Persistent *N*-Chirality as the Only Source of Asymmetry in Nonracemic N_2PdCl_2 Complexes

Kathryn A. Pelz, Peter S. White, and Michel R. Gagné*

Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290

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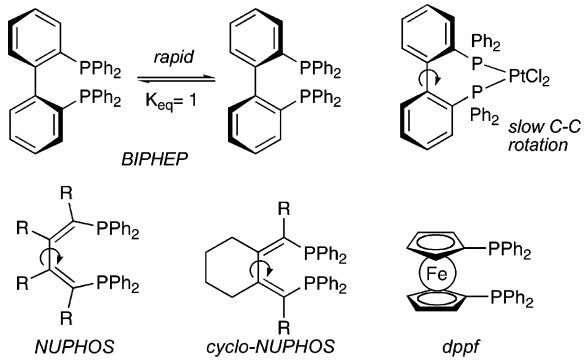
The combination of prochiral 1,2-diamines, $Pd(OAc)_2$, and (*R*)-K_2-3,3′-Me_2BINOL leads to enantio- and diastereopure N_2Pd(3,3′-Me_2BINOL) complexes. HCl removes the Me_2BINOL resolving ligand and provides a family of enantiopure N_2PdCl_2 complexes whose only stereochemistry resides on the stereogenic nitrogen centers. In effect, nitrogen inversion ($>10^5$ s^{-1}) is halted by metal coordination and utilized to generate enantiopure complexes. When the diamine substituents are relatively small, the *N*-chirality is stable; however, large substituents accelerate *N*-dissociation processes and concomitant racemization. Enantiopure N_2Pd^{2+}-Lewis acid catalysts can be generated for the Diels−Alder reaction, and although enantioselectivities are low (<25% ee), this is due to inefficient stereochemical transfer and not a degradation of the catalyst's chirality.

Introduction

The development of new approaches for achieving enantiomer selective catalysis continues to stimulate research in the area of fundamental coordination chemistry. One intriguing direction of research is the design of new catalysts for asymmetric synthesis that are composed of metal−ligand assemblies whose stereochemistries are meta-stable;[1] that is, the ligand stereochemistry is held in a specific absolute configuration solely due to metal coordination. In some of these cases, the ligands (e.g., BIPHEP, NUPHOS, cyclo-NUPHOS) were held in nonracemic states because the barrier to atropinversion was enhanced upon coordination to a substitutionally inert metal such as Pt(II).[2,3] Under other circumstances where the on-metal rotation rates were still too high to enable resolution, chiral diamines could be reliably employed to reversibly bind to the metal (Ru, Pd) and favor a single enantiomeric form of the dynamic ligand on the metal (e.g., BIPHEP, dppf).[4,5] The term *tropos* has been coined[4] for ligands whose axial chirality cannot otherwise be resolved because of rapid off-metal C−C bond rotation,[6] but can when coordinated to a metal center.[7,8]



In addition to ligands made configurationally metastable by metal coordination, we considered the possibility that ligands that rapidly inverted their configurations when off-metal might also be amenable to resolution via this strategy. In particular we wished to determine if prochiral amines could be locked into nonracemic *N*-chiral forms by metal coordination and used in asymmetric catalysis. At the onset of this work we noted that there were no known examples of asymmetric catalysis with solely *N*-chiral ligands, since the high rate of inversion (5×10^5 s^{-1}, 25 °C)[9] precludes

(1) Walsh, P. J.; Lurain, A. E.; Balsells, J. *Chem. Rev.* **2003**, *103*, 3297−3344.

(2) (a) Becker, J. J.; White, P. S.; Gagné, M. R. *J. Am. Chem. Soc.* **2001**, *123*, 9478−9479. (b) Tudor, M. D.; Becker, J. J.; White, P. S.; Gagné, M. R. *Organometallics* **2000**, *19*, 4376−4384.

(3) (a) Doherty, S.; Newman, C. R.; Rath, R. K.; van den Berg, J.-A.; Hardacre, C.; Nieuwenhuyzen, M.; Knight, J. G. *Organometallics* **2004**, *23*, 1055−1064. (b) Doherty, S.; Newman, C. R.; Rath, R. K.; Luo, H.-K.; Nieuwenhuyzen, M.; Knight, J. G. *Org. Lett.* **2003**, *5*, 3863−3866. (c) Doherty, S.; Robins, E. G.; Nieuwenhuyzen, M.; Knight, J. G.; Champkin, P. A.; Clegg, W. *Organometallics* **2002**, *21*, 1383−1399.

(4) (a) Mikami, K.; Aikawa, K.; Yusa, Y.; Hatano, M. *Org. Lett.* **2002**, *4*, 91−94. (b) Mikami, K.; Aikawa, K.; Yusa, Y. *Org. Lett.* **2002**, *4*, 95−97. (c) Mikami, K.; Aikawa, K. *Org. Lett.* **2002**, *4*, 99−101. (d) Mikami, K.; Aikawa, K.; Korenaga, T. *Org. Lett.* **2001**, *3*, 243−245.

(5) These experiments are a subset of a broader program on asymmetric activation of achiral or racemic catalysts, see: (a) Mikami, K.; Terada, M.; Korenaga, T.; Matsumoto, Y.; Matsukawa, S. *Acc. Chem. Res.* **2000**, *33*, 391−401. (b) Mikami, K.; Terada, M.; Korenaga, T.; Matsumoto, Y.; Ueki, M.; Angelaud, R. *Angew. Chem., Int. Ed.* **2000**, *112*, 3532−3556.

(6) For related references see: (a) Tissot, O.; Gouygou, M.; Dallemer, F.; Daran, J.-C.; Balavoine, G. G. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 1076−1078. (b) Ringwald, M.; Stürmer, R.; Brintzinger, H. H. *J. Am. Chem. Soc.* **1999**, *121*, 1524−1527.

(7) A conceptually fascinating set of biaryl phosphines has recently been disclosed wherein the phosphines are *atropos*, but achiral until coordinated to a metal. (a) Aikawa, K.; Mikami, K. *Angew. Chem., Int. Ed.* **2003**, *42*, 5458−5461. (b) Aikawa, K.; Mikami, K. *Angew. Chem., Int. Ed.* **2003**, *42*, 5455−5458.

(8) Examples of selective coordination of diamines with an axis of chirality are also known; see for example: (a) Ashby, M. T.; Alguindigue, S. S.; Schwane, J. D.; Daniel, T. A. *Inorg. Chem.* **2001**, *40*, 6645−6650. (b) Alguindigue, S. S.; Khan, M. A.; Ashby, M. T. *Organometallics* **1999**, *18*, 5112−5119.

(9) Saunders, M.; Yamada, F. *J. Am. Chem. Soc.* **1963**, *85*, 1882.

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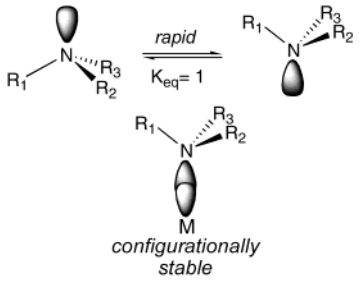
free-base resolution. This contrasts the many successful *P*-chiral ligands that have been reported since the higher barrier to *P*-inversion allows *P*-enantiomers to be resolved under ambient conditions.[10,11]

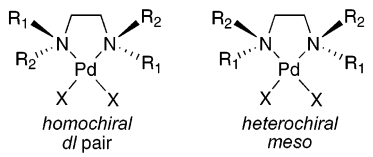


Numerous examples exist of chiral diamine ligands wherein the chirality in the backbone of a 1,2-diamine favors the coordination of a single *N*-epimer.[1,12] These ligands can be exquisitely selective, at least partly due to the close proximity of the *N*-stereocenter to the reactive metal.[13] Interligand interactions between chiral ligands and achiral or meso ligands (amines) have also been utilized to magnify asymmetric induction in chiral catalysts.[1,14] In contrast to both intra- and interligand control of *N*-chirality, cases where the *N*-chirality is the only source of stereochemistry have not been explored. This situation could be problematic since the experimental challenges include solving the issue of resolving the stereogenic N atoms with also preventing *N*-dissociation (and subsequent fast *N*-inversion).

