

Chemical Modification of Amide-Based Catenanes and Rotaxanes I. Synthesis of *secondary* Amine [2]Catenanes and [2]Rotaxanes by the Borane Reduction of *secondary* Amide [2]Catenanes and [2]Rotaxanes and Mobility of Their Components

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Various *secondary* amine [2]catenanes and [2]rotaxane were prepared by borane reduction of the corresponding *secondary* amide [2]catenanes and [2]rotaxane. Their structures were characterized by NMR, IR, and FAB-MS spectroscopies. The mobility of the components in solution was examined by ^{1}H NMR spectroscopy. The substituents on the isophthaloyl units of the catenanes prevented complete circumrotation of the macrocyclic components (“half rotation”). On the other hand, macrocyclic ring components bearing unsubstituted isophthaloyl units completely circumrotated through the other faster than on the ^{1}H NMR time scale (“full rotation”). In the case of the *secondary* amine [2]catenanes, no hydrogen bonding interaction between the *secondary* amino groups was observed. A dynamic ^{1}H NMR study showed a highly enhanced mobility of the components of the *secondary* amine [2]catenanes and [2]rotaxane compared with the corresponding amide compounds, even at lower temperature.

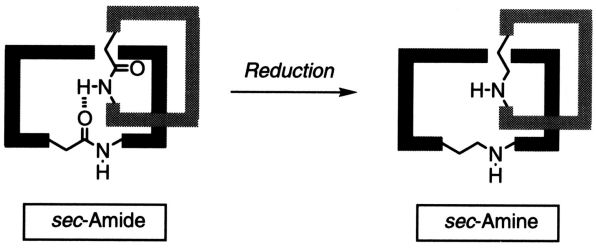
During the last two decades, chemists have developed synthetic methodologies, and have clarified the characteristics of mechanically interlocked molecules, such as catenanes, rotaxanes, and knots,[1] since Sauvage's pioneering work of Cu(I)-templated synthesis of a [2]catenane.[2] These methodologies rely on the utilization of some attractive interactions, such as the coordination of heterocyclic ligands to a metal cation, a π-π stacking interaction between electron-rich species and electron-deficient ones, or a hydrogen-bonding interaction. One very essential feature of these molecules is that their mechanically interlocked units have a high degree of freedom in relative motion of the components. Based on this aspect, one could easily expect that polymers having mechanical bonds would exhibit unusual viscoelastic properties, such as a very large loss modulus, a low activation energy for viscous flow, and a rapid stress relaxation.[3,4] A design for rotaxane- or catenane-based polymers should meet two criteria to endow them with unusual viscoelastic properties: (1) their topological units have high mobility; (2) the linkages between two adjoining topological units are rigid and compact.[3] To meet the former criterion, it is necessary to minimize the attractive interactions between the components of catenanes or rotaxanes. Most of the mechanically interlocked molecules reported so far, however, have attractive interactions between the components, which were utilized as synthetic templates and restrict the relative movement of the components. Therefore, chemical removal of the attractive interactions is necessary to prepare mechanically interlocked molecules with high mobility. For example, demetallation enhances the mobility of Sauvage's catenates and chemical removal of hydrogen-bonding interaction would increase the mobility of amide-based catenanes. Leigh reported that the use of a highly polar solvent, such as DMSO, resulted in an apparent removal of the hydrogen-bonding interaction between the components in *secondary* amide [2]catenanes.[5c] Geerts et al. reported the synthesis of poly[2]catenanes employing Vögtle's amide-based [2]catenanes. In the synthesis, they carried out *N*-methylation of the *secondary* amide groups to remove the hydrogen-bonding interaction between their components.[4] The mobility of the resulting *N*-methylated [2]catenanes, however, remained low, due to the steric hindrance of the *N*-methyl groups. Previously, we reported[3a] a *secondary* amine [2]catenane **4a** synthesized from the corresponding *secondary* amide [2]catenane **3a**[5a] by borane reduction of the eight *secondary* amide groups to *secondary* amine ones. By using a VT ^{1}H NMR spectroscopic technique, we showed that its two macrocyclic amine components rotated smoothly relative to each other, and no hydrogen bonding interaction between the *secondary* amino groups was observed in $CDCl_3$. We examined the applicability of the borane reduction method to a variety of amide-based catenanes and rotaxanes,

because this borane reduction of amide-based catenanes is promising for creating novel amine-based catenanes having highly mobile components. In this paper, we describe the synthesis, structural characterization, and mobility of various *secondary* amine [2]catenanes **4** and *secondary* amine [2]rotaxane **9** together with the corresponding *secondary* amide [2]catenanes **3** and [2]rotaxane **8**.

Results and Discussion

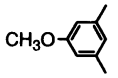
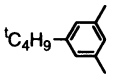
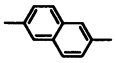
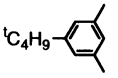
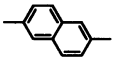
Design of *Secondary* Amide and Amine [2]Catenanes and [2]Rotaxanes. [2]Catenanes having isophthaloyl (*m*-xylylene) and *p*-xylylene units **3a** and **4a** were chosen as the base molecules. To investigate effects of the substituents on the mobility of the components, [2]catenanes bearing methoxy (**3b** or **4b**) and *t*-butyl (**3c** or **4c**) groups on the isophthaloyl units were designed. [2]Catenanes having a 2,6-naphthalenediyl spacer instead of a *p*-xylylene one (**3d** and **3e**, or **4d** and **4e**) were designed to increase the ring size of the macrocyclic components. One can expect an enhancement of the mobility from the increase in ring size. From the viewpoint that relaxation of the components will lead to an increase in mobility, [2]rotaxanes (**8** and **9**) were designed because they can be regarded as *[2]catenane derivatives* whose one ring is cut off and opened to form an axis with two stoppers.

Synthesis of *Secondary* Amide and Amine [2]Catenanes and [2]Rotaxane. (1) [2]Catenanes: *Secondary* amide [2]catenane **3** were prepared by the reaction of substituted and unsubstituted isophthaloyl chlorides **1** and diamines **2** in amylene-stabilized chloroform at room temperature, according to the literature that reported the synthesis of **3a** and **3c** (Scheme 1).[5] Pure **3d** was isolated only by a separatory funnel technique, as that reported for **3a** without chromatography, while the purification of **3b**, **3c**, and **3e** needed careful chromatography on silica gel (Table 1). The reduction of **3** with an excess of borane was carried out in refluxing THF for 1 day. The reaction was terminated by the addition of water at 0 °C to decompose the excess borane. The acidic hydrolysis of the amine-borane adduct with 1 M HClaq (M = mol dm^{-3}), followed by neutralization with NaOH, gave the corresponding *secondary* amine [2]catenanes **4**. A variety of chromatographic purification methods with silica gel, alumina, and cellulose gel were unsuccessful, probably due to the strong adsorption of **4** to such stationary phases under any applied conditions. The purification of **4** was achieved only by recycling preparative HPLC with polystyrene gel as a stationary phase (0.05% triethylamine in chloroform as eluent) to afford pure **4** in 33–78% yields (Scheme 2, Table 2). A cyclic tetramine **6** was

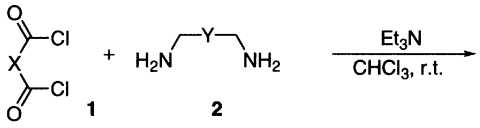


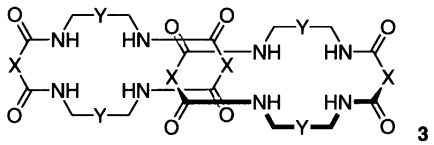
Scheme 1.

