JOC*Note*

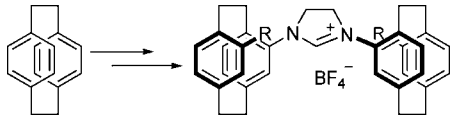
Design and Synthesis of Planar Chiral Heterocyclic Carbene Precursors Derived from [2.2]Paracyclophane

Wenzeng Duan,[†,‡] Yudao Ma,*[,†] Houqi Xia,[†] Xueying Liu,[†] Qingshuang Ma,[†] and Junshan Sun[‡]

Department of Chemistry, Shandong University, Shanda South Road No. 27, Jinan 250100, People's Republic of China, Department of Chemistry, Taishan University, Taian 271021, People's Republic of China

ydma@sdu.edu.cn

Received February 28, 2008



A unique family of planar chiral symmetrical N-heterocyclic carbene precursors with restricted flexibility derived from [2.2]paracyclopane were obtained by a new synthetic route. The resolution of 4-amino-13-bromo[2.2]paracyclophane was achieved with relatively high efficiency. Starting from ($4S_p$,$13R_p$)-4-amino-13-bromo[2.2]paracyclophane, the planar chiral *pseudogem*-disubstituted [2.2]paracyclophanyl dihydroimidazoliums were prepared in a four-step sequence with good yields. The resulting dihydroimidazolium salts were fully characterized with a series of methods including single-crystal X-ray diffraction technique.

Öfele and Wanzlick concurrently reported the first metal complexes of N-heterocyclic carbenes (NHC) in 1968.[1] However, it had received little attention until the synthesis of stable free carbenes by Arduengo,[2] Herrmann, [3] Nolan,[4] and Grubbs[5] made further development in this field by preparing numerous NHCs as well as their metal complexes and finding applications for these complexes in catalysis reaction. NHCs offer good potential for coordination with metal ions as a neutral two-electron-donating (s-donating) ligand with negligible π back-bonding. As a result, dihydroimidazolium salts were revealed to give corresponding carbene as very effective ligands in both ruthenium- and palladium-catalyzed transformations. In addition, the complexes of NHCs with transition metals have demonstrated catalytic activity for a series of reactions such as hydrosilylation,[6] Heck,[7] Suzuki−Miyaura,[8] Kumada,[9] Sonogashira couplings,[10,11] olefin cyclopropanation,[12] aryl amination,[13,14] and olefin metathesis.[15]

It is well-known that the increase in the bulkiness of chiral groups may lead to increased enantiocontrol in asymmetric reactions. Many strategies therefore have been developed during the past years for introducing different chirality elements into NHC ligands, which include the alkyl side chains containing stereogenic center, a chiral backbone in the heterocycle, chiral biaryl units, and the combination with ferrocene-based planar chirality.[16] In particular, the catalytic activity revealed for imidazole-NHCs attracted great research interests in chiral NHCs for asymmetric catalysis.[17] The chemistry of the parent imidazole system is well established; the preparation of tailor-made NHC precursors bearing bulky [2.2]paracyclophane substituent, however, is still a challenge for organic chemists.

Planar chiral [2.2]paracyclophane-based ligand possesses a rigid [2.2]paracyclophanyl unit, and such a versatile backbone structure opens the possibility of designing different types of chiral ligands.[18] The thus far reported [2.2]paracyclophane-based

* Corresponding author. Phone: 0086-531-88361869. Fax: 0086-531-88565211.
† Shandong University.
‡ Taishan University.

