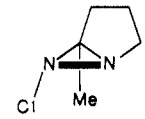
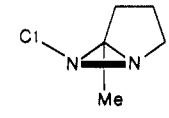
observed red shifts in the first transition of the cis isomers relative to the trans isomers, 0.48 and 0.62 eV for **6** and **7**, respectively, correspond well with that calculated for **11**, namely 0.44 eV.

The second electronic transition of **11a** and **11b** is calculated to have a much lower dipole strength than the first (Table III) and is predicted to originate from the second highest occupied MO but to terminate in the same antibonding orbital, namely $3p_{Cl}-\sigma^*_{NCl}$. No isomer red shift is expected for this transition. The calculated separation of the two transitions in *trans*-**11b**, 0.7 eV, is the same as observed in the case of **5** (Table III). The electric and magnetic dipole transition moments are very nearly orthogonal in **11a** and **11b**. On this basis one expects the sign and magnitude of the CE of this transition to be dependent on the intramolecular and extramolecular environment of the chromophore. In compounds **5**, **6a**, and **6b** the signs observed for the CE of the second transition (Table I, Figure 3) are as calculated by the origin-independent form of the rotational strength, $[R]^v$. The ester and amide groups of **7-10** also absorb in the region of the second *N*-halodiaziridine band precluding direct comparison with computed results for **11** for this transition.

We return to the question of the discrepancy between the experimental observations on compounds **6** and **7** from which one may conclude that the first CE of *N*-chlorodiaziridines changes sign upon inversion of configuration at the halogenated nitrogen and the theoretical results from **11** that predict that the decisive configuration is at the non-halogenated nitrogen atom. whether the discrepancy is real or not hinges on how good a model **11** is for the *N*-halodiaziridines **5-10**. The most serious objection to the use of **11** as a model is the presence of the highly polar substituent (CF_3, CO_2Me, or CONHMe) at the C position of the diaziridine ring (position 5 of the 1,6-diazabicyclo[3.1.0]hexane skeleton) which is present in all compounds except **5** which has a more innocuous Me group at this position. The computed results for **11b** should be most comparable to the experimental observations on compound **5** and indeed agree in all important details. Extrapolating the computed results for **11a** to the *cis* isomer of **5**, namely **13**, the theory predicts that the sign of the first CE of



5



13

13 is negative as it is in the case of **5**. Extrapolation from the experimental results for **6** and **7** suggests that the first CE of **13** should be positive. The discrepancy may be resolved if one assumes that the chiral moiety **12** which is also present in the diaziridines does not play a benign role as one may suppose from the CD spectra of **6** and **7** (Figures 3 and 4) but rather a dominant role, reversing the sign of the first CE of the cis *N*-halodiaziridines, in the same manner as in the case of *N*-haloaziridines (compare **3** and **4** with **1b**, Figures 1 and 2.) Unfortunately, in contrast to the *N*-chlorodiaziridines **6a** and **7a**, low configurational stability of **13** does not allow the synthesis of this compound by chlorination of 5-methyl-1,6-diazabicyclo[3.1.0]hexane.[1a,31] In addition, direct computation on systems the size of **5** and **13** is not possible at present.

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Excited-State Behavior of Tryptamine and Related Indoles. Remarkably Efficient Intramolecular Proton-Induced Quenching[1]

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Abstract: The excited-state behavior of tryptamine and 1,2,3,4-tetrahydrocarbazoles possessing alkylamino side chains in the absence and presence of 18-crown-6 in MeOH-H_2O (9:1) mixtures has been studied by means of nanosecond single-photon counting, fluorimetry, and photochemical H-D isotope exchange. The fluorescence intensity of these indoles increases significantly with increasing concentration of 18-crown-6. The relatively short lifetime of the tryptamine ammonium ion **1** is not ascribed to external quenching but rather to internal quenching. The rate constant k_q for internal quenching can be estimated from the equation $k_q = \tau_0^{-1} - \tau_{max}^{-1}$, where τ_0 and τ_{max} represent the fluorescence lifetimes for free **1** and the 1:1 **1**-crown ether complex, respectively. Internal quenching originates from electrophilic proton attack by the $-N^+H_3$ (or $-N^+D_3$) group of **1** at the C-4 position of the excited indole ring. For **3** (the tetrahydrocarbazole derivative $R(CH_2)_3N^+H_3$) the k_q value comprises the electrophilic proton attack at the C-8 position plus other quenching (probably charge-transfer quenching) between the excited indole moiety (R*) and the $-N^+H_3$ (or $-N^+D_3$) group. The stabilization constant K_g for the corresponding ammonium ion and 18-crown-6 can be determined by fluorimetry. The kinetic and thermodynamic parameters for the internal quenching and the complex formation, respectively, have been described.

The mechanistic study on the fluorescence decay of tryptophan (Trp) in polar media is of special interest in photophysics and photobiochemistry.[3,4] A number of mechanisms for the decay process of the excited Trp have been proposed.[3] Two types of quenching mechanisms have been proposed: internal and external as described below. The internal quenching of Trp has been

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attributed to (a) simultaneous emission from uncoupled ^1L_a and ^1L_b[5] states (this explanation was later discarded by the authors), (b) intramolecular charge-transfer quenching caused by the interaction between the excited indole moiety and the alanyl side chain,[6] (c) intramolecular charge-transfer quenching arising from different ground-state C_α–C_β rotamers (the conformer model[7]) or the modified conformer model containing both C_α–C_β and C_β–C_γ rotamers in the ground state,[8] and (d) proton-transfer quenching by the ammonium group.[9-14] In the early stage, the C-2 position of the indole ring was assumed to be the reactive site.[12] Recently, Saito et al.[13,14] have shown by a photochemical H–D isotope exchange reaction that the major reactive position of the indole ring is not the C-2 but the C-4 position. The external quenching mechanism was assumed to be caused by (a) the formation of an exciplex between indole and a polar solvent molecule,[15,16] (b) the charge transfer to solvent (CTTS),[17] and (c) photoelectron ejection[18] from the excited indole moiety.

