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Change of Connectivity on Catenane Ring: Ring Expansion by Annulation–Ring Scission Sequence

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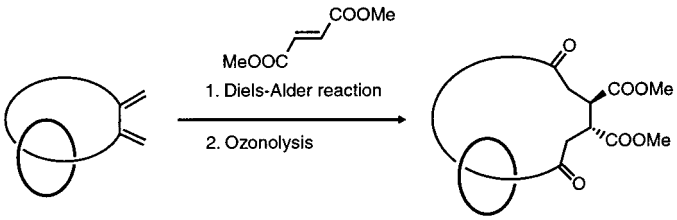
ABSTRACT



Ring expansion of a catenane without destruction of the interlocked structure was attained by Diels–Alder reaction followed by ozonolysis. Annulation by Diels–Alder reaction introduced a C4 fragment onto the ring, and the ozonolysis scissored the resulting double bond to expand the catenane ring. The annulation–ring scission sequence provides a general approach for changing the connectivity on a catenane ring without destroying the interlocked structure.

Recent advances in the chemistry of noncovalent bonding systems have increased the expectancy for a molecular device based on interlocked molecules such as rotaxane, catenane, and trefoil knot.[1] A number of chemical modifications of the interlocked molecules are often necessary to turn an original molecule into a sophisticated molecular system or device. So far, however, only a few simple chemical reactions of interlocked molecules have been reported. Introduction,[2] redox reaction,[3] conversion,[4] and interconnection[5] of the functional groups have been reported, especially for catenanes, where the connectivity on the ring component is preserved throughout the transformation. At present, the only successful technique for the modification of an interlocked compound with change of connectivity is the "unlock-lock approach".[6,7] In this approach, the bond-scission-formation process is thermodynamically well-controlled, since one component is readily released from the other during ring

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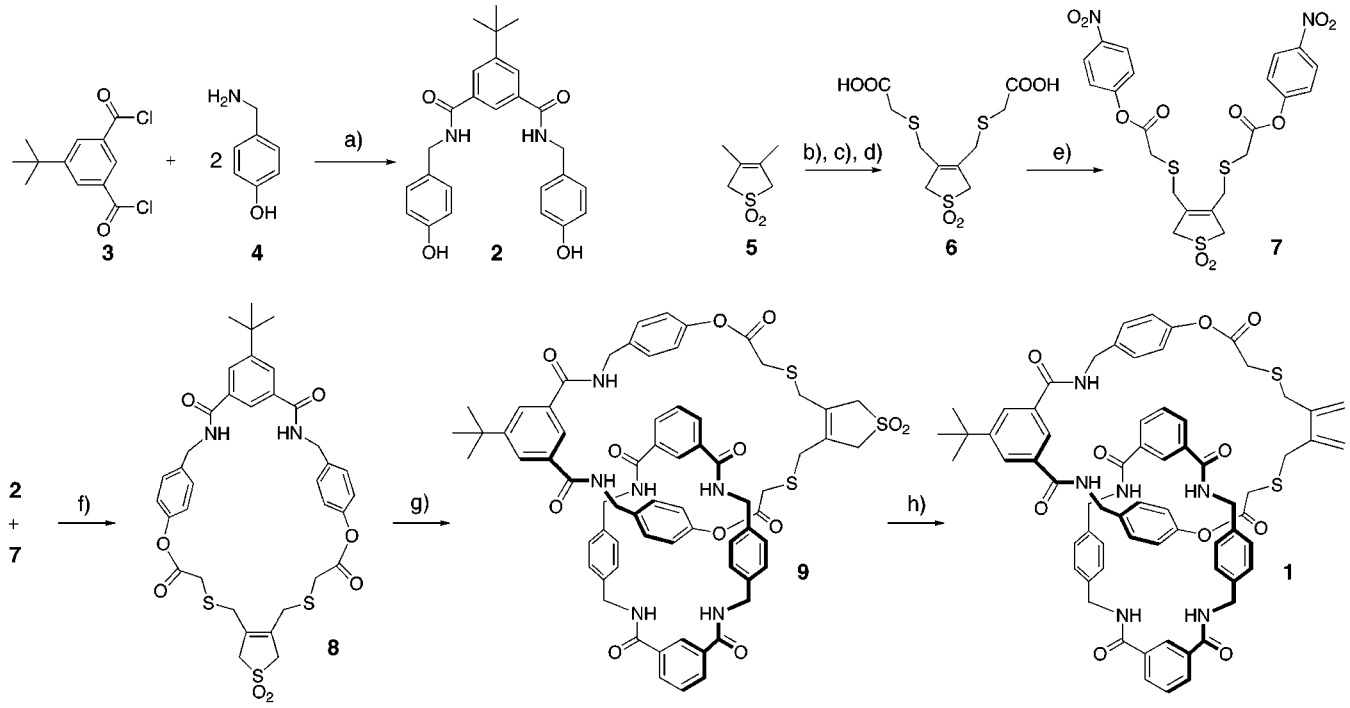
Scheme 1[a]