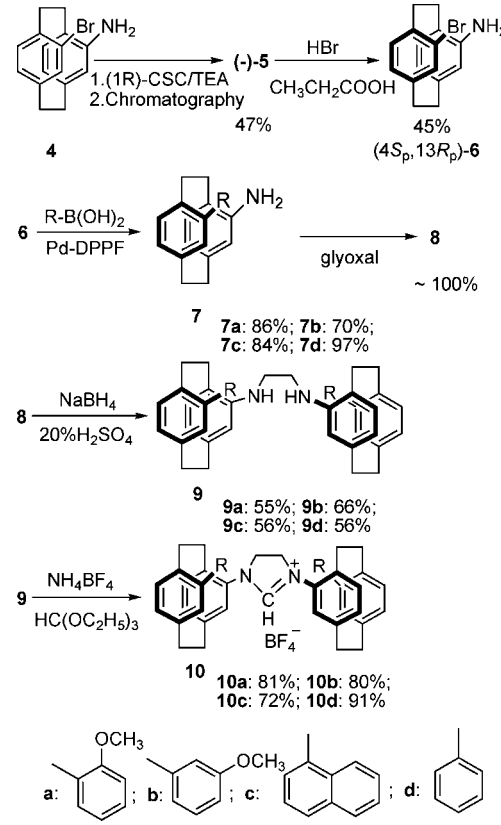
(1) (a) Öfele, K. *J. Organomet. Chem.* **1968**, *12*, 42–43. (b) Wanzlick, H. W.; Schönherr, H. J. *Angew. Chem., Int. Ed.* **1968**, *7*, 141–142.
(2) (a) Arduengo, A. J.; Harlow, R. L.; Kline, M. *J. Am. Chem. Soc.* **1991**, *113*, 361–363. (b) Arduengo, A. J.; Krafczyk, R.; Schmutzler, R. *Tetrahedron* **1999**, *55*, 14523–14534.
(3) (a) Herrmann, W. A. *Angew. Chem., Int. Ed.* **2002**, *40*, 1290–1309. (b) Bourissou, D.; Guerret, O.; Gabbaï, F. P.; Bertrand, G. *Chem. Rev.* **2000**, *100*, 39–91. (c) Herrmann, W. A.; Böhm, V. P. W.; Gstöttmayr, C. W. K.; Grosche, M. C.; Reisinger, C.; Weskamp, T. *J. Organomet. Chem.* **2001**, *617*, 616–628. (d) Herrmann, W. A.; Elison, M.; Fischer, J.; Köcher, C.; Artus, G. R. *Angew. Chem., Int. Ed.* **1995**, *34*, 2371–2374. (e) Herrmann, W. A.; Reisinger, C. P.; Spiegler, M. *J. Organomet. Chem.* **1998**, *557*, 93–98.
(4) (a) Huang, J.; Nolan, S. P. *J. Am. Chem. Soc.* **1999**, *121*, 9889–9890. (b) Navarro, O.; Nolan, S. P. *J. Org. Chem.* **2004**, *69*, 3173–3180.
(5) (a) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18–29. (b) Hong, S. H.; Grubbs, R. H. *J. Am. Chem. Soc.* **2004**, *126*, 7414–7415.
(6) Enders, D.; Gielen, H. *J. Organomet. Chem.* **2001**, *617−618*, 70–80.
(7) Yang, C.; Lee, H. M.; Nolan, S. P. *Org. Lett.* **2001**, *3*, 1511–1514.
(8) (a) Fürstner, A.; Leitner, A. *Synlett* **2001**, 290–292. (b) Grasa, G. A.; Hillier, A. C.; Nolan, S. P. *Org. Lett.* **2001**, *3*, 1077–1079. (c) Song, C.; Ma, Y. D.; Chai, Q.; Ma, C. Q.; Jiang, W.; Andrus, M. B. *Tetrahedron* **2005**, *61*, 7438–7446. (d) Gstöttmayr, C. W. K.; Böhm, V. P. W.; Herdtweck, E.; Grosche, M.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **2002**, *41*, 1363–1365.
(9) Böhm, V. P.; Weskamp, T.; Gstottmayr, C. W.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **2000**, *39*, 1602–1604.
(10) (a) Altenhoff, G.; Würtz, S.; Glorius, F. *Tetrahedron Lett.* **2006**, *47*, 2925–2928. (b) Grasa, G. A.; Viciu, M. S.; Huang, J.; Zhang, C.; Trudell, M. L.; Nolan, S. P. *Organometallics* **2002**, *21*, 2866–2873.
(11) Ma, Y. D.; Song, C.; Jiang, W.; Wu, Q. S.; Wang, Y.; Liu, X. Y.; Andrus, M. B. *Org. Lett.* **2003**, *5*, 3317–3319.
(12) Cetinkaya, B.; Özdemir, I.; Dixneuf, P. H. *J. Organomet. Chem.* **1997**, *534*, 153–158.
(13) Cheng, J.; Trudell, M. L. *Org. Lett.* **2001**, *3*, 1371–1374.
(14) Stauffer, S. R.; Lee, S.; Stambuli, J. P.; Hauck, S. I.; Hartwig, J. F. *Org. Lett.* **2000**, *2*, 1423–1426.
(15) (a) Sanford, M. S.; Love, J. A.; Grubbs, R. H. *J. Am. Chem. Soc.* **2001**, *123*, 6543–6554. (b) Garber, S. B.; Kingsbury, J. S.; Gray, B. L.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2000**, *122*, 8168–8179. (c) Bujok, R.; Bieniek, M.; Masnyk, M.; Michrowska, A.; Sarosiek, A.; Stepowska, H.; Arlt, D.; Grela, K. *J. Org. Chem.* **2004**, *69*, 6894–6896. (d) Wakamatsu, H.; Blechert, S. *Angew. Chem., Int. Ed.* **2002**, *41*, 2403–2405. (e) Gillingham, D. G.; Kataoka, O.; Garber, S. B.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2004**, *126*, 12288–12290. (f) Funk, T. W.; Berlin, J. M.; Grubbs, R. H. *J. Am. Chem. Soc.* **2006**, *128*, 1840–1846.
(16) (a) Hahn, F. E. *Angew. Chem., Int. Ed.* **2006**, *45*, 1348–1352. (b) Glorius, F., Ed. *N-Heterocyclic Carbenes in Transition Metal Catalysis*; Topics in Organometallic Chemistry, Vol. 21; Springer: Berlin, Germany, 2007. (c) Nolan, S. P., Ed. *N-heterocyclic Carbenes in Synthesis*; Wiley-VCH: Weinheim, Germany, 2006.
(17) (a) Perry, M. C.; Burgess, K. *Tetrahedron: Asymmetry* **2003**, *14*, 951–961. (b) Douthwaite, R. E. *Coord. Chem. Rev.* **2007**, *251*, 702–717. (c) Faller, J. W.; Fontaine, P. P. *Organometallics* **2006**, *25*, 5887–5897. (d) Larsen, A. O.; Leu, W.; Oberhuber, C. N.; Campbell, J. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2004**, *126*, 11130–11131. (e) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606–5655.