Table 1. Synthesis and Mobility of *sec*-Amide [2]Catenanes (**3**)

3	**x**	**y**	Yield/%	Circumrotation[a] 243–295 K[b]	295–403 K[c]
a			19	H	F
b			12	H	H
c			11	H	H
d			15	F	F
e			7	H	H

a) The modes of circumrotation of the macrocyclic components classified in terms of ^{1}H NMR (270 MHz) timescale. "F" denotes "full-rotation". "H" denotes "half-rotation". b) In DMSO-d_6/$CDCl_3$ (1/1). c) In DMSO-d_6.



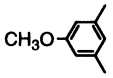
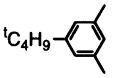
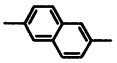
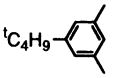
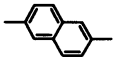


Scheme 2.

also obtained by borane reduction of the corresponding *secondary* amide macrocycle **5**, which was collected as a polymer-containing mixture from the precipitate formed in the preparation of **3a** (Scheme 3).

(2) [2]Rotaxanes: A thread component consisting of isophthaloyl and *p*-xylylenediamine moieties **7** was synthesized in three steps to produce *secondary* amide [2]rotaxane **8** by a clipping method. Equimolar amounts of isophthaloyl chloride and *p*-xylylenediamine were slowly added to a chloroform solution of **7**. The reaction mixture was filtered and washed with an acid and a base to leave three products in the organic layer. These were separated by chromatography and identified as the unrotaxanated thread **7**, the *secondary* amide [2]rotaxane **8** (19% yield), and the *secondary* amide [2]catenane **3a** (20%). **8** was converted to the corresponding *secondary* amine [2]rotaxane **9** (24%) by borane reduction in a similar manner to that for the catenanes (Scheme 4).

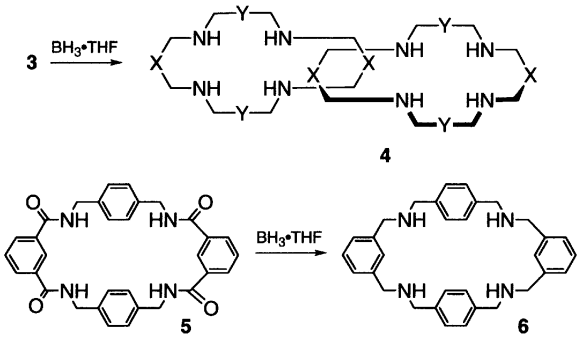
Table 2. Synthesis and Mobility of *sec*-Amine [2]Catenanes (**4**)

4	x	y	Yield/%	Circumrotation[a] 213–295 K[b]
a			51	F
b			54	H
c			62	H
d			33	F
e			78	H

a) The modes of circumrotation of macrocyclic components classified in terms of ^{1}H NMR (270 MHz) timescale. "F" denotes "full-rotation". "H" denotes "half-rotation".

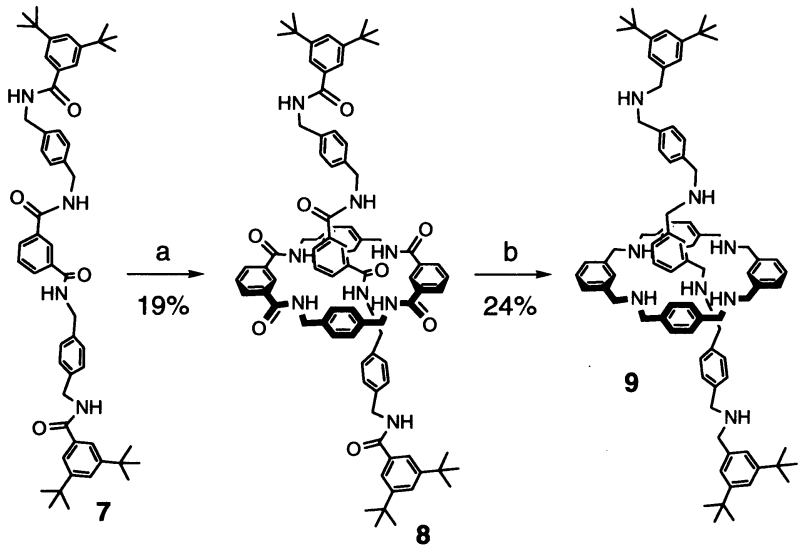
Structural Characterization and Mobility of *Secondary* Amide and Amine [2]Catenanes. (1) *Secondary* Amide [2]Catenanes. The structures of the *secondary* amide [2]catenanes **3** were determined by the IR, NMR and FAB-MS spectra, which were completely consistent with the proposed structures. The FAB-MS results showed that **3** have the [2]catenane skeletons; in each case, no fragmentation was observed between m/z = M + H and M/2 + H.

The structure of **3d** was also confirmed by X-ray crystallography (Fig. 1). Both macrocycles adopted boat-like conformations, but their structures were slightly different from each other. One macrocycle (A) contained four *exo*-carbonyl groups and the other macrocycle (B) had one *endo*- and three *exo*-carbonyl groups. Naphthalene spacers provided a larger internal cavity of 5 × 7.5 Å in each ring than that of **3a** (4 × 6 Å).[5a] The two macrocyclic rings of **3d** were held together and fixed by networks of the inter- and intramolecular hydrogen bondings together with π-stacking interactions between the aromatic rings, as illustrated in the schematic diagram for the crystal packing (Fig. 1c). This solid-state structure of **3d** is quite similar to that of **3a** reported by Leigh.[5a]



Scheme 3.

NMR spectroscopy revealed that the mobility of **3** can be classified into two types in terms of the NMR time scale (Table 1).[6] The substituents on the isophthaloyl units of the catenanes (**3b**, **3c**, and **3e**) prevent complete circumrotation, leaving the two *p*-xylylene units in different chemical environments, that is, surrounded and unsurrounded one. This mobility is denoted as "half rotation" in this paper. The reduction in symmetry is apparent from the ^{1}H NMR (270 MHz, DMSO-d_6, 295 K) spectrum of **3c** (Fig. 2b), which shows a set of signals for most protons. The protons *a* as well as *c*, which are on the axis of the border separating the "surrounded" and "unsurrounded" parts, give a single signal for each proton. On the contrary, in



Scheme 4. (a) Isophthaloyl chloride (8 equiv), *p*-xylylenediamine (8 equiv), $Et_3N/CHCl_3$. (b) BH_3•THF, reflux.

