Application of the Russig−Laatsch Reaction to Synthesize a Bis[5]helicene Chiral Pocket for Asymmetric Catalysis

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The enantiomers of a bis[5]helicenediol ligand ([5]HELOL) have been synthesized in appreciable amounts by a procedure in which key steps are the union of *p*-benzoquinone with an enol ether of 3-acetylphenanthrene and the displacement of phenol and phenol ether functions by alcohols (the Russig−Laatsch reaction). This diol catalyzes the addition of diethylzinc to aldehydes and gives nonracemic alcohols with enantiomeric excesses as high as 81%. The stereoselectivities and yields are much greater than when the catalyzing diol is BINOL. The enantioselectivities are greater also than those of other reactions catalyzed by helicene ligands.

Introduction

Despite their apparent potential, helicenes have been used as ligands in asymmetric catalysis only once.[1] The probable reason, that they have been difficult to obtain in large amounts, should be obviated by the procedure recently developed to make them from *p*-benzoquinone and the enol ethers of aryl methyl ketones. This procedure has already made available substantial quantities of [5] -, [6]-, and [7]carbo-[2] and heterohelicenes.[3] These in turn have been used to prepare the first examples of helical conjugated polymers,[4] helical columnar mesophases,[5] and chiral aggregates.[6] The aggregates exhibit large optical rotations and large nonlinear optical responses, and they have been used to demonstrate that quasi-phase matched second harmonics can be produced by making use of a material's chirality.[6f]

1,1′-Binaphthalene-2,2′-diol (BINOL) (**1**, R = H) is probably the ligand most frequently used for asymmetric catalysis,[7] and although the enantioselectivities and yields achieved with it are often excellent, they are not always.[8] Because the large distance between the center of chirality and the metal may be to blame, ways have been studied to move the chirality closer to the metal. One way has been to prepare derivatives of BINOL in which the 3 and 3′ positions are substituted, and these ligands have proven effective in, for example, Diels−Alder,[9] ene,[10] and olefin-metathesis[11] reactions, Claisen rearrangements,[12] and dialkylzinc additions to aldehydes.[8b−d,13] Another way, developed by Wulff, uses a "vaulted biaryl" ligand (**2**), "VAPOL",[14] to extend the ring system in the direction of the phenolic hydroxyls, forming a chiral pocket[14a] around the metal. The enantioselectivities attained with this ligand in Diels−Alder reactions are excellent.[14] In view of the successes achieved with substituted BINOLS and VAPOL, we wondered whether a bis-helicene diphenolic ligand such as **3**, because it should form a larger chiral pocket around the catalytic metal center, would be an even better asymmetric catalyst.

A significant feature of **3**'s structure is that the stereochemistry of the single bond uniting the two helicene moieties is constrained, but not by the bulk of

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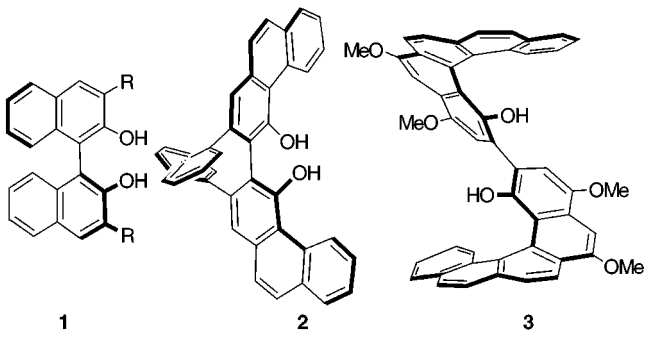


1 **2** **3**

adjacent substituents, as in biaryls such as **1** and **2**, but by the bulk of the distant helicene rings. Adjacent substituents are not required. If the bond linking the two aryls were rotated to the (*R*)-stereochemistry, the helicenes in structure **3** would collide. Thus, when the structure comprises two (*P*)-helicenes, the stereochemistry about the biaryl single bond *must* be (*S*).

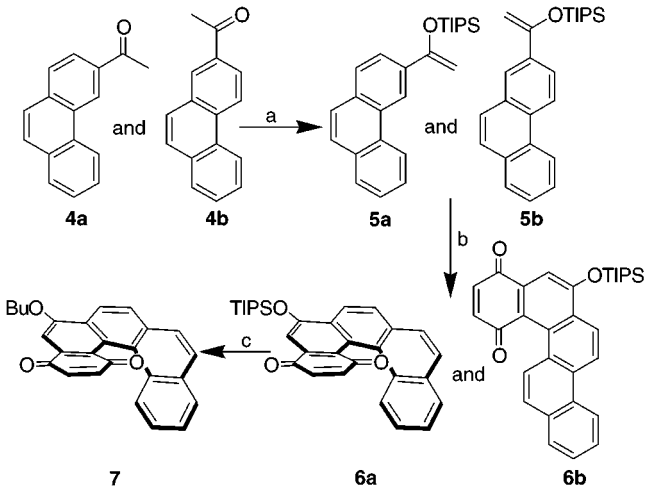
This paper describes the synthesis of both enantiomers of this ligand, which we call [5]HELOL, on a significant scale and in eight steps from commercially available materials. The [5]HELOL ligand is stable to racemization at room temperature. Moreover, it acts as a catalyst for the addition of diethylzinc to aldehydes,[8,15] and when it does, the enantioselectivities and yields are larger than those produced by BINOL.

Results and Discussion

In designing a helicene ligand for asymmetric catalysis the following points were considered. First, to be useful, the ligand must be cheaply and easily preparable on a large scale. Second, it must be stable both to racemization and decomposition under the conditions used for catalyzed transformations. Third, a dimeric helicene is likely to be more effective than a monomer because it can surround a metal with a chiral pocket. The idea then was that an appropriate bis-helicenediol might be made easily from a [5]helicenequinone such as **7**, which in turn should be preparable in just two steps from 3-acetylphenanthrene (**4a**).

3-Acetylphenanthrene containing approximately 10% 2-acetylphenanthrene (**4b**) is available commercially, but we obtained it more cheaply by acetylating phenanthrene on a 100 g scale.[16] 2-Acetylphenanthrene is a side product, and it is difficult to remove.[16c] Accordingly, an 11:1 mixture was used as the starting material for the synthesis (Scheme 1). This mixture, when treated with triisopropylsilyl triflate and triethylamine, gave in 99% yield a mixture of silyl enol ethers **5**a and **5b**. These, when combined for 24 h with *p*-benzoquinone in refluxing toluene, gave a mixture of [5]helicenequinone **6a** (from 3-acetylphenanthrene) and its isomer **6b** (from 2-acetylphenanthrene). They seemed inseparable. However, the structures separated unexpectedly when the mixture was treated with *n*-butyl iodide and K_2CO_3 in DMF at 60 °C, for helicene **6a** readily alkylates, while the planar molecule **6b** does not. Thus, when the reaction mixture was poured into water, only the helicene precipitated. After the three steps, the yield of [5]helicenequinone **7** from 3-acetylphenanthrene was 81%.

Scheme 1[a]



[a] Key: (a) triisopropylsilyl triflate, Et_3N, CH_2Cl_2, 0 to 25 °C, 2 h, 99% yield; (b) *p*-benzoquinone, toluene, reflux, 24 h; (c) *n*-BuI, K_2CO_3, DMF, 60 °C, 2 h, 81% yield (two steps).

