Photoresponsive Crown Ethers. Part 7.[1] Proton and Metal Ion Catalyses in the *cis—trans* Isomerisation of Azopyridines and an Azopyridine-bridged Cryptand

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A 2,2′-azopyridine-bridged crown ether (5) has been synthesised for the purpose of controlling the ion-binding functions by an on-off light switch mechanism. Since the *trans*-azopyridine moiety of compound (5) [*i.e. trans*-(5)] is vertically over the crown ether ring and the photoisomerised *cis*-azopyridine moiety of (5) [*i.e. cis*-(5)] is almost parallel to the crown ether plane, it would be expected that only the pyridine nitrogens of *trans*-(5) are capable of co-ordinating to metal ions bound into the crown ether ring. The thermal isomerisation of *cis*-2,2′-azopyridine [*cis*-(3)] to *trans*-2,2′-azopyridine [*trans*-(3)] was speeded up either by protonation of the pyridine nitrogen or by complexation with heavy-metal ions (*e.g.* Cu^{2+}, Ni^{2+}, and Co^{2+}). Similarly, the thermal isomerisation of *cis*-(5) to *trans*-(5) was speeded up by protonation of the azopyridine, but the metal ion catalysis was observed only for the metal ions which were bound into the crown ether ring (*e.g.* Cu^{2+} and Pb^{2+}). The result of solvent extraction of alkali-metal ions with (5) was very similar to that with an azobenzene-bridged crown ether (1), indicating that the 2,2′-azopyridine-bridge of (5) has almost no effect on the extraction of alkali-metal ions. On the other hand, *trans*-(5) was capable of extracting considerable amounts of heavy-metal ions (Cu^{2+}, Ni^{2+}, Co^{2+}, and Hg^{2+}), whereas photoisomerised *cis*-(5) scarcely extracted these metal ions. Such a difference in the extractability was not observed between *trans*-(1) and photoisomerised *cis*-(1). Neither the *trans*- nor the *cis*-form of 6,6′-bis(morpholinocarbonyl)-2,2′-azopyridine[non-crown analogue of (5)] could extract these metal ions under comparable extraction conditions. These results suggest that pyridine nitrogens of *trans*-(5) are directed towards the crown ether plane so as to co-ordinate to metal ions in the crown ether ring, whereas those of *cis*-(5) have no such co-ordination ability due to the distorted configuration. Therefore, compound (5) would act as a ' photoresponse cryptand ' for heavy metal ions.

Chemical substances which exhibit photoinduced structure changes are candidates not only for the storage of light energy but also of mediators for the conversion of light into other forms of energy.[2] Further, if the structure changes occurring in the photoresponsive chromophores can be transmitted to the functional molecules, the fundamental functions of photoresponsive systems in nature may be mimicked. Azobenzene derivatives which exhibit photoinduced reversible *cis-trans* isomerism have frequently been employed as a photoantenna to control the physical and chemical functions of membranes,[3] microemulsions,[4] polypeptide chains,[5–7] synthetic polymers,[8–10] cyclodextrins,[11,12] and crown ethers.[13–17] Similarly, photoinduced dimerisation of anthracene was employed to prepare the ' switched-on ' crown ethers.[18,19]

The purpose of our investigation has been to control the functions of a crown ether family by light, which would lead to photoresponsive ion-extraction and light-driven ion-transport across membranes.[14–17] We have been utilising azobenzene derivatives which are isomerised to *cis*-forms by u.v. light and isomerised back to *trans*-forms by visible light.[2] In order to give new photoresponsive functionalities to the crown ether family, we have now investigated the behaviour of 2,2′-azopyridine derivatives. It is known that the isomerisation of azobenzene is catalysed by heavy-metal ions complexed with the azo-linkage.[20,21] However, such a co-ordination bond is generally unstable. For 2,2′-azopyridine, one may expect that the complexation with the azo-linkage would be stabilised by neighbouring pyridine nitrogens and that the isomerisation processes would be mediated not only by light energy but also by the co-ordination of heavy-metal ions. With these objects in view, we have synthesised 4,4′-azopyridine (2), 2,2′-azopyridine (3), 6,6′-bis(morpholinocarbonyl)-2,2′-azopyridine (4), and a crown ether with a 2,2′-azopyridine-bridge (5) and compared their photoresponsive behaviour with a crown ether with an azobenzene-bridge (1).[14,15]

