ORGANIC
LETTERS

2004
Vol. 6, No. 6
861−864

Chiral Metallacyclophanes: Self-Assembly, Characterization, and Application in Asymmetric Catalysis

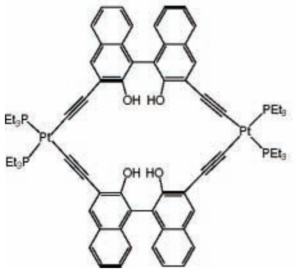
Jiang Hua and Wenbin Lin*

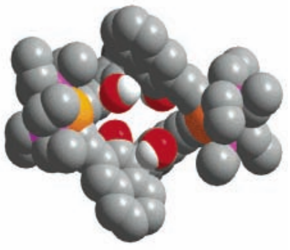
Department of Chemistry, CB 3290, University of North Carolina,
Chapel Hill, North Carolina 27599

wlin@unc.edu

Received October 29, 2003

ABSTRACT





A family of chiral metallacyclophanes has been readily assembled based on robust Pt-acetylide linkage and characterized by a variety of spectroscopic techniques and X-ray crystallography. The steric congestion around the chiral dihydroxy groups in rigid metallacyclophane 4 prevents their reactions with Ti(O^{i}Pr)$_4$ to form active catalysts for enantioselective diethylzinc additions to aromatic aldehydes. In contrast, chiral dihydroxy groups in more flexible unclosed metallacyclophane 5 are effective ligands for enantioselective catalytic diethylzinc additions to aromatic aldehydes.

The field of metallosupramolecular chemistry has witnessed tremendous growth over the past decade. In particular, the synthesis of metallocycles and metallocages is now well-established, primarily owing to seminal contributions from Fujita's and Stang's groups.[1] Functional metallosupramolecular assemblies are, however, still rare despite their perceived advantages over the constituent building blocks.[2] We are particularly interested in rational design of chiral metallosupramolecular assemblies that combine the functionalities and precise spatial placements of the building blocks in order to create functional enzyme mimics. To this end, we have recently reported the first chiral molecular square for enantioselective sensing and the first chiral molecular triangle for asymmetric catalysis.[3] We have also observed the tuning of enantioselectivity patterns of an asymmetric catalyst by rigidification of the chiral ligand upon its incorporation into metallacyclophane [*cis*-(PEt$_3$)$_2$Pt(**L$_1$**)]$_2$, **1** (where **L$_1$** is 6,6′-bis(alkynyl)-1,1′-binaphthalene).[4] Herein we wish to report self-assembly of supramolecular isomers of **1** using topologically different 3,3′-bis(alkynyl)-1,1′-binaphthalene bridging ligands (**L$_{2-4}$**) that are geometric isomers of **L$_1$**. We also report here photophysical properties of chiral metallacyclophanes [*cis*-(PEt$_3$)$_2$Pt(**L$_{2-4}$**)]$_2$, as well as the synthesis of a unclosed metallacyclophane *cis*-(PEt$_3$)$_2$-

---

[1] (a) Fujita, M.; Ogura, K. *Coord. Chem. Rev.* **1996**, *148*, 249. (b) Fujita, M. *Chem. Soc. Rev.* **1998**, *27*, 417. (c) Stang, P. J.; Olenyuk, B. *Acc. Chem. Res.* **1997**, *30*, 502. (d) Stang, P. J.; Olenyuk, B. *Acc. Chem. Res.* **1997**, *30*, 502. (e) Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853.

[2] (a) Dinolfo, P. H.; Hupp J. T. *Chem. Mater.* **2001**, *13*, 3113. (b) Benlanger, S.; Hupp J. T.; Guzei, I. A.; Rheingold, A. L. *Coord. Chem. Rev.* **1998**, *171*, 221. (c) Merlau, M. L.; del Pilar Mejia M.; Nguyen, S. T.; Hupp, J. T. *Angew. Chem., Int. Ed.* **2001**, *113*, 4369. (d) Gianneschi, N. C.; Bertin, P. A.; Nguyen, S. T.; Mirkin, C. A.; Zakharov, L. N.; Rheingold, A. L. *J. Am. Chem. Soc.* **2003**, *125*, 10508. (e) Yoshizawa, M.; Kusukawa, T.; Fujita, M.; Sakamoto, S.; Yamaguchi, K. *J. Am. Chem. Soc.* **2001**, *123*, 10454. (f) Yoshizawa, M.; Takeyama, Y.; Kusukawa, T.; Fujita, M. *Angew. Chem., Int. Ed.* **2002**, *41*, 1347.

