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Modular Spiro Bidentate Nitrogen Ligands – Synthesis, Resolution and Application in Asymmetric Catalysis

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A family of new modular, chiral, bidentate, nitrogen-donor ligands containing the large spirobi(chroman) backbone **1** (SPAN) has been prepared. Enantiopure diamines containing the nitrogen donors at the 8,8′ positions of spirobi(chroman) **1** have been synthesized through the resolution of the 8,8′-diamino racemate **3**. Accordingly, secondary and tertiary amines [(+)-**6**/(–)-**6** and (+)-**5**/(–)-**5**, respectively] and imino derivatives [(+)-**7**/(–)-**7**] were obtained in both enantiomeric forms. A new SPAN derivative incorporating aldehyde groups at the 8,8′ positions of the spirobi(chroman) unit [(+)-**9**/(–)-**9**] has been synthesized with the aim to extend the ligand library by means of Schiff base chemistry. The derivatization of the isolated enantiomers of **9** obtained by diastereomer resolution gave derivatives containing the nitrogen atoms at the benzylic positions. The syntheses of ligands (+)-**10**/(–)-**10**, (+)-**11** and (+)-**12** illustrate the scope of this methodology. The coordination ability of ligand (–)-**3** has been tested by the synthesis and characterization of complex [Pd(OAc)$_2${(–)-**3**}] [(–)-**13**]. Some preliminary results related to the oxidative kinetic resolution of 1-phenylethanol with this Pd complex are reported.

Introduction

Transition-metal complexes with ligands containing nitrogen-donor atoms constitute an important class of coordination compounds able to perform a wide range of asymmetric transformations.[1] Well-known advantages of nitrogen-based ligands are: (a) their chemical robustness (in comparison to phosphanes), (b) their wide availability in enantiomerically pure form (from the chiral pool or through well-established racemate resolutions), (c) their rich coordination chemistry in combination with inexpensive first-row transition metals, and (d) their stabilization of high-oxidation-state transition-metal species (useful for oxidation catalysis). Not only simple amines and diamines,[2] but also ligands containing sp^2-hybridized, nitrogen donor atoms (chiral oxazolines[3] and pyridines[4]) and one tertiary diamine, (–)-sparteine,[5] have received much attention during the past decades. Nitrogen-donor ligands possessing a spiro chiral center, a frequently occurring theme in diphosphane-ligand chemistry, have been reported only recently.[6]

The development of wide-bite-angle ligands, especially the *trans*-chelating ones, has been a worthwhile challenge during recent decades. They provide access to scarcely explored catalysts with unusual ligand dispositions around the metal center. The coordination geometries typical of *cis*-coordinating ligands are not accessible, and catalysts with new properties may be discovered.[7,8] Despite the large research effort in this area, purely *trans*-coordinating ligands are still elusive.[9] In recent years, our group has devoted a considerable effort to develop a new series of preferentially *trans*-coordinating spirobi(chroman) diphosphanes (SPANphos and its homologs), and their catalytic applications have been studied.[10,11] We found that the spirobi(chroman) is flexible enough to allow for the formation of *cis* complexes when *trans* sites are not available. While the synthesis and catalytic application of *trans*-coordinating phosphorus ligands has been intensively investigated by us[10,11] and other groups,[7,12] nitrogen-containing analogs remain largely unexplored.[13]

Herein, we report on the design and synthesis of a new set of chiral, C_2-symmetric, nitrogen-donor ligands containing the 4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (SPAN) backbone. As for SPANphos, molecular modeling shows a slight preference for the formation of *trans* complexes in the absence of metal preferences. Small substituents at the nitrogen atoms diminish the destabilizing steric interactions in the *cis* complexes. The preparation, resolution and complete characterization of ligands (+)-**3**/(–)-**3**, (+)-**5**/(–)-**5**, (+)-**6**/(–)-**6**, (+)-**7**/(–)-**7** bearing a wide variety of nitrogen-containing functional groups is described (Scheme 1). They can be prepared in a few steps from cheap reagents and isolated in their enantiomerically pure forms. In addition, the introduction of an extra carbon atom be-

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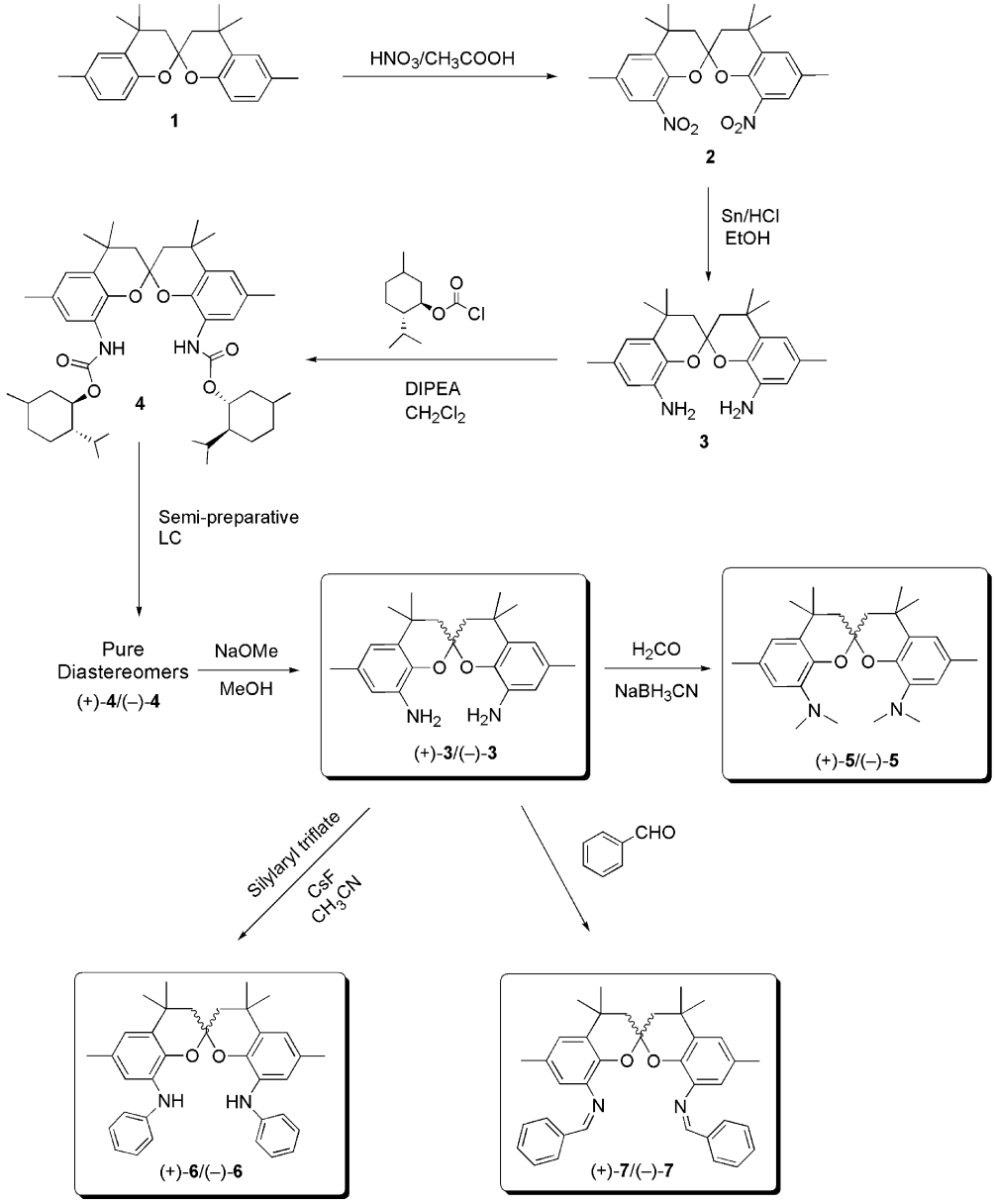
tween the backbone structure and the nitrogen donor atoms has been investigated. These larger backbones have been obtained in enantiopure forms by the derivatization of building block **9**. By using these starting materials [(+)-**9**, (–)-**9**], a new group of modular, axially chiral ligands has been developed [(+)-**10**, (–)-**10**, (+)-**11** and (+)-**12**, Scheme 2]. Furthermore, the coordination behavior of some of these ligands towards Pd, as well as the catalytic activity of the formed complexes in the oxidative kinetic resolution of secondary alcohols has been investigated.

