ORGANIC LETTERS

2007
Vol. 9, No. 5
887−890

Competing Supramolecular Assembly of Amphiphiles to Form Micelles or Pseudorotaxanes

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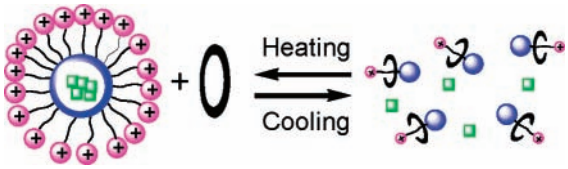
Received December 28, 2006

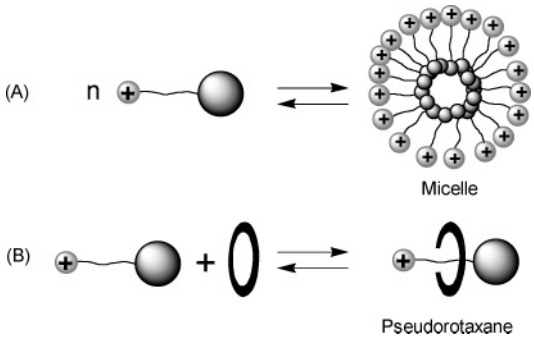
ABSTRACT



Micelles of an amphiphile that encapsulate the added dye in water can be released, upon addition of α-CD, to form pseudorotaxane. The equilibrium between the micelles and the pseudorotaxanes and the absorption spectra of solution are controlled by temperature reversibly.

Organic compounds having an ionic group and long alkyl chains, such as cetyltrimethylammonium bromide (CTAB), decyltrimethylammonium bromide (DTAB), and sodium *n*-dodecyl sulfate (SDS), function as amphiphiles and form micelles in water.[1] The intermolecular interaction of the hydrophobic groups of the molecules and the affinity of the ionic group to water stabilize the aggregation. Changing such nonbonding interactions, induced by an external stimulus, enables control of the reversible formation and degradation of micelles.[1,2] Consequently, amphiphiles with an alkyl group in an aqueous solution containing α-CD may aggregate to form micelles (Scheme 1A) or may form individual pseudorotaxanes with α-CD (Scheme 1B).[3−6] There have been a limited number of studies of competing supramolecular assembly reported.[7−9] Merbach observed the transformation of a perfluoroalkyl surfactant in micelle aggregation into its

Scheme 1. Competitive Formation of Micelles and Pseudorotaxanes of Amphiphilic Molecules



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10.1021/ol063137o CCC: $37.00
Published on Web 02/02/2007

pseudorotaxane with β-CD by using special NMR techniques.[9] On the other hand, Matsuo reported that amphiphic viologen derivatives $[C_{12}H_8N\text{-}N\text{-}(CH_2)_n\text{-}4,4'\text{-bpy-}N\text{-}^nPr]^+\text{-}(Br^-)_2$ (n = 4, 6, 8, 10, 12) form their pseudorotaxanes with CDs below critical micelle concentration (CMC, 1.2 mM for n = 12).[10] Here, we report the reversible conversion between micelles and pseudorotaxanes of cationic amphiphiles in the presence of α-CD and control of the micellization by changing temperature of the solution.

The amphiphilic compounds $[4,4'\text{-bpy-}N\text{-}(CH_2)_{10}OC_6H_3\text{-}3,5\text{-}R_2]^+(Cl^-)$ (R = ^{t}Bu (**1**) and OMe (**2**)), which are prepared by a reaction of 4,4′-bipyridine with $Cl(CH_2)_{10}OC_6H_3\text{-}3,5\text{-}R_2$ (R = ^{t}Bu, OMe),[11] are soluble in water and in organic solvents such as dichloromethane, chloroform, and acetone (Figure 1). Pseudorotaxanes of **1**, **2**, and CTAB with α-CD