[a] Conditions: (a) Et_3N, $CHCl_3$, rt, 95%; (b) NBS, BPO, $CHCl_3$, reflux, 42%; (c) methyl thioglycolate, Et_3N, THF/MeOH (2/1), 71%; (d) 6 M HCl, 70 °C, 90%; (e) $SOCl_2$, 50 °C, then 4-nitrophenol, Et_3N, CH_2Cl_2, rt, 62%; (f) Et_3N, $CHCl_3$, rt, 28%; (g) *p*-xylylenediamine, isophthaloyl dichoride, Et_3N, $CHCl_3$, rt, 25%; (h) DMF/xylene (1/5), 150 °C, 36%.

modification without thermodynamic stabilization of the interlocked structure. A technique allowing modification of the size or the shape of a component while also achieving a change of connectivity is strongly desired to prepare various interlocked molecules.[8] We need to find a way to prevent the destruction of the interlocked structure during the change of connectivity on the ring component. As a possible solution, we developed a new protocol, the annulation−ring scission sequence, where initial annulation on the ring component to introduce a new connectivity is followed by successive scission of the original bonding. In this report, we describe the successful expansion of a ring component in a [2]catenane system as a typical example of the annulation−ring scission sequence.

[2]Catenane **1** bearing a 1,3-diene moiety was designed. To ensure the high reactivity of the diene, a 2,3-dialkyl-1,3-diene structure was introduced. The synthetic route of **1** is illustrated in Scheme 1. Bisphenol **2** was prepared from 5-*tert*-butylisophthaloyl chloride **3** and 4-hydroxyphenylmethylamine **4**. Sulfolene **5** was derived from 2,3-dimethyl-1,3-butadiene. The radical bromination of **5** was followed by reaction with methyl thioglycolate, and hydrolysis afforded bisacid **6**, which was converted to the corresponding active ester **7**. Macrolactam **8** was prepared by the 1:1 cyclization of bisphenol **2** and active ester **7** under high dilution conditions. Secondary amide groups of **8** provided hydrogen bonding sites that can interact with other secondary amide groups for the construction of the interlocked structure. According to the reported procedure,[9] the cyclization of isophthaloyl dichloride and *p*-xylylenediamine in the presence of **8** afforded [2]catenane **9** in 25% yield. Deprotection by thermolysis of **9** at 150 °C gave [2]catenane **1** by the elimination of SO_2 from the sulfolene moiety. The ^{1}H NMR spectrum of **9** is more complicated than that of **1**. Figure 1 shows the aromatic region of the ^{1}H NMR spectra of **9** (a) and **1** (b). All of the signals of ring A in **9** were observed as a pair in a 1:1 area ratio, except for the signals of *tert*-butyl protons and H(b). This observation clearly suggests that both sulfolene and *tert*-butylphenyl groups on ring A are too bulky for ring B to thread (Figure 2a). Since ring B is confined to within one of the arms of ring A, each arm was placed under a different environment. *tert*-Butyl protons and H(b) were observed as singlets because they were located on the symmetrical axis of ring A. Meanwhile, ring B of **1** could thread the 1,3-diene group on ring A (Figure 2b). Therefore, ring B exists on both arms of ring A by circumrotation in the same probability, and both arms are under the same

