Inorg. Chem. **2007**, *46*, 8445–8447

[2]Pseudorotaxane and [2]Rotaxane Molecular Shuttles: Self-Assembly through Second-Sphere Coordination of Thiocyanate Ligands

Barry A. Blight, Xu Wei, James A. Wisner,* and Michael C. Jennings

Department of Chemistry, The University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 5B7, Canada

Received May 25, 2007

A $Pd(Py)_2(SCN)_2$ complex is shown to form a [2]pseudorotaxane complex with a macrocyclic tetralactam, which binds in the solid state through an unexpected complexation geometry. The intermolecular complexation is further applied to template the formation of a [2]rotaxane. The interlocked product acts as a degenerate molecular shuttle in solution, which is consistent with the coconformation observed in the solid state.

The design and synthesis of molecular machines and switches is an area of significant current interest because of the great potential to harness their properties for advanced materials applications.[1] Interlocked molecules such as rotaxanes and catenanes constitute a significant subset of these systems because of the unique mechanically bonded relationship their individual components possess with respect to one another. Specifically, molecular shuttles often feature the shuttling of a macrocyclic ring between two or more sites along the backbone of the axle in a rotaxane.[2,3] If the sites are identical, the shuttle is degenerate and no preference for one site over the other is observed. Herein, we describe the serendipitous discovery of a new template for [2]pseudorotaxane formation and its application to the synthesis of a [2]rotaxane, which displays the features of a degenerate molecular shuttle.

We have previously demonstrated that, through hydrogen bonding, second-sphere coordination of halide ligands of a palladium(II) bispyridine complex by the amide hydrogens of isophthalamide-based tetralactam macrocycle **1** is an effective template for the self-assembly of [2]pseudorotaxanes.[4] With the success and information gained from this study, we began exploring various methods to "stopper" the threadlike molecule while maintaining the integrity of the template, resulting in the synthesis of a [2]rotaxane in good yield using pyridine ligands with sterically demanding termini.[5]

A further extension of this methodology is the investigation of different anionic ligands that could replace the halides in the palladium complex as hydrogen-bond acceptors. Molecular models suggested that thiocyanate ligands might act in a similar manner if the tetralactam was hydrogen-bonded to their sulfur atoms, which would, in turn, be ligated to the palladium metal center.

Macrocycle **1**[6] and axle **2**[8] (Scheme 1) were easily synthesized according to existing literature preparations. [2]-Pseudorotaxanes are in equilibrium with their uncomplexed components because of the absence of covalent or mechanical attachment. The resultant ^{1}H NMR spectrum of an admixture of equimolar amounts of **1** and **2** at a concentration of 1×10^{-3} M in $CDCl_3$ is markedly different from those of the individual starting materials (Figure 1), implying complexation in solution. Notable differences include the downfield shifts of protons a ($\Delta\delta = -0.75$ ppm), due to hydrogen bonding, and d ($\Delta\delta = -0.25$ ppm), as a result of its proximity to the deshielding regions of the pyridine rings, and upfield shifts of f ($\Delta\delta = 0.67$ ppm) and g ($\Delta\delta = 0.89$

* To whom correspondence should be addressed. E-mail: jwisner@uwo.ca.

(1) (a) Kay, E. R.; Leigh, D. A.; Zerbetto, F. *Angew. Chem., Int. Ed.* **2007**, *46*, 72. (b) Kinbara, K.; Aida, T. *Chem. Rev.* **2005**, *105*, 1377. (c) Volume on "Molecular Machines": *Top. Curr. Chem.* **2005**, *262*, 1−236. (d) Balzani, V.; Credi, A.; Raymo, F. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2000**, *39*, 3349.

(2) Tian, H.; Wang, Q.-C. *Chem. Soc. Rev.* **2006**, *35*, 361.