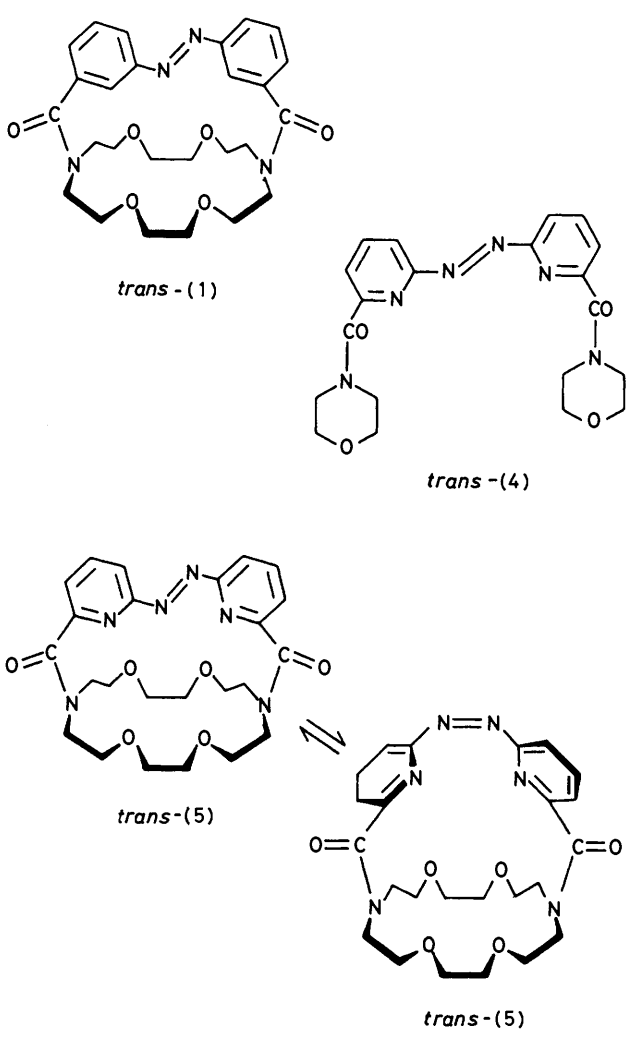
When inspecting the CPK model of compound (1), we noticed that the *trans*-azobenzene-bridge of (1) [*i.e. trans*-(1)] stands vertically over the crown ether plane, whereas the *cis*-azobenzene-bridge of (1) [*i.e., cis*-(1)] is almost parallel to the crown ether plane.[15] Therefore, pyridine nitrogens of *trans*-(5) are directed toward the crown ether plane and would be able to co-ordinate to metal ions in the crown ether ring, whereas those of *cis*-(5) would have no such co-ordination ability due to the distorted configuration. One may thus expect a photoresponsive crown-cryptand transformation for compound (5).

Results and Discussion

pH-*Dependence of Photo and Thermal Isomerisation.*—When aqueous solutions (pH 7.1 with 0.02 M phosphate) of compounds (3)—(5) (5.00×10^{-5} M) were photoirradiated with a 500-W high-pressure Hg-lamp with a UV-D35 filter (330 nm < λ < 380 nm), the photostationary states were attained within 4 min: *trans*% at the photostationary state,† (3) 51%, (4) 58%, and (5) 60%. In contrast, 4,4′-azopyridine (2) was not photoisomerised under these conditions. Probably, this is either due to the instability of the *cis*-form to photoirradiation or to the rapid thermal *cis*-to-*trans* isomerisation. It is worth mentioning that the π-π* band of compound (2) shifts to shorter wavelength by *ca.* 50 nm as compared with those of compounds (3)—(5) (Table 1). Similarly, Campbell *et al.*[22] reported that the *cis*-form of (3) can be isolated, whereas our attempts to isolate the *cis*-form of (2) were unsuccessful.

We found that both the *trans*% at the photostationary state and the rate of the thermal *cis*-to-*trans* isomerisation are

† The *trans*-percentage was calculated from the optical density (OD) at the absorption maxima (see Table 1), assuming that the OD of the *cis*-forms at these wavelengths is negligible in comparison with that of the *trans*-forms.



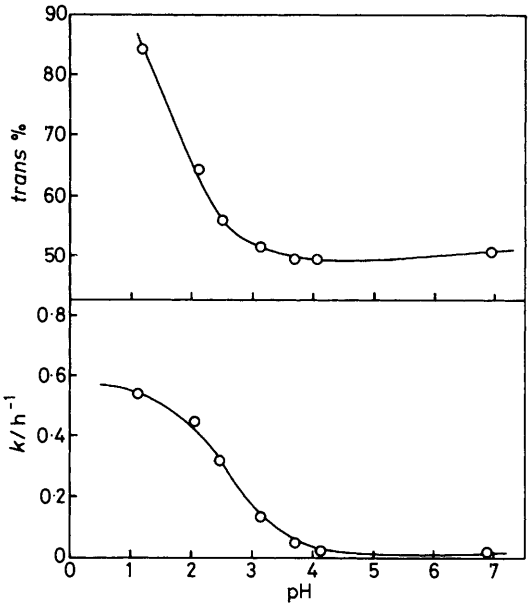


Figure 1. pH Dependence of k and *trans*% of (3). 30 °C, 3.3 vol% ethanol, [(3)] = 5.00×10^{-5}M. The pH was adjusted with HCl (pH 1—3), acetate (0.01M, pH 3—5), and phosphate (0.01M, pH 6.81)

protonation of the pyridine nitrogen. Hence, the observed rate (v_{obs}) can be expressed by equation (1), where k_0 and k_H

$$v_{obs} = k_0[\text{free } cis\text{-azopyridine}] + k_H[\text{protonated } cis\text{-azopyridine}] = \frac{1}{K_a + a_H}(k_0K_a + k_Ha_H)[\text{total } cis\text{-azopyridine}] \quad (1)$$

are the first-order rate constants for free and protonated *cis*-azopyridines, respectively, and K_a is the acid dissociation

Table 1. pK_a of *trans*- and *cis*-Forms and first-order rate constants (k) for thermal *cis*-to-*trans* isomerisation [a]