In this paper we report that enantiopure *N*-chiral N_2PdCl_2 complexes can be synthesized and that the *N*-chirality can be stable enough to survive activation and use in catalysis. The focus of this paper is the development of a method for on-metal dynamic resolution[15] of the *N*-chirality, determining conditions necessary for maintaining it, and the use of *N*-chiral compounds in catalysis.

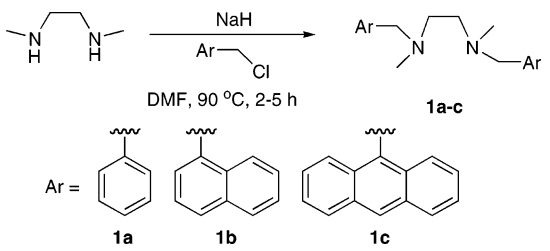
Results and Discussion

Diamine Ligand Design and Synthesis. On the basis of the utility and general availability of N_2PdX_2 complexes wherein N_2 is a chelating dinitrogen ligand, we chose to first examine 1,2-diamines made prochiral by virtue of two different nitrogen substituents. Homochiral coordination of the two amines would lead to a *dl* ligand array (*R*,*R* and *S*,*S*), while the heterochiral coordination mode would lead to the *meso* ligand arrangement (*R*,*S*).

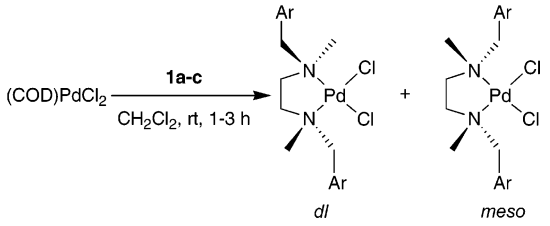


The prochiral 1,2-diamine ligands used in this study were synthesized by a double *N*-alkylation of *N*,*N*′-dimethylethylenediamine (Scheme 1). While a number of protocols were found to be either sluggish or prone to overalkylation, the reaction of a variety of benzyl chlorides with NaH in DMF (100 °C) led to reproducibly high yields of the desired dialkylated ligands. Scheme 1 shows the synthesis of diamine ligands where increasing bulk around the nitrogen was achieved by changing the third *N*-substituent from benzyl to 1-naphthyl methyl and 9-anthracenyl methyl. ^{1}H NMR spectra of the crude diamines showed clean, complete conversion to the desired product with no apparent mono- or overbenzylated product.

Scheme 1



Scheme 2



2a-c

	dl:*meso*	% Yield
2a	2:1	95%
2b	2:1	93%
2c	3:1	96%

Synthesis of N_2PdX_2 Complexes. To provide an initial test for the coordinating ability of the new prochiral diamines, the ligands **1a**−**c** were stirred with $(COD)PdCl_2$ in dichloromethane (Scheme 2). The family of N_2PdCl_2 complexes **2a**−**c** was isolated, each as a bright orange powder, by precipitating with hexanes. ^{1}H NMR analysis of **2a** indicated a 2:1 mixture of isomers, the diastereotopic resonances of the benzylic protons between 3 and 5 ppm being particularly diagnostic. The major product was obtained in pure form by fractional crystallization and confirmed to be the *dl* isomer by single-crystal X-ray diffraction (Figure 1).[16] Comparison of the ^{1}H NMR spectrum of the crystals to that of the mixture enabled the benzyl CH's for *dl*-**2a** to be assigned to the pair of doublets at δ 3.15 and 4.71 ppm (J = 12.8 Hz) and *meso*-**2a** to the doublets at δ 3.62 and 4.11 ppm (J = 13.2 Hz). Compounds **2b** and **2c** were obtained in similar *dl*:*meso* ratios of 2:1 and 3:1,

(10) Eliel, E. L.; Wilen, S. H.; Mander, L. N. *Stereochemistry of Organic Compounds*; John Wiley & Sons: New York, 1994.

(11) Pietrusiewicz, K. M.; Zablocka, M. *Chem. Rev.* **1994**, *94*, 1375−1411.

(12) For a recent report utilizing 1,2-diamines with a chiral backbone that are prochiral at nitrogen, see: Kobayashi, S.; Matsubara, R.; Nakamura, Y.; Kitagawa, H.; Sugiura, M. *J. Am. Chem. Soc.* **2003**, *125*, 2507−2515.

(13) A typical Pd−NR_3 bond length (∼2.08 Å) is significantly shorter than a typical Pd−PR_3 bond (∼2.27 Å).

(14) Costa, A. M.; Jimeno, C.; Gavenonis, J.; Carroll, P. J.; Walsh, P. J. *J. Am. Chem. Soc.* **2002**, *124*, 6929−6941. For a review of additive effects in asymmetric catalysis, see footnote and: Vogl, E. M.; Gröger, H.; Shibasaki, M. *Angew. Chem., Int. Ed.* **1999**, *38*, 1571−1577.

(15) Pellisier, H. *Tetrahedron* **2003**, *59*, 8291−8327.

(16) The orientation of the *N*-substituents is remarkably similar to those in the monoprotonated form of *N*,*N*′-Me_2-*N*,*N*′-dibenzyl proton sponge; see: Charmant, J. P. H.; Lloyd-Jones, G. C.; Peakman, T. M.; Woodward, R. L. *Tetrahedron Lett.* **1998**, *39*, 4733−4736.

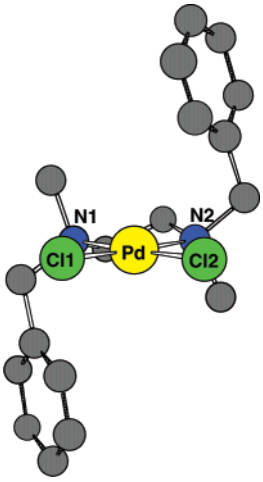


Figure 1. X-ray structure representation of one independent molecule ($Z' = 2$) in the structure of *dl*-**2a**. Bond distances (Å) and angles (deg) are averaged. Pd−N = 2.075(3), Pd−Cl = 2.3018(9), N−Pd−N = 85.2(1), and Cl−Pd−Cl = 90.8(1).