(3) For recent examples, see: (a) Marlin, D. S.; González Cabrera, D.; Leigh, D. A.; Slawin, A. M. Z. *Angew. Chem., Int. Ed.* **2006**, *45*, 77. (b) Marlin, D. S.; González Cabrera, D.; Leigh, D. A.; Slawin, A. M. Z. *Angew. Chem., Int. Ed.* **2006**, *45*, 1385. (c) Tokunaga, Y.; Nakamura, T.; Yoshioka, M.; Shimomura, Y. *Tetrahedron Lett.* **2006**, *47*, 5901. (d) Qu, D.-H.; Wang, Q.-C.; Tian, H. *Angew. Chem., Int. Ed.* **2005**, *44*, 5296. (e) Murakami, H.; Kawabuchi, A.; Matsumoto, R.; Ido, T.; Nakashima, N. *J. Am. Chem. Soc.* **2005**, *127*, 15891. (f) Jeppesen, J. O.; Nygaard, S.; Vignon, S. A.; Stoddart, J. F. *Eur. J. Org. Chem.* **2005**, 196. (g) Cooke, G.; Garety, J. F.; Mabruk, S.; Rabani, G.; Rotello, V. M.; Surpateanu, G.; Woisel, P. *Tetrahedron Lett.* **2006**, *47*, 783. (h) Badjić, J. D.; Ronconi, C. M.; Stoddart, J. F.; Balzani, V.; Silvi, S.; Credi, A. *J. Am. Chem. Soc.* **2006**, *128*, 1489. (i) Clemente-León, M.; Credi, A.; Martínez-Díaz, M. V.; Mingotaud, C.; Stoddart, J. F. *Adv. Mater.* **2006**, *18*, 1291.

(4) Blight, B. A.; Van Noortwyk, K. A.; Wisner, J. A.; Jennings, M. C. *Angew. Chem., Int. Ed.* **2005**, *44*, 1499.

(5) Blight, B. A.; Wisner, J. A.; Jennings, M. C. *Chem. Commun.* **2006**, 4593.

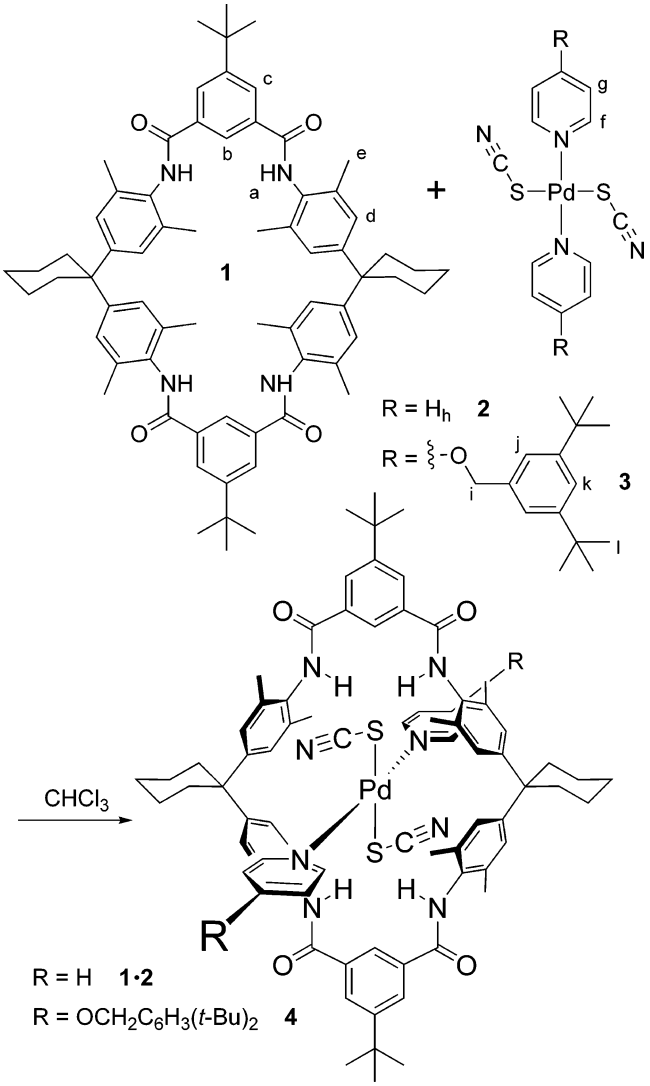
(6) Fischer, C.; Nieger, M.; Mogck, O.; Böhmer, V.; Ungaro, R.; Vögtle, F. *Eur. J. Org. Chem.* **1998**, *1*, 155.

