Thermodynamic Parameters for Formation of Through-Ring α-Cyclodextrin Complexes of Donor–Acceptor Linked Compounds: Comparison between D_2O and H_2O Solutions of Anthracene–Viologen Systems with Intramolecular Charge-Transfer Absorption Spectra(1)

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On the addition of α-cyclodextrin (CD), an intramolecular charge-transfer absorption band of an anthracene-viologen linked compound rapidly disappeared with elapsed time. The reason was ascribed to formation of a through-ring CD complex, which hinders direct interaction between the donor- and acceptor moieties. Thermodynamic parameters, including the energy of activation for complexation of α-CD, were evaluated by the use of the charge-transfer absorption band in D_2O- and H_2O solutions. Solvent deuterium isotope effects were observed with the free energy change on complexation, but not with the energy of activation for formation of the through-ring CD complex. An open, extended conformer of the linked compound was proposed as the model of the activated state for forming the through-ring CD complex.

Rotaxane-type cyclodextrin (CD) complexes have intensively been studied as one of the most important supramolecular assemblies in various fields.(2) The present authors have demonstrated that NMR spectroscopy is an extremely powerful means to study the rotaxane-type CD complexes (**1**, Chart 1).(3,4) Distinct ^{1}H NMR signals due to the rotaxane-type complex were clearly observed apart from the uncomplexed species, and the equilibrium constants were calculated from the signal intensities.

When the guest molecule was a viologen derivative attached to an aromatic donor moiety, such as phenothiazine or carbazole, an intramolecular charge-transfer absorption band was observed. On the addition of α-CD, the intensity of charge-transfer band rapidly decreased and reached a plateau region within 1 h. The observation was taken to indicate conformational change in the linked compounds on going from free species into the rotaxane-type complexes.

The remarkable effect of α-CD on the charge-transfer absorption band can also be used to elucidate unique feature of the rotaxane-type CD complex. This method might be more versatile than the above mentioned NMR spectroscopic investigation because of the following reasons:

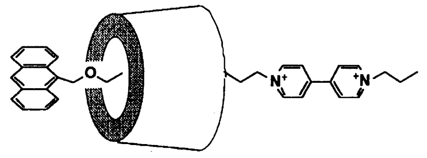
1) The sample concentration could be much lower than that for the NMR spectroscopy,

2) The solvent molecules are not necessarily deuterated, and

3) Better time resolution should be obtained, since the electronic spectral change is spontaneous.

In the present study, equilibrium constants for formation of the rotaxane-type α-CD complex of the following anthracene–viologen linked compound (AnC_8V, Chart 2), as estimated by the above two methods (NMR and CT), were carefully compared to establish the methodology.

The linked compound was associated with a pronounced charge-transfer absorption band, which indicates some difference between D_2O and H_2O solutions. Then, thermodynamic parameters of the charge-transfer complexes, as well as the rotaxane-type complexes, in D_2O and H_2O solutions were evaluated from the CT absorption band.



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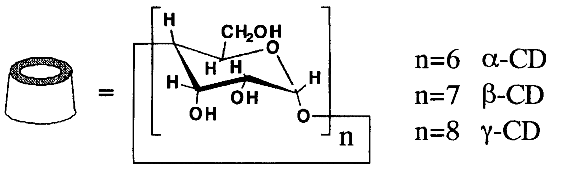
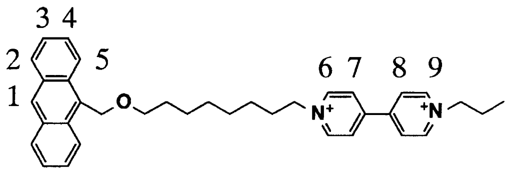


Chart 1.

Experimental

The linked compound (AnC_8V) was prepared by coupling 9-hydroxymethylanthracene with 1,8-dibromooctane, followed by the reaction with 1-propyl-4-(4-pyridinyl)-pyridinium bromide. Anal. Calcd for $C_{36}H_{42}Br_2N_2O$: C, 63.72; H, 6.24; N, 4.13%. Found: C, 63.86; H, 6.18; N, 4.11%.