The fluorescence decay of Trp is complicated. The multiexponential decay functions (double or triple) have been observed in measuring the fluorescence decay or Trp in polar media.[7,8,12,17,19] The mechanism of the fluorescence decay of the excited Trp has been a matter of much current controversy.[3]

On the other hand, the excited-state proton-transfer reactions involving the proton-induced quenching of aromatic compounds have been extensively studied.[20] It has been shown that the proton-induced fluorescence quenching is caused by electrophilic protonation at one of the carbon atoms of the aromatic ring in the excited state, leading to hydrogen exchange (or deuterium exchange).[21] Both ground- and excited-state properties of the 1:1 complex of an aromatic ammonium ion with 18-crown-6 have been revealed as follows:[22-24] (1) The stabilization constant for complex formation, which is affected by the steric interaction between an aromatic ammonium ion and 18-crown-6, can be determined by the fluorimetric method. (2) There is no change in electronic character in both ground and excited states of the complex compared to the free ammonium ion, i.e., no spectral change in the absorption and emission. (3) The proton dissociation rate in the S_1 state decreases drastically, resulting in the fluorescence enhancement of the protonated amine (in contrast, the fluorescence intensity of the neutral amine decreases significantly). (4) The contribution of back proton transfer process (protonation process) in the S_1 state is negligibly small; the ammonium nitrogen atom in the complex is sterically protected by the aromatic ring and 18-crown-6, and no proton attack by the bulky hydronium ions occurs in the S_1 state (i.e., there is no acid–base equilibrium in the excited complex). However, (5) the proton-induced quenching (electrophilic proton attack to one of the carbon atoms of the aromatic ring) occurs effectively.

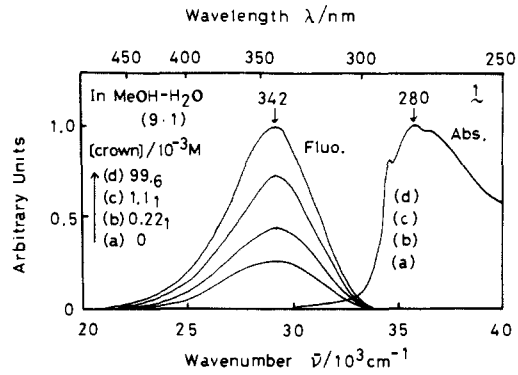

Figure 1. Concentration effect of 18-crown-6 upon the absorption and fluorescence spectra of tryptamine ammonium ion (**1**) in MeOH–H_2O (9:1) at 300 K.

The deactivation process in the excited state of Trp is rather complicated as stated above, and hence tryptamine and its related compounds having a π-isoelectronic structure of Trp were chosen as a simple model in the present study. In exploring the quenching mechanism of tryptamine and its related compounds, the present work was carried out by means of nanosecond single-photon counting and fluorimetry in the presence and absence of 18-crown-6 in MeOH–H_2O (9:1). The efficiency of photochemical H–D isotope exchange reaction of tryptamine and related compounds was examined quantitatively in CH_3OD/D_2O (9:1).

Experimental Section

Tryptamine hydrochloride (**1**) from Wako was purified by recrystallizations from methanol. 3-[9′-(1′,2′,3′,4′-Tetrahydrocarbazolyl)]ethylamine hydrochloride (**2**), 3-[9′-(1′,2′,3′,4′-tetrahydrocarbazolyl)]-propylamine hydrochloride (**3**), and 3-[9′-(1′,2′,3′,4′-tetrahydrocarbazolyl)]pentylamine hydrochloride (**4**) were the same as those reported previously.[14] 18-Crown-6 (Merck) was purified by repeated recrystallizations from dichloromethane. Methanol (Spectrosol, Wako) and distilled water were used for a MeOH–H_2O mixture (9:1 by volume). For the H–D isotope effect measurements, CH_3OD (Merck) and D_2O (Merck) were used as a MeOD–D_2O mixture (9:1 by volume). All sample solutions were thoroughly degassed by freeze–pump–thaw cycles on a high vacuum line.

Absorption and fluorescence spectra were measured with Hitachi 139 and 200 spectrophotometers and a Hitachi M850 fluorimeter, respectively. Spectral corrections were made. The fluorescence response functions were recorded with a nanosecond time-resolved spectrophotometer (Horiba NAES-1100, 2-ns pulse width). This single-photon-counting apparatus is able to measure both the exciting pulse and emission response functions simultaneously and to compute the decay parameters (up to triple decay components) by the deconvolution method.

The photochemical H–D isotope exchange reaction was carried out at 254 nm by using a low-pressure mercury lamp (Toshiba, 80W) with a Vycor glass filter according to the procedure reported previously.[21] Actinometry at 254 nm was made by using a ferric oxalate solution.[25] The careful assignment of the aromatic protons of tryptamine and 1,2,3,4-tetrahydrocarbazole derivatives was made by an NOE technique by using 400 MHz ^1H NMR as reported previously.[13,14]

Results and Discussion

Absorption and Fluorescence Spectra of Tryptamine Ammonium Ion–18-Crown-6 Complex. Figure 1 shows the absorption and fluorescence spectra of the tryptamine ammonium ion (**1**) ($5.3_5 \times 10^{-5}$ M) in the absence (a) and the presence (b–d) of 18-crown-6 in MeOH–H_2O (9:1) at 300 K. Since the pK_a value of tryptamine is greater than 9, it is therefore completely protonated in MeOH–H_2O (9:1) to exist as the ammonium ion **1**. Similarly, the compounds **2–4** (see Figure 4) exist as the corresponding ammonium ions in neutral solutions. The absorption spectrum of **1** is similar to that of indole or tryptophan, indicating that **1** has the π-isoelectronic structure with indole or tryptophan in polar media, i.e., the side chain of **1** scarcely affects the π-electronic structure of the indole chromophore. Spectral change in absorption (at 280 nm) was scarcely observed in the absence and the presence

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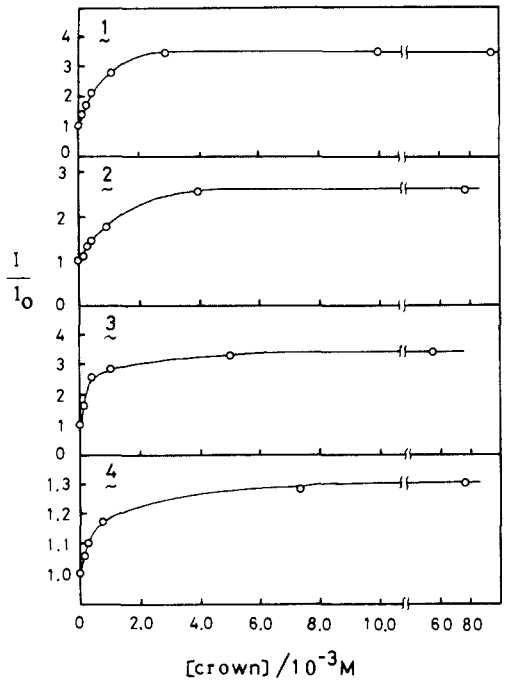