(7) Burmeister, J. L.; Basolo, F. *Inorg. Chem.* **1964**, *3*, 1587.

(8) Sutherland, I. O. *Annu. Rep. NMR Spectrosc.* **1971**, *4*, 71.

10.1021/ic701021p CCC: $37.00
Published on Web 09/19/2007

Scheme 1. Self-Assembly of Both a [2]Pseudorotaxane and a [2]Rotaxane Molecular Shuttle



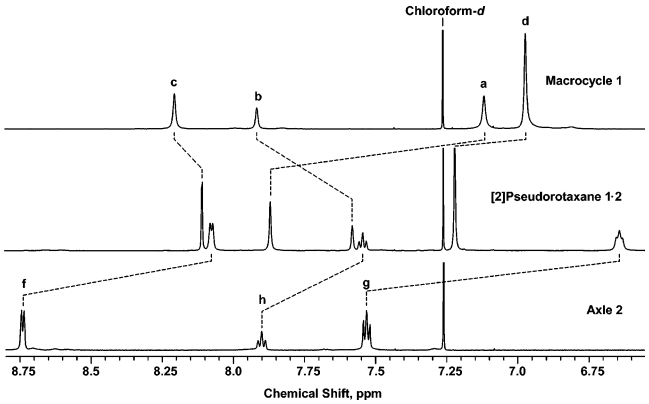


Figure 1. Aromatic region of the ^{1}H NMR spectra (600 MHz, 298 K) of free macrocycle **1** (top), [2]pseudorotaxane **1·2** (middle), and free axle **2** (bottom). Illustrated are the observed perturbations in the chemical shift between free and complexed components (dashed lines).

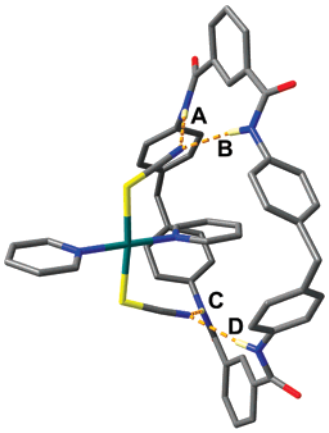


Figure 2. Stick representation of interpenetrated [2]pseudorotaxane **1·2** in the solid state. All C−H hydrogen atoms and methyl, cyclohexyl, and *tert*-butyl groups have been removed for clarity. NH···NCS hydrogen bonds are indicated by orange dashed lines. Color code: C, gray; H, pale yellow; N, blue; O, red; S, yellow; Pd, teal.

ppm), which are interpreted as C−H···π interactions with the sidewalls of the macrocycle as a result of our earlier investigations.[4,5] Isothermal titration calorimetry of **1** with **2** in $CHCl_3$ at room temperature revealed an association constant (K_a) of 5300 ± 100 M^{-1} (ΔG = 21.0 ± 0.1 kJ mol^{-1}), which was confirmed by a ^{1}H NMR titration experiment.