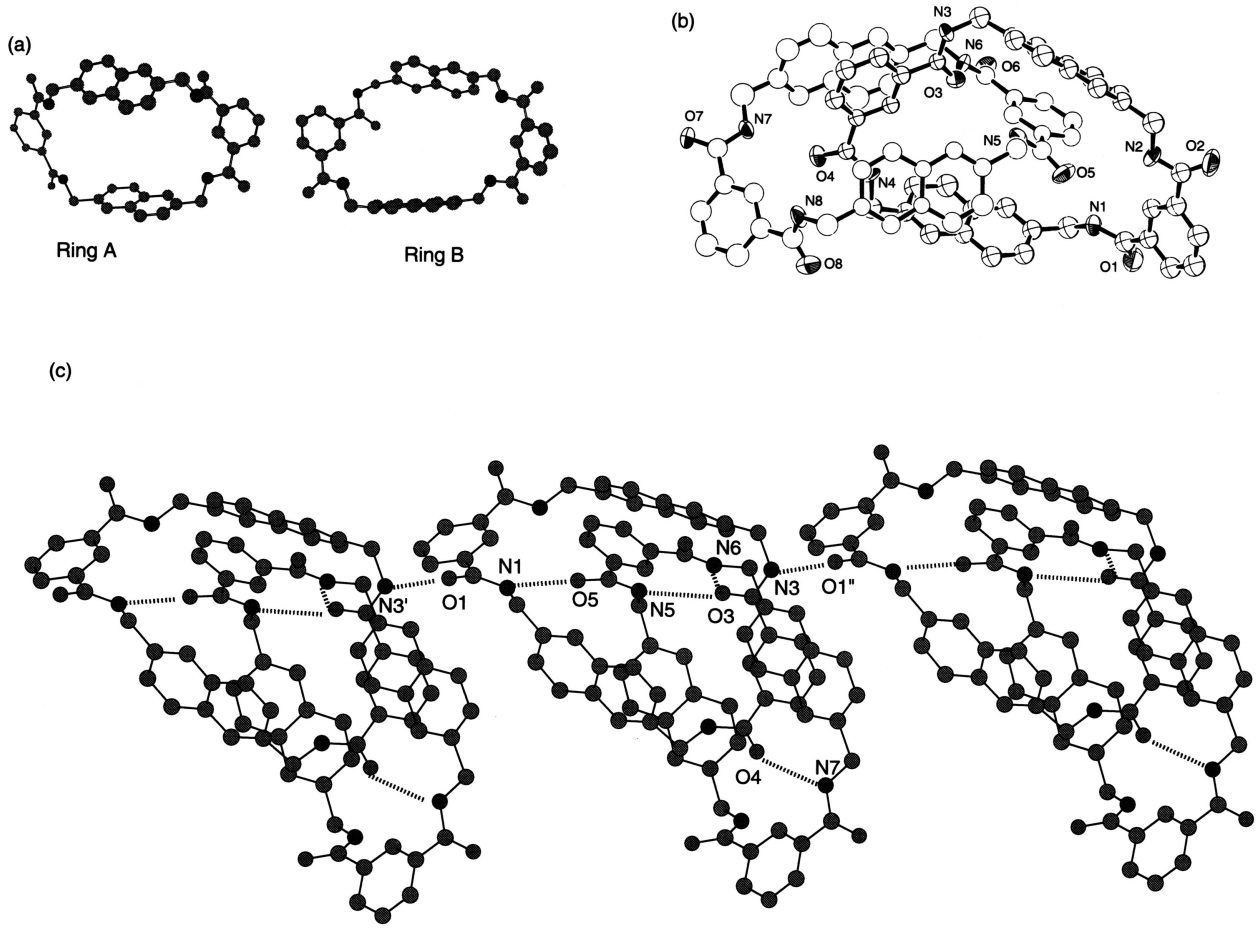


Fig. 1. The solid state structure of *secondary* amide [2]catenane (**3d**) determined by X-ray crystallography. Hydrogen atoms are omitted for clarity. (a) Two single macrocyclic rings A and B. (b) An ORTEP drawing of **3d**. Four intramolecular hydrogen bonds hold the two macrocyclic rings of **3d** in a fixed orientation: O3–N5 3.38(1), O3–N6 2.91(1), O4–N7 2.98(1), O5–N1 3.03(1) in Å. (c) Interlayer packing of **3d** in which intra- and intermolecular hydrogen bonds are clearly shown. The layers are held together by the intramolecular hydrogen bonds (O1–N3′ 2.80(1) Å).

the cases of catenanes **3a** and **3d**, each of which bears the unsubstituted isophthaloyl unit, each macrocyclic component rotates rapidly through the other on the NMR time scale at room temperature. This mobility is denoted as "full rotation" in this paper. The "full rotation" of the components gave the time-averaged ^{1}H NMR spectra for **3a** and **3d** at room temperature (Fig. 2a).

To examine the mobility of **3** over a wide range of temperature, variable temperature ^{1}H NMR (270 MHz) spectra of **3** were acquired for each catenane. In the cases of [2]catenanes bearing substituted isophthaloyl units **3b**, **3c**, and **3e**, their spectral patterns did not change at all over the range of 233 to 295 K in DMSO-d_6/$CDCl_3$ (1/1) or 295 to 403 K in DMSO-d_6. Thus, the substituents on the isophthaloyl units completely locked the circumrotation of the macrocyclic components. The ^{1}H NMR spectra of **3a** showed a characteristic behavior on varying the measuring temperature: each signal of almost all protons of **3a** split into two peaks at lower temperature in DMSO-d_6/$CDCl_3$ (1/1). This splitting of the signals means that the rate of circumrotation became slower than on the NMR time scale. From the coalescence temperatures for the signal of *p*-xylylene protons measured at different magnetic fields (T_c = 273 K for 270 MHz and 283 K for 500 MHz), thermodynamic parameters of the process were estimated: $\Delta H = 40.6$ kJ mol^{-1}; $\Delta S = -47.6$ J mol^{-1} K^{-1}; $\Delta G^{\ddagger}_{298} = 54.8$ kJ mol^{-1}. The data suggest that the rings of **3a** can rotate only slowly at a rate of 800 Hz at 298 K. In contrast, the ^{1}H NMR spectra (270 MHz, DMSO-d_6/$CDCl_3$ (1/1)) of **3d** showed no coalescence temperature, even when cooled down to 243 K. This is attributable to the fact that each macrocyclic ring of **3d** is larger than that of **3a**, due to the 2,6-naphthalenediyl spacer. Thus, the larger macrocyclic ring enhances the mobility of the components, although **3d** still held the intramolecular hydrogen bond, which was confirmed from the solid-state structure.

(2) *Secondary* Amine [2]Catenanes. The FAB-MS results supported the finding that that the *secondary* amine [2]catenanes **4** have the [2]catenane skeletons, that is, no fragmentation between M + H and M/2 + H was observed, similarly to the cases of the *secondary* amide [2]catenanes **3**. The ^{1}H NMR spectra well supported the structures of **4**. In the ^{1}H NMR ($CDCl_3$, 295 K) spectrum for each catenane, the N–*H* signal appeared as a broad singlet at ca. 1.6 ppm, corresponding to a

