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Photoresponsive Crown Ethers. 1. Cis–Trans Isomerism of Azobenzene as a Tool to Enforce Conformational Changes of Crown Ethers and Polymers[1]

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Abstract: An azobenzene-bridged crown ether (**2**) and a polymer containing both crown ether unit and azobenzene unit (**4**) were synthesized. **2** bridged with *trans*-azobenzene (*trans*-**2**) bound an ammonium cation (**5**) and methyl orange salts of Li$^+$ and Na$^+$ preferably, whereas **2** bridged with photo- (UV) isomerized *cis*-azobenzene (*cis*-**2**) bound methyl orange salts of K$^+$ and Rb$^+$ preferably. The result was rationalized in terms of photoinduced expansion of the crown ether size. The binding ability of polymer **4** was also subject to photoirradiation. In particular, the crown ether units adjoining the *cis*-azobenzene unit lost the affinity toward Na$^+$ ion. The conformational changes of the crown ether and the polymer were conveniently monitored by following the spontaneous regeneration of *trans*-azobenzene in the dark. It was established on the basis of the rate measurements that (i) the conformational fluctuation of the crown ether is suppressed by K$^+$ and ammonium cations, (ii) the extension of the polymer chain in solution accompanies a large entropy increase, and (iii) $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ for the rates of regeneration of *trans*-azobenzene are subject to an isokinetic relationship with $\beta = 328$ K. These results indicate that photoinduced cis–trans isomerism of azobenzene, which has been found in former days, is useful as a new tool to enforce the conformational changes of crown ethers and polymers. The findings provide a possibility of controlling chemical functions of crown ethers and polymers by light.

Chemical substances which exhibit photoinduced structure changes are the candidates not only of chemical condensers for the storage of light energy but also of mediators for the conversion of light energy to chemical functions. Azobenzene derivatives exhibit photoinduced reversible cis–trans isomerism and the structural change is considerably large.[2,3] The possibility thus arises that conformations of azobenzene-containing compounds are changed (or controlled) by photoinduced configurational changes of azobenzene so that they may provide desired chemical functions. Expectedly, this would lead to the possibility of controlling the chemical functions by "on–off switch". Several investigations along this line have been reported. Balasubramanian et al.[4] found that azobenzene incorporated into the lamellar multibilayer produced in a water–hexadecane microemulsion causes a change in the electric resistance due to the isomerization. Kunitake et al.[5] applied the phenomenon to change the structure of a synthetic bilayer membrane. The azobenzene group attached to polypeptides is effective for changing the conformation.[6,7] Ueno et al.[8] found that the binding ability of β-cyclodextrin capped with azobenzene is subject to photoirradiation. We have been aiming at utilizing the phenomenon in controlling the chemical functions of crown ethers and polymer catalysts. In 1979, we communicated our first preliminary results on photocontrol of the binding ability of crown ether.[1] In 1980, Yamashita et al.[9] utilized the dimerization of anthracene to design a photoresponsive crown ether.

In this paper, we wish to discuss the availability of photoinduced cis–trans isomerism of azobenzene as a tool (i) to change the ion extractability of a crown ether family, (ii) to enforce a change in the conformation of macromolecules in solution, and (iii) to monitor the rate of the conformational changes of crown ethers and polymers. It has been well established that the binding properties of crown ethers are significantly related to the effective size.[10] Rebek et al.[10d] reported that the conformation of crown ethers can be changed by binding of transition metals to 2,2′-bipyridyl functions incorporated into part of the crown ether ring. We considered that, if the conformation can be changed by photoinduced cis–trans isomerism of azobenzene functions incorporated (or attached) to the macrocyclic ring, it would lead to the control of the complexation ability by light. The behavior of functional polymers is also related to the polymer conformation.[11] The functions of macromolecules containing crown ethers, which have been reported by several groups,[12-15] are with no apparent exception affected by the polymer conformation in solution. It is thus expected that copolymers containing both crown ether unit and azobenzene unit would act as photoresponsive

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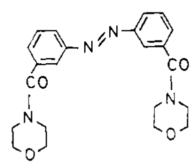
functional polymers. Another interesting application of the cis–trans isomerism is to use the regeneration of *trans*-azobenzene as a chromophore to see the conformational changes of crown ethers and polymers. Since *trans*-azobenzene has a strong absorption band at around 330 nm, the conformational change which occurs with the regeneration process can be easily followed spectrophotometrically. This would enable us to estimate the influence of complexed cations on the rate of the conformational change of crown ethers and to determine the thermodynamic parameters governing the change in the polymer conformation.

With these objects in view, we synthesized azobenzene derivatives **1–4** and examined their availability as a tool to enforce the conformational changes.



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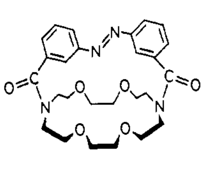

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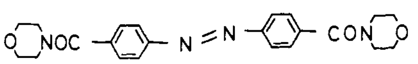

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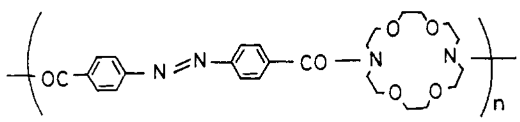

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Experimental Section

Materials. 3,3′-Bis(morpholinocarbonyl)azobenzene (**1**) and 4,4′-bis(morpholinocarbonyl)azobenzene (**3**) were prepared by treatment of 3,3′- and 4,4′-bis(chlorocarbonyl)azobenzene with excess morpholine in benzene. Recrystallization from methanol gave yellow needles. **1**: yield 71%; mp 181–182 °C; IR (KBr disk) $\nu_{C=O}$ 1610, $\nu_{N=N}$ 1590 cm^{-1}; NMR (CDCl$_3$) CH$_2$ 3.70 (16 H), aromatic 7.50 and 7.90 ppm (8 H). Anal. ($C_{22}H_{24}N_4O_4$) C, H, N. **3**: yield 59%; mp 195–196 °C. Anal. ($C_{22}H_{24}N_4O_4$) C, H, N.