Guaranteed grade α-CD was used without further purification (Tokyo Kasei Kogyo Co., Ltd.). Electronic absorp-



AnC_8V

Chart 2.

tion spectra were recorded with a Shimadzu Model UV-2200 spectrophotometer. Proton NMR spectra (400 MHz, D_2O solution) were measured by the use of a JEOL Model JNM-GSX 400 spectrometer. A DSS sample in sealed capillary tube was used as the external standard for chemical shifts.

Sample concentration of AnC_8V was kept below critical micellar concentration (7.79 mM (1 M=1 mol dm^{-3})) so that no aggregation of the solute took place in the aqueous solutions.

Results and Discussion

Equilibrium Constant for the Rotaxane-Type CD Complexes as Evaluated from ^{1}H NMR Spectra and Charge-Transfer Absorption Band. The ^{1}H NMR spectra were examined with and without α-CD. Distinct signals due to the complex were clearly observed apart from the uncomplexed species as shown in Figs. 1a and 1b. The equilibrium constant for formation of the rotaxane-type complex was evaluated by the use of integrated signal intensities of the respective species.[4] The results are summarized in Table 1 (Method 1).

Disappearance of the charge-transfer absorption bands, on the addition of α-CD (Fig. 2), was also used to evaluate the equilibrium constant. The charge-transfer absorption band was ascribed to intramolecular interaction, since the apparent molar absorptivity was not affected by the concentration change (0.1—0.5 mM) of the linked compound. α-CD was added to a solution containing anthracene–viologen linked compound, and decrease in the charge-transfer absorption band intensity was used to evaluate the concentration of the rotaxane-type complex.

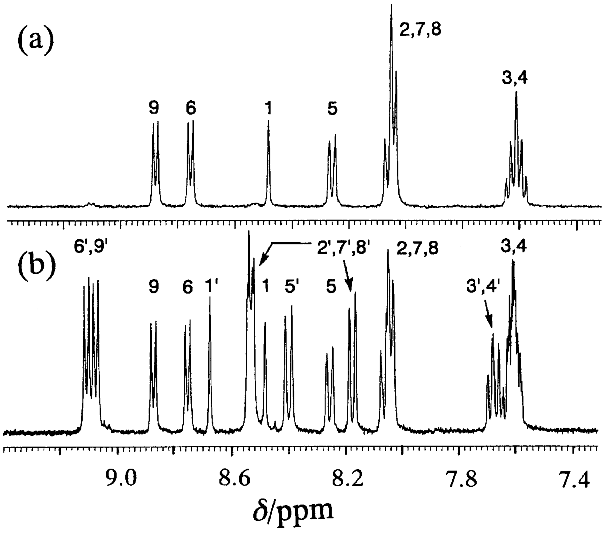


Fig. 1. Effects of α-CD (1 mM) on ^{1}H NMR spectra of AnC_8V (1 mM) in D_2O solution at 303 K: (a) without α-CD and (b) with α-CD. Assignments were made as shown in (a), and the corresponding signals in the complexed species were indicated by the same letters with a prime.

Table 1. The Equilibrium Constant for Formation of the Rotaxane-Type α-CD Complex[a,b]

Temp/K	$K/10^3$M^{-1}	
	Method 1	Method 2
283		3.82±0.56
293	2.43±0.28	2.52±0.26
298		2.29
303	1.80±0.24	1.83±0.18
308		1.56
313	1.00±0.18	1.11±0.06
323		0.64
333	0.38±0.09	

a) The K-values were evaluated either from ^{1}H NMR spectra (Method 1) or from CT- absorption band (Method 2). b) Standard deviation was estimated from results of repeated experiments (n=1—7).