Figure 2. Concentration effect of 18-crown-6 upon the fluorescence intensity ratio (I/I_0) in MeOH–H_2O (9:1) at 300 K, where I and I_0 denote the fluorescence intensities with and without 18-crown-6, respectively.

of 18-crown-6 as shown in Figure 1. There is no absorption due to 18-crown-6 itself at wavelengths longer than ~250 nm.[22-24]

In contrast, the fluorescence intensity at 342 nm increases considerably with an increase in the concentration of 18-crown-6 without any spectral change as illustrated in Figure 1. This finding strongly suggests that the ammonium ion of **1** plays an important role in the internal quenching of **1**. The fluorescence enhancement is ascribable to the complex formation between **1** and 18-crown-6:

$$\mathbf{1} + \text{18-crown-6} \overset{K_g}{\rightleftharpoons} \mathbf{1}\text{-18-crown-6} \qquad (1)$$

The ammonium ion complexed with 18-crown-6 cannot interact intramolecularly with the indole moiety in the excited singlet state, resulting in a decrease of the internal fluorescence quenching as discussed below.

Similar absorption and emission properties in the presence of 18-crown-6 were observed for the compounds **2–4**. The fluorescence enhancement was observed in the presence of 18-crown-6 as obtained for **1** without any spectral change. Therefore, the effect of 18-crown-6 on the absorption and emission properties seems to be a general phenomenon for **1** ~ **4**.

Figure 2 shows the plots of the fluorescence intensity ratio I/I_0 as a function of [18-crown-6] at 300 K, where I and I_0 are fluorescence intensities at 342 nm with and without 18-crown-6, respectively, and the concentrations of **1–4** were $4.8_6 \times 10^{-5}$, $5.0_9 \times 10^{-5}$, $4.6_5 \times 10^{-5}$, and $8.5_5 \times 10^{-5}$ M, respectively, in MeOH–H_2O (9:1). The I/I_0 ratio increases with increasing [crown] and reaches a maximum value at a higher concentration of 18-crown-6. The maximum values of I_{max}/I_0 at 300 K for **1**, **2**, **3**, and **4** were obtained as 3.7_3 ([**1**] = $4.8_6 \times 10^{-5}$ M; [crown] = $9.9_6 \times 10^{-2}$ M), 2.5_6 ([**2**] = $5.0_9 \times 10^{-5}$ M; $7.5_1 \times 10^{-2}$ M), 3.5_3 ([**3**] = $4.6_5 \times 10^{-5}$ M; [crown] = $5.4_1 \times 10^{-2}$ M), and 1.3 ([**4**] = $8.5_5 \times 10^{-5}$ M; [crown] = $7.2_6 \times 10^{-2}$ M), respectively. The I_{max}/I_0 values are in the order of **1** > **3** > **2** > **4**, which may reflect the magnitude of internal quenching of these compounds. The experimental results are summarized in Table I.

Determination of Ground-State Association Constants K_g for Tryptamine Ammonium Ion–18-Crown-6 Complex. It is well-known that the 1:1 complex of organic (or inorganic) ammonium ion is readily formed with 18-crown-6.[20,22-24,26-28] The association constant for the aromatic ammonium ion-18-crown-6 system has been determined by means of fluorimetry.[22,24] For the present system, the fluorimetric method was employed for the determination of the association constant K_g between the tryptamine ammonium ion (**1**) or its related compounds, $R(CH_2)_nN^+H_3$ (**2**, **3**, and **4**) and 18-crown-6. The concentration of R-$(CH_2)_nN^+H_3$–crown complex in the ground state is given by[22,24]

$$[\text{complex}] = \frac{I - I_0}{I_{max} - I_0}[R(CH_2)_nN^+H_3]_0 = \frac{(I/I_0) - 1}{(I_{max}/I_0) - 1}[R(CH_2)_nN^+H_3]_0 \qquad (2)$$

where I and I_0 denote the fluorescence intensities of $R(CH_2)_nN^+H_3$ at 342 nm with and without 18-crown-6, respectively, I_{max} is the maximum fluorescence intensity of $R(CH_2)_nN^+H_3$ in the presence of a sufficient amount of 18-crown-6 (see Table I), and [R-$(CH_2)_nN^+H_3]_0$ represents the concentration of the added tryptamine (**1**) or its related compounds (**2**, **3**, and **4**).

According to the law of mass action, the association constant K_g for the 1:1 complex between $R(CH_2)_nN^+H_3$ and 18-crown-6 in the ground state is expressed as

$$K_g = \frac{[\text{complex}]}{([R(CH_2)_nN^+H_3]_0 - [\text{complex}])([\text{crown}]_0 - [\text{complex}])} \qquad (3)$$

where $[\text{crown}]_0$ represents the concentration of 18-crown-6 added to the system. Equation 4 is, therefore, derived from eq 3.

$$\frac{[\text{complex}]}{[R(CH)_2N^+H_3]_0 - [\text{complex}]} = K_g([\text{crown}]_0 - [\text{complex}]) \qquad (4)$$

Figure 3 shows the plots of $[\text{complex}]([R(CH_2)_nN^+H_3]_0 - [\text{complex}])^{-1}$ versus $([\text{crown}]_0 - [\text{complex}])$: (a) for the **1** ($4.8_6 \times 10^{-5}$ M)–18-crown-6 (0–$9.9_6 \times 10^{-2}$ M) system, (b) for the **2** ($5.0_9 \times 10^{-5}$ M)–18-crown-6 (0–$7.5_1 \times 10^{-2}$ M) system, (c) for

