Chiral Metal Template Promoted Asymmetric Pyrrole Diels−Alder Reaction between *N*-(Diphenylphosphino)pyrrole and Diphenylvinylphosphine

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An organoplatinum complex containing ortho-metalated (*S*)-(1-(dimethylamino)ethyl)-naphthalene as the chiral auxiliary has been used to promote the asymmetric [4 + 2] Diels−Alder reaction between diphenylvinylphosphine and *N*-(diphenylphosphino)pyrrole. The reaction was complete in 7 days at room temperature, with the formation of three isomeric chelating diphosphine exo cycloadducts in the ratio 10:3:1. The cycloadducts are thermodynamically unstable and undergo retro-cycloaddition reactions slowly in solution. When the major isomer of the pyrrole cycloadducts was heated with 2-(diphenylphosphino)furan, the respective furan cycloadducts were formed via the retro pyrrole Diels−Alder pathway, followed by an asymmetric furan Diels−Alder reaction. The cyclic diene *N*-(diphenylphosphino)pyrrole was regenerated from this retro cycloaddition reaction. The undesired retro Diels−Alder reaction could be deterred by hydrogenation of the azanorbornene double bond. The chiral naphthylamine auxiliary could be removed chemoselectively from the metal template by treatment with concentrated hydrochloric acid to generate the corresponding dichloroplatinum(II) complex. The azabicyclic skeleton and the P−N bond remained unchanged in this acid treatment. Further treatment of the dichloro complex with aqueous cyanide liberates the chiral diphosphine cycloadduct, which could be coordinated to the Au(I) metal ion.

Introduction

The asymmetric Diels−Alder reaction is one of the most efficient and elegant methods for the synthesis of chiral cyclic compounds. Cyclopentadiene is perhaps one of the most reactive and commonly used dienes. However, the analogous five-membered heteroaromatic compounds are poor dienes, due to their aromaticity. Nevertheless, these cyclic heterodienes constitute an important class of dienes for Diels−Alder reactions, as the corresponding 7-heterobicyclo[2.2.1]heptene cycloadducts are key intermediates for the synthesis of many biologically important compounds.[1,2] A resurgence of interest in pyrrole Diels−Alder reactions[2] took place after the discovery of epibatidine,[3] which displays powerful analgesic properties. Importantly, epibatidine is the first natural product found to contain the 7-azabicyclo[2.2.1]heptane framework. In contrast to furan, pyrrole and its derivatives do not undergo cycloadditions efficiently, due to their higher resonance energy. Furthermore, as a result of their π-excessive aromatic character, pyrroles tend to undergo the competing Michael addition reactions,[4] resulting in substitution at the α-position of the pyrrole rings. The difficulty in the isolation of pyrrole Diels−Alder cycloadducts has also been attributed to their instability. The cycloadducts are known to undergo retro Diels−Alder reactions[2] readily and are also susceptible to ring-opening reactions under acidic or basic conditions.[2c,5] One approach to improve the reactivity of pyrroles as cyclic dienes is to place an electron-withdrawing group on the nitrogen of the pyrrole ring. Using this approach, the aromaticity and the reactivity of pyrroles toward Michael addition reactions will be reduced. Consequently, N-substituted pyrroles are reactive toward cycloaddition reactions with various highly reactive dienophiles such as arynes, electron-deficient alkynes, and allenes.[2b−d,6] It is noteworthy that alkenes are generally unreactive toward N-substituted pyrroles at ambient pressure. High-pressure techniques have been used to activate pyrroles toward cycloaddition reactions.

(1) (a) Kappe, C. O.; Murphree, S. S.; Padwa, A. *Tetrahedron* **1997**, *53*, 14179. (b) Vogel, P.; Cossy, J.; Plumet, J.; Arjona, O. *Tetrahedron* **1999**, *55*, 13521. (c) Vogel, P.; Fattori, D.; Gasparini, F.; Le Drian, C. *Synlett* **1990**, 173.

(2) (a) Lipshutz, B. H. *Chem. Rev.* **1986**, *86*, 795. (b) Bird, C. W., Katritzky, A. R., Rees, C. W., Scriven, E. F. V., Eds.; *Comprehensive Heterocyclic Chemistry II*; Pergamon Press: Elsevier: Oxford, U.K., 1996. (c) Chen, Z.; Trudell, M. L. *Chem. Rev.* **1996**, *96*, 1179. (d) Kricka, L. J.; Vernon, J. M. *Adv. Heterocycl. Chem.* **1974**, *16*, 87.

(3) Spande, T. F.; Garraffo, H. M.; Edwards, M. W.; Yeh, H. J. C.; Pannell, L.; Daly, J. W. *J. Am. Chem. Soc.* **1992**, *114*, 3475.

(4) (a) Jones, R. A. *The Chemistry of Heterocyclic Compounds: Pyrroles*; Wiley: New York, 1990; Vol. 48. (b) Noland, W. E.; Lee, C. K. *J. Org. Chem.* **1980**, *45*, 4573. (c) Bennett, R. A.; Cann, M. C. *J. Heterocycl. Chem.* **1994**, *31*, 293.

(5) (a) Gonzalez, J.; Koontz, J. I.; Hodges, L. M.; Nilsson, K. R.; Neely, L. K.; Myers, W. H.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **1995**, *117*, 3405. (b) Hodges, L. M.; Gonzalez, J.; Koontz, J. I.; Myers, W. H.; Harman, W. D. *J. Org. Chem.* **1993**, *58*, 4788. (c) Kozikowski, A. P.; Kuniak, M. P. *J. Org. Chem.* **1978**, *43*, 2083.

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However, reactive dienophiles such as N-phenylmaleimide are still required for cycloaddition reactions with activated pyrroles under high pressures.[2c,7] Lewis acids have been reported to catalyze the pyrrole Diels−Alder reactions and lead to improved yields of the desired cycloadducts.[8] However, a limitation of this approach has often been found to be the sensitivity of substrates to the acidic media.[2c,9] Other physical and chemical methods, such as the use of ultrasound[10] and an ionic reaction medium,[9] have also been adopted to overcome the low reactivity of pyrroles as a diene.

Over the past decade, chiral cyclometalated amine complexes have contributed significantly to many aspects of synthetic chemistry. These organometallic compounds have been routinely used as resolving agents for chiral ligands,[11] clear and reliable references for the NMR assignment of unknown absolute configurations,[12] diamagnetic chiral shift reagents for the determination of optical purity of organic compounds,[13] efficient chiral catalysts for asymmetric Claisen rearrangements,[14] reaction promoters for the oxidative coupling between vinylphosphines and imines,[15] and asymmetric hydroamination reactions.[16] Recently, we have also reported the synthesis of a series of functionalized chiral mono- and diphosphines using chiral ortho-metalated amine template promoted asymmetric Diels−Alder reactions.[17] Our approach involves the activation of the five-membered heterocycle 3,4-dimethyl-1-phenylphosphole (DMPP) as a cyclic diene for the cycloaddition reaction with various dienophiles. A key conceptual feature in this synthetic approach is that DMPP itself is not a reactive cyclic diene but becomes reactive when it is coordinated onto a transition metal, and by incorporating an appropriate chiral auxiliary onto the activating metal ion, the stereochemistry of the cycloaddition reaction can be controlled. The chiral ortho-metalated amine templates are also found to promote efficiently the asymmetric Diels−Alder reaction involving 2-(diphenylphosphino)furan.[18] In these asymmetric syntheses, the chiral metal templates not only activate the substrates and provide the desired stereochemical control for the cycloaddition reaction but also stabilize the resulting cycloadducts. In pursuing our interest and extending the scope of this class of metal template promoted cycloaddition reactions, we hereby present the chiral platinum template promoted asymmetric Diels−Alder reaction between *N*-(diphenylphosphino)pyrrole and diphenylvinylphosphine. The corresponding cycloadducts could not be obtained via the thermal pathway.

Results and Discussion

Stereoisomerisms. The chiral platinum complex (*S*)-**1** was used as the template precursor in the asymmetric cycloaddition reaction between *N*-(diphenylphosphino)pyrrole and diphenylvinylphosphine. Interestingly, (*S*)-**1** itself is not an efficient chiral template, as it could not induce the desired Diels−Alder reaction. The Pt−Cl bond that is trans to the coordinated aromatic carbon is thermodynamically and kinetically stable.[18,19] Thus, the chloro ligand which occupied one of the two essential coordination sites hindered the simultaneous coordination of *N*-(diphenylphosphino)-pyrrole and diphenylvinylphosphine onto the metal template and no Diels−Alder reaction was observed. However, upon removal of the chloro ligand with a stoichiometric amount of silver tetrafluroborate, (*S*)-**1** was converted to an excellent activator for the targeted cycloaddition reaction (Scheme 1). Apparently, activation by coordination of both the diene and dienophile to the metal template is essential for the subsequent intramolecular [4 + 2] Diels−Alder reaction. In principle, four stereoisomeric diphosphine exo cycloadducts may be generated from this intramolecular exo cycloaddition reaction. The two pairs of isomers, labeled **a** and **b**, are regioisomers in which the absolute stereochemistries of the chelating diphosphine cycloadducts are identical but differ in the relative regioarrangement of the four nonequivalent donor atoms on the metal. Thus, in isomers *exo*-**2a** and *exo*-**3a**, the Ph_2PN moieties on the azanorbornene skeletons occupy the positions trans to the NMe_2 groups. On the other hand, in isomers *exo*-**2b** and *exo*-**3b**, the Ph_2PN moieties on the azanorbornene skeletons occupy the positions trans to the aromatic carbon atoms. For isomers **2** and **3**, their diphosphine ligands are of opposite absolute configura-

(6) (a) Anderson, P. S.; Christy, M. E.; Engelhardt, E. L.; Lundell, G. F.; Ponticello, G. S. *J. Heterocycl. Chem.* **1977**, *14*, 213. (b) Davies, J. W.; Durrant, M. L.; Walker, M. P.; Belkacemi, D.; Malpass, J. R. *Tetrahedron* **1992**, *48*, 861. (c) Padwa, A.; Bullock, W. H.; Norman, B. H.; Perumattam, J. *J. Org. Chem.* **1991**, *56*, 4252. (d) Scheufler, F.; Maier, M. E. *Eur. J. Org. Chem.* **2000**, 3945. (e) Nishide, K.; Ichihashi, S.; Kimura, H.; Katoh, T.; Node, M. *Tetrahedron* **2001**, *42*, 9237. (f) Prinzbach, H.; Fuchs, R.; Kitzing, R. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 67. (g) Kitzing, R.; Fuchs, R.; Joyeux, M.; Prinzbach, H. *Helv. Chim. Acta* **1968**, *51*, 888.