10.1021/jo800468x CCC: $40.75
Published on Web 04/29/2008

ligands include diphosphanes,[19] oxazoline-phosphanes,[20] imidazoliums,[21] oxazoline-alcohols,[22] and imine ligands.[23] Recently, a series of planar chiral *pseudo-ortho*-disubstituted [2.2]paracyclophanyl dihydroimidazoliums have been prepared by this group and their applications as rhodium or ruthenium complexes in highly enantioselective transformations have also been demonstrated.[24] Very lately, efforts have been paid to extend the previous studies toward the synthesis of planar chiral *pseudogem*-disubstituted [2.2]paracyclophanyl dihydroimidazoliums. These novel ligands are expected to give higher stereoselectivity in asymmetric reactions due to their increased steric hindrance. As part of our continuous study for employing chiral [2.2]paracyclophanyl dihydroimidazoliums in asymmetric reactions, herein we describe the synthesis of novel planar chiral *pseudogem*-disubstituted [2.2]paracyclophanyl dihydroimidazoliums.

(±)-4-Amino-13-bromo[2.2] paracyclophane **4** was prepared first by Cram in 1975.[25] However, to the best of our knowledge, the resolved enantiomers of this compound have never been reported. As a consequence, our synthetic strategy was based on constructing the ($4S_p$,$13R_p$)-4-amino-13-bromo[2.2]paracyclophane **6** core by utilization of readily available building blocks (Scheme 1). Staring with the commercial available [2.2]paracyclophane **1**, 4-nitro[2.2]paracyclophane **2** was obtained from the nitration of **1** with fuming nitric acid and acetic acid.[26] Bromination of **2** under standard condition led to the isolation of the desired compound **3** in good chemoselectivity.[27] According to a previously described procedure,[25] 4-nitro-13-bromo[2.2]paracyclophane **3** was reduced to afford **4** in excellent yield. The