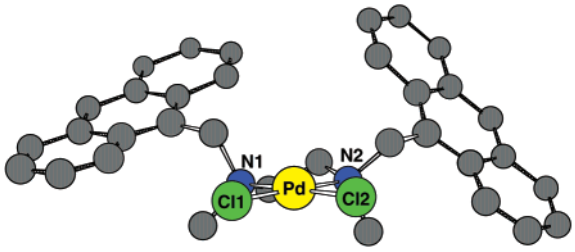


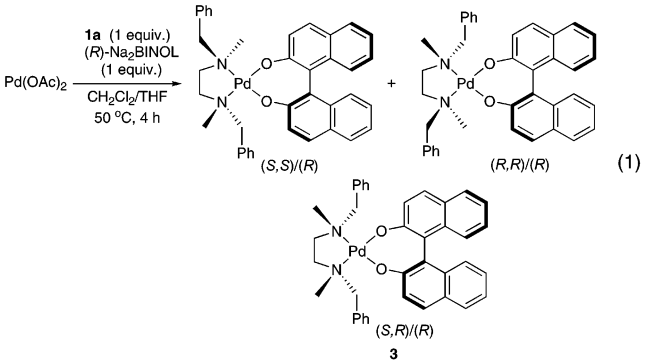
Figure 2. X-ray structure representation of one independent molecule ($Z' = 2$) in the refined structure of *meso*-**2c**. Bond distances (Å) and angles (deg) for this molecule include N1−Pd1 = 2.083(5), N2−Pd 2.088(5), Cl1−Pd = 2.3085(15), Cl2−Pd 2.3207(16), N1−Pd−N2 = 85.8(2), and Cl1−Pd−Cl2 = 89.80(6).

respectively (Scheme 2). The major diastereomer, which was obtained by a selective precipitation procedure, was also shown to be *dl* in both cases (vide infra).

In the case of **2c**, the minor diastereomer turned out to be the more crystalline isomer and provided crystals suitable for X-ray analysis (Figure 2). As Figures 1 and 2 show, coordination of the 1,2-diamine provides a distinctive skew conformation to the backbone, a result of the *N*-substituents adopting pseudoaxial and -equatorial orientations. In *dl*-**2a**, the sterically subordinate methyl groups position in the axial sites and the molecule has C_2-symmetry, whereas in *meso*-**2c** one anthracenyl methyl occupies an axial position and the other an equatorial position.

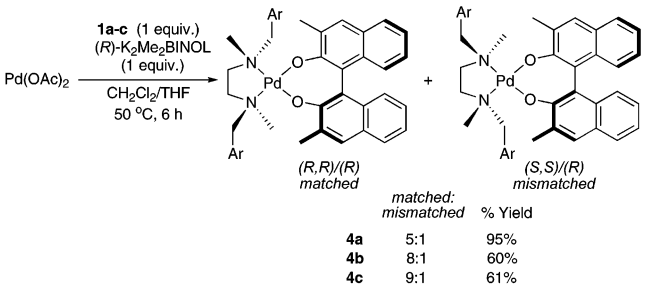
Following the procedures developed for the on-metal resolution of Biphep,[2] NUPHOS,[3] and cyclo-NUPHOS,[3] we envisioned synthesizing N_2Pd(BINOL) complexes wherein BINOL stereochemistry could dynamically resolve[15] the *N*-stereochemistry. BINOL removal would then lead to new complexes whose stereochemistry was solely located at the stereogenic nitrogen centers. Suggesting the feasibility of this approach is Walsh's X-ray crystal structure of (3,3′-Ph_2BINOL)Zn(^{t}BuNHCH_2-NH^{t}Bu), which clearly shows how the BINOL ligand effectively resolves the 1,2-diamine in a tetrahedral environment.[14]

Synthesis of the desired N_2Pd(BINOL) complexes followed directly from a one-pot procedure developed by van Koten for $N_2Pd(OAr)_2$ compounds.[17] Stirring Pd(OAc)$_2$ with diamine **1a** and 1 equiv of (*R*)-Na_2BINOL provided air and moisture stable **3** as an inseparable 1:4:3 mixture of three diastereomers, two symmetric (*S*,*S*/*R* and *R*,*R*/*R*) and one asymmetric (*S*,*R*/*R*) (eq 1); that is, the chiral BINOL ligand failed to significantly influence the diamine configuration. Previous studies have shown that methyl substituents at the 3- and 3′-positions of BINOL more strongly interact with ligands coordinating across the square plane.[4a,18] Synthesis of N_2Pd(*R*)-(Me_2BINOL) complexes **4a**−**c** supported this notion, as the products were obtained with significantly improved diastereoselectivities (Scheme 3).



(1)

Scheme 3



	matched:mismatched	% Yield
4a	5:1	95%
4b	8:1	60%
4c	9:1	61%

In the case of **4a**, two diastereomers were obtained in a 5:1 ratio and ^{1}H NMR analysis revealed that both were symmetric, i.e., (*R*,*R*)/(*R*) and (*S*,*S*)/(*R*).[19,20] Representative of the complex's symmetry, the benzylic CH's of the major diastereomer appeared as a pair of doublets at δ 2.73 and 4.26 ppm (J = 12.4 Hz), as did the diamine backbone CH's (δ 1.58 and 2.94 ppm; J = 8.8 Hz). Singlets were observed for the Me_2BINOL (2.46 ppm) and ligand (2.26 ppm) methyl groups. The minor *dl*-diastereomer revealed a similar though slightly broadened pattern in the ^{1}H NMR spectrum. The asymmetric (*R*,*S*)/(*R*) diastereomer was not observed.

The major diastereomer of the **4a** mixture was obtained in pure form by recrystallization (CH_2Cl_2/hexanes). As shown in Figure 3, single crystals of the major diastereomer (confirmed by ^{1}H NMR) were obtained and X-ray analysis revealed it to be the *dl*-(*R*,*R*)/

(17) Kapteijn, G. M.; Grove, D. M.; Kooijman, H.; Smeets, W. J. J.; Spek, A. L.; van Koten, G. *Inorg. Chem.* **1996**, *35*, 526−533.

(18) (a) Becker, J. J.; White, P. S.; Gagné, M. R. *Organometallics* **2003**, *22*, 3245−3249. (b) Brunkan, N. M.; White, P. S.; Gagné, M. R. *J. Am. Chem. Soc.* **1998**, *120*, 11002−11003.

(19) Although conversion to product does not require the elevated temperature, it enhances the rate of isomer equilibration and the product diastereomeric ratio.

(20) The bracketed pair of stereochemical labels represents the *N*-stereocenters, while the third refers to the BINOL's axial chirality.

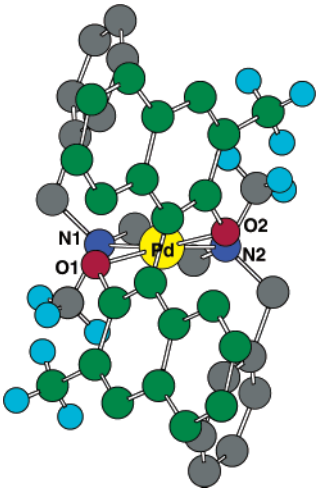
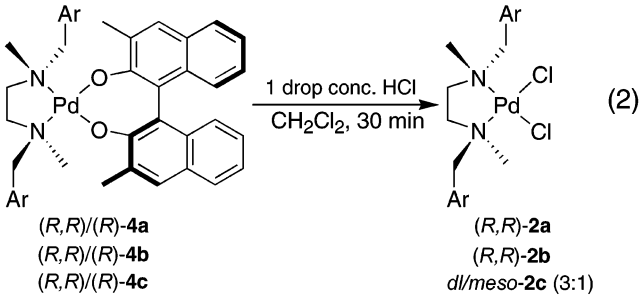


Figure 3. Structural representation of the refined X-ray structure of (*R*,*R*)/(*R*)-**4a**. Relevant bond distances (Å) and angles (deg) include Pd−N1 = 2.060(5), Pd−N2 = 2.062(5), Pd−O1 = 2.034(4), Pd−O2 = 2.028(4), N1−Pd−N2 = 85.91(24), and O1−Pd−O2 = 94.97(14).

(*R*) stereoisomer. This isomer projects the BINOL 3,3′-methyl substituents into the sterically less crowded quadrants occupied by the *N*-methyl groups,[2−4,18,21] which additionally causes a counterclockwise rotation of 15° for the O−Pd−O plane relative to the N−Pd−N plane.[22] The minor *trans* diastereomer must therefore project the BINOL 3,3′-methyl groups into the more crowded *N*-benzyl-containing quadrants of space. On the basis of this crystallographic analysis, the major and minor *trans* diastereomers will be referred to as being stereochemically "matched" and "mismatched", respectively.