Table I. Concentration Effects of 18-Crown-6 on the Fluorescence Intensity Ratio (I/I_0) of **1–4** in MeOH–H_2O (9:1) at Various Temperatures[a]

compd	concn, 10^{-5} M	18-crown-6, 10^{-4} M	I/I_0 at T (K) 280	290	300	310	320
1	4.8_6	0	1.0	1.0	1.0	1.0	1.0
		1.1_1	1.2_7	1.4_3	1.3_5	1.3_3	1.2_7
		2.2_1	1.6_5	1.6_7	1.6_3	1.5_9	1.4_8
		4.4_2	1.9_4	2.0_2	2.0_7	2.0_7	1.9_8
		$11._1$	2.2_3	2.5_2	2.7_4	2.7_7	2.7_8
		29	2.3_5	2.9_3	3.3_8	3.7_1	3.9_3
		$99._6$	2.4_1	2.9_6	3.5_5	3.8_4	4.2_8
		996	2.4_8	3.0_7	3.7_3	4.0_6	4.6_7
2	5.0_9	0	1.0	1.0	1.0	1.0	1.0
		0.83_3	1.1_3	1.1_3	1.1_1	1.1_1	1.0_5
		2.5	1.2_9	1.3	1.3_1	1.2_4	1.0_7
		3.3_3	1.3_5	1.3_9	1.3_7	1.2_6	1.1_3
		8.3_3	1.6	1.7_1	1.7_5	1.7_3	1.5_2
		$39._1$	1.8_6	2.1_6	2.5_2	2.8_5	2.7_7
		751	1.8_6	2.1_6	2.5_6	2.8_9	2.8_5
3	4.6_5	0	1.0	1.0	1.0	1.0	1.0
		0.94_7	1.5_7	1.6_2	1.5_8	1.4_3	1.2_7
		3.7_9	2.1_7	2.4_1	2.5_5	2.5_4	2.2_9
		9.4_7	2.3	2.5_9	2.8_6	3.0_4	2.9_4
		$54._1$	2.3_9	3.8_7	3.3_2	3.7_3	3.9_3
		541	2.4_7	3.8_6	3.5_3	4.0_7	4.4_1
4	8.5_5	0	1.0	1.0	1.0	1.0	1.0
		0.71_2	1.0_3	1.0_6	1.0_6	1.0_2	1.0_3
		1.4_2	1.0_6	1.0_7	1.0_8	1.0_5	1.0_5
		2.8_5	1.1_2	1.1_3	1.1_4	1.0_7	1.1_2
		7.1_2	1.1_5	1.1_7	1.1_7	1.1_9	1.2
		$72._6$	1.2_1	1.2_4	1.2_9	1.3_6	1.4
		726	1.2_2	1.2_6	1.3	1.4	1.4_9

[a] Errors within 5%.

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Table II. Ground-State Equilibrium Constants K_g for 18-Crown-6 Complexes of **1**–**4** in MeOH–H_2O (9:1) Determined by Fluorimetry[a]

compd	$K_g/10^3$ M^{-1} at T (K)					ΔG,[b] kcal mol^{-1}	ΔH, kcal mol^{-1}	ΔS, eu
	280	290	300	310	320			
1	4.4_1	2.4_4	1.7_8	1.2_5	1.0_7	−4.5	−6.3	−5.9
2	2.5_2	1.7_7	1.2_7	0.75_5	0.49	−4.2	−7.3	−10
3	9.0	5.8_5	3.6_8	2.3_9	1.6_8	−4.9	−7.6	−9.0
4	3.0_5	2.1_3	1.8_2	1.1_4	0.79_9	−4.4	−5.9	−4.9

[a] Errors within 5%. The experiments were carried out three times. [b] At 300 K.

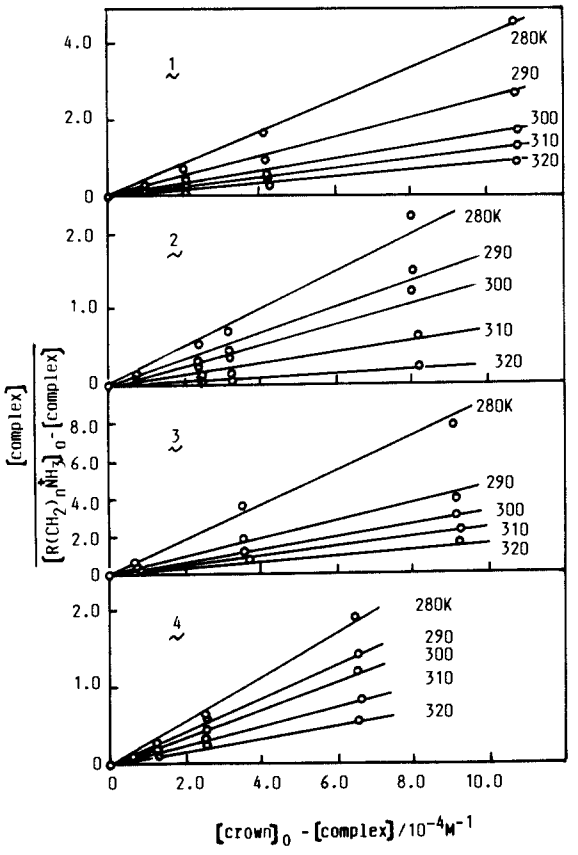

Figure 3. Plots of [complex] $([R(CH_2)_nN^+H_3]_0 - [complex])^{-1}$ as a function of ($[crown]_0$ − [complex]) at various temperatures.

the **3** ($4.6_5 \times 10^{-5}$ M)–18-crown-6 ($0–5.4_1 \times 10^{-2}$ M) system, and (d) for the **4** ($8.5_5 \times 10^{-5}$ M)–18-crown-6 ($0–7.2_6 \times 10^{-2}$ M) system in MeOH–H_2O (9:1) mixtures at various temperatures, each of which gives a straight line. The experimental results are in fair agreement with eq 4.

For example, the K_g values in MeOH–H_2O (9:1) at 300 K are determined to be $1.7_8 \times 10^3$, $1.2_7 \times 10^3$, $3.6_8 \times 10^3$, and $1.8_2 \times 10^3$ M^{-1} for the complexes of **1**, **2**, **3**, and **4** with 18-crown-6, respectively. The K_g values obtained at various temperatures are listed in Table II. The order of magnitude for the K_g values is $\sim 10^3$ M^{-1}, showing that the complexes of these ammonium ions with 18-crown-6 are very stable at moderate temperatures. Of special interest is that the K_g value of **3** (the number of methylene chain $n = 3$) is the largest one. The K_g value is highly dependent upon the steric interaction between the aromatic moiety and 18-crown-6.[22-24,27] It seems very likely that the ammonium cation

