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Synthesis and Application of Hexamethyl-1,1'-spirobiindane-based Phosphine-Oxazoline (HMSI-PHOX) Ligands in Ni-Catalyzed Asymmetric Arylation of Cyclic Aldimines

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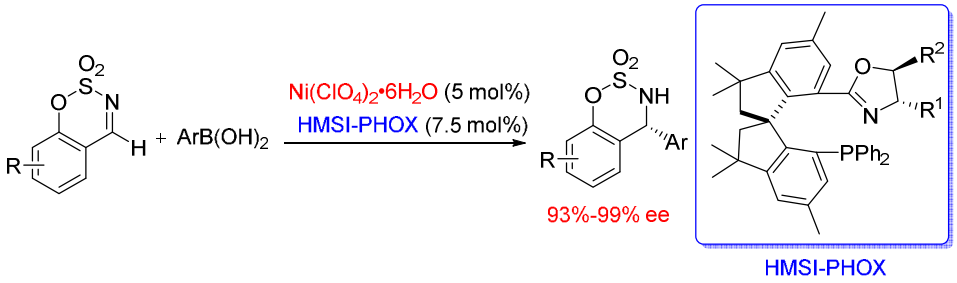


Abstract: With the vastly increasing applications of chiral phosphine-oxazoline (PHOX) hybrid ligands in various transition-metal-catalyzed reactions, novel PHOX ligands bearing innovative backbones are highly valuable and in great demand. This study describes the development of a new type of chiral PHOX ligands based on a hexamethyl-1,1'-spirobiindane scaffold and incorporating both a phosphine and an oxazoline moiety. The optimal ligand provided high yields and excellent enantioselectivities for the Ni-catalyzed asymmetric arylation of cyclic N-sulfonyl imines with arylboronic acids leading to chiral amines.

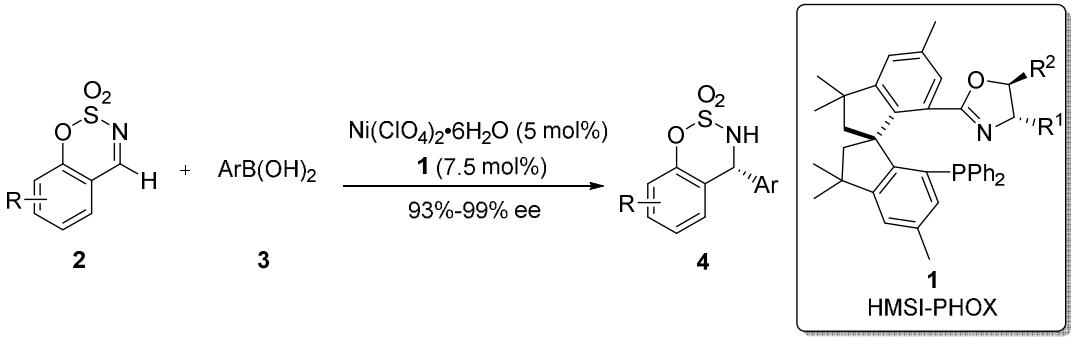
INTRODUCTION

The design and synthesis of novel chiral ligands are always a very important and challenging task in the development of efficient transition-metal-catalyzed asymmetric reactions.[1] Chiral P, N ligands play a significant role in transition-metal-catalyzed asymmetric synthesis due to its characteristics of both phosphine ligands and nitrogen ligands.[2] The chiral phosphine-oxazoline (PHOX) ligand, which coordinates to a metal center with a N- and a P-atom, is one of the more classic category among P, N ligands, and has been recognized as one of the most versatile types of chiral inducers in various transition-metal-catalyzed reactions.[3] The steric and electronic properties can be tailored for a specific application by variation of the phosphine, the oxazoline ring, and the backbone moiety due to their modular structure. As pioneering works in this area, Pfaltz, Helmchen, and Williams independently reported the first synthesis and application of PHOX in 1993.[4] After that, various kinds of skeletons such as biphenyl, hetero aryl, cyclophane, ferrocenyl, Ruthenocenyl, and binaphthyl backbones, also found successful applications in asymmetric catalysis during the past dacades, and the backbone of the chiral ligands had remarkable influence on its catalytic performance in many cases.[5]