SCHEME 1

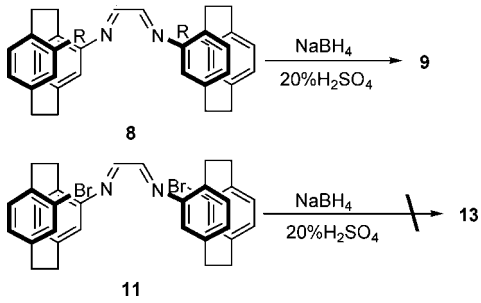


initial trial to resolve (±)-**4** by modifying an authentic method using fractional crystallization of the diastereoisomeric salts of (1*R*)-(−)-10-camphorsulfonic acid in various solvents failed to give a satisfactory result.[28] We therefore turned our attention to resolve (±)-**4** by means of a chiral auxiliary reagent, (1*R*)-(−)-10-camphorsulfonyl chloride ((−)-CSC). In the presence of triethylamine, (±)-**4** was converted to a mixture of diastereomeric amides **5**, which were successfully separated by chromatography on silica gel. The lower polarity portion (−)-**5** (47% yield, >99% de determined by ^{1}H NMR) was hydrolyzed with 48% HBr and propionic acid, affording (−)-**6** in 45% yield. The single-crystal X-ray diffraction analysis result of (−)-**5** confirms the absolute stereochemistry of (−)-**6**, whose configuration was assigned to ($4S_p$,$13R_p$)-4-amino-13-bromo[2.2]paracyclophane (Figure S1, Supporting Information).

As reported previously by this group, Suzuki coupling with arylboron compounds under palladium-NHC catalysis gave the 4-amino-12-aryl[2.2]paracyclophanes.[24a] Rozenberg and coworkers have also investigated the synthesis of *pseudogem*-substituted aryl[2.2]paracyclophanes using the Suzuki cross-coupling reaction.[29] A palladium-catalyzed Suzuki cross-coupling reaction is therefore expected to be suitable for forming the hindered amino[2.2]paracyclophane derivatives (**7a**−**d**). Repeated experimental results led to the optimal reaction condition including the reaction temperature of 80 °C and time of 96 h for the reaction between Pd-DPPF and KF in dioxane. Moreover, it has been found that addition of 5% Pd-DPPF in

