Headline Articles

A New Application of High-Viscosity Kinetics. An Attempt to Identify a Site of Solvent Reorganizations around a Reactant[#]

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Thermal fading of a colored species photochemically generated from so-called chromenes was kinetically studied in highly viscous media. The reaction was retarded by an increase in viscosity at viscosities higher than 10^2 Pa s. We propose to use substituent dependence of this retarding effect as a tool to identify the main site of solvent reorganizations around the reactant molecule in the activation step.

Solvent effects on the rate of chemical reactions have attracted many chemists; various techniques have been developed to study roles of solvent in the activation step.[1] For example, the activation volume obtained from kinetic effects of externally applied pressure[2] was shown to be effective to study solvation/desolvation in the activation step. Such efforts mainly aimed at a static side of solvent effects, however. When people refer to "kinetic solvent effects", it usually means dependence of $\Delta G^{\neq}$ on the reaction medium. Dynamic solvent effects, i.e., kinetic effects of slow solvent thermal fluctuations, have been neglected except in fast reactions such as photo-induced isomerizations.[3] Some ten years ago[4] we extended the dynamic-solvent-effect study to "slow" thermal isomerizations of molecules in their electronic ground state. By combining high pressure and viscous solvents, we realized highly viscous conditions where thermal isomerizations with a relatively large activation energy, $E_a > 50\ \mathrm{kJ\,mol^{-1}}$, were retarded by an increase in pressure. In all of the reactions we studied, a pressure increase resulted in a suppression of the reaction irrespective of the sign of the activation volume if the viscosity was sufficiently high, $\eta > 10$–100 Pa s. Such retarding effects were not observed in structurally similar but less viscous solvents and, therefore, it was difficult to explain these effects without invoking the dynamic solvent effects. Our conclusion was that the observed pressure dependence was a manifestation of a breakdown of the thermodynamic equilibrium between the initial and the transition state because of slow solvent thermal fluctuations at high viscosities. In other words, the observed "pressure" effects were actually viscosity-induced retardations. The temperature dependence of the rate constant k at a constant viscosity clearly indicated that solvent reorganizations and chemical structural changes had to be described by two separate coordinates, i.e., the medium and the chemical coordinate, respectively.[5–13] These two coordinates, although possibly strongly coupled, are independent of each other. Solvent molecules are reorganized around the reactant, more or less, prior to chemical structural changes. In other words, *asynchronism* between the chemical structural changes and the solvent reorganizations had to be assumed in the explanation of the experimental results. The extent of coupling of these two coordinates was found to be heavily dependent on the nature of the reaction and on the solvent.[14–18]

In this paper, we would like to propose yet another application of the viscosity effect to the elucidation of dynamic routes of solution reactions. There are two possibilities in solvent reorganizations. The first is that reorganizations take place around the whole reactant molecule without any preference. The second possibility is that solvent molecules are reorganized mainly around a particular part of the reactant. In the first case, any structural modification of the reactant would result in a change in the viscosity dependence. In the second case, only a modification of the moiety around which solvent molecules are reorganized would exert influences on the viscosity effect. As our first experimental attempt along this line, we studied substituent dependence of the viscosity effect in a cyclization shown in Scheme 1, where a photochemically generated open-chain species **a** goes back to a thermodynamically more stable "chromene" **b**. In this isomerization, a rotation around the central carbon–carbon single bond brings the naphthalenone ring and the ethenyl gourp close to each other and a carbon–oxygen bond-formation follows.[17] Solvent molecules have to be reorganized to realize a solvation sphere which stabilizes the cyclic transition state. If the viscosity dependence is influenced by a structural modification of the ethenyl group but not by a modification on the naphthalenone side, it would be reasonable to conclude that solvent molecules are reorganized mainly around the ethenyl group. If both modifications are found to influence the viscosity effect, it may be concluded