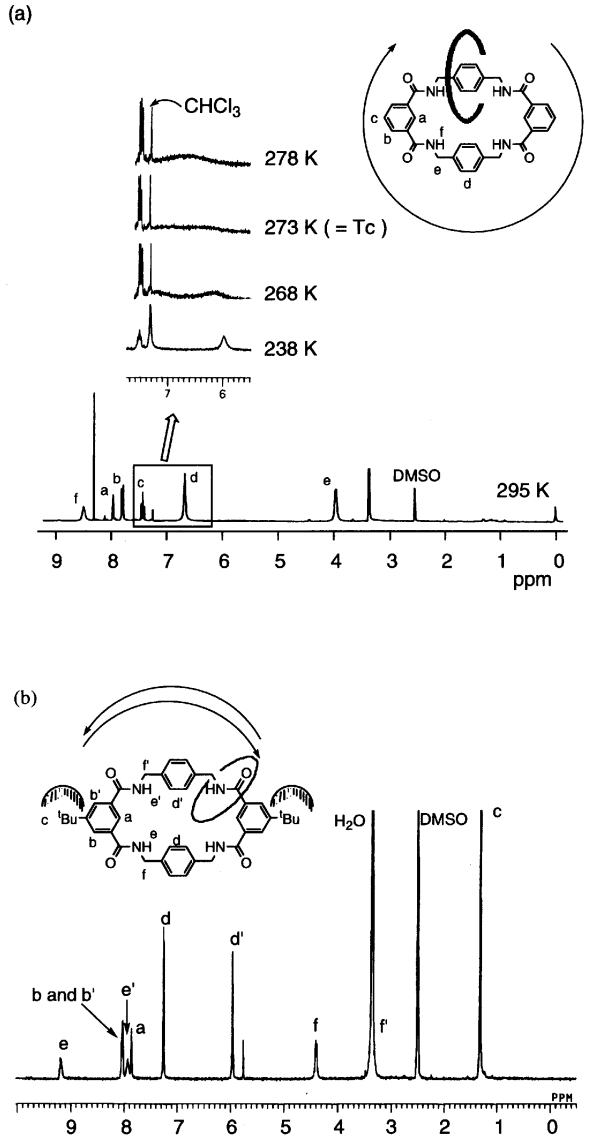


Fig. 2. (a) ^{1}H NMR (270 MHz, $CDCl_3$: DMSO-d_6 = 1 : 1 (v/v), 238–278 K) spectra of **3a**. (b) ^{1}H NMR (270 MHz, DMSO-d_6, 295 K) spectrum of **3c**.

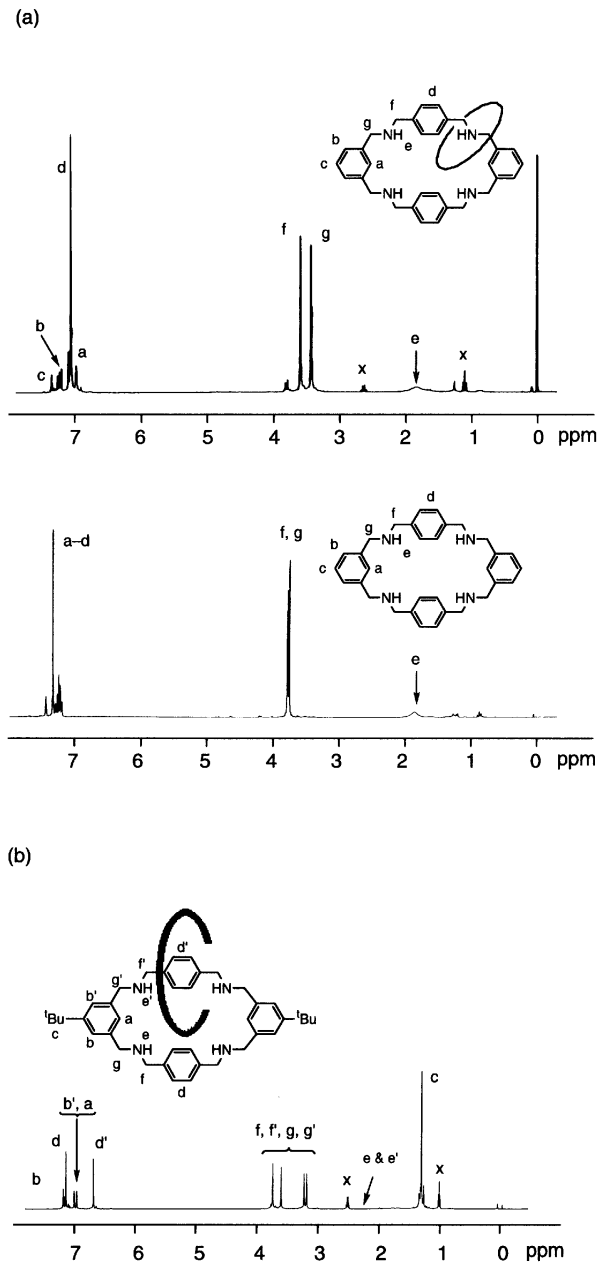


Fig. 3. (a) ^{1}H NMR (270 MHz, $CDCl_3$, 295 K) spectra of **4a** (above) and **6** (below). (b) ^{1}H NMR (270 MHz, $CDCl_3$, 295 K) spectrum of **4c**. "x" denotes signals of triethylamine.

free amine region at room temperature (Fig. 3). The chemical shift value clearly indicated that the N–*H* protons of the *secondary* amine [2]catenanes **4** do not take part in hydrogen bonding interaction, even in a less polar solvent, such as $CDCl_3$, in contrast to those of the *secondary* amide [2]catenanes. Thus, the removal of the attractive interaction between the two ring components of the [2]catenanes was achieved by the borane reduction of the eight *secondary* amide groups.

The modes of circumrotation of these *secondary* amine [2]catenanes **4** were classified into two types in a similar manner to that for the *secondary* amide [2]catenanes **3** (Table 2). The mobility of [2]catenanes **4a** and **4d** bearing unsubstituted *m*-xylylene group was categorized into the "full rotation" mode, which showed simple time-averaged ^{1}H NMR spectra at room temperature. That of the [2]catenanes **4b**, **4c**, and **4e** was categorized into the "half rotation" mode, which means that the substituents on the *m*-xylylene units prevent complete circumrotation on the ^{1}H NMR time scale at room temperature.

Dynamic ^{1}H NMR measurements revealed that the modes of circumrotation of the *secondary* amine [2]catenanes **4** do not change at all over the range of 213 K to 295 K. In all cases, however, a characteristic shift of the signals in the aromatic region was observed. In the ^{1}H NMR ($CDCl_3$) of **4a**, for example, signals of aromatic protons of the *m*-xylylene units shifted to a higher magnetic field with a decrease in temperature, while those of *p*-xylylene units shifted a little to a lower magnetic field (Fig. 4). The signal of the N–*H* proton did not shift at all.

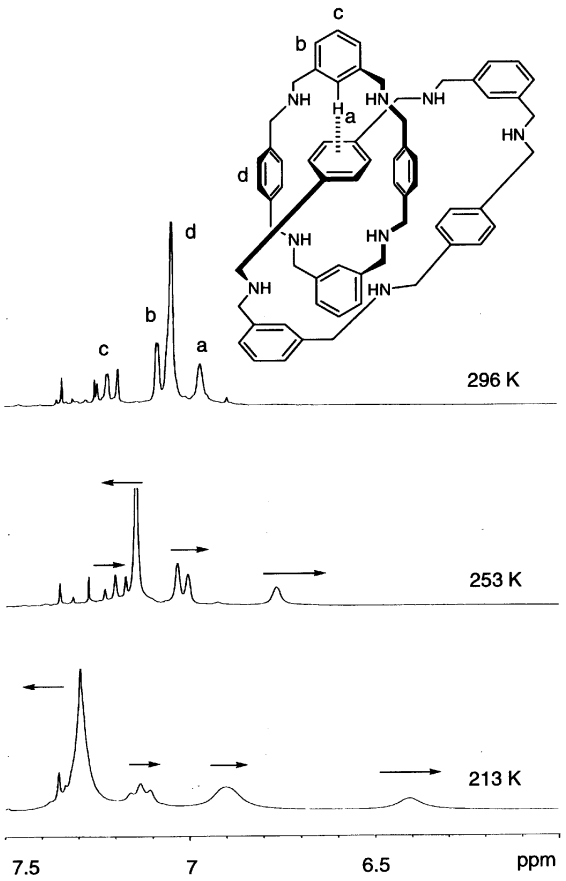


Fig. 4. ^{1}H NMR (270 MHz, $CDCl_3$, 213–296 K) spectra of **4a**.