(7) (a) Drew, M. G. B.; George, A. V.; Isaccs, N. S.; Rzepa, H. S. *J. Chem. Soc., Perkin Trans. 1* **1985**, 1277. (b) Kotsuki, H.; Mori, Y.; Nishizawa, H.; Ochi, M.; Matsuoka, K. *Heterocycles* **1982**, *19*, 1915. (c) Keijsers, J.; Hams, B.; Kruse, C.; Scheeren, H. *Heterocycles* **1989**, *29*, 79.

(8) (a) Bansal, R. C.; McCulloch, A. W.; McInnes, A. G. *Can. J. Chem.* **1969**, *47*, 2391. (b) Bansal, R. C.; McCulloch, A. W.; McInnes, A. G. *Can. J. Chem.* **1970**, *48*, 1472. (c) Rajakumar, P.; Kanan, A. *Indian J. Chem.* **1993**, *32B*, 1275.

(9) Heard, N. E.; Turner, J. *J. Org. Chem.* **1995**, *60*, 4302.

(10) Cury, A. B.; Gore, J. *Bull. Soc. Chim. Fr.* **1992**, *129*, 490.

(11) (a) Wild, S. B. *Coord. Chem. Rev.* **1997**, *166*, 291. (b) Hockless, D. C. R.; Gugger, P. A.; Leung, P. H.; Mayadunne, R. C.; Pabel, M.; Wild, S. B. *Tetrahedron* **1997**, *53*, 4083. (c) Doucet, H.; Brown, J. M. *Tetrahedron: Asymmetry* **1997**, *8*, 3775. (d) Albert, J.; Cadena, J. M.; Granell, J.; Muller, G.; Ordinas, J. I.; Panyella, D.; Puerta, C.; Sanudo, C.; Valerga, P. *Organometallics* **1999**, *18*, 3623. (e) He, G. S.; Mok, K. F.; Leung, P. H. *Organometallics* **1999**, *18*, 4027.

(12) (a) Bookham, J. L.; McFarlane, W. *J. Chem. Soc., Chem. Commun.* **1993**, 1352. (b) Aw, B. H.; Selvaratnam, S.; Leung, P. H.; Rees, N. H.; McFarlane, W. *Tetrahedron: Asymmetry* **1996**, *7*, 1753. (c) Leung, P. H.; Selvaratnam, S.; Cheng, C. R.; Mok, K. F.; Rees, N. H.; McFarlane, W. *Chem. Commun.* **1997**, 751. (d) Dunina, V. V.; Kuzmina, L. G.; Rubina, M. Y.; Grishin, Y. K.; Veits, Y. A.; Kazakova, E, I. *Tetrahedron: Asymmetry* **1999**, *10*, 1483.

(13) (a) Chooi, S. Y. M.; Leung, P. H.; Lim, C. C.; Mok, K. F.; Quek, G. H.; Sim, K. Y.; Tan, M. K. *Tetrahedron: Asymmetry* **1992**, *3*, 529. (b) Lopez, C.; Bosque, R.; Sainz, D.; Solans, X.; Font-Bardia, M. *Organometallics* **1997**, *16*, 3261. (c) Uccello-Barretta, G.; Bernardini, R.; Lazzaroni, R.; Salvadori, P. *Org. Lett.* **2000**, *2*, 1795. (d) Dunina, V. V.; Gorunova, O. N.; Livantsov, M. V.; Grishiu, Y. K. *Tetrahedron: Asymmetry* **2000**, *11*, 2907.

(14) (a) Hollis, T. K.; Overman, L. E. *Tetrahedron Lett.* **1997**, *38*, 8837. (b) Leung, P. H.; Ng, K. H.; Li, Y.; White, A. J. P.; Williams, D. J. *Chem. Commun.* **1999**, 2435.

(15) Liu, X. M.; Mok, K. F.; Vittal, J. J.; Leung, P. H. *Organometallics* **2000**, 19, 3722.

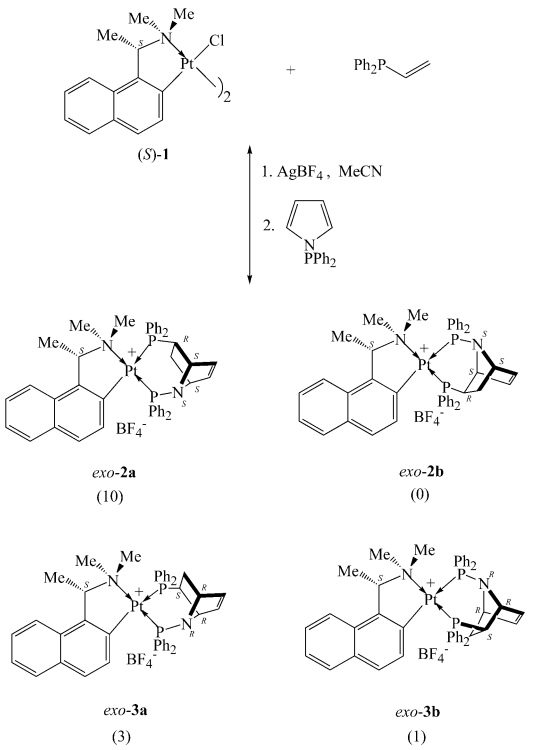
(16) Liu, X. M.; Mok, K. F.; Leung, P. H. *Organometallics* **2001**, *20*, 3918.

(17) Leung, P. H. *Acc. Chem. Res.* **2004**, *37*, 169.

(18) Yeo, W. C.; Vittal, J. J.; White, A. J. P.; Williams, D. J.; Leung, P. H. *Organometallics* **2001**, *20*, 2167.

(19) (a) Aw, B. H.; Hor, T. S. A.; Selvaratnam, S.; Mok, K. F.; White, A. J. P.; Williams, D. J.; Rees, N. H.; McFarlane, W.; Leung, P. H. *Inorg. Chem.* **1997**, *36*, 2138. (b) He, G.; Qin, Y.; Mok, K. F.; Leung, P. H. *Chem. Commun.* **2000**, 167.

Scheme 1



tions. For instances, in both *exo*-**2a** and *exo*-**2b**, the absolute configurations at C(1), C(4), C(5), and N(7) are *S*, *S*, *R*, and *S*, respectively. In contrast, in isomers *exo*-**3a** and *exo*-**3b**, the absolute configurations at C(1), C(4), C(5), and N(7) are *R*, *R*, *S*, and *R*, respectively.

Asymmetric Diels−Alder Synthesis. Upon the removal of the chloro ligands with silver tetrafluoroborate, (*S*)-**1** promotes the cycloaddition between *N*-(diphenylphosphino)pyrrole and diphenylvinylphosphine stereoselectively. The reaction was found to be complete in 7 days at room temperature. Prior to purification, the ^{31}P NMR spectrum of the reaction mixture in CD_2Cl_2 exhibited three pairs of doublets in the ratio 10:3:1, thus indicating that three stereochemically distinct cycloadducts were formed. The three products could be separated by fractional crystallization and column chromatography. The major diastereomer was obtained as yellow crystals from acetonitrile−diethyl ether in 25% isolated yield; $[\alpha]_{365} = +45°$ (CH_2Cl_2). The ^{31}P NMR spectrum of this crystallized product in CD_2Cl_2 showed two doublets at δ 35.5 ($J_{PP} = 22.9$ Hz, $J_{PtP} = 1842$ Hz) and 59.5 ($J_{PP} = 22.9$ Hz, $J_{PtP} = 3670$ Hz). It is important to note that the phosphorus−platinum coupling constants recorded for the two doublet resonance signals from this complex are markedly different. The relatively small phosphorus−platinum coupling constant observed for the doublet signal at δ 35.5 is diagnostic of the PPh_2 group coordinated trans to the strongly π-accepting ortho-metalated carbon atom.[18,19b,20] On the other hand, the doublet at δ 59.5, which showed the larger phosphorus−platinum coupling constant, is unambiguously assigned to the PPh_2 group