2 was prepared from 1,10-diaza-4,7,13,16-tetraoxa-18-crown-6 and 3,3′-bis(chlorocarbonyl)azobenzene according to the high-dilution method. 3,3′-Bis(chlorocarbonyl)azobenzene was chosen because the CPK model building suggested that the distance between 1-N and 10-N of the aza crown ether is almost equal to that between two carbonyl groups. In a 1-L three-necked flask with a reflux condenser were placed 200 mL of benzene and 2 mL of triethylamine, and 0.525 g (2.0 mmol) of 1,10-diaza-4,7,13,16-tetraoxa-18-crown-6 in 50 mL of benzene from one buret and 0.614 g (2.0 mmol) of 3,3′-bis(chlorocarbonyl)azobenzene in 50 mL of benzene from another buret were added simultaneously. The speed of the addition was adjusted by reading the graduations so that equal amounts of the benzene solutions could be introduced. The reaction mixture was stirred vigorously at room temperature for 30 min. The solution was washed with water to remove triethylamine hydrochloride, and the benzene layer was evaporated to dryness in vacuo. The residue was recrystallized from benzene: mp 215–216 °C; yield 23%; IR (KBr disk) $\nu_{C=O}$ 1618, $\nu_{N=N}$ 1578 cm^{-1}; NMR (CDCl$_3$) NCH$_2$ 3.6–3.9 (8 H), OCH$_2$ 4.1–4.8 (16 H), aromatic 8.1–8.6 ppm (8 H); mass spectra M$^+$ *m/e* 497. Anal. ($C_{26}H_{32}N_4O_6$) C, H, N. The polycondensation products were not recovered by this method. Based on the solubility of **4** (vide post), we consider that the polymeric products, if they were formed, would be solubilized in the filtrate.

Polymer **4** was prepared from 1,10-diaza-4,7,13,16-tetraoxa-18-crown-6 and 4,4′-bis(chlorocarbonyl)azobenzene according to the procedure described for the preparation of **2**. *o*-Dichlorobenzene was used as solvent. The *o*-dichlorobenzene solution was washed with water to remove triethylamine hydrochloride and then poured into *n*-hexane. The polymer was purified by reprecipitation from methylene chloride to *n*-hexane. The recovered polymer (orange powder) was dried in vacuo and subjected to elemental analysis and IR measurement. IR (KBr disk): $\nu_{C=O}$ 1610 cm^{-1}. Anal. ($C_{26}H_{32}N_4O_6$) C, H, N. The size of the polymer was evaluated by viscosity measurement. The polymer was soluble in *o*-dichlorobenzene and nitrobenzene, slightly soluble in benzene, tetrahydrofuran, and methanol, and almost insoluble in *n*-hexane.

4-*p*-Nitrophenylazo-1-*N*-(β-aminoethyl)naphthylamine hydrochloride (**5**) was prepared by diazo coupling of *p*-nitroaniline and *N*-(1-naphthyl)ethylenediamine, mp 193–198 °C dec. Anal. ($C_{18}H_{17}N_5O \cdot HCl$) C, H, N.

Viscosity Measurements. Viscosities of polymer **4** were measured at 30 °C in *o*-dichlorobenzene, using a modified Ubbelohde viscometer. Since the regeneration of trans polymer in the dark was slow enough (see Results section), the change in the cis/trans ratio in the workup time (about 1 h) could be neglected.

General Procedure of Ion Extraction. The combination of alkali picrates and alkyl halogen solvents has been frequently employed for the solvent extraction with the crown ether family. However, the system was improper under the photo- (UV) irradiation, since (i) alkyl halogen solvents caused photostimulated side reactions of azobenzene and (ii) the absorption maximum of picrate (355 nm) overlapped with that of azobenzene. Methyl orange (λ_{max} 466 nm, ϵ_{max} 45 100) was thus chosen as counteranion, and benzene (for **2**) or *o*-dichlorobenzene (for **4**) was used as the organic phase. The detailed conditions are recorded below each table.

An organic solution containing azobenzene derivatives was irradiated at room temperature with a 500-W high-pressure Hg lamp. The distance from the lamp to the sample was 12.5 cm. The absorption band of the *trans*-azobenzenes (see Table VI) decreased rapidly with photoirradiation time and reached equilibrium intensities: it took 3 min for **1**, 1 min for **2**, and 10 min for **3** and **4**. The cis percentages which were calculated from the decrease in the absorbance at around 330 nm assuming that the absorbance of cis isomers is negligible in comparison to that of trans isomers are summarized in Table VI.

Equal volumes of an organic solution containing **2** or **4** and an aqueous solution containing alkali methyl orange were agitated thoroughly on a Vortex mixer for 5 min. A similar extraction was performed with pure organic solvents. The extractability was determined by reading the difference between two absorbances of methyl orange in the aqueous solutions. All the extractions were conducted at 30 ± 0.5 °C. Photoirradiation of the organic solution was performed before solvent extraction.

The determination of the extractability for phthalic acid derivatives was more complicated. A trace amount of *o*-dichlorobenzene was transferred to the aqueous phase on extraction, and the absorption band overlapped with those of phthalic acid derivatives. We thus derived the equation $OD_{obs} = \epsilon_{phthalic\ acid}[\text{phthalic acid}] + \epsilon_{o\text{-dichlorobenzene}}[o\text{-dichlorobenzene}]$ at two wavelengths, and each concentration was calculated simultaneously. One wavelength was λ_{max} of *o*-dichlorobenzene (268 nm, ϵ 241) and the other was each λ_{max} of phthalic acid derivatives (279 nm, ϵ 2250, for potassium *o*-phthalate; 266 nm, ϵ 756, for potassium isophthalate; 239 nm, ϵ 13 600, for potassium terephthalate).

