Rotaxanes Functionalized by Chirality: Novel Rotaxanes Consisting of Binaphthol-Based Chiral Crown Ether

Yuya Tachibana, Nobuhiro Kihara,* Yasuko Ohga, and Toshikazu Takata*
Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University, Gakuen-cho, Sakai, Osaka 599-8531

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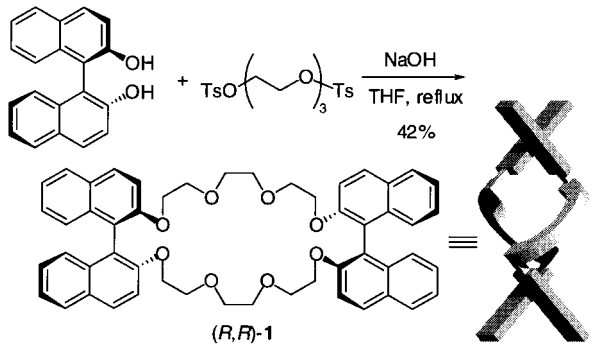
A chiral crown ether **1** was synthesized from (*R*)-1,1'-bi-2-naphthol. Chiral rotaxanes were prepared by end-capping of pseudorotaxanes consisting of **1** and secondary ammonium salts. An ammonium salt bearing terminal anthracene group gave stable pseudorotaxane. Chiral induction was observed during end-capping by radical conjugate addition of a bulky thiol to the pseudorotaxane bearing methacrylate group at the terminus.

Interlocked compounds such as rotaxanes and catenanes have been effectively constructed using intermolecular interactions of the components.[1–3] It has been demonstrated that the combination of crown ether and secondary ammonium salt, where hydrogen-bonding interaction plays an important role, is one of the most promising couples.[4,5] Since 24-membered ring is, at least, necessary as a ring component for preparation of rotaxane,[6] 24-crown-8 ether and its benzologues have been extensively used except for one report.[7] Functional crown ethers with different ring size should be necessary for the preparation of rotaxanes that are designed for certain applications, although little is known for the construction of rotaxanes with larger ring-size of crown ethers.

As a simply functionalized crown ether, we have designed a novel chiral crown ether **1** that is easily accessible from 1,1'-bi-2-naphthol.[8] A rotaxane functionalized by chirality is expected to be prepared using **1** as a source of excellent chiral environment.[9,10] Since **1** has 28-membered ring with non-planar structure, however, we have found that specific design of axle ammonium salt is necessary for the construction of rotaxane from **1**. In this paper, we wish to report syntheses of **1** and rotaxanes consisting of **1** as a ring component utilizing end-capping methods developed by us.[5]

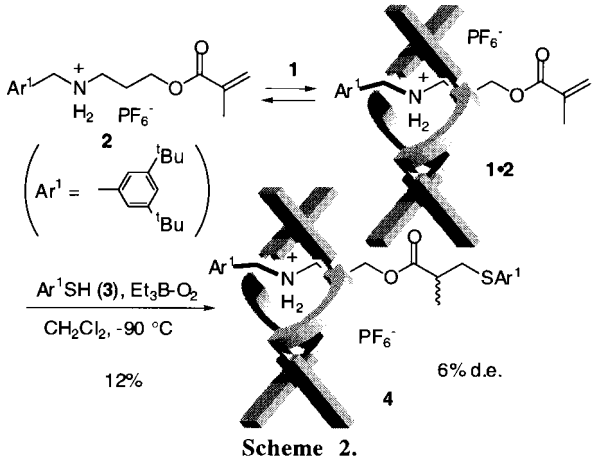
(*R*,*R*)-**1** was successfully synthesized by direct [2+2] condensation of (*R*)-1,1'-bi-2-naphthol and triethyleneglycol ditosylate in 42% yield.[11] Sodium hydroxide was the best base for the condensation among alkali metal hydroxides examined.



Scheme 1.