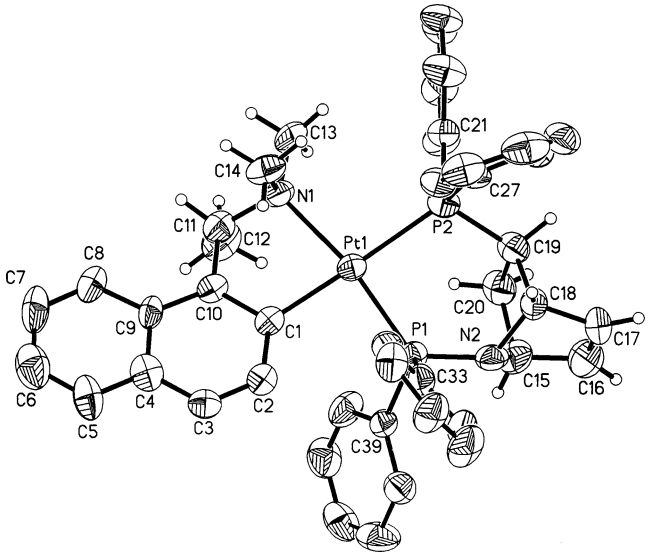


Figure 1. Molecular structure and absolute stereochemistry of the cationic complex *exo*-**2a**.

which is coordinated trans to the σ-donating nitrogen atom. This major diastereomer was subsequently confirmed by X-ray crystallography to be the isomer *exo*-**2a**, as depicted in Scheme 1. The cycloadduct *exo*-**2a** crystallizes with two crystallographically independent molecules in the asymmetric unit. However, they have identical stereochemistry and differ only slightly in bond lengths and angles. For clarity, only one molecule (molecule A) is shown in Figure 1. The structural analysis affirmed that a bis(diphenylphosphino)-substituted exo cycloadduct has been produced in the cycloaddition reaction, and the absolute configurations at C(15), C(18), C(19), and N(2) are *S*, *S*, *R*, and *S*, respectively. Selected bond distances and angles of *exo*-**2a** are given in Table 1. In agreement with the marked differences in the two Pt−P coupling constants observed in the ^{31}P NMR spectrum, the Pt(1)−P(1) distances (2.242(2) Å in molecule A and 2.237(2) Å in molecule B) are clearly shorter than the Pt(1)−P(2) bonds (2.343(2) Å] in molecule A and 2.336(2) Å in molecule B). These spectroscopic and structural data are consistent with the unique trans-electronic influences which originate from the organoplatinum unit.[18,19b,20] Despite the fact that the asymmetric pyrrole Diels−Alder reaction proceeds cleanly to give the cycloaddition adducts, the resulting low yields obtained are due to the difficulties in the separation of the stereoisomeric cycloadducts.

The lesser of the two minor cycloadducts was obtained as yellow crystals from dichloromethane−diethyl ether in 2% isolated yield; $[\alpha]_{365} = +68.3°$ (CH_2Cl_2). The ^{31}P NMR spectrum of this diastereomer in CD_2Cl_2 exhibited a pair of doublets at δ 36.1 ($J_{PP} = 22.9$ Hz, $J_{PtP} = 3822$ Hz) and 72.8 ($J_{PP} = 22.9$ Hz, $J_{PtP} = 1789$ Hz). This crystallized isomer was confirmed by X-ray crystallography to be *exo*-**3b** (Figure 2). The X-ray structural analysis established the C(15)-*R*, C(18)-*R*, C(19)-*S*, and N(2)-*R* absolute configurations and the fact that the Ph_2-PN moiety is coordinated trans to the aromatic carbon atom.

The other minor product was isolated as white cotton-wool-like crystals from dichloromethane−diethyl ether in 3% yield; $[\alpha]_{365} = -65°$ (CH_2Cl_2). The ^{31}P NMR spectrum of this cycloadduct in CD_2Cl_2 showed two

(20) (a) Chooi, S. Y. M.; Ranford, J. D.; Leung, P. H.; Mok, K. F. *Tetraheron: Asymmetry* **1994**, *5* 1805. (b) Chooi, S. Y. M.; Siah, S. Y.; Leung, P. H.; Mok, K. F. *Inorg. Chem.* **1993**, *32*, 4812. (c) Chooi, S. Y. M.; Hor, T. S. A.; Leung, P. H.; Mok, K. F. *Inorg. Chem.* **1992**, *31*, 1494.

Table 1. Selected Bond Lengths (Å) and Angles (deg) for *exo*-2a, *exo*-3b, and *exo*-5a

	exo-**2a**			*exo*-**5a**	
	molecule A	molecule B	*exo*-**3b**	molecule A	molecule B
Pt(1)−C(1)	2.079(6)	2.050(7)	2.084(4)	2.057(8)	2.082(8)
Pt(1)−N(1)	2.178(5)	2.186(6)	2.151(4)	2.143(9)	2.146(7)
Pt(1)−P(1)	2.242(2)	2.237(2)	2.333(1)	2.230(3)	2.233(3)
Pt(1)−P(2)	2.343(2)	2.336(2)	2.233(1)	2.349(2)	2.348(2)
P(1)−N(2)	1.694(6)	1.672(6)	1.718(4)	1.678(7)	1.675(7)
P(2)−C(19)	1.819(8)	1.808(8)	1.822(4)	1.81(1)	1.818(9)
N(2)−C(15)	1.477(9)	1.485(9)	1.478(6)	1.49(1)	1.49(1)
N(2)−C(18)	1.467(8)	1.471(8)	1.478(6)	1.47(1)	1.47(1)
C(15)−C(16)	1.48(1)	1.477(9)	1.507(7)	1.49(1)	1.53(1)
C(16)−C(17)	1.32(1)	1.34(1)	1.321(7)	1.60(1)	1.58)1)
C(17)−C(18)	1.50(1)	1.50(1)	1.516(7)	1.50(1)	1.53(1)
C(18)−C(19)	1.58(1)	1.57(1)	1.571(6)	1.58(1)	1.56(1)
C(19)−C(20)	1.57(1)	1.569(9)	1.554(6)	1.57(1)	1.58(1)
C(15)−C(20)	1.540(9)	1.55(1)	1.559(6)	1.48(1)	1.51(1)
C(1)−Pt(1)−P(1)	91.0(2)	92.4(2)	175.6(1)	91.4(3)	90.8(3)
C(1)−Pt(1)−P(2)	173.4(2)	174.1(2)	93.7(1)	176.2(2)	174.5(2)
C(1)−Pt(1)−N(1)	79.4(2)	77.7(2)	78.6(2)	78.4(3)	79.0(3)
P(1)−Pt(1)−P(2)	90.34(7)	90.53(7)	90.63(4)	90.92(9)	90.78(9)
N(1)−Pt(1)−P(1)	170.2(2)	170.1(2)	97.14(9)	169.8(2)	169.8(2)
N(1)−Pt(1)−P(2)	99.4(2)	99.4(2)	170.80(9)	99.3(2)	99.4(2)
N(2)−P(1)−Pt(1)	122.7(2)	123.2(2)	122.1(1)	122.9(3)	123.0(3)
C(19)−P(2)−Pt(1)	113.0(3)	113.6(3)	115.8(2)	113.6(3)	112.9(3)
P(1)−N(2)−C(15)	124.7(5)	124.5(5)	124.0(3)	124.5(6)	123.9(6)
P(1)−N(2)−C(18)	118.8(5)	118.6(5)	116.1(3)	118.7(6)	118.1(6)
N(2)−C(15)−C(16)	101.5(6)	101.2(6)	99.4(4)	99.2(8)	100.4(8)
N(2)−C(18)−C(17)	101.9(6)	101.5(6)	99.8(4)	104.5(7)	104.3(8)
N(2)−C(15)−C(20)	103.7(6)	102.7(6)	103.3(4)	103.8(7)	106.1(7)
N(2)−C(18)−C(19)	102.8(6)	103.0(6)	102.3(4)	102.2(7)	104.1(8)
C(15)−C(16)−C(17)	107.2(8)	107.2(7)	106.8(4)	103.1(8)	102.4(7)
C(16)−C(17)−C(18)	105.1(7)	104.7(7)	106.5(4)	98.6(8)	98.7(8)
C(18)−C(19)−C(20)	100.6(6)	100.7(6)	101.8(3)	99.9(7)	100.8(7)
C(15)−C(20)−C(19)	100.6(6)	101.1(6)	101.6(4)	102.6(8)	100.6(8)

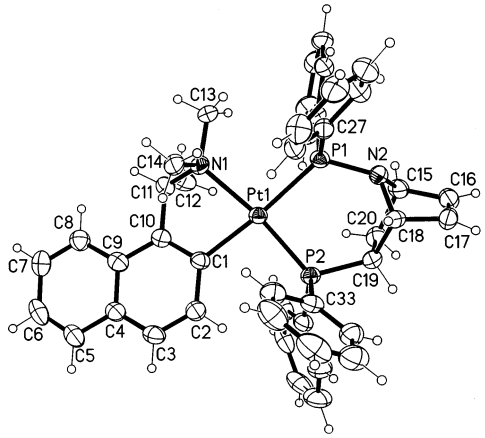


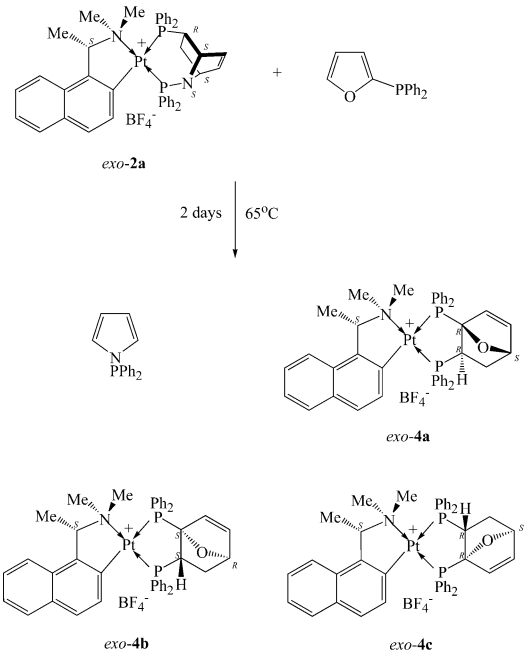
Figure 2. Molecular structure and absolute stereochemistry of the cationic complex *exo*-**3b**.