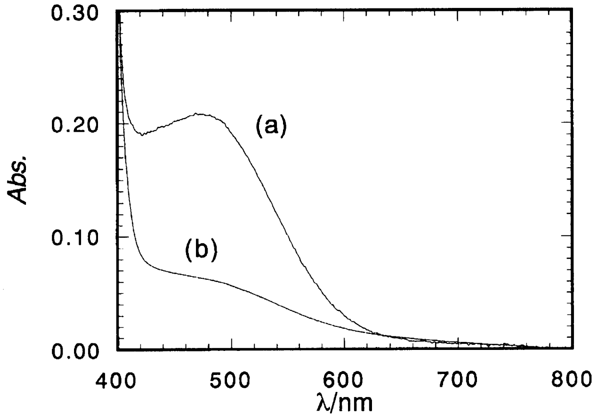


Fig. 2. Change of charge-transfer absorption bands of AnC_8V in H_2O solution (1 mM) at 293 K on the addition of α-CD: (a) without α-CD and (b) with α-CD (4 mM).

The absorption due to charge-transfer interaction was measured at 480 nm. In the presence of large-excess amount of α-CD (40 mM with respect to 0.2 mM AnC_8V), tailing of the absorption band extended beyond 480 nm. The molar absorption coefficient of the tailing due to complexed AnC_8V at 480 nm was 34. Then,

$$Abs_{480\ \mathrm{nm}} = \varepsilon_{\mathrm{CT}}[\mathrm{free}] + 34[\mathrm{complex}] \tag{1}$$

where $\varepsilon_{\mathrm{CT}}$ was evaluated from the absorption of AnC_8V at 480 nm in the absence of α-CD. The concentration of uncomplexed AnC_8V ([free]) was estimated by the use of the following equation:

$$\begin{aligned} Abs_{480\ \mathrm{nm}} &= \varepsilon_{\mathrm{CT}}[\mathrm{free}] + 34([\mathrm{total}] - [\mathrm{free}]) \\ &= (\varepsilon_{\mathrm{CT}} - 34)[\mathrm{free}] + 34[\mathrm{total}] \end{aligned} \tag{2}$$

$$K = \frac{[\mathrm{complex}]}{[\mathrm{free}][\alpha - \mathrm{CD}]} \tag{3}$$

The equilibrium constants (K) in D_2O solutions, thus obtained by the two different procedures (NMR and CT), were in reasonable agreement with each other as shown in Table 1.

Free Energy Changes for Formation of α-CD- and Charge-Transfer Complexes. For a given concentration of the linked compound, absorbance of the charge-transfer band in D_2O solution was certainly larger than that in H_2O solution (Fig. 3).

The equilibrium constants for the rotaxane-type CD complex in H_2O and D_2O solutions were carefully evaluated from the absorbance of charge-transfer band at different temperatures. Thermodynamic parameters for the complexation were evaluated and the results are summarized in Table 2. Difference in the thermodynamic parameters between the D_2O and H_2O solutions was rather small but not discernible.

Detailed studies were further carried out to elucidate the roles of charge-transfer interaction in dynamic behavior of the linked compounds. At lower temperatures, the absorbance of charge-transfer band increased, while the absorption at vibrational peaks of the ^1L_a-band (330—380 nm) for anthracene correspondingly decreased. The effect of charge-transfer interaction on the spectra of anthracene moiety (i.e., ^1L_a-band) became clear, when the spectra were compared with those in the presence of large excess amount of α-CD. The difference spectra, as given in Fig. 4, indicated that the charge-transfer interaction in D_2O was certainly stronger than that in H_2O. The decrease of the absorbance at vibrational peaks of ^1L_a-band was in good agreement with the increase of charge-transfer absorption at 480 nm throughout the investigated temperature range.

The decrease of the absorption of ^1L_a-band at 385 nm, for example, could be well correlated with the increase of charge-transfer absorption at 480 nm by the following equations:

$$D_2O: \Delta Abs_{^1L_a} = -4.74\Delta Abs_{CT} - 19.4 \ (r = 0.999)$$

$$H_2O: \Delta Abs_{^1L_a} = -5.74\Delta Abs_{CT} - 96.6 \ (r = 0.998)$$

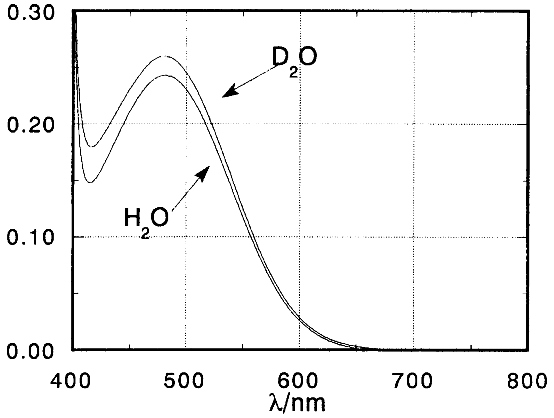


Fig. 3. Difference in the charge-transfer absorption band between D_2O and H_2O.

Table 2. Thermodynamic Parameters for Complexation with α-CD

Solvent	$\Delta G^{a)}$/kJ mol^{-1}	ΔH/kJ mol^{-1}	ΔS/J mol^{-1} K^{-1}
H_2O	−16.7±0.3	−34.9±0.3	−59.9±8.1
D_2O	−17.5±0.2	−30.0±0.2	−41.6±6.5

a) 303 K.

On the basis of these observations, the concentration of the charge-transfer complex was evaluated from the difference spectra of the ^1L_a band as the first approximation. Then, the concentration of the CT-complex was estimated by the following equation:

$$[\text{CT-complex}] = \frac{\Delta Abs_{^1L_a}}{\varepsilon_{^1L_a}} \tag{4}$$

The denominator ($\varepsilon_{^1L_a}$) is the absorbance of the ^1L_a band in the presence of large excess of α-CD, which was practically identical with that of amphiphilic-anthracene homologue with an ammonium head group as expected.

The free energy change in forming the charge-transfer complex at each temperature was calculated to afford the thermodynamic parameters summarized in Table 3. The difference between H_2O- and D_2O solutions was small but beyond experimental errors. It was also noticed that the entropy change became dominant over the enthalpy change at room temperatures.

Complexation Rate of α-CD with Anthracene–Viologen Linked Compound in D_2O and H_2O Solutions. Dehydration of viologen unit is definitely required before the linked compound is complexed with α-CD. Then, one might expect that the complexation rate of α-CD on the linked compound in D_2O is different from that in H_2O. The rate constants could be evaluated from the change in absorbance of the charge-transfer band along the elapsed time after the addition of α-CD (Fig. 5).

Since the complexation reaction was investigated by the use of α-CD in large excess with respect to AnC_8V:

$$AnC_8V + \alpha\text{-CD} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \text{complex} \tag{5}$$

then

$$k_1' = k[\alpha\text{-CD}] = \text{constant} \tag{6}$$

and

$$\frac{d[AnC_8V]}{dt} = -k_1'[AnC_8V] + k_{-1}[\text{complex}] \tag{7}$$

$$[\text{complex}] = [AnC_8V]_{\text{total}} - [AnC_8V] \tag{8}$$

Table 3. Thermodynamic Parameters for the Formation of Intramolecular CT Complexes Evaluated with CT Absorption Band

Solvent	$\Delta G^{a)}$/kJ mol^{-1}	ΔH/kJ mol^{-1}	ΔS/J mol^{-1} K^{-1}
H_2O	5.07±0.08	−11.9±0.08	−56.0±1.2
D_2O	4.01±0.05	−10.5±0.05	−47.9±0.7

a) 303 K.