First, radical conjugate addition protocol was investigated as an end-capping method for rotaxane synthesis.[5b] While 3,5-di-*t*-butylphenyl and 9-anthracenyl groups were bulky enough as end-caps to prevent threading of **1** by CPK molecular model experiments, 3,5-dimethylphenyl and *t*-butyl groups were too small as the end-cap. Therefore, the most bulky 3,5-di-*t*-butylphenyl group was selected as the end-cap substituent. Although ammonium salt **2**[5a] was insoluble in $CDCl_3$, **2** became soluble by the addition of **1**, suggesting the formation of a complex. In the ^1H NMR spectrum of the mixture, a new set of signals that are assignable to pseudorotaxane **1·2** appeared. The association constant K_a of **1** and **2** was estimated from each integral of the ^1H NMR signals. The results are summarized in Table 1. The K_a of **2** with **1** is far smaller than that with dibenzo-24-crown-8 ether.[5a] The radical addition of bulky thiol **3** to **1·2** at –90 °C was carried out in dichloromethane initiated by triethylborane-oxygen. The desired [2]rotaxane **4** was obtained in 12% yield.[12] Rotaxane structure of **4** was confirmed by several spectral data including ^1H NMR, FAB-MS, and IR spectra, and also the fact that repeated chromatography did not separate each component.

Second, acylative end-capping protocol was also investigated for the construction of rotaxane based on **1**.[5c] Since the low yield of **4** came from the low K_a of **1·2**, terminal group on the ammonium salt that does not disturb the complexation with



Scheme 2.

Table 1. The association constant *Ka* of ammonium salt with **1**

Salt	Temp. / °C	Solvent	Ka [a] / M^{-1}
2	10	dichloromethane	8.6
2	-60	dichloromethane	22.3
2	10	chloroform	3.3
5	22	chloroform	730

[a]Estimated from integral of ^1H NMR signals of pseudorotaxane and free salt (for **2**) or those of pseudorotaxane extracted by the addition of **1** (for **5**).[17]

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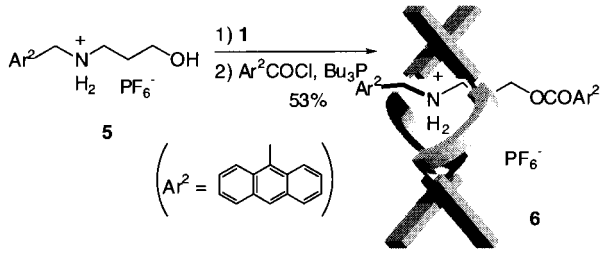
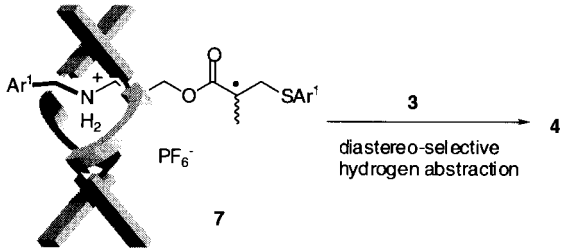
1 would increase the stability of the pseudorotaxane and hence the yield of rotaxane. We found anthracene-based ammonium salt **5** showed higher K_a with **1** as shown in Table 1. The π–π interaction of the planar anthracene moiety might increase the stability of the pseudorotaxane **1·5** by fitting in the cleft of the binaphthol group. Thus, **1·5** was successfully acylated by anthracenecarbonyl chloride using tributylphosphine as a catalyst to give corresponding [2]rotaxane **6** in 53% yield.[13] Rotaxane structure of **6** was confirmed similarly to that of **4**.



Scheme 3.