doublets at δ 36.9 (J_{PP} = 22.9 Hz, J_{PtP} = 1865 Hz) and 58.9 (J_{PP} = 22.9 Hz, J_{PtP} = 3654 Hz). For this diastereomer, suitable single crystals for X-ray analysis could not be obtained. However, the identity of this isomer could be established unambiguously by NMR spectroscopy. The phosphorus−platinum coupling observed in the ^{31}P NMR spectrum of this isomer indicates that both phosphorus atoms are coordinated on platinum. Thus, the cycloadduct chelates as a diphosphine bidentate ligand in which the exo stereochemistry must be adopted. The ^{1}H NMR spectrum is also consistent with this exo stereochemical assignment. The absence of coupling between the bridgehead and adjacent endo C−H protons is in agreement with the exo stereochemistry adopted by the azanorbornene skeleton.[2c,d,5a,7a] Therefore, this isomer must be either *exo*-**2b** or *exo*-**3a**. It has been well established that for a pair of regioisomers such as *exo*-**3a** and *exo*-**3b**, formed by an optically pure chiral diphosphine ligand on this class of organoplatinum and organopalladium units, the differences in ^{31}P NMR chemical shifts (>10 ppm) and phosphorus−platinum coupling constants would be significantly large.[11e,12a,18,19,21] On the other hand, for diastereomeric complexes such as *exo*-**2a** and *exo*-**3a**, which have the same regioarrangements but differ in the absolute configurations of the diphosphine chelates, their ^{31}P NMR signals and coupling constants would be quite similar, differing only slightly in their chemical shifts.[11e,12a,18,19,21] Since the ^{31}P NMR chemical shifts and platinum−phosphorus coupling constants of this crystallized product are similar to those of *exo*-**2a**, the compound is assigned as *exo*-**3a**.

Stability of the Cycloadducts. Isomer *exo*-**2a** is stable in the crystalline state (no change after being stored for 1 year). However, the cycloadduct was found to undergo retro-cycloaddition reaction slowly when it was dissolved in solution. For instance, a small amount of *exo*-**3a** was detected by the ^{31}P NMR spectroscopy from a dichloromethane solution containing pure *exo*-**2a** that had been dissolved and stored at room temperature for two weeks. When a sample of pure *exo*-**2a** was heated (65 °C) in 1,2-dichloroethane for 4 days, the ^{31}P NMR spectrum showed that all three isomers, *exo*-**2a**, *exo*-**3a** and *exo*-**3b** were present in the ratio 19:8:1. Furthermore, when a mixture of *exo*-**2a** and 2-diphenylphosphinofuran were heated (65 °C) in 1,2-dichloroethane for 2 days, the ^{31}P NMR spectrum showed that *exo*-**2a** was converted to *N*-diphenylphosphinopyrrole

(21) Aw, B. H.; Leung, P. H. *Tetrahedron: Asymmetry* **1994**, *7*, 1167.

Scheme 2



and the respective known furan Diels−Alder products,[18] *exo*-**4a**, *exo*-**4b** and *exo*-**4c** (Scheme 2). Presumably *exo*-**2a** first undergoes retro-cycloaddition reaction to give the platinum complex in which both *N*-diphenylphosphinopyrrole and diphenylvinylphosphine are coordinated to the metal. Subsequent ligand exchange between *N*-diphenylphosphinopyrrole and 2-diphenylphosphinofuran, followed by asymmetric furan Diels−Alder reaction would give the respective chelating oxanorbornene cycloadducts which are stable to retro Diels−Alder reaction.[18] Similarly, both *exo*-**3a** and *exo*-**3b** are stable in the crystalline state, but undergo the retro Diels−Alder reaction slowly in solution. Heating of pure *exo*-**3a** and *exo*-**3b** separately at 65 °C for several days, similarly gives the same equilibrium mixture that contained all three isomers, *exo*-**2a**, *exo*-**3a** and *exo*-**3b** in the ratio 19:8:1. The above observations are indicative that the isomeric pyrrole cycloadducts are thermodynamically unstable and undergo retro Diels−Alder reaction slowly in solution. This thermodynamic property is different from the analogous furan cycloadducts.[18] Nevertheless, only the various isomeric cycloadducts could be detected in the equilibrium mixture. The diene and dienophile could not be detected by the ^{31}P NMR spectroscopy. Thus the platinum template favored the cycloadduct formation in this equilibrium process.

Stabilization of the Cycloadducts. One way to deter the undesirable retro Diels−Alder reaction is to hydrogenate the carbon−carbon double bond of the azanorbornene skeleton.[5a,b,7a] By using Pd/C as the catalyst for the hydrogenation reaction, *exo*-**2a** was converted to *exo*-**5a** efficiently (Scheme 3). The hydrogenated product *exo*-**5a** was isolated as yellow crystals from acetonitrile−diethyl ether in 97% yield; $[\alpha]_{365}$ = +134° (CH_2Cl_2). The ^{31}P NMR spectrum of *exo*-**5a** in CD_2Cl_2 exhibited a pair of doublets at δ 25.6 (J_{PP} = 24.8 Hz, J_{PtP} = 1827 Hz) and 55.7 (J_{PP} = 24.8 Hz, J_{PtP} = 3683 Hz). The molecular structure and the absolute configurations of *exo*-**5a** were confirmed by X-ray crystallography. The complex crystallized with two independent but very similar and nearly superimposable

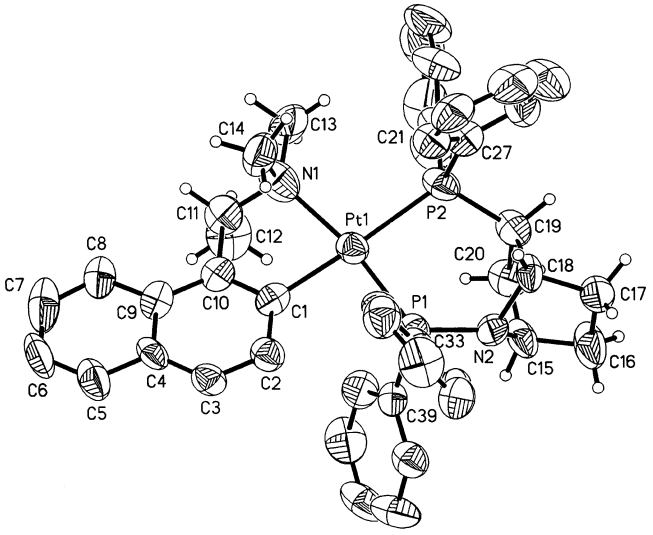
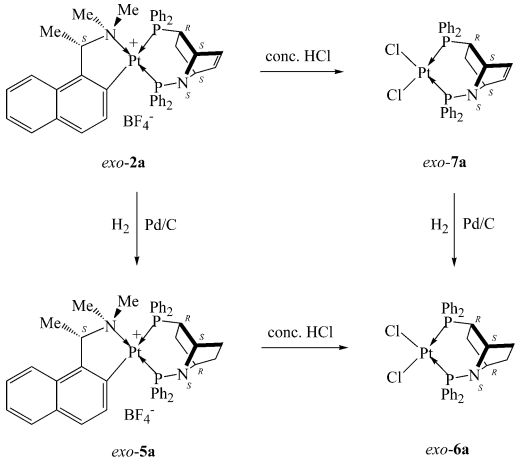


Figure 3. Molecular structure and absolute stereochemistry of the cationic complex *exo*-**5a**.

Scheme 3



molecules in the asymmetric unit. For clarity, only one molecule (molecule A) is depicted in Figure 3. Selected bond lengths and angles are listed in Table 1. The absolute configurations at C(15), C(18), C(19), and N(2) are *R*, *S*, *R*, and *S*, respectively. It is noteworthy that the apparent inversion of configuration that takes place at C(15) in the hydrogenated product *exo*-**5a** is merely a consequence of the CIP sequence rules.[22] Upon hydrogenation of the double bond, the azanorbornane cycloadduct is stable toward the undesirable retro Diels−Alder reaction. Complex *exo*-**5a** remained unchanged after being heated in 1,2-dichloroethane at 65 °C for 6 days. The naphthylamine auxiliary could be removed chemoselectively from *exo*-**5a** by treatment with concentrated hydrochloric acid to generate *exo*-**6a** (Scheme 3). The diphosphine-substituted azanorbornane chelate and P−N bond were found to be stable toward this acid treatment. The dichloro complex was subsequently crystallized from dichloromethane−diethyl ether as colorless crystals in 93% yield, $[\alpha]_D$ = −3.6° (CH_2Cl_2). The ^{31}P NMR spectrum of this neutral dichloro complex in CD_2Cl_2 showed two doublets at δ 18.9 (J_{PP} = 21.0 Hz, J_{PtP} = 3727 Hz) and 45.7 (J_{PP} = 21.0 Hz,

(22) Cahn, R. S.; Ingold, C. K.; Prelog, V. *Angew. Chem., Int. Ed. Engl.* **1966**, *5*, 385.