Results and Discussion

Synthesis of Axially Chiral, Spiro, Bidentate, Nitrogen Ligands

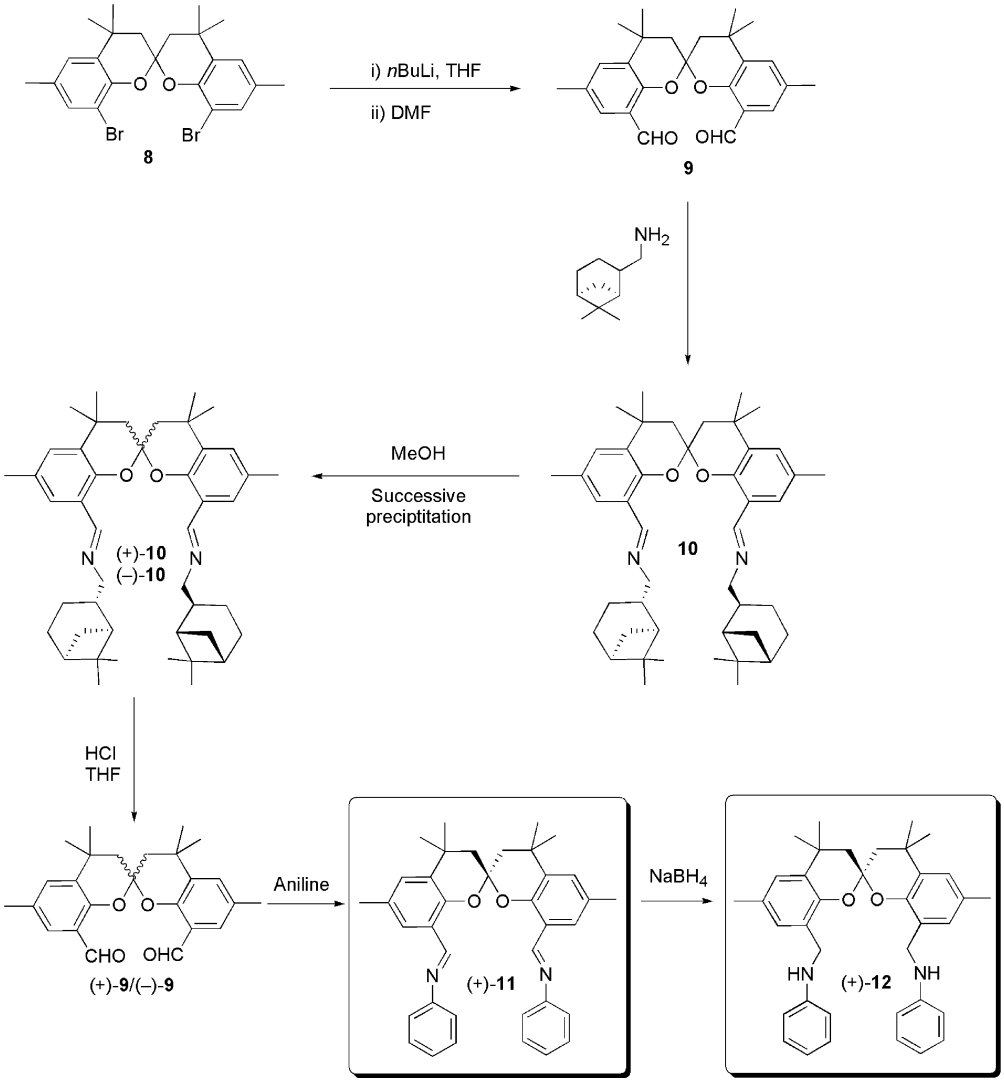
Racemic 4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (**1**) (obtained on a 25 g scale by the acid-catalyzed reaction of *p*-cresol with acetone[14]) was employed as the starting material in the synthesis of ligands (+)-**3**/(–)-**3**, (+)-**5**/(–)-**5**, (+)-**6**/(–)-**6**, and (+)-**7**/(–)-**7** (Scheme 1). The synthesis of dinitro compound **2** was initially attempted with metal nitrates[15] or $NaNO_2$,[16] but no conversion was achieved. Nitric acid nitration was then employed (HNO_3/CH_3COOH, room temperature, 3 h), which afforded **2** in moderate yield (53%) due to partial backbone decomposition. The subsequent reduction of the nitro group (Sn powder, HCl, EtOH, 80 °C, 1 h) rendered the racemic SPANamine **3** in good yield (83%; for larger scale synthesis, more environmentally friendly catalytic methods are available[17]). The optical resolution of **3** was first attempted unsuccessfully by means of diastereomeric salt formation [L-(+)-tartaric acid and derivatives] and diastereomeric Pd complexation [di-μ-chloridobis{(*R*)-2-[1-(dimethylamino)ethyl]phenyl-*C*,*N*}dipalladium(II)].[18]



Scheme 1.

The derivatization of **3** with carbamates was then attempted by means of (–)-menthyl chloroformate (DIPEA, CH_2Cl_2, room temp., 16 h), and the expected diastereomeric mixture of the (–)-menthyl carbamate derivatives **4** were obtained in excellent yield (90%). The separation of the diastereomers was accomplished by semi-preparative LC (silica gel column, hexane/ethyl acetate, 50 mg/injection), affording carbamates (+)-**4** and (–)-**4** as enantiopure compounds. The subsequent carbamate cleavage was achieved by reaction with NaOMe in an autoclave (MeOH, 145 °C, 15 h; then H_2O, 145 °C, 3 h), leading to the desired, enantiopure, chiral SPANamines (+)-**3** and (–)-**3** (Scheme 1) in an almost quantitative yield (96 and 95%, respectively). These chiral primary SPANamines were used as the starting material to expand the ligand series to other nitrogen functional groups such as imines [(+)-**7**/(–)-**7**] and secondary [(+)-**6**/(–)-**6**] and tertiary [(+)-**5**]/[(–)-**5**] amines (Scheme 1), thus demonstrating the modularity of the synthetic approach.