X-ray crystallographic analysis confirmed the desired interpenetrated geometry of **1·2** in the solid state but revealed an unanticipated complexation geometry for the [2]pseudorotaxane (Figure 2). Although the macrocyclic recognition site is the appropriate size to accommodate the S−Pd−S subunit, the solid-state structural result displays hydrogen-bonding interactions between the tetralactam amide hydrogen atoms and the terminal nitrogen atoms of the thiocyanate ligands [N−N = 3.15 (A), 3.08 (B), 3.08 (C), and 3.18 (D) Å; N−H···N = 172° (A), 171° (B), 168° (C), and 172° (D)], which are arranged in a manner parallel to the N−Pd−N axis. This geometry displaces the Pd^{2+} center from the plane of the macrocyclic component (the least-squares plane defined by the four carbonyl carbons) by 4.74 Å, which, in turn, requires all four amide groups to deviate from coplanarity (24−40°) with the attached *tert*-butylphenyl rings. The result is a dissymmetric complex in which one pyridine ligand is encircled by the macrocycle and the other is not. Fortunately, the solid-state structure remains consistent with the results from the NMR analysis (assuming fast exchange during the complexation/decomplexation process; see below) and may further be viewed as a precursor for its interlocked [2]rotaxane counterpart. This mechanically bonded analogue could be generated by introducing "stopper" groups at the para position of the pyridine rings, which was our next target.

Dumbbell **3** was synthesized by dissolution of $K_2Pd(SCN)_4$ in ethanol, followed by dropwise addition of an ethanolic solution of the previously reported 4-[(3,5-di-*tert*-butylbenzyl)oxy]pyridine stopper ligand.[5] The synthesis of **4** was then achieved by harnessing the utility of the labile palladium(II)−pyridine coordinate bonds of the non-interlocked axle. Stoichiometric amounts of **1** and **3** were combined in chloroform and allowed to stir for 5 days, resulting in self-assembled [2]rotaxane **4** (76% yield after purification). It is interesting to note that a pure sample of **4** is kinetically stable at room temperature and may be chromatographed or left in a $CDCl_3$ solution for substantial periods of time (1 week) with no observable decomposition into the component parts.

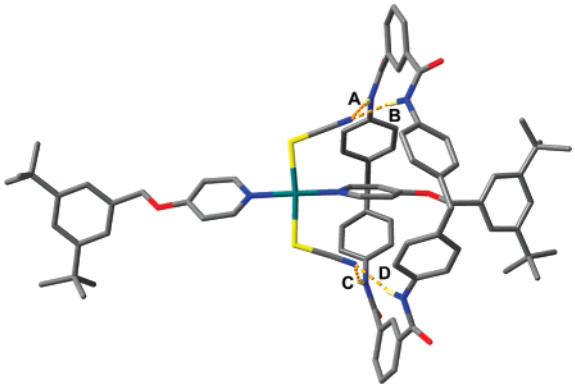


Figure 3. Stick representation of interlocked [2]rotaxane **4** in the solid state. All methyl, cyclohexyl, and *tert*-butyl groups from macrocycle **1** and all C−H hydrogen atoms have been removed for clarity. NH···NCS− hydrogen bonds are indicated by orange dashed lines. Color code: C, gray; H, pale yellow; N, blue; O, red; S, yellow; Pd, teal.

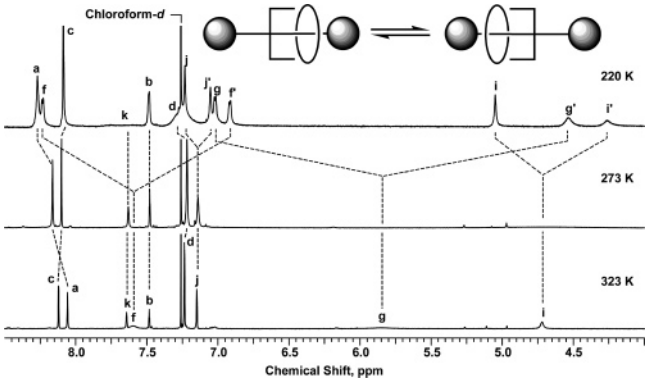


Figure 4. Aromatic region of the ^{1}H NMR spectra (600 MHz, 298 K) of [2]rotaxane **4** at 220 K (top), 273 K (middle), and 323 K (bottom). Illustrated are the observed chemical shift perturbations caused by the shuttling motion of macrocycle **1** along dumbbell **3** (dashed lines). Variable-temperature ROESY NMR experiments were performed to allow individual proton assignments. Proton k is baseline-resolved at 220 K, as are f and g at 273 K.