Kinetic Measurements. The rates of the regeneration of trans isomer from cis isomer in the dark were determined by monitoring the increase in the absorption band of trans isomer at around 330 nm. The OD plotted against reaction time satisfied the first-order equation. The first-order rate constants (k_1) thus determined are summarized in Table V.

Results and Discussion

Photoenforced Conformational Changes. Conformational behavior of polymers in solution is conveniently assessed by viscosity measurements, since the extension of polymer chains is reflected by the viscosity. Viscosity measurements of **4** in *o*-dichlorobenzene at 30 °C provided good linear plots of η_{sp}/C vs. C (C = 0.348–0.695 g/dL). The intrinsic viscosities ([η]) determined by extrapolating the plots to $C = 0$ were 0.057 dL/g for all-trans polymer and 0.047 dL/g for photoirradiated polymer. The result suggests that the *cis*-azobenzene unit produced by photoirradiation changes the polymer conformation to a more compact one. According to Irie et al.,[16] the large viscosity change is observed for a stiff azobenzene-containing polymer. Since the aza crown ether unit in polymer **4** is relatively flexible, the observed viscosity change was not as large as that observed by Irie et al.[16] (40% decrease).

The conformational change of the crown ether moiety of **2** which expectedly occurs with cis–trans isomerism of azobenzene was inferred on the basis of the CPK model building (Figure 1). The CPK model shows that the azobenzene moiety of *trans*-**2** stands vertically over the crown ether plane, whereas that of *cis*-**2**

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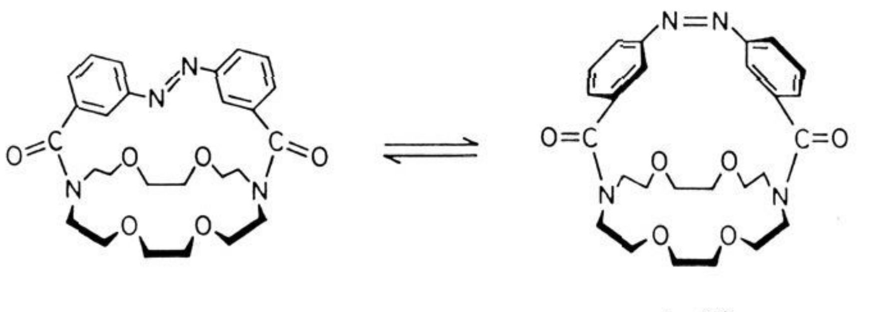
[16] Irie, M.; Hashimoto, S.; Hayashi, K. *Polym. Prepr.* **1978**, *6*, 1004.



trans-(2) cis-(2)

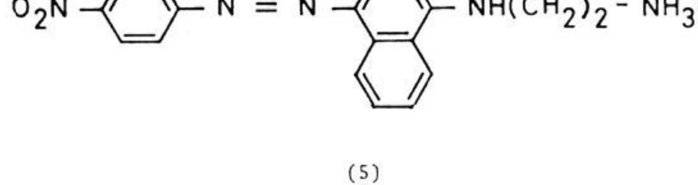
is almost parallel to the crown ether plane. Two nitrogens in the aza crown ether employ either an sp^2 (Figure 1a) or an sp^3 orbital (Figure 1b). Based on the following reasons, we considered that *trans*-**2** employs sp^3 nitrogens in preference to sp^2 nitrogens: (i) the aza crown ether in the model with sp^3 nitrogens is almost planar, whereas that in the model with sp^2 nitrogens is bent to the boat-like form; (ii) both structures require an amide linkage which is twisted by ca. 90° to *N*-alkyl groups, and the structure which has an amide linkage enjoying coplanarity with both *N*-alkyl groups and the aromatic group in the same plane is almost inconceivable for *trans*-**2**. The term (ii) implies that there is no energetic merit to employ an sp^2 orbital. Since the $\nu_{C=O}$ of **2** in the IR (1618 cm^{-1}) is very close to that of **1** (1610 cm^{-1}), the amide linkage of **1** may also employ sp^3 nitrogens. The CPK model of **1** supports this presumption.

The steric difference between *trans*-**2** and *cis*-**2** is reflected by the size of the crown ether; that is, the CPK model predicts the size of *cis*-**2** to be greater than that of *trans*-**2**. Interestingly, this trend is in line with the conclusion observed for azobenzene-capped β-cyclodextrin.[8] Ueno et al.[8] reported on the basis of the binding ability of the cyclodextrin that the inner space of β-cyclodextrin capped with *cis*-azobenzene is more expanded than that capped with *trans*-azobenzene. Also suggested from the CPK model building is that in *trans*-**2** the ortho hydrogen of the azo linkage penetrates partially into the plane of the crown ether. This is seen in Figure 1b. This would interfere with deep complexation of alkali metal cations. On the other hand, there is no steric hindrance around the crown ether ring of *cis*-**2** (see Figure 1c).

The azobenzene-bridged crown ether **2** and the azobenzene-containing polymer **4** were used for solvent extraction of alkali metal and ammonium cations to test whether the photoinduced conformational changes are reflected by the complexation abilities.