Repeating the **4a** synthesis procedure with ligands **1b** and **1c** led to similarly stable complexes but with higher levels of diastereoselectivity, presumably reflecting the larger size of the naphthyl and anthracenyl substituents (Scheme 3). Again, C_2 symmetry was apparent in the ^{1}H NMR spectra for both compounds. The major diastereomers of **4b** and **4c** were purified by passing the crude mixture through a plug of silica gel (9:1 EtOAc/hexanes) and precipitating from CH_2Cl_2/hexanes, although this method resulted in reduced yields (~60%).

Revealing the *N*-Chirality. To assess the stability of the *N*-stereocenters in the absence of a chiral controlling group, the Me_2BINOL ligands of the dark red (*R*,*R*)/(*R*)-**4a**, (*R*,*R*)/(*R*)-**4b**, and (*R*,*R*)/(*R*)-**4c** were removed (HCl) (eq 2). The bright yellow dichloride complexes were precipitated away from cleaved Me_2BINOL by the addition of hexanes, isolated, and analyzed for retention of stereochemistry at the nitrogen centers. ^{1}H NMR analysis of the crude products from **4a** and **4b** showed no *meso* product, consistent with a BINOL cleavage that does not randomly epimerize the nitrogen stereocenter. On the other hand, the ^{1}H NMR spectrum of the **4c** cleavage product showed a mixture of *dl* and *meso* dichlorides, *dl*/*meso*-**2c**. The presence of the *meso* isomer is clearly indicative of at least partial epimerization and/or racemization during the Me_2BINOL/Cl^- exchange.



Optical rotation measurements on (*R*,*R*)-**2a** and (*R*,*R*)-**2b** provided specific rotations ($[\alpha]_D$) of +195° and +89°, respectively,[23] whereas $[\alpha]_D$ for *dl*/*meso*-**2c** was significantly lower (+8°). The large nonzero value for (*R*,*R*)-**2a** and (*R*,*R*)-**2b** suggested, along with the lack of *meso*-**2a** and *meso*-**2b** in the ^{1}H NMR, that one enantiomer was predominant. The observation of significant optical activity clearly showed that the *dl* dichlorides **2a** and **2b** were highly enantioenriched.

Although the optical rotation measurements clearly indicated an excess of one enantiomer, a quantitative measurement of the enantiomer ratio (er) was desired. To measure the er we drew from the fact that all three diastereomers of **3** and two diastereomers of **4a**−**c** were observable in the ^{1}H NMR. Thus, converting an N_2PdCl_2 set of enantiomers into an N_2Pd(*R*)-BINOL set of diastereomers would indirectly provide the er of the N_2PdCl_2 compound, provided that no *N*-isomerization occurred during the reaction. In a typical experiment, a solution of NaO^{t}Bu and BINOL or KO^{t}Bu and 6,6′-Br_2BINOL[24] in THF was added to a solution of the **2a**−**c** cleavage product in CH_2Cl_2 and stirred for 4 h (eq 3). The mixture was then filtered through Celite, the solvent removed, and the crude product directly analyzed by ^{1}H NMR. The results of these experiments for the different BINOL and N_2 ligands are collected in Table 1. Addition of (*R*)-Na_2BINOL to *dl*-**2a** (entry 1) provided a 1:1 mixture of matched and mismatched BINOL diastereomers, confirming that no *N*-epimerization occurred.[25] Addition of (*R*)- and (*S*)-Na_2BINOL to (*R*,*R*)-**2a** (entries 2 and 3) resulted in the matched and mismatched diastereomers of **3**, respectively (Figure 4). Since (*R*,*R*)-**2a** and (*R*)-Na_2BINOL regenerated the matched diastereomer (previously shown to be (*R*,*R*)/(*R*) for **1a**-Pd(Me_2BINOL)), this further indicates that the protonolysis of the Me_2BINOL ligand goes with retention of nitrogen stereochemistry. Similarly, rebinding (*R*,*R*)-**2b** with (*R*)- and (*S*)-K_2Br_2BINOL resulted in clean conversion to the matched and mismatched diastereomers, respectively (entries 4−6). Obtaining diastereomerically pure products showed that (*R*,*R*)-**2a** and (*R*,*R*)-**2b** are enantiomerically pure (>95:5) and that *N*-chirality is indeed viable.

(21) (a) Koh, J. H.; Larsen, A. O.; White, P. S.; Gagné, M. R. *Organometallics* **2002**, *21*, 7−9. (b) Brunkan, N. M.; White, P. S.; Gagné, M. R. *Angew. Chem., Int. Ed.* **1998**, *37*, 1579−1582. (c) Brunkan, N. M.; White, P. S.; Gagné, M. R. *J. Am. Chem. Soc.* **1998**, *120*, 11002−11003.

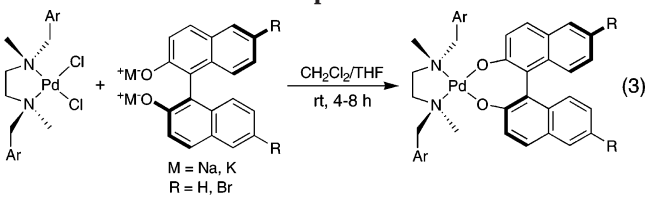
(22) This is in contrast to the nearly perfect square plane of the N_2PdCl_2 complexes.

(23) Optical rotation measurements were taken in dichloromethane. Analysis of the authentic *dl* mixtures confirmed that $[\alpha]_D$ was 0.

(24) 6,6′-Br_2BINOL complexes are more soluble than BINOL complexes.

(25) A similar experiment with (*R*)-3,3′-Me_2BINOL caused the mismatched diastereomer to isomerize to the matched, a result of steric interactions with the 3,3′ substituents.

Table 1. Assaying the er of N_2PdCl_2 Complexes by Conversion to Diastereomeric N_2Pd(BINOL) Complexes



entry	N_2PdCl_2 source	BINOL source[a]	result[b]
1	*dl*-**2a**	(*R*)-BINOL	(*R*,*R*)/(*R*)-**3**:(*S*,*S*)/(*R*)-**3** (1:1)
2	(*R*,*R*)-**2a**	(*R*)-BINOL	(*R*,*R*)/(*R*)-**3**
3	(*R*,*R*)-**2a**	(*S*)-BINOL	(*R*,*R*)/(*S*)-**3**
4	*dl*-**2b**[c]	(*R*)-6,6′-Br_2BINOL	(*R*,*R*)/(*R*):(*S*,*S*)/(*R*) (1:1)
5	(*R*,*R*)-**2b**	(*R*)-6,6′-Br_2BINOL	(*R*,*R*)/(*R*)
6	(*R*,*R*)-**2b**	(*S*)-6,6′-Br_2BINOL	(*R*,*R*)/(*S*)
7	*dl*-**2c**[d]	(*R*)-6,6′-Br_2BINOL	(*R*,*R*)/(*R*):(*S*,*S*)/(*R*) (∼1:1)
8	*dl*-**2c**	(*S*)-6,6′-Br_2BINOL	(*R*,*R*)/(*S*):(*S*,*S*)/(*S*) (∼1:1)

[a] The BINOL or Br_2BINOL was treated with NaO^{t}Bu or KO^{t}Bu, respectively, and transferred via cannula to the N_2PdCl_2 source (see text and Experimental Section). [b] The dr was obtained by ^{1}H NMR analysis of the crude reaction mixture. The NCH_2Ar resonances were diagnostic. [c] Obtained from the reaction in Scheme 2. [d] The **2c** obtained from eq 2 was a mixture of *dl* diastereomers.