[3] (a) Lee, S.; Lin, W. *J. Am. Chem. Soc.* **2002**, *124*, 4554. (b) Lee, S. J.; Hu, A.; Lin, W. *J. Am. Chem. Soc.* **2002**, *124*, 12948.

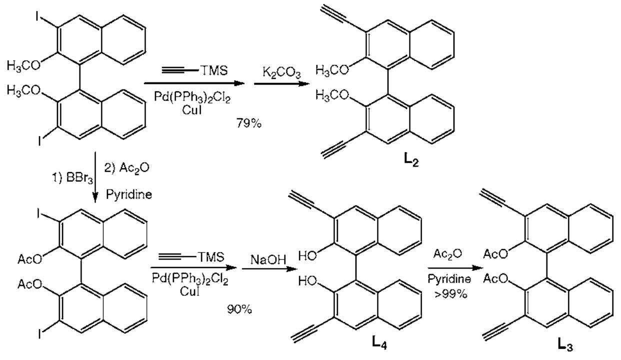
[4] Jiang, H.; Hu, A.; Lin, W. *Chem. Commun.* **2003**, 96.

10.1021/ol036111v CCC: $27.50

$Pt(\mathbf{L_6})_2$ (where $\mathbf{L_6}$ is 3-alkynyl-1,1′-binaphthalene) and its application in enantioselective diethylzinc additions to aromatic aldehydes to afford chiral secondary alcohols.

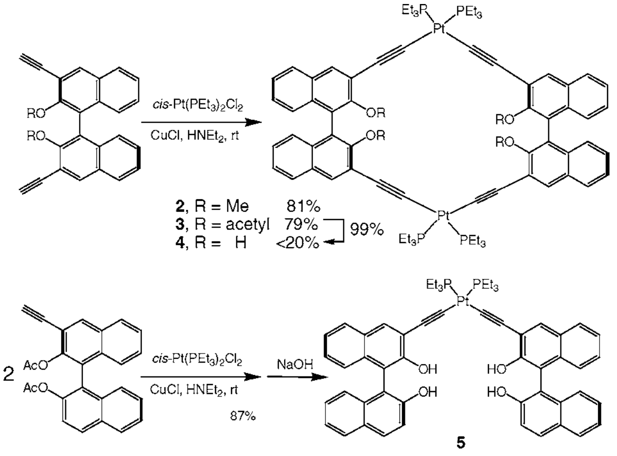
Enantiomerically pure atropisomeric bis(acetylenes) $\mathbf{L_{2-4}}$ were synthesized in high overall yields by Sonogashira coupling reactions between trimethylsilylacetylene and appropriate 3,3′-diiodo-1,1′-binaphthyl starting materials as shown in Scheme 1.[5] 3-Alkynyl-2,2′-diacetyl-1,1′-binaphthalene, $\mathbf{L_5}$, was prepared from 3-iodo-2,2′-diacetyl-1,1′-binaphthalene in 90% overall yield in a fashion similar to that for $\mathbf{L_2}$. New binaphthalene-derived alkynes $\mathbf{L_2}$, $\mathbf{L_3}$, $\mathbf{L_5}$, and $\mathbf{L_6}$ have been characterized by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy and mass spectrometry.