Photocontrolled Solvent Extraction of Alkali Metal and Ammonium Cations. The results of the solvent extraction with **2** are summaried in Table I. Examination of Table I reveals that (i) the extractability of *trans*-**2** is in the order $K^+ > Na^+ > Li^+ > Rb^+, Cs^+$, whereas that of *cis*-**2** is in the order $K^+ > Na^+ > Rb^+ > Li^+, Cs^+$; (ii) large alkali metal ions such as Rb^+ and Cs^+ are hardly extracted by *trans*-**2**, (iii) *trans*-**2** extracts Li^+ which cannot be extracted by *cis*-**2**, whereas *trans*-**2** cannot extract Rb^+, which is extracted to a smaller extent by *cis*-**2**; (iv) for Na^+ *trans*-**2** possesses an extractability slightly greater than that of *cis*-**2**, but the reverse trend becomes true for K^+. These results are consistent with the proposal that the crown ether size of *cis*-**2** is greater than that of *trans*-**2**. The conclusion is compatible with that expected on the basis of the CPK model building. It is still difficult to describe quantitatively how much the size of the crown ether ring is enlarged. We presume that the magnitude may be approximately equal to the difference in the ion radius between Na^+ and K^+ (ca. 0.3 Å), for the selectivity of *cis*-**2**/*trans*-**2** reverses itself between Na^+ and K^+.

trans-**2** and *cis*-**2** showed different affinity toward the ammonium group. When **5** (λ_{max} 518 nm, ϵ 28 300) in an aqueous solution was extracted with a benzene solution containing 1.68 × 10^{-5} M *trans*-**2**, 8 (±1)% of **5** was transferred to the benzene solution. Under the same extraction conditions, only 1.5 (±0.5)% of **5** was extracted by the photoirradiated benzene solution of **2**. This indicates that the ammonium group best fits the crown ether size of *trans*-**2**.



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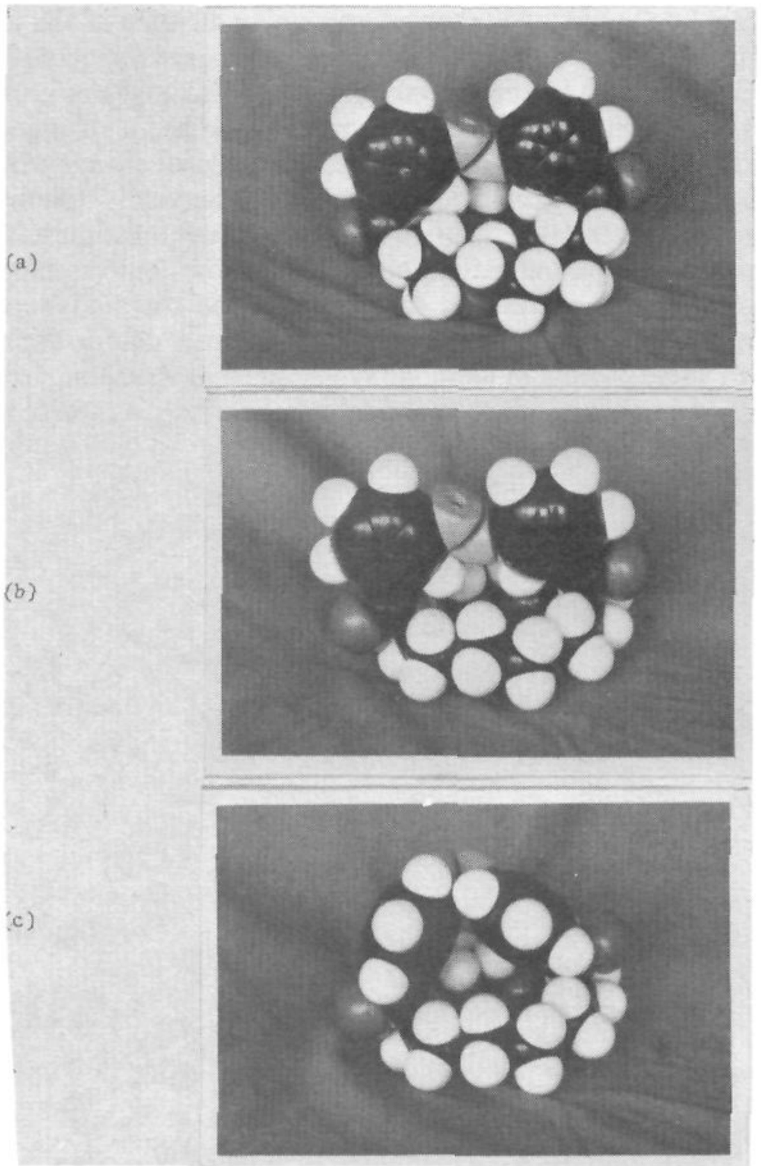

Figure 1. CPK models of azobenzene-bridged crown ether **2**: (a) *trans*-**2** with sp^2 amide nitrogens; (b) *trans*-**2** with sp^3 amide nitrogens; (c) *cis*-**2** with sp^3 amide nitrogens.

Table I. Extraction of Alkali Metal Salts of Methyl Orange with Azobenzene-Bridged Crown Ether (**2**)[a]

	extractability, %				
2	Li^+	Na^+	K^+	Rb^+	Cs^+
trans-**2**	1.1	14.8	15.8	(<0.1)	(<0.1)
photoirradiated **2**	(<0.1)	13.5	27.2	1.1	(<0.1)
cis-**2**[b]	0	12.6	34.8	1.8	0

[a] 30 °C. Aqueous phase: [methyl orange salt] = 6.66 × 10^{-5} M. Benzene phase: [**2**] = 1.32 × 10^{-4} M. [b] Calculated by the equation $Ex_{cis\text{-}2} = (Ex_{photoirradiated\ 2} - 0.40Ex_{trans\text{-}2})/0.60$.