In the formation of **4**, a new stereogenic center is generated at the position α to the carbonyl group. The stereoselectivity on the newly formed chiral center was 53:47 that was indirectly estimated by reduction of **4** to the corresponding alcohol followed by chiral HPLC analysis.[14] The first step of the end-capping is the addition of thiyl radical derived from **3** to C=C double bond of **2** to afford intermediate [2]rotaxane radical **7**. The chiral ring **1** surrounds the axle radical that has the sp^2 prochiral face at the radical center. The face selective hydrogen abstraction of **7** from **3** takes place under the chiral environment of **1**.[15] Although the degree of chirality induction is not high, this is the first example of asymmetric induction on rotaxane. Further, radical asymmetric reaction in acyclic system has not been known except for 1,2-asymmetric induction.[16]



Scheme 4.

In conclusion, rotaxanes functionalized by chirality were prepared using binaphthol-based crown ether **1** that had 28 membered ring. Although **1** has low complexation ability with 3,5-di-*t*-butylphenyl-terminated secondary ammonium salts, K_a greatly enhanced with 9-anthracenyl terminal group to increase the yield of rotaxane. Further, the rotaxane based on **1** provides an effective chiral environment. Asymmetric reactions on the rotaxane systems are under active investigation.

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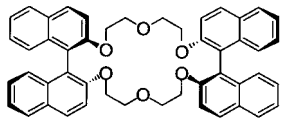
References and Notes

1 G. Schill, in "Catenanes, Rotaxanes and Knots," Academic Press, New York (1971).
2 H. W. Gibson, M. C. Bheda, and P. T. Engen, *Prog. Polym. Sci.*, **19**, 843 (1994).
3 J.-M. Lehn, in "Supramolecular Chemistry. Concepts and Perspectives," VCH, Weinheim (1995).
4 a) A. G. Kolchinski, D. H. Busch, and N. W. Alcock, *J. Chem. Soc., Chem. Commun.*, **1995**, 1289. b) P. R. Ashton, P. T. Glink, J. F. Stoddart, P. A. Tasker, A. J. P. White, and D. J. Williams, *Chem. Eur. J.*, **2**, 709 (1996). c) P. R. Ashton, R. Ballardini, V. Balzani, I. Baxter, A. Credi, M. C. T. Fyfe, M. T. Gandolfi, M. Gomez-Lopez, M.-V. Martinez-Diaz, A. Piersanti, N. Spencer, J. F. Stoddart, M. Venturi, A. J. P. White, and D. J. Williams, *J. Am. Chem. Soc.*, **120**, 11932 (1998). d) A. G. Kolchinski, N. W. Alcock, R. A. Roesner, and D. H. Busch, *Chem. Commun.*, **1998**, 1437. e) S. J. Rowan, S. J. Cantrill, and J. F. Stoddart, *Org. Lett.*, **1**, 129 (1999). f) S. J. Cantrill, D. A. Fulton, M. C. T. Fyfe, J. F. Stoddart, A. J. P. White, and D. J. Williams, *Tetrahedron Lett.*, **40**, 3669 (1999). g) S. J. Cantrill, S. J. Rowan, and J. F. Stoddart, *Org. Lett.*, **1**, 1363 (1999).
5 a) T. Takata, H. Kawasaki, S. Asai, N. Kihara, and Y. Furusho, *Chem. Lett.*, **1999**, 111. b) T. Takata, H. Kawasaki, S. Asai, Y. Furusho, and N. Kihara, *Chem. Lett.*, **1999**, 223. c) H. Kawasaki, N. Kihara, and T. Takata, *Chem. Lett.*, **1999**, 1015. d) Y. Furusho, T. Hasegawa, A. Tsuboi, N. Kihara, and T. Takata, *Chem. Lett.*, **2000**, 18.
6 S. Ganguly and H. W. Gibson, *Macromolecules*, **26**, 2408 (1993).
7 S. J. Cantrill, M. C. T. Fyfe, A. M. Heiss, J. F. Stoddart, A. J. P. White, and D. J. Williams, *Chem. Commun.*, **1999**, 1251.
8 Although well-known crown ether **8** provides excellent chiral environment,[9] we could observe no pseudorotaxane formation of **8** with any ammonium salt because its 22-membered ring is too small to thread alkyl chain.