Other *secondary* amine [2]catenanes showed a similar ^{1}H NMR behavior with a decrease in temperature. However, no such shift was observed in the case of the corresponding monomacrocyclic tetramine **6** under the same conditions. This phenomenon, characteristic of the [2]catenane structure, was also observed in the case of *N*-octamethylated derivatives of the **3a** and **4a**.[3b,3c] In that case, this kind of ^{1}H NMR behavior was explained in terms of intramolecular CH–π interaction, which was unambiguously confirmed by the X-ray crystallographic analysis. It can, therefore, be presumed here, in the case of the *secondary* amine [2]catenanes, that the hydrogen atom at the 2-position of the *m*-xylylene unit serves as a proton donor for the *p*-xylylene unit of the other macrocyclic ring to form a T-shaped π-π stacking, as illustrated in Fig. 4. As a result, the signals of the *m*-xylylene unit, in the ^{1}H NMR spectra, shifted to a higher magnetic field due to the shielding effect of the *p*-xylylene unit. Although such weak interaction as CH–π interaction was observed in solution at lower temperature, these *secondary* amine [2]catenanes **4** have the desired high mobility, as is evident from the fact that their ^{1}H NMR spectra showed no coalescence with a decrease in temperature down to 213 K.

(3) *Secondary* Amide [2]Rotaxane and *Secondary* Amine [2]Rotaxane. The structures of the *secondary* amide [2]rotaxane **8** and the *secondary* amine [2]rotaxane **9** were characterized by FAB-MS and ^{1}H NMR spectra. The [2]rotaxane skeletons of **8** and **9** were unambiguously confirmed by the FAB-mass spectra in which no fragmentation between M(rotaxane) + H and M(axis) + H was observed. The four *t*-butyl groups greatly increased the solubility of the [2]rotaxane **8** to a less polar solvent such as chloroform. The enhanced solubility made the ^{1}H NMR measurement of **8** in $CDCl_3$ possible (Fig. 5). At 323 K, the ^{1}H NMR ($CDCl_3$) spectrum of **8** displayed a sharp signal for each proton. With a decrease in temperature, however, all of the signals of the spectra were extraordinarily broadened. The broadening indicates that the mobility of the components of **8** was more restricted, at lower temperature, by the intramolecular hydrogen bond. On the other hand, the *secondary* amine [2]rotaxane **9** showed a simple ^{1}H NMR ($CDCl_3$) spectra, where each proton gave a sharp signal at room temperature. As in the case of the *secondary* amine [2]catenanes **4**, no coalescence was observed over a range of 213 to 295 K. From the results, it is evident that the components of **9** retain high mobility even at lower temperature. It was also observed that the signals in the aromatic region shifted in a similar manner to the case of **4**. This ^{1}H NMR behavior evidently suggested that CH–π interaction exists between the axis and the ring components.

Summary

A borane reduction of *secondary* amide [2]catenanes was proved to be an effective way to synthesize *secondary* amine [2]catenanes and to be well-tolerant to the modification of the backbone structures. The mobility of the components of the [2]catenanes and [2]rotaxanes was examined by ^{1}H NMR spectroscopy and the following results were obtained. As for the [2]catenanes, the modes of the mobility of the components

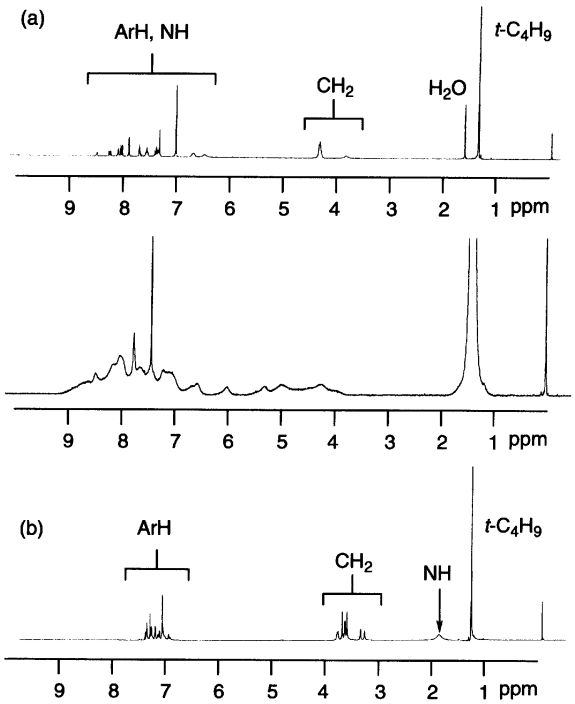


Fig. 5. (a) ^{1}H NMR (270 MHz, $CDCl_3$) spectrum of **8** at 323 K (above) and at 213 K (below). (b) ^{1}H NMR (270 MHz, $CDCl_3$) spectrum of **9** at 295 K.

were classified into two types: (1) the substituents on the isophthaloyl (*m*-xylylene) units prevented complete circumrotation, leading to a lowering of the mobility of the [2]catenanes (''half rotation'' for **3b**, **3c**, **4b**, **4c**, and **4e**); (2) the catenanes bearing unsubstituted isophthaloyl (*m*-xylylene) units underwent complete circumrotation (''full rotation'' for **3a**, **3d**, **4a**, and **4d**). The results obtained for the *secondary* amide [2]catenane **3d** suggested that an increase in the size of the macrocyclic component enhanced the mobility. A reduction of the amides groups of the *secondary* amide [2]catenanes into amino groups led to a large increase in the mobility, although much weaker CH–π interaction was observed in solution at lower temperature. Similar results were obtained with respect to the [2]rotaxanes. Thus, we have demonstrated here that the *secondary* amine [2]catenanes and [2]rotaxane, which had components of higher mobility and which were not directly obtainable by the well-known template methods, were prepared by simple borane reduction of the easily accessible *secondary* amide [2]catenanes and [2]rotaxane.

Experimental

General: Melting points were measured on a Yanagimoto micro melting-point apparatus and were uncorrected. IR spectra were recorded on a JASCO FT-IR model 230 spectrometer. ^{1}H NMR (270 MHz, 400 MHz, and 500 MHz) and ^{13}C NMR (100 MHz and 125 MHz) measurements were performed in $CDCl_3$ or $(CD_3)_2SO$ on JEOL JNM-GX-270, JNM-L-400 and JNM-A-500 spectrometers, where the chemical shift were determined with respect to $CHCl_3$ (δ 7.26) or DMSO-d_6(δ 2.50) for ^{1}H and $CHCl_3$ (δ 77.1) for ^{13}C. For recycling preparative HPLC, a JAICO LC-908 system using columns JAIGEL 1 (20 mmϕ × 600 mm) and JAIGEL 2 (20 mmϕ × 600 mm). FABMS measurements were performed on a Finnigan TSQ-70 instrument.