The reaction of SPANamines (+)-**3** and (–)-**3** with paraformaldehyde and a reducing agent ($NaBH_3CN$, CH_3CN, AcOH, 2 h) led to SPANdimethylamines (+)-**5** and (–)-**5** in moderate yields (61 and 58%, respectively) after chromatographic purification. The *N*-arylation of (+)-**3** and (–)-**3** was also attained by means of a transition-metal-free procedure recently published by Larock et al. (silylaryl triflate, CsF, $MeCN/CHCl_3$, room temp., overnight),[19] which yielded secondary SPANamines (+)-**6** and (–)-**6** in good yields (72 and 71%, respectively). We envisaged that a wide set of imines may be synthesized from (+)-**3** and (–)-**3** through Schiff base condensation reactions. This simple approach allows for a quick variation of the steric bulk around the coordinating nitrogen atom and a fine tuning of its electronic properties just by modifying the aldehyde used in the condensation reaction (and even to introduce additional chirality!). As an example, SPANimines (+)-**7** and (–)-**7** were synthesized by the condensation of (+)-**3** and (–)-**3** with benzaldehyde (PhCHO, toluene, Dean–Stark apparatus, 20 h, 77% and 81%, respectively). The X-ray structure of the racemic form of this SPANimine has been solved, and its ORTEP plot is presented as supporting information (Figure S1, Supporting Information). In ad-



Scheme 2.

dition, SPANamines (+)-**3**/(–)-**3** can be employed as chiral building blocks for the synthesis of tetradentate ligands in combination with different chiral and achiral pyridinecarboxaldehydes.[20]

Synthesis of the SPANamine Homologs

Having developed synthetic routes for axially chiral SPANamines and SPANimines, we envisaged modifying the procedures to enlarge the ligand library. As mentioned above, aldehydes (+)-**9**/(–)-**9** (Scheme 2) were synthesized as key building blocks for the preparation of this extended library. They allow the use of Schiff base chemistry to potentially synthesize a large number of new ligand derivatives (SPANimines) by condensation with different primary amines. Also, the corresponding reduced species (secondary SPANamines) will be accessible through simple procedures. Along these lines, ligands (+)-**11** and (+)-**12** were synthesized to illustrate the potential of the synthetic methodology.

Racemic dibromo derivative **8** [obtained on a 10 g scale from 4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (**1**)] was employed as the starting material.[10] The lithiation of **8** through metal/halogen exchange with *n*BuLi (THF, –78 °C, 30 min), followed by the slow addition of DMF in THF (–78 °C, 2 h; then –78 °C to room temperature) rendered racemic aldehyde **9** in 74% yield (Scheme 2). Derivatization through diastereomeric imine formation was the resolution strategy selected in this case. (–)-Myrtanylamine was condensed with **9**, and diastereomeric imines **10** were obtained in excellent yield (absolute EtOH/$CHCl_3$, 18 h, 25 °C, 96%). The diastereomer separation was accomplished by successive precipitation from methanol. Imine (+)-**10** was obtained in good yield and purity as a white solid (82%, >99% *de*), and its diastereomeric counterpart, (–)-**10**, was isolated in lower yield but similar purity from the mother liquor (19%, >99% *de*). The X-ray structure of diastereomeric imine (–)-**10** was solved, and its ORTEP plot is presented in Figure 1. Subsequent imine hydrolysis by means of 3 M HCl (THF, 30 min, room temp.) afforded the axially enantiopure aldehydes (+)-**9**/(–)-**9** in almost quantitative yields (97% in both cases). Building block (+)-**9** was then employed for the synthesis of new nitrogen-donor ligands by means of Schiff base chemistry. Aniline was selected, and SPANimine (+)-**11** was obtained in excellent yield (toluene, 4 Å molecular sieves, Dean–Stark apparatus, 12 h, 91%). The subsequent C=N bond reduction afforded the secondary SPANamine (+)-**12** ($NaBH_4$, toluene, 12 h, room temp., 98%). Ligands (+)-**11** and (+)-**12** are only selected examples of the large number of compounds potentially available from aldehydes (+)-**9**/(–)-**9**. The synthesis of a variety of SPANamine and SPANimine derivatives is currently under development in our laboratory.

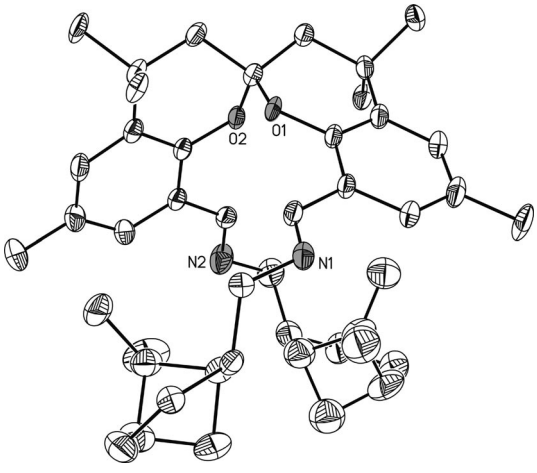


Figure 1. ORTEP view (ellipsoids are drawn at a 50% probability level) of the molecular structure of (–)-**10**.

Coordination Chemistry and Catalysis

In a preliminary attempt to explore the coordinating ability of the synthesized ligands, chiral SPANamine (–)-**3** was treated with [Pd(COD)Cl_2] (CH_2Cl_2, 6 h, room temp.). To the orange-red suspension formed, Ag(OAc) was added, to afford complex (–)-**13** in good yield (75%) as an orange-brown solid. Structural characterization has been performed in solution through NMR spectroscopy and in the solid state by means of the X-ray diffraction analysis of its racemic equivalent complex (Figure 2). In solution, a symmetric monomeric species containing ligand (–)-**3** and two acetate molecules coordinated to the Pd center was observed (Figures S36 and S37, Supporting Information). In the solid state, however, a dimeric species was formed, in which one of the SPANamine groups was converted into

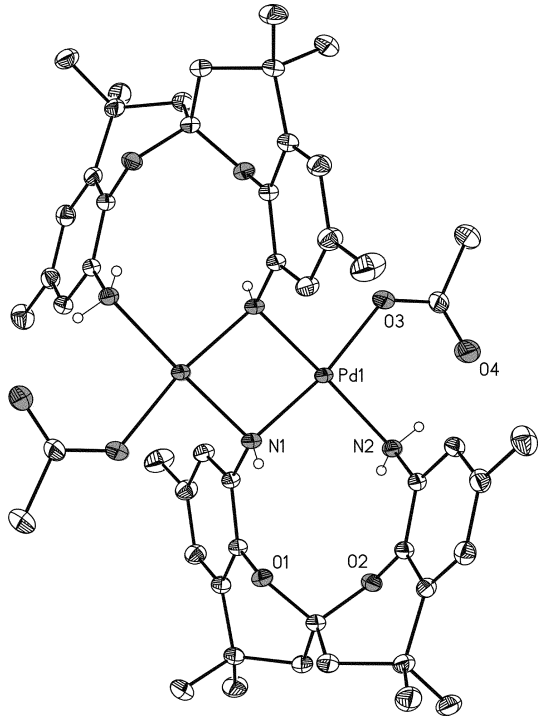


Figure 2. ORTEP view (ellipsoids are drawn at a 50% probability level) of the molecular structure of complex **13**.

an amido group bridging two Pd atoms. Apparently, upon crystallization one molecule of acetic acid was eliminated. Remarkably, this SPANamine coordinated in a *cis* fashion.

As a first test reaction for catalysis we chose the oxidative kinetic resolution of 1-phenylethanol, as this reaction may not necessarily need *cis* coordination of the diamine, although previous studies all involved *cis*-diamines.[4] The preliminary results for the catalytic activity of the (–)-**3**/$Pd(OAc)_2$ system are collected in Table 1.

Table 1. Pd/(–)-**3**-catalyzed oxidative kinetic resolution of 1-phenylethanol.[a]

Entry	Pd source	Temp. [°C]	Time [h]	Conv. [%]	*ee* [%]
1	$[PdCl_2(COD)]$	80	42	22	12
2	$[Pd(allyl)Cl]_2$	80	42	32	7
3	$[Pd(OAc)_2]$	80	42	40	22
4	$[Pd(OAc)_2]$	80	95	61	21
5	$[Pd(OAc)_2]$	65	42	36	33
6	$[Pd(OAc)_2]$	55	42	30	41
7	$[Pd(OAc)_2]$	35	42	20	23
8	$[Pd(OAc)_2]$	50[b]	42	20	23

[a] Reactions were performed in toluene and with KO*t*Bu. [b] 3 h incubation at 80 °C.

