Catenane Formation from Two Molecular Rings through Very Rapid Slippage. A Möbius Strip Mechanism

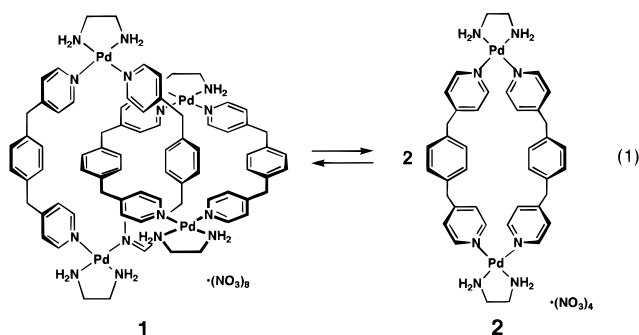Makoto Fujita,*,† Fumiaki Ibukuro,† Hiroko Seki,‡ Osamu Kamo,§ Mamoru Imanari,§ and Katsuyuki Ogura*,†

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Catenane **1** exists in rapid equilibrium with monomer ring **2** (eq 1).[1] Elucidation of the mechanism of the rapid interconversion is essential to precise design and construction of related self-assembling interlocked systems.[2,3] A conventional explana-

tion for the catenane formation involves dissociating a ring at a Pd−N linkage, threading another ring on the thread, and reconnecting the ends of the thread (Scheme 1a). However, the results of the present study negated this simple mechanism and strongly supported an alternative. Here we suggest that the rapid interconversion is explained in terms of ligand exchange between Pd−N bonds.[4] More strictly, our proposed pathway leading to the catenane involves *two sequential ligand exchanges between two molecular rings concomitant with a twisting of the rings around each other* (Scheme 1b).

The mechanistic elucidation initially follows from NMR experiments. Rapid chemical exchange between the C_6H_4 signals of **1** and **2** was clearly observed by ^{1}H NMR truncated

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(1) Fujita, M.; Ibukuro, F.; Hagihara, H.; Ogura, K. *Nature* **1994**, *367*, 720.
(2) For reviews, see the following: (a) Sauvage, J.-P.; Dietrich-Buchecker, C. O.; Chambron, J.-C. In *Comprehensive Supra-molecular Chemistry*; Lehn, J.-M. Ed.; Pergamon Press: Oxford, 1996; Chapter 2 (in press). (b) Stoddart, J. F.; Raymo, F.; Amabilino, D. B. In *Comprehensive Supra-molecular Chemistry*; Lehn, J.-M. Ed.; Pergamon Press: Oxford, 1996; Chapter 3 (in press).
(3) For recent other catenane syntheses, see the following: (a) Hunter, C. A. *J. Am. Chem. Soc.* **1992**, *114*, 5303. (b) Vögtle, F.; Meier, S.; Hoss, R. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1619. (c) O.-Hildebrandt, S.; Meier, S.; Schmidt, W.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1767. (d) Gunter, M. J.; Hockless, D. C. R.; Johnston, M. R.; Skelton, B. W.; White, A. H. *J. Am. Chem. Soc.* **1994**, *116*, 4810. (e) Gruter, G.-J.; de Kanter, F. J. J.; Markies, P. R.; Nomoto, T.; Akkerman, O. S.; Bickelhaupt, F. *J. Am. Chem. Soc.* **1993**, *115*, 12179. (f) Piguet, C.; Bernardinelli, G.; Williams, A. F.; Bocquet, B. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 582. (g) Johnston, A. G.; Leigh, D. A.; Pritchard, R. J.; Deegan, M. D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1209. (h) Johnston, A. G.; Leigh, D. A.; Nezhat, L.; Smart, J. P.; Deegan, M. D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1212. (i) Mingos, D. M. P.; Yau, J.; Menzer, S.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1894.
(4) Ligand exchange on Pd(II) is a very rapid process: Basolo, F.; Chatt, J.; Gray, H. B.; Pearson, R. G.; Shaw, B. L. *J. Chem. Soc.* **1961**, 2207.