Scheme 1



Treatment of ligands $\mathbf{L_2}$ and $\mathbf{L_3}$ with 1 equiv of *cis*-$Pt(PEt_3)_2Cl_2$ in the presence of catalytic amounts of CuCl in diethylamine at room temperature afforded chiral metallacyclophanes [*cis*-$(PEt_3)_2Pt(\mathbf{L_2})]_2$, **2**, and [*cis*-$(PEt_3)_2Pt(\mathbf{L_3})]_2$, **3**, in 81% and 79% yield, respectively (Scheme 2). Treatment of $\mathbf{L_4}$ with 1 equiv of *cis*-$Pt(PEt_3)_2Cl_2$ under a variety of conditions gave the hydroxy cycle **4** in very low yields (<20%), presumably as a result of undesired competitive coordination of the dihydroxy groups of $\mathbf{L_4}$ to lead to intractable products. Instead, **4** can be obtained in quantitative yield by treating **3** with aqueous solution of sodium hydroxide in a mixture of THF and methanol. Treatment of $\mathbf{L_5}$ with 0.5 equiv of *cis*-$Pt(PEt_3)_2Cl_2$ under similar conditions afforded *cis*-$(PEt_3)_2Pt(\mathbf{L_5})_2$, which was directedly deprotected with an aqueous solution of sodium hydroxide in a mixture of THF and methanol to afford *cis*-$(PEt_3)_2Pt(\mathbf{L_6})_2$, **5**, in 87% overall yield. Compounds **2**−**5** have been characterized by ^{1}H, ^{13}C{^{1}H}, and ^{31}P{^{1}H} NMR spectroscopy; FAB- and MALDI-TOF MS; elemental analysis; and IR, UV−vis, and circular dichroism (CD) spectroscopies.

Scheme 2



NMR spectra of **2**−**4** indicated a single ligand environment, consistent with the formation of cyclic species. FAB-MS data showed the presence of molecular ions due to dimeric species for **2**−**4**. The terminal acetylenic C−H stretches of $\mathbf{L_{2-4}}$ at ∼3280 cm^{-1} disappeared upon the formation of **2**−**4**. The IR spectra of **2**−**4** exhibit expected C≡C stretches at ∼2110 cm^{-1}. All of these spectroscopic data are consistent with a cyclic dimeric structure of approximate D_2 symmetry in solution. In contrast, the ^{1}H and ^{13}C{^{1}H} spectra of **5** show the presence of inequivalent naphthalene units, consistent with the formation of unclosed metallacyclophane structures. The identity of **5** has been confirmed by the MALDI-TOF spectrum, which indicated the presence of molecular ion due to **5**.

Single-crystal X-ray diffraction studies on compound **2** and **4** unambiguously demonstrated the formation of chiral metallacyclophanes (Figure 1).[6] The asymmetric unit of **2** contains two molecules of **2** and one dichloromethane solvent molecule, whereas the asymmetric unit of **4** contains two molecules of **4** and one ethyl acetate solvent molecule. No crystallographic symmetry is present in the molecules of **2**

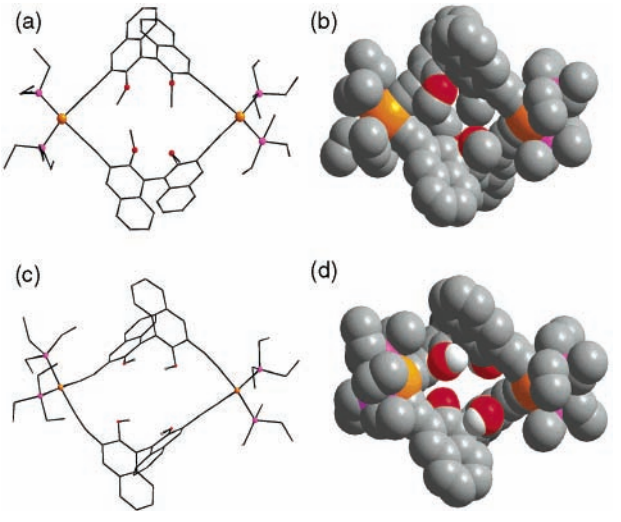


Figure 1. X-ray crystal structures and space-filling models of **2** (a and b) and **4** (c and d). In **2**, average Pt−C distance is 1.99 Å, average Pt−P distance is 2.30 Å, average C−Pt−C angle is 86.0°, and average P−Pt−P angle is 100.9°. In **4**, average Pt−C distance is 1.988 Å, average Pt−P distance is 2.309 Å, average C−Pt−C angle is 86.0°, and average P−Pt−P angle is 101.6°.

and **4** in the solid state. Close proximity of the 1,1′-binaphthalene units is clearly evident in X-ray structures of **2** and **4**, which prevents the reaction of **4** with Ti(O^{i}Pr)$_4$ to generate the active catalyst for the addition of diethylzinc to aromatic aldehydes (see below).