These results clearly demonstrate the capacity of the SPANamine (–)-**3**/$Pd(OAc)_2$ system to enantiodifferentiate in the oxidation of a racemic substrate such as 1-phenylethanol (up to 41% *ee*), and it is evident that SPANamine **3** is coordinated to the Pd atom during the catalysis. We are currently investigating the coordination chemistry of SPANamines under these reaction conditions. In addition, we are developing the coordination chemistry of all the SPAN nitrogen-donor ligands described in this paper with other metals and studying their enantioselective reactivity towards prochiral substrates.

Conclusions

A new, axially chiral, diamine ligand [(+)-**3**/(–)-**3**], containing a spirobi(chroman) core, has been prepared in both enantiomeric forms by the resolution of diastereoisomeric intermediates. With this primary amine as the starting material, several new ligands containing diverse nitrogen functional groups and substitution patterns around the nitrogen atoms have been prepared. This asymmetric synthetic procedure was subsequently extended to a second modular family of nitrogen donors through the synthesis and resolution of building block (+)-**9**/(–)-**9**. The potential of this chiral dialdehyde for the synthesis of a wide range of SPANimines and secondary SPANamines by means of simple Schiff base chemistry was exemplified by the preparation of ligands (+)-**11** and (+)-**12**. The coordination behavior of the new ligands was illustrated by the syntheses of Pd complexes. The preliminary catalytic results for the (–)-**3**/$Pd(OAc)_2$ system showed moderate enantioselectivities in the oxidative kinetic resolution of 1-phenylethanol.

Experimental Section

General: See Supporting Infoarmation.

Syntheses: 4,4,4′,4′,6,6′-Hexamethylspiro-2,2′-bi(chroman) (**1**)[14] and 8,8′-dibromo-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (**9**) were obtained according to the methods previously described by our group.[10]

8,8′-Dinitro-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (2): To a solution of **1** (4 g, 11.89 mmol) in AcOH (440 mL) was added dropwise a solution of nitric acid (44 mL) in AcOH (44 mL) over 1 h, and the solution was stirred at room temperature for 3 h. The volume was then reduced under reduced pressure (45 °C), and H_2O (100 mL) was added. The precipitates were collected, washed with H_2O and dried in vacuo to yield **2** as a white-yellow solid (2.7 g, 53%). M.p. 171–173 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.34 (s, 6 H), 1.55 (s, 6 H), 2.12 (d, J = 14.3 Hz, 2 H), 2.22 (d, J = 14.3 Hz, 2 H), 2.31 (s, 6 H), 7.25 (s, 2 H), 7.29 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.6 (CH_3), 30.9 (C), 31.9 (CH_3), 33.1 (CH_3), 46.2 (CH_2), 98.8 (C), 122.8 (CH), 131.3 (CH), 131.6 (C), 134.9 (C), 140.0 (C), 141.1 (C) ppm. ESI-MS: m/z = 449.2 [M + Na]$^+$. $C_{23}H_{26}N_2O_6$ (426.46): calcd. C 64.78, H 6.15, N 6.57; found C 64.55, H 6.42, N 6.33.

8,8′-Diamino-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chroman) (3): Sn powder (5.57 g, 46.9 mmol) was added portionwise to a solution of **2** (2.5 g, 5.87 mmol) in EtOH (27 mL) and HCl (23.1 mL, 235 mmol). The resulting suspension was refluxed for 1 h. The reaction was quenched with ice, and aqueous $NaHCO_3$ (1 M, 50 mL) was added. The product was extracted with ethyl acetate (3 × 100 mL), the combined organic layers were washed with brine (100 mL) and dried ($MgSO_4$), and the solvent was evaporated in vacuo. The crude product was then recrystallized from MeOH to afford pure **3** as a white powder (1.750 g, 83%). M.p. 236–238 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.34 (s, 6 H), 1.55 (s, 6 H), 2.06 (d, J = 14.3 Hz, 2 H), 2.18 (d, J = 14.3 Hz, 2 H), 3.30 (s, 4 H), 6.32 (s, 2 H), 6.52 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.1 (CH_3), 31.0 (C), 31.9 (CH_3), 32.1 (CH_3), 48.0 (CH_2), 98.6 (C), 114.0 (CH), 115.9 (CH), 130.7 (C), 132.0 (C), 135.7 (C), 136.2 (C) ppm. HRMS (ESI): calcd. for $C_{23}H_{31}N_2O_2$ [M$^+$] 367.2386; found 367.2385. $C_{23}H_{30}N_2O_2$ (366.50): calcd. C 75.38, H 8.25, N 7.64; found C 75.30, H 8.23, N 7.55.

Bis[(–)-menthyl] 4,4,4′,4′,6,6′-Hexamethylspiro-2,2′-bi(chroman)-8,8′-bis(carbamate) (4): To a solution of **3** (2 g, 5.46 mmol) and DIPEA (3.56 g, 27.3 mmol) in CH_2Cl_2 (86 mL) was added slowly (–)-(1*R*,2*S*,5*R*)-menthyl chloroformate (5.78 mL, 27.3 mmol) at 0 °C. The mixture was stirred at room temperature for 16 h. After the addition of aqueous $NaHCO_3$ (50 mL), the organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (3 × 60 mL). The combined organic layers were dried ($MgSO_4$) and concentrated, and the residue was purified by flash chromatography with silica gel (40 g) and hexane/ethyl acetate (10:0.8) to afford a diastereomeric mixture of **4** as a colorless oil that solidified upon standing (3.5 g, 90%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.70 (d, J = 7.0 Hz, 6 H), δ = 0.74 (d, J = 7.0 Hz, 6 H), 0.80 (s, 6 H), 0.82 (s, 6 H), 0.90 (m, 8 H), 1.35 (s, 12 H), 1.55 (s, 6 H), 1.56 (s, 12 H), 1.57 (m, 6 H), 2.06 (m, 4 H), 2.07 (d, J = 14.4 Hz, 4 H), 2.20 (d, J = 14.4 Hz, 4 H), 2.27 (s, 6 H), 2.29 (s, 6 H), 4.47 (m, 2 H), 4, 73 (m, 2 H) 6.38 (s, 2 H), 6.50 (s, 2 H), 6.78 (s, 2 H), 6.80 (s, 2 H), 7.65 (s, 4 H) ppm. ESI-MS: m/z = 732 [M + H]$^+$. HRMS (ESI): calcd. for $C_{45}H_{66}N_2O_6$ [M$^+$] 731.0212; found 731.0215.

Bis[(–)-menthyl] 4,4,4′,4′,6,6′-Hexamethylspiro-2,2′-bi(chroman)-8,8′-bis(carbamates) [(+)-4 and (–)-4]: Carbamates **4** were separated by semi-preparative LC with a silica gel column eluting with hex-