Despite these elegant contributions, the continued innovation of novel and practical backbone of PHOX is still a highly valuable but very challenging task. On the other hand, the spiro backbone has been recognized as a privileged structure to provide an excellent platform for chiral ligand and catalyst diversification[6] since the pioneering work of Chan et al. with SpirOP.[7] In this context, Zhou group[8] and Ding group[9] have developed spirobiindane-based PHOX and spirononadiene-based PHOX respectively, which have shown impressive activity in versatile transition-metal-catalyzed asymmetric transformations. Inspired by these elegant pioneering studies, we became interested in developing the hexamethyl-1,1'-spirobiindane-PHOX ligands (HMSI-PHOX, Scheme **1**) with its readily accessible stable and rigid spiro backbone. The hexamethyl-1,1'-spirobiindane motif in HMSI-PHOX has one axially chiral center and can be easily derived from hexamethyl-1,1'-spirobiindane-6,6'-diol which is easily prepared from industrially available Bisphenol C. Herein, we report the preliminary results on the

development of one new type of chiral phosphine-oxazoline ligands based on a hexamethyl-1,1'-spirobiindane backbone (HMSI-PHOX, **1**) and their application in the Ni-catalyzed enantioselective arylation of cyclic N-sulfonyl imines with arylboronic acids. The reactions proceed smoothly under mild conditions with excellent enantioselectivities (93-99% ee), as shown in Scheme 1.