Scheme 1. Possible Mechanisms for the Rapid Slippage of Two Molecular Rings: (a) Conventional Mechanism and (b) Ligand Exchange Mechanism[a]
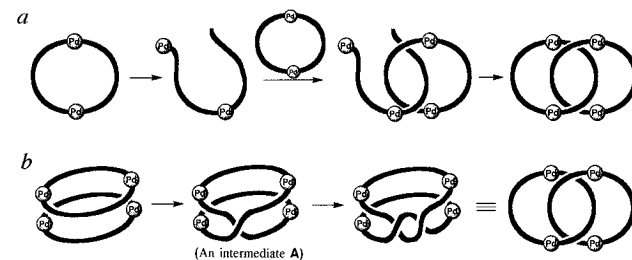
[a] Note that these schemes present only the topology of the pathways. Thus, the second ligand exchange in mechanism b may happen between any Pd−N bonds.
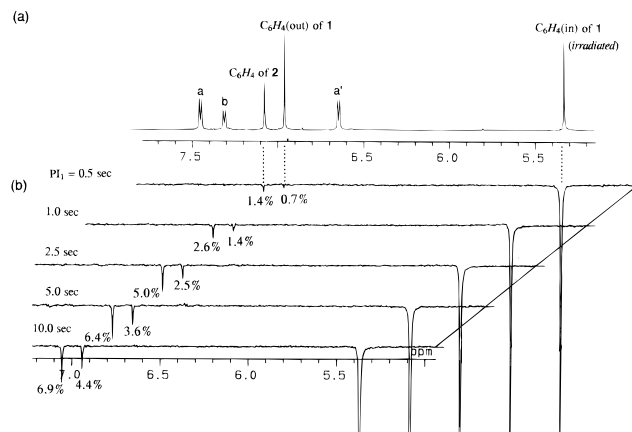
Figure 1. (a) ^{1}H NMR spectrum of the mixture of **1** and **2** (59:41, aromatic regions). Doublet signals a, a′, and b are assigned as PyH_β-(out) of **1**, PyH_β(in) of **1**, and PyH_β of **2**, respectively.[1] (b) TOE difference spectra of the above mixture. Percentages shown below the negative peaks appearing at δ 6.95 and 7.1 indicate the proportion of saturation transfer from saturated C_6H_4(in) of **1**.

driven nuclear Overhauser effect (TOE) difference spectroscopies (Figure 1).[5] Thus, an equilibrium mixture of **1** and **2** (59:41) at 10 mM/Pd(II) in D_2O was used for the NMR study, and the signal of the inside C_6H_4 of **1** (δ 5.3) was irradiated with initial pulse interval (PI$_1$) times ranging from 0.5 to 25 s. A negative differential signal appearing at δ 7.1 (Figure 1b) provided reliable evidence for the chemical exchange or the interconversion, which is so rapid as to be observed even on an NMR time scale (PI$_1$ = 0.5 s).[6]

In this experiment, we unexpectedly observed another negative peak appearing at δ 6.95, which showed the existence of a chemical exchange between the inside and outside C_6H_4 groups. This observation led us to ask, how did the inside phenylene exchange with the outside one? That is to say, how was **1**** formed from **1*** (**1*** and **1**** stand for **1** in which protons of the inside and the outside C_6H_4 group(s) are magnetically saturated,[7] respectively)? A straightforward formation of **1**** via internal rotation of one ring in **1*** around the inside unit of another ring is inhibited because of the steric bulkiness of the

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(5) (a) Noggle, J. H.; Schirmer, R. E. *The Nuclear Overhauser Effect*; Academic Press: New York, 1971. (b) Dahlquist, F. W.; Longmuir, K. J.; Du Vernet, R. B. *J. Magn. Reson.* **1975**, *17*, 406. (c) Wagner, G.; Wüthrich, K. *J. Magn. Reson.* **1979**, *33*, 675.
(6) Compare with a very slow rotaxane self-assembly involving complete dissociation of a Fe(III)−py coordinate bond: Wylie, S.; Macartney, D. H. *J. Am. Chem. Soc.* **1992**, *114*, 3136.
(7) Species **1**** may involve one or two saturated C_6H_4 (outside), though only one form is shown in eq 2.
(8) (a) Fujita, M.; Ibukuro, F.; Yamaguchi, Y.; Ogura, K. *J. Am. Chem. Soc.* **1995**, *117*, 4175. (b) Catenane **3** has the same structure as **1**, except Pd atoms are replaced by Pt atoms. The crystal structure of **3**[8a] showed that this molecule was very tight and the internal rotation was impossible.