ane/ethyl acetate (80:20) to give diastereomerically pure (+)-**4** and (–)-**4** as colorless oils. **(+)-4:** Yield: 1.560 g, >99% *de*. $[\alpha]_D^{20}$ = +55 (*c* = 0.69, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.72 (d, *J* = 7.0 Hz, 6 H), 0.89 (m, 12 H), 1.06 (m, 2 H), 1.22 (m, 2 H), 1.37 (s, 6 H), 1.59 (s, 6 H), 1.66 (m, 4 H), 1.81 (m, 2 H), 2.06 (m, 2 H), 2.07 (d, *J* = 14.4 Hz, 2 H), 2.20 (d, *J* = 14.4 Hz, 2 H), 2.29 (s, 6 H), 4.49 (m, 2 H), 6.51 (s, 2 H), 6.80 (s, 2 H), 7.65 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 16.5 (CH_3), 20.7 (C), 21.3 (CH_3), 21.9 (CH_3), 23.7 (CH_2), 26.2 (CH_3), 30.8 (C), 31.3 (CH_3), 31.9 (CH), 32.3 (CH), 34.3 (CH_2), 41.2 (CH_2), 47.2 (CH_3), 47.4 (CH_2), 74.8 (CH), 98.9 (C), 117.4 (CH), 120.0 (CH), 127.3 (C), 131.2 (C), 131.2 (C), 136.4 (C), 153.1 (C) ppm. HRMS (ESI): calcd. for $C_{45}H_{66}N_2O_6Na$ [M^+] 753.4819; found 753.4849. $C_{45}H_{66}N_2O_6$ (731.02): calcd. C 73.94, H 9.10, N 3.83; found C 73.10, H 9.32, N 3.75. **(–)-4:** Yield: 1.580 g, >99% *de*. $[\alpha]_D^{20}$ = –198 (*c* = 0.69, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.70 (d, *J* = 7.0 Hz, 6 H), 0.89 (m, 12 H), 1.04 (m, 2 H), 1.26 (m, 2 H), 1.35 (s, 6 H), 1.57 (s, 6 H), 1.64 (m, 4 H), 1.781 (m, 2 H), 2.06 (m, 2 H), 2.06 (d, *J* = 14.4 Hz, 2 H), 2.18 (d, *J* = 14.4 Hz, 2 H), 2.27 (s, 6 H), 4.47 (m, 2 H), 6.50 (s, 2 H), 6.78 (s, 2 H), 7.63 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 16.6 (CH_3), 20.7 (C), 21.4 (CH_3), 22.0 (CH_3), 23.7 (CH_2), 26.2 (CH_3), 30.9 (C), 31.3 (CH_3), 31.9 (CH), 32.4 (CH), 34.3 (CH_2), 41.2 (CH_2), 47.2 (CH_3), 47.4 (CH_2), 74.8 (CH), 98.9 (C), 117.4 (CH), 120.0 (CH), 127.2 (C), 131.2 (C), 131.3 (C), 136.5 (C), 153.2 (C) ppm. HRMS (ESI): calcd. for $C_{45}H_{66}N_2O_6Na$ [M^+] 753.4819; found 753.4814. $C_{45}H_{66}N_2O_6$ (731.02): calcd. C 73.94, H 9.10, N 3.83; found C 73.11, H 9.21, N 3.56.

8,8′-Diamino-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chromans) [(+)-3 and (–)-3]: To a stirred solution of (–)-**4** or (+)-**4** (1.5 g, 2.05 mmol) in dry MeOH (30 mL) was added slowly NaOMe (5.55 g, 102.7 mmol), and the resulting solution was stirred at 145 °C for 15 h in an autoclave. H_2O (15 mL) was then added, and the solution was refluxed for a further 3 h. The mixture was then poured onto ice, partitioned between CH_2Cl_2 and H_2O, and the combined organic layers were washed with brine and dried with anhydrous $MgSO_4$. The solvent was evaporated under reduced pressure to afford pure (+)-**3** or (–)-**3** as a pale yellow solid. **(+)-3:** Yield: 0.720 g, 96%. M.p. 236–238 °C. $[\alpha]_D^{20}$ = +187 (*c* = 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.34 (s, 6 H), 1.55 (s, 6 H), 2.06 (d, *J* = 14.3 Hz, 2 H), 2.18 (d, *J* = 14.3 Hz, 2 H), 2.20 (s, 6 H), 3.30 (s, 4 H), 6.32 (s, 2 H), 6.52 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.1 (CH_3), 31.0 (C), 31.9 (CH_3), 32.1 (CH_3), 48.0 (CH_2), 98.6 (C), 114.0 (CH), 115.9 (CH), 130.7 (C), 132.0 (C), 135.7 (C), 136.2 (C) ppm. HRMS (ESI): calcd. for $C_{23}H_{30}N_2O_2Na$ [M^+] 389.2205; found 389.2221. $C_{23}H_{30}N_2O_2$ (366.50): calcd. C 75.38, H 8.25, N 7.64; found C 75.19, H 8.41, N 7.50. **(–)-3:** Yield: 0.712 g, 95%. M.p. 236–238 °C. $[\alpha]_D^{20}$ = –187 (*c* = 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.34 (s, 6 H), 1.55 (s, 6 H), 2.06 (d, *J* = 14.3 Hz, 2 H), 2.18 (d, *J* = 14.3 Hz, 2 H), 2.20 (s, 6 H), 3.30 (s, 4 H), 6.32 (s, 2 H), 6.52 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.1 (CH_3), 31.0 (C), 31.9 (CH_3), 32.1 (CH_3), 48.0 (CH_2), 98.6 (C), 114.0 (CH), 115.9 (CH), 130.7 (C), 132.0 (C), 135.7 (C), 136.2 (C) ppm. HRMS (ESI): calcd. for $C_{23}H_{31}N_2O_2Na$ [M^+] 367.2386; found 367.2397. $C_{23}H_{30}N_2O_2$ (366.50): calcd. C 75.38, H 8.25, N 7.64; found C 75.30, H 8.23, N 7.55.

8,8′-Bis(dimethylamino)-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chromans) [(+)-5 and (–)-5]: To a stirred solution of (+)-**3** or (–)-**3** (0.1 g, 0.27 mmol), $NaBH_3CN$ (0.052 g, 0.82 mmol) and CH_2O (0.076 mL, 2.72 mmol) in CH_3CN (1.5 mL) was added dropwise AcOH (0.95 mL) at room temperature. After 2 h, the mixture was diluted with Et_2O (2 mL), washed with aqueous $NaHCO_3$ (3 mL), H_2O (3 mL) and brine (3 mL) and dried with $MgSO_4$. The organic fraction was then concentrated in vacuo, and the yellow oil obtained was recrystallized from MeOH to afford pure (+)-**5** or (–)-**5** as a white solid. **(+)-5:** Yield: 0.075 g, 65%. M.p. 220–222 °C. $[\alpha]_D^{20}$ = +156.3 (*c* = 0.36, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.33 (s, 6 H), 1.66 (s, 6 H), 2.02 (d, *J* = 14.4 Hz, 2 H), 2.19 (d, *J* = 14.3 Hz, 2 H), 2.23 (s, 6 H), 2.33 (s, 12 H), 6.49 (s, 2 H), 6.77 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.2 (CH_3), 31.1 (C), 32.0 (CH_3), 32.2 (CH_3), 42.2 (CH_3), 48.3 (CH_2), 98.7 (C), 114.3 (CH), 115.9 (CH), 130.5 (C), 132.0 (C), 135.7 (C), 136.2 (C) ppm. ESI-MS: *m*/*z* = 443.50 [M + H]$^+$. $C_{37}H_{38}N_2O_2$ (442.60): calcd. C 76.74, H 9.01, N 6.63; found C 76.60; H 9.35; N 6.34. **(–)-5:** Yield: 0.072 g, 63%. M.p. 220–222 °C. $[\alpha]_D^{20}$ = –156.1 (*c* = 0.36, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.33 (s, 6 H), 1.66 (s, 6 H), 2.02 (d, *J* = 14.4 Hz, 2 H), 2.19 (d, *J* = 14.4 Hz, 2 H), 2.23 (s, 6 H), 2.33 (s, 12 H), 6.49 (s, 2 H), 6.77 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 1.33 (s, 6 H), 1.66 (s, 6 H), 2.02 (d, *J* = 14.4 Hz, 2 H), 2.19 (d, *J* = 14.3 Hz, 2 H), 2.23 (s, 6 H), 2.33 (s, 12 H), 6.49 (s, 2 H), 6.77 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.2 (CH_3), 31.1 (C), 32.0 (CH_3), 32.2 (CH_3), 42.2 (CH_3), 48.3 (CH_2), 98.7 (C), 114.3 (CH), 115.9 (CH), 130.5 (C), 132.0 (C), 135.7 (C), 136.2 (C) ppm. ESI-MS: *m*/*z* = 443.62 [M + H]$^+$. $C_{37}H_{38}N_2O_2$ (442.60): calcd. C 76.74, H 9.01, N 6.63; found C 76.62, H 9.56, N 6.50.