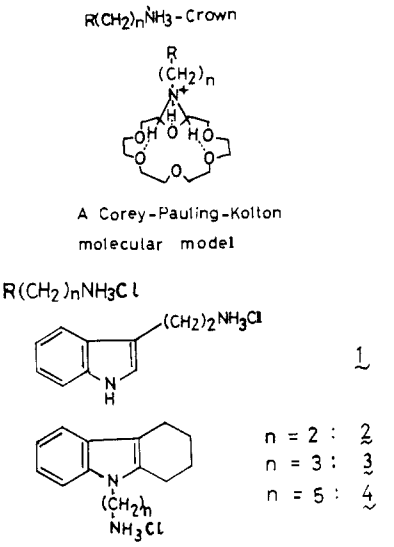

Figure 4. Schematic drawing of the 18-crown-6 complexes of tryptamine (**1**) and 1,2,3,4-tetrahydrocarbazoles **2**, **3**, and **4**.

in the complex may be displaced by about 1 Å above from the mean oxygen plane of 18-crown-6 as reported by Nagano et al.[29] Therefore, the steric interaction imposed by 18-crown-6 complex should decrease the value of K_g significantly. However, for the present systems $R(CH_2)_nN^+H_3$ (n = 2–5), the indole or tetrahydrocarbazole moiety R and the ammonium group $-N^+H_3$ are separated from each other by the methylene chain $-(CH_2)_n-$, resulting in a decrease of the steric interaction between R and $-N^+H_3$. Thus, the complexes of $R(CH_2)_nN^+H_3$ (except **2**) with 18-crown-6 are more stable compared to those of aromatic ammonium ions having no methylene chain,[22,24] as can be seen in a Corey–Pauling–Kolton molecular model as shown in Figure 4. For **2**, the methylene chain at $n = 2$ is not enough to reduce the steric interaction between the bulky tetrahydrocarbazole moiety and 18-crown-6.

From the van't Hoff plots of log K_g versus T^{-1}, the values of thermodynamic parameters, the free energy change (ΔG), enthalpy change (ΔH), and entropy change (ΔS) in MeOH–H_2O (9:1) were determined as shown in Table II. The ΔG values obtained are −4.2 ~ −4.9 kcal mol^{-1} at 300 K, which are slightly more negative than those of phenanthrylammonium ions (−1.8 ~ −4.3 kcal mol^{-1} at 300 K)[24] and naphthylammonium ions (−2.3 ~ −4.4 kcal mol^{-1} at 300 K).[22] These values are in the range −9.0 kcal mol^{-1} > ΔG > −2.9 kcal mol^{-1} observed for the complexes of *tert*-butylammonium salts with crown ethers.[30] The ΔH values are also negative (−5.9 ~ −7.6 kcal mol^{-1}), indicating that the complex formation between $R(CH_2)_nN^+H_3$ and 18-crown-6 is an exothermic reaction. The ΔS values are not so largely negative (−5.9 ~ −10 eu), although the hydrogen-bonded $R(CH_2)_nN^+H_3$–crown complexes are produced as shown in Figure 4. The result suggests that in an initial stage both $R(CH_2)_nN^+H_3$ and 18-crown-6 are hydrogen bonded to protic solvents. This suggestion seems to be supported by the fact that there is no spectral change in absorption

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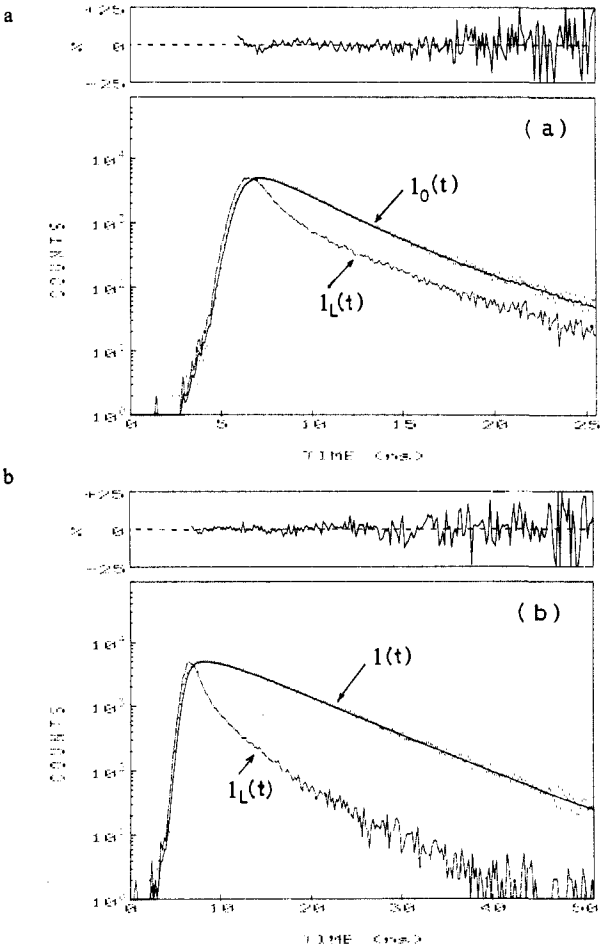
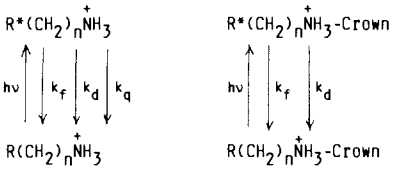


Figure 5. Observed fluorescence response functions $I_0(t)$ and $I(t)$ of **1** excited at 280 nm and monitored at 342 nm for the free **1** (a) and the **1**–crown complex ([crown] = $9.9_6 \times 10^{-2}$ M) (b), respectively, in MeOH–H_2O (9:1) at 300 K. The lamp functions monitored at 280 nm are shown as $I_L(t)$.

between free $R(CH_2)_nN^+H_3$ and the $R(CH_2)_nN^+H_3$–crown complex in MeOH–H_2O (9:1). These experimental results are in accordance with the previous observations.[22-24] Thus, we are able to demonstrate that the fluorimetric method[22-24] is very effective for the determination of the association constant K_g for the 18-crown-6 complexes of $R(CH_2)_nN^+H_3$. This method is very simple, compared to the usual calorimetric method.

