Unusual Temperature Effect on Induced Circular Dichroism of Charge-transfer Complex in Micelles

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In sodium tetradecylsulfate micelles, a charge-transfer (CT) complex of amphiphilic [5]thiaheterohelicene with a chiral tetranitrofluorenone derivative induced intense circular dichroism (CD) absorption. The CD intensity decreased by up to about one fourth with a temperature decrease from 40 to 17 °C, and this temperature dependence was completely reversible.

The intensity of circular dichroism (CD) stemming from the chirality of substances may be considered as a measure of the degree of order in systems.[1] The higher the degree of order, the more intense the CD absorption. Thus, CD intensity increases with decreasing temperature and decreases with increasing temperature. This trend has been distinctly observed for macromolecules, such as peptides,[2] proteins,[3] and oligonucleotides,[4] and for supramolecular aggregates.[5] In this paper, we describe that the intensity of an induced CD of a charge-transfer (CT) complex embedded in micelles inversely correlates with temperature.

Previously, we reported an effective probe that can recognize chirality of chiral environments such as micelles[6] and bilayered membranes.[7] The compounds **1**[8] and **2**, which function as probes, are in rapid equilibrium between left-handed (*M*) and right-handed (*P*) enantiomers in solution, owing to a weak repulsion between hydrogen atoms of terminal rings. The equilibrium, however, shifts to either the *M* or *P* side when the probes are placed in chiral surroundings, thereby inducing CD absorption. **1**, possessing an electron-donating ability, forms a 1:1 CT complex with 2-(2,4,5,7-tetranitrofluoren-9-ylideneaminooxy)-propionic acid (TAPA) capable of withdrawing an electron cloud.[9] In a micellar solution, **2** undergoes CT and chiroptical interactions with (*R*)-TAPA, thereby inducing CD absorption. Herein, we investigated the CD absorption intensity of the amphiphilic suberic acid monoester **3**, which is expected to enhance the alignment of **3** with micellar molecules through van der Waals interaction and hydrogen bonding (Scheme 1).

As soon as **3** and (*R*)-TAPA were incorporated into sodium tetradecylsulfate (STS) micelles, their mixture became transparent with the red color of the CT complex and gradually, CD absorptions were induced. When the micellar solution was left to stand at 40 °C for approximately 4 h, the intensity of the absorption became steady with positive Cotton effects at approximately 337 nm due to the fixation of the helical moiety of **3** to a *P* enantiomer.[10] This micellar solution was stable at 40 °C for at least one day. However, with a gradual decrease in temperature, the CD absorption intensity of the solution decreased abruptly, whereas the UV absorptions were almost unchanged. The CD intensity at 337 nm declined by up to about one-fourth with a temperature decrease from 40 to 17 °C (Figure 1A). The temperature dependence of CD intensity was indicated by an S-shaped curve with an inflection point at about 27 °C (Figure 1B). This suggests that there are two stable states: a strong CD absorption at a high temperature of approximately 40 °C and a weak CD absorption at a low temperature of approximately 17 °C. Below 15 °C, the micellar solution became turbid, and above 42 °C, CD intensity gradually decreased due to the increasing instability of micelles because of the faster motion of the molecules.

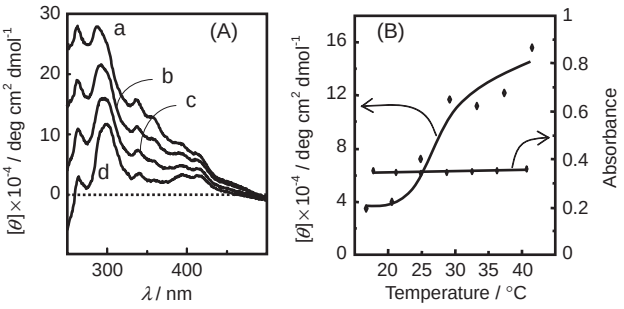
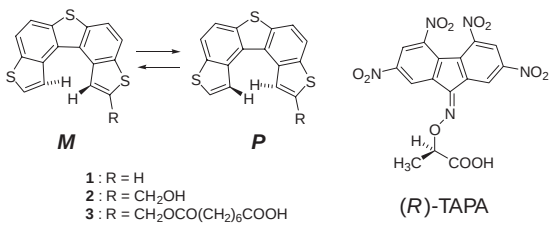


Figure 1. (A) Alterations of CD spectra of *P* enantiomer complex. 41.5 °C (a), 33.3 °C (b), 24.9 °C (c), and 16.7 °C (d). (B) Temperature dependence of CD (337 nm) and UV intensities (335 nm). [**3**] = [(*R*)-TAPA] = 1.01×10^{-4} M and [STS] = 2.5×10^{-3} M.

Furthermore, CD intensity was restored by an increase in temperature from 17 to 40 °C, revealing that both states are reversible and are equilibrated with each other. Then, CD intensity at 337 nm was measured at alternating temperatures of 40 and 17 °C. The reversibility of CD intensity at both temperatures was completely maintained for at least several cycles and the difference ($\Delta[\theta]$) in molecular ellipticity attained was large at approximately 134,000 deg cm^2 dmol^{-1} (Figure 2). The induced CD, caused by the equilibrium displacement between the *M* and *P* enantiomers of **3**, decreased with increasing temperature owing to the increase in helix inversion rate. The trend of temperature dependence in Figure 2 is clearly opposite to the trend of this equilibrium displacement, thus suggesting another mechanism of this reversible change.