8,8′-Bis(phenylamino)-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chromans) [(+)-6 and (–)-6]: To a stirred solution of (+)-**3** or (–)-**3** (0.1 g, 0.27 mmol) and silylaryl triflate (0.147 mL, 0.6 mmol) in $CH_3CN/CHCl_3$ (4 mL) was added CsF (0.207 g, 1.36 mmol). The reaction mixture was stirred at room temperature overnight and monitored by TLC to establish completion. The resulting solution was washed with brine (5 mL) and extracted with Et_2O (3 × 7 mL). The combined Et_2O fractions were dried with $MgSO_4$ and concentrated in vacuo. The residue was then purified by flash chromatography with silica gel (8 g) with hexane/ethyl acetate (10:1) to afford pure (+)-**6** or (–)-**6** as a pale yellow solid. **(+)-6:** Yield: 0.184 g, 87%. $[\alpha]_D^{20}$ = +135.4 (*c* = 3.9, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.41 (s, 6 H), 1.60 (s, 6 H), 2.22 (d, *J* = 14.4 Hz, 2 H), 2.24 (d, *J* = 14.4 Hz, 2 H), 2.27 (s, 6 H), 5.28 (s, 2 H), 6.71 (m, 6 H), 6.83 (t, ^3J = 7.3 Hz, 2 H), 6.85 (s, 2 H), 7.14 (t, *J* = 7.4 Hz) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4 (CH_3), 31.4 (C), 32.1 (CH_3), 32.7 (CH_3), 47.8 (CH_2), 99.5 (C), 113.3 (CH), 117.3 (CH), 117.7 (CH), 118.3 (CH), 120.5 (CH), 128.9 (CH), 129.1 (CH), 1131.3 (C), 133.1 (C), 133.4 (C), 136.8 (C), 142.6 (C) ppm. ESI-MS: *m*/*z* = 519.63 [M + H]$^+$. $C_{35}H_{38}N_2O_2$ (518.69): calcd. C 81.05, H 7.38, N 5.40; found C 81.25, H 7.50, N 5.10. **(–)-6:** Yield: 0.170 g, 80%. $[\alpha]_D^{20}$ = +135.3 (*c* = 3.9, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.41 (s, 6 H), 1.60 (s, 6 H), 2.22 (d, *J* = 14.4 Hz, 2 H), 2.24 (d, *J* = 14.4 Hz, 2 H), 2.27 (s, 6 H), 5.28 (s, 2 H), 6.71 (m, 6 H), 6.83 (t, ^3J = 7.3 Hz, 2 H), 6.85 (s, 2 H), 7.14 (t, *J* = 7.4 Hz) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4 (CH_3), 31.4 (C), 32.1 (CH_3), 32.7 (CH_3), 47.8 (CH_2), 99.5 (C), 113.3 (CH), 117.3 (CH), 117.7 (CH), 118.3 (CH), 120.5 (CH), 128.9 (CH), 129.1 (CH), 131.3 (C), 133.1 (C), 133.4 (C), 136.8 (C), 142.6 (C) ppm. ESI-MS: *m*/*z* = 519.53 [M + H]$^+$. $C_{35}H_{38}N_2O_2$ (518.69): calcd. C 81.05, H 7.38, N 5.40; found C 81.15, H 7.70, N 5.22.

8,8′-Bis(benzylideneamino)-4,4,4′,4′,6,6′-hexamethylspiro-2,2′-bi(chromans) [(+)-7 and (–)-7]: To a stirred solution of (+)-**3** or (–)-**3** (0.3 g, 0.81 mmol) in toluene (30 mL) were added molecular sieves (4 Å, 4 g) and benzaldehyde (0.197 mL, 1.88 mmol). The mixture was then refluxed in a Dean–Stark apparatus, and completion was observed after 20 h. The resulting solution was washed with H_2O (2 × 20 mL), the organic layers were combined and dried ($MgSO_4$), and the solvent was evaporated in vacuo to provide pure (+)-**7** or

(–)-**7** as a yellow solid. **(+)-7:** Yield: 0.340 g, 77%. M.p. 155–157 °C. $[\alpha]_D^{20}$ = +147.1 (*c* = 0.37, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.26 (s, 6 H), 1.36 (s, 6 H), 2.01 (d, *J* = 13.9 Hz, 2 H), 2.07 (d, *J* = 13.9 Hz, 2 H), 2.24 (s, 6 H), 6.52 (s, 2 H), 6.71 (s, 2 H), 7.39 (m, 7 H), 7.56 (m, 5 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.9 (CH_3), 31.0 (C), 32.0 (CH_3), 33.1 (CH_3), 46.5 (CH_2), 97.4 (C), 118.4 (CH), 123.7 (CH), 128.0 (CH_3), 128.4 (CH_3), 128.7 (CH_3), 130.2 (C), 130.8 (CH_3), 132.9 (C), 136.0 (CH), 136.3 (C), 139.1 (C), 142.2 (C), 161.9 (CH) ppm. ESI-MS: *m*/*z* = 543 $[M + H]^+$. $C_{37}H_{38}N_2O_2 \cdot 2.8H_2O$ (593.11): calcd. C 74.92, H 7.41, N 4.72; found C 75.07, H 7.18, N 4.72. **(–)-7:** Yield: 0.360 g, 82%. M.p. 155–157 °C. $[\alpha]_D^{20}$ = –147.2 (*c* = 0.37, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.26 (s, 6 H), 1.36 (s, 6 H), 2.01 (d, *J* = 13.9 Hz, 2 H), 2.07 (d, *J* = 13.9 Hz, 2 H), 2.24 (s, 6 H), 6.52 (s, 2 H), 6.71 (s, 2 H), 7.39 (m, 7 H), 7.56 (m, 5 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.9 (CH_3), 31.0 (C), 32.0 (CH_3), 33.1 (CH_3), 46.5 (CH_2), 97.4 (C), 118.4 (CH), 123.7 (CH), 128.0 (CH_3), 128.4 (CH_3), 128.7 (CH_3), 130.2 (C), 130.8 (CH_3), 132.9 (C), 136.0 (CH), 136.3 (C), 139.1 (C), 142.2 (C), 161.9 (CH) ppm. ESI-MS: *m*/*z* = 543 $[M + H]^+$.$C_{37}H_{38}N_2O_2 \cdot 2.0H_2O$ (578.71): calcd. C 76.79, H 7.31, N 4.84; found C 76.37, H 7.46, N 4.72.