Internal Quenching of Tryptamine Ammonium Ion (1) and Its Related Compounds (2–4). Kinetic analyses of the excited singlet state of the $R(CH_2)_nN^+H_3$–18-crown-6 complexes have been carried out in MeOH–H_2O (9:1) at various temperatures by means of the nanosecond single-photon-counting method (Horiba NAES-1100). Typical results are shown in Figure 5: (a) the observed fluorescence response function $I_0(t)$ for the free **1** in the absence of 18-crown-6 and (b) the observed fluorescence response function $I(t)$ for the **1**-18-crown-6 complex monitored at 342 nm together with the lamp function, $I_L(t)$, monitored at 280 nm. The decay functions $I_0(t)$ and $I(t)$ show single exponential decay (within the accuracy of Horiba NAES-1100) with lifetimes of 1.7_6 and 6.7_8 ns (error limit within 5%) at 300 K, respectively. The lifetime of the excited **1**–crown complex is 3.8_5 times greater than that of free **1**. This value is in good accordance with that (3.73) obtained from fluorescence intensity ratio I_{max}/I_0 of **1** at 300 K (see Table I) within experimental errors. The fluorescence decay of **1** is rather simple, in contrast to that of Trp having multiexponential decay as reported previously.[7,8,12,17,19] The radiative rate constant k_f of the excited complex was equal to that (ca. 6×10^7 s^{-1}) in the free excited **1** (the fluorescence quantum yield of free **1** was obtained to be 0.12_8 (±0.005) at 290 K). The result seems to be reasonable judging from the fact that no spectral change in both absorption and emission was observed with and without

Scheme I



18-crown-6. The difference in the fluorescence lifetimes does not originate from the nature of their excited singlet states, because no spectral difference in absorption and emission between the free **1** and the **1**–crown complex was observed. Recently, Gudgin-Templeton and Ware[17] have shown that reorientation of the solvent molecules occurs very rapidly after excitation leading to stabilization of the ^1L_a state below the ^1L_b state of tryptophan. In the present system, the fluorescent state is assumed to be the ^1L_a state at room temperature. The difference in the fluorescence lifetimes and intensities with and without 18-crown-6 is not ascribable to the photoionization[18] or charge transfer from the indole ring to solvent (CTTS)[17] for the following reason. The **1**–crown complex presumably has an extended conformation due to the steric repulsion between R and crown. That is, the R (indole) part is solvated by polar solvent molecules as well as the free **1**. Under such circumstances, it is very unlikely for such a complex that the rate constant of the photoionization or charge transfer to solvent becomes significantly small, compared to that of the free **1**. This difference cannot be explained by the photoionization.[18] In other words, the difference in the fluorescence lifetimes is not attributable to intermolecular quenching but should be due to intramolecular quenching. The ammonium group may well interact intramolecularly with the excited indole moiety R* resulting in the internal quenching. The complex formation of **1** with 18-crown-6 prohibits such an interaction, and as a result a relatively long lifetime (or a strong fluorescence intensity) is attained. Recently, James and Ware[31] have reported that the fluorescence decay behavior of tryptophan-like molecules (indole-3-alkanoic acids) is explained in terms of a dynamic interaction of the side chain with the solvated indole group during the excited lifetime.

The rate constant k_q for the intramolecular quenching is, therefore, expressed as

$$k_q = \tau_0^{-1} - \tau_{max}^{-1} \quad (5)$$

where τ_0^{-1} (= $k_f + k_d + k_q$) and τ_{max}^{-1} (= $k_f + k_d$) are the fluorescence decay rates of free tryptamine ammonium ion (**1**) (or its related compounds **2–4**) and the 1:1 corresponding ammonium ion–18-crown-6 complex, respectively (see Scheme I). For example, the value k_q of **1** at 300 K was obtained to be $4.2_1 \times 10^8$ s^{-1}, whose quantum yield Φ_q was determined to be 0.74. The value of Φ_q is simply given by

$$\Phi_q = k_q\tau_0 \quad (6)$$

Similarly, the fluorescence lifetimes for **2–4** increased considerably by complex formation with 18-crown-6 as shown in Table III. These experimental data can be reasonably accounted for by Scheme I where k_f, k_d, and k_q represent the rate constants for the radiative, radiationless (other than k_q), and internal quenching processes, respectively. The free $-N^+H_3$ group can attack the excited indole moiety $R^*(^1L_a)$ having intramolecular charge-transfer character with the rate constant k_q, but this was not the case for the excited complex $R^*(CH_2)_nN^+H_3$–crown as stated above.

From the linear Arrhenius plots of log k_q versus T^{-1} as shown in Figure 6 the frequency factor A and the activation barrier ΔE for the internal quenching process were obtained as 3.8×10^{11} s^{-1} and 4.1 kcal mol^{-1}, respectively, for **1**. The large A value appears to be reasonable, considering the fact that k_q is an intramolecular process. Similarly, the values of A and ΔE obtained for **2–4** are listed in Table III.

Kinetic H–D Isotope Exchange Reaction. In order to reveal the internal quenching process in more detail the kinetic H–D isotope exchange reaction has been quantitatively examined for

Table III. Fluorescence Lifetimes (τ_0 and τ_{max}),[a] Internal Quenching Rate Constant (k_q), the Quantum Yield for Internal Quenching (Φ_q), Frequency Factor (A) and Activation Energy (ΔE) for the Internal Quenching of **1**–**4** in MeOH–H_2O (9:1)[b,c]

compd	T, K	τ_0, ns	τ_{max}, ns	k_q, 10^8 s^{-1}	Φ_q	A, 10^{10} s^{-1}	ΔE, kcal mol^{-1}
1	223	5.8_6	7.7_2	0.41_1	0.24		
	243	5.0_5	7.5_1	0.64_9	0.33		
	263	3.5_1	7.3_9	1.5	0.53		
	280	2.4_9	7.0_3	2.5_9	0.64	3.8 × 10	4.1
	290	2.0_5	6.9_9	3.4_5	0.71		
	300	1.7_6	6.7_8	4.2_1	0.74		
	310	1.5	6.5_5	5.0_5	0.77		
	320	1.4	6.2	5.4	0.77		
2	223	9.7_5	$11._1$	0.12_5	0.12		
	243	8.5	$10._9$	0.25_9	0.22		
	263	7.1_6	$10._3$	0.42_6	0.31		
	280	5.2_4	8.7_4	0.76_4	0.40	2.0 × 10	4.3
	290	4.2_9	8.4_8	1.1_5	0.49		
	300	3.8_6	8.4_1	1.4	0.54		
	310	3.2_2	7.9_5	1.8_5	0.60		
	320	2.7_6	7.7_9	2.3_4	0.65		
3	223	8.5_9	$10._8$	0.23_8	0.20		
	343	7.1_8	$10._6$	0.44_9	0.32		
	263	5.8	10	0.72_4	0.42		
	280	4.6_5	9.5_2	1.1	0.51	1.5 × 10	3.9
	290	3.6	9.3_7	1.7_1	0.62		
	300	3.2_5	9.1_8	1.9_9	0.65		
	310	2.5_5	8.9_4	2.8	0.71		
	320	2.1_3	8.8_4	3.5_6	0.76		
4	280	8.6_6	9.8_3	0.14_1	0.12		
	290	8.3_6	9.7_9	0.17_5	0.15		
	300	7.9_4	9.7_7	0.23_6	0.19	1.1	3.7
	310	7.5_1	9.4_2	0.27	0.20		
	320	7.1_9	9.3_2	0.31_8	0.23		

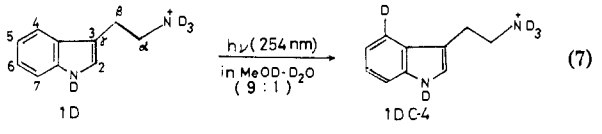
[a] τ_0 and τ_{max} denote the fluorescence lifetimes for the free compounds and the complexes with 18-crown-6, respectively. [b] Errors within 10%. [c] For details, see text.