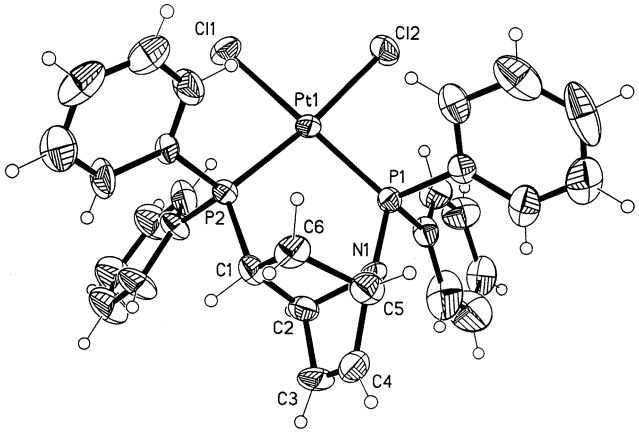


Figure 4. Molecular structure and absolute stereochemistry of the dichloro complex *exo*-**7a**.

Table 2. Selected Bond Lengths (Å) and Angles (deg) for *exo*-7a

Pt(1)–P(1)	2.233(3)	N(1)–C(5)	1.54(1)
Pt(1)–P(2)	2.240(2)	C(2)–C(3)	1.53(1)
Pt(1)–Cl(1)	2.365(3)	C(3)–C(4)	1.32(2)
Pt(1)–Cl(2)	2.350(3)	C(4)–C(5)	1.48(2)
P(1)–N(1)	1.632(8)	C(5)–C(6)	1.58(2)
C(1)–P(2)	1.85(1)	C(1)–C(6)	1.50(2)
N(1)–C(2)	1.55(1)	C(1)–C(2)	1.52(2)
P(1)–Pt(1)–Cl(1)	176.8(1)	P(1)–N(1)–C(5)	123.6(7)
P(1)–Pt(1)–Cl(2)	90.8(1)	N(1)–C(2)–C(3)	99.7(8)
P(2)–Pt(1)–Cl(1)	87.3(1)	N(1)–C(5)–C(4)	100.3(9)
P(2)–Pt(1)–Cl(2)	173.9(1)	N(1)–C(2)–C(1)	103.8(8)
P(1)–Pt(1)–P(2)	94.35(9)	N(1)–C(5)–C(6)	103.2(8)
Cl(1)–Pt(1)–Cl(2)	87.8(1)	C(2)–C(3)–C(4)	105(1)
N(1)–P(1)–Pt(1)	120.1(3)	C(3)–C(4)–C(5)	109(1)
C(1)–P(2)–Pt(1)	115.3(4)	C(5)–C(6)–C(1)	101.0(9)
P(1)–N(1)–C(2)	121.3(6)	C(6)–C(1)–C(2)	104.7(9)

J_{PtP} = 3521 Hz). It is noteworthy that, in the absence of the asymmetric naphthylamine auxiliary, the two Pt–P coupling constants are similar in magnitude.

The hydrogenation reaction could be conducted via an alternative approach in which the naphthylamine auxiliary was removed prior to the reductive process. The chiral auxiliary was first chemoselectively removed from *exo*-**2a** by treatment with concentrated hydrochloric acid to form *exo*-**7a** (Scheme 3). The dichloro complex *exo*-**7a** was isolated as colorless crystals from dichloromethane–diethyl ether in 94% yield; $[\alpha]_{365} = +90°$ (CH_2Cl_2). The ^{31}P NMR spectrum of *exo*-**7a** in CD_2Cl_2 showed two doublets at δ 29.8 (J_{PP} = 21.0 Hz, J_{PtP} = 3738 Hz) and 50.5 (J_{PP} = 21.0 Hz, J_{PtP} = 3525 Hz). Similar to the hydrogenated analogue *exo*-**5a**, acid treatment of the template complex *exo*-**2a** only chemoselectively removed the naphthylamine auxiliary. It is noteworthy that the successful chemoselective removal of the naphthylamine auxiliary from these complexes was rather unexpected, as many organic azanorbornenes and aminophosphines have been found to undergo ring opening[2c,d,5a,b] and P–N cleavage[23] under acidic conditions. An X-ray structural analysis of *exo*-**7a** (Figure 4 and Table 2) confirmed the absolute configurations and structure, in which the azanorbornene skeleton and P–N bond are intact. The dichloro complex *exo*-**7a** is stable in the crystalline state but completely racemized in dichloromethane solution after being kept for 3 months at room temperature. Clearly the racemization was due to the undesired retro Diels–Alder reaction. Nevertheless, when the optically pure *exo*-**7a** was subjected to a hydrogenation reaction with Pd/C as catalyst, the stable azanorbornane *exo*-**6a** was obtained efficiently in 94% yield. Hence, the synthesis of *exo*-**6a** from *exo*-**2a** is equally efficient from both pathways, as illustrated in Scheme 3.

(23) Corbridge, D. E. C. *Phosphorus 2000: Chemistry, Biochemistry and Technology*; Elsevier: New York, 2000; Chapter 7.

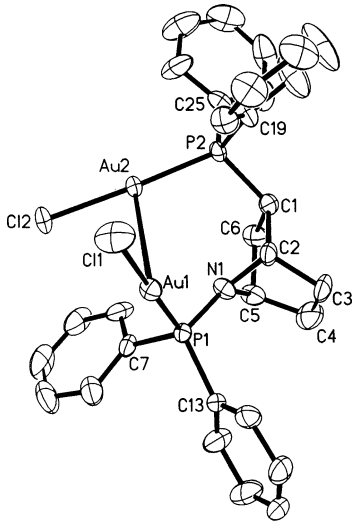
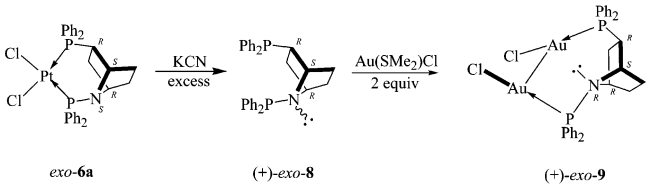


Figure 5. Molecular structure and absolute stereochemistry of (+)-*exo*-**9**.

Scheme 4



Liberation of Chiral Diphosphine Ligand and Coordination to Au(I). The optically pure bis(diphenylphosphino)-substituted exo cycloadduct could be liberated from *exo*-**6a** by the treatment of the complex with aqueous cyanide (Scheme 4). The ^{31}P NMR spectrum of this liberated chiral diphosphine ligand, (+)-*exo*-**8**, in THF-d_8 exhibited two singlets at δ −8.1 and 39.2. The free cycloadduct (+)-*exo*-**8** is unstable and undergoes decomposition in solution. Thus, within 30 min, the free ligand (+)-*exo*-**8** was recoordinated to Au(I) metal ion, for the synthesis of a diphosphine–gold(I) complex. As illustrated in Scheme 4, the coordination of (+)-*exo*-**8** to 2 equiv of chloro(dimethyl sulfide)gold(I) gave the dinuclear gold(I) complex (+)-*exo*-**9** as colorless crystals in 81% yield; $[\alpha]_{365} = +70.7°$ (CH_2Cl_2). The ^{31}P NMR spectrum of this dinuclear complex in $CDCl_3$ showed two singlets at δ 38.7 and 66.2. The molecular structure and absolute configurations of (+)-*exo*-**9** were established by X-ray crystallography (Figure 5). Selected bond lengths and angles are given in Table 3. The X-ray structural analysis showed that the two gold(I) atoms adopt a linear coordination mode with small deviations from 180° (178.75(9) and 177.63(8)°). The two Au–Cl bonds (2.298(2) and 2.295(2) Å) and two Au–P bonds (2.236(2) and 2.232(2) Å) are within the expected range.[24] However, the relatively long Au–Au distance (3.2614(4) Å) shows that only a weak interaction exists between the two gold atoms. The weak Au–Au interac-