The electronic spectra of $\mathbf{L_{2-4}}$ show three major $\pi\rightarrow\pi^*$ transitions at ~240 nm due to naphthyl groups and three weak absorptions at ~290 nm due to acetylenic $\pi\rightarrow\pi^*$ transitions that have been delocalized into naphthyl ring systems. Monoacetylenated compound $\mathbf{L_6}$ exhibits a naphthyl $\pi\rightarrow\pi^*$ transition at ~227 nm, which is at higher energy comparing with $\mathbf{L_{2-4}}$, because of the lack of delocalization of acetylenic $\pi\rightarrow\pi^*$ in one of the naphthyl rings. In addition, $\mathbf{L_6}$ also shows $\pi\rightarrow\pi^*$ transitions at lower energies due to the delocalization of acetylenic $\pi\rightarrow\pi^*$ transitions into the other naphthyl ring.

Upon the formation of metallacyclophanes **2**−**4**, a new peak appears at 224 nm, which can be assigned to the *cis*-Pt(PEt$_3$)$_2$ moiety. The naphthyl $\pi\rightarrow\pi^*$ transitions have red-shifted by ~15 nm, while the acetylenic $\pi\rightarrow\pi^*$ transitions have significantly red-shifted by ~35 nm (Figure 2). Such bathochromic shifts are well-established in platinum acetylides, assignable to the mixing of Pt p-orbitals into the acetylenic $\pi\rightarrow\pi^*$ bands.[7] The $\pi\rightarrow\pi^*$ transitions at ~325 nm in **2**−**4** thus have significant ligand-to-metal charge transfer (LMCT) character. For compound **5**, an intense peak at ~225 nm is generated as a result of the overlap of unconjugated naphthyl $\pi\rightarrow\pi^*$ transition and *cis*-Pt(PEt$_3$)$_2$ moiety. Bathochromic shifts similar to those in **2**−**4** are also observed for the $\pi\rightarrow\pi^*$ transitions in compound **5**.

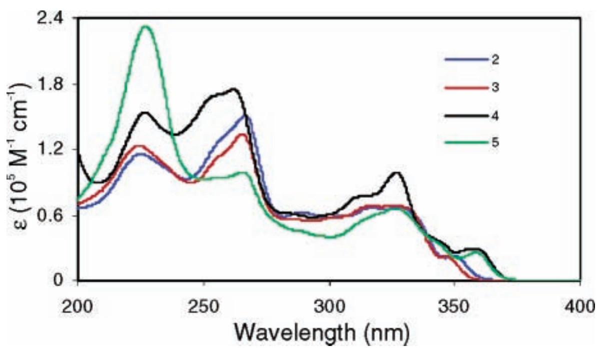


Figure 2. UV−vis spectra of **2**−**5** in acetonitrile.

