Kinetic Studies of the Complex Formation in the System of Cyclodextrin, Iodine, and Iodide

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(Received August 4, 1983)

Kinetic studies of complex formation in the system consisting of cyclodextrin, iodine, and iodide have been made by the temperature-jump method. By addition of α-cyclodextrin to the iodine–iodide solution, a new relaxation in addition to that due to I_6^{2-}, formation was observed, but not in the case of addition of β-cyclodextrin. The reciprocal relaxation time is independent of the iodine concentration, but increases with increase of both iodide and α-cyclodextrin concentration, with a tendency to reach a constant value at their high concentrations. From these concentration dependences of the relaxation time, the observed relaxation was assigned to the conformational change of the complex between α-cyclodextrin and iodide ion, and the rate constants were estimated to be 5.9×10^5 and 1.2×10^5 s^{-1} for the forward and backward processes, respectively. A rationalization for the difference between α-cyclodextrin and β-cyclodextrin in this complex formation is proposed in terms of the molecular structure of cyclodextrin.

The cyclodextrins are well known for their ability to form inclusion complexes with a variety of guests,[1-3] and the main driving forces of the complex formation have been attributed to hydrogen bonding,[4] hydrophobic interaction,[5] and van der Waals forces[6] depending on the nature of the guest molecules. Kinetic studies[7-9] of the inclusion complex formation of cyclodextrin have revealed the importance of the conformational change of cyclodextrin and the breakdown of the water structure around guest substances. However, the details of the reaction mechanism are still obscure especially with respect to the effect of the structure of cyclodextrin.

Meanwhile, Noltmeyer and Saenger[10] have reported that the α-cyclodextrin–iodine complex has the same structure as the amylose–iodine complex. This fact motivated us to start some kinetic studies of the complex formation of the cyclodextrin with iodine in connection with our previous studies on the amylose–iodine complex formation.[11] In the preliminary temperature-jump experiment, an addition of α-cyclodextrin to the iodine–iodide solution gives rise to new relaxation besides that which was observable without cyclodextrin.[12] The present work was undertaken to clarify the mechanism of the new relaxation with use of both α- and β-cyclodextrins.

Experimental

Materials. The α- and β-cyclodextrins were purchased from Nakarai Co., and used as received. Iodine and potassium iodide were of reagent grade and used without further purification.

Measurements. Kinetic measurements were carried out by a temperature-jump method[13] with detection of transmittance at 500 nm which corresponds to the absorption band of iodine. The ionic strength of the solution was kept at 0.023 M†† to attain a rapid temperature rise within 0.75 μs. Spectrophotometric measurements were made on a Union Giken SM-401 spectrophotometer. All the experiments were carried out at 25 °C.

†† 1 M=1 mol dm^{-3}.

Results and Discussion

A typical relaxation curve observed in a solution containing α-cyclodextrin, iodine, and iodide is shown in Fig. 1. This relaxation becomes predominant with increase of α-cyclodextrin concentration, and is obviously different from that observed in the iodine–iodide solution in both the relaxation time and the direction of the relaxation signal.[12] The present relaxation spectra show a decrease of iodine concentration and was characterized by a single relaxation. In order to simplify the analysis, the kinetic experiments were undertaken by changing the concentration of one species while keeping those of the other two constant. The plots of the reciprocal relaxation time, τ^{-1} against the total concentration of α-cyclodextrin, iodine, and iodide are shown in Figs. 2, 3, and 4. As shown in these figures, the value of τ^{-1} increases with concentration of α-cyclodextrin and iodine, showing a trend to level off at high concentration, but it is independent of that of iodine. In contrast to the α-cyclodextrin, the addition of β-cyclodextrin to the iodine–iodide solution did not give rise to any new re-

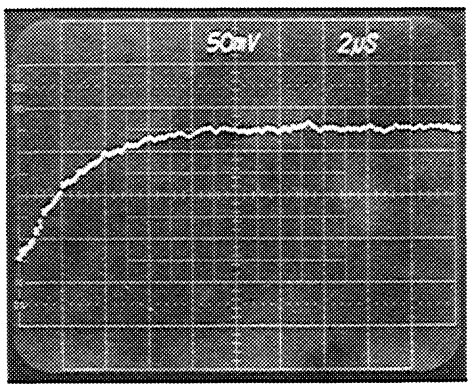

Fig. 1. Typical relaxation curve for the solution containing α-cyclodextrin, potassium iodide, and iodine at 25 °C; $[\alpha\text{-CD}]=6.0\times10^{-3}$ M, $[KI]=2.3\times10^{-2}$ M, $[I_2]=6.0\times10^{-3}$ M; sweep 2 μs/division and $\lambda=500$ nm.