***Secondary* Amide [2]Catenanes (3): General Procedure:** To a stirred solution of triethylamine (1.19 g, 11.8 mmol) in anhydrous chloroform (130 mL, stabilized with amylenes) under argon were added dichloride **1** (4.3 mmol) in anhydrous chloroform (130 mL) and diamine **2** (4.3 mmol) in anhydrous chloroform (130 mL) simultaneously, over 1 h. The mixture was stirred for 12 h and then filtered. The filtrate was washed with 1 M hydrochloric acid (3 × 200 mL), 5% sodium hydroxide (3 × 200 mL), and finally water (3 × 200 mL). The organic layer was then dried over anhydrous magnesium sulfate and concentrated under reduced pressure to afford *secondary* amide [2]catenanes (**3**). Pure **3a** as well as **3d** was isolated simply by a separatory funnel technique, although **3b**, **3c**, and **3e** needed chromatography (silica gel, dichloromethane containing 1–10% of MeOH as eluent) for the purification.

3a[5]**:** 19% yield; a white solid; Mp > 280 °C; IR (KBr) 3316 (N–H), 1640 (C=O) cm^{-1}; ^{1}H NMR (DMSO-d_6, 270 MHz, 295 K) δ 8.31 (8H, br s, CON*H*), 7.97 (4H, t, $J_{2,4}$ = 1.2 Hz, isophthaloyl-2*H*), 7.80 (8H, dd, $J_{4,5}$ = 7.9 Hz, $J_{2,4}$ = 1.2 Hz, isophthaloyl-4,6*H*), 7.42 (4H, t, $J_{5,4}$ = 8.0 Hz, isophthaloyl-5*H*), 6.66 (16H, br s, *p*-xylylene-*H*), 3.92 (16H, br s, benzyl-CH_2); FABMS (matrix: *m*-nitrobenzyl alcohol) *m*/*z* 1065 [(M+H)$^+$], 533 [(M/2+H)$^+$].

3b: 12% yield; a white solid; Mp > 300 °C; IR (KBr) 3288 (N–H), 1641 (C=O) cm^{-1}; ^{1}H NMR (500 MHz, DMSO-d_6, 295 K) δ 9.08 (4H, t, J = 5.8 Hz, CON*H*), 7.81 (4H, t, J = 5.5 Hz, CON*H*), 7.62 (4H, s, isophthaloyl-*H*), 7.50 (4H, s, isophthaloyl-*H*), 7.31 (4H, s, isophthaloyl-*H*), 7.28 (8H, s, *p*-xylylene-*H*), 6.00 (8H, s, *p*-xylylene-*H*), 4.39 (8H, s, benzyl-CH_2), 3.84 (12H, s, OCH_3), 3.45 (8H, s, benzyl-CH_2); ^{13}C NMR (125 MHz, DMSO-d_6, 295 K) δ 165.7, 165.5, 159.1, 138.2, 136.2, 135.7, 135.6, 129.1, 127.4, 119.0, 115.2, 55.6, 54.9, 43.2, 42.4; FAB-MS (matrix: *m*-nitrobenzyl alcohol) *m*/*z* 1185 [(M+H)$^+$], 593 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{68}H_{64}N_8O_{12}$ (M+Na) 1270.4541, found 1207.5062.

3c[5]**:** 11% yield; a white solid; Mp 263–265 °C; IR (KBr) 3312 (N–*H*), 1639 (C=O) cm^{-1}; ^{1}H NMR (270 MHz, DMSO-d_6, 295 K) δ 9.19 (4H, br t, CON*H*), 8.02 (8H, m, isophthaloyl 4,6-*H*), 7.93 (4H, br t, CON*H*), 7.86 (4H, m, isophthaloyl-2*H*), 7.25 (s, 8H, *p*-xylylene-*H*), 5.96 (s, 8H, *p*-xylylene-*H*), 4.40 (s, 8H, benzyl-CH_2), 3.34 (s, 8H, benzyl-CH_2), 1.32 (s, 36H, ^{t}C$_4H_9$); FAB MS (matrix: *m*-nitrobenzyl alcohol) *m*/*z* 1289 [(M+H)$^+$], 645 [(M/2+H)$^+$].

3d: 15% yield; a white solid; Mp 265 °C (dec.); IR (KBr) 3312 (N–*H*), 1639 (C=O) cm^{-1}; ^{1}H NMR (500 MHz, DMSO-d_6, 295 K) δ 8.75 (8H, br s, CON*H*), 8.30 (4H, s, isophthaloyl-2*H*), 7.96 (8H, d, $J_{4,5}$ = 7.6 Hz, isophthaloyl-4,6*H*), 7.56 (4H, t, $J_{4,5}$ = 7.6 Hz, isophthaloyl-5*H*), 7.14 (8H, br s, naphthalene-1,5*H*), 6.87 (16H, br s, naphthalene-3,4,7,8*H*), 4.22 (16H, s, benzyl-CH_2); ^{13}C NMR (125 MHz, DMSO-d_6, 295 K) δ 166.6, 135.8, 134.6, 131.3, 129.7, 128.5, 127.1, 126.3, 125.8, 125.6, 42.9; FAB MS (matrix: *m*-nitrobenzyl alcohol) *m*/*z* 1296 [(M+H)$^+$], 663 [(M/2+H)$^+$]; HRMS(FAB) calcd for $C_{80}H_{64}N_8O_8$ (M+Na) 1287.4744, found 1287.6095.

3e: 7% yield; a colorless viscous oil; .); IR (KBr) 3430 (N–H), 1644 (C=O) cm^{-1}; ^{1}H NMR (270 MHz, DMSO-d_6, 295 K) δ 9.17 (8H, br s, CON*H*), 8.31 (8H, br s, CON*H*), 8.17 (4H, s, isophthaloyl-*H*), 8.09 (8H, s, isophthaloyl-*H*), 8.07 (4H, s, isophthaloyl-*H*), 7.44 (8H, br s, naphthalene-1,5H_{out}), 7.10 (8H, ABq, J = 8.6, 7.9 Hz, naphthalene-3,7*H* and -4,8*H*), 4.58 (8H, br s, naphthalene-CH_{2out}), 3.90 (8H, br s, naphthalene-CH_{2in}), 1.39 (36H, s, *t*-C$_4$H$_9$); ^{13}C NMR (100 MHz, DMSO-d_6, 295 K) δ 166.0, 165.5, 151.2, 136.3, 134.8, 134.1, 131.5, 130.9, 127.2, 126.9, 126.7(2 peaks), 125.8, 125.4(2 peaks), 125.3, 123.0, 54.7, 43.2, 42.7, 34.6, 30.9; FABMS (matrix: *m*-nitrobenzyl alcohol) *m*/*z* 1489 [(M+H)$^+$], 744 [(M/2+H)$^+$]; HRMS(FAB) calcd for $C_{96}H_{97}N_8O_8$ (M+H) 1489.7429, found 1489.6052.