Azopyridines	*trans*-form $\lambda_{max.}$/nm	*trans*-form $\varepsilon_{max.}$	pK_a *trans* [b]	pK_a *cis* [c]	k/h^{-1} k_0	k/h^{-1} k_H
4,4′-Azopyridine (2)	282	18 100				
	445	340				
2,2′-Azopyridine (3)	318	9 520	2.9	2.6	0.014	0.57
	433	370				
(4)	323	12 600	*d*	1.4	0.0076	0.096
	440	710				
(5)	322	12 200	2.2	1.6	0.0072	0.13
	434	880				

[a] 30 °C, 3.3 vol% ethanol. [b] Determined by a potentiometric titration. [c] Determined by a plot of k *versus* pH. [d] The solubility is too low to determine the pK_a by a potentiometric titration.

dependent upon medium pH.* The rates of the thermal *cis*-to-*trans* isomerisation satisfied the first-order rate equation for up to 4 half-lives. The plots of the first-order rate constants (k) *versus* medium pH gave sigmoid curves (Figures 1 and 2), indicating that the rate acceleration at low pH region is due to

constant for *cis*-azopyridines. The equation is essentially analogous to the titration curve, and the pK_a values for *cis*-(3)—(5) were easily determined (Table 1). On the other hand, the pK_a values for the *trans*-forms were determined by a potentiometric titration.† When comparing the pK_a values

* The *trans*% was determined by photoirradiating the azopyridines in the buffered aqueous solutions, while the rate was determined by photoirradiating the azopyridines in deionised distilled water before mixing with the buffered aqueous solutions.

† The solubility of *trans*-(4) in aqueous solution was too low to determine the pK_a by a potentiometric titration. We also tried a photometric titration but could not find the appropriate wavelength which was sensitive to medium pH.

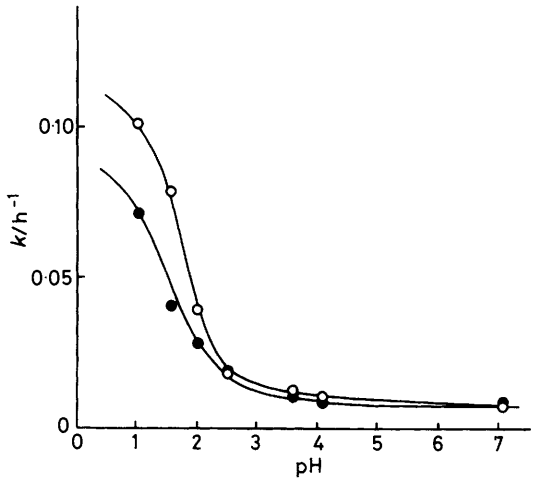
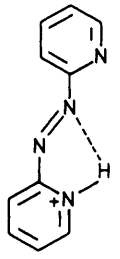


Figure 2. pH Dependence of k of (4) (●) and (5) (○). [(4)] = [(5)] = 5.00×10^{-5}M. The reaction conditions are identical with those given for Figure 1

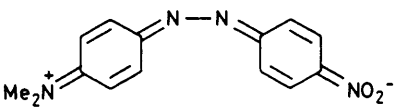


(6)

of the *trans*-forms with those of the *cis*-forms, we noticed that the *trans*-forms have pK_a values higher by 0.3—0.6 pK unit than the *cis*-isomers. The higher basicity is probably due to the stabilisation of the protonated species through the hydrogen-bonding interaction with the azo-linkage [see (6)]. Since the *cis*-forms cannot enjoy the co-planarity between the azo-group and the pyridine ring, such stabilisation effect cannot be expected.

Two opposing mechanisms have been proposed for the thermal *cis*-to-*trans* isomerisation of azobenzene derivatives: that is, the reaction may proceed either *via* a rotational mechanism involving rotation about the N=N bond or an inversion mechanism involving flip-flop inversion of one of the nitrogen atoms. It is now believed that the isomerisation of most azobenzene derivatives proceeds *via* the inversion mechanism and the rotational mechanism is operative only when azobenzenes have both of the push-and-pull substituents (*e.g.*, 4-dimethylamino-4′-nitroazobenzene).[23-27] The rotational mechanism (reactions which operate by this usually have large rate constants), probably occurs as a result of a contribution of a resonance structure [for example, (7)] which affords a single-bonded N–N linkage in the ground state.[25-27]

Comparison of k_H with k_0 (Table 1) reveals that protonation of one of the pyridine nitrogens remarkably facilitates the thermal isomerisation, the rate increases being of the order of 12.6—40.7-fold. The effect is explained either by the substituent effect or by a change in the reaction mechanism. We consider that the change in the reaction mechanism is highly unlikely because (i) protonated *cis*-2,2′-azopyridine derivatives cannot adopt the resonance structure such as (7) in the ground



(7)

state and (ii) the rate acceleration by protonation is also observed for *cis*-(5), in which two pyridine rings are covalently-linked to the crown ether ring and thus the rotational mechanism is hardly conceivable.[25] Probably, the rate acceleration observed in acidic pH region is rationalised in terms of the enhanced electron-withdrawing effect of the protonated pyridine ring.

Figure 1 also shows that the *trans*% of (3) at the photostationary state increases with a decrease in the pH medium. This implies that protonated *cis*-(3) is more destabilised than protonated *trans*-(3) on photoirradiation. This finding is in line with the rate acceleration of the thermal *cis*-to-*trans* isomerisation in the acidic pH region. On the other hand, the *trans*% of (4) and (5) was found to be almost constant at pH 1—7: *trans*%, 58 ± 4% for (4) and 60 ± 5% for (5). Since the pK_a values of (4) and (5) are lower than that of (3) by *ca.* 1 pK unit, the increase in the *trans*% of (4) and (5) may take place at pH < 1. We noticed, however, that the spectra of (4) and (5) in strongly acidic solution change irreversibly. Probably, this is due to the hydrolytic cleavage of the amide linkages. Further experiments on the *trans*% of (4) and (5) were not carried out.

