental results are plotted in Fig. 5. A satisfactory linear relationship, with the slope of minus one, was obtained, in agreement with the prediction from Eq. 11. If the assumption of $\delta\Delta G_{\mathrm{B}}-\delta\Delta G_{\mathrm{X}}=\text{const}$ does not hold, the slope will differ from a minus one. Consequently, in this case the states most affected by the solvent are suggested to be the keto and enol forms, contrary to the results of the homogeneous amine catalysis. It is of interest that the solvent effect is in reverse directions in the two systems, *i.e.*, the heterogeneous and homogeneous catalyses. Further investigation employing a variety of solvents will enable us to assess the generality of this conclusion.

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