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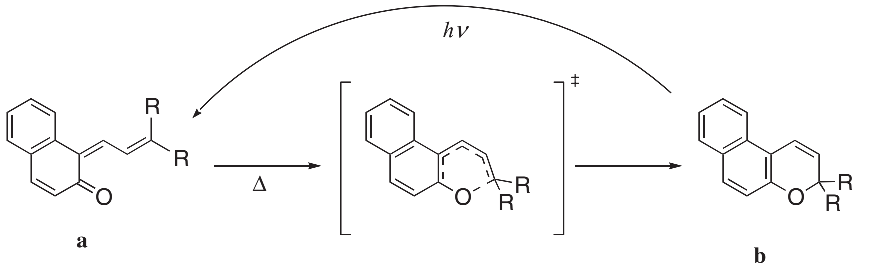

Scheme 1.

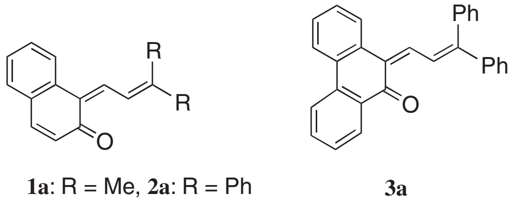

Chart 1.

that solvent reorganizations take place with little preference. Reactants used in the present study were 1-(3-methylbut-2-enylidene)naphthalen-2-one, MBNO **1a**, 1-(3,3-diphenylprop-2-enylidene)napthalen-2-one, PPNO **2a**, and 10-(3,3-diphenylprop-2-enylidne)phenanthren-9-one, PPPO **3a** (Chart 1).

Experimental

All of the reactants **1a**, **2a**, and **3a** were photochemically generated in situ from their cyclic precursors 3,3-dimethyl-3*H*-naphtho[2,1-*b*]pyran **1b**, 3,3-diphenyl-3*H*-naphtho[2,1-*b*]pyran **2b**, and 2,2-diphenyl-2*H*-phenanthro[9,10-*e*]pyran **3b**, respectively. The precursors were synthesized as described in the literature.[19] The viscosity of the system was manipulated by applying external pressures of 0.1–600 MPa.[20] Details of high-pressure kinetics were described elsewhere.[21] Solvents used were 2-methylpentane-2,4-diol (MPD), glycerol triacetate (GTA), and their nonviscous counterparts, i.e., ethanol and methyl acetate. Pressure effects were studied in the latter solvents in order to confirm the absence of essential mechanistic differences among the three reactants. At all of the conditions studied, the reaction obeyed the first-order rate law and the rate constants could be determined unequivocally.

Results and Discussion

Activation Parameters in Nonviscous Solvents. Logarithms of the first-order rate constant k for the cyclization of **1a**, **2a**, and **3a** in methyl acetate at 25 °C and those of **1a** in ethanol at various temperatures are plotted against the pressure in Figs. 1 and 2, respectively. As observed for **2a**,[17] the reaction was moderately accelerated by a pressure increase in **1a** and **3a**, suggesting essentially the same mechanism in all of the present reactants. Although the polarity of the reactant decreases in this cyclization,[22] a volume decrease by a loss of internal freedom of motion was more than enough to compensate for a volume increase caused by desolvation. Rate constants at 25 °C and 0.1 MPa are listed in Table 1 together with several activation parameters. The reaction rate decreased in the order of **1a** > **2a** > **3a**; however, none of the activation parameters indicated a fundamental difference in the reaction mechanism in these compounds.

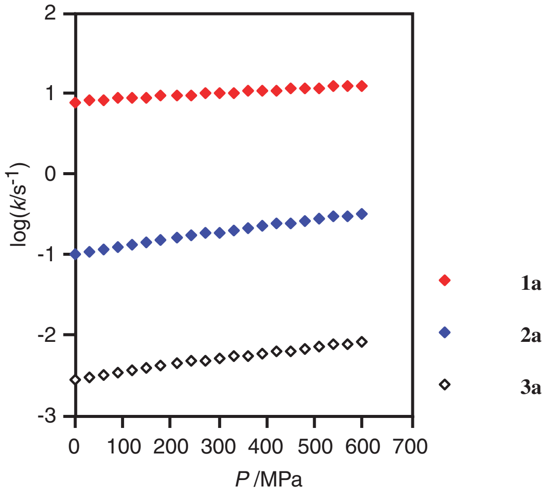

Fig. 1. Pressure dependence of the cyclization rate (k/s^{-1}) of **1a**, **2a**, and **3a** in methyl acetate at 25 °C.