(18) Rozenberg, V.; Sergeeva, E.; Hopf, H. In *Modern Cyclophane Chemistry*; Gleiter, R., Hopf, H., Eds.; Wiley-VCH: Weinheim, Germany, 2004; p 435.
(19) (a) Pye, P. J.; Rossen, K.; Reamer, R. A.; Tsou, N. N.; Volante, R. P.; Reider, P. J. *J. Am. Chem. Soc.* **1997**, *119*, 6207–6208. (b) Pye, P. J.; Rossen, K.; Reamer, R. A.; Volante, R. P.; Reider, P. J. *Tetrahedron Lett.* **1998**, *39*, 4441–4443. (c) Zanotti-Gerosa, A.; Malan, C.; Herzberg, D. *Org. Lett.* **2001**, *3*, 3687–3690. (d) Dominguez, B.; Zanotti-Gerosa, A.; Hems, W. *Org. Lett.* **2004**, *6*, 1927–1930.
(20) (a) Wu, X. W.; Yuan, X. K.; Sun, W.; Zhang, M. J.; Hou, X. L. *Tetrahedron: Asymmetry* **2003**, *14*, 107–112. (b) Whelligan, D. K.; Bolm, C. *J. Org. Chem.* **2006**, *71*, 4609–4618. (c) Stemmler, R. T.; Bolm, C. *Adv. Synth. Catal.* **2007**, *349*, 1185–1198.
(21) (a) Bolm, C.; Focken, T.; Raabe, G. *Tetrahedron: Asymmetry* **2003**, *14*, 1733–1746. (b) Focken, T.; Rudolph, J.; Bolm, C. *Synthesis* **2005**, *3*, 429–436. (c) Focken, T.; Raabe, G.; Bolm, C. *Tetrahedron: Asymmetry* **2004**, *15*, 1693–1706.
(22) (a) Hou, X. L.; Wu, X. W.; Dai, L. X.; Cao, B. X.; Sun, J. *Chem. Commun.* **2000**, 1195–1196. (b) Wu, X. W.; Hou, X. L.; Dai, L. X.; Tao, J.; Cao, B. X.; Sun, J. *Tetrahedron: Asymmetry* **2001**, *12*, 529–532. (c) Wu, X. W.; Zhang, T. Z.; Yuan, K.; Hou, X. L. *Tetrahedron: Asymmetry* **2004**, *15*, 2357–2365. (d) Bolm, C.; Whelligan, D. K. *Adv. Synth. Catal.* **2006**, *348*, 2093–2100.
(23) (a) Bräse, S.; Dahmen, S.; Höfener, S.; Lauterwasser, F.; Kreis, M.; Ziegert, R. E. *Synlett* **2004**, *15*, 2647–2669. (b) Lauterwasser, F.; Nieger, M.; Mansikkamäki, H.; Nättinen, K.; Bräse, S. *Chem. Eur. J.* **2005**, *11*, 4509–4525. (c) Lauterwasser, F.; Vanderheiden, S.; Bräse, S. *Adv. Synth. Catal.* **2006**, *348*, 443–448. (d) Danilova, T. I.; Rozenberg, V. I.; Sergeeva, E. V.; Starikova, Z. A.; Bräse, S. *Tetrahedron: Asymmetry* **2003**, *14*, 2013–2019. (e) Dahmen, S. *Org. Lett.* **2004**, *13*, 2113–2116. (f) Danilova, T. I.; Rozenberg, V. I.; Starikova, Z. A.; Bräse, S. *Tetrahedron: Asymmetry* **2004**, *15*, 223–229. (g) Sugiyama, S.; Aoki, Y.; Ishii, K. *Tetrahedron: Asymmetry* **2006**, *17*, 2847–2856. (h) Lauterwasser, F.; Gall, J.; Höfener, S.; Bräse, S. *Adv. Synth. Catal* **2006**, *348*, 2068–2074. (i) Danilova, T. I.; Rozenberg, V. I.; Vorontsov, E. V.; Starikova, Z. A.; Hopf, H. *Tetrahedron: Asymmetry* **2003**, *14*, 1375–1383. (j) Bräse, S.; Höfener, S. *Angew. Chem. Int. Ed.* **2005**, *44*, 7879–7881. (k) Kreis, M.; Nieger, M.; Bräse, S. *J. Organomet. Chem.* **2006**, *691*, 2171–2181. (l) Dahmen, S.; Bräse, S. *J. Am. Chem. Soc.* **2002**, *124*, 5940–5941.
(24) (a) Ma, Y. D.; Song, C.; Ma, C. Q.; Sun, Z. J.; Chai, Q.; Andrus, M. B. *Angew. Chem., Int. Ed.* **2003**, *42*, 5871–5874. (b) Song, C.; Ma, C. Q.; Ma, Y. D.; Feng, W. H.; Ma, S. T.; Chai, Q.; Andrus, M. B. *Tetrahedron Lett.* **2005**, *46*, 3241–3244.
(25) Allgeier, H.; Siegel, M. G.; Cram, D. J. *J. Am. Chem. Soc.* **1975**, *97*, 3782–3789.
(26) Norcross, B. E.; Becker, D.; Schultz, R. M. *J. Org. Chem.* **1967**, *32*, 220–222.
(27) Reich, H. J.; Cram, D. J. *J. Am. Chem. Soc.* **1969**, *91*, 3505–3516.
(28) Cipiciani, A.; Fringuelli, F.; Mancini, V.; Piermatti, O.; Pizzo, F. *J. Org. Chem.* **1997**, *62*, 3744–3747.
(29) (a) Rozenberg, V. I.; Zhuravsky, R.; Sergeeva, E. V. *Chirality* **2006**, *18*, 95–102. (b) Rozenberg, V. I.; Antonov, D. Y.; Zhuravsky, R. P.; Vorontsov, E. V.; Starikova, Z. A. *Tetrahedron Lett.* **2003**, *44*, 3801–3804.