Table IV. Fluorescence Lifetimes (τ_0^D and τ_{max}^D)[a] in the Absence and Presence of 18-Crown-6, Respectively, the Quantum Yield for Internal Quenching (Φ_q^D), Reaction Quantum Yield for the Kinetic H–D Isotope Exchange Reaction (Φ_R^D), Frequency Factor (A_D) and Activation Energy (ΔE_D) for the Internal Quenching of **1D** and **3D**, the Rate Constants k_q^D and k_σ^D for the Internal Quenching and the σ-Complex Formation, Respectively, and the Rate Constant (k_{CT}^D) for the Internal CT Quenching in CH_3OD–D_2O (9:1)[b,c]

compd	T, K	τ_0^D, ns	τ_{max}^D, ns	k_q^D, 10^8 s^{-1}	Φ_q^D	A_D, 10^{10} s^{-1}	ΔE_D, kcal mol^{-1}	Φ_R^D	position	k_σ^D, 10^8 s^{-1}	k_{CT}^D, 10^8 s^{-1}	$k\sigma/k_q^D$
1D	280	4.8_1	7.1_1	0.67_3	0.3_2							
	290	4.3	7.0_6	0.90_9	0.39			0.26	C-4	0.9_6	~0	~1
	300	3.7_1	6.9_1	1.2_5	0.46	2.7 × 10	4.6					
	310	3.2_2	6.7_1	1.5_7	0.51							
	320	2.9_6	6.5_7	1.8_6	0.55							
3D	280	7.8_2	$10._1$	0.28_9	0.23							
	290	6.7_4	9.8_4	0.46_7	0.31			0.07	C-8	0.16	0.30_9	0.34
	300	5.8_6	9.4_6	0.64_9	0.38	9.5 × 10	5.7					
	310	5.1_8	9.2_2	0.84_6	0.44							
	320	4.6_5	9.2_3	1.0_7	0.50							

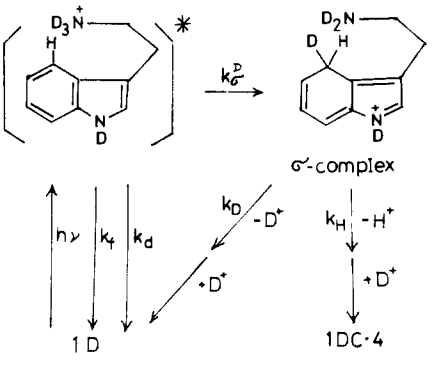
[a] τ_0^D and τ_{max}^D represent the fluorescence lifetimes of **1D** or **3D** with and without 18-crown-6 (9×10^{-2} M), respectively, whose fluorescence response functions showed single exponential decay. [b] Errors within 10%. [c] For details, see text.

1 and **3** in MeOD–D_2O (9:1) at 254 nm at 290 K. Saito et al.[14] have shown that the photochemical H–D isotope exchange reaction of **1** and **3** occurs mainly at C-4 and C-8 positions, respectively. In the present case, the kinetic H–D isotope exchange reaction of **1D** at 254 nm at 290 K took place highly selectively at C-4 with the reaction quantum yield $\Phi_R^D = 0.26$ (±0.02).[32] On the other hand, the rate constant k_q^D for the internal quenching of **1D** in MeOD–D_2O (9:1) was determined to be 0.91×10^8 s^{-1} at 290 K by measurements of τ_0^D and τ_{max}^D (see Table IV). There are kinetic isotope effects on the lifetime of the excited free tryptamine as well as the rate constant for the internal quenching.



1D 1DC-4 (7)

Scheme II



The quantum yield Φ_q^D for the internal quenching was obtained as 0.39 from the equation $\Phi_q^D = k_q^D \tau_0^D$. The experimental results of the photochemical H–D isotope exchange reactions are also listed in Table IV. The mechanism of the photochemical H–D exchange reaction may be represented by Scheme II where k_σ^D

(31) James, D. R.; Ware, W. R. *J. Phys. Chem.* **1985**, *89*, 5450.
(32) The conversion was about 7%. The amount of the H–D exchanged product was proportional to the irradiation time.

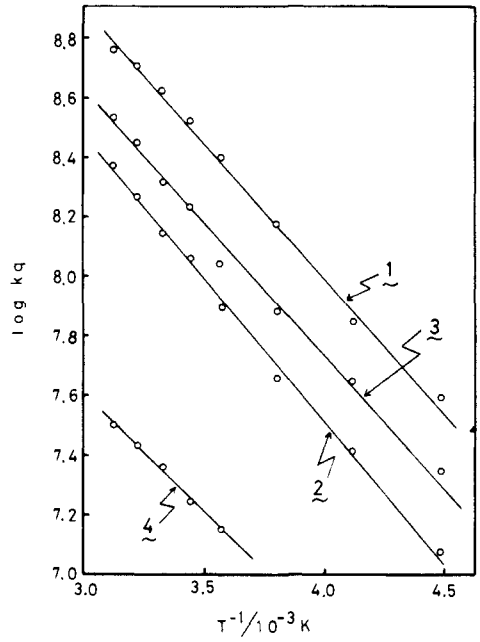


Figure 6. Arrhenius plots of log k_q versus T^{-1}.