Metal Ion Catalyses.—We have previously reported that the thermal *cis*-to-*trans* isomerisation of *cis*-(1) is suppressed by added alkali-metal and ammonium cations in n-butanol–benzene (2 : 1, v/v).[15] In aqueous solution, however, addition of potassium acetate (50 mM) exhibited no effect on the rate of the thermal isomerisation of *cis*-(1) and *cis*-(5). On the other hand, we found that k and the *trans*% for compounds (3)—(5) are affected by added heavy-metal ions in aqueous solution adjusted to pH 4.5 ± 0.5 (Figures 3 and 4).* This implies that as observed in other metal-catalysed reactions,[28,29] the co-ordination of metal ions exerts the effect similar to the protonation.

The first-order rate constants at [M^{2+}] = 10 mM are summarised in Table 2. The examination of this Table reveals that (i) the isomerisation rate of *cis*-(3) is enhanced by several heavy-metal ions and, in particular, the largest rate increase (486-fold) is observed in the presence of Cu^{2+}; (ii) the catalytic effect on the isomerisation of *cis*-(4) and *cis*-(5) is generally small, but the isomerisation rate of *cis*-(5) is selectively enhanced by Cu^{2+} and Pb^{2+} (26-fold and 11-fold, respectively); and (iii) the *trans*% of (3) at the photostationary state also increases with increasing metal ion concentration (Figure 3), whereas the photostationary state of (4) and (5) is hardly affected by the addition of these metal ions. The large catalytic effect on compound (3) relative to (4) and (5) is ascribed to the relatively high basicity of (3). The selective rate acceleration of *cis*-(5) by Cu^{2+} and Pb^{2+} is accounted for by the high complexation ability of (5) with these metal ions. In fact, compound (5) is able to extract Cu^{2+} and Pb^{2+} efficiently into the organic phase, whereas (4) has no such extraction ability (see later). Hence, one may conclude that the thermal isomerisation of *cis*-(5) is mediated only by metal ions bound into the crown ether ring.

Subsequently, we tried to determine the association con-

* To determine the *trans*%, photoirradiation was performed after the addition of metal ions, whereas to determine k, photoirradiation was performed before the addition of metal ions.

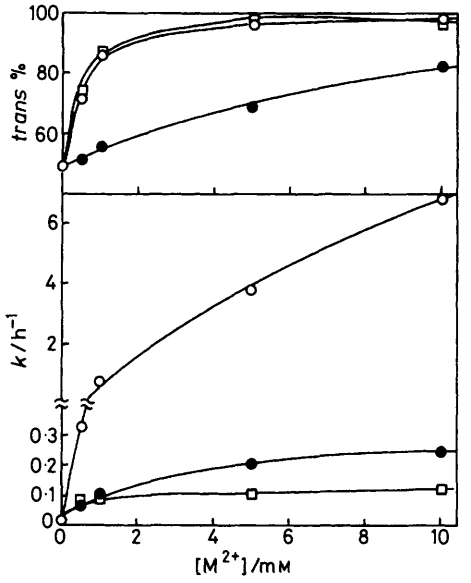


Figure 3. Metal-ion catalysis on k and *trans*% of (3). 30 °C, 3.3 vol% ethanol, [(3)] = 5.00×10^{-5}M. The pH was adjusted to 4.5 ± 0.5 with Et_4NOH and HCl. ○, Cu; ●, Co^{2+}; □, Ni^{2+}

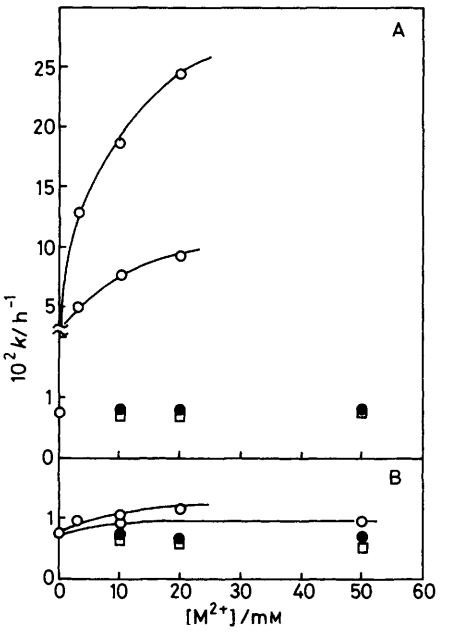


Figure 4. Metal-ion catalysis on k of (4) (Figure 4B) and (5) (Figure 4A). The reaction conditions are identical with those given for Figure 3. ○, Cu^{2+}; ◑, Pb^{2+}; ●, Co^{2+}; □, Ni^{2+}

stants for the *trans*- and *cis*-forms. The association constants (K_t) for the *trans*-forms (L_t) were evaluated by using equation (2),[30] which holds for the formation of a 1 : 1 complex under $[M^{2+}]_0 \gg [L_t]_0$, where OD_0 and OD are the absorbances of