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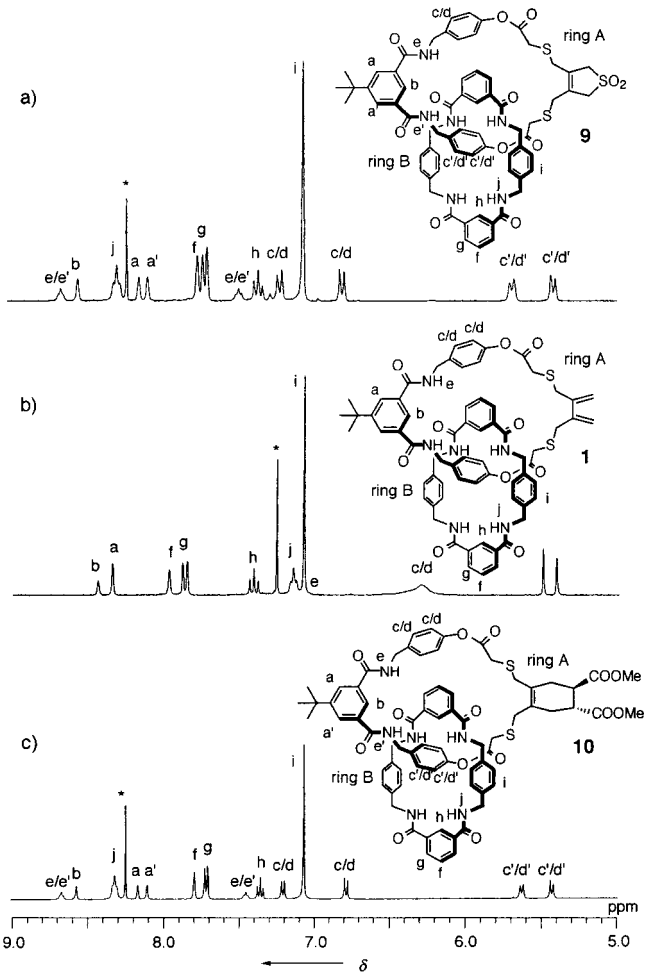


Figure 1. Partial ^{1}H NMR spectra of (a) **9** in [d_6]DMSO, (b) **1** in $CDCl_3$, and (c) **10** in [d_6]DMSO. Asterisk (*) denotes the signals of the remaining solvents.

environment. A Diels−Alder reaction was carried out without isolation of the diene intermediate **1**, and then **9** was refluxed with 10 equiv of dimethyl fumarate in 1,2-dichlorobenzene/DMSO (10/1) to give cyclohexane-fused [2]catenane **10** in 85% yield (Scheme 2). Since the 4,5-disubstituted cyclohexene moiety was too bulky for ring B to thread (Figure 2c), two sets of ^{1}H NMR signals of ring A of **10** were observed, like those of **9** (Figure 1c).

For comparison, a Diels−Alder reaction of **8** was similarly conducted and gave bicyclic compound **11** in 83% yield. The ozonolysis of **10** and **11** was carried out in CH_2Cl_2/MeOH (5/1) at −98 °C. After treatment with dimethyl sulfide, the crude products were oxidized with *m*-CPBA to convert the sulfide groups to sulfone, because the sulfide groups were partially oxidized during the ozonolysis. The ozonolysis of **10** followed by the treatment with dimethyl sulfide and then with *m*-CPBA gave [2]catenane **12** in 40% yield, while single ring product **13** was obtained from **11** in 88% yield. Since free ring B was not observed in the reaction mixture, the ring-expansion sequence did not destroy the catenane structure of **10**. The ^{1}H NMR spectrum of **12** was

