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Thermoresponsive Shuttling of Rotaxane Containing Trichloroacetate Ion

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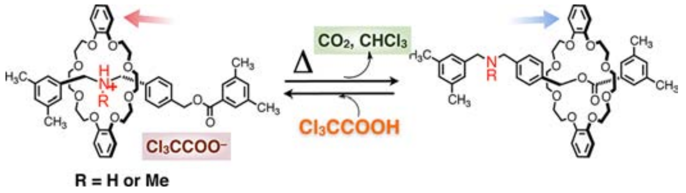
ABSTRACT



A thermoresponsive rotaxane shuttling system was developed with a trichloroacetate counteranion of an ammonium/crown ether-type rotaxane. Chemoselective thermal decomposition of the ammonium trichloroacetate moiety on the rotaxane yielded the corresponding nonionic rotaxane accompanied by a positional change of the crown ether on the axle. The rotaxane skeleton facilitated effective dissociation of the acid, markedly lowering the thermal decomposition temperature.

Ammonium/crown ether-type rotaxane is a fascinating member of the rotaxane class, which consists of crown ether as the wheel component and dumbbell-shaped *sec*-ammonium salt as the axle component.[1] The ammonium moiety localizes at the center of the crown ether cavity. Deprotonation of the ammonium axle is quite difficult because of both thermodynamic stabilization (delocalized ammonium cation charge through hydrogen bonds with the crown ether) and kinetic stabilization (because steric hindrance prevents the approach of a base).[2] However, achieving deprotonation brings about a unique and attractive molecular switch, changing the location of the crown ether from the ammonium to another position. Several methods of producing nonionic rotaxanes, such as direct neutralization with the help of a metastable position,[3] *N*-acylation reaction of the ammonium moiety,[4] tertiarization of the nitrogen atom,[5] and counteranion exchange,[6] have been developed and applied to versatile stimuli-responsive systems.[7] We have recently developed several

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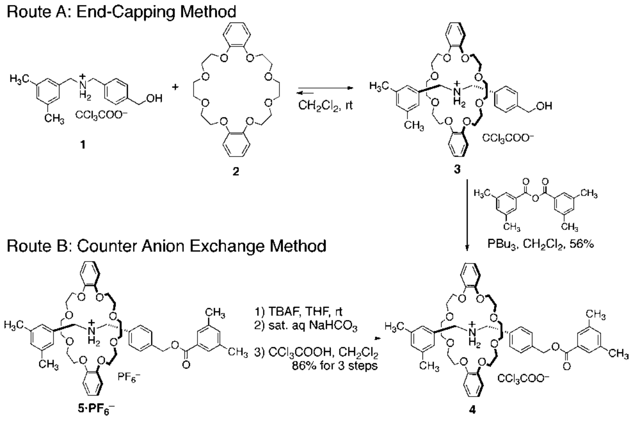
rotaxane-incorporated polymer systems capable of amplifying subtle and precise rotaxane movements to macroscopic polymer property changes, e.g., molecular switch-linked reversible helical switches,[8] stimuli-degradable network polymers,[9] and dynamic graft polymer systems.[10] However, these polymer systems suffer serious limitations on repeated use because accumulated residues of the salts and catalysts used can degrade the polymer material. To improve such polymer systems, we became intrigued by the potential usefulness of the trichloroacetate ion (CCl_3COO^-) as a rotaxane counteranion. It is well-known that CCl_3COOH (bp 198 °C) undergoes decomposition at 167 °C to CO_2 gas and volatile $CHCl_3$.[11] Therefore, we envisaged that heating ammonium trichloroacetate-type rotaxane could yield the free amine-type rotaxane *without any residue*. The addition of CCl_3COOH to the free amine-type rotaxane residue could reproduce the original ammonium trichloroacetate-type rotaxane, providing a novel switching system.

Herein, we describe the development of the accumulation-free thermoresponsive rotaxane shuttling system driven by the chemoselective thermal decomposition of ammonium trichloroacetate. In this study, it turned out that the rotaxane skeleton facilitated effective dissociation of the acid, markedly lowering the thermal decomposition temperature of trichloroacetic acid.