Crystallographic Data for 3d: A single crystal suitable for x-ray analysis was grown from a solution of DMSO–$CHCl_3$–MeOH. Intensity data were collected on a Rigaku AFC-5R automated four-circle diffractometer equipped with a graphite monochromator by using Mo-$K\alpha$ radiation (λ = 0.71069 Å) at 299 K with the 2θ-ω scan method. Structure solution and refinements were performed by using the SIR92 program package. All carbon atoms were refined isotopically, whereas oxygen and nitrogen ones were refined anisotopically. Crystal data for **3d** ($C_{80}H_{64}N_8O_8$, FW = 1265): crystal dimensions 0.40 × 0.10 × 0.05 mm, monoclinic, $P\bar{1}$(#2), a = 29.058(7), b = 13.039(6), c = 9.708(3) Å, α = 101.06(3), β = 102.22(3), γ = 75.18(2)°, V = 3438(2) Å^3, Z = 2, ρ_{calcd} = 1.284 g cm^{-3}, F(000) = 1328, μ = 0.40 cm^{-1}, $2\theta_{max}$ = 50.0°, 10812 reflections measured, 2804 observed (I > 2.70(σ (I))), number of parameters 491, R = 0.084, R_W = 0.103, residual electron density +0.39/–0.39 e/Å^3.

Crystallographic data have been deposited at the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK and copies can be obtained on request, free of charge, by quoting the publication citation and the deposition number 153727. The details of structures have been deposited as Document No. 73066 at the Office of the Editor of Bull. Chem. Soc. Jpn.

***Secondary* Amine [2]catenanes (4): General Procedures:** A suspension of **3** (0.15 mmol) in 67 mL of 1.0 M borane in THF (67 mmol) was refluxed under argon atmosphere for 24 h. The heterogeneous reaction mixture gradually became clear. The reac-

tion was monitored by the IR spectra of the reaction mixture. The reaction was terminated by a slow addition of water at 0 °C to decompose excess borane, after no change of the IR spectrum in the carbonyl region was observed. The hydrolysis of the borane-amine complex was achieved by the addition of 1.0 M HCl (30 mL) to the residual white solid obtained by evaporation, after which B–H absorption (in the 2500 to 2300 cm^{-1} region) of the complex in the IR spectrum disappeared completely. A treatment of the mixture with excess alkali (NaOH pellet, up to pH > 13) under cooling yielded a white solid. The solid material was subjected to dichloromethane extraction to afford crude **4**, which was purified by recycling preparative HPLC (eluent: $CHCl_3$ containing 0.05% Et_3N) to afford pure **4**.

4a: 51% yield; a white solid; Mp 44–46 °C; IR (KBr) 3289 (N–H) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$, 295 K) δ 7.22 (4H, t, $J_{5,4}$ = 7.6 Hz, *m*-xylylene-5*H*), 7.06 (8H, d, $J_{4,5}$ = 7.9 Hz, *m*-xylylene-4,6*H*), 7.04 (16H, s, *p*-xylylene-*H*), 6.97 (4H, s, *m*-xylylene-2*H*), 3.58 (16H, br s, benzyl-CH_2), 3.34 (16H, br s, benzyl-CH_2), 1.68 (8H, br s, N*H*); ^{13}C NMR (125 MHz, $CDCl_3$, 295 K) δ 139.9, 138.8, 128.7, 128.2, 128.1, 126.9, 54.0, 53.4; FABMS (matrix: glycerine) *m*/*z* 953 [(M+H)$^+$], 477 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{64}H_{73}N_8$ (M+H) 953.5958, found 953.8134.

4b: 54% yield; a white solid; Mp 38–40 °C; IR (KBr) 3203 (N–H) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$, 295 K) δ 7.25 (8H, s, *p*-xylylene-*H*), 6.83 (4H, s, *m*-xylylene-*H*), 6.79 (8H, s, *p*-xylylene-*H*), 6.63 (4H, s, *m*-xylylene-*H*), 6.59 (4H, s, *m*-xylylene-*H*), 3.83 (8H, s, benzyl-CH_2), 3.82 (12H, s, OCH_3), 3.65 (8H, s, benzyl-CH_2), 3.31 (8H, s, benzyl-CH_2), 3.17 (8H, s, benzyl-CH_2), 2.30 (8H, br s, N*H*); ^{13}C NMR (125 MHz, $CDCl_3$, 297 K) δ 159.6, 141.3, 141.1, 138.8, 138.3, 128.7, 128.5, 120.6, 112.8, 112.1, 55.3, 53.9, 53.6, 53.5, 53.1; FAB-MS (matrix: glycerine) *m*/*z* 1074 [(M+H)$^+$], 537 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{68}H_{80}N_8O_4$ (M+Na) 1095.6200, found 1095.6790.

4c: 62%; a colorless oil; IR (KBr) 3450 (N–H) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$, 295 K) δ 7.27 (4H, s, *m*-xylylene-*H*), 7.22 (8H, s, *p*-xylylene-*H*), 7.09 (4H, s, *m*-xylylene-*H*), 7.04 (4H, s, *m*-xylylene-*H*), 6.76 (8H, s, *p*-xylylene-*H*), 3.81 (8H, s, benzyl-CH_2), 3.67 (8H, s, benzyl-CH_2), 3.29 (8H, s, benzyl-CH_2), 3.25 (8H, s, benzyl-CH_2), 1.80 (8H, br s, N*H*), 1.35 (36H, s, *t*-C_4H_9); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 150.9, 139.9, 139.6, 139.1, 138.5, 128.6, 128.5, 125.3, 123.9, 123.7, 54.2, 54.0, 53.9, 53.7, 34.6, 31.5; FABMS (matrix: glycerine) *m*/*z* 1178 [(M+H)$^+$], 589 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{80}H_{105}N_8$ (M+H) 1177.8462, found 1178.0125.

4d: 33% yield; a white solid; Mp 49–50 °C; IR (KBr) 3450 (N–H) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$, 295 K) δ 7.34 (8H, d, *J* = 8.5 Hz, naphthalene-4,8*H*), 7.29 (8H, s, naphthalene-1,5*H*), 7.25 (4H, t, *J* = 8.6 Hz, *m*-xylylene-5*H*), 7.14 (8H, d, *J* = 7.9 Hz, *m*-xylylene-4,6*H*), 7.03 (8H, d, *J* = 7.9 Hz, naphthalene-3,7*H*), 6.47 (4H, s, *m*-xylylene-2*H*), 3.61 (16H, s, benzyl- or naphthalene-CH_2), 3.26 (16H, s, benzyl- or naphthalene-CH_2), 1.62 (8H, br s, N*H*); ^{13}C NMR (125 MHz, $CDCl_3$, 295 K) δ 139.7, 136.6, 132.1, 128.4, 127.9, 127.7, 126.9, 126.6, 126.4, 53.4, 52.5; FABMS (matrix: glycerine) *m*/*z* 1154 [(M+H)$^+$], 577 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{80}H_{80}N_8$ (M+Na) 1175.6404, found 1175.6370.

4e: 78% yield; a white solid; Mp 110–115 °C; IR (KBr) 3301 (N–*H*) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$, 297 K) δ 7.65 (4H, s, *m*-xylylene-*H*), 7.52 (4H, d, *J* = 8.2 Hz, naphthalene-4,8*H*), 7.38 (4H, d, *J* = 8.5 Hz, naphthalene-3,7*H*), 7.11 (4H, s, *m*-xylylene-*H*), 6.94 (4H, d, *J* = 8.2 Hz, naphthalene-1,5*H*), 6.89 (4H, s, naphthalene-1,5*H*), 6.61 (4H, d, *J* = 8.6 Hz, naphthalene-3,7*H*), 6.28 (4H, s, *m*-xyxylene-*H*), 3.89 (8H, s, naphthalene-CH_2), 3.47 (8H, s, naphthalene-CH_2), 3.09 (8H, s, naphthalene-CH_2), 2.77 (8H, s, naphthalene-CH_2), 1.33 (36H, s, *t*-C_4H_9); FABMS (matrix: glycerine) *m*/*z* 1378 [(M+H)$^+$], 690 [(M/2+H)$^+$]; HRMS(FAB): calcd for $C_{96}H_{113}N_8$ (M+H) 1377.9088, found 1377.8759.