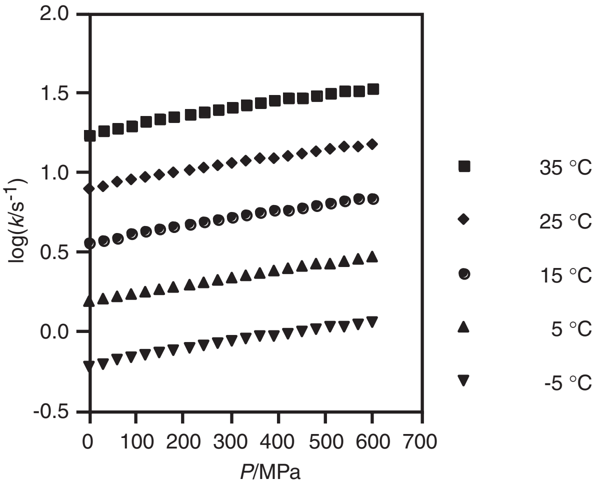

Fig. 2. Pressure dependence of the cyclization rate (k/s^{-1}) of **1a** in ethanol at various temperatures.

Viscosity Dependence. Pressure dependence of the reaction rate in GTA and MPD at two different temperatures are illustrated in Figs. 3 and 4, respectively. For the sake of clarity, results at the other temperatures are omitted in the plots. Rate constants and activation parameters at 0.1 MPa given in Table 2 are more or less the same as the values in Table 1, a clear indication that the nature of the reaction in the viscous

Table 1. Rate Constants (k/s^{-1}), Activation Enthalpies ($\Delta H^{\neq}$/kJ mol^{-1}), Activation Entropies ($\Delta S^{\neq}$/J K^{-1} mol^{-1}), and Activation Volumes ($\Delta V^{\neq}$/cm^3 mol^{-1}) in Nonviscous Solvents at 0.1 MPa[a)]

	1a		**2a**		**3a**	
	AcOMe	EtOH	AcOMe	EtOH	AcOMe	EtOH
k, 25 °C	7.81 ± 0.12	7.88 ± 0.06	$(1.00 \pm 0.01) \times 10^{-1}$	$(8.28 \pm 0.05) \times 10^{-2}$	$(2.82 \pm 0.10) \times 10^{-3}$	$(2.19 \pm 0.05) \times 10^{-3}$
$\Delta H^{\neq}$	58.9 ± 0.4	54.7 ± 0.2	65.2 ± 0.2	63.3 ± 0.7	76.7 ± 2.0	77.5 ± 1.4
$\Delta S^{\neq}$	-30 ± 1	-44 ± 1	-45 ± 1	-53 ± 2	-36 ± 6	-36 ± 5
$\Delta V^{\neq}$, 25 °C	-2.3 ± 0.1	-3.9 ± 0.2	-7.0 ± 0.5	-8.6 ± 0.5	-6.2 ± 0.3	-6.7 ± 0.2

a) Temperature ranges were −5 to 35 °C (**1a**), 25–55 °C (**2a** in AcOMe), 5–65 °C (**2a** in EtOH), and 25–55 °C (**3a**).

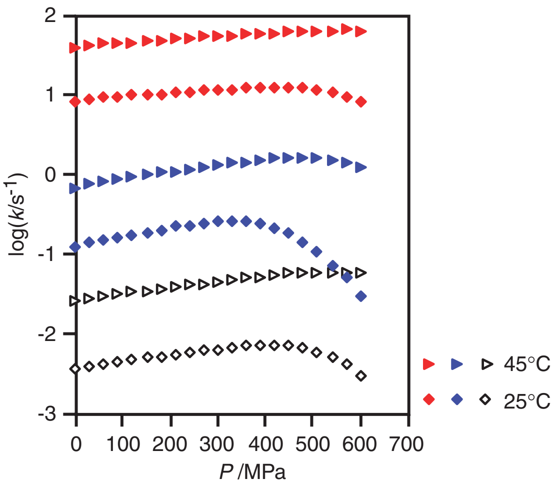

Fig. 3. Pressure dependence of the cyclization rate of **1a**, **2a**, and **3a** in GTA at different temperatures.