Table 3. Selected Bond Lengths (Å) and Angles (deg) for (+)-*exo*-9

P(1)−Au(1)	2.236(2)	N(1)−C(5)	1.494(8)
P(2)−Au(2)	2.232(2)	C(2)−C(3)	1.54(1)
Au(1)−Au(2)	3.2614(4)	C(3)−C(4)	1.54(2)
Au(1)−Cl(1)	2.298(2)	C(4)−C(5)	1.53(1)
Au(2)−Cl(2)	2.295(2)	C(5)−C(6)	1.52(1)
P(1)−N(1)	1.660(6)	C(1)−C(6)	1.57(1)
C(1)−P(2)	1.816(8)	C(1)−C(2)	1.55(1)
N(1)−C(2)	1.47(1)		
P(1)−Au(1)−Cl(1)	178.75(9)	N(1)−C(5)−C(4)	103.5(7)
P(2)−Au(2)−Cl(2)	177.63(8)	N(1)−C(2)−C(1)	99.7(6)
P(1)−Au(1)−Au(2)	80.78(5)	N(1)−C(5)−C(6)	98.5(6)
P(2)−Au(2)−Au(1)	104.72(5)	C(2)−C(3)−C(4)	101.5(7)
N(1)−P(1)−Au(1)	108.0(2)	C(3)−C(4)−C(5)	103.4(7)
C(1)−P(2)−Au(2)	113.6(3)	C(5)−C(6)−C(1)	102.4(7)
P(1)−N(1)−C(2)	124.0(5)	C(6)−C(1)−C(2)	101.2(6)
P(1)−N(1)−C(5)	130.7(6)		
N(1)−C(2)−C(3)	104.7(7)		

tion may be attributed to the strain of the awkward seven-membered ring formed. The X-ray structural analysis of (+)-*exo*-**9** revealed that the absolute configurations at C1, C2, C5, and N1 are *R*, *S*, *R*, and *R*, respectively, in the solid state. It is noteworthy that the stereogenic centers in (+)-*exo*-**9**, except nitrogen, are consistent with those in the corresponding platinum precursor, *exo*-**6a**. Due to chelation of diphosphine to the metal and the size of the resultant six-membered ring formed, the stereogenic nitrogen in the Pt complex could only adopt the *S* configuration. However, in (+)-*exo*-**8** and (+)-*exo*-**9**, the absence of this chelation constraint allows the facile inversion of nitrogen in solution. Indeed, the adoption of the *R* absolute configuration on nitrogen in the dinuclear gold complex (+)-*exo*-**9** is sterically favorable, as the steric repulsion between the two bulky diphenylphosphino groups is diminished. It is noteworthy that the enantiomeric form of the gold complex (−)-*exo*-**9** could be obtained similarly using either *exo*-**3a** or *exo*-**3b** as the starting material. Similar removal of the naphthylamine auxiliary from *exo*-**3a** or *exo*-**3b** by treatment with concentrated hydrochloric acid gives the enantiomeric complex of *exo*-**7a**, which upon subsequent hydrogenation, liberation of free ligand with potassium cyanide, and recoordination to Au(I) gives (−)-*exo*-**9**. Indeed, the formation of the gold complex (−)-*exo*-**9** from the platinum complex *exo*-**3a** reaffirms the earlier stereochemical assignment of the platinum cycloadduct.

In conclusion, the chiral organoplatinum template promoted asymmetric [4 + 2] Diels−Alder reaction between *N*-(diphenylphosphino)pyrrole (a poor diene) and diphenylvinylphosphine (a poor dienophile) has been demonstrated. The chiral metal template not only served as a chiral inducer and reaction promoter for the intramolecular Diels−Alder reaction but also favored the formation of the resulting diphosphine cycloadducts. The bis(tertiary phosphine)-substituted azanorbornane could be liberated from the platinum template and recoordinated to Au(I). We have recently reported that diphosphine−gold(I) complexes derived from substituted norbornenes and norbornanes are potential anticancer agents.[25] The biological properties of *exo*-**9** are currently being investigated.

Experimental Section

Reactions involving air-sensitive compounds were performed under a positive pressure of purified nitrogen. NMR spectra were recorded at 25 °C on Bruker ACF 300 and AMX500 spectrometers. The spectral assignments in the ^{1}H NMR spectrua are based on selective decoupling of the two types of ^{31}P nuclei and NOE data from 2D-ROESY spectra.[12b] Optical rotations were measured on the specified solution in a 0.1 dm cell at 25 °C with a Perkin-Elmer Model 341 polarimeter. Elementary analyses were performed by the Elemental Analysis Laboratory of the Department of Chemistry at the National University of Singapore.

N-(Diphenylphosphino)pyrrole,[26] diphenylvinylphosphine,[27] 2-(diphenylphosphino)furan,[28] and (*S*)-**1**[18] were prepared according to standard literature methods. Silver tetrafluoroborate and chloro(dimethyl sulfide)gold(I) were purchased from Aldrich Chemical Co.

Asymmetric Pyrrole Diels−Alder Reaction. A solution of silver tetrafluoroborate (0.750 g, 3.85 mmol) in water (20 mL) was added to a solution of (*S*)-**1** (1.644 g, 1.744 mmol) and diphenylvinylphosphine (0.750 g, 3.53 mmol) in dichloromethane (130 mL) and acetonitrile (10 mL). The mixture was stirred vigorously at room temperature for 2 h and then filtered through Celite (to remove AgCl), washed with water, and dried ($MgSO_4$). The mixture was subsequently treated with *N*-(diphenylphosphino)pyrrole (0.880 g, 3.50 mmol) and stirred at room temperature for 7 days. The three cycloadducts were isolated by column chromatography on a silica column with acetone−dichloromethane as eluent and fractional crystallization with dichloromethane−diethyl ether or acetonitrile−diethyl ether to give the three stereoisomeric products.

[*SP*-4-3-{(*S*)-1-[1-(Dimethylamino)ethyl]naphthyl-κ^2C^2,N}{(1*S*,4*S*,5*R*,7*S*)-5,7-bis(diphenylphosphino)-7-azabicyclo[2.2.1]hept-2-ene-κ^2P^5,P^7}]platinum(II) tetrafluoroborate (*exo*-2a) was obtained as yellow crystals from acetonitrile−diethyl ether: mp 228−230 °C dec; $[\alpha]_D = +6.0°$ (*c* 0.7, CH_2Cl_2); 0.835 g (25% yield). Anal. Calcd for $C_{44}H_{43}BF_4N_2P_2Pt$: C, 56.0; H, 4.6; N, 3.0. Found: C, 56.1; H, 4.4; N, 3.1. ^{31}P NMR (CD_2Cl_2): δ 35.5 (d, 1P, $J_{PP} = 22.9$ Hz, $J_{PtP} = 1842$ Hz, P^5), 59.5 (d, 1P, $J_{PP} = 22.9$ Hz, $J_{PtP} = 3670$ Hz, P^7). ^{1}H NMR (CD_2Cl_2): δ 1.75 (ddd, 1H, $^3J_{HH} = 7.9$ Hz, $^3J_{PH} = 9.6$ Hz, $^2J_{HH} = 12.3$ Hz, H_{6endo}), 1.96 (d, 3H, $^3J_{HH} = 6.3$ Hz, CH*Me*), 2.25 (dddd, 1H, $^2J_{PH} = 9.6$ Hz, $^4J_{PH} = 1.7$ Hz, $^3J_{HH} = 7.6$ Hz, $^3J_{HH} = 3.6$ Hz, H_5), 2.42 (dd, 3H, $^4J_{PH} = 2.2$ Hz, $^4J_{PH} = 3.9$ Hz, N*Me*$_{eq}$), 2.76−2.84 (m, 1H, H_{6exo}), 2.85 (d, 3H, $^4J_{PH} = 1.9$ Hz, N*Me*$_{ax}$), 3.39 (tdd, 1H, $^3J_{PH} = 7.4$ Hz, $^3J_{PH} \approx {}^3J_{HH} = 2.7$ Hz, $^4J_{HH} = 1.4$ Hz, H_4), 3.62−3.64 (m, 1H, H_1), 4.75 (qn, 1H, $^3J_{HH} = {}^4J_{PH} = 6.3$ Hz, C*H*Me), 6.19 (dd, 1H, $^3J_{HH} = 2.7$ Hz, $^3J_{HH} = 5.8$ Hz, H_3), 6.41 (ddd, 1H, $^3J_{HH} = 2.7$ Hz, $^3J_{HH} = 5.8$ Hz, $^4J_{PH} = 1.1$ Hz, H_2), 6.81−8.45 (m, 26H, aromatics). **[*SP*-4-3-{(*S*)-1-[1-(Dimethylamino)ethyl]naphthyl-κ^2C^2,N}{(1*R*,4*R*,5*S*,7*R*)-5,7-bis(diphenylphosphino)-7-azabicyclo[2.2.1]hept-2-ene-κ^2P^5,P^7}]platinum(II) tetrafluoroborate (*exo*-3a)** was obtained as white cotton-wool-like crystals from dichloromethane−diethyl ether: mp 200−202 °C dec; $[\alpha]_D = -42°$ (*c* 1.0, CH_2Cl_2); 0.0830 g (3% yield). Anal. Calcd for $C_{44}H_{43}BF_4N_2P_2Pt$: C, 56.0; H, 4.6; N, 3.0. Found: C, 55.4; H, 4.5; N, 3.1. ^{31}P NMR (CD_2Cl_2): δ 36.9 (d, 1P, $J_{pp} = 22.9$ Hz, $J_{PtP} = 1865$ Hz, P^5), 58.9 (d, 1P, $J_{PP} = 22.9$ Hz, $J_{PtP} = 3654$ Hz, P^7). ^{1}H NMR (CD_2Cl_2): δ 1.49−1.54 (m, 1H, H_{6endo}), 1.91 (d, 3H, $^3J_{HH} = 6.3$ Hz, CH*Me*), 2.13 (dddd, 1H, $^2J_{PH} = 10.1$ Hz, $^4J_{PH} = 1.4$ Hz, $^3J_{HH} = 7.6$ Hz, $^3J_{HH} = 3.8$ Hz, H_5), 2.42 (tdd, 1H, $^2J_{HH} = 12.3$ Hz, $^3J_{PH} = 19.9$ Hz, $^3J_{HH} \approx {}^3J_{HH'} = 3.8$ Hz, H_{6exo}), 2.59

(24) Eggleston, D. S.; Chodosh, D. F.; Girard, G. R.; Hill, D. T. *Inorg. Chim. Acta* **1985**, 108, 221.