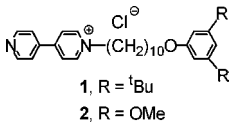


Figure 1. Structure of the amphiphilic molecule.

are formed in situ in water and characterized by NMR spectroscopy. Dissolution of α-CD and amphiphilic compounds leads to the appearance of new ^{1}H NMR signals, which indicate the inclusion complex of the linear molecules with α-CD. Parts A−C of Figure 2 show the $^{13}C\{^1H\}$ NMR

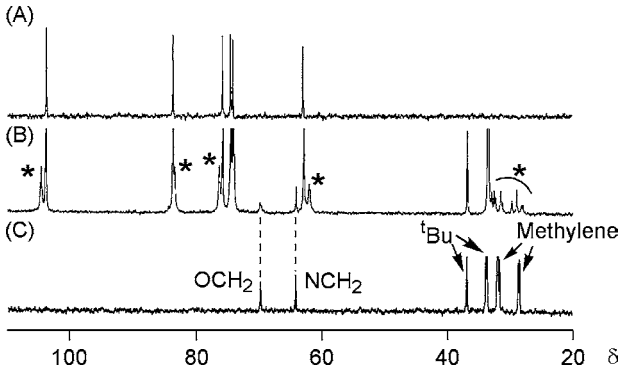


Figure 2. $^{13}C\{^1H\}$ NMR spectra of (A) α-CD, (B) a mixture of **1** and α-CD ($[\mathbf{1}]_0$ = 100 mM, $[\alpha\text{-CD}]_0$ = 300 mM), and (C) **1** in D_2O at room temperature (100 MHz). Sodium 3-(trimethylsilyl)-1-propanesulfonate (DSS) was used as an external standard. Peaks with an asterisk indicate the signals of the complex of α-CD and **1**.

spectra of α-CD, a mixture of α-CD and **1**, and **1** in D_2O, respectively. Spectrum B contains signals of the inclusion complex at 62.0, 76.5, 83.5, and 104.8 ppm, whose positions differ from those of the corresponding signals of α-CD (63.1, 76.0, 83.9, 104.0 ppm). CH_2 carbons of the axis molecule are observed as broad signals at lower magnetic field positions than those of **1**. The Job plot for formation of the inclusion complex, obtained from the ^{1}H NMR spectra data, showed a maximum at a molar fraction close to 0.4 (Figure 3), suggesting that **1** and α-CD form not only [2]pseudoro-

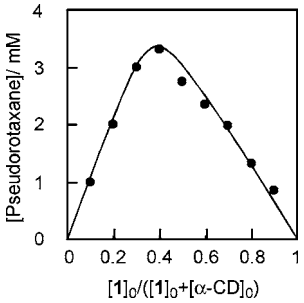
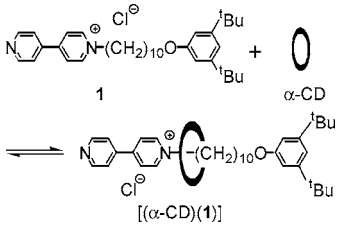


Figure 3. Job plot between **1** and α-CD based on ^{1}H NMR peak area ratios of bipyridinium protons. $[\mathbf{1}]_0 + [\alpha\text{-CD}]_0$ = 10 mM.

taxane, [(α-CD)(**1**)], Scheme 2, but also higher pseudorotaxanes such as $[(\alpha\text{-CD})_2(\mathbf{1})]$ in which the second α-CD

Scheme 2. Complexation of α-CD and **1**



includes the polymethylene group or an external ^{t}Bu group.[5,12,13]

Dissolution of **1** and pyrene ([pyrene] = 10 μM) in water leads to the aggregation of **1** to form micelles that encapsulate pyrene molecules in its core. Figure 4A shows absorption spectra of solutions with different concentrations of [**1**] (from 5×10^{-6} to 2.5×10^{-3} g mL^{-1}). The absorbance at 338 nm does not change in the solution with [**1**] < 2.5×10^{-4} g mL^{-1}, but increases remarkably at concentrations of **1** higher than 5×10^{-4} g mL^{-1} caused by encapsulation of the dye within micelles. The CMC of **1** was determined to be 1.4×10^{-4} g mL^{-1} (0.26 mM) at 25 °C on the basis of plots of