$$\frac{OD - OD_0}{[M^{2+}]_0} = \varepsilon K_t[L_t]_0 - K_t OD \qquad (2)$$

trans-forms in the absence and the presence of metal ions, respectively, and ε is the apparent molar absorption coefficient of *trans*-form-metal complexes. In the aqueous solution of *trans*-(3) (5.00×10^{-5}M) adjusted to pH 4.5, new absorption bands appeared on the addition of Cu^{2+} and Co^{2+} at 358 and 344 nm, respectively. The spectral change induced by Co^{2+} gave a tight isosbestic point at 324 nm, whereas that induced by Cu^{2+} did not give such a tight one (around 330 nm). For an aqueous solution of *trans*-(5), only Pb^{2+} resulted in the spectral change with a new absorption maximum (333 nm) and an isosbestic point (327 nm). On the other hand, no appreciable spectral change was observed for *trans*-(4). The plots of $(OD\text{-}OD_0)/[M^{2+}]_0$ (where $[M^{2+}]_0$ = 0.5—50 mM) against OD gave straight lines with $r > 0.98$. The K_t values were determined from the slopes ($-K_c$) by the least-squares procedure. The association constants (K_t) for *cis*-forms (L_c) and the first-order rate constants (k_c) for the thermal isomerisation of *cis*-form-metal complexes were evaluated by using equation (3),[31] which holds for the formation of a 1 : 1 complex where $[M^{2+}]_0 \gg [L_c]$; k_0 and k are

$$\frac{k_0}{k - k_0} = \frac{1}{qK_c} \cdot \frac{1}{[M^{2+}]_0} + \frac{1}{q} \qquad (3)$$

the first-order rate constants in the absence and the presence of metal ions, respectively, and $q = (k_c/k_0) - 1$. Since several metal ions [Cu^{2+} and Co^{2+} in *cis*-(3), Cu^{2+} and Pb^{2+} in *cis*-(4) and *cis*-(5)] showed the clear rate increases with increasing metal concentrations, the data were subjected to the determination of K_c and k_c by equation (3). From the plots of $k_0/(k - k_0)$ against $[M^{2+}]_0^{-1}$, we determined $(qK_c)^{-1}$ (slope) and q^{-1} (intercept) by the least-squares procedure ($r > 0.99$); K_c and k_c were calculated from these two terms. Values of K_t, K_c, and k_c thus obtained are summarised in Table 3.

Examination of Table 3 reveals that K_t is generally greater than K_c. The large association tendency of the *trans*-forms is attributable to the co-ordination ability as a bidentate ligand of compound (8).

In the *cis*-forms, such co-ordination structure is inconceivable because the pyridine rings and the azo-linkage cannot be in a same plane. Table 3 also shows that the observed rate enhancements are mainly caused by k_c and not by K_c. In particular, the k_c value for the Cu^{2+}[*cis*-(3)] complex is 970 times greater than the first-order rate constant in the absence of metal ion. The k_c values for *cis*-(5) are selectively enhanced by Cu^{2+} and Pb^{2+}. Supposedly, the metal ions fixed in the crown ether ring exert an efficient catalytic effect on the thermal isomerisation of the azopyridine-bridge.

The foregoing results consistently suggest that *trans*-(5) has greater binding ability than *cis*-(5) owing to co-ordination of the azopyridine-bridge to metal ions in the crown ether ring: that is, compound (5) would act as a 'photoresponsive cryptand'. We tested whether such a structural change is also effective in solvent extraction and ion-transport across a liquid miembrane (see below).

Solvent Extraction of Alkali- and Heavy-metal Cations.— For solvent extraction with (1), we observed that the *trans*-form binds ammonium ions, Li^+, and Na^+ preferably, whereas the *cis*-form binds K^+ and Rb^+ preferably.[14,15] This result was rationalised in terms of photoinduced expansion of the crown ether size. The extraction ability of compound (5) for alkali-metal cations was generally inferior to that of compound (1) because of the hydrophilic nature of the 2,2′-azopyridine moiety. We thus used the organic phase (*o*-dichlorobenzene–n-butyl alcohol = 80 : 20, v/v) containing a high concentration of (5) (4.00 mM) and estimated the extractability (Ex) on the basis of partition of picrate anion between the organic and the aqueous phase. The results are summarised in Table 4.

Table 2. First-order rate constants (k) for metal-catalysed thermal *cis*-to-*trans* isomerisation [a]

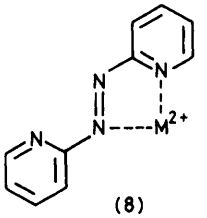
Azopyridines	k/h^{-1} at $[M^{2+}] = 10$ mM				
	None	Cu^{2+}	Ni^{2+}	Co^{2+}	Pb^{2+}
2,2′-Azopyridine (3)	0.014	6.8	0.120	0.240	
(4)	0.0076	0.0105	0.0066	0.0070	0.0092
(5)	0.0072	0.186	0.0070	0.0077	0.078

[a] 30 °C, 3.3 vol% ethanol, [azopyridine] = 5.00×10^{-5}M, pH 4.0—5.0. Cu^{2+}, Ni^{2+}, and Co^{2+} were added as their chloride salts, and Pb^{+2} was added as its acetate salt.