(en)Pd moiety. Indeed, the inhibition of the internal rotation was confirmed using analogous platinum catenane **3**,[8] in which inert Pt−N bonds do not dissociate at room temperature:[9] no chemical exchange was observed between the inside and outside phenylenes in **3**, even over a prolonged PI$_1$ time (30 s). Consecutive formation of **1*** via **2*** (**1*** → **2*** → **1****, eq 2, where phenylene rings marked with asterisks are magnetically saturated),[10] is another plausible pathway. However, a PI, time-

$$\text{(2)}$$

○ = (en)Pd(II),   ⌒ = PyCH$_2$(C$_6$H$_4$)CH$_2$Py,   *H**: a magnetically saturated proton
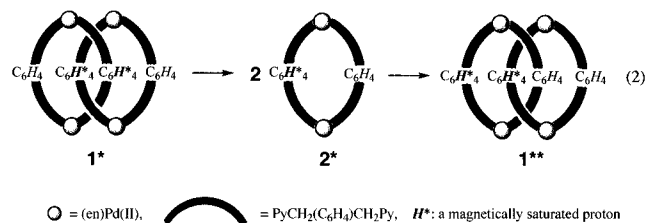
dependent measurement of the chemical exchange showed that **2*** and **1**** must be formed not consecutively but simultaneously, because the ratio of **1**** to **2*** did not vary significantly at an early stage, which can be treated as an unsteady state (PI < ∼5 s, Figure 1b).[11]

These spectroscopic observations led us to conclude that *a certain intermediate must exist* from which **2*** and **1**** are formed simultaneously.[12] To our best consideration, mechanism b in Scheme 1 agrees very well with the NMR experiments. That is, initially formed **1*** undergoes intramolecular ligand exchange to give intermediate **A**. A second ligand exchange can then either lead back to **1**** or give two molecules of **2***.[13] Although catenane **1** and monomer ring **2** are stabilized by enthalpy and entropy effects, respectively,[14] neither makes **A** stable. Due to this thermodynamic disadvantage, the concentration of intermediate **A** in the equilibration mixture is too low to be detected in the NMR spectrum.

(9) Fujita, M.; Yazaki, J.; Ogura, K. *Chem. Lett.* **1991**, 1031.
(10) Species **2*** stands for **2** in which a phenylene ring is magnetically saturated.
(11) This stage is an unsteady state because the increase of signal intensities of **2*** and **1**** is not saturated yet.
(12) If no intermediate existed, **1**** had to be formed directly from **1*** or consecutively via **2***. However, both paths were negated by the NMR study, as discussed.
(13) Internal rotation of one ring during a momentary dissociation of another ring could explain the NMR results. However, this process does not meet the scrambling experiments using **4** discussed later.
(14) Molecular ring **2** assembling from four components (two (en)Pd units plus two ligand molecules) is much more favored in entropy than **1** assembling from eight components. On the other hand, catenane **1** is stabilized by aromatic−aromatic contacts, as suggested by the crystal structure.[8]
(15) For example, the chemical shift of C$_6$H$_4$ of **2** varied as follows: δ 7.07, 7.00, 6.86, and 6.69 at 1, 10, 25, and 50 mM/Pd, respectively. Original spectra were provided in Figure 1B of ref 1.
(16) Fujita, M.; Nagao, S.; Iida, M.; Ogata, K.; Ogura, K. *J. Am. Chem. Soc.* **1993**, *115*, 1574.
(17) We found that fluorinated rings **4** self-associate to give a catenated dimer analogous to **1** at high concentration. The ratios of monomer ring **4** to the catenated dimer [mM/Pd] are as follows: >95:<5 [1]; 93:7 [2]; 84:16 [5]; 68:32 [10]. ^{1}H NMR data of the catenane (D$_2$O, [Pd(II)] = 10 mM): δ 2.87 (s, 16 H, NH$_2$CH$_2$-), 3.24 (s, 8 H, PyCH$_2$(in)), 4.11 (s, 8 H, PyCH$_2$(out)), 6.64 (d, *J* = 6.4 Hz, 8 H, PyH$_\beta$(in)), 7.57 (d, *J* = 6.4 Hz, 8 H, PyH$_\beta$(out)), 8.60 (d, *J* = 6.4 Hz, 8 H, PyH$_\alpha$(in)), 8.86 (d, *J* = 6.4 Hz, PyH$_\alpha$(out)). Physical data of **4** have already been reported.[16]
(18) Besides preferred electronic interaction, a catenane arising from **4** and **5** is sterically matching. Δ*H* of the catenation was roughly estimated to be −105 kJ mol^{-1} by an MM2 study, where MM2 parameters supplied by the CAChe system (Ver. 3.5, Sony/Tektronix Corp.) were used for the refinement of the molecular modeling (see Supporting Information).
(19) van Gulick, N. *New J. Chem.* **1993**, *17*, 619. A preprint of this paper was first written in 1960; see the preface to this paper by Walba: *New J. Chem.* **1993**, *17*, 618.
(20) Strictly speaking, a Möbius strip, when cut in half, always gives one piece like intermediate **A**; a strip that leads to the catenane upon cutting of the strip is *not* a Möbius strip. However, the overgeneralization regarding twisted strips seems to be accepted in older literature, and we hope one can easily understand what is meant by our "Möbius strip mechanism", although it does not involve a real Möbius strip.