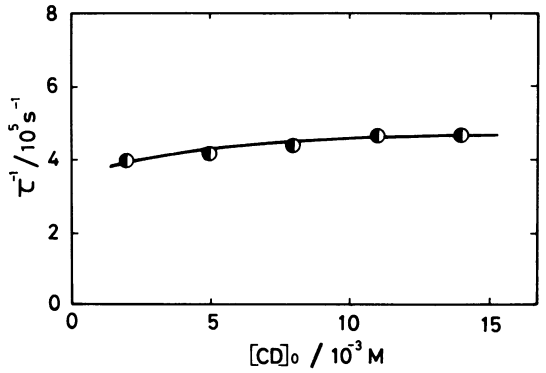

Fig. 2. Dependence of the reciprocal relaxation time on the α-cyclodextrin concentration at constant $[I_2]=5.0\times10^{-3}$ M and $[KI]=2.3\times10^{-2}$ M at 25 °C.

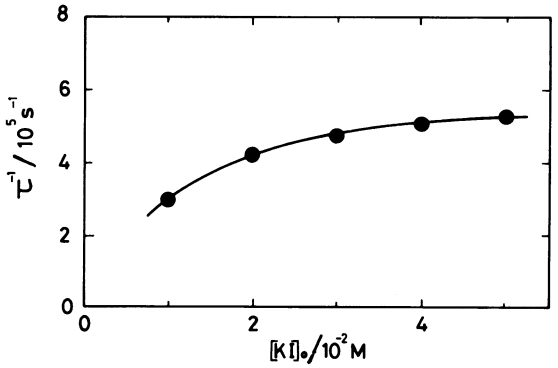

Fig. 3. Dependence of the reciprocal relaxation time on the potassium iodide concentration at constant $[I_2]=5.0\times10^{-3}$ and $[\alpha\text{-CD}]=5.0\times10^{-3}$ M at 25 °C.

laxation, which is indicative of the specificity of the present relaxation to α-cyclodextrin.

In the solution containing the α-cyclodextrin, iodine, and iodide, according to the investigations reported so far,[7,13-15] the following reactions are at least expected to proceed,

$$I^- + I_2 \rightleftharpoons I_3^- \qquad K_I, \qquad (I)$$

$$2I_3^- \rightleftharpoons I_6^{2-} \qquad K_{II}, \qquad (II)$$

$$CD + I^- \rightleftharpoons CDI \qquad K_{III}, \qquad (III)$$

where CD and CDI denote the free α-cyclodextrin and the complex of α-cyclodextrin and iodide, respectively. Among these three reactions, the relaxations due to the reactions I and II, which are much faster than the present relaxation, have been already investigated kinetically by the temperature-jump method.[13,14] As for the reaction III, the kinetic studies have not been performed successfully because of the existence of relaxation due to the conformational change of α-cyclodextrin.[7] Accordingly, we first examined reaction III, and also the complex formations of α-cyclodextrin with I_2, I_3^-, or I_6^{2-} as origin of the present relaxation, but failed to explain all the concentration dependences of the relaxation time in Figs. 2, 3, and 4. By reference to the concentration dependence of relaxation time in Figs. 2 and 3 specific to the intramolecular process following the fast binding process, we analyzed the kinetic data with the reaction scheme as follows:

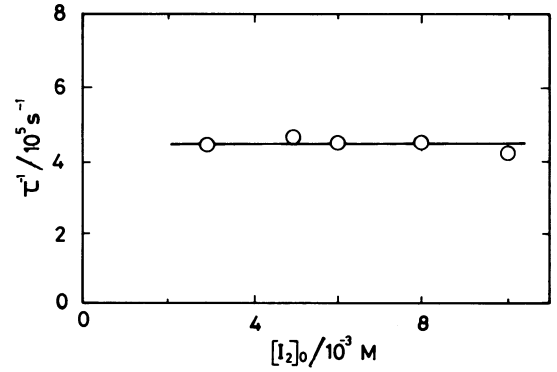

Fig. 4. Dependence of the reciprocal relaxation time on the iodine concentration at constant $[KI]=2.3\times10^{-2}$ M and $[\alpha\text{-CD}]=4.0\times10^{-3}$ M at 25 °C.

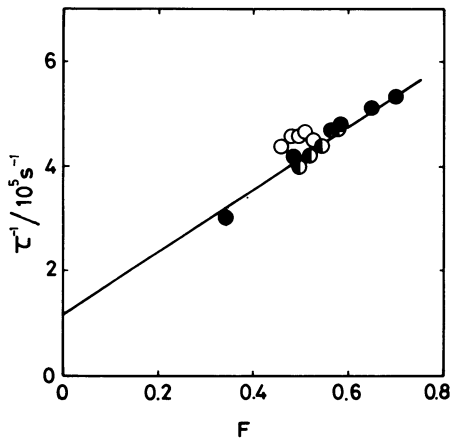

Fig. 5. Plots of τ^{-1} *vs.* the concentration term F in the Eq. (1). The circles correspond to those in Figs. 2, 3, and 4.