Table 3. Association constants for *trans*- and *cis*-forms (K_t and K_c/M^{-1}, respectively) and first-order rate constants (k_c/h^{-1}) for *cis*-azopyridine-metal complexes [a]

Azopyridines	Cu^{2+}			Co^{2+}			Pb^{2+}		
	K_t	K_c	k_c	K_t	K_c	k_c	K_t	K_c	k_c
2,2′-Azopyridine (3)	1 950	361	13.6	373	286	0.332	[b]		
(4)	[b]	304	0.012	[b]			[b]	213	0.0099
(5)	[b]	286	0.279	[b]			379	261	0.106

[a] 30 °C, 3.3 vol% ethanol, [azopyridine] = 5.00×10^{-5}M, pH 4.0—5.0. [b] The spectral change was too small to determine the association constants.



(8)

In the extraction of alkali-metal cations with compound (5), we observed the extraction trend of dark (*i.e. trans*, Ex 39.8%) > photoirradiated (Ex 35.6%) for Na^+ and photoirradiated (Ex 37.8%) > dark (*i.e. trans*, Ex 22.0%) for K^+. The result is quite similar to the extraction trend of (1). If the extractability upon photoirradiation (Ex_{photo}) is expressed by equation (4), the extractabilities of the *cis*-(5) for Na^+ and K^+ are estimated to be 29.9 and 60.5%, respectively. On the

$$Ex_{photo} = \frac{trans\%}{100} \cdot Ex_{trans} + \frac{cis\%}{100} \cdot Ex_{cis} \qquad (4)$$

other hand, the extraction trend of dark (Ex 17.2%) > photoirradiation (Ex 10.8%) for Rb^+ is not in accord with that of compound (1). Presumably, the concentration of compound (5) in the organic phase is so high that large alkali-metal cations would be extracted as 1 : 2 cation/crown complexes.

In the extraction of heavy-metal cations with compound (1), photoirradiation showed no marked influence (except for Pb^{2+}). It was also found that, in the extraction of heavy-metal cations with compound (5), *trans*-(5) was capable of extracting considerable quantities of these metal cations, whereas with *cis*-(5) they were scarcely extracted (except for Pb^{2+}). We also tested the extraction with compound (4) (4.00 mM) under identical conditions and found that neither *trans*-(4) nor *cis*-(4) extracted these heavy metal cations to any appreciable extent. These results suggest that the 2,2′-azopyridine moiety of *trans*-(5) contributes to the stabilisation of *trans*-(5)-metal complexes *via* co-ordination to bound metal ions; in contrast the pyridine rings of *cis*-(5) are so distorted as to be parallel to the crown ether plane and thus fail to have a stabilising effect. In a separate study, we determined the concentration of Cu^{2+} in the organic phase after

Table 4. Influence of photoirradiation on the extraction of alkali- and heavy-metal cations to the organic phase [*o*-dichlorobenzene–n-butyl alcohol, 80 : 20 (v/v)] at 30 °C [a]

Metal	Extracted picrate (%)			
	(1)		(5)	
	Dark	Light [b]	Dark	Light [c]
Na^+	14.8 [d]	13.5 [d]	39.8	35.6
K^+	15.8 [d]	27.2 [d]	22.0	37.8
Rb^+	~0 [d]	1.1 [d]	17.2	10.8
Cs^+	~0 [d]	~0 [d]	8.9	5.1
Ca^{2+}			6.7	9.3
Ba^{2+}			8.1	11.6
Cu^{2+}	1.9	2.2	9.5	1.0
Ni^{2+}	1.0	0.4	0.6	~0
Co^{2+}	3.0	2.6	3.7	~0
Hg^{2+}	1.9	2.3	3.1	~0
Pb^{2+}	7.9	4.3	10.8	8.8

[a] Extraction conditions for alkali-metal cation: aqueous phase, [MOH] = 0.10M, [picric acid] = 1.00×10^{-4}M; organic phase, [(5)] = 4.00×10^{-3}M. Extraction conditions for heavy-metal cations: aqueous phase, pH 4.5 ± 0.5, [MCl_2] = 0.010M, [picric acid] = 1.00×10^{-4}, [Et_4NOH] = 1.10×10^{-4}M; organic phase, [(1) or (5)] = 4.00×10^{-3}M. [b] *cis*-Form, 60% for the extraction of alkali-metal cations [15] and 77% for the extraction of heavy-metal cations. [c] *cis*-Form, 42%. [d] Cited from ref. 15. The counteranion is Methyl Orange.

the extraction with *trans*-(5) by atomic absorption spectroscopy. The concentration was found to be 94% of picrate ion. The implication of this result is that the main extraction species is $[Cu^{2+}][picrate]\,[X]$ (X = OH or Cl). The anomaly of Pb^{2+} stems from its high affinity for the crown ether ring [32,33] so that in the extraction with compound (5), the complex is so stabilised by the interaction of Pb^{2+} with the crown ether ring that the association constant is less affected by the structure change in the azopyridine moiety.