In the present micellar system, in which the mobility of the molecule is fairly suppressed, two major interactions are considered to be responsible for this reversible change: CT interaction and hydrogen bonding. The apparent extinction coefficient (ε_{app})



Scheme 1.

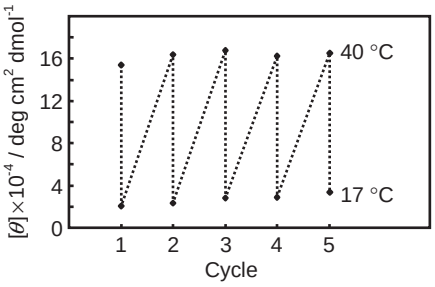


Figure 2. Reversibility of CD intensities at 337 nm measured at alternating 40.3 ± 0.2 and 17.2 ± 0.2 °C. Every measurement was performed at 20 min intervals.

of the CT band observed at approximately 520 nm did not show a monotonic decrease with increasing temperature (Figure 3). The profile of the plots in Figure 3 implies the existence of two different states at temperatures higher or lower than approximately 27 °C, in accordance with the result of $\Delta[\theta]$ in Figure 1B. The reversibility of this CT alteration was reproducible and is attributable to the difference between the relative locations of both **3** and (*R*)-TAPA in micelles. The composition of the CT complex in micelles was **3**/(*R*)-TAPA = 1/1, as determined using Job plots for the intensities of the CT band.

The carboxyl groups of **3** and (*R*)-TAPA are presumed to be linked by hydrogen bonds to the anionic moieties of the micellar molecules. Thus, a methyl ester of (*R*)-TAPA was prepared and adopted for this system to assess the effect of the hydrogen-bond disappearance. The micellar solution of the methyl ester and **3** induced marked CD absorption with negative Cotton effects. However, its CD intensity increased slightly with decreasing temperature from 40 to 18 °C (Figure 4). These results indicate that the hydrogen-bond largely contributed to the reversible change shown in Figure 2.

From the results mentioned above, the reversible change in CD intensity may be tentatively explained as follows: Below 27 °C, the strong hydrogen bonding of the carboxyl groups of **3** and (*R*)-TAPA to the STS ionic moieties separates the aromatic rings of both compounds, due to the longer chain of **3** than that of (*R*)-TAPA. This inevitably results in a separation between the helical moiety of **3** and the asymmetric carbon of (*R*)-TAPA, yielding a weaker chiroptical interaction and thus, a less intense CD absorption. Above 27 °C, on the other hand, the hydrogen bonds weaken and elongate, bringing the aromatic rings of both compounds closer to each other, because of the CT interaction between both aromatic ring moieties. This induces a close approach between both chiral centers, providing a stronger interaction and a more intense CD absorption.

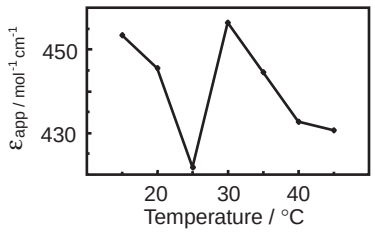


Figure 3. Temperature dependence of CT band intensities of *P* enantiomer complex at approximately 520 nm. [**3**] = [(*R*)-TAPA] = 1.01×10^{-4} M and [STS] = 2.5×10^{-3} M.

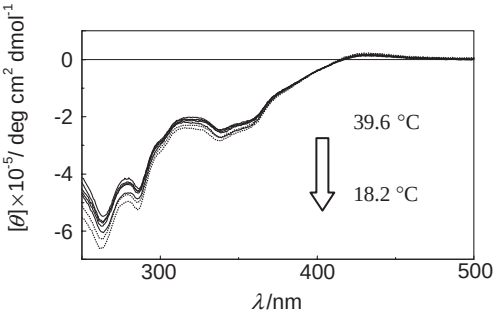


Figure 4. Temperature dependence of CD absorptions for the CT complex between methyl ester of (*R*)-TAPA and compound **3** in STS micelles. Temperatures are 39.6, 36.8, 33.1, 29.5, 21.9, and 18.2 °C. [**3**] = [methyl ester] = 1.01×10^{-4} M, [STS] = 2.5×10^{-3} M.

This unusual temperature effect was also observed for a combination of (*R*)-TAPA and a monoester of sebacic acid (8 methylenes), although the $[\theta]$ difference at 40 and 17 °C was small (50,000 deg cm^2 dmol^{-1}). On the other hand, the combinations of (*R*)-TAPA and monoesters of succinic (2 methylenes) or adipic (4 methylenes) acid showed induced CD with negative Cotton effects, and demonstrated no decrease in CD intensity with decreasing temperature. Furthermore, the use of sodium dodecylsulfate micelles instead of STS micelles also showed no unusual effect on temperature variations. These findings suggest that the suitable sizes of the molecules involved in the present system are essential for the occurrence of this anomalous phenomenon, which mimics biological reactions from the viewpoint of molecular recognition between receptors and substrates.

References and Notes

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