To complete the synthesis of the ligand, the following transformations were needed: (1) the quinone had to be reduced; (2) of the resulting phenolic hydroxyls, the one on the outer periphery had to be converted selectively to an ether, so only the other, on the inside of the ring system, could participate in the oxidative dimerization that would yield the desired bisphenol; and (3) the enantiomers had to be resolved. Since preliminary studies showed that dimethyl ether **8** is particularly easy to resolve (see below), we attempted to synthesize it by following steps similar to those that led to **7**, but with methyl iodide in place of *n*-butyl iodide. However, this approach was unsatisfactory, for the methylation, unlike the butylation, did not separate the ring system derived from **6a** from that derived from **6b**. Remarkably, the procedure discovered by Russig[17] and Laatsch[18] to convert naphthoquinones into monoalkylated ethers of naphthohydroquinones—reduction with sodium dithionite followed by reaction with an alcohol saturated with HCl—achieves the desired result. It converts **7** into **8** in two simple steps (eq 1). This means it not only transforms the quinone into the monomethyl ether of the hydroquinone, but at the same time it replaces the butoxyl by a methoxyl. It also proved useful for attaching side-chains to [6]- and [7]carbohelicenes, and a paper describing these experiments provides details of the procedure's application.[19] The best reaction conditions we could find—methanol saturated with HCl, with added 1,2-dichloroethane cosolvent, 30 min at 60 °C—gave a 75% yield of **8** (22.0 g). No trace of isomers was found, and the butoxy side chain was cleanly replaced.

Ambient temperatures sufficed to introduce the methoxy group at the 4-position, but to replace the butoxy side chain required a temperature that was higher.[19] At this higher temperature, a significant amount of a white solid side product (20% yield) was also produced. Analyses of

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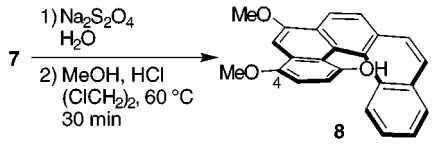
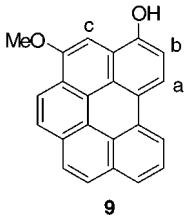
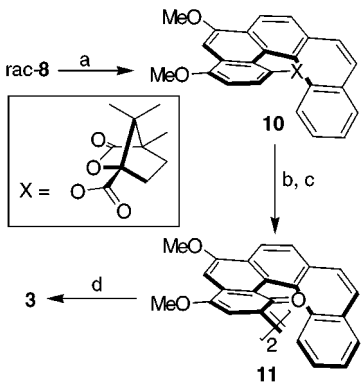


its mass and the NOEs in its ^{1}H NMR spectrum suggested it to have structure **9**.[20] As more of this product was formed when the reaction was run in the light, further studies were carried out in the dark. But even in the dark, heating for 24 h at 60 °C converted **8** in methanolic HCl completely into **9**. Fortunately, **9** is insoluble in CH_2Cl_2, and filtration therefore easily separated it from the soluble **8**.



The [5]HELOL ligand, unlike BINOL, has two independently chiral domains. It therefore has both *dl* and *meso* forms. Indeed, when racemic **8** is dimerized with silver(I) oxide, a mixture of the two is obtained. This means that to obtain one enantiomer of the *dl*-dimer, the precursor **8** must be resolved before it is dimerized. The resolution was easy to accomplish on a 10 mmol scale (Scheme 2). Thus, **8** was combined for 1 h at 80 °C with (*S*)-(−)-camphanoyl chloride,[6b] triethylamine, and a catalytic amount of DMAP, and after acidic and basic workup and trituration with diethyl ether, the [5]helicene camphanate (+)-**10** was obtained in 80% yield (9.6 g). Its diastereomeric excess was >98% according to ^{1}H NMR analysis.[21] The mother liquor contained (−)-**10** of >90% diastereomeric purity, which was purified to >98% de, also in 80% yield, by eluting it with CH_2Cl_2 from a short plug of silica gel. The small amount of (+)-**10** it contained remained on the silica. That the (+)-diastereomer is more polar than the (−)-diastereomer is implied by the former exhibiting the lower R_f on silica gel and the lower solubility in ether. These observations accord with both analogies and conformational analyses.[22] The camphanate esters (+)- and (−)-**10**, which are 1-substituted [5]helicenes,[23] showed no signs of racemizing during six months at room temperature.

Scheme 2[a]



[a] Key: (a) (1*S*)-(−)-camphanoyl chloride, DMAP, Et_3N, 1,2-dichloroethane, 2 h, reflux, 80%yield of each diastereomer; (b) KOH, EtOH, 0 °C, 2 h; (c) Ag_2O, Et_3N, CH_2Cl_2, 0 °C, 2 h, 90% yield (two steps); (d) Zn, AcOH, acetone, 0 °C, 2 h, 100% yield of each enantiomer.

Resolved (+)- and (−)-**8**, obtained by de-esterifying (+)- and (−)-**10**, appeared to racemize appreciably at room temperature, so they and the reaction mixtures in which they were used were maintained at 0 °C. Accordingly, to obtain stereochemically pure **11**, (+)- and (−)-**10** were combined with cold KOH in EtOH−THF in the absence of air and quenched with acetic acid. Freshly prepared silver(I) oxide[24] and triethylamine in CH_2Cl_2 were immediately added to the resulting (+)- and (−)-**8**. The intensely blue-green quinoidal (*P*,*P*)-**11** and (*M*,*M*)-**11**[25] were formed in 91% and 89% yields. Because the enantiomers of **11** absorb light strongly, their specific rotations at the sodium-D wavelength could not be measured. Therefore they are designated according to their absolute configurations, analyzed below. ^{1}H NMR analysis showed that the samples of **11** each contained less than 2% of the meso diastereomer.[26] The implication is that the helicene configuration inverted immeasurably during the de-esterification and dimerization steps.

The [5]HELOL ligands, (+)- and (−)-**3**, obtained in high purity and quantitative yields when (*P*,*P*)- and (*M*,*M*)-**11** were reduced by zinc dust and acetic acid in acetone, were analyzed to be >98% enantiopure. This analysis was carried out by measuring the intensities of the ^{31}P NMRs of the diastereomers formed when (+)- and (−)-**3** were combined with PCl_3 and then with enantiopure (*S*)-(−)-1-phenylethylamine.[27] That kinetic effects did not bias

(20) Evidence for the assignment of structure **9** includes the following: (a) HRMS determined the mass to be 322 (corresponding to the loss of water from **8**); (b) ^{1}H NMR analysis showed 1 methoxyl (a singlet at 4.26 ppm) and 1 phenolic hydroxyl (a singlet at 9.37 ppm that is removed when D_2O is added); and (c) irradiating the hydroxyl resonance gave rise to NOEs for the singlet at 7.78 ppm (proton c) and the doublet at 7.57 ppm (proton b), while irradiating the methoxyl's resonance gave an NOE only for proton c.

(21) The diastereoselectivity was determined by comparing the intensities of the singlet at 0.60 ppm in the ^{1}H NMR spectrum of (*P*)-(+)-**10** and the singlet at 0.65 ppm in the spectrum of (*M*)-(−)-**10**. Had 2% of the one diastereomer been present in the other, the analysis would have detected it.

(22) Thongpanchang, T.; Paruch, K.; Katz, T. J.; Rheingold, A. L.; Lam, K.-C.; Liable-Sands, L. *J. Org. Chem.*, in press.