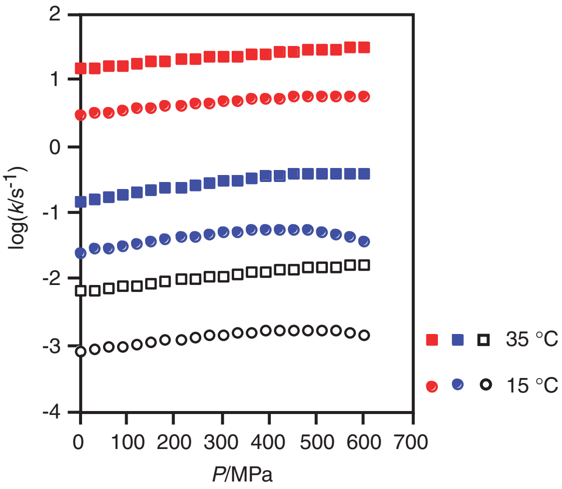

Fig. 4. Pressure dependence of the cyclization rate of **1a**, **2a**, and **3a** in MPD at different temperatures.

Table 2. Rate Constants (k/s^{-1}), Activation Enthalpies ($\Delta H^{\neq}$/kJ mol^{-1}), Activation Entropies ($\Delta S^{\neq}$/J K^{-1} mol^{-1}), and Activation Volumes ($\Delta V^{\neq}$/cm^3 mol^{-1}) in Viscous Solvents at 0.1 MPa[a)]

	1a		**2a**		**3a**	
	GTA	MPD	GTA	MPD	GTA	MPD
k, 25 °C	8.29 ± 0.07	6.68 ± 0.07	$(1.24 \pm 0.003) \times 10^{-1}$	$(6.27 \pm 0.09) \times 10^{-2}$	$(3.47 \pm 0.03) \times 10^{-3}$	$(2.32 \pm 0.06) \times 10^{-3}$
$\Delta H^{\neq}$	58.3 ± 0.5	56.0 ± 0.4	65.0 ± 0.4	63.9 ± 0.4	73.6 ± 1.8	76.2 ± 1.4
$\Delta S^{\neq}$	-32 ± 2	-41 ± 2	-44 ± 1	-54 ± 4	-45 ± 6	-39 ± 5
$\Delta V^{\neq}$, 25 °C	-3.3 ± 0.2	-4.4 ± 0.3	-9.8 ± 1.4	-8.0 ± 0.3	-6.7 ± 0.2	-7.9 ± 0.6

a) Temperature ranges were as in Table 1.

and the nonviscous solvents is identical. The transition state theory (TST) remained valid at lower pressures ($P < 300$ MPa) even in these viscous solvents. The reaction rate increased with increasing pressure because of a negative activation volume. However, a further increase in pressure resulted in a retardation, as observed in the other cases studied.[4,14–18] If we assume thermodynamic equilibrium between the initial and the transition state, it is difficult to explain these retardations. A pressure increase will not induce a change in mechanism from the one with a negative $\Delta V^{\neq}$ to the one with a positive $\Delta V^{\neq}$, because the former is accelerated and the latter is retarded by pressure. Therefore, the retardation must be a result of a change in the rate-determining step. However, it is hard to imagine a step with a large volume increase in a unimolecular reaction, as in the present case. The most reasonable way to explain the retardation would be to assume that the solvent thermal fluctuations became too slow to maintain the thermodynamic equilibrium between the initial and the transition state because of high viscosities ($\eta > 10^2$ Pa s); then solvent reorganizations around the reactant became rate-determining. This nonequilibrium state will be reached at a lower viscosity in a faster reaction if the other factors are the same, because the faster consumption of the reactant requires faster solvent reorganizations.