Polymeric crown ethers have been prepared by Feigenbaum and Michel,[13] Blasius et al.,[14] Lehn et al.,[15] and Smid et al.[12] The polymers which contain the 18-crown-6 (or its equivalent) unit in the main chain show a general affinity in the order $K^+ > Na^+, Rb^+, Cs^+ > Li^+$.[13-15] Poly(vinylbenzo-18-crown-6), which has the benzo-18-crown-6 unit in the side chain, shows a higher affinity for alkali metal cations with large ion radii (i.e., $Cs^+ > K^+ > Na^+$).[12] On the other hand, the affinity of 4′-methylbenzo-18-crown-6 itself is in the order $K^+ > Na^+ > Cs^+$. These results indicate that the polymers which contain the crown ether unit in the main chain exhibit an affinity analogous to that of the monomeric analogues, while the polymers which contain the crown ether unit in the side chain favor large alkali metal cations owing to the formation of sandwich-type 2:1 crown/cation complexes.[17]

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[17] (a) Bourgoin, M.; Wong, K. H.; Hui, J. Y.; Smid, J. *J. Am. Chem. Soc.* **1975**, *97*, 3462. (b) Mallison, P. R.; Truter, M. R. *J. Chem. Soc., Perkin Trans. 2* **1972**, 1818.

Table **II**. Extraction of Alkali Metal Salts of Methyl Orange with Photoresponsive Crown Ether Polymer (4)[a]

	extractability, %				
4	Li^+	Na^+	K^+	Rb^+	Cs^+
trans-4	0	24.6	19.8	0	9.1
photoirradiated 4	0	17.8	23.5	0	1.3
cis-4[b]	0	0[c]	34.8	0	0[d]

[a] 30 °C. Aqueous phase: [methyl orange salt] = 8.10×10^{-5} M, [MCl] = 0.10 M. *o*-Dichlorobenzene phase: [crown ether unit] = 2.82×10^{-3} M. [b] Hypothetical extraction ability of cis polymer (4) calculated by $(Ex_{obsd} - 0.754Ex_{trans\text{-}4})/0.246$. [c] The calculation by the above equation gave −3.0. [d] The calculation by the above equation gave −22.6.

Table III. Extraction of Dipotassium Salts of Dicarboxylates with Photoresponsive Crown Ether Polymer (4)[a]

	extractability, %		
4	phthalic acid	iso-phthalic acid	tere-phthalic acid
trans-4	48.6	0	1.2
photoirradiated 4	41.4	0	0
cis-4	19.3	0	0

[a] 30 °C. Aqueous phase: [dicarboxylic acid] = 5.00×10^{-4} M, [KOH] = 1.10×10^{-3} M, [KCl] = 0.10 M. *o*-Dichlorobenzene phase: [crown ether unit] = 2.82×10^{-3} M.

Table II shows the results of solvent extraction with polymer **4**. The extractability of *trans*-**4** is $Na^+ > K^+ > Cs^+ > Li^+, Rb^+$. The order is similar to that of the cyclic analogue **2** (Table I), indicating that *trans*-**4** also belongs to a class of the polymers with crown ether in the main chain. As expected, extraction with **4** is also subject to photoirradiation. We expected that two crown ether units adjoining an azobenzene unit with cis configuration may form complexes preferably with large alkali metal cations. Although the extractability of K^+ becomes somewhat greater under photoirradiation, Table II shows that the expectation is not the case. One of the most interesting findings in Table II is that the extractability of Na^+, which is the greatest among alkali metal cations tested herein, is markedly reduced under photoirradiation. Photoirradiation produced 24.6% of cis unit, and as a result the extractability decreased from 24.6 to 17.8% (relative decrease in extractability 27.6%). This implies that the crown ether units adjoining the *cis*-azobenzene unit cannot extract Na^+ at all. The marked influence of photoirradiation may be applied to the selective ion extraction of Na^+ if the percentage of *cis*-azobenzene unit can be further increased. According to Smid et al.,[12b] the binding constant of poly(vinylbenzo-18-crown-6) with alkali metal cations decreases as the number of cations attached to the polymer increases. This is attributed to electrostatic repulsion between bound cations. Expectedly, two crown ether units adjoining a *cis*-azobenzene unit, which presumably employ a face-to-face orientation, suffer a disadvantage in forming a 1:1 crown/cation complex. We cannot rationalize, however, why the marked decrease in extractability was not observed for K^+.

Polymer **4** was applied to the extraction of dipotassium salts of phthalic acid derivatives (Table III). This work was stimulated by a finding by Sutherland et al.[18] that polymeric crown ethers act as good receptors for dications. Table III shows that only potassium phthalate is extracted by polymer **4**. The finding suggests that ortho isomer can be easily separated from meta and para isomers by solvent extraction with **4**. The extractability was hardly affected by photoirradiation.

As a summary of the results described in this section, one can conclude that the complexation ability of crown ethers can be controlled by light in principle. To our knowledge, this is the first example of photocontrolled solvent extraction with the crown ether family. We expect that the finding can be readily applicable to the control of ion transport through membranes by light.

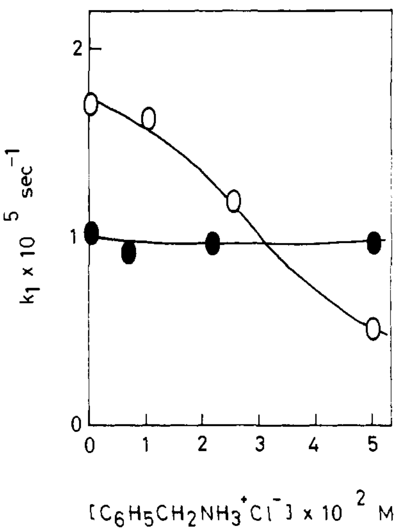

Figure 2. Influence of added benzylammonium chloride on the regeneration rates [(●) **1**, (○) **2**], 53 ± 0.1 °C, solvent 1-butanol–benzene (4.0:0.1) v/v).