(25) (a) Song, Y. C.; Vittal, J. J.; Srinivasan, N.; Chan, S. H.; Leung, P. H. *Tetrahedron: Asymmetry* **1999**, *10*, 1433. (b) Leung, P. H.; Chan, S. H.; Song, Y. C. Patent WO 2001077121, 2001. (c) Leung, P. H.; Chan, S. H.; Song, Y. C. U.S. Patent 2003/0114695A1, 2003.

(26) Moloy, K. G.; Petersen, J. L. *J. Am. Chem. Soc.* **1995**, *117*, 7696.

(27) Berlin, K. D.; Butler, G. B. *J. Org. Chem.* **1961**, *26*, 2537.

(28) Allen, D. W.; Hutley, B. G.; Rich, T. C. *J. Chem. Soc., Perkin Trans. 2* **1973**, 820.

Table 4. Crystallographic Data for *exo*-2a, *exo*-3b, *exo*-5a, *exo*-7a, and (+)-*exo*-9

	exo-**2a**	*exo*-**3b**	*exo*-**5a**	*exo*-**7a**	(+)-*exo*-**9**
formula	$C_{44}H_{43}BF_4N_2P_2Pt$	$C_{44}H_{43}BF_4N_2P_2Pt$	$C_{44}H_{45}BF_4N_2P_2Pt$	$C_{30}H_{27}Cl_2NP_2Pt$	$C_{30}H_{29}Cl_2NP_2Au_2$
fw	943.64	943.64	945.66	729.46	930.32
space group	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$	$P2_1$	$P2_1$
cryst syst	orthorhombic	orthorhombic	orthorhombic	monoclinic	monoclinic
a/Å	10.6389(5)	9.6457(2)	10.6047(8)	9.8845(8)	8.9993(4)
b/Å	17.7628(8)	19.8625(5)	18.151(1)	14.073(1)	19.717(1)
c/Å	41.513(2)	20.6599(5)	41.647(4)	10.8796(9)	9.3112(5)
β/deg	90	90	90	114.313(2)	114.809(1)
V/Å^3	7845.1(6)	3958.2(2)	8016(1)	1379.2(2)	1499.7(1)
Z	8	4	8	2	2
T/K	223(2)	223(2)	223(2)	223(2)	295(2)
ρ_{calcd}/g cm^{-3}	1.598	1.584	1.567	1.757	2.060
λ/Å	0.710 73 (Mo)	0.710 73 (Mo)	0.710 73 (Mo)	0.710 73 (Mo)	0.710 73 (Mo)
μ/cm^{-1}	37.12	36.79	36.33	54.17	100.76
Flack param	0.004(5)	-0.021(4)	-0.036(5)	-0.01(1)	0.018(8)
R1 (obsd data)[a]	0.0523	0.0364	0.0475	0.0395	0.0340
wR2 (obsd data)[b]	0.0604	0.0637	0.0592	0.1016	0.0746

[a] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [b] $wR2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{1/2}$; $w^{-1} = \sigma^2(F_o^2) + (aP)^2 + bP$.

(dd, 3H, $^4J_{PH}$ = 2.7 Hz, $^4J_{PH}$ = 4.1 Hz, N*Me*$_{eq}$), 2.65 (d, 3H, $^4J_{PH}$ = 2.2 Hz, N*Me*$_{ax}$), 3.38 (tdd, 1H, $^3J_{PH}$ = 7.9 Hz, $^3J_{PH} \approx {}^3J_{HH}$ = 2.7 Hz, $^4J_{HH}$ = 1.4 Hz, *H*$_4$), 3.46−3.49 (m, 1H, *H*$_1$), 4.79 (qn, 1H, $^3J_{HH} = {}^4J_{PH}$ = 6.3 Hz, C*H*Me), 6.16 (dd, 1H, $^3J_{HH}$ = 2.7 Hz, $^3J_{HH}$ = 5.8 Hz, *H*$_3$), 6.40 (ddd, 1H, $^3J_{HH}$ = 2.7 Hz, $^3J_{HH}$ = 5.8 Hz, $^4J_{PH}$ = 1.1 Hz, *H*$_2$), 6.72−8.62 (m, 26H, aromatics).

[*SP*-4-4-{(*S*)-1-[1-(Dimethylamino)ethyl]naphthyl-κ^2C^2,*N*}-{(1*R*,4*R*,5*S*,7*R*)-5,7-bis(diphenylphosphino)-7-azabicyclo-[2.2.1]hept-2-ene-κ^2P^5,*P*^{7}}]platinum(II) tetrafluoroborate (*exo*-3b) was obtained as yellow crystals from dichloromethane−diethyl ether: mp 229−231 °C dec; $[\alpha]_D$ = +4.9° (*c* 1.2, CH_2Cl_2); 0.0527 g (2% yield). Anal. Calcd for $C_{44}H_{43}BF_4N_2P_2Pt$: C, 56.0; H, 4.6; N, 3.0. Found: C, 56.0; H, 4.4; N, 3.1. ^{31}P NMR (CD_2Cl_2): *δ* 36.1 (d, 1P, J_{PP} = 22.9 Hz, J_{PtP} = 3822 Hz, *P*^{5}), 72.8 (d, 1P, J_{PP} = 22.9 Hz, J_{PtP} = 1789 Hz, *P*^{7}). ^{1}H NMR (CD_2Cl_2) *δ* 1.37 (dt, 1H, $^2J_{HH}$ = 12.6 Hz, $^3J_{PH} = {}^3J_{HH}$ = 8.3 Hz, H_{6endo}), 2.02 (d, 3H, $^3J_{HH}$ = 6.3 Hz, CH*Me*), 2.16 (tdd, 1H, $^2J_{HH}$ = 12.6 Hz, $^3J_{HH} = {}^3J_{HH'}$ = 4.0 Hz, $^3J_{PH}$ = 20.5 Hz, H_{6exo}), 2.23−2.33 (m, 1H, *H*$_5$), 2.43 (dd, 3H, $^4J_{PH}$ = 4.0 Hz, $^4J_{PH}$ = 2.4 Hz, N*Me*$_{eq}$), 2.68 (d, 3H, $^4J_{PH}$ = 1.9 Hz, N*Me*$_{ax}$), 3.56 (tdd, 1H, $^3J_{PH}$ = 7.4 Hz, $^3J_{PH} \approx {}^3J_{HH}$ = 2.7 Hz, $^4J_{HH}$ = 1.3 Hz, *H*$_4$), 3.77−3.80 (m, 1H, *H*$_1$), 4.77 (qn, 1H, $^3J_{HH} = {}^4J_{PH}$ = 6.3 Hz, C*H*Me), 6.25 (dd, 1H, $^3J_{HH}$ = 2.7 Hz, $^3J_{HH}$ = 5.8 Hz, *H*$_3$), 6.39 (dd, 1H, $^3J_{HH}$ = 2.7 Hz, $^3J_{HH}$ = 5.8 Hz, *H*$_2$), 6.93−8.44 (m, 26H, aromatics).

Hydrogenation of Pt-*exo*-2a and Isolation of [*SP*-4-3-{(*S*)-1-[1-(Dimethylamino)ethyl]naphthyl-κ^2C^2,*N*}{(1*R*,4*S*,5*R*,7*S*)-5,7-bis(diphenylphosphino)-7-azabicyclo[2.2.1]-hept-2-ane-κ^2P^5,*P*^{7}}]platinum(II) tetrafluoroborate (*exo*-5a). Hydrogen gas was bubbled slowly into a solution of *exo*-**2a** (0.210 g, 0.223 mmol) and 10% Pd/C (0.021 g) in dichloromethane (30 mL) for 2 h at room temperature under atmospheric pressure. The mixture was then filtered through Celite, and *exo*-**5a** was obtained from acetonitrile−diethyl ether as yellow crystals: mp 302−303 °C dec; $[\alpha]_D$ = +11.2° (*c* 1.3, CH_2Cl_2); 0.204 g (97% yield). Anal. Calcd for $C_{44}H_{45}BF_4N_2P_2Pt$: C, 55.9; H, 4.8; N, 3.0. Found: C, 56.0; H, 4.7; N, 3.3. ^{31}P NMR (CD_2Cl_2): *δ* 25.6 (d, 1P, J_{pp} = 24.8 Hz, J_{PtP} = 1827 Hz, *P*^{5}), 55.7 (d, 1P, J_{pp} = 24.8 Hz, J_{PtP} = 3683 Hz, *P*^{7}). ^{1}H NMR (CD_2Cl_2): *δ* 1.30−1.43 (m, 2H, H_{2exo}, H_{3endo}), 1.62−1.78 (m, 2H, H_{3exo}, H_{2endo}), 1.86−1.94 (m, 1H, H_{6endo}), 1.96 (d, 3H, $^3J_{HH}$ = 6.3 Hz, CH*Me*), 2.42 (dd, 3H, $^4J_{PH}$ = 3.9 Hz, $^4J_{PH}$ = 1.8 Hz, N*Me*$_{eq}$), 2.49−2.54 (m, 1H, *H*$_5$), 2.57−2.69 (m, 1H, H_{6exo}), 2.78 (d, 3H, $^4J_{PH}$ = 1.4 Hz, N*Me*$_{ax}$), 3.04−3.09 (m, 1H, *H*$_4$), 3.23−3.27 (m, 1H, *H*$_1$), 4.73 (qn, 1H, $^3J_{HH} = {}^4J_{PH}$ = 6.3 Hz, C*H*Me), 6.82−8.51 (m, 26H, aromatics).