MBNO **1a** isomerized more than fifty times faster than PPNO **2a**. However, the retardation started appearing at a *higher* viscosity in **1a** both in GTA and MPD. Converting the two phenyl groups by sterically smaller methyl groups made the reactant less sensitive to the viscosity increase. Figures 5 and 6 clearly show that the viscosity with the maximum rate constant k, $\eta_{\max}$, decreased in the order: **1a** > **2a**. This may be considered as a good indication that the solvent molecules were rearranged around the diphenylethenyl moiety in **2a**. A conversion of PPNO **2a** to PPPO **3a** by adding four

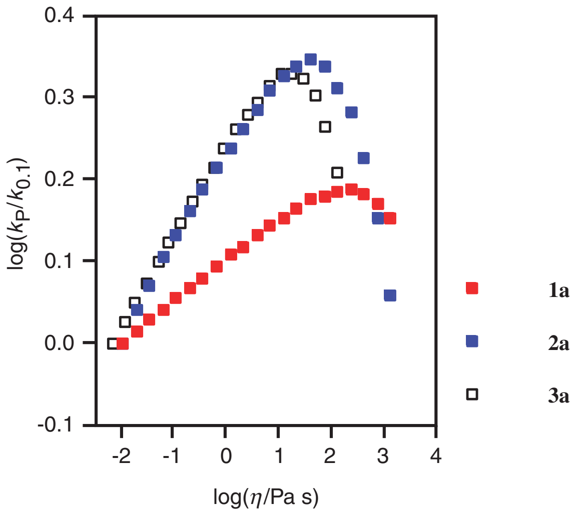

Fig. 5. Pressure effects plotted against viscosity η for the three reactants at 35 °C in GTA.

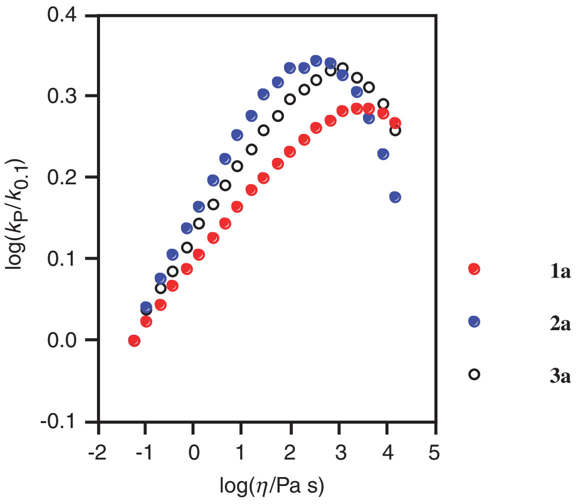

Fig. 6. Pressure effects plotted against viscosity η for the three reactants at 15 °C in MPD.

carbon atoms to the naphthalenone group did not cause a shift of η_{max} to an even lower value. On the contrary, the structural change moved the η_{max} to a slightly *higher* value, probably because the reaction was slower in **3a**. A higher viscosity was required to break the equilibrium between the initial and the transition state in **3a**. This structural dependence of the viscosity effect may be considered as an indication of the absence of major solvent reorganizations in the vicinity of the naphthalenone moiety in **2a**.

Conclusion

From the present results, it would be reasonable to conclude that solvent reorganizations took place mainly around the ethenyl moiety in the cyclization shown in Scheme 1. Since all of the movements are relative to each other, this conclusion can be rephrased as follows. During the cyclization, the substituted ethenyl group changed its position in the solvation sphere while the naphthalenone group stayed in the same position. To the best of our knowledge, this is the first successful attempt to demonstrate the existence of *spatial selectivity* in the solvent reorganizations in a homogenous solution reaction. The *asynchornism* between the solvent reorganizations and the chemical structural changes and the *spatial selectivity* in the solvent reorganizations may be considered as two fundamental features of solution reactions.

Further experiments with different chromenes are under way and the results will be reported when they are completed.

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