CD spectra of ligands $\mathbf{L_{2-4}}$ exhibit two major bisignate bands corresponding to naphthyl $\pi\rightarrow\pi^*$ transitions at 234 and 248 nm for $\mathbf{L_2}$, 230 and 243 nm for $\mathbf{L_3}$, and 232 and 242 nm for $\mathbf{L_4}$, as well as two minor bands at ~293 and ~356 nm due to acetylenic $\pi\rightarrow\pi^*$ transitions. For ligand $\mathbf{L_6}$, there are two major bisignate bands corresponding to naphthyl $\pi\rightarrow\pi^*$ transitions at ~230 and 245 nm, and one minor band at ~306 nm due to acetylenic $\pi\rightarrow\pi^*$ transition. CD spectra of metallacyclophanes **2**−**4** exhibit a strong bisignate band at ~265−268 nm due to the naphthyl $\pi\rightarrow\pi^*$ transitions and an intense band at 330−333 nm assignable to the acetylenic $\pi\rightarrow\pi^*$ transitions, along with a band at ~230 nm that can be attributed to the chiral arrangement of the PEt$_3$ groups on the Pt centers (Figure 3). This observation of chiral arrangement of PEt$_3$ groups is consistent with those in supramolecular isomers **1**.[4] For compound **5**, the bisignate band corresponding to naphthyl $\pi\rightarrow\pi^*$ transitions appears at higher energy (at ~249 nm), consistent with less conjugation of the acetylene group. The CD signal due to acetylenic $\pi\rightarrow\pi^*$ transitions for **5** appears at ~315 nm with smaller intensity compared to those of **2**−**4**.

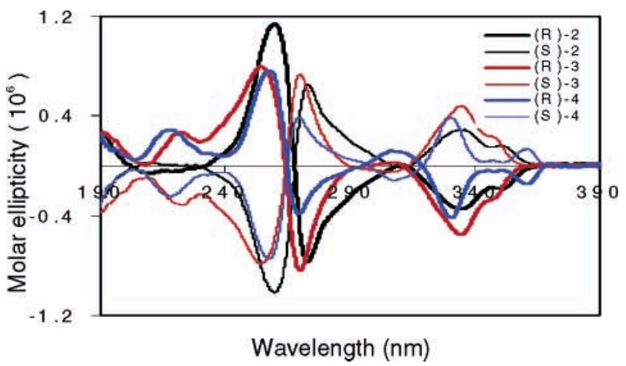


Figure 3. Circular dichroism spectra of **2**−**4** in acetonitrile.

We were interested in exploring the proximately positioned chiral dihydroxy groups in **4** for asymmetric catalysis. Unfortunately, a combination of **4** and Ti(O^{i}Pr)$_4$ did not catalyze the addition of diethylzinc to aromatic aldehydes, a prototypical reaction catalyzed by Ti-binolate complexes.[8] Our ^{1}H NMR studies indicated that **4** did not react with Ti(O^{i}Pr)$_4$ to form the Ti-binolate moieties at room temperature. We believe that steric hindrance around the dihydroxy groups in **4** is responsible for its lack of reactivity with Ti(O^{i}Pr)$_4$, which has been corroborated by the X-ray structure of **4**. Space-filling model of **2** and **4** in Figure 1 unambiguously illustrated the steric congestion in these rigid metallacyclophanes.

---

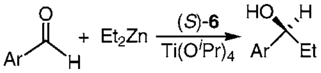
(5) (a) 3,3′-Diiodo-2,2′-dimethoxy-1,1′-binaphthalene and 3-iodo-2,2′-dimethoxy-1,1′-binaphthalene were prepared according to a modified literature procedure. See: Cox, P. J.; Wang, W.; Snieckus, V. *Tetrahedron Lett.* **1992**, *33*, 2253. (b) Sonagashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *50*, 4467.

(6) X-ray single-crystal diffraction data for $\mathbf{2}\cdot0.5CH_2Cl_2$ were collected on a Siemens SMART CCD diffractometer at −100 °C. Crystal data: orthorhombic, space group $P2_12_12_1$, $a = 19.089(2)$, $b = 27.889(2)$, $c = 28.778(2)$ Å, $V = 15320(2)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.41$ g·cm^{-3}, μ(Mo Kα) = 38.1 cm^{-1}. Least-squares refinement based on 15071 reflections with $I > 2\sigma(I)$ and 806 parameters led to convergence, with a final R1 = 0.076, $_w$R2 = 0.177, and GOF = 1.02. Flack parameter = −0.04(2). X-ray single-crystal diffraction data for $\mathbf{4}\cdot0.5$EtAc were collected on a Siemens SMART CCD diffractometer at −100 °C. Crystal data: monoclinic, space group $P2_1$, $a = 13.999(1)$, $b = 38.171(3)$, $c = 14.534(2)$ Å, $\beta = 114.387(1)°$, $V = 7073.1(9)$ Å^3, $Z = 2$, $\rho_{calcd} = 1.48$ g·cm^{-3}, μ(Mo Kα) = 40.9 cm^{-1}. Least-squares refinement based on 17621 reflections with $I > 2\sigma(I)$ and 813 parameters led to convergence, with a final R1 = 0.068, $_w$R2 = 0.135, and GOF = 1.06. Flack parameter = −0.005(8).