Removal of the Chiral Auxiliary. Isolation of [*SP*-4-3-{(1*R*,4*S*,5*R*,7*S*)-Dichloro[5,7-bis(diphenylphosphino)-7-azabicyclo[2.2.1]hept-2-ane-κ^2P^5,*P*^{7}]}]platinum(II) (*exo*-6a). The naphthylamine auxiliary in *exo*-**5a** was removed chemoselectively by the addition of concentrated hydrochloric acid (10 mL) to a solution of the complex (0.150 g, 0.159 mmol) in dichloromethane (30 mL). The mixture was stirred vigorously at room temperature overnight, washed with water (4 × 40 mL), and dried ($MgSO_4$). Recrystallization of the crude product from dichloromethane−diethyl ether gave colorless crystals: mp 385−386 °C dec; $[\alpha]_D$ = −3.6° (*c* 1.1, CH_2Cl_2); 0.108 g (93% yield). Anal. Calcd for $C_{30}H_{29}Cl_2NP_2Pt$: C, 49.3; H, 4.0; N, 1.9. Found: C, 49.1; H, 4.0; N, 2.1. ^{31}P NMR (CD_2Cl_2): *δ* 18.9 (d, 1P, J_{PP} = 21.0 Hz, J_{PtP} = 3727 Hz, *P*^{5}), 45.7 (d, 1P, J_{PP} = 21.0 Hz, J_{PtP} = 3521 Hz, *P*^{7}). ^{1}H NMR (CD_2Cl_2): *δ* 1.29−1.72 (m, 4H, H_{2exo}, H_{2endo}, H_{3exo}, H_{3endo}), 1.78−1.91 (m, 1H, H_{6endo}), 2.19−2.48 (m, 2H, H_{6exo}, *H*$_5$), 3.17−3.23 (m, 1H, *H*$_1$), 3.25−3.33 (m, 1H, *H*$_4$), 7.38−8.43 (m, 20H, aromatics).

[*SP*-4-3-{(1*S*,4*S*,5*R*,7*S*)-Dichloro[5,7-bis(diphenylphosphino)-7-azabicyclo[2.2.1]hept-2-ene-κ^2P^5,*P*^{7}]}]platinum-(II) (*exo*-7a). The complex *exo*-**2a** (0.419 g 0.444 mmol), dissolved in dichloromethane (30 mL), and concentrated hydrochloric acid (10 mL) were stirred vigorously at room temperature overnight. Then the mixture was washed with water (4 × 40 mL), dried ($MgSO_4$), and subsequently crystallized from dichloromethane−diethyl ether as colorless crystals: mp 273−274 °C dec; $[\alpha]_D$ = +17° (*c* 0.8, CH_2Cl_2); 0.305 g (94% yield). Anal. Calcd for $C_{30}H_{27}Cl_2NP_2Pt$: C, 49.4; H, 3.7; N, 1.9. Found: C, 49.3; H, 3.8; N, 2.2. ^{31}P NMR (CD_2Cl_2): *δ* 29.8 (d, 1P, J_{pp} = 21.0 Hz, J_{PtP} = 3738 Hz, *P*^{5}), 50.5 (d, 1P, J_{pp} = 21.0 Hz, J_{PtP} = 3525 Hz, *P*^{7}). ^{1}H NMR (CD_2Cl_2): *δ* 1.37 (dt, 1H, $^2J_{HH}$ = 12.4 Hz, $^3J_{HH} = {}^3J_{PH}$ = 8.4 Hz, H_{6endo}), 1.93−2.18 (m, 1H, *H*$_5$), 2.42 (tdd, 1H, $^2J_{HH}$ = 12.4 Hz, $^3J_{PH}$ = 20.1 Hz, $^3J_{HH} = {}^3J_{HH'}$ = 4.0 Hz, H_{6exo}), 3.52−3.57 (m, 1H, *H*$_1$), 3.63 (tdd, 1H, $^3J_{PH}$ = 7.2 Hz, $^3J_{PH} \approx {}^3J_{HH}$ = 2.4 Hz, $^4J_{HH}$ = 1.2 Hz, *H*$_4$), 6.33 (dd, 1H, $^3J_{HH}$ = 2.4 Hz, $^3J_{HH}$ = 5.6 Hz, *H*$_3$), 6.42 (ddd, 1H, $^3J_{HH}$ = 2.4 Hz, $^3J_{HH}$ = 5.6 Hz, $^4J_{PH}$ = 1.0 Hz, *H*$_2$), 7.38−8.38 (m, 20H, aromatics).

Hydrogenation of *exo*-7a. Isolation of [*SP*-4-3-{(1*R*,4*S*,5*R*,7*S*)-Dichloro[5,7-bis(diphenylphosphino)-7-azabicyclo-[2.2.1]hept-2-ane-κ^2P^5,*P*^{7}]}]platinum(II) (*exo*-6a). Hydrogen gas was bubbled slowly into a solution of *exo*-**7a** (0.276 g, 0.378 mmol) and 10% Pd/C (0.027 g) in dichloromethane (30 mL) for 2 h at room temperature under atmospheric pressure. The reaction mixture was then filtered through Celite. Recrystallization of the reaction crude product from dichloromethane−diethyl ether gave *exo*-**6a** as colorless crystals, 0.259 g (94% yield).

Similarly, the removal of the naphthylamine auxiliary and hydrogenation of *exo*-**3a** and *exo*-**3b** gave the enantiomeric complex of *exo*-**6a**.

Liberation of 5,7-Bis(diphenylphosphino)-7-azabicyclo-[2.2.1]hept-2-ane ((+)-*exo*-8) and Isolation of [*μ*-(1*R*,4*S*,5*R*,7*R*)-5,7-Bis(diphenylphosphino)-7-azabicyclo[2.2.1]hept-2-ane]bis[chlorogold(I)] ((+)-*exo*-9). A solution of *exo*-**6a** (0.215 g, 0.294 mmol) in tetrahydrofuran (40 mL) was stirred vigorously with a saturated aqueous solution of potassium

cyanide (2 g) for 3 h. The organic layer was separated, and THF was removed under reduced pressure. Diethyl ether (40 mL) was then added, and the solution was washed with water (3 × 30 mL) and dried ($MgSO_4$). After that, the solvent was removed and the crude product redissolved in THF (10 mL). The free diphosphine ligand ((+)-*exo*-**8**, ^{31}P NMR (THF-d_8) δ −8.1 (s, 1P, P^5), 39.2 (s, 1P, P^7)) was then added to a solution of chloro(dimethyl sulfide)gold(I) (0.158 g, 0.536 mmol) in dichloromethane (20 mL). The mixture was stirred at room temperature for 3 h and filtered through Celite. The dinuclear complex (+)-*exo*-**9** was subsequently crystallized from dichloromethane−diethyl ether as colorless crystals: mp 275−276 °C dec; $[\alpha]_D = +33.7°$ (*c* 2.0, CH_2Cl_2); 0.222 g (81% yield). Anal. Calcd for $C_{30}H_{29}Cl_2NP_2Au_2$: C, 38.7; H, 3.1; N, 1.5. Found: C, 39.1; H, 3.2; N, 1.6. ^{31}P NMR ($CDCl_3$): δ 38.7 (s, 1P, P^5), 66.2 (s, 1P, P^7). ^{1}H NMR ($CDCl_3$): δ 1.52−1.59 (m, 2H, H_{2exo}, H_{3endo}), 1.91−1.99 (m, 1H, H_{6endo}), 2.16−2.33 (m, 3H, H_{2endo}, H_{3exo}, H_{6exo}), 2.65−2.72 (m, 1H, H_5), 3.47−3.52 (m, 1H, H_4), 3.92−3.96 (m, 1H, H_1), 7.32−8.23 (m, 20H, aromatics).

Similarly, (−)-*exo*-**9** was synthesized from the enantiomeric complex of *exo*-**6a**.

Crystal Structure Determination of *exo*-2a, *exo*-3b, *exo*-5a, *exo*-7a, and (+)-*exo*-9. Crystal data for all five complexes and a summary of the crystallographic analyses are given in Table 4. The structures were analyzed at the National University of Singapore using a Siemens SMART CCD diffractometer with graphite-monochromated Mo Kα radiation. For all five complexes, semiempirical absorption corrections were applied. All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were introduced at fixed distances from carbon atoms and were assigned fixed thermal parameters. The absolute configurations of all chiral complexes were determined unambiguously using the Flack parameter.[29]

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Supporting Information Available: For *exo*-**2a**, *exo*-**3b**, *exo*-**5a**, *exo*-**7a**, and (+)-*exo*-**9** tables of crystal data and data collection, solution. and refinement details, final positional parameters, bond distances and angles, thermal parameters of non-hydrogen atoms, and calculated hydrogen parameters. This material is available free of charge via the Internet at http://pubs.acs.org.

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(29) Flack, H. D. *Acta Crystallogr.* **1983**, *A39*, 876.