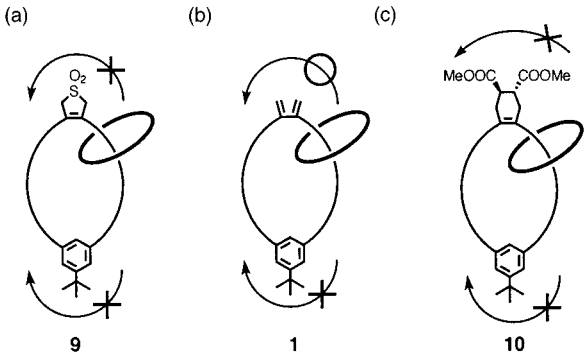


Figure 2. Schematic representation of circumrotation of ring B on ring A. *tert*-Butylphenyl group prevents circumrotation of ring B on ring A. Whereas the 1,3-diene moiety of **1** does not prevent the circumrotation (b), the sulfolene group of **9** (a) and the 4,5-disubstituted cyclohexene moiety of **10** (c) are too bulky for ring B to circumrotate.

similar to that of **10**, since **10** and **12** have similar functionality, and the ester groups in **12** are bulky enough to prevent the circumrotation of ring B. The ^{13}C NMR spectra clearly indicated successful ring expansion, as shown in Figure 3. In the transformation from **11** to **13**, the signal at 120.6 ppm observed for the C=C double bond of **11** disappeared. Instead, a new signal due to the ketone groups of **13** was observed at 201.3 ppm. Similarly, two carbon signals were