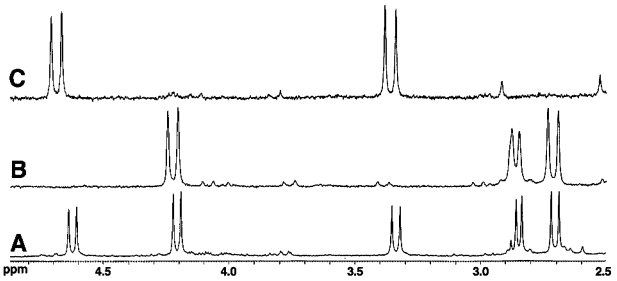


Figure 4. Crude ^{1}H NMR spectra of the reaction products of (A) *dl*-**2a** and (*R*)-Na_2BINOL to form the matched and mismatched diastereomers; (B) (*R*,*R*)-**2a** and (*R*)-Na_2-BINOL to form the matched diastereomer (*R*,*R*)/(*R*)-**3**; and (C) (*R*,*R*)-**2a** with (*S*)-Na_2BINOL to form the mismatched diastereomer (*R*,*R*)/(*S*)-**3**.

In contrast, the complexes synthesized using ligand **1c** were found to be insufficient at maintaining *N*-chirality. This was first suggested by the appearance of the *meso* diastereomer in eq 2 and further confirmed in entries 7 and 8, wherein rebinding of a single Br_2-BINOL enantiomer resulted in a mixture of diastereomers. In summary, enantiopure N_2PdCl_2 complexes could be prepared and isolated with ligands **1a** and **1b**, but the larger size of the anthracenyl groups in **1c** caused an instability that led to *N*-epimerization and eventual racemization.

Asymmetric Catalysis with *N*-Chiral Ligands. Once the retention of stereochemistry was confirmed, the compounds were tested as catalysts in the benchmark Diels−Alder reaction between cyclopentadiene (CpH) and *N*-acryloyl oxazolidinone (eq 4).[2,26] Two protocols were investigated for generating N_2Pd^{2+} catalysts. The first involved directly treating the diastereopure complexes **4a**−**c** with a slight deficiency of triflic acid (∼1.9 equiv), to provide a reactive $N_2Pd(OTf)_2$ Lewis acid and free Me_2BINOL. The second method took the

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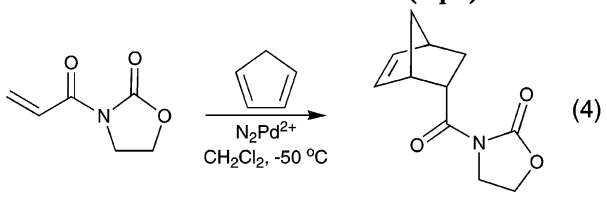
Table 2. Application of *N*-Chiral Catalysts to the Diels−Alder Reaction (eq 4)



entry	catalyst[a]	activation temp[b]	% conversion (h)[c]	*endo*:*exo*	*endo* % ee[d]
1	**1a**-Pd$(OTf)_2^{2+}$	rt	98 (5)	97:3	21
2	**1a**-Pd$(OTf)_2^{2+}$	−78	80 (20)	96:4	23
3	**1b**-Pd$(OTf)_2^{2+}$	rt	100 (4)	95:5	17
4	**1b**-Pd$(OTf)_2^{2+}$	−78	100 (22)	93:7	20
5	**1c**-Pd$(OTf)_2^{2+}$	rt	87 (6)	77:23	9
6	**1c**-Pd$(OTf)_2^{2+}$	−78	100 (12)	93:7	25
7	(*R*,*R*)-**2a**/$AgSbF_6$	rt	96 (6)	96:4	18
8	(*R*,*R*)-**2a**/$AgSbF_6$	−78	98 (6)	95:5	17
9	(*R*,*R*)-**2b**/$AgSbF_6$	rt	75 (6)	95:5	9
10	*dl*/*meso*-**2c**/$AgSbF_6$	rt	95 (6)	90:10	15

[a] The ditriflate catalysts were obtained by first treating the N_2Pd(3,3′-Me_2BINOL) complex with HOTf (1.9 equiv) at the indicated temperature and then cooling to −50 °C to carry out the reaction. [b] Activation was carried out for 15 min prior to preequilibrating at −50 °C and adding CpH. [c] Conversion was monitored by passing an aliquot through a plug of silica gel, eluting with EtOAc to remove the catalyst, then assaying by HPLC. [d] Chiracel OD-H.

isolated dichloride ((*R*,*R*)-**2a**, (*R*,*R*)-**2b**, and *dl*/*meso*-**2c**) and generated the dication by halide abstraction with $AgSbF_6$. As shown in Table 2, the catalysts were successful and provided the product after several hours at −50 °C.

General observations include typically high *endo*:*exo* ratios, the exception being **1c**-Pd$(OTf)_2^{2+}$ (entry 5), and higher reactivities for the catalysts activated with $AgSbF_6$. Regarding enantiomeric excess, however, catalysts typically performed poorly, with the highest selectivities reaching into the mid-20s.

In the case of the ditriflate catalysts we considered the possibility that HOTf protonolysis of Me_2BINOL at ambient temperature might lead to in situ racemization prior to the addition of substrate; therefore a series of low-temperature (−78 °C) activations were carried out. In the case of **1a**-Pd$(OTf)_2$ and **1b**-Pd$(OTf)_2$, the product selectivities were nearly identical, suggesting that generation of the ditriflate is stereospecific regardless of activation temperature. The increase in selectivity between low and ambient HOTf activation in the most labile **1c**-Pd$(OTf)_2$ catalysts suggests that the ambient conditions used to remove Me_2BINOL causes partial racemization of the catalyst.

To determine if the *N*-chirality was maintained during catalysis, a series of chloride quenches were examined, with the expectation that diastereopure N_2PdCl_2 complexes would be obtained if the *N*-chirality survived activation and turnover. Addition of brine to the HOTf-activated catalysts inexplicably produced no N_2PdCl_2; however, addition of brine to solutions containing the catalyst activated with $AgSbF_6$ generated N_2PdCl_2 complexes, which were isolated for ^{1}H NMR analysis. In the case of (*R*,*R*)-**2a**/$AgSbF_6$ and (*R*,*R*)-**2b**/$AgSbF_6$ **2a** and **2b** were recovered free of the *meso* isomer, suggesting that *N*-epimerization had not occurred. The obvious conclusion of these experiments is that the low

enantioselectivities reflect a poor stereochemical transfer of information during turnover, and not compromised catalyst.

Summary

To the broader question of whether *N*-chirality is viable and usable, the results described herein clearly indicate that asymmetric catalysis can be performed with enantiopure catalysts whose chirality resides solely on stereogenic nitrogen centers, although stereochemical induction in the present case is inefficient (<25% ee). The chirality of the catalyst has been shown to be robust enough to confidently assess the overall feasibility of exclusive *N*-chirality, and since some ligand systems (with chiral backbones) have successfully utilized this feature in asymmetric catalysis,[1,12] we suggest that other transformations will be better suited to these catalysts.