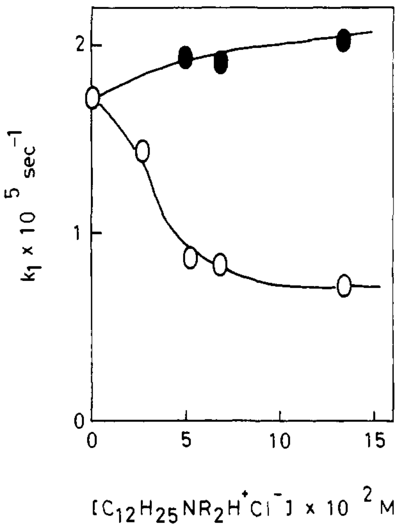

Figure 3. Influence of added dodecylammonium chloride (○, R = H) and *N,N*-dimethyldodecylammonium chloride (●, R = Me) on the regeneration rates of **2**, 53 ± 0.1 °C, solvent 1-butanol–benzene (2:1 v/v).

Influence of Complexed Cations on the Rate of the Conformational Change of the Crown Ether. The binding properties of crown ethers are sensitive to changes in conformations or effective size, and added cations frequently induce conformational changes so that they can fit the size of crown ethers.[10,19] A question arises whether the free energy of activation required for conformational change is affected by complexed cations. The problem is of considerable importance, but there has been no strategy to answer the query. An azobenzene-bridged crown ether (**2**) becomes a useful tool for this purpose. Since the size (or the conformation) of the crown ether is changed by a photoenforced configurational change of the azobenzene moiety, the regeneration of *trans*-**2** from *cis*-**2** in the dark should occur in concert with the conformational change of the crown ether moiety. One can easily estimate, therefore, the influence of complexed cations on the rate of the conformational change by monitoring the increase in the absorption band of *trans*-**2** spectrophotometrically. Based on the solvent extraction study, we can presume that the size of the crown

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(18) (a) Johnson, M. R.; Sutherland, I. O.; Newton, R. F. *J. Chem. Soc., Chem. Commun.* **1979**, 306, 309. (b) Mageswaran, R.; Mageswaran, S.; Sutherland, I. O. *Ibid.* **1979**, 722.

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Table IV. Cation-Induced Rate Suppression of the Regeneration of *trans*-**2**[a]

additive	M	$k_1 \times 10^5$, s^{-1}	$\Delta\Delta G^{\ddagger}$,[c] kcal/mol
none		1.71	0
$C_6H_5CH_2NH_3^+$	0.050	0.514[b]	0.78
$C_{12}H_{25}NH_3^+$	0.067	0.854	0.45
$C_{11}H_{23}CO_2Li$	0.0067	1.93	−0.08
$C_{11}H_{23}CO_2Na$	0.0067	1.77	−0.02
$C_{11}H_{23}CO_2K$	0.053	1.20	0.23
$C_{11}H_{23}CO_2Cs$	0.053	1.44	0.11

[a] [**2**] = 2.50×10^{-5} M, 1-butanol:benzene = 2:1 v/v, 53 ± 0.1 °C. [b] 1-Butanol:benzene = 4:0.1 v/v. [c] The difference in free energy of activation as compared with the nonadditive system (i.e., $k_1 = 1.71 \times 10^{-5}$ s^{-1}).

Table V. First-Order Rate Constants (k_1) for the Regeneration of Trans Isomers in the Dark[a]

	$k_1 \times 10^5$, s^{-1}				
temp, °C	**1** in benzene	**1** in *o*-DCB	**2** in benzene	**3** in *o*-DCB	**4** in *o*-DCB
30					0.306
40	0.628	12.0	1.56	4.58	1.81
50	1.73	20.3	4.16	9.22	9.56
55	3.36		5.84		
60	5.36	39.8	9.64	15.8	

[a] *o*-DCB denotes *o*-dichlorobenzene.

Table VI. Absorption Maxima of Trans Isomers, Cis/Trans at Equilibrium, and Thermodynamic Parameters for the Regeneration of Trans Isomers in the Dark[a]

	1 in benzene	**1** in *o*-DCB	**2** in benzene	**3** in *o*-DCB	**4** in *o*-DCB
λ_{max}, nm	318	322	324	331	331
cis/trans	51/49	33/67	60/40	26/74	25/75
$\Delta H^{\ddagger}$, kcal/mol	23.0	11.8	18.2	12.3	32.9
$\Delta S^{\ddagger}$, eu	−9.3	−39.0	−22.6	−39.3	24.7

[a] *o*-DCB denotes *o*-dichlorobenzene.

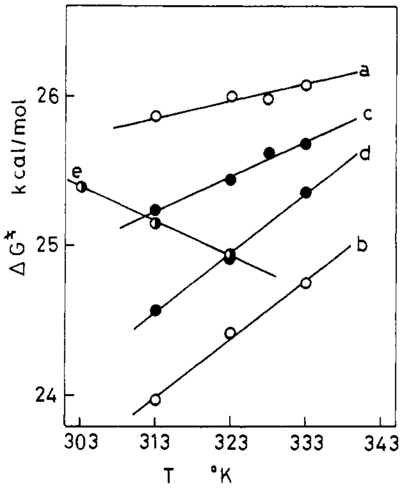

Figure 4. $\Delta G^{\ddagger}$ vs. T: (a) **1** in benzene; (b) **1** in *o*-dichlorobenzene; (c) **2** in benzene; (d) **3** in *o*-dichlorobenzene; (e) **4** in *o*-dichlorobenzene.

ether contracts in the regeneration process.