(23) The introduction of a methyl group at the 1-position of [5]helicene raises the racemization barrier to that of [6]helicene. The figures are $\Delta G^{\ddagger} = 24.1$ kcal mol^{-1} for [5]helicene, 38.7 for 1-methyl-[5]helicene, and 37.0 for [6]helicene. (a) Goedicke, C.; Stegemeyer, H. *Tetrahedron Lett.* **1970**, 937. (b) Scherübl, H.; Fritzche, U.; Mannschreck, A. *Chem. Ber.* **1984**, *117*, 336.

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(25) The double bond between the helicenes is probably trans as in other 2,2′-diphenoquinones, a preference attributed to repulsion of C−O dipoles. Hewgil, F. R.; La Greca, B.; Legge, F.; Roga, P. E. *J. Chem. Soc., Perkin Trans. 1* **1983**, 131.

(26) The intensities were analyzed of a doublet at 9.31 ppm in the ^{1}H NMR spectrum of *(P,P)*-**11** and a doublet at 9.1 ppm expected in the spectrum of *meso*-**11**. While we did not isolate *meso*-**11**, we did isolate the same structure with butyls in place of methyls. It exhibited a doublet ^{1}H NMR at 9.1 ppm. This compound was isomeric with the analogue of (*P*,*P*)-**11** that had butyls in place of methyls. It showed no circular dichroisms. The ^{1}H NMR spectra of these compounds are displayed in the Supporting Information.

(27) The analysis is related to others (a) in which chiral 1,2-diols were distinguished by menthyldichlorophosphate (Garner, C. M.; McWhorter, C.; Goerke, A. R. *Tetrahedron Lett.* **1997**, *38*, 7717), (b) in which the phosphonamide formed from its chlorophosphate and (*S*)-1-phenylethylamine was used to determine VAPOLs absolute stereochemistry (ref 14c), and (c) [5]HELOLs chlorophosphite was used to distinguish chiral alcohols, amines, and carboxylic acids (Weix, D.; Dreher, S. D.; Katz, T. J. Unpublished results).

this analysis was proven by analyzing the phosphonamides that formed when (±)-1-phenylethylamine was added to (+)-[5]HELOL and PCl_3. The intensities of the two ^{31}P resonances in this case were in the ratio 1:1.

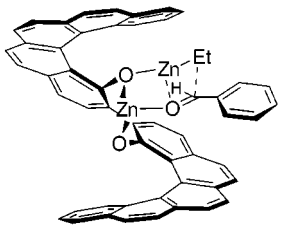
The absolute configurations of the [5]HELOL ligands were determined by analyzing the crystal structure of (−)-**10**. This camphanate was found to have the (*M)* or left-handed configuration. Since it gave **11** and (−)-**3**, the ring systems in these compounds also have the (*M)*-configurations.

Asymmetric Catalysis. To investigate the catalytic activity of [5]HELOL, the additions of diethylzinc to aryl aldehydes[15] were studied because in these reactions BINOL itself and other simple chiral diols (those without additional heteroatoms at the active site[28]) are usually not very effective.[8,30] In fact, only one simple diol has been found that is.[8a,31]

The optimized experimental conditions used to study [5]HELOL in the diethylzinc additions were to combine 0.70 mmol of benzaldehyde, 1.1 mmol of diethylzinc, and 0.035 mmol of [5]HELOL in 1.4 mL of toluene at room temperature for 24 h. 1-Phenylpropanol was formed in 93% yield[32] and 81% enantiomeric excess (ee).[33] When the solvents were methylene chloride or THF, or when the temperature was lower, the reactions were very slow. When additional diethylzinc was added, or when the reaction mixtures were more concentrated, the enantioselectivities decreased. If BuLi, Et_3N, or pyridine was added to the reaction mixtures, the products were essentially racemic. As a basis for comparison, BINOL was substituted for [5]HELOL. The yield of 1-phenylpropanol then dropped to 56% and the ee to 34%.[34]

Several other aromatic aldehydes were substituted for benzaldehyde. *p*-Chlorobenzaldehyde gave a 90% yield and a 69% ee. *o*-Chlorobenzaldehyde and *p*-methoxybenzaldehyde reacted only slowly,[35] the former perhaps because it is sterically hindered. Thus, for *o*-chlorobenzaldehyde to give the expected 1-(2-chlorophenyl)propanol in good yield (75%), its concentration had to be doubled to 1.0 M. The ee was 72%. Accompanying this product was a 25% yield of 2-chlorobenzyl alcohol.[36] For *p*-methoxybenzaldehyde to give a good yield (91%), its concentration had to be doubled to 1.0 M and the time allowed for it to react had to be doubled as well (to 48 h). The ee was only 46%.

The stereochemistries of the predominant 1-arylpropanols produced by (*P*,*P*)-(+)-[5]HELOL and (*R*)-(+)-BINOL are opposite, (*S*) by the former, (*R*) by the latter, which is reasonable bacause, as discussed in the Introduction and as seen in structure **12**, the biaryl link in the (*P*,*P*)-([5]HELOL must have the (*S*)-stereochemistry, the opposite of that in (*R*)-BINOL. Moreover, the favored way in which benzaldehyde should coordinate to the zinc is the one pictured in structure **12**, not the one in which the phenyl and hydrogen are interchanged, for the latter would cause the phenyl to bump against the upper helicene. Since a zinc atom that is coordinated to one of the oxygens is believed to transfer the ethyl group to the aldehyde carbon,[37,38] and only the oxygen at the top of structure **12** is positioned to allow such a transfer, the ethyl must add to the aldehyde's *Si*-face. This agrees with the observations made above as well as those made previously, that under catalysis by derivatives of (*R*)-(+)-BINOL, diethylzinc adds to benzaldehydes to give (*R*)-1-arylpropanols.[13,29] However, [5]HELOL amplifies this stereospecificity, and the greater hindrance around the zinc atoms, evident in **12**, would account for why. The additional crowding might also prevent zinc−oxygen aggregates from forming and therefore account for why [5]HELOL is more reactive than BINOL. The latter forms such aggregates, and their inertness has explained why it reacts so sluggishly.[8b−d,13a,15b,37]



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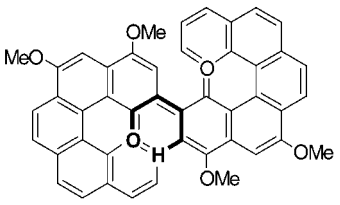

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Potential problems that might restrict the usefulness of the [5]HELOL ligand are oxidizability and stereomutability. However, the bright yellow [5]HELOL (**3**) was found to be only moderately sensitive to oxidation. When exposed to air for long periods, especially in solution, it oxidized to blue-green **11**, a transformation that is probably promoted by the electron-rich alkoxy side chains and, when compared to **1** and **2**, the low barrier to rotation about the 2,2′-bond. However, this oxidation did not affect [5]HELOL's ability to function as a catalyst. The ligand was generally stored under nitrogen at 4 °C and was used in air-free solutions. The color of the reaction mixtures remained yellow throughout.