Monocyclic tetramine (6): Cyclic tetramine **6** was obtained by the borane reduction of the corresponding *secondary* amide macrocycle **5**, which was collected from the precipitate of the reaction mixture for the preparation of **3a**. The crude reaction mixture was purified by the use of recycling preparative HPLC in a similar procedure to that used for the *secondary* amine [2]catenanes **4**. IR (KBr) 3304 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.26–7.14 (m, 16H, Ar*H*), 3.71 (s, 8H, benzyl-CH_2), 3.69 (s, 8H, benzyl-CH_2), 2.08 (br s, 4H, N*H*); FABMS (matrix: glycerine) *m*/*z* 477 [(M+H)$^+$]. The structure was spectroscopically identified with that of **6** previously obtained by independent preparation.[7]

[2]Rotaxanes: Axis (7): To a $CHCl_3$ solution (300 mL) of *N*-(4-aminomethylphenylmethyl)-3,5-di-*t*-butylbenzamide[8] (3.52 g, 10.0 mmol) and triethylamine (1.5 g, 15 mmol) was added a $CHCl_3$ solution (300 mL) of isophthaloyl chloride (1.02 g, 5.00 mmol). After being stirred at room temperature for 4 h, the reaction mixture was washed with 1 M HClaq, 5% NaOHaq, and water. After evaporation of the solvent, the residue was purified by chromatography (SiO_2, CH_2Cl_2 containing 5% of MeOH (v/v) as eluent) to give **7** as a white solid in 95% yield. Mp 185–190 °C; IR (KBr) 1641 (C=O) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 8.41 (1H, br s, isophthaloyl-2*H*), 7.99 (2H, dd, $J_{4,5}$ = 8 Hz, $J_{2,4}$ = 2 Hz, isophthaloyl-4,6*H*), 7.68 (4H, d, *J* = 2 Hz, Ar*H*), 7.59 (2H, br t, *J* = 6 Hz, CON*H*), 7.55 (2H, t, *J* = 2 Hz, Ar*H*), 7.40 (1H, t, $J_{4,5}$ = 8 Hz, isophthaloyl-5*H*), 7.28 (2H, br t, *J* = 6 Hz, CON*H*), 6.93 (8H, s, *p*-xylylene-*H*), 4.33 (4H, d, *J* = 6 Hz, CH_2), 4.24 (4H, d, *J* = 6 Hz, CH_2), 1.29 (36H, s, *t*-C_4H_9).

***Secondary* Amide [2]Rotaxane (8):** To a stirred $CHCl_3$ solution (900 mL) of the axis **7** (4.3 g, 5.2 mmol) and triethyamine (8.1 g, 80 mmol) was added a $CHCl_3$ solution (150 mL) of *p*-xylylenediamine (5.44 g, 40 mmol) and a $CHCl_3$ solution (150 mL) of isophthaloyl chloride (8.12 g, 40 mmol) simultaneously over a 5 hours period by the use of a motor-driven syringe pump. The mixture was stirred for about 12 h and then filtered. The filtrate was washed successively with 1 M HClaq (× 3), 5% NaOHaq (× 3), and water (× 3), dried over anhydrous $MgSO_4$, and evaporated to dryness. The residue was chromatographed over silica gel by the use of CH_2Cl_2 containing 2% MeOH (v/v) as eluent. The first fraction eluted was identified as the unreacted axis **7**, the second fraction was characterized as **8** (1.3 g, 19% yield), and the third fraction was identified as *secondary* amide [2]catenane **3a** (20%). **8**: Mp 155–159 °C; IR (KBr) 1643 (C=O) cm^{-1}; ^1H NMR (270 MHz, DMSO-d_6, 323 K) δ 8.82 (4H, br t, *J* = 5 Hz, macrocyclic (mc)-N*H*), 8.71 (2H, br s, axis-N*H*), 8.60 (2H, br s, axis-N*H*), 8.40 (1H, br s, axis-isophthaloyl-2*H*), 7.99 (2H, d, $J_{4,5}$ = 8 Hz, axis-isophthaloyl-4,6*H*), 7.77 (4H, d, $J_{2,4}$ = 2 Hz, axis-3,5-di-*t*-Bu-phenyl-2,6*H*), 7.71 (4H, d, $J_{4,5}$ = 8 Hz, mc-isophthaloyl-4,6*H*), 7.60 (1H, t, $J_{4,5}$ = 8 Hz, axis-isophthaloyl-5*H*), 7.56 (2H, br s, mc-isophthaloyl-2*H*), 7.53 (2H, t, $J_{2,4}$ = 2 Hz, axis-3,5-di-*t*-Bu-phenyl-4*H*), 7.29 (2H, t, $J_{4,5}$ = 8 Hz, mc-isophthaloyl-5*H*), 7.09 (8H, s, mc-*p*-xylylene-*H*), 6.64 (8H, ABq, *J* = 16, 8 Hz, axis-*p*-xylylene-*H*), 4.22 (8H, d, *J* = 5 Hz, mc-CH_2), 3.95 (4H, br s, axis-CH_2), 3.80 (4H, br s, axis-CH_2), 1.29 (36H, s, *t*-C_4H_9); FABMS (matrix: mNBA) *m*/*z* 1368 [(M+H)$^+$], 836 [(axis+H)$^+$]; HRMS(FAB): calcd for $C_{86}H_{94}N_8O_8$ (M+Na) 1389.7092, found 1389.8859.

***Secondary* Amine [2]Rotaxane (9):** The *secondary* Amine [2]Rotaxane **9** was obtained from **8** as a white solid by borane re-

duction in 24% yield in a similar manner to that for the *secondary* amine [2]Catenanes **4**. A complete assignment of the signals of the ^{1}H NMR spectrum was not possible, because the most of the signals were two close to each other, especially for those in the aromatic region. However, a partial assignment of the benzylic protons was achieved by synthesizing a partially deuterated **9** (**9**-d_{16}) by the BD_3 (generated from $NaBD_4$ and I_2 in situ) reduction of the *secondary amide* [2]rotaxane **8**. ^{1}H NMR (270 MHz, $CDCl_3$, 295 K) δ 7.4–6.9 (34H, m, Ar*H*), 3.72 (8H, s, macrocyclic (mc) -*p*-xylylene-CH_2), 3.67, 3.66 (8H, s × 2, axis-*m*-xylylene-CH_2 and axis-*p*-xylylene-CH_2, one of these singlets disappeared in the spectrum of **9**-d_{16}), 3.63 (8H, s, mc-*m*-xylylene-CH_2, disappeared in the spectrum of **9**-d_{16}), 3.38 (4H, s, axis-*p*-xylylene-CH_2), 3.31 (4H, s, axis-*m*-xylylene-CH_2, disappeared in the spectrum of **9**-d_{16}), 1.87 (8H, br s, N*H*), 1.32 (36H, s, *t*-C_4H_9); FABMS (matrix: mNBA) *m*/*z* 1256 [(M+H)$^+$], 779 [(axis+H)$^+$]; HRMS(FAB): calcd for $C_{86}H_{111}N_8$ (M+H) 1255.8932, found 1255.9663.

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