In Figure 2, first-order rate constants (k_1) for the transformation of cis isomers of **1** and **2** to the corresponding trans isomers are plotted against the concentration of benzylammonium chloride. It is seen from Figure 2 that the k_1 value for **2** decreases with increasing benzylammonium concentration, whereas that for **1** is almost unaffected by added benzylammonium ion ($k_1 = (9.5 \pm 0.6) \times 10^{-6}$ s^{-1}). Figure 3 shows the influence of primary and tertiary ammonium ions on the rate of the regeneration. Dodecylammonium chloride causes similar rate suppression, whereas the rate is unaffected or slightly accelerated by *N*,*N*-dimethyldodecylammonium chloride (nonbinding ammonium ion). Alkali-metal cations also affect the rates (Table IV). The effect of Li^+ and Na^+ should have been examined at the higher concentrations, but these salts were sparingly soluble in 1-butanol. The results in Table IV are summarized as follows: (i) among alkali metal cations K^+, which best fits the size of **2** (vide infra), exerts the most efficient inhibition; (ii) Li^+ and Na^+ slightly accelerate the rate; (iii) ammonium ions suppress the rate more efficiently than alkali metal cations.

Based on the foregoing results, we can safely conclude that cations that fit the size of the crown ether are able to suppress the rate of conformational change. On the other hand, a slight rate acceleration was observed for Li^+ salt and *N*,*N*-dimethyldodecylammonium chloride. This is attributed to a salt effect. As described below, the rate of regeneration is speeded up in polar solvents. The trend is in line with the fact that, when a nonbinding salt is added to the reaction medium, the rate is accelerated owing to the enhanced polarity of the medium (i.e., salt effect).

The rate suppression can be accommodated by two potential factors, that is, (i) the interaction between crown ether and complexed cation restricts the conformational fluctuation, and (ii) complexed cations strengthen the electron-withdrawing nature of the 3-amide group. The factor (ii) is based on the fact that electron-withdrawing substituents generally suppress the rate of the regeneration of trans isomer in the dark.[20] As seen in Figures 1b and 1c, the carbonyl groups exist at the outside of the crown ether ring, suggesting that the carbonyl oxygens cannot coordinate the complexed cation. We thus consider that the factor (ii) would be a minor effect.

Transformation of *cis*-**2** to *trans*-**2** accompanies the contraction of the crown ether cavity. This suggests that the rate might be suppressed more efficiently by the cation that fits the crown ether size of *cis*-**2**. The solvent extraction study is incompatible with this expectation, however. As shown in Table IV, both K^+ (extractability, *cis*-**2** > *trans*-**2**) and ammonium ion (extractability, *trans*-**2** > *cis*-**2**) increase the free energy of activation by 0.2–0.8 kcal/mol. This implies that the rate suppression should be accommodated in terms of destabilization of the transition state and not in terms of the difference between the initial state and the final state. Unfortunately, we cannot specify further what kind of conformational change occurs in the transition state. The most probable rationalization is that transformation from *cis*-**2** to *trans*-**2** proceeds via some metastable transient conformation and the conformational change disrupts (or weakens) the interaction between the crown ether and the complexed cation temporarily. This would require the additional free energy of activation.

It is now clear from the foregoing results that the conformational change of crown ethers is restricted, although not greatly, by complexed cations.

On the Thermodynamic Parameters Governing Cis–Trans Isomerism of Azobenzene. The mechanism of cis–trans isomerism of azobenzene has been investigated from three different viewpoints: photochemical interests,[21] effect of substituents and solvents,[3,20] and steric course (i.e., inversion mechanism vs. rotational mechanism).[22] We have been interested in the use of the configurational change as a chromophore monitoring the rate of the conformational changes of crown ethers and polymers rather than the detailed isomerization mechanism itself. The foregoing results prove that the configurational change of azobenzene accompanies the conformational changes of the crown ether and the polymer itself. The rate constants (and the thermodynamic parameters) are thus expected to reflect the energy barrier arising from cyclic and polymeric structure. We determined the rate

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[21] (a) Yamashita, S.; Ono, H.; Toyama, O. *Bull. Chem. Soc. Jpn.* **1962**, *35*, 1849. (b) Ronayette, J.; Arnaud, R.; Lebourgeois, P.; Lemaire, J. *Can. J. Chem.* **1974**, *52*, 1848.

[22] (a) Nerbonne, J.; Weiss, R. G. *J. Am. Chem. Soc.* **1978**, *100*, 5953. (b) Haberfield, P.; Block, P. M.; Lux, M. S. *Ibid.* **1975**, *97*, 5804.

constants for the regeneration of *trans*-**2** and *trans*-**4** and compared them with those of noncyclic and monomeric analogues, **1** and **3**.

The rate constants (k_1) for the regeneration of trans isomers in the dark were determined by monitoring spectrophotometrically the increase in the absorption maximum of trans isomers. The rates were first order with respect to cis isomers. The results are summarized in Table V. $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were determined from linear plots of $\Delta G^{\ddagger}$ against T (Figure 4). The linearity was generally excellent ($r > 0.998$). The activation parameters thus obtained are summarized in Table VI.

Previously, Zalukaev et al.[20] have reported that the rate of regeneration of *trans*-azobenzene is enhanced by electron-donating substituents and by polar reaction media. The results in Table V are in line with their observation; for example, the rate constant for **1** in *o*-dichlorobenzene is greater by a factor of 20 than those in benzene. Activation parameters in Table VI demonstrate that the rate acceleration observed in *o*-dichlorobenzene is due to the reduced $\Delta H^{\ddagger}$ value. On the contrary, the $\Delta S^{\ddagger}$ term becomes rather unfavorable in *o*-dichlorobenzene. Probably polar solvents stabilize the charged transition state,[22] which is reflected by the $\Delta H^{\ddagger}$ term.

The influence arising from the cyclic structure can be estimated by comparing the activation parameters of **2** with those of **1**. Examination of Table VI reveals that the $\Delta S^{\ddagger}$ term of **2** is more negative by 13.3 eu than that of **1**. This indicates the transition state of bicyclic **2** to be more crowded than that of noncyclic **1**. On the other hand, the observed rate constants are not very different. This is due to the compensation by the $\Delta H^{\ddagger}$ term. The results are thus summarized as follows: the conformational fluctuation of **2** (and probably cyclic compounds in general) is accompanied by $\Delta S^{\ddagger}$ loss and $\Delta H^{\ddagger}$ gain.