The low barrier to [5]helicenes racemizing[39] also turned out not to be as great a problem as at first seemed possible. To study the stereomutation of nonracemic **11**,

(28) BINOLs that have, besides the ligating diols, other heteroatoms at the active sites do catalyze the reactions of diethylzinc and aldehydes and, like chiral amino alcohols,[15b] give excellent enantioselectivities.[13] The addition of chiral amines to BINOL derivatives also achieves good asymmetric catalysis[8c] as does replacing one of BINOL's phenol functions with an amino group.[29]

(29) Vyskočil, S.; Jaracz, S.; Smrčina, M.; Štícha, M.; Hanus, V.; Polášek, M.; Kočovsky, P. *J. Org. Chem*. **1998**, *63*, 7727.

(30) In the presence of excess titanium tetraisopropoxide, a titanate of BINOL, like titanates of other chiral diols, is effective [Zhang, F.-Y.; Yip, C.-W.; Cao, R.; Chan, A. S. C. *Tetrahedron*: *Asymmetry* **1997**, *8*, 585].

(31) Rosini, C.; Franzini, L.; Pini, D.; Salvadori, P. *Tetrahederon*: *Asymmetry* **1990**, *1*, 587.

(32) The yields in this reaction were determined by analyzing the ^1H NMR spectra in $CDCl_3$, with **3** serving as an internal standard. The intensities of a multiplet at 4.55 ppm (1 H) in the spectrum of 1-phenylpropanol, a singlet at 9.98 ppm (1 H) in the spectrum of benzaldehyde, and a singlet at 4.64 ppm (2 H) in the spectrum of benzyl alcohol were compared with the intensity of a doublet at 8.4 ppm (2 H) in the spectrum of **3**. The other reactions were analyzed similarly.

(33) Determined by analyzing the ^1H NMRs of α-methoxy-α-trifluoromethylphenylacetic acid esters. (a) Dale, J. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 512. (b) Parker, D. *Chem. Rev.* **1991**, *91*, 1441.

(34) BINOL at room temperature with diethylzinc and benzaldehyde in toluene was reported in ref 8a to give no appreciable reaction and in ref 8b to transform 37% of the benzaldehyde and give 1-phenylpropanol with an ee of 32.9%. To provide a uniform comparison, the reaction parameters that had been optimized for [5]HELOL were applied to both it and to BINOL.

(35) The *p*-methoxy group lowers reactivity in similar reactions. See: ref 31 and Corey, E. J.; Yuen, P.-W.; Hannon, F. J.; Wierda, D. A. *J. Org. Chem*. **1990**, 55, 784.

(36) Benzyl alcohols are common side products of such reactions. Examples are in ref 8a,b.

(37) Yamakawa, M.; Noyori, R.*J. Am. Chem. Soc.* **1995**, *117*, 6327.

(38) In structure **12**, a group attached to the Zn that delivers the ethyl has been omitted to make the drawing clearer.

(39) Laarhoven, W. H.; Prinsen, W. J. C *Top. Curr. Chem*. **1984**, *125*, 63.

it was necessary to monitor the isomerizations until they had taken place only to a small extent, <15%, because one enantiomer almost surely converts into the meso isomer before it converts into the other. Thus, (*P,P*)-**11** was heated at three temperatures, and the conversion to *meso*-**11** was analyzed by ^{1}H NMR spectroscopy. For the first-order rate constants, $\Delta H^{\ddagger} = 106 \pm 3$ kJ mol^{-1} and $\Delta S^{\ddagger} = -10.0 \pm 0.1$ J mol^{-1} K^{-1}. The half-life at 25 °C should therefore be 19 days and at 4 °C 1.4 years. As a solid at ca. 4 °C, (*P,P*)-**11** seems at least this stable. It did not convert to detectable amounts of the meso form during 6 months. The figures show that the barrier to stereomutation is higher for (*P,P*)-**11** than for [5]helicene ($\Delta H^{\ddagger} = 95.8$ kJ mol^{-1} and $\Delta S^{\ddagger} = -17.2$ J mol^{-1} K^{-1}),[40] smaller than for [6]helicene ($\Delta H^{\ddagger} = 148$ kJ mol^{-1} and $\Delta S^{\ddagger} = -7.9$ J mol^{-1} K^{-1}),[41] but similar to that for a [5]helicenebisquinone ($\Delta H^{\ddagger} = 116.2 \pm 0.4$ kJ mol^{-1} and $\Delta S^{\ddagger} = -16.4 \pm 4$ J mol^{-1} K^{-1}).[42] Even though the latter has one more blocking carbonyl than the [5]helicenequinone moiety of **11**, when two [5]helicenes are united, the ring system of each half of the molecule should interfere with the stereomutation of the ring system of the other half. This is indicated in structure **13**.

The thermal racemization of [5]HELOL (**3**) was studied by comparing the CD spectra of samples of the solid dextrorotatory enantiomer that had and had not been heated at 45 °C for 72 h.[43] The intensities of the CDs did not decrease. The CDs of a degassed acetonitrile solution kept at room temperature for 6 days also did not decrease. Thus, **3** should not racemize significantly when it is stored for prolonged periods as a solid at 4 °C under N_2 (to minimize oxidation to **11**) or when it is kept in solution under the conditions usually used for catalyzed reactions. Further evidence of its stability was the observation that in a diethylzinc addition to benzaldehyde catalyzed by [5]HELOL at 25 °C, the enantiopurities of the 1-phenylpropanol found in aliquots removed after 1 h and after 24 h were identical within 1%. Moreover, the stability to stereomutation should be enhanced when, during a catalytic process, the ring system is attached to a metal ion, for the complexation should make **3**'s helicene moieties much more rigid.

Conclusion

Both enantiomers of the [5]HELOL (**3**) can be prepared in nonracemic form on a large scale. They are stable to racemization and decomposition under the experimental conditions typically used to bring about catalyzed transformations, and they catalyze the additions of diethylzinc to aldehydes. [5]HELOL is only the second simple alkanediol (one that does not have an additional heteroatom at the active site) to be catalytically active in this reaction, and the enantioselectivities it achieves (up to 81%) are the highest yet obtained in any processes brought about by a helicene-containing catalyst.

(40) Goedicke, C.; Stegemeyer, H. *Tetrahedron Lett.* **1970**, 937.
(41) See footnote 56 in ref 6b.
(42) Liu, L.; Katz, T. J. *Tetrahedron Lett.* **1990**, *31*, 3983.
(43) A more precise analysis of the stereomutation of **3** was difficult because **3** oxidizes to **11**, which absorbs strongly at 589 nm, making it hard to determine specific rotations. An ^{1}H NMR analysis similar to that carried out for (*P,P*)-**11** was impossible because no cleanly resolvable peaks could be found in the spectra of (*P,P*)- and *meso*-**3**. Their resonances were too broad. CD spectroscopy proved too imprecise to measure small changes when less than 10−20% stereomutation had taken place.

Experimental Section

THF was distilled from Na/benzophenone, toluene from Na, and CH_2Cl_2, $(CHCl)_2$, and Et_3N from CaH_2. 1-Iodobutane (99% Aldrich), triisopropylsilyl triflate (GFS, 98%), sodium dithionite (Aldrich, ca. 85%), (dimethylamino)pyridine (Aldrich, 99%), diethylzinc (Aldrich), benzaldehyde (Aldrich, 99+%), *o*-chlorobenzaldehyde (Aldrich, 99%), *p*-chlorobenzaldehyde (Aldrich, 97%), and *p*-methoxybenzaldehyde (Aldrich, 98%) were used without further purification. *p*-Benzoquinone (Aldrich, 98%) was purified by slurrying it in CH_2Cl_2 with four times its weight of basic alumina, filtering through Celite, and drying under vacuum. 3-Acetylphenanthrene was prepared on a 100 g scale[15] and (1*S*)-(−)-camphanic acid on a 100 g scale.[44] (*S*)-(+)-α-Methoxy-α-(trifluoromethyl)phenylacetyl chloride was prepared by refluxing (*R*)-(+)-α-methoxy-α-(trifluoromethyl)-phenylacetic acid with $SOCl_2$ for 1 h.[45] Zn dust (Aldrich, <10 μm, 98%) was activated prior to use.[46] Glassware was flame-dried under vacuum and cooled under N_2. Reactions were carried out under N_2. Additions by syringe were through rubber septa. Whatman 60 A silica plates were used for TLC analyses.