(7) Yam, V. W.-W. *Acc. Chem. Res.* **2002**, *35*, 555.

(8) (a) Pu, L.; Yu, H.-B. *Chem. Rev.* **2001**, *101*, 757. (b) Walsh, P. J. *Acc. Chem. Res.* **2003**, *36*, 739.

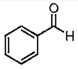
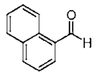
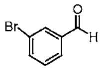
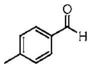
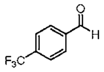
To further prove this negative proximity effect in rigid metallacyclophane **4**, we have also carried out asymmetric diethylzinc additions to aromatic aldehydes catalyzed by a combination of unclosed metallacyclophane **5** and $Ti(O^iPr)_4$. As expected, the unclosed metallacyclophane **5** is more flexible and reacts with $Ti(O^iPr)_4$ to form the Ti-binolate moieties that effectively catalyze the additions of diethylzinc to a variety of aromatic aldehydes (eq 1). As shown in Table 1, a combination of **5** and $Ti(O^iPr)_4$ catalyzes the additions of diethylzinc to a variety of aromatic aldehydes with complete conversions and ee values of 78.9−91.5% at room temperature. For comparison, a combination of $\mathbf{L_6}$ and $Ti(O^iPr)_4$ catalyzes the additions of diethylzinc to aromatic aldehydes with much lower ee's (56.6−61.1%, see Table 1). This level of enantioselectivity for **5** is comparable to that of **1**[4] but slightly inferior to that of a molecular triangle.[3b]



(1)

In summary, a family of novel chiral metallacyclophanes has been readily assembled on the basis of robust Pt-acetylide linkage. The steric congestion around the chiral dihydroxy groups in rigid metallacyclophane **4** prevents their reactions with $Ti(O^iPr)_4$ to form active catalysts for enantioselective diethylzinc additions to aromatic aldehydes. In contrast, chiral dihydroxy groups in more flexible unclosed metallacyclophane **5** are effective ligands for enantioselective catalytic diethylzinc additions to aromatic aldehydes. This work thus reinforces the notion that reactivity and enantioselectivity of a chiral catalyst can be readily tuned by incorporation into a supramolecular structure. Future work is directed toward the exploration of cooperative effects of proximately positioned functionalities in supramolecular systems.

Table 1. Asymmetric Diethylzinc Additions to Aromatic Aldehydes Catalyzed by a Combination of **5** or $\mathbf{L_6}$ and $Ti(O^iPr)_4$[a]

aldehyde	conversion	e.e. (%) for **5**	e.e. (%) for $\mathbf{L_6}$
	>95%	80.5	59.9
	>95%	87.1	61.1
	>95%	81.2	56.6
	>95%	91.4	59.6
	>95%	78.9	59.3

[a] All reactions were carried out with 10% **5** and 20 equiv of $Ti(O^iPr)_4$ relative to the chiral dihydroxy groups for 16 h. Conversions and ee values were determined by integrations of the GC peaks with a Supelco β-Dex chiral GC column.

Acknowledgment. We thank Dr. Aiguo Hu for help with asymmetric catalysis. We acknowledge financial support from ACS-PRF. W.L. is an Alfred P. Sloan Fellow, an Arnold and Mabel Beckman Young Investigator, a Cottrell Scholar of Research Corp., and a Camille Dreyfus Teacher-Scholar.

Supporting Information Available: Detailed experimental procedures, six figures, and CIF file. This material is available free of charge via the Internet at http://pubs.acs.org.

OL036111V