Azobenzene-containing polymers have been synthesized by several groups.[16,23] For example, Chen and Morawetz[23a] measured the rate of the photochemical isomerization process (trans → cis) and the regeneration process (cis → trans) of the polymers containing azobenzene unit in the main chains. They found that there is no significant difference between the rates of the polymers and the monomeric analogues, so that they concluded that the "crankshaft-like motion" of the azobenzene unit is not reflected by the solution behavior of macromolecules. As shown in Table V, the rate constants of **4** are apparently in the same order as those of **3** (monomeric analogue). Table VI indicates, however, that the activation parameters of **4** are remarkably different from those of **3**. **3** (and also **1** and **2**) possesses the negative $\Delta S^{\ddagger}$ term, indicating that the transition state is more crowded than the initial state. On the contrary, polymer **4** features a positive $\Delta S^{\ddagger}$ term. The increase in the entropy term, when compared with that of **3**, amounts to 64.0 eu! Since the chemical nature of the azobenzene moiety of **4** must be similar to that of **3**, the remarkable entropy increase is solely ascribed to the effect of the polymer. The finding proves that the conformational change of the polymer which is caused by the crankshaft-like configurational change of azobenzene unit alleviates the steric crowding along the polymer chain. It has been believed without unambiguous evidence that the conformational fluctuation of polymers in solution is largely governed by an entropy term.[24] The activation parameters obtained from **3** and **4** clearly support this traditional proposal. These results suggest that the compact polymer conformation a priori is unstable entropically. The polymer in solution tends to extend itself, attaining the entropy gain. This means, in other words, that in the polymer adopting the compact conformation the entropy loss has to be offset by other chain-chain interactions (e.g., hydrogen bonding, hydrophobic interaction, etc.).

Examination of Table VI proves that the remarkable $\Delta S^{\ddagger}$ increase of **4** is accompanied by an increase in $\Delta H^{\ddagger}$ (20.6 kcal/mol). The reverse situation is seen between **1** and **2**: bicyclic compound **2** features a $\Delta S^{\ddagger}$ loss of 13.3 eu, which is accompanied by a decrease in $\Delta H^{\ddagger}$ (4.8 kcal/mol). These results consistently suggest that the activation parameters for **1**–**4** are subject to a compensation relationship.[25] We tentatively plotted $\Delta H^{\ddagger}$ against $\Delta S^{\ddagger}$ and found that they exhibit an excellent linear relationship ($r = 0.998$) (Figure 5). Hence, the isomerism occurs by a sole mechanism over the wide range of activation parameters, and a change in the reaction mechanism (e.g., from rotational to inversion),[22] depending on the structure of azobenzene derivatives, is most unlikely.

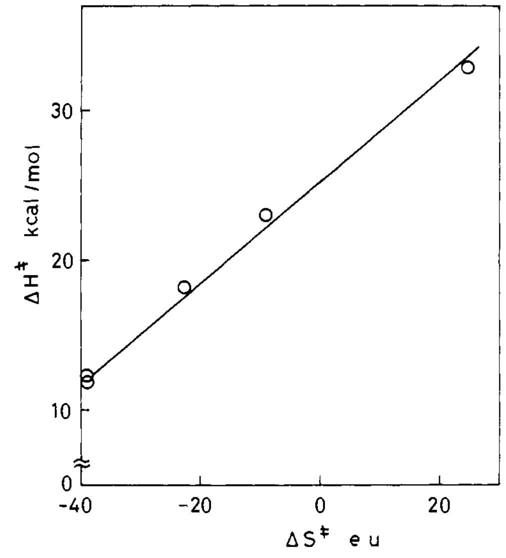

Figure 5. Isokinetic relationship.

The linear relation in Figure 5 can be expressed by eq 1 with isokinetic temperature β = 328 K.

$$\Delta H^{\ddagger}\ (\text{cal/mol}) = 328\Delta S^{\ddagger}\ (\text{eu}) + 25.3 \times 10^3 \qquad (1)$$

Equation 1 implies that all the $\Delta G^{\ddagger}$ values have to be identical at 328 K. In fact, $\Delta G^{\ddagger}_{328}$ is 25.3 ± 0.7 kcal/mol. On the basis of the isokinetic relationship, $\Delta G^{\ddagger}$ is given by

$$\Delta G^{\ddagger}\ (\text{cal/mol}) = (328 - T)\Delta S^{\ddagger}\ (\text{eu}) + 25.3 \times 10^3 \qquad (2)$$

One should note, therefore, that the $\Delta S^{\ddagger}$ increase at $T < 328$ K leads to an increase in the $\Delta G^{\ddagger}$ value, while the $\Delta S^{\ddagger}$ increase at $T > 328$ K leads to a decrease in the $\Delta G^{\ddagger}$ value.

The generality of the isokinetic relationship in other azobenzene derivatives is being addressed in current work in our laboratory.

Conclusion

The present study establishes, for the first time, that (i) the binding ability of crown ethers can be controlled by light, (ii) the rate of the conformational change of crown ethers is affected by complexed cations, (iii) the rate of the conformational changes of crown ethers and polymers can be followed spectrophotometrically, (iv) the extension of polymers in solution accompanies a large entropy gain, and (v) $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ for the regeneration of trans isomers are subject to a compensation relationship with isokinetic temperature β = 328 K.

These results are obtained on the basis of the isomerization phenomenon of azobenzene. The phenomenon belongs to an old concept, but it is useful as a new tool to enforce the conformational changes of crown ethers and polymers. We believe that the phenomenon can be applied more generally to control many other chemical functions by light.

Acknowledgments. The authors thank Professors T. Kunitake and M. Takagi for helpful discussions.

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