Transport of Cu^{2+} *Across a Liquid Membrane.*—Since the greatest photoirradiation effect was observed for the extraction of Cu^{2+} with (5), we examined the transport of Cu^{2+} across a liquid membrane (*o*-dichlorobenzene–n-butyl alcohol =

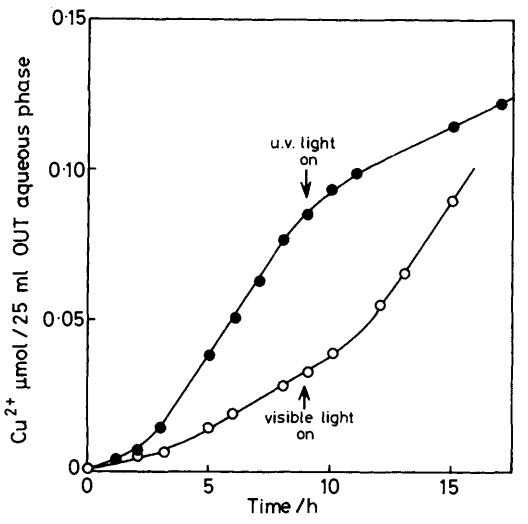


Figure 5. Transport of Cu^{2+} across a liquid membrane at 30 °C. Organic phase (100 ml): [(5)] = 2.00×10^{-3}M in *o*-dichlorobenzene: n-butyl alcohol (80 : 20, v/v). IN aqueous phase (25 ml): [$CuCl_2$] = 0.010M, [picric acid] = 1.00×10^{-3}M, [Et_4NOH] = 1.10×10^{-3}M, pH *ca.* 4.5. OUT aqueous phase (25 ml): deionised distilled water. ●: The liquid membrane phase contained *trans*-(5) and the ion-transport was carried out in the dark. After 9 h, the membrane phase was irradiated with a Hg-lamp through a UV-D35 filter (330 nm < λ < 380 nm) for 1.5 h. ○: The liquid membrane phase contained photoirradiated (5) (*cis*-form, 42%) and the ion-transport was carried out in the dark. After 9 h, the membrane phase was irradiated with a Hg-lamp with a L-42 filter (λ > 420 nm) for 1.5 h. The distance from the lamp to the U-tube was 6 cm

80 : 20, v/v) in a U-tube. The detailed transport conditions are recorded in the caption for Figure 5.

When the liquid membrane containing *trans*-(5) was used, the concentration of Cu^{2+} in the second (OUT) aqueous phase (25 ml) increased linearly after an induction period (*ca.* 2 h). After 9 h, the liquid membrane phase was subjected to u.v. light irradiation for 1.5 h. The rate of Cu^{2+} transport was suppressed gradually and a new linear increase was observed after 11 h. The rates in the dark and after u.v. light irradiation were calculated from the linear slopes to be 0.0119 and 0.0042 μmol/25 ml h^{-1}, respectively. On the other hand, when the liquid membrane was irradiated with u.v. light for 1.5 h in advance (*trans*-form, 58%) and then Cu^{2+} transport was started, the initial linear slope was comparable with that of the second stage of the above experiment (rate: 0.0044 μmol/25 ml h^{-1}). After 9 h, the liquid membrane phase was subjected to visible light irradiation for 1.5 h which would mediate the *cis*-to-*trans* isomerisation of (5) (*trans*-form, 96%). The rate was speeded up to 0.0110 μmol/25 ml h^{-1}, which is comparable with that of the initial stage of the above experiment. The results clearly establish that the rate of Cu^{2+} transport is reversibly controlled by an on-off light switch. Under u.v. light irradiation, the content of *trans*-(5) was reduced by *ca.* 40% and the rate was suppressed by *ca.* 60%. Hence, *cis*-(5) in the membrane phase scarcely contributes to the transport of Cu^{2+}.

Conclusions.—We have demonstrated that a crown ether with a 2,2′-azopyridine-bridge exhibits a crown-cryptand transformation in response to photoirradiation. It has been shown that the novel transformation is associated with the photoinduced configurational change of the 2,2′-azopyridine moiety and is applicable to photocontrol of both ion extraction and ion transport. The concept is interesting in relation to photoresponsive systems in nature where the physiological events are frequently linked with photoinduced structure changes of photo-antennae. Further applications are currently under investigation in this laboratory.

Experimental

Materials.—4,4′-Azopyridine (2) and 2,2′-azopyridine (3) were prepared from 4-aminopyridine and 2-aminopyridine, respectively, according to the method of Campbell *et al.*,[22] m.p. of (2) 108—109 °C (lit.,[22] 108—109 °C); m.p. of (3) 84.5—86 °C (lit.,[22] 85—86 °C).

6-Aminopyridine-2-carboxylic acid was prepared from 6-amino-2-methylpyridine according to the method of Ferrari and Marcom,[34] m.p. >250 °C (lit.,[34] 317—319 °C) (Found: C, 52.1; H, 4.3; N, 20.4. Calc. for $C_6H_6N_2O_2$: C, 52.17; H, 4.38; N, 20.28%). 6-Amino-2-methylpyridine was kindly supplied from Kohei Kagaku Co. Ltd.

2,2′-Azopyridine-6,6′-dicarboxylic acid was synthesised from 6-aminopyridine-2-carboxylic acid in a manner similar to that used to prepare azobenzene from aniline.[35] The 10% NaOCl solution (260 ml) in an ice–water bath was stirred efficiently, and the 10% NaOH solution (50 ml) containing 11 g (0.08 mol) of 6-methylpyridine-2-carboxylic acid was added dropwise. The reaction was continued for 3 h at 0 °C. The precipitate was recovered by suction. When the filtrate was made strongly alkaline with NaOH, the precipitate was formed again. The orange solid thus collected was dissolved in 10% NaOH solution (50 ml). The solution was treated with activated charcoal at 50 °C. After filtration, the filtrate was acidified to pH 3 by concentrated HCl. The precipitate was collected and dried *in vacuo*, yield 48%, m.p. >250 °C (Found: C, 52.9; H, 2.9; N, 20.7. Calc. for $C_{12}H_8N_4O_4$: C, 52.95; H, 2.96; N, 20.58%).