SCHEME 2

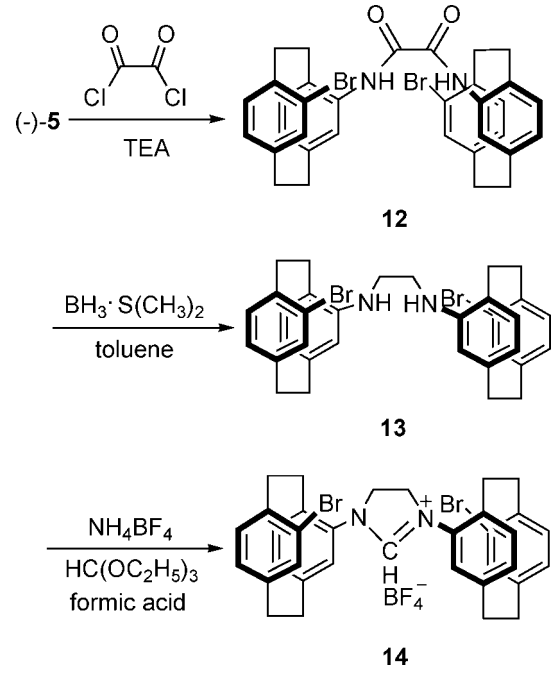


three portions is more effective than adding it in one portion. As shown in Scheme 1, the highest isolated product yield was reached with phenylboronic acid at 97%. 3-Methoxyphenylboronic acid, at 70%, was shown to be inferior. 1-Naphthaleneboronic acid and 2-methoxyphenylboronic acid displayed moderate reactivity.

Our first approach to NHC precursors relied on the utilization of *N*,*N*′-disubstituted ethylenediamine derivatives as a key intermediate since their well-established ring closure with trialkyl orthoformates was expected to give the desired dihydroimidazolium salts. The preparation of the diamines (**9a**−**d**) followed a two-step condensation−reduction sequence. Treatment of the *pseudogem*-substituted amino[2.2]paracyclophanes (**7a**−**d**) with aqueous gloxal gave corresponding diimines (**8a**−**d**), which were reduced to the diamines (**9a**−**d**) with $NaBH_4$/20% H_2SO_4 in a yield range of 55−66%. The open-chain intermediates (**9a**−**d**) were subjected to ring-closure with triethyl orthoformate in the presence of a catalytic amount of formic acid. The desired dicyclophane dihydroimidazolium tetrafluoroborates (**10a**−**d**) were obtained in good yield (72%−91%) by using ammonium tetrafluoroborate.[30] It is worth noting that ammonium chloride and hydrochloride are less efficient since the analogous dihydroimidazolium chlorides could not be purified by chromatography and recrystallization.[2b,31] Both mass and ^{1}H NMR spectroscopic results on the synthetic compounds **10a**−**d**, and in particular the X-ray diffraction analysis result on **10c** (Figure S2, Supporting Information), proved the expected nature of these products. Additionally, (−)-**6** reacted with excess aqueous glyoxal, providing glyoxal diimine **11**. This compound, however, could not be reduced by $NaBH_4$/20% H_2SO_4 due to its insolubility (Scheme 2).

The second approach to NHC precursor **14** was based on the reported route by employing the acylation of amine.[31c−f] Oxalyl chloride and (−)-**6** were used to generate oxalamide **12**, which then underwent a reduction with $BH_3 \cdot S(CH_3)$, yielding diamine **13** in good yield. Treatment of the diamine **13** with triethyl orthoformate and ammonium tetrafluoroborate in the presence

SCHEME 3



of a catalytic amount of formic acid gave the expected dihydroimidazolium **14** in the yield of 81% (Scheme 3). This newly synthesized compound was characterized by mass and ^{1}H NMR spectroscopy.

In summary, novel planar chiral dihydroimidazolium salts have been designed and synthesized by using a simple route starting with commercially available [2.2]paracyclophane. The large-scale synthesis of these new carbene precursors is in progress in our laboratory and their application in the asymmetric synthesis reaction is under way.