3-[1-(Triisopropylsiloxy)ethenyl]phenanthrene (5a). Triisopropylsilyl triflate (37.9 mL, 141 mmol, 43.1 g) was added to a solution, cooled in an ice bath, of an 11:1 mixture of 3- and 2-acetylphenanthrenes (28.2 g, 128 mmol)[15] and Et_3N (53.4 mL) in CH_2Cl_2 (380 mL), and after the mixture had been warmed to room temperature it was stirred for 2 h. The reaction mixture was then diluted with CH_2Cl_2, washed three times with saturated aqueous $NaHCO_3$, and dried (Na_2SO_4). The solvent was evaporated. The oily product was purified by dissolving it in 1:1 hexanes/benzene (+ 3% Et_3N) and quickly flushing it with more of the same solvents down a short column (3 in × 3 in) of neutral alumina. This gave 47.6 g (99%) of a light yellow oil, a mixture of **5a** and **5b**. The ^{1}H NMR spectrum of the mixture is in the Supporting Information.

Helicenequinone 7. A flask containing a mixture of **5a** and **5b** (47.6 g, 128 mmol) and *p*-benzoquinone (111 g, 1.0 mol) was fitted with a reflux condenser and then evacuated and filled with N_2 three times. Toluene (510 mL) was syringed in, and the mixture under N_2 was refluxed for 14 h. The hot reaction mixture was poured from the flask, and CH_2Cl_2 was added. The mixture was filtered through Celite, and the solvent was evaporated. After it had been shaken vigorously with hexanes (500 mL) and filtered, the insoluble portion, which was mostly benzoquinone, was washed with hexanes (500 mL). Solvent was stripped from the filtrate. Heating at 120 °C under a vacuum of ca. 1 mmHg for ca. 1 h sublimed the remaining benzoquinone into a cold trap. ^{1}H NMR analysis (in the Supporting Information) showed the residual dark red-brown glassy solid to be a 11:1 mixture of **6a** and **6b**. Since we could not separate these, the mixture was used for the next reaction.

It was dissolved in DMF (750 mL), and after a flask containing the solution had been evacuated and filled with N_2 three times, 1-iodobutane (51.0 mL, 128 mmol) was added, followed by K_2CO_3 (216 g, 1.56 mol). The mixture was heated at 60 °C for 2 h. It turned green and then slowly orange-brown. The precipitates, which formed when the mixture was cooled to 25 °C and poured into water (2 L), were filtered through Celite and washed with water. An orange-brown solid was washed from the Celite with CH_2Cl_2, and the solvent was stripped. The residue was heated and stirred with EtOH (400 mL), and the solids were filtered and dried, giving 36.0 g of **7**, a brick-red solid (an 81% yield if the starting material was 91% **4a**). A sample recrystallized from EtOAc was characterized. Mp: 187−187.5 °C. IR (CCl_4): 2962, 1666, 1298 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.44 (d, 1 H, 7.8 Hz), 8.38 (d, 1

(44) Gerlach, H.; Kappes, D.; Boeckmann, R. K.; Maw, G. N. *Organic Syntheses*; Wiley: New York, 1990; Vol. 71, p 48.
(45) Dale, J. A.; Dull, D. L.; Moser, H. S. *J. Org. Chem.* **1969**, *34*, 2543.
(46) Shriner, R. L.; Neumann, F. *Organic Syntheses*; Wiley: New York, 1990; Collect. Vol. III, p 73.

H, 8.7 Hz), 7.94 (m, 3 H), 7.84 (d, 1 H, 8.6 Hz), 7.49 (m, 2 H, 4.3 Hz), 6.95 (d, 1 H, 10.0 Hz), 6.86 (d, 1 H, 10.3 Hz), 4.39 (m, 2 H), 2.01 (m, 2 H), 1.65 (m, 2 H), 1.07 ppm (t, 3 H, 7.4 Hz). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 185.7, 185.3, 158.8, 140.0, 135.9, 132.9, 132.4, 132.2, 129.7, 129.2, 128.5, 128.2, 128.0, 126.1, 125.9, 125.7, 120.0, 101.2, 69.0, 31.1, 19.4, 13.9 ppm. UV−vis (CH_3CN, $c = 7.5 \times 10^{-5}$ M): λ_{max} (log ϵ) 427 (3.71), 385 (3.58), 355 (sh, 3.00), 315 (sh, 4.18), 287 nm (4.21). Anal. Calcd for $C_{26}H_{20}O_3$, C 82.08; H, 5.30. Found: C, 81.79; H, 5.14.

Helicene 8. Sodium dithionite (172 g, 0.99 mol), EtOAc (1 L), and water (1.5 L) were added to a solution of **7** (30 g, 79.0 mmol) in CH_2Cl_2 (500 mL) contained in a 4 L separatory funnel. The mixture was shaken for 0.5 h. The organic materials were separated and washed with water, and the yellow-brown solution was dried (Na_2SO_4). The solvent was stripped. Methanol saturated with HCl (1 L) was added in the dark to the solid residue dissolved in 1,2-dichloroethane (250 mL), and the reaction mixture, contained in a flask equipped with a reflux condenser and wrapped in aluminum foil, was heated at 60 °C for 30 min. The reaction mixture, cooled to 25 °C, was poured slowly into saturated aqueous $NaHCO_3$, and organic materials were extracted into CH_2Cl_2 (2 L), which was then dried (Na_2SO_4) and evaporated. When 500 mL of the solvent remained, the suspension was filtered, giving 5.0 g (a 20% yield) of **9**. To remove small amounts of impurities, the filtrate was then quickly chromatographed under reduced pressure on silica gel contained in a 600 mL coarse fritted funnel that was wrapped in aluminum foil. The eluent was CH_2Cl_2. The yield of **8**, a tan foam, was 20.2 g (72%). ^{1}H NMR analysis showed it to contain <5% of **9**. A sample purified by silica gel chromatography, eluting with CH_2Cl_2, was characterized. IR (CCl_4): 3566, 2937, 1606 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.48 (d, 1 H, 8.4 Hz), 8.23 (d, 1 H, 8.4 Hz), 7.93 (m, 4 H), 7.68 (s, 1 H), 7.54 (t, 1 H, 7.2 Hz), 7.28 (t, 1 H, 7.3 Hz), 6.96 (d, 1 H, 8.4 Hz), 6.69 (t, 1 H, 8.4 Hz), 4.60 (s, 1H), 4.18 (s, 3 H), 4.08 ppm (s, 3 H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 153.2, 148.4, 146.5, 131.6, 131.5, 130.3, 127.9, 127.7, 127.3, 127.1, 126.8, 126.4, 125.6, 125.3, 125.1, 123.5, 120.8, 117.8, 109.6, 107.3, 97.5, 56.1, 55.9 ppm. HRMS (FAB): *m*/*z* calcd for $C_{24}H_{18}O_3$ 354.1256, found 354.1268.