4,4,4′,4′,6,6′-Hexamethylspiro-2,2′-bi(chroman)-8,8′-dicarbaldehyde (9): Dibromo compound **8** (2 g, 4.1 mmol) was dissolved in THF (90 mL), and the resulting solution was cooled to –78 °C. *n*BuLi (8.54 mmol, 5.35 mL, 1.6 M solution) in hexanes was added dropwise to the cooled solution. After stirring the mixture for 40 min, DMF (0.342 mL, 4.41 mmol in 0.671 mL of THF) was added to the solution of the lithium compound. After stirring the mixture at –78 °C for 2 h, the mixture was warmed to ca. 0 °C and the reaction quenched with HCl (6 N, 2 mL). The crude product was partitioned between $CHCl_3$ and H_2O, and the organic layers were combined and dried with anhydrous $MgSO_4$. The solvent was removed under reduced pressure. The crude product was purified by flash chromatography with silica gel (40 g) with hexane/ethyl acetate (10:3) to give pure **9** as a white solid. Yield: 1.180 g, 74%. M.p. 197–199 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.38 (s, 6 H), 1.59 (s, 6 H), 2.17 (d, *J* = 14.3 Hz, 2 H), 2.28 (d, *J* = 14.3 Hz, 2 H), 2.30 (s, 6 H), 7.36 (s, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.7 (CH_3), 30.6 (C), 32.2 (CH_3), 32.9 (CH_3), 46.9 (CH_2), 98.9 (C), 124.9 (C), 126.3 (CH), 131.6 (C), 133.3 (C), 133.8 (CH), 150.8 (C), 189.4 (CH) ppm. HRMS (ESI): calcd. for $C_{25}H_{28}O_4Na$ $[M^+]$ 415.1885; found 415.1877. $C_{25}H_{28}O_4 \cdot 0.4H_2O$ (399.69): calcd. C 75.13, H 7.26; found C 74.83, H 7.16.

4,4,4′,4′,6,6′-Hexamethyl-8,8′-bis{[(–)-*cis*-myrtanylimino]methyl}-spiro-2,2′-bi(chroman) (10): To a stirred solution of **9** (1.3 g, 3.31 mmol) in EtOH/$CHCl_3$ (1:1, 15 mL) was added (–)-*cis*-myrtanylamine (1.21 mL, 7.13 mmol), and the mixture was stirred at room temperature for 18 h. The solvent was then removed under reduced pressure to afford a pure diastereomeric mixture of **10** as a colorless oil. Yield: 2.112 g, 96%. ^1H NMR (200 MHz, $CDCl_3$): δ = 0.87 (m, 4 H), 0.93 (s, 6 H), 0.97 (s, 6 H), 1.08 (s, 6 H), 1.14 (s, 6 H), 1.18 (s, 12 H), 1.36 (s, 12 H), 1.60 (s, 12 H), 2.09 (m, 20 H), 3.30 (m, 8 H), 7.16 (s, 4 H), 7.41 (s, 4 H), 7.91 (s, 2 H), 7.96 (s, 2 H) ppm. HRMS (ESI): calcd. for $C_{45}H_{63}N_2O_2$ $[M^+]$ 663.4811; found 663.4815.

(4,4,4′,4′,6,6′-Hexamethyl-8,8′-bis{[(–)-*cis*-myrtanylimino]methyl}-spiro-2,2′-bi(chromans) [(+)-10 and (–)-10]: The addition of MeOH to the diastereomeric mixture **10** (1.720 g, 2.59 mmol) afforded pure (–)-**10** by selective precipitation. Pure (+)-**10** was then isolated from the mother liquor in lower yield. **(+)-10:** Yield: 0.720 g, 84%, >99% *de*. M.p. 150–152 °C. $[\alpha]_D^{20}$ = + 65, (c 0.69, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.86 (d, *J* = 9.5 Hz, 2 H), 0.94 (s, 6 H), 1.15 (s, 6 H), 1.22 (m, 2 H), 1.37 (s, 6 H), 1.58 (s, 6 H), 1.60 (s, 6 H), 1.75 (m, 2 H), 1.85 (d, *J* = 6.1 Hz, 4 H), 2.12 (d, *J* = 14.1 Hz, 2 H), 2.22 (d, *J* = 14.1 Hz, 2 H), 2.3 (m, 2 H), 3.23 (m, 2 H), 3.31 (m, 2 H), 7.16 (s, 2 H), 7.42 (s, 2 H), 7.91 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.23 (CH_3), 20.76 (CH_2), 23.26 (CH_2), 26.23 (CH), 27.94 (CH_2), 30.87 (CH), 31.96 (CH_2), 32.72 (CH_3), 33.54 (CH_3), 38.62 (C), 41.48 (CH_2), 42.11 (CH_2), 44.52 (CH_2), 47.51 (CH_3), 68.47 (CH), 98.75 (C), 124.98 (C), 125.41 (CH), 128.90 (C), 131.0 (C), 147.85 (CH), 157.27 (C) ppm. ESI-MS: *m*/*z* = 663 $[M + H]^+$. HRMS (ESI): calcd. for $C_{45}H_{63}N_2O_2$ $[M^+]$ 663.4811; found 663.4819. **(–)-10:** Yield: 0.140 g, 12%, >99% *de*. M.p. 150–152 °C. $[\alpha]_D^{20}$ = –171 (*c* = 0.69, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.87 (d, *J* = 9.6 Hz, 2 H), 0.91 (s, 6 H), 1.09 (s, 6 H), 1.22 (m, 2 H), 1.36 (s, 6 H), 1.60 (s, 6 H), 1.83 (m, 10 H), 2.11 (d, *J* = 14.1 Hz, 2 H), 2.21 (d, *J* = 14.1 Hz, 2 H), 2.23 (s, 6 H), 2.30 (m, 4 H), 3.31 (m, 4 H), 7.16 (s, 2 H), 7.41 (s, 2 H), 7.96 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.23 (CH_3), 20.76 (CH_2), 23.26 (CH_2), 26.23 (CH), 27.94 (CH_2), 30.87 (CH), 31.96 (CH_2), 32.72 (CH_3), 33.54 (CH_3), 38.62 (C), 41.48 (CH_2), 42.11 (CH_2), 44.52 (CH_2), 47.51 (CH_3), 68.47 (CH), 98.75 (C), 124.98 (C), 125.41 (CH), 128.90 (C), 131.0 (C), 147.85 (CH), 157.27 (C) ppm. ESI-MS: *m*/*z* = 663 $[M + H]^+$. HRMS (ESI): calcd. for $C_{45}H_{63}N_2O_2$ $[M^+]$ 663.4811; found 663.4813.

4,4,4′,4′,6,6′-Hexamethylspiro-2,2′-bi(chroman)-8,8′-dicarbaldehydes [(+)-9 and (–)-9]: To a stirred solution of (+)-**10** or (–)-**10** (0.120 g, 0.181 mmol) in THF (20 mL) was added HCl (0.661 mL, 18.2 mmol), and the mixture was stirred at room temperature for 30 min. H_2O (30 mL) was then added, and a white precipitate appeared, which was collected and dried under vacuum for 12 h to afford pure aldehydes (+)-**9** and (–)-**9** as white solids. **(+)-9:** Yield: 0.065 g, 92%. M.p. 197–199 °C. $[\alpha]_D^{20}$ = –147.2 (*c* = 0.37, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.38 (s, 6 H), 1.59 (s, 6 H), 2.17 (d, *J* = 14.3 Hz, 2 H), 2.28 (d, *J* = 14.3 Hz, 2 H), 2.30 (s, 6 H), 7.36 (s, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.7 (CH_3), 30.6 (C), 32.2 (CH_3), 32.9 (CH_3), 46.9 (CH_2), 98.9 (C), 124.9 (C), 126.3 (CH), 131.6 (C), 133.3 (C), 133.8 (CH), 150.8 (C), 189.4 (CH) ppm. HRMS (ESI): calcd. for $C_{25}H_{28}O_4Na$ $[M^+]$ 415.1885; found 415.1881. $C_{25}H_{28}O_4$ (392.49): calcd. C 76.50, H 7.19; found C 76.31, H 7.37. **(–)-9:** Yield: 0.066 g, 92%. M.p. 197–199 °C. $[\alpha]_D^{20}$ = +147.2 (*c* = 0.37, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.38 (s, 6 H), 1.59 (s, 6 H), 2.17 (d, *J* = 14.3 Hz, 2 H), 2.28 (d, *J* = 14.3 Hz, 2 H), 2.30 (s, 6 H), 7.36 (s, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.7 (CH_3), 30.6 (C), 32.2 (CH_3), 32.9 (CH_3), 46.9 (CH_2), 98.9 (C), 124.9 (C), 126.3 (CH), 131.6 (C), 133.3 (C), 133.8 (CH), 150.8 (C), 189.4 (CH) ppm. ESI-MS: *m*/*z* (%) = 393 $[M + H]^+$. $C_{25}H_{28}O_4$ (392.49): calcd. C 76.50, H 7.19; found C 76.31, H 7.41.