Experimental Section

General Procedure for the Synthesis of *N*,*N*′-Bis[(4*S*$_p$,13*R*$_p$)-(−)-13-(1-naphthyl)-4-[2.2]paracyclophanyl]-4,5-dihydroimidazolium Tetrafluoroborate. The mixture of (4*S*$_p$,13*R*$_p$)-4-amino-13-bromo[2.2]paracyclophane (**6**, 501.3 mg, 1.66 mmol), 1-naphthaleneboronic acid (428.3 mg, 2.49 mmol), KF (289.7 mg, 4.98 mmol), and Pd-DPPF (13.6 mg, 1.66×10^{-2} mmol) in 1,4-dioxane (5 mL) was stirred at 80−90 °C for 24 h under a slight positive pressure of nitrogen. At 24, 48, and 72 h, 1-naphthaleneboronic acid (95.2 mg, 0.55 mmol), KF (72.4 mg, 1.25 mmol), and Pd-DPPF (13.6 mg, 1.66×10^{-2} mmol) were added to the flask, respectively. After completion of the reaction as indicated by TLC, the mixture was cooled to room temperature, water (5 mL) was added, and the solution was filtered. The solution was then extracted by dichloromethane (3 × 10 mL), and the solvent was removed by rotary evaporation. The crude material was purified by chromatography on silica gel (eluent: hexanes/ethyl acetate = 20:1), and pure (4*S*$_p$,13*R*$_p$)-4-amino-13-(1-naphthyl)[2.2]paracyclophane (**7c**) was obtained as a white solid (490 mg, 84%). Mp 234−236 °C; R_f 0.64 (hexanes/ethyl acetate = 5:1); $[\alpha]^{20}_D$ +61.5 (*c* 0.31, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.97−8.10 (m, 2H), 7.84−7.87 (d, 2H), 7.55−7.60 (t, 1H), 7.34−7.46 (m, 2H), 6.97 (s, 1H), 6.63 (s, 2H), 6.48−6.50 (d, 1H), 6.24−6.27 (dd, 1H), 5.77 (s, 1H), 3.06−3.18 (m, 6H), 2.90−3.00 (m, 2H), 2.17−2.84 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.1, 140.8, 139.4, 139.1, 138.4, 137.4, 135.3, 134.4, 133.5, 133.3, 131.8, 131.7, 128.2, 127.7, 127.3, 126.4, 126.0, 125.5, 124.9, 124.0, 122.8, 119.9, 35.3, 35.1, 33.3, 30.9. Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01. Found: C, 89.03; H, 6.62; N, 3.93.

(30) (a) Kingsbury, J. S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2005**, *127*, 4510–4517. (b) Grasa, G. A.; Viciu, M. S.; Huang, J.; Nolan, S. P. *J. Org. Chem.* **2001**, *66*, 7729–7738. (c) Seiders, T. J.; Ward, D. W.; Grubbs, R. H. *Org. Lett.* **2001**, *3*, 3225–3227. (d) Scarborough, C. C.; Grady, M. J. W.; Guzei, I. A.; Gandhi, B. A.; Bunel, E. E.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2005**, *44*, 5269–5272. (e) Paczal, A.; Bényei, A. C.; Kotschy, A. *J. Org. Chem.* **2006**, *71*, 5969–5979. (f) Saba, S.; Brescia, A. M.; Kaloustian, M. K. *Tetrahedron Lett.* **1991**, *32*, 5031–5034.

(31) (a) Fleckenstein, C.; Roy, S.; Leuthäusser, S.; Plenio, H. *Chem. Commun.* **2007**, 2870–2872. (b) Trnka, T. M.; Morgan, J. P.; Sanford, M. S.; Wilhelm, T. E.; Scholl, M.; Choi, T. L.; Ding, S.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2003**, *125*, 2546–2558. (c) Xu, G.; Gilbertson, S. R. *Org. Lett.* **2005**, *7*, 4605–4608. (d) Delaude, L.; Szypa, M.; Demonceau, A.; Noels, A. F. *Adv. Synth. Catal.* **2002**, *344*, 749–756. (e) Dinger, M. B.; Nieczypor, P.; Mol, J. C. *organometallics* **2003**, *22*, 5291–5295. (f) Hadei, N.; Kanichev, E. A. B.; O'Brien, C. J.; Organ, M. G. *J. Org. Chem.* **2005**, *70*, 8503–8507.

The mixture of **7c** (258 mg, 0.738 mmol) and 40% glyoxal (42 mg, 0.886 mmol) in THF (1 mL) was stirred at room temperature over 5 h. After the reaction was completed as indicated by TLC, the solution was concentrated and the residue was purified by silica gel chromatography with dichloromethane, affording diimine **8c**.