On the other hand, these studies also revealed a weakness in the strategy of relying exclusively on *N*-chirality. First and foremost were issues related to inversion of stereochemistry. Two unambiguous experiments attested to the sensitivity of nitrogen coordination to excessive steric hindrance: (1) the rapid isomerization of diastereopure N_2PdCl_2 complexes containing bulky *N*-anthracenyl substituents and (2) the conversion of *dl*-**2a** to the matched diastereomer (exclusively) on (*R*)-Me_2BINOL coordination.[25] That is, bulky metal centers enhance the propensity for dissociation of the amine ligand via either pure dissociation or associative Pd−N bond breakage and lead to racemization of the *N*-chirality. Since associative ligand substitution is normally the operative mechanism in square planar d^8 metals,[27] the stability of the *N*-chirality is clearly in the hands of a complex combination of steric and electronic factors.

In summary, enantio- and diastereopure $N_2Pd(Me_2$-BINOL) complexes can be synthesized using prochiral diamine ligands. In the cases of **4a** and **4b**, cleavage of the chiral resolving agent resulted in the corresponding enantiopure N_2PdCl_2 complexes, wherein the *N*-stereochemistry had been retained. Compound **4c** was found to be significantly less stable as *N*-racemization occurred upon removal of the chiral resolving agent. Use of diastereo- and enantiopure catalysts in a benchmark Diels−Alder reaction resulted in high *endo*:*exo* selectivity and moderate reactivity, but low ee's. Quenching studies showed no racemization was occurring during catalysis and that these low inductions reflected poor stereochemical transfer of information rather than unachievable *N*-chirality.

Experimental Section

General Methods. Manipulations of all air/water sensitive compounds were performed under an N_2 atmosphere using standard Schlenk techniques or in an MBraun Labmaster drybox. NMR spectra were obtained on a Bruker AMX 400 or AMX 300 spectrometer using deuterated solvents (CD_2Cl_2, $CDCl_3$) purchased from Cambridge Isotope Labs. ^{1}H spectra were referenced to residual solvent resonances. Optical rotation measurements were obtained on a Jasco DIP-1000 digital polarimeter in CH_2Cl_2, where a concentration of 1.0 corresponds to 100 mg/10 mL. Elemental analyses were performed by Complete Analysis Laboratories, Inc. THF and CH_2Cl_2 were dried by passage through a column of activated alumina before use. DMF was dried over $CaSO_4$, distilled, and stored in the drybox. $Pd(OAc)_2$ was purchased from Strem and stored in the drybox. (*R*)- and (*S*)-BINOL were purchased from Kankyo Kagaku Center Co., Ltd., Japan, and used as received. (*R*)- and (*S*)-3,3′-Me_2BINOL and (*R*)- and (*S*)-6,6′-Br_2BINOL were synthesized according to literature procedures.[28,29] KO^{t}Bu was purchased from Aldrich, purified by sublimation at 100 °C, and stored in a drybox. All other chemicals were purchased from Aldrich or Acros and used with no further purification.

***N,N′*-Dibenzyl-*N,N′*-dimethylethylenediamine (1a).** *N*,*N*′-Dimethylethylenediamine (2.00 mL, 18.8 mmol) was added to a suspension of NaH (1.35 g, 56.2 mmol) in dry DMF (75 mL). The flask was vented, and benzyl chloride (4.75 mL, 40.8 mmol) was added to the reaction mixture. The reaction mixture was heated at 100 °C for 4 h, after which the cooled mixture was filtered through a pad of Celite. Solvent was removed in vacuo with gentle heating to yield a viscous yellow product. The product was dissolved in CH_2Cl_2 and washed twice with water and once with brine. The aqueous layer was back-extracted with CH_2Cl_2, and the combined organic layers were stirred over $MgSO_4$. Filtering and removal of the solvent under vacuum gave pure product in 90% yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 2.19 (s, 6H, CH_3), 2.54 (s, 4H, NCH_2CH_2N), 3.49 (s, 4H, NCH_2Ph), 7.21−7.28 (m, 10H, Ar*H*). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ 43.1, 55.6, 63.1, 127.3, 128.6, 129.5, 139.4. This material was spectroscopically identical to a commercial sample purchased from Lancaster. Unfortunately, **1a** ceased to be available midway through our studies.

***N,N′*-Dimethyl-*N,N′*-bis(naphthalen-1-ylmethyl)ethane-1,2-diamine (1b).** Compound **1b** was prepared by a procedure analogous to **1a** to yield an off-white solid. The crude product was recrystallized from CH_2Cl_2/hexanes to give off-white crystals in 85% yield, mp 99−102 °C. Anal. Calcd for $C_{26}H_{28}N_2$: C, 84.74; H, 7.66; N, 7.60. Found: C, 84.06; H, 8.10; N, 6.97. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 2.21 (s, 6H, CH_3), 2.72 (s, 4H, NCH_2CH_2N), 3.89 (s, 4H, NCH_2Ph), 7.33−7.43 (m, 8H, Ar*H*), 7.73 (m, 2H, Ar*H*), 7.81 (m, 2H, Ar*H*), 8.25 (m, 2H, Ar*H*). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ 43.1, 56.1, 61.1, 125.0, 125.5, 125.9, 126.2, 127.9, 128.3, 128.8, 132.8, 134.2.

***N,N′*-Bis(anthracen-1-ylmethyl-*N,N′*-dimethyl)ethane-1,2-diamine (1c).** Compound **1c** was prepared by a procedure similar to **1a** to yield a bright yellow solid. The crude product was recrystallized from CH_2Cl_2/hexanes to give thin needlelike crystals in 70% yield, mp 190−193 °C. Anal. Calcd for $C_{34}H_{32}N_2$: C, 87.14; H, 6.88; N, 5.98. Found: C, 87.03; H, 7.06; N, 5.89. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 2.19 (s, 6H, CH_3), 2.87 (s, 4H, NCH_2CH_2N), 4.40 (s, 4H, NCH_2Ph), 7.40 (m, 8H, Ar*H*), 7.95 (m, 4H, Ar*H*), 8.37 (s, 2H, Ar*H*), 8.41 (m, 4H, Ar*H*). ^{13}C-{^{1}H} NMR ($CDCl_3$, 100 MHz): δ 42.8, 54.4, 56.5, 125.2, 125.5, 126.0, 127.8, 129.3, 131.7, 131.8.

***dl*-2a.** *N*,*N*′-Dibenzyl-*N*,*N*′dimethylethylenediamine (590 μL, 1.76 mmol) was added to a solution of (COD)$PdCl_2$ (500 mg, 1.75 mmol) in CH_2Cl_2, and the mixture was stirred for 1 h. The solution was concentrated to ~5 mL, and the product was precipitated from solution with hexanes. The sticky solid was isolated on a frit and washed with hexanes to remove excess COD to give the *dl*:*meso* mix (2:1) of N_2PdCl_2 in 95% yield. Recrystallization of the crude mixture from CH_2Cl_2/hexanes provided pure *dl* material. Anal. Calcd for $C_{18}H_{24}Cl_2N_2Pd$: C, 48.50; H, 5.43; N, 6.28. Found: C, 48.32; H, 5.47; N, 6.29. ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 1.81 (d, J = 9.2 Hz, 2H, NCH*H*CH*H*N), 2.48 (s, 6H, CH_3), 2.93 (d, J = 9.6 Hz, 2H, NC*H*HC*H*HN), 3.15 (d, J = 12.8 Hz, 2H, NC*H*HPh), 4.71 (d,

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J = 12.8 Hz, 2H, NCH*H*Ph), 7.45−7.52 (m, 6H, Ar*H*), 8.04 (m, 4H, Ar*H*). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 100 MHz): δ 49.3, 57.7, 66.5, 129.2, 129.7, 132.6, 133.0.