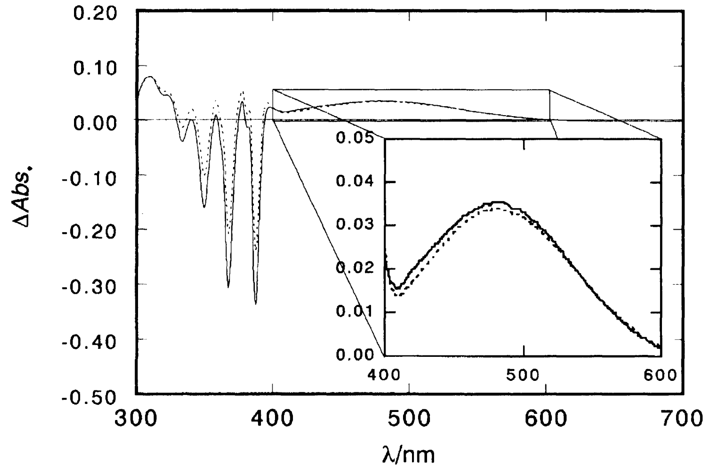


Fig. 4. Comparison in electronic spectra of AnC_8V between D_2O (solid line) and H_2O (dotted line) solution. Effects of the charge-transfer interaction was revealed by the use of difference spectra as obtained by subtracting the spectra in the presence of 40 mM α-CD where the concentration of CT-complexes was negligible.

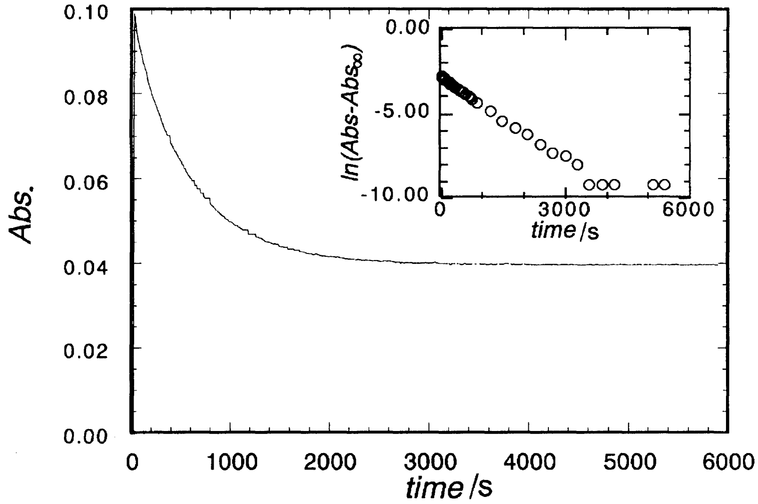


Fig. 5. Variation of charge-transfer absorption band intensity with elapsed time after the addition of α-CD. The absorption was measured at 480 nm with an aqueous solution (H_2O) of AnC_8V (0.468 mM) and α-CD (3.944 mM) at 293 K.

$$\therefore [\mathrm{AnC_8V}] = \frac{k'_1}{k'_1 + k_{-1}}[\mathrm{AnC_8V}]_{\mathrm{total}} \exp\{-(k'_1 + k_{-1})t\} + \frac{k_{-1}}{k'_1 + k_{-1}}[\mathrm{AnC_8V}]_{\mathrm{total}} \quad (9)$$

Thus Eq. 9 is simplified to give the following equation.

$$(Abs)^t_{\mathrm{CT}} = a \exp(-ct) + b \quad (10)$$

The time-profile of absorbance due to charge-transfer interaction $(Abs)^t_{\mathrm{CT}}$ in uncomplexed AnC_8V is expected to follow Eq. 10. A curve-fitting analysis was carried out to explain the observed time-dependence of the charge-transfer absorption band in Fig. 5. The constant b was taken as the asymptotic value of the absorbance, and the two other parameters (a and c) were estimated from the analysis. The relevant rate constants were given as the following:

$$\frac{a}{b} = \frac{k'}{k_{-1}} \quad (11)$$

$$c = \left(1 + \frac{a}{b}\right) k_{-1} \quad (12)$$

then

$$k_{-1} = \frac{c}{(1 + \frac{a}{b})} \quad (13)$$

$$k'_1 = \frac{a}{b}\frac{c}{(1 + \frac{a}{b})} \quad (14)$$

or

$$k_1 = \frac{k'_1}{[\alpha\text{-CD}]} \quad (15)$$

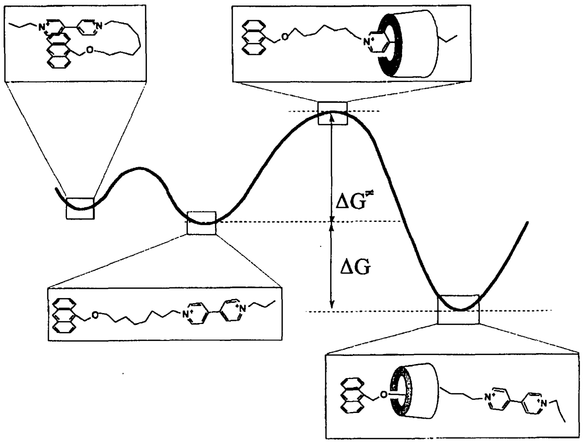
The energy of activation for the complexation was calculated from the rate constant by the use of Eyring's formula, and the results are summarized in Table 4. It is clearly observed that activation process is not affected at all by the change from D_2O to H_2O solution.

Overall Picture of Complexation between α-CD and Anthracene–Viologen Linked Compound. While solvent-deuterium effect was not

Table 4. The Rate Constant and Energy of Activation for Complexation with α-CD

Temp/K	H_2O			D_2O		
	$k_1/M^{-1}\,s^{-1}$	$k_{-1}/10^{-4}\,s^{-1}$	$\Delta G^{\ddagger}/kJ\,mol^{-1}$ [a]	$k_1/M^{-1}\,s^{-1}$	$k_{-1}/10^{-4}\,s^{-1}$	$\Delta G^{\ddagger}/kJ\,mol^{-1}$ [a]
283	0.129	0.80	74.0	0.115	1.57	74.3
293	0.350	2.70	74.3	0.280	2.82	74.9
303	0.734	8.89	75.1	0.854	8.77	74.7

a) 303 K.



Scheme 1.

observed with the energy of activation for the complexation with α-CD (Table 4), the free-energy change in charge-transfer interaction of the anthracene–viologen linked compound was reduced by 1.0 kJ mol^{-1} on changing the solvent from H_2O to D_2O (Table 3).

The open, extended conformer of the linked compound must be the precursor for the activated state of forming the through-ring complex as schematically shown in Scheme 1.

Charge-transfer spectra of the anthracene–viologen linked compound served as an excellent probe to study kinetics of complexation between α-CD and the amphiphilic viologen units in aqueous solution (H_2O and D_2O). Formation of the through-ring complexes was strongly suggested to proceed via open, extended conformer of the linked compound. As to the uncomplexed, linked compound, rapid equilibrium between a folded structure and open, extended conformer was indicated by the thermodynamic parameters in H_2O and D_2O solutions.

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References

1) Contribution No. 978 from the Department of Chemical Sience and Technology, Kyusyu University.

2) a) A. Harada, J. Li, and M. Kamachi, *Nature*, **356**, 325 (1992); b) H. Ogino, *J. Am. Chem. Soc.*, **103**, 1303 (1981); c) J. F. Stoddart, *Angew. Chem., Int. Ed. Engl.*, **31**, 846 (1992); d) R. S. Wylie and D. H. Macartney, *J. Am. Chem. Soc.*, **114**, 3136 (1992); e) G. Wenz, E. V. D. Bey, and L. Schmidt, *Angew. Chem., Int. Ed. Engl.*, **31**, 783 (1992); f) R. Isnin and A. E. Kaifer, *J. Am. Chem. Soc.*, **113**, 8188 (1991); g) T. V. S. Rao and D. S. Lawrence, *J. Am. Chem. Soc.*, **112**, 3614 (1990); h) M. Born and H. Ritter, *Makromol. Chem., Rapid Commun.*, **12**, 471 (1991).

3) a) H. Yonemura, H. Saito, S. Matsushima, H. Nakamura, and T. Matsuo, *Tetrahedron Lett.*, **30**, 3143 (1989); b) H. Yonemura, H. Nakamura, and T. Matsuo, *Chem. Phys. Lett.*, **155**, 157 (1989); c) H. Yonemura, H. Nakamura, and T. Matsuo, *Chem. Phys.*, **162**, 69 (1992).

4) H. Yonemura, M. Kasahara, H. Saito, H. Nakamura, and T. Matsuo, *J. Phys. Chem.*, **96**, 5765 (1992).