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9 X. X. Zhang, J. S. Bradshaw, and R. M. Izatt, *Chem. Rev.*, **97**, 3313 (1997).
10 Recent example of chiral rotaxanes, a) A. Harada, *Acta Polym.*, **49**, 3 (1998). b) R. Schmieder, G. Hübner, C. Seel, and F. Vögtle, *Angew. Chem., Int. Ed. Engl.*, **38**, 3528 (1999). c) P. R. Ashton, J. A. Bravo, F. M. Raymo, J. F. Stoddart, A. J. P. White, and D. J. Williams, *Eur. J. Org. Chem.*, **1999**, 899.
11 White crystal. mp 212–218 °C (benzene–ether). $[\alpha]_D^{24}$ 142.2° (*c* 0.1, CH_2Cl_2). ^{1}H-NMR (270 MHz, $CDCl_3$): δ 7.93 (d, *J* = 8.9 Hz, 4H), 7.85 (d, *J* = 7.8 Hz, 4H), 7.44 (d, *J* = 8.9 Hz, 4H), 7.31 (ddd, *J* = 1.3, 6.8, and 8.4 Hz, 4H), 7.19 (ddd, *J* = 1.3, 6.8, and 7.8 Hz, 4H), 7.11 (d, *J* = 8.4 Hz, 4H), 4.16–4.05 (m, 4H), 4.02–3.93 (m, 4H), 3.52–3.42 (m, 4H), 3.41–3.31 (m, 4H), 3.23–3.11 (m, 8H). FAB-MS: *m/z* 800 (M^+). Found: C 75.85; H 5.95%. Calcd for $C_{52}H_{48}O_8 \cdot H_2O$: C 76.26; H 6.15%.
12 Colorless amorphase solid. ^{1}H NMR (270 MHz, $CDCl_3$): δ 8.0–6.8 (m, 31H), 6.60 (dd, *J* = 7.4 and 9.0 Hz, 1H), 4.4–2.6 (m, 38H), 1.32 (s, 9H), 1.31 (s, 9H), 1.24 (s, 18H). IR (KBr): 1733, 1591, 1506, 1456, 1222, 1074, 843, 557 cm^{-1}. FAB-MS: *m/z* 1368.5 ($[M - PF_6]^+$).
13 White crystal. mp 175–178 °C. $[\alpha]_D^{24}$ 223° (*c* 0.1, CH_2Cl_2). ^{1}H-NMR (270 MHz, $CDCl_3$): δ 8.60 (s, 1H), 8.59 (s, 1H), 8.19 (d, *J* = 8.6 Hz, 2H), 8.07 (d, *J* = 8.4 Hz, 2H), 8.00 (d, *J* = 8.4 Hz, 2H), 7.7–6.7 (m, 30H), 6.62 (d, *J* = 8.4 Hz, 2H), 6.18 (br, 2H), 6.13 (t, *J* = 7.4 Hz, 2H), 5.2–3.9 (m, 8H), 3.3–2.2 (m, 24H). IR (KBr): 1724, 852, 559 cm^{-1}. FAB-MS: *m/z* 1270.5 ($[M - PF_6]^+$).
14 Reduction of **4** by lithium aluminum hydride to give 3-(3,5-di-*t*-butylphenyl)thio-2-methyl-1-propanol. The ratio of the enantiomers was determined by chiral HPLC analysis (Chiracel OD®, eluted by hexane with 0.1% 2-propanol) to be 53:47.
15 Although similar asymmetric radical reaction in the system based on anthracene end-cap is very interesting, we do not investigate it because of potential reactivity of anthracene to radical.
16 D. P. Curran, N. A. Porter, and B. Giese, in "Stereochemistry of Radical Reactions," VCH, Weinheim (1996).
17 a) S. Ahrland and I. Grenthe, *Acta Chem. Scand.*, **11**, 1111 (1957). b) G. P. Haight, *Acta Chem. Scand.*, **16**, 209 (1962).