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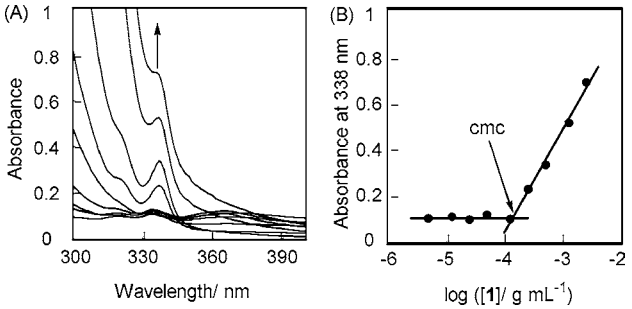


Figure 4. (A) Absorption spectra of pyrene and **1** in aqueous solutions with various concentrations of **1** (from 5×10^{-6} to 2.5×10^{-3} g mL^{-1}). (B) Plots of absorbance at 338 nm vs concentration of **1**.

absorbance at 338 nm versus [**1**] (Figure 4B). The CMC of **2** was similarly determined to be 0.65 mM (25 °C). Dynamic light scattering measurement showed the hydrodynamic radius of a micelle in an aqueous solution ([**1**] = 18.6 mM) to be 61 ± 11 nm at 25 °C. The addition of α-CD to the micellar solution of **1** containing pyrene ([**1**] = 9.5 mM, [α-CD] = 47.5 mM) at 25 °C significantly decreased absorption at 338 nm (Figure 5A, a,b).

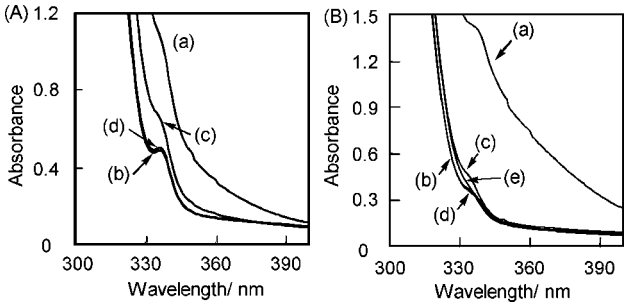


Figure 5. (A) Absorption spectra of pyrene ([Pyrene]$_0$ = 10 μM) in the presence of **1** and α-CD and ([**1**]$_0$ = 9.5 mM, [α-CD]$_0$ = 47.5 mM) (B) of **2** and α-CD ([**2**]$_0$ = 5.0 mM, [α-CD]$_0$ = 30 mM). The spectra were obtained in the following order: (a) at 25 °C, (b) after the addition of α-CD at 25 °C, (c) after heating to 60 °C, (d) after cooling to 25 °C, and (e) after heating to 60 °C.

Heating the solution to 60 °C caused a partial restoration of absorbance. These results indicate that the micelles of **1** are destructed by α-CD and form a pseudorotaxane at 25 °C, and that they are converted back into micelles by heating. Figure 5B shows the absorption spectrum of an aqueous solution containing **2**, pyrene, and α-CD under conditions similar to those of the solution containing **1**, pyrene, and α-CD. The change in absorption caused by a temperature change is much smaller than that shown in Figure 5A. A mixture of CTAB, α-CD, and pyrene also exhibits slight temperature-dependent change. The pseudorotaxanes of **2** and CTAB with α-CD seem to be too stable to undergo significant destruction by heating. CTAB and α-CD form a pseudorotaxane with a high association constant (K_a = 1110 M^{-1} at 25 °C).[14,15] Figure 6 shows the reversibility of the change in the absorbance of a solution of α-CD, **1**, and pyrene at 338 nm induced by a temperature change between 25 and 60 °C. Cycles of decreasing and increasing absorbance caused by the reversible formation and destruction of micelles were observed at least five times without differences in the change in absorbance. Scheme 3 shows a plausible