***dl*-2b.** This compound was prepared by the same procedure described for *dl*-**2a**. A mixture of the product (*dl:meso*, 2:1) was synthesized in 93% yield, which was selectively precipitated to the (±)-*trans* product in 55% yield. Anal. Calcd for $C_{26}H_{28}Cl_2N_2Pd$: C, 57.21; H, 5.71; N, 5.13. Found: C, 56.96; H, 5.49; N, 5.22. ^1H NMR (CD_2Cl_2, 400 MHz): δ 1.81 (d, J = 9.2 Hz, 2H, NCH*H*CH*H*N), 2.48 (s, 6H, CH_3), 2.93 (d, J = 9.6 Hz, 2H, NC*H*HC*H*HN), 3.15 (d, J = 12.8 Hz, 2H, NC*H*HPh), 4.71 (d, J = 12.8 Hz, 2H, NCH*H*Ph), 7.45−7.52 (m, 6H, Ar*H*), 8.04 (m, 4H, Ar*H*). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 100 MHz): δ 49.3, 57.7, 66.5, 129.2, 129.7, 132.6, 133.0.

***dl*-2c.** This compound was prepared by the same procedure described for *dl*-**2a**. A mixture of the product (*trans:cis*, 3:1) was synthesized in 91% yield, which was selectively precipitated to the *dl* product in 60% yield. Anal. Calcd for $C_{34}H_{32}Cl_2N_2Pd$: C, 63.22; H, 4.99; N 4.34. Found: C, 62.87; H, 5.05; N, 4.24. ^1H NMR (CD_2Cl_2, 300 MHz): δ 0.75 (br d, J = 10.2, 2H, NCH*H*CH*H*N), 1.97 (br d, J = 10.2, 2H, NC*H*HC*H*HN), 2.13 (s, 6H, CH_3), 4.75 (d, J = 14.4, 2H, NC*H*HPh), 5.42 (d, J = 14.4, 2H, NCH*H*Ph), 7.43 (m, 4H, J = 7.8, Ar*H*), 7.61 (t, J = 7.5, 2H, Ar*H*), 7.87 (t, J = 6.6, 2H, Ar*H*), 7.97 (d, J = 7.5, 2H, Ar*H*), 8.04 (d, J = 8.7, 2H, Ar*H*), 8.12 (d, J = 8.4, 2H, Ar*H*), 8.53 (s, 2H, Ar*H*), 9.75 (d, J = 8.4, 2H, Ar*H*). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 100 MHz): δ 57.3, 60.7, 123.7, 124.1, 125.6, 125.9, 126.7, 127.6, 127.8, 128.7, 129.3, 130.0, 130.6, 131.7, 132.3, 132.6.

1a-Pd(*R*-Me$_2$BINOL) (4a). To a solution of $Pd(OAc)_2$ (400 mg, 1.80 mmol) and **1a** (495 μL, 1.81 mmol) in 50 mL of CH_2Cl_2 under a N_2 atmosphere was added a solution of (*R*)-Me$_2$BINOL (562 mg, 1.81 mmol) and KO^{t}Bu (400 mg, 3.64 mmol) in 10 mL of THF. The dark red solution was stirred at 50 °C for 5 h. After cooling, the solution was filtered through Celite and the solvent was removed in vacuo to yield a dark red solid in 90% yield as a mixture of two diastereomers. The major diastereomer was isolated via crystallization of the mixture from CH_2Cl_2/hexanes, which also provided crystals of X-ray quality. Yield: 85%. Anal. Calcd for $C_{40}H_{40}N_2O_2Pd$: C, 69.91; H, 5.87; N, 4.08. Found: C, 69.49; H, 5.93; N, 4.11. ^1H NMR (CD_2Cl_2, 400 MHz): δ 1.58 (d, J = 8.8 Hz, 2H, NCH*H*CH*H*N), 2.26 (s, 6H, NCH_3), 2.46 (s, 6H, CCH_3), 2.73 (d, J = 12.4 Hz, 2H, NC*H*HPh), 2.94 (d, J = 8.8 Hz, 2H, NC*H*HC*H*HN), 4.26 (d, J = 12 Hz, 2H, NCH*H*Ph), 6.72 (d, J = 8.4 Hz, 2H, Ar*H*), 6.87 (t, 2H, Ar*H*), 7.1 (m, 6H, Ar*H*), 7.34 (t, 2H, Ar*H*), 7.64 (s, 2H, Ar*H*), 7.70 (d, J = 8.0 Hz, 2H, Ar*H*), 7.95 (d, J = 7.2 Hz, 4H, Ar*H*). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 100 MHz): δ 20.3, 47.8, 55.2, 64.5, 121.1, 123.8, 124.8, 125.7, 126.5, 127.1, 128.5, 129.0, 131.0, 132.3, 134.6, 162.7. $[\alpha]_D$ +39° (c 0.99, CH_2Cl_2, 298 K).

1b-Pd(*R*-Me$_2$BINOL) (4b). 4b was prepared by the same procedure described above for **4a**. The major diastereomer was purified by passing the mixture through a plug of silica gel (EtOAc/Hex, 9:1), albeit in a diminished yield of 60%. Anal. Calcd for $C_{48}H_{44}N_2O_2Pd$: C, 73.23; H, 5.63; N, 3.56. Found: C, 73.39; H, 5.81; N, 3.80. ^1H NMR ($CDCl_3$, 400 MHz): δ 1.49 (d, J = 8.8 Hz, 2H, NCH*H*CH*H*N), 2.21 (s, 6H, NCH_3), 2.51 (s, 6H, CCH_3), 2.56 (d, J = 8.8 Hz, 2H, NC*H*HC*H*HN), 3.43 (d, J = 12.8 Hz, 2H, NC*H*HAr), 4.44 (d, J = 12.8 Hz, 2H, NCH*H*Ar) 6.78 (d, J 8.8 Hz, 2H, Ar*H*), 6.91 (t, J = 7.6 Hz, 2H, Ar*H*), 7.13−7.21 (m, 4H, Ar*H*), 7.39−7.47 (m, 4H, Ar*H*), 7.73−7.77 (m, 4H, Ar*H*), 7.88 (d, J = 3.2 Hz, 6H, Ar*H*), 9.18 (d, J = 7.2 Hz, 2H, Ar*H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 20.8, 48.8, 56.3, 58.9, 121.6, 122.8, 124.4, 125.3, 125.8. 126.5, 126.9, 127.0, 127.7, 129.3, 129.8, 130.2, 131.6, 133.5, 133.8, 134.8, 135.0, 160.3. $[\alpha]_D$ +43° (c 0.99, CH_2Cl_2, 298 K).

1c-Pd(*R*-Me$_2$BINOL) (4c). 4c was prepared by the same procedure described above for **4a**. The major diastereomer was obtained by passing the mixture through a plug of silica gel (EtOAc/Hex, 9:1) and then precipitating from CH_2Cl_2/hexanes (61% yield). Anal. Calcd for $C_{56}H_{48}N_2O_2Pd$: C, 75.79; H, 5.45; N, 3.16. Found: C, 75.76; H, 5.44; N, 3.12. ^1H NMR ($CDCl_3$, 400 MHz): δ 1.07 (d, J = 8.8 Hz, 2H, NCH*H*CH*H*N), 1.96 (d, J = 9.2 Hz, 2H, NC*H*HC*H*HN), 2.33 (s, 6H, NCH_3), 2.50 (s, 6H, CCH_3), 4.02 (d, J = 14 Hz, 2H, NC*H*HAr), 5.53 (d, J = 14.4 Hz, 2H, NCH*H*Ar), 6.38 (t, J = 8.0 Hz, 2H, Ar*H*), 6.72 (d, J = 8.4 Hz, 2H, Ar*H*), 6.90 (t, J = 8.0 Hz, 2H, Ar*H*), 7.15 (t, J = 6.8 Hz, 2H, Ar*H*), 7.34 (m, 4H, Ar*H*), 7.41 (t, J = 6.8 Hz, 2H, Ar*H*), 7.72 (s, 2H, Ar*H*), 7.80 (m, 4H, Ar*H*), 7.95 (d, J = 9.2 Hz, 4H, Ar*H*), 8.45 (s, 2H, Ar*H*), 10.23 (d, J = 8 Hz, 2H, Ar*H*). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 100 MHz): δ 20.7, 50.1, 55.4, 56.1, 121.6, 123.7, 124.3, 124.5, 124.9, 125.2, 125.4, 126.0, 126.4, 126.9, 127.2, 127.5, 127.7, 128.3, 128.4, 129.3, 130.0, 130.2, 131.3, 131.7, 131.9, 132.6, 133.0, 135.5, 163.6. $[\alpha]_D$ +42° (c 0.98, CH_2Cl_2, 298 K).