To a solution of **8c** (263 mg, 0.365 mmol) in THF (4 mL) at 0 °C was added $NaBH_4$ (192 mg, 5.074 mmol) in 40-mg portions. H_2SO_4 (20%, 0.73 mL) in THF (1 mL) was slowly added dropwisely for 15 min. After being stirred at 0 °C for another 15 min, the suspension was poured into a 2% NaOH (36 mL) solution. The solution was extracted with dichloromethane (3 × 30 mL). The solvent was removed on a rotary evaporator and the crude product was subjected to chromatography on silica gel with hexanes/dichloromethane (1:1) to give the desired glyoxal diamine **9c** as a white solid (148 mg, 56%). Mp 175−177 °C; R_f 0.58 (hexanes/ethyl acetate = 5:1); $[\alpha]^{20}_D$ −39.1 (*c* 0.1, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.90−7.97 (m, 6H), 7.77−7.79 (d, 2H), 7.63−7.68 (t, 2H), 7.45−7.50 (t, 2H), 7.35−7.40 (t, 2H), 6.79 (s, 2H), 6.49−6.58 (m, 4H), 6.30−6.33 (d, 2H), 6.06−6.09 (d, 2H), 5.16 (s, 2H), 3.73 (s, 2H), 3.05−3.08 (d, 2H), 2.76−2.98 (m, 12H), 2.47−2.52 (m, 2H), 2.25−2.35 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.8, 141.8, 139.5, 138.9, 138.1, 136.8, 134.8, 134.1, 133.6, 132.8, 131.7, 131.4, 128.2, 127.5, 126.9, 126.4, 126.0, 125.5, 124.6, 124.1, 120.9, 114.6, 43.8, 43.4, 35.3, 34.9, 32.9, 31.7. Anal. Calcd for $C_{54}H_{48}N_2$: C, 89.46; H, 6.67; N, 3.86. Found: C, 89.23; H, 6.72; N, 3.91.

A mixture of the diamine **9c** (116 mg, 0.16 mmol), triethyl orthoformate (2 mL), one drop of formic acid, and ammonium tetrafluoroborate (16.8 mg, 0.16 mmol) was stirred at 125 °C for 10 h. After completion of the reaction as indicated by TLC, the solvent was removed on a rotary evaporator. The crude product was subjected to chromatography on silica gel (eluent: dichloromethane/ethanol = 20:1), and the target *N*,*N*′-bis[(4S_p,13R_p)-(−)-13-(1-naphthyl)-4-[2.2]paracyclophanyl]-4,5-dihydroimidazolium tetrafluoroborate was obtained as a yellow solid (95 mg, 72%). Mp 245 °C dec; R_f 0.84 (dichloromethane/ethanol = 10:1), $[\alpha]^{20}_D$ −129.6 (*c* 0.25, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.05−8.07 (m, 1H), 7.74−7.76 (d, 2H), 7.66−7.69 (d, 2H), 7.60−7.62 (d, 2H), 7.25−7.44 (m, 7H), 6.72−6.87 (m, 10H), 6.53−6.55 (d, 3H), 4.72 (m, 2H), 4.17 (m, 2H), 3.36−3.39 (m, 2H), 3.11−3.30 (m, 10H), 2.84−2.92 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 162.2, 151.7, 143.2, 140.6, 137.8, 137.3, 137.1, 134.4, 133.7, 133.3, 133.2, 133.1, 132.6, 130.6, 128.9, 128.5, 127.8, 127.7, 126.5, 125.9, 125.6, 124.9, 123.2, 50.5, 35.1, 35.0, 34.9, 32.7; LRMS [ESI (methanol)] ms (+) *m*/*z* (%) 635.5 (100), 639.5 (10); ms (−) *m*/*z* (%) 679.7 (43), 725.8 (100), 771.5 (16); mass calcd for $C_{55}H_{47}N_2BF_4$ 822.8. Anal. Calcd for $C_{55}H_{47}N_2BF_4 \cdot 0.5H_2O$: C, 79.42; H, 5.82; N, 3.37. Found: C, 79.46; H, 5.74; N, 3.37.

Acknowledgment. Financial support from the National Natural Science Foundation of China (Grant Nos. 20441004 and 20671059) and the Department of Science and Technology of Shandong Province is gratefully acknowledged.

Supporting Information Available: Experimental procedures, characterization data for selected compounds, and crystallographic data (CIF files) for (−)-**5** and **10c**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO800468X