Initial ^{1}H NMR analysis of **4** at room temperature exhibited chemical shift values corresponding to the interlocked geometry with extreme broadening of pyridine protons f, g, and i, suggesting chemical exchange near their coalescence points. Chemical shifts of interest ($\Delta\delta$) in comparison to the isolated components **1** and **3** include a (−0.99 ppm), d (−0.26 ppm), f (0.87 ppm), g (1.28 ppm), and i (0.39 ppm), which are of the same quality as those in **1·2** but are exaggerated as a result of the interlocked nature of the components.[4]

Based on the crystallographic results of **1·2**, it was predictable that **4** would adopt a similar dissymmetric geometry. This feature was confirmed upon examination of the solid-state structure obtained by X-ray diffraction analysis (Figure 3). In a similar manner, the thiocyanate ligands engage in hydrogen bonding with the N−H groups of the macrocycle [N−N = 3.32 (A), 3.06 (B), 3.06 (C), and 3.11 (D) Å; N−H···N = 178° (A), 172° (B), 161° (C), and 168° (D)] in **4**. The Pd^{2+} center is displaced from the macrocyclic cavity by 4.52 Å, forcing the NH groups from coplanarity (30−37°), with the attached *tert*-butylphenyl rings directed toward the hydrogen-bond acceptors. This results in a structurally dissymmetric [2]rotaxane in the solid state. However, in solution **4** has the option of two degenerate co-conformations involving encirclement of either of the two pyridyl ligands. The potential shuttling between these two states, if present, in **4** was probed through variable-temperature ^{1}H NMR.

As mentioned above, at room temperature (298 K), the system is engaged in chemical exchange, evident from the broadening of the pyridine protons. Upon cooling to 220 K, two sets of signals for f, g, i, and j appear (protons attached to the encircled ligand are denoted by a prime). These signals may be assigned via a low-temperature ROESY NMR experiment, which exhibits distinct exchange cross-peaks for each set. Figure 4 illustrates the significant effect macrocycle **1** imposes on these perturbed protons (g is particularly noteworthy). In addition, broadening of d and e (not shown) is evidence of desymmetrization of the two faces of the macrocycle. Warming the system to 323 K increased the rate of the exchange process, resulting in the spectrum of a completely degenerate [2]rotaxane under fast exchange conditions. Coalescence temperatures and exchange rates were determined by variable-temperature ^{1}H NMR for protons g (288 K, 3300 Hz), f (278 K, 1800 Hz), i (268 K, 1100 Hz), j (253 K, 240 Hz), and l (248 K, 160 Hz) of **4**, yielding an average $\Delta G^{\ddagger}$ value of 48.4 kJ mol^{-1} for shuttling, as determined by the Eyring equation.[8]

In conclusion, we have demonstrated that second-sphere coordination of a palladium(II) thiocyanate complex is an effective means to template the formation of both a [2]-pseudorotaxane and [2]rotaxane. The directional nature of the thiocyanate ligands affords dissymmetric binding geometries in the solid state and subsequently a degenerate [2]-rotaxane molecular shuttle in solution. We are currently undertaking a comprehensive analysis of this shuttling behavior to determine whether the site exchange is a result of ligand dissociation or simple conformational changes of the components, which will be reported in due course.

Acknowledgment. We are grateful for the financial support provided by the Natural Sciences and Engineering Research Council of Canada and the University of Western Ontario.

Supporting Information Available: All experimental procedures, characterization information for **1·2**, **3**, and **4**, isothermal titration calorimetry data, and all crystallographic data and refinement procedures in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

IC701021P