(*R,R*)-2a. To a solution of (*R,R*)/(*R*)-N$_2$Pd(Me$_2$BINOL) in CH_2Cl_2 was added 2 drops of concentrated HCl. Upon stirring for ∼15 min the solution turned from dark red to bright orange, indicating Me$_2$BINOL cleavage. The solution was filtered through Celite and concentrated to a few milliliters. The product was precipitated with hexanes, isolated, and washed with hexanes to remove excess HCl. $[\alpha]_D$ +195° (c 0.984, CH_2Cl_2, 298 K).

(*R,R*)-2b. The compound was prepared with a procedure analogous to (*R,R*)-**2a**. Yield: 80%. $[\alpha]_D$ +90° (c 0.980, CH_2Cl_2, 298 K).

***dl/meso*-2c.** The compound was prepared with a procedure analogous to (*R,R*)-**2b**. Yield: 65%. $[\alpha]_D$ +8° (c 0.56, CH_2Cl_2, 298 K).

General Method for Diels−Alder Catalysis. Diels−Alder catalysis reactions were kept at a constant temperature in a Neslab CB-80 low-temperature cryobath equipped with a Cryotrol temperature controller. Gas chromatography (conversion) was performed on a DB-1 column (column temperature 180 °C, injection port temperature 200 °C, N_2 as the carrier gas). HPLC data were obtained on an Agilent 1100 series instrument using a Diacel Chiracel OD-H column (0.75 mL/min flow rate, 90% hexanes, 8% 2-propanol, 2% ethanol). Enantiomeric excess and *endo*:*exo* ratio were calculated from the HPLC profile. HOTf was distilled prior to use (35 °C/30 mTorr). Cyclopentadiene (CpH) was collected by distillation during thermal cracking of dicyclopentadiene and used immediately. The dienophile (*N*-acryloyl oxazolidinone) was synthesized by a literature procedure[30] and stored in the drybox freezer.

Diels−Alder Catalysis, HOTf Method. A typical procedure for catalysis is as follows. (*R,R*)/(*R*)-N$_2$Pd(Me$_2$BINOL) (17.1 mg, 25.0 μmol) and dienophile (35.3 mg, 250 μmol) were loaded into a flame-dried flask under an N_2 atmosphere and dissolved in 3 mL of CH_2Cl_2. HOTf (4.0 μL, 45 μmol) was added at either rt or −78 °C, and the solution was allowed to stir for 15 min at the respective temperatures. The flask was then transferred to a cryobath set at −55 °C, and freshly distilled CpH (311 μL, 373 μmol) was added. Aliquots were taken (0.2 mL) and quenched by filtering through silica gel, eluting with EtOAc, followed by immediate injection onto the GC column. After ∼100% conversion was reached, the reaction mixture was quenched by filtering through silica gel, eluting with EtOAc. Solvent was removed in vacuo, and the residue was taken up in HPLC grade 2-propanol for analysis.

Diels−Alder Catalysis, AgSbF$_6$ Method. A typical procedure for the catalysis is as follows. (*R,R*)-**2a** (11.0 mg, 25.0 μmol) and dienophile (35.3 mg, 250 μmol) were added to a dry flask under N_2 and dissolved in 3 mL of CH_2Cl_2. $AgSbF_6$ (19.0 mg, 55.0 μmol) was added and the mixture stirred for 10 min. The reaction mixture was cooled to −78 °C and cannula filtered to remove excess $AgSbF_6$ and precipitated AgCl. The filtrate was transferred to a cryobath cooled to −55 °C, and CpH (310

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Table 3. Crystallographic Data and Collection Parameters for 4a, (*R*,*R*)-2a, and *meso*-2c

	4a·$2CH_2Cl_2$	(*R*,*R*)-**2a**	*meso*-**2c**·CH_2Cl_2
empirical formula	$PdC_{42}H_{44}N_2O_2Cl_4$	$PdC_{18}H_{24}Cl_2N_2$	$PdC_{35}H_{34}N_2Cl_4$
fw	857.02	445.70	730.87
space group	trigonal, $P3_2$	monoclinic, *Pc*	$P2_1/c$
a, Å	10.4804(6)	14.8129(3)	26.1762(6)
b, Å		9.5230(2)	12.9859(3)
c, Å	31.8116(17)	14.1217(3)	19.9658(5)
V, Å^3	3026.0(2)	1923.49(7)	6340.3(3)
Z	3	4	8
T, °C	−100	−100	−100
D_c, g/cm^3	1.411	1.539	1.531
λ, Å	0.71073	0.71073	0.71073
μ, mm^{-1}	0.76	1.24	0.95
R_f[a]	0.046	0.028	0.054
R_w[b]	0.057	0.034	0.055
GoF[c]	1.8799	1.6535	1.8190

[a] $R_f = \sum(F_o - F_c)/\sum F_o$. [b] $R_w = [\sum w(F_o - F_c)^2/\sum wF_o^2]^{1/2}$. [c] GoF $= [\sum w(F_o - F_c)^2/(n - p)]^{1/2}$, where n = number of reflections and p = number of parameters.

μL, 373 μmol) was added. Workup and analysis of the catalysis reaction is the same as previously described for the HOTf method.

Catalyst Isolation after Diels−Alder Catalysis. After ~100% conversion the reaction mixture was quenched with brine. The mixture was filtered through Celite, the organic layer separated, and solvent removed in vacuo. The residue was dissolved in CD_2Cl_2 for analysis by ^{1}H NMR.

Crystallography. Crystals suitable for X-ray crystallography of **4a** were obtained from a saturated CH_2Cl_2 solution layered with hexanes, which was cooled to 0 °C. Crystals of (*R*,*R*)-**2a** were grown at room temperature by slow diffusion of hexanes into a saturated CH_2Cl_2 solution. Crystals of *cis*-**2c** were grown at room temperature in a solution of CH_2Cl_2/hexanes. Single crystals were mounted in oil on the end of a fiber. Intensity data were collected on a Bruker-AXS SMART 1K diffractometer with CCD detector using Mo Kα radiation of wavelength 0.71073 Å (ω scan mode). The structures were solved by direct methods and refined by least-squares techniques on *F* using structure solution programs from the NRCVAX system.[31] All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were placed in calculated positions (C−H = 0.96 Å) and allowed to ride on the atoms to which they were bonded. Crystal data, data collection, and refinement parameters are listed in Table 1. Absorption corrections were made using SADABS.

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Supporting Information Available: Tables of bond lengths and angles for structures **4a**, (*R*,*R*)-**2a**, and *meso*-**2c**. This material is available free of charge via the Internet at http://pubs.acs.org.

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