4,4,4′,4′,6,6′-Hexamethyl-8,8′-bis[(phenylimino)methyl]spiro-2,2′-bi(chroman) [(+)-11]: To a stirred solution of (+)-**9** or (–)-**9** (0.560 g, 1.43 mmol) in toluene (40 mL) were added molecular sieves (5 g) and aniline (0.3 mL, 3.28 mmol). The mixture was then refluxed in a Dean–Stark apparatus, and completion was observed after 20 h. The resulting solution was washed with H_2O (2 × 30 mL), and the organic layers were combined and dried ($MgSO_4$). The solvent was evaporated in vacuo to provide pure (+)-**11** or (–)-**11** as a white solid. **(+)-11:** Yield: 0.702 g, 91%. M.p. 214–216 °C (dec.). $[\alpha]_D^{20}$ = +234.7 (*c* = 0.37, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.39 (s, 6 H), 1.58 (s, 6 H), 2.19 (d, *J* = 14.8 Hz, 2 H), 2.26 (d, *J* = 14.8 Hz, 2 H), 2.30 (s, 6 H), 6.82 (s, 2 H), 6.84 (s, 2 H), 7.17 (t, ^3J = 7.4 Hz, 2 H), 7.28 (m, 6 H), 7.64 (s, 2 H), 8.11 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.7 (CH_3), 31.1 (C), 32.0 (CH_3), 32.8 (CH_3), 47.5 (CH_2), 99.7 (C), 115.1 (CH), 121.0 (CH), 125.0 (C), 125.4 (CH), 125.5 (CH), 128.8 (CH), 130.2 (CH), 131.7 (C),

133.3 (C), 133.8 (C), 148.8 (C), 156.3 (CH) ppm. HRMS (ESI): calcd. for $C_{37}H_{39}N_2O_2$ [M^+] 543.3012; found 543.3018. $C_{37}H_{38}N_2O_2$ (542.71): calcd. C 81.88, H 7.06, N 5.16; found C 81.85, H 7.01, N 5.20.

4,4,4′,4′,6,6′-Hexamethyl-8,8′-bis[(phenylamino)methyl]spiro-2,2′-bi(chroman) [(+)-12]: To a stirred solution of (+)-**11** (0.1 g, 0.184 mmol) in toluene (15 mL) was added portion-wise $NaBH_4$ (0.056 g, 1.48 mmol), and the mixture was stirred overnight. The resulting mixture was quenched with H_2O (5 mL), and the solvent was removed under reduced pressure. The crude product was then partitioned between CH_2Cl_2 and H_2O, and the organic layers were combined and dried with anhydrous $MgSO_4$. The solvent was removed under reduced pressure to provide pure (+)-**12** as a yellowish solid. **(+)-12:** Yield: 0.98 g, 98%. M.p. 100–102 °C. $[\alpha]_D^{20}$ = +265.5 (c = 0.41, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.37 (s, 6 H), 1.54 (s, 6 H), 2.12 (d, J = 14.2 Hz, 2 H), 2.20 (d, J = 14.2 Hz, 2 H), 2.29 (s, 6 H), 3.40 (s, 2 H), 3.89 (s, 4 H), 6.23 (dd, ^3J = 8.1, ^4J = 1.2 Hz, 4 H), 6.64 (dt, ^3J = 8.1, ^4J = 1.2 Hz, 2 H), 6.95 (s, 2 H), 7.04 (s, 2 H), 7.07 (t, ^3J = 8.1 Hz, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.9 (CH_3), 30.7 (C), 32.0 (CH_3), 33.3 (CH_3), 43.6 (CH_2), 47.1 (CH_2), 97.7 (C), 112.9 (CH), 116.9 (CH), 126.5 (CH), 127.1 (C), 127.7 (CH), 128.7 (CH), 130.8 (C), 131.9 (C), 145.9 (C), 148.0 (C) ppm. HRMS (ESI): calcd. for $C_{37}H_{43}N_2O_2$ [M^+] 547.3325; found 547.3318. $C_{37}H_{42}N_2O_2$ (546.74): calcd. C 81.28, H 7.74, N 5.12; found C 81.01, H 7.85, N 4.83.

[$Pd^{II}(OAc)_2${(–)-3}] [(–)-13]: To a sample of (–)-**3** (0.154 g, 0.42 mmol) in CH_2Cl_2 (20 mL) was added [$PdCl_2$(COD)] (0.120 g, 0.42 mmol), and the mixture was stirred at room temperature for 6 h. $Ag(OAc)_2$ was then added, and the mixture was stirred overnight. The dark brown solution was filtered through a frit containing Celite to remove the AgCl formed, and the volume was reduced under vacuum to provide complex (–)-**13** as an orange-brown solid. Yield: 0.205 g, 83%. ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.28. (s, 6 H), 1.42 (s, 6 H), 2.06 (s, 6 H), 2.14 (d, ^3J = 14.4 Hz, 2 H), 2.41 (d, ^3J = 14.4 Hz, 2 H), 2.42 (s, 6 H), 3.38 (d, ^2J = 8.6 Hz, 2 H), 5.58 (d, ^2J = 8.6 Hz, 2 H), 6.94 (s, 2 H), 7.57 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.3 (CH_3), 24.8 (CH_3), 27.1 (CH_3), 27.7 (CH_3), 33.3 (C) 53.6 (CH_2), 107.1 (C), 121.6 (CH), 122.2 (CH), 130.7 (C), 134.5 (C), 138.1 (C), 140.4 (C), 183.9 (C) ppm. ESI-MS: m/z = 543 [M + H]$^+$. $C_{37}H_{38}N_2O_2$ (542.72): calcd. C 81.88, N 5.16, H 7.06; found C 81.62, N 5.01, H 7.41.

Oxidative Kinetic Resolution of 2-Propanol: A 10 mL Schlenk flask equipped with a magnetic stir bar was charged with powdered molecular sieves (3 Å, 200 mg) and flame-dried under vacuum. After the flask was cooled under argon, ligand (–)-**3** (18 mg, 0.049 mmol), base (0.044 mmol) and a Pd source (0.0375 mmol) were added, followed by toluene (2.5 mL). The flask was evacuated and filled with O_2, and the cycle of evacuation and filling with O_2 was repeated two more times. The mixture was then incubated for 1 h at the reaction temperature indicated, and the alcohol (60 μL, 0.385 mmol) was subsequently introduced. The reaction mixture was stirred for 42 h. The mixture was cooled to room temperature and then filtered through a small plug of silica gel (ethyl acetate), and biphenyl (38.5 mg, 0.25 mmol, 0.5 equiv.) was added as an internal standard. The percent conversion was determined by GC.

CCDC-683397 (**11**), -683398 (**13**), and -683399 [(–)-**10**] contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB21EZ, UK [Fax: (+44) 1223-336-033; or E-mail: deposit@ccdc.cam.ac.uk].

Supporting Information (see footnote on the first page of this article): ORTEP plot for the X-ray structure of ligand **11**; ^{1}H and ^{13}C NMR spectra of the final ligands and intermediates, 1D and 2D NMR spectra of complex **14** and further experimental details.

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