Scheme 1 shows the synthesis of trichloroacetate ion containing rotaxane *via* two pathways, the end-cap method (route A) and the counteranion exchange method (route B). Treatment of *sec*-ammonium salt **1** as the axle moiety in the presence of dibenzo-24-crown-8-ether (DB24C8, **2**) in CH_2Cl_2 gave pseudorotaxane **3**. The end-capping reaction of **3** with 3,5-dimethylbenzoic anhydride gave a moderate yield (56%) of trichloroacetate ion containing rotaxane **4** (Scheme 1, route A).[12] Rotaxane **4** could also be synthesized *via* the counteranion exchange method (route B)[6b] recently developed by our group. The easily prepared PF_6-type rotaxane $\mathbf{5{\cdot}PF_6}^-$ was exposed to a solution of $Bu_4N^+F^-$ (TBAF) in THF to give a dynamic equilibrium mixture of ($\mathbf{5{\cdot}PF_6}^- + Bu_4N^+F^-$) and ($\mathbf{5{\cdot}F}^- + Bu_4N^+PF_6^-$). Successive deprotonation of $\mathbf{5{\cdot}F}^-$ with sat. aq $NaHCO_3$ proceeded smoothly to give a nonionic rotaxane because of the low thermodynamic stability of $\mathbf{5{\cdot}F}^-$ on the basis of the HSAB principle.[13] Subsequent treatment of the neutral rotaxane with CCl_3COOH and repeated precipitation of the crude material into Et_2O afforded rotaxane **4** at 86% overall yield.

Scheme 1. Synthesis of Trichloroacetate Ion Containing Rotaxane **4**



Considering its potential for application in versatile polymer systems, we investigated the solid state thermal decomposition behavior of rotaxane **4** (shown in Scheme 2). The reaction progress was confirmed by thermogravimetric analysis (TGA). The TGA profile of **4** exhibited two weight-loss steps (Figure 1); the first degradation occurred between 59 and 84 °C, and the second one occurred at approximately 240 °C. When heating was stopped at 200 °C it was apparent that chemoselective thermal decomposition of the ammonium trichloroacetate moiety on rotaxane **4** had occurred, yielding the nonionic rotaxane **6** as a single product with quantitative yield. The structure of **6** was confirmed by ^1H NMR, ^{13}C NMR, IR, and MS spectra.[12] The measured weight loss (15.7%), from **4** to **6**, during the first degradation step (59−84 °C) was almost the same as the calculated weight loss expected from the loss of trichloroacetic acid from **4** (16.3%).

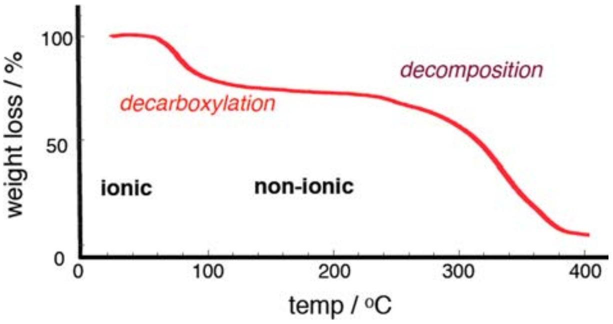


Figure 1. TGA profile of **4** under nitrogen atmosphere (heating rate of 10 °C·min^{-1}).

Figure 2 shows the ^1H NMR spectra of DB24C8 (**2**), rotaxane **4**, and nonionic rotaxane **6**. In spectrum B, the characteristic signals of *N*-benzyl protons (d and e, $\delta = 4.45$ and 4.63 ppm) in the axle component of **4** appeared as broad peaks because of geminal coupling, strongly

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[12] See Supporting Information.

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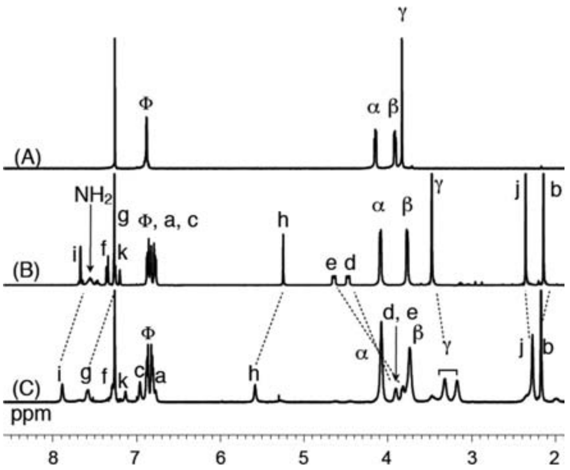
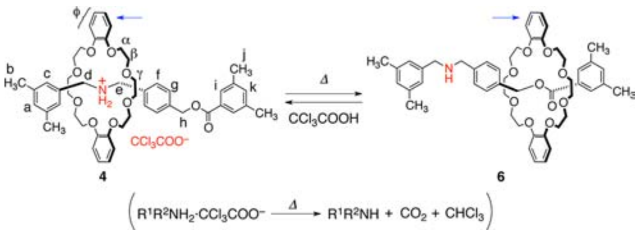