$$CD + I^- \underset{}{\overset{K_1}{\rightleftharpoons}} CDI' \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} CDI''. \qquad (IV)$$

This reaction is a modification of reaction III and the binding process of iodide ion to α-cyclodextrin is followed by the intramolecular process of the complex. If the reactions I and II and the first step of reaction IV are faster than the second step, the relaxation time for the second step can be finally represented by

$$\tau^{-1} = k_2 F + k_{-2}, \qquad (1)$$

with

$$F = \frac{K_1[CD + I^-(1 + K_I(I^- + I_2 + CD))]}{K_1[CD + I^-(1 + K_I(I^- + I_2 + CD))] + 1}. \qquad (2)$$

The derivation of this equation will be described in the appendix section. The value of K_1, 2.1±0.3 M^{-1}, was determined so as to obtain a best linear relationship between the observed τ^{-1} and the concentration term F, in the Eq. 1. The final results are shown in Fig. 5. The values of k_2, $(5.9\pm0.5)\times10^5$ s^{-1}, and k_{-2}, $(1.2\pm0.5)\times10^5$ s^{-1}, were obtained from the slope and intercept of the straight line, respectively. Using

these values of K_1 and $K_2=k_2/k_{-2}$, the overall binding constant of reaction IV, $K_{IV}=K_1(1+K_2)$, was found to be 13±2 M^{-1}. The good agreement of this value with the binding constant obtained statically by the conductometric method (12.4 M^{-1})[15] gives proof of the validity of an assignment of the present relaxation to reaction IV. Furthermore, it was recognized from the spectrophotometric experiments that the addition of α-cyclodextrin to the iodine–iodide solution results in the increase in I_2 concentration and the decrease in I_3^- concentration in solution. This spectrophotometric result implies the complex formation of α-cyclodextrin with I^- rather than I_2, I_3^-, and I_6^{2-}, supporting the present assignment of the kinetic data.

The apparent difference in the kinetic behavior observed in the present studies for the α-cyclodextrin and β-cyclodextrin can be discussed from the viewpoint of the molecular structure of cyclodextrin. For α-cyclodextrin, a conformational change in the inclusion complex formation was proposed by X-ray crystallographic studies,[16] while there is no evidence of such conformational change for the β-cyclodextrin. Accordingly, at the present stage, the second process of reaction IV can be ascribed to a conformational change resulting from the "strained"[16] structure of α-cyclodextrin.

In conclusion, the present work clarifies that, in contrast to the polyiodide chain structure proposed by Noltemeyer and Saenger[10] for the α-cyclodextrin–iodine complex in the solid state, α-cyclodextrin binds predominantly with I^- rather than I_2, I_3^-, or I_6^{2-} in solution. Furthermore, the difference observed in the present kinetic experiments on the α- and β-cyclodextrins was ascribed to the "strained" conformation of α-cyclodextrin.

Appendix

If reactions I, II, and the first step in IV in the text are much faster than the second step of reaction IV, the following relationships can be derived from the mass balance and the mass conservation laws;

$$K_I(I^-\Delta I_2+I_2\Delta I^-) = \Delta I_3^-, \tag{A1}$$

$$2K_{II}I_3^-\Delta I_3^- = \Delta I_6^{2-}, \tag{A2}$$

$$K_1(I^-\Delta CD+CD\Delta I^-) = \Delta CDI', \tag{A3}$$

$$\Delta I^- + \Delta I_3^- + 2\Delta I_6^{2-} + \Delta CDI' + \Delta CDI'' = 0, \tag{A4}$$

$$\Delta I_2 + \Delta I_3^- + 2\Delta I_6^{2-} = 0, \tag{A5}$$

$$\Delta CD + \Delta CDI' + \Delta CDI'' = 0. \tag{A6}$$

The rate equation for the second step of reaction IV is

$$\frac{d\Delta CDI''}{dt} = k_2\Delta CDI' - k_{-2}\Delta CDI'', \tag{A7}$$

Combining the Eqs. A1—A6, the Eq. A7 is converted into the next equation

$$\frac{d\Delta CDI''}{dt} = -(k_2F+k_{-2})\Delta CDI'', \tag{A8}$$

with

$$F = \frac{K_1(I^-+CD)+(1+4K_{II}I_3^-)K_IK_1I^-(I^-+I_2+CD)}{1+K_1(I^-+CD)+K_IK_1I^-(I^-+I_2+CD)(1+4K_{II}I_3^-)}. \tag{A9}$$

Accordingly, the relaxation time can be represented by

$$\tau^{-1} = k_2F + k_{-2}.$$

Under the present experimental conditions, Eq. A10 can be rewritten in good approximation as

$$\tau^{-1} = k_2\frac{K_1\{CD+I^-(1+K_I(I^-+I_2+CD))\}}{1+K_1\{CD+I^-(1+K_I(I^-+I_2+CD))\}} + k_{-2}. \tag{A11}$$

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