Properties of **9**, an off-white solid, were as follows. ^{1}H NMR (acetone-d_6, 300 MHz): δ 9.37 (s, 1 H), 8.95 (d, 1 H, 7.3 Hz), 8.82 (d, 1 H, 8.5 Hz), 8.72 (d, 1 H, 8.5 Hz), 8.41 (d, 1 H, 8.5 Hz), 8.14 (dd, 2 H, 8.9, 6.6 Hz), 7.98 (t, 1 H, 7.8 Hz), 7.78 (s, 1 H), 7.57 (d, 1 H, 8.5 Hz), 4.26 ppm (s, 3 H). ^{13}C NMR (acetone-d_6, 75 MHz): δ 154.3, 152.7, 133.3, 131.8, 130.2, 128.5, 128.1, 127.4, 126.3, 125.9, 125.8, 125.7, 124.8, 124.6, 123.9, 123.4, 122.2, 120.5, 120.4, 120.1, 113.3, 97.7, 56.0 ppm. HRMS (FAB): *m*/*z* calcd for $C_{23}H_{14}O_2$ 322.0994, found 322.1004.

Monocamphanates (*P*)-(+)- and (*M*)-(−)-10. 1,2-Dichloroethane (1 L) and Et_3N (125 mL) were added to a flask containing **8** (16.0 g, 45.2 mmol), (1*S*)-(−)-camphanoyl chloride (14.6 g, 67.5 mmol), and 4-(dimethylamino)pyridine (DMAP, 2.7 g, 22.1 mmol), and the mixture was heated in an oil bath at 60 °C for 1 h, then cooled to room temperature and diluted with CH_2Cl_2. After the solution had been washed with aqueous HCl (1 M), water, twice with saturated aqueous $NaHCO_3$, and again with water, it was dried (Na_2SO_4), and the solvent was evaporated, giving an off-white solid. This was triturated four times with Et_2O (800 mL each). ^{1}H NMR analysis of the solid (*P*)-(+)-**10** (9.6 g, 80% yield) showed the de to be >98%.[21] This diastereomer exhibited the lower R_f when analyzed by TLC on silica. Mp: >250 ° C. $[\alpha]_D$: +970 (*c* 0.0079, CH_2Cl_2). IR (CCl_4): 1782, 1760 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.38 (d, 1 H, 8.5 Hz), 8.17 (d, 1 H, 8.5 Hz), 7.90 (m, 4 H), 7.65 (s, 1 H), 7.47 (t, 1 H, 7.0 Hz), 7.24 (t, 1 H, 7.0 Hz), 6.96 (d, 1 H, 8.4 Hz), 6.78 (d, 1 H, 8.4 Hz), 4.17 (s, 3 H), 4.13 (s, 3 H), 1.54 (m, 1 H), 1.37 (m, 1 H), 1.06 (m, 1 H), 0.94 (s, 4 H), 0.60 (s, 3 H), 0.47 ppm (s, 3 H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 177.5, 165.8, 154.1. 152.8, 141.0, 132.1, 132.0, 131.6, 128.2, 127.9, 127.8, 127.6, 126.2, 126.1, 125.9, 125.3, 123.3, 121.5, 120.2, 116.6, 105.1, 97.1, 90.6, 56.0, 54.4, 53.9, 28.7, 16.4, 16.2, 9.5 ppm. UV−vis (CH_3CN, $c = 4.2 \times 10^{-5}$ M): λ_{max} (log ϵ) 406 (3.22), 384 (3.27), 358 (3.63), 338(3.96), 300 (4.14); 280 nm (4.15). CD ($c = 4.2 \times 10^{-5}$ M, CH_3CN), nm ($\Delta\epsilon$): 409 (−5), 396 (−2), 388, (−3), 356 (sh, 15), 336 (sh, 44), 321 (87), 304 (sh, 32), 280 (−19), 272 (−19). Anal. Calcd for $C_{34}H_{30}O_6$: C, 76.39; H, 5.65. Found: C, 76.18; H, 5.56.

The ether solutions were evaporated, leaving the diastereomer with higher R_f. Its de was >90%.[21] It was chromatographed under aspirator vacuum in two equal batches on silica gel contained in a 600 mL coarse fritted funnel that was wrapped with aluminum foil. The product was eluted with solvents ranging from 1:1 hexanes−CH_2Cl_2 to CH_2Cl_2. A small amount of the slow-moving diastereomer remained on the column. Isolated was 9.6 g (80%) of (*M*)-(−)-**10** and its de was found by ^{1}H NMR analysis to be >98%.[21] Mp: >250 °C. $[\alpha]_D$: −1110 (*c* 0.010, CH_2Cl_2). IR (CCl_4): 2967, 1796, 1750 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.40 (d, 1 H, 8.4 Hz), 8.12 (d, 1 H, 8.4 Hz), 7.92 (m, 3 H), 7.82 (d, 1 H, 8.4 Hz), 7.66 (s, 1 H), 7.52 (t, 1 H, 7.9 Hz), 7.25 (t, 1 H), 6.96 (d, 1 H, 8.4 Hz), 6.91 (d, 1 H, 8.5 Hz), 4.18 (s, 3 H), 4.13 (s, 3 H), 1.52 (m, 1 H), 1.35 (m, 1 H), 1.25 (m, 1 H), 0.92 (s, 3 H), 0.84 (m, 1 H), 0.65 (s, 3 H), 0.50 ppm (s, 3 H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 177.8, 165.4, 153.9, 152.5, 141.0, 132.0, 131.8, 131.3, 128.1, 127.9, 127.7, 127.4, 126.3, 125.6, 125.5, 125.2, 123.5, 121.2, 120.0, 116.0, 105.1, 96.9, 89.8, 55.9, 54.2, 54.0, 29.0, 28.5, 16.3, 16.1, 9.5 ppm. UV−vis (CH_3CN, $c = 4.2 \times 10^{-5}$ M): λ_{max} (log ϵ) 406 (3.22), 384 (3.27), 358 (3.63), 338(3.96), 300 (4.14); 280 nm (4.15). CD ($c = 4.2 \times 10^{-5}$ M, CH_3CN), nm ($\Delta\epsilon$): 409 (5), 396 (2), 388, (3), 356 (sh, −15), 336 (sh, −44), 321 (−90), 304 (sh, −31), 280 (19), 272 (18).

Crystallographic Analysis of (*M*)-(−)-10. X-ray quality crystals, light yellow prisms, were grown by dissolving (*M*)-(−)-**10** in CH_2Cl_2, adding this to hexanes at 25 °C, and then cooling the solution to 4 °C for several days. The crystal data were as follows: $M = 534.58$, orthorhombic $P2_12_12_1$, $a = 8.5136(2)$ Å, $b = 14.0322(2)$ Å, $c = 22.3887(4)$ Å, $V = 2674.64(11)$ Å^3, $Z = 4$, $T = 173(2)$ K, $D_{calc} = 1.328$ g cm^{-3}, $\mu = 0.90$ cm^{-1}, $R(F) = 5.24\%$, $R_w(F^2) = 14.90$, with a GOF of 1.259 for 5176 observed independent reflections ($4° \leq 2\theta \leq 52°$). Intensity data were collected using a standard P4 X-ray diffractometer equipped with a SMART CCD area detector and a graphite monochromator ($\lambda = 0.710\ 73$ Å).