Figure 2. ^1H NMR spectra (400 MHz, $CDCl_3$, 298 K) of (A) DB24C8 (**2**), (B) rotaxane **4**, and (C) nonionic rotaxane **6**.

Scheme 2. Shuttling System of **4** and **6**, Driven by Heating and Addition of CCl_3COOH

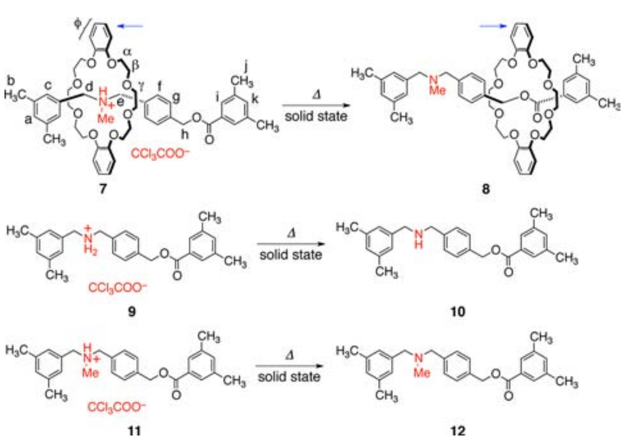


supporting the rotaxane structure, in accordance with the literature.[14] The *N*-benzyl proton signals (d and e) in the spectrum of **6** were upfield-shifted, agreeing with a nonionic structure (see Figure 2C). In addition, some axle signals in the spectrum of **6** were shifted by a ring current effect from DB24C8; the *O*-benzyl proton signal (h, δ = 5.29 ppm) and aromatic proton signals (g and i, δ = 7.26 and 7.68 ppm) were downfield-shifted. The end group methyl proton signals (b and j, δ = 2.16 and 2.38 ppm) showed the opposite behavior to such signals, probably because of shielding effects from DB24C8. These spectral changes were most characteristic and led toward our understanding of the translation of the wheel component to a new position on the axle.[6b]

Treatment of **6** with CCl_3COOH yielded **4** (see Scheme 2), suggesting that the shuttling system was established without any residue accumulation.

Next, we investigated the thermal decomposition reactions of various ammonium trichloroacetates, including rotaxane **7**, axle **9**, and axle **11** (Scheme 3), to determine why the rotaxane **4** ammonium trichloroacetate moiety thermally decomposed at a much lower temperature (59−84 °C) than CCl_3COOH (167 °C). Progress of the reactions was confirmed by TGA (Figure 3). Heating **7**, **9**, and **11** to 200 °C resulted in the chemoselective degradation of the ammonium trichloroacetate moiety to give quantitative yields of the free amines **8**, **10**, and **12**, respectively. The structures of **8**, **10**, and **12** were confirmed by ^1H NMR, ^{13}C NMR, IR, and MS spectra.[12]

Scheme 3. Thermal Decomposition Reactions of **7**, **9**, and **11**



The ^1H NMR spectra of rotaxanes **7** and **8** (Figure 4) showed that heating *tert*-ammonium-type rotaxane **7** also resulted in the wheel translation seen with rotaxane **4**. In spectrum B the *N*-benzyl proton signals (d and e) and the *N*-Me proton signals were upfield-shifted compared to spectrum A, suggesting a nonionic structure of **8**. The *O*-benzyl proton (h), aromatic proton (g and i), and methyl proton (b and j) peak-shift patterns from the conversion from **7** to **8** were similar to those seen from the conversion **4** to **6**, indicating that wheel translation occurred during the conversion of **7** to **8**.[5]