To undergo the ring slippage through ligand exchange, two molecules of **2** must self-associate before the event. The self-association was also implied by NMR. That is, the chemical shifts of signals of **2** gradually shifted upfield with increasing concentration, while those of **1** were intact. The upfield shift is most probably ascribed to the self-association of **2**.[15]

The following experiments also supported mechanism b. When the catenane fomation from **2** and fluorinated molecular ring **4**[16] was examined, we observed the assembly of immediately scrambled catenanes (eq 3).[17] If catenanes are formed

$$\text{(3)}$$

○ = (en)Pd(II),   ⌒ = PyCH$_2$(C$_6$H$_4$)CH$_2$Py,   ⌒ = PyCH$_2$(C$_6$F$_4$)CH$_2$Py
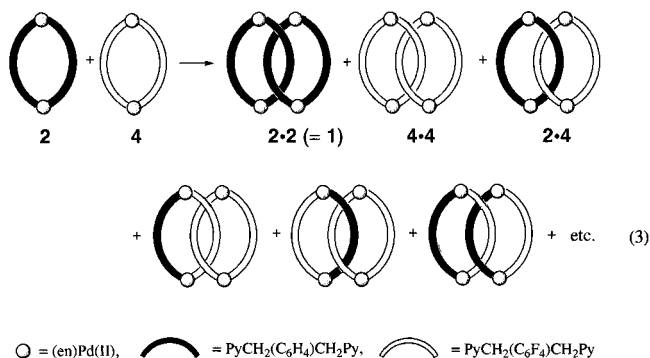
via mechanism a, this experiment should give only three catenanes **1**, **2·4**, and **4·4**. The immediate scrambling of two ligands suggested the existence of an intermediate analogous to **A** from which a molecular ring possessing both fluorinated and non-fluorinated ligands is formed.

It is interesting that, in contrast to the rapid formation of catenanes from **2** and/or **4**, no interaction was observed between **4** and Stoddart's polyether ring **5**,[2e] despite their high ability to recognize electronically complementary aromatic rings: i.e., **4** recognizes *p*-dimethoxybenzene[16] (a partial structure of **5**) with a K_a value of 2680 L mol^{-1}, while **5** strongly binds cationic pyridinium systems.[2e,18] This result is in good accordance with mechanism b, which needs reversible coordinate bonds to be involved in *both* rings.

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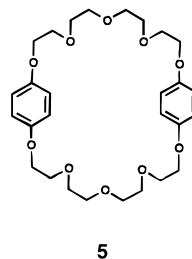
In 1960, van Gulick proposed a Möbius strip strategy for catenane synthesis, in which a catenane arises upon cutting a doubly twisted molecular Möbius strip into two halves.[19,20] Later, a singly twisted Möbius strip was prepared by Walba.[21] It is particularly interesting that our proposed mechanism is reminiscent of the success of the Möbius strip approach to a [2]catenane through ligand exchange.

Supporting Information Available: Details for the force-field calculations of **4**, **5**, and **6** (11 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA9507325

(21) Walba, D. M.; Richards, R. M.; Haltiwanger, R. C. *J. Am. Chem. Soc.* **1982**, *104*, 3219. Walba, D. M.; Homan, T. C.; Richards, R. M.; Haltiwanger, R. C. *New J. Chem.* **1993**, *17*, 661.