The systematic absences in the diffraction data were uniquely consistent with the orthorhombic space group $P2_12_12_1$. The assumption that this is the space group gave results on refinement that were chemically reasonable and computationally stable. The structure was solved using direct methods, completed by subsequent difference Fourier syntheses, and refined by full-matrix least-squares procedures. Empirical *SADABS* absorption corrections were applied to the data set. All non-hydrogen atoms were refined with anisotropic displacement coefficients. Hydrogen atoms were treated as idealized contributions. The absolute configuration could be assigned because that of the camphanate moiety was known. The software and sources of scattering factors were those in the SHELXTL (5.10) program library (G. Sheldrick, Siemens XRD, Madison, WI).

Helicene Dimer 11. A flask containing (*M*)-(−)-**10** (8.0 g, 15.0 mmol) was evacuated and filled with N_2 three times. THF (90 mL) was added, and the solution was cooled to 0 °C. A solution of KOH (82 g, 55 mmol) in absolute ethanol (230 mL), which previously had been degassed by boiling under N_2, was added by cannula during 15 min, and the reaction mixture was stirred for 2 h at 0 °C. Acetic acid (115 mL), which had previously been degassed by boiling under N_2, was added sufficiently slowly by cannula so the temperature remained at 0 °C. After it had stirred at 0 °C for 10 min, the mixture was poured into a 2 L separatory funnel containing water (1 L) and ice (500 g). The organic materials were extracted with CH_2Cl_2 and then washed three more times with ice water. Drying (Na_2SO_4), and evaporation gave a yellow-brown solid. CH_2Cl_2 (50 mL) was immediately added, the solution was cooled to 0 °C, and freshly prepared silver(I) oxide (5.3 g, 22.5 mmol)[24a] and Et_3N (1.3 mL) were added. The color immediately turned deep blue-green. Stirring was continued for 2 h at 0 °C. Filtration through Celite, which was then washed with CH_2Cl_2, evaporation of the solvents, and chromatography on silica gel (eluents: 1:1 hexanes−CH_2Cl_2 to CH_2Cl_2), gave 4.7

g (89%) of (*M,M*)-**11**, a blue-green solid. Mp: >250 ° C. IR (CCl_4): 1598 cm^{-1}. ^1H NMR ($CDCl_3$, 300 MHz): δ 9.31 (d, 2 H, 7.6 Hz), 8.28 (d, 2 H, 8.6 Hz), 7.92 (m, 4 H), 7.82 (d, 4 H, 8.8 Hz), 7.51 (m, 4 H), 7.30 (s, 2 H), 7.10 (s, 2 H), 4.18 (s, 6 H), 3.52 ppm (s, 6 H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 158.6, 154.5, 133.4, 132.9, 132.4, 132.0, 128.5, 128.0, 127.7, 127.5, 127.2, 126.3, 124.9, 120.2, 102.6, 98.4, 56.2, 55.7 ppm. UV−vis (CH_3CN, $c = 5.6 \times 10^{-5}$ M): λ_{max} (log ϵ) 630 (3.92), 600 (sh, 3.87), 470 (3.77), 390 (3.99), 319 (sh, 4.21), 283 nm (4.27). CD ($c = 5.6 \times 10^{-5}$ M, CH_3CN), nm ($\Delta\epsilon$): 263 (−13), 283 (57), 296 (sh, 26), 315 (−117), 337 (−80), 354 (−140), 400 (−15), 430 (−23), 630 (21). HRMS (FAB): *m/z* calcd for $C_{48}H_{32}O_6$ 704.2199, found 704.2200.

(*P,P*)-**11** was prepared similarly. (*P*)-(+)-**10** (7.0 g, 13.1 mmol) in THF (80 mL) was combined with KOH (46.9 g) in EtOH (200 mL) and, after 2 h at 0 °C, quenched with acetic acid (100 mL). Oxidation using silver(I) oxide (4.6 g, 19.7 mmol) and Et_3N (1.1 mL) in CH_2Cl_2 (44 mL) at 0 °C, followed by chromatography, gave 4.2 g (91%) of (*P,P*)-**11**, mp >250 ° C. Its ^1H NMR, ^{13}C NMR, and UV−vis spectra were identical to those of (*M,M*)-**11**. CD ($c = 5.6 \times 10^{-5}$ M, CH_3CN), nm ($\Delta\epsilon$): 263 (11), 283 (−59), 296 (sh, −28), 315 (120), 337 (81), 354 (143), 400 (16); 430 (24), 630 (−21).

(*P,P*)-(+)-[5]HELOL (3). Acetone (20 mL) and then acetic acid (0.80 mL) were added to a flask containing (*P,P*)-**11** (1.0 g, 1.4 mmol) and zinc dust (4.6 g, 70 mmol) at 0 °C. The mixture turned yellow after several minutes. After it had stirred for 2 h at 0 °C, the reaction mixture was quickly filtered through Celite, which was then washed with CH_2Cl_2. The organic solutions were washed three times with water, dried ($MgSO_4$), and filtered, and the solvent was evaporated. When most of the solvent had been removed, a small amount of pentane was added to precipitate a brilliant yellow solid, which was subjected to a vacuum for 24 h at 25 °C. Obtained was 1.0 g (100%) of (*P,P*)-(+)-**3**, dec 210 °C, which was stored under N_2 at 4 °C. $[\alpha]_D$: +2580 (*c* 0.010, CH_3CN). IR (CCl_4): 3527, 2955, 1607 cm^{-1}. ^1H NMR (DMSO-d_6, 400 MHz): δ 8.34 (br s, 2H), 8.28 (d, 2H, 8.4 Hz), 8.00 (m, 8H), 7.55 (s, 2H), 7.49 (br s, 2H), 7.23 (s, 2H), 7.04 (s, 2H), 4.21 (s, 6H), 3.92 (s, 6H), 3.33 ppm (s, 2H). ^{13}C NMR (DMSO-d_6, 75 MHz): δ 152.6, 146.7, 145.2, 132.9, 130.5, 130.4, 128.5, 127.8, 127.4, 126.9, 126.0, 125.6, 125.0, 124.9, 124.6, 124.2, 120.3, 119.1, 110.6, 96.8, 56.2, 55.9 ppm. UV−vis (CH_3CN, $c = 4.6 \times 10^{-5}$ M): λ_{max} (log ϵ) 467 (3.33), 419 (sh, 3.96), 300 (4.46), 256 (4.41), 243 (4.43), 227 nm (4.31). CD ($c = 4.6 \times 10^{-5}$ M, CH_3CN), nm ($\Delta\epsilon$): 216 (−122), 229 (−5), 238 (−48), 262 (61), 285 (sh, −91), 296 (−112), 328 (152), 359 (sh, 104). HRMS (FAB): *m/z* calcd for $C_{48}H_{34}O_6$ 706.2355, found 706.2379.

(*M,M*)-(−)-[5]HELOL (3). Under identical conditions (*M,M*)-**11** (1 g) gave (*M,M*)-(−)-**3**, dec 210 °C, also in 100% yield. $[\alpha]_D$: −2470 (*c* 0.016, CH_2Cl_2). The ^1H NMR and ^{13}C NMR spectra of its solutions in DMSO-d_6 and its UV−vis spectrum in CH_3CN were identical to those of (*P,P*)-(+)-**3**. The CD spectra of solutions of the two materials in CH_3CN were mirror images of one another.