The results of the thermal decomposition of **7**, **9**, and **11** are summarized in Table 1. The measured weight-loss values of **7**, **9**, and **11** agree well with calculated values. The 50% decarboxylation temperature estimated by TGA analysis ($T_{d1/2}$) of rotaxane **7** was higher (100 °C) than that of **4** (71 °C), indicating decreased decarboxylation capability of the counteranion of **7**, which we attribute to the

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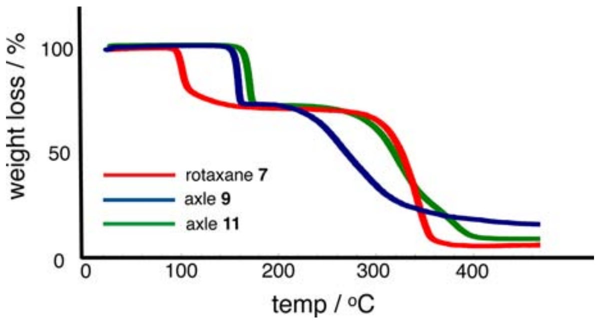

Figure 3. TGA profiles of **7**, **9**, and **11** under nitrogen atmosphere (heating rate of 10 °C·min^{-1}).

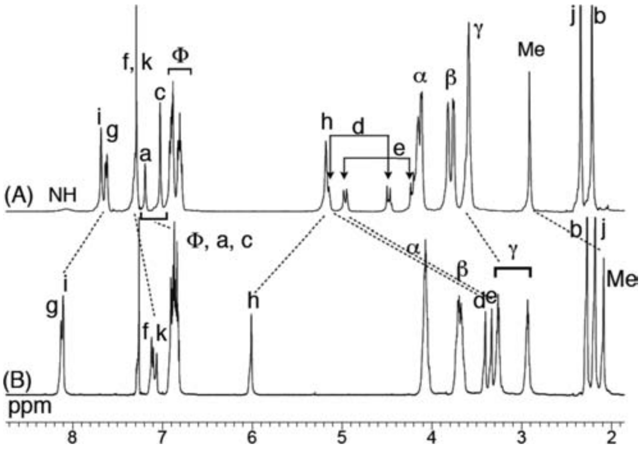

Figure 4. ^{1}H NMR spectra (400 MHz, $CDCl_3$, 298 K) of (A) rotaxane **7** and (B) nonionic rotaxane **8**.

Table 1. Effect of Ammonium Structure on Thermal Decomposition of Ammonium Trichloroacetates

ammonium trichloroacetate	$T_{d1/2}$/°C^a	weight loss (measured)/%^{b}	weight loss (calculated)/%^{c}
rotaxane **4**	71	15.7	16.3
rotaxane **7**	100	19.0	16.1
axle **9**	158	26.2	29.7
axle **11**	169	29.2	28.9

^{a} 50% Decarboxylation temperature determined by TGA analysis (under nitrogen atmosphere, heating rate of 10 °C min^{-1}) on the basis of the weight-loss value at the sharp inclination region. ^{b} Measured by TGA analysis. ^{c} Calculated weight loss of the substrate.

introduction of a substituent on the nitrogen atom. Steric factors in **7** will reduce the kinetic acidity and lead to partial generation of CCl_3COOH in an equilibrium mixture. The $T_{d1/2}$'s of DB24C8-free axles **9** (158 °C) and **11** (169 °C) were higher than the $T_{d1/2}$'s of the corresponding rotaxanes **4** and **7**. It is particularly interesting that the threading structure of DB24C8 with the ammonium cation facilitates decarboxylation of the counteranion without any residue accumulation, in contrast to the decarboxylation of an alkali metal trichloroacetate with 18-crown-6-ether, which leads to inorganic salt residues.[15]

In conclusion, in this study, we present the construction of an accumulation-free thermoresponsive rotaxane shuttling system driven by the chemoselective thermal decomposition of ammonium trichloroacetate, which could prove ideal for repeated use of rotaxane-incorporated polymer systems. This is a new synthetic method for producing a nonionic rotaxane and a new molecular switch. Further studies on the application of this system to polyrotaxane and stimuli-responsive polymer systems are currently underway.

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Supporting Information Available. Full experimental details for all new compounds are provided, including ^{1}H NMR, ^{13}C NMR, and IR spectra and TGA profiles of ammonium trichloroacetates. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.

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