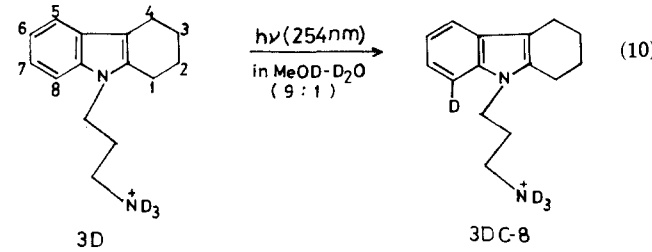
denotes the rate constant for the electrophilic attack at C-4 to produce the σ-complex. The deprotonation from the σ-complex gives the H–D exchanged product **1DC-4**, whereas the starting material **1D** is regenerated by deuteron loss from the σ-complex. The ratio (k_H/k_D) of the rate constants for deprotonation versus deuteron loss is estimated to be 1.7 from an analogous reaction.[21] The reaction quantum yield Φ_R^D for the H–D exchange reaction is thus expressed as

$$\Phi_R^D = \frac{k_\sigma^D}{k_f + k_d + k_q^D} \cdot \frac{k_H}{k_H + k_D} = k_\sigma^D \tau_0^D k_H (k_H + k_D)^{-1} \quad (8)$$

where Φ_R^D and τ_0^D are 0.26 and 4.3 ns, respectively, and the value of $k_H \cdot (k_H + k_D)^{-1}$ is estimated to be 0.63.[21] From eq 8, the value of k_σ^D can be evaluated as $0.9_6 \times 10^8$ s^{-1}. Thus, the rate constant k_q^D ($0.9_1 \times 10^8$ s^{-1}) for the internal quenching of **1D** is approximately equal to the rate constant k_σ^D for the deuteriation at C-4 in the excited state of **1D** within experimental error. Therefore,

$$k_q^D \simeq k_\sigma^D \quad (9)$$

the internal quenching of **1** is originated solely from the electrophilic proton transfer from the ammonium group to C-4 of the excited indole moiety, leading to hydrogen exchange (or deuterium exchange). It is known that external proton-induced quenching of aromatic compounds such as methoxynaphthalenes[21] occurs effectively due to the electrophilic protonation to one of the carbon atoms of the aromatic ring, leading to the hydrogen exchange (or deuterium exchange).[20,21] The LUMO coefficients of indole nuclei calculated by the INDO SCF method are as follows: C-2 (0.414), C-4 (0.502), and C-7 (0.458).[33] There is a possibility of the attack of the $-N^+D_3$ group to one of these three positions in the excited state of **1D**. However, the CPK molecular model suggests that it is only feasible for the C-4 position to interact with the $-N^+D_3$ group by rotation around both C_α–C_β and C_β–C_γ axes of the methylene side chain as already pointed out by Fleming's group.[8] For **3D**, similar experiments have been performed. The H–D isotope exchange reaction took place regioselectively at C-8 as shown in eq 10. The Φ_R^D value for **3D** at 290 K was 0.07 within 10% error limit. The intramolecular deuterium attack at C-8 was predictable by the CPK molecular model of **3D**. The k_q^D value of **3D** at 290 K was obtained to be $0.46_7 \times 10^8$ s^{-1} (see Table IV). The quantum yield Φ_q^D for the internal quenching of **3D** was



(10)

evaluated to be 0.31. The value of k_σ^D was estimated as 0.16×10^8 s^{-1} by using eq 8. The value of k_q^D is thus ca. 3 times greater than that of k_σ^D, indicating that the internal quenching k_q^D for **3D** involves a different quenching process in addition to the quenching leading to the deuteriation at C-8. Presumably, the former quenching mechanism may be due to the charge-transfer type quenching[6-8] between the excited indole moiety R* (electron donor) and the ammonium ion (electron acceptor) by considering the $n = 3$ rule in the case of **3**.[34] The intra- and intermolecular quenching of indole by carbonyl compounds is interpreted as resulting through the formation of an excited-state CT complex in which the excited indole acts as the donor.[35] For **3D**, eq 11 holds instead of eq 9

$$k_q^D = k_\sigma^D + k_{CT}^D \quad (11)$$

where k_{CT}^D is the rate constant for the CT quenching. An alternative explanation for quenching in **3D** is that the major quenching pathway may involve reversible deuteriation at the aromatic nitrogen, resulting in no net deuterium incorporation; CPK models suggest that the deuteriation at nitrogen may be favored conformationally over deuteriation at C-8. However, the exact mechanism for the CT quenching is not clear at present. These data are summarized in Table IV. The photochemical H–D isotope exchange reactions clearly show that the ratio of k_σ^D/k_q^D is unity for **1D**, but the ratio for **3D** is less than unity (0.34). That is, the internal quenching of **1** is caused exclusively by the intramolecular proton attack at C-4, but for **3** the quenching is caused only partially by proton attack at C-8. Another quenching mechanism, probably charge-transfer quenching is involved in the internal quenching of **3**.

Summary

(1) The association constants K_g for the 1:1 complex formation between tryptamine ammonium ion (**1**) or other indoles (**2–4**) and 18-crown-6 can be determined by the fluorimetric method, whose values are $\sim 10^3$ M^{-1} in MeOH–H_2O (9:1).

(2) The fluorescence lifetime of indoles **1–4** complexed with 18-crown-6 becomes longer compared to that of the corresponding free ammonium ion, resulting in the remarkable fluorescence enhancement.

(3) The relatively short lifetime in the excited singlet state of **1** is ascribed to the intramolecular quenching originating from the interaction between the excited indole moiety and the ammonium group.

(4) The rate constant k_q for the internal quenching can be estimated easily from eq 5 ($k_q = \tau_0^{-1} - \tau_{max}^{-1}$), where τ_0 and τ_{max} are the fluorescence lifetimes of free **1** (or its related compounds **2–4**) and the corresponding ammonium ion–18-crown-6 complex, respectively.

(5) The quantitative examination of the photochemical H–D isotope exchange reaction led to the finding that for the tryptamine ammonium ion **1** the internal quenching is caused completely by the electrophilic protonation at C-4 by the $-N^+H_3$ group (i.e., $k_q \simeq k_\sigma$) and that for the tetrahydrocarbazole derivative **3** the internal quenching comprises the electrophilic protonation at C-8 by the $-N^+H_3$ group in addition to the other quenching process. Probably, the charge-transfer quenching between the excited indole ring (electron donor) and the ammonium ion (electron acceptor) is involved in the latter process.

(33) The LUMO coefficients were calculated by Dr. K. Yamaguchi, Osaka University, by using the INDO SCF method.

(34) Hirayama, F. *J. Chem. Phys.* **1965**, *42*, 3163.
(35) Ricci, R. W.; Nesta, J. M. *J. Phys. Chem.* **1976**, *80*, 974.