6,6′-*Bis*(*chlorocarbonyl*)-2,2′-*azopyridine*.—2,2′-Azopyridine-6,6′-dicarboxylic acid (3.0 g, 0.011 mol) was placed in a three-necked 100 ml flask equipped with a mechanical stirrer and a calcium chloride tube and, after addition of thionyl chloride (15 ml) and two drops of dimethylformamide, the reaction mixture was stirred under reflux for 13 h. The acid soon dissolved to give an homogeneous solution. After *ca.* 4 h red needles were precipitated. Xylene (50 ml) was added to the final reaction mixture and excess of thionyl chloride and xylene was distilled off at atmospheric pressure. The residual solid was washed with ligroin, yield 94%, m.p. 204—209 °C (Found: C, 46.8; H, 2.0; N, 18.1%. Calc. for $C_{12}H_6Cl_2N_4O_2$: C, 46.63; H, 1.96; N, 18.13%). The elemental analysis shows that the two pyridine nitrogens are not protonated.

Compound (5).—In a 1-l three-necked flask with a reflux condenser were placed chlorobenzene (200 ml) and triethylamine (2 ml); simultaneously, 6,6′-bis(chlorocarbonyl)-2,2′-azopyridine (0.618 g, 2.0 mmol) in chlorobenzene (120 ml) in a graduated dropping funnel and 1,10-diazo-4,7,13,16-tetraoxa-18-crown-6 (0.525 g, 2.0 mmol) in chlorobenzene (120 ml) in another graduated dropping funnel were then added. The speed of the addition was adjusted so that equal quantities of the chlorobenzene solutions were added. Subsequently, the reaction mixture was stirred vigorously at room temperature for 1 h after which it was washed with water to remove triethylamine hydrochloride; the chlorobenzene layer was then concentrated under reduced pressure. The resultant solution (*ca.* 15 ml) was cooled in an ice-water bath. The precipitate so formed was collected by suction, washed with small amount of benzene, and dried *in vacuo*, yield 45%, m.p.

247—249 °C, M^+, 498 (Found: C, 57.9; H, 6.1; N, 16.8%. Calc. for $C_{24}H_{30}N_6O_6$: C, 57.82, H, 6.07; N, 16.86%.

Compound (4).—Compound (4) was synthesised from 6,6′-bis(chlorocarbonyl)-2,2′-azopyridine and morpholine in a manner similar to that described above. Less attention was paid to maintaining conditions of high dilution; yield 31%, m.p. 251—253 °C (Found: C, 58.8; H, 5.4; N, 20.2. Calc. for $C_{20}H_{22}N_6O_4$: C, 58.53, H, 5.40; N, 20.48%).

Photoisomerisation.—*trans*-to-*cis* Isomerisation was carried out by using a 500 W high-pressure Hg-lamp with a coloured glass filter, Toshiba UV-D35 (330 nm $< \lambda <$ 380 nm). *cis*-to-*trans* Isomerisation of compound (5) in the membrane transport system was achieved by visible light from the same Hg-lamp with a coloured glass filter, Toshiba L-42 ($\lambda >$ 420 nm). The distance from the Hg-lamp to the sample solution was 6.0 cm.

Kinetic Measurements of Thermal cis-*to*-trans *Isomerisation.* —The kinetic measurements was carried out spectrophotometrically at 30 °C by monitoring the increase in the absorption maxima (π-π^* bands) of the *trans*-forms. To obviate possible photoisomerisation (*trans* ⟶ *cis*) by light from the spectrophotometer, we measured the absorbance for a few seconds per minute. Details of the method has been described previously.[15-17]

Solvent Extraction.—The method of solvent extraction has been described in detail previously.[15] In this study, the extractability was estimated on the basis of the partition of picrate ion between equal volumes of the organic [*o*-dichlorobenzene–n-butyl alcohol, 80 : 20 (v/v)] and the aqueous phase adjusted to pH 4.5 with HCl–Et_4NOH. In order to confirm the method, we determined the concentration of Cu^{2+} in the organic phase. After extraction with *trans*-(5), the organic layer was separated, evaporated under reduced pressure, and the residue dissolved in water. The aqueous solution was subjected to the measurement by atomic absorption spectroscopy (Shimadzu AA-640). As described in the Results and Discussion section, the concentration of Cu^{2+} was very close to that of the picrate ion.

Ion Transport.—Transport of Cu^{2+} across a liquid membrane [*o*-dichlorobenzene–n-butyl alcohol, 80 : 20 (v/v)] with the aid of compound (5) was carried out within a U-tube. The tube was immersed in a thermostatted water-bath (30 °C) and, when required, was irradiated by a 500 W high-pressure Hg-lamp either with a UV-D35 filter (for u.v. light) or with a L-42 filter (for visible light). The distance from the tube to the lamp was 6.0 cm. The volume of the membrane phase was 100 ml and those of the first (IN) and the second (OUT) aqueous phase were 25 ml. The concentration of Cu^{2+} in the OUT aqueous phase was determined by atomic absorption spectroscopy. Further details of the transport conditions are recorded in the caption for Figure 5.

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