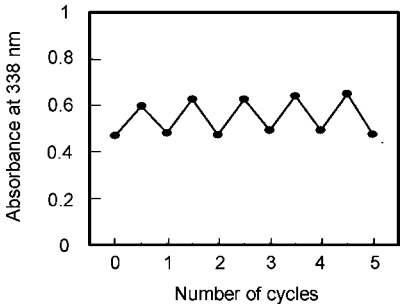
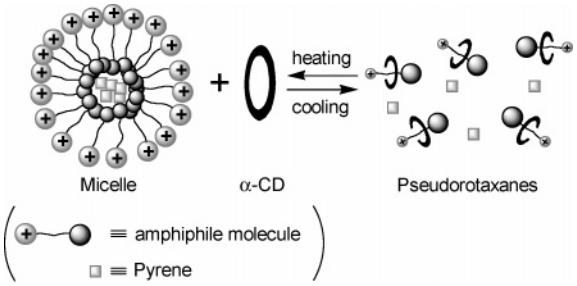


Figure 6. Five switching cycles of decreasing and increasing absorbance of mixture of **1**, α-CD, and pyrene at 338 nm between 25 and 60 °C.

Scheme 3. Plausible Mechanism of Changes in Absorption Spectrum of a Solution of Pyrene, α-CD, and Amphilic Molecules at Various Temperatures



mechanism that accounts for the changes in the absorption spectrum. Amphiphile molecules form micelles via the encapsulation of dye in water or pseudorotaxanes with α-CD. Since the latter complexation is highly entropy-dependent,[3−5] the pseudorotaxane formed tends to be destructed to free-axis and macrocyclic molecules at a high temperature.[16] Thus, the aggregation of amphiphile molecules, forming micelles, is favored at 60 °C. Although the stability of micelles may

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(15) The higher stability of pseudorotaxanes of **2** and α-CD than that of **1** and α-CD is confirmed by following ^{1}H NMR experiments. Dissolution of α-CD and **2** ([α-CD]$_0$ = [**2**]$_0$ = 10 mM) in D_2O forms pseudorotaxanes. The ^{1}H NMR spectrum of the solution shows consumption of free **2**. A similar aqueous solution of **1** ([α-CD]$_0$ = [**1**]$_0$ = 10 mM) shows the ^{1}H NMR signals of free **1** as well as signals of pseudorotaxane. Further addition of α-CD (30 mM) to the solution was required to converts all free **1** into pseudorotaxanes. See the Supporting Information for the change of NMR signals depending on addition of α-CD.

(16) Complexation of CD onto ^{t}Bu substituents of the axis molecules may also influence the equilibrium in part.

also be influenced by temperature, micelles composed of **1** and pyrene in an aqueous medium do not undergo destruction at 60 °C.

Other amphiphiles, for example, **2** and CTAB, form stable pseudorotaxanes with α-CD and do not exhibit a temperature-dependent change into micelles. Although the switching system using **1** and α-CD is based on the balance of a small energy difference between the supramolecular assemblies, it can be performed precisely and repeatedly.

In summary, we presented supramolecular switching between pseudorotaxanes and micelles by temperature alteration. This approach using the transformations of a supramolecule switching system may provide a new means of designing an artificial molecular device that responds to a small temperature change.

Acknowledgment. We thank Prof. Takakazu Yamamoto of our institute for dynamic light scattering (DLS) measurements. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and by a 21st Century COE Program "Creation of Molecular Diversity and Development of Educationalities".

Supporting Information Available: Synthesis of compounds and ^{1}H NMR spectra of the mixtures of **1** (or **2**) and α-CD. This material is available free of charge via the Internet at http://pubs.acs.org.

OL063137O