Determination of the Stereochemical Purities of (*P,P*)-(+)- and (*M,M*)-(−)-3. DMAP (a small single crystal) was added to (*P,P*)-(+)-**3** (25 mg, 0.035 mmol) in a small vial, which was then evacuated and purged with N_2. Then PCl_3 (0.39 mL of a 0.10 M solution in CH_2Cl_2, 0.039 mmol) was added, followed by Et_3N. After the mixture had stirred for 15 min at 25 °C, (*S*)-(−)-1-phenylethylamine (42 mg, 0.035 mmol, 4.5 μL) was added, and stirring was continued for 2 h. $CDCl_3$ was added, and with a capillary containing 85 wt % H_3PO_4 as an external reference, the ^{31}P NMR spectrum at 121.5 MHz was determined. A single resonance was observed, at 150.44 ppm. When the same analysis was performed starting with (*M,M*)-(−)-**3**, again only a single resonance was observed, but it was at 149.67 ppm. When the analysis was performed with (*P,P*)-(+)-**3** and (±)-1-phenylethylamine, both resonances were seen, and their intensities were equal within 1%. The data are displayed in the Supporting Information. The conclusion is that the amount of (*M,M*)-(−)-**3** in (*P,P*)-(+)-**3** and the amount of (*P,P*)-(+)-**3** in (*M,M*)-(−)-**3** must both be <2%.

Diethylzinc Additions. (*P,P*)-(+)-**3** (0.025 g, 0.035 mmol), followed by toluene (1.4 mL), was added under N_2 to a small flamed-dried air-free flask. Neat Et_2Zn was added, and the reaction mixture under N_2 was stirred for 1 h. A yellow precipitate formed. Benzaldehyde (0.071 mL, 0.070 g, 0.70 mmol) was added, whereupon the precipitate immediately dissolved. After the mixture, sealed under N_2, had stirred for 24 h, it was poured into aqueous NH_4Cl, and the reaction flask was washed with CH_2Cl_2. The organic solution was dried (Na_2SO_4), and the solvent was evaporated. The ^1H NMR spectrum of the entire sample dissolved in $CDCl_3$ was analyzed to determine the yield, the (*P,P*)-(+)-**3** acting as an internal standard. The yield of 1-phenylpropanol[47] was 93%, and, as analyzed by the procedure below, it was predominantly (*S*) with 81% ee. Also present were 3% of unreacted benzaldehyde[47] and 4% of benzyl alcohol.[47] The same reaction was performed but with (*R*)-(+)-BINOL in place of the HELOL. The yield of 1-phenylpropanol was 56%, and it was predominantly (*R*) with 34% ee. Also present were 37% of unreacted benzaldehyde and 7% of benzyl alcohol.

In similar experiments with [5]HELOL, *p*-chlorobenzaldehyde gave (*S*)-1-(4-chlorophenyl)propanol[8a] in 90% yield. Its ee was 69%. Also present were 5% of 4-chlorobenzyl alcohol[47] and 5% of *p*-chlorobenzaldehyde.[47]

o-Chlorobenzaldehyde under conditions that were identical, except that only 0.7 mL of toluene was used, gave a 75% yield of (*S*)-1-(2-chlorophenyl)propanol[48] (ee 72%) and a 25% yield of 2-chlorobenzyl alcohol.[47]

p-Methoxybenzaldehyde[49] under these last conditions gave, after 48 h, (*S*)-1-(4-methoxyphenyl)propanol in 91% yield. Its ee was 46%. Also present was a 3% yield of 4-methoxybenzyl alcohol[44] and 6% of residual *p*-methoxybenzaldehyde.[47]

Enantioselectivity Determinations. The reaction mixtures were distilled under reduced pressure (ca. 0.1 mm), mixed for 12 h with excess (*S*)-(+)-α-methoxy-α-(trifluoromethyl)phenylacetyl chloride,[45] DMAP, Et_3N, and CH_2Cl_2, and the enantioselectivities were measured by analyzing the resonances of the protons on the carbons next to the oxygens.[33] The chemical shifts for the substituted 1-phenylpropanol derivatives were as follows: H, δ 5.89, 5.82 ppm; *p*-OCH_3, δ 5.85, 5.77 ppm; *p*-Cl, δ 5.85, 5.78 ppm; *o*-Cl, 6.37, 6.27 ppm. In each case in which (*P,P*)-(+)-[5]HELOL was the asymmetric catalyst, the diastereomer with the resonance at higher field predominated. This is the ester of the (*S*)-1-arylpropanol.[50] When (*R*)-(+)-BINOL was the asymmetric catalyst, the other diastereomer predominated.

Rates of Racemization. Samples of (*P,P*)-**11** (ca. 5 mg) in 0.75 mL of $CDCl_3$ contained in an NMR tube were heated at 43.0, 53.5, and 59.6 °C, cooled to 25 °C, and their ^1H NMR spectra were analyzed quickly. The first-order rate constants for the stereomutation were: at 43.0 °C, 5.2×10^{-6} s^{-1}; at 53.5 °C, 2.02×10^{-5} s^{-1}; and at 59.6 °C, 4.07×10^{-5} s^{-1}.

(*P,P*)-(+)-**3** (1.4 mg) was dissolved in CH_3CN (50 mL), and the yellow solution was degassed by freeze-pump-thawing. The CD spectra of aliquots were the same whether they were removed when the solution was first prepared or after the solution had been kept, sealed under N_2, for 6 days at ambient temperature (ca. 25 °C). In a similar experiment in which solid (*P,P*)-(+)-**3** was heated at 45 °C for 2 days, the CD spectra before and after the heating were essentially identical.

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(47) These compounds were identified by their ^1H NMR resonances (*The Aldrich Library of ^{13}C and ^1H FT NMR Spectra*; Pouchert, C. J., Behnke, J., Eds.; Aldrich Chemical Co.: Milwaukee, 1993; Vol. 2).

(48) A multiplet in the ^1H NMR spectrum at 4.99 ppm, similar to resonances in the spectra of 1-phenylpropanol (4.52 ppm), 1-(4-chlorophenyl)propanol (4.40 ppm), and 1-(4-methoxyphenyl)propanol (4.47 ppm) was used to analyze for 1-(2-chlorophenyl)propanol.

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Supporting Information Available: ^{1}H NMR spectra of **5a** plus **5b**, **6a** plus **6b**, and *meso*- and (*P*,*P*)-**11** (but with butyls in place of methyls); IR, ^{1}H NMR, and ^{13}C NMR spectra of **7**, **8**, **9**, (*P*)-(+)- and (*M*)-(−)-**10**, (*P*,*P*)-**11**, and (*P*,*P*)-(+)-**3**; UV−vis spectra of **7** and (*P*)-(+)- and (*M*)-(−)-**10**; CD and UV−vis spectra of (*P*,*P*)- and (*M*,*M*)-**11** and of (*P*,*P*)-(+)- and (*M*,*M*)-(−)-**3**; ^{31}P NMR spectra of adducts of (*P*,*P*)-(+)- and (*M*,*M*)-(−)-**3**, PCl_3, and both (*S*)-(−)- and (±)-1-phenylethylamine; NOEs in the ^{1}H NMR spectrum of **9**; X-ray diffraction data for (*M*)-(−)-**10**. This material is available free of charge via the Internet at http://pubs.acs.org.

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