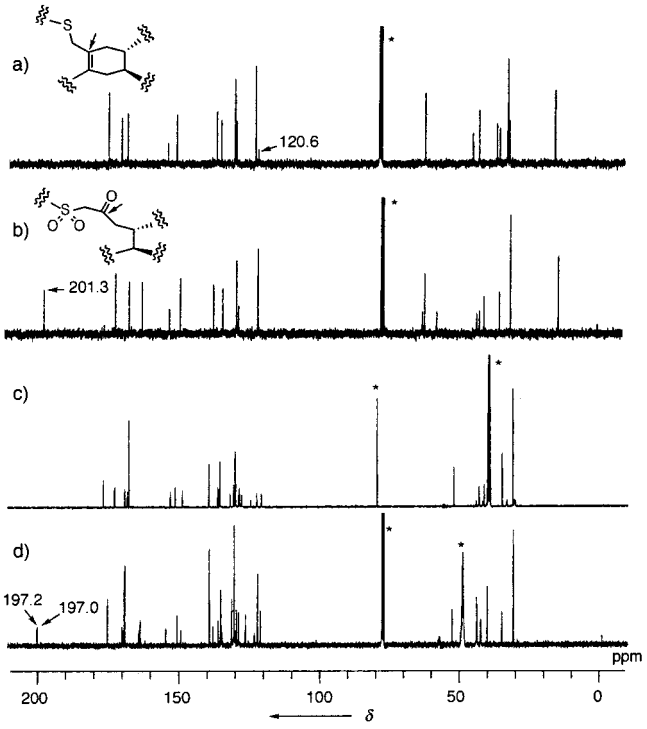
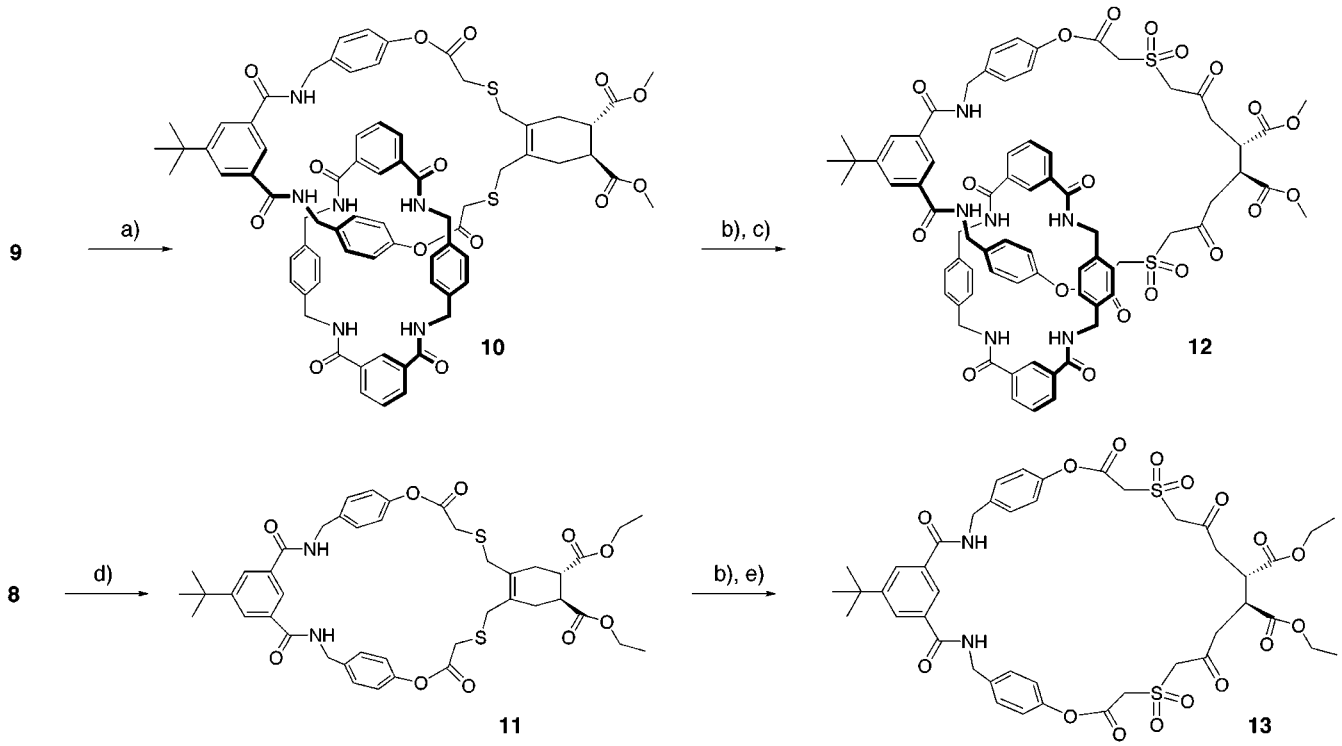


Figure 3. ^{13}C NMR spectra of (a) **11** in $CDCl_3$, (b) **13** in $CDCl_3$, (c) **10** in [d_6]DMSO, and (d) **12** in $CDCl_3$/CD_3OD (5/2). Asterisk (*) denotes the signals of the remaining solvents.

Scheme 2[a]



[a] Conditions: (a) dimethyl fumarate, dichlorobenzene, reflux, 85%; (b) O_3, CH_2Cl_2/MeOH (5/1), −98 °C, then Me_2S, rt; (c) *m*-CPBA, CH_2Cl_2, rt, 40% from **10**; (d) diethyl fumarate, dicholorobenzene/DMSO (10/1), reflux, 84%; (e) *m*-CPBA. CH_2Cl_2, rt, 88% from **11**.

clearly observed at 197.2 and 197.0 ppm in the ^{13}C NMR spectrum of **12**. Because of the restricted circumrotation of ring B of **12**, the two ketone groups were actually under different conditions.

In summary, we have demonstrated the first modification of [2]catenane by ring expansion. The results clearly reveal that the "annulation followed by ring scission" protocol provides an excellent approach to ring expansion without destroying the interlocked structure. During the ring-expansion protocol, functional groups and frameworks can be introduced to the catenane ring. This protocol and its application are under active development.

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Supporting Information Available: Details for preparation of **1**, **8**−**10**, and **12**. This material is available free of charge via the Internet at http://pubs.acs.org.

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