Scheme 1. Ni/HMSI-PHOX-catalyzed asymmetric arylation of cyclic aldimines

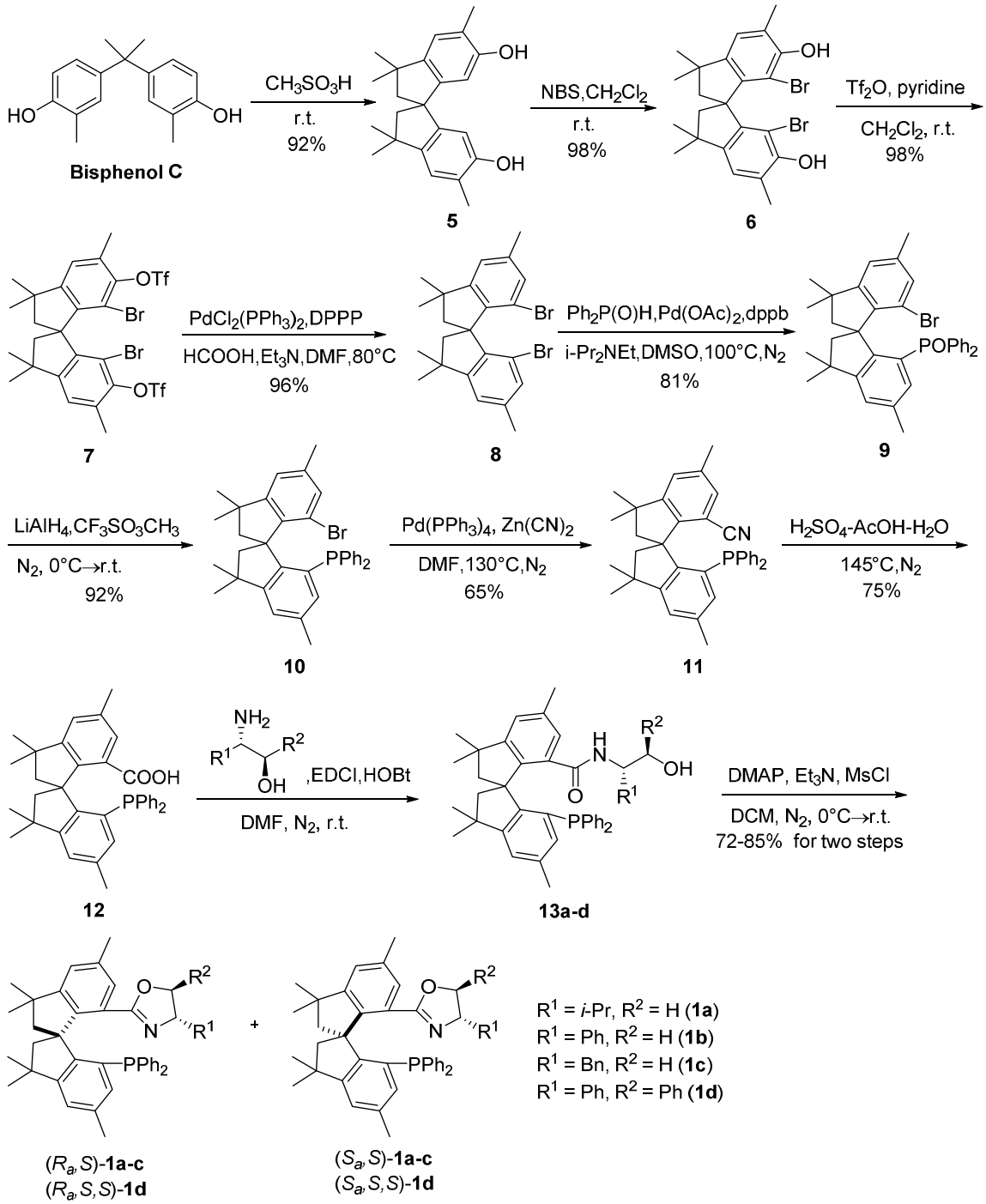


RESULTS AND DISCUSSION

As illustrated in Scheme 2, the synthesis of enantiopure HMSI-PHOX (1) ligands started from industrially available Bisphenol C. Bisphenol C was firstly converted into hexamethyl-1,1'-spirobiindane-6,6'-diol **5** in 92% yield by acid-catalyzed rearrangement in one step at room temperature on a large scale by a modified procedure.[10] Then the bromination of **5** with N-bromosuccinimide (NBS) gave the brominated product **6** in 98% yield. The subsequent esterification of **6** with trifluoromethane sulfonic anhydride afforded the ditriflate **7** in nearly quantitative yield. The Pd-catalyzed selective reduction with formic acid in DMF furnished spiro-dibromide **8** as the key intermediate in 96% yield. Then, the Pd-catalyzed cross-coupling of **8** with diphenylphosphine oxide afforded compound **9** with high selectivity despite the moderate conversion.[11] The monophosphine **10** was obtained in 92% yield by reduction of **9** with $LiAlH_4$.[12] The Pd-catalyzed reaction of **10** with zinc cyanide to afford cyanide **11** in 65% yield,[13] followed by hydrolyzing with dilute H_2SO_4 to give the acid **12** in 75% yield. The acid **12** was further transformed to the corresponding hydroxyl amides **13a-d** as a diastereomer mixture in quantitative yield by reacting with a variety of enantiopure amino alcohols in the presence of EDCI and HOBt.[14] Finally, the target ligands **1a-d** were obtained by cyclization of **13a-d** with MsCl in the

presence of triethylamine.[15] To our delight, the two diastereomers of **1a-d,** respectively, could all be readily separated by flash chromatography with high yields (72-85% for two steps from racemic **12**) to provide the enantiopure phosphine-oxazoline ligands based on a hexamethyl-1,1'-spirobiindane scaffold (HMSI-PHOX, **1**). The absolute configuration of the ligand (*S*$_a$,*S*,*S*)-**1d** was determined by X-ray crystallographic analysis of a single crystal which was obtained from diisopropyl ether (Figure 1).

Scheme 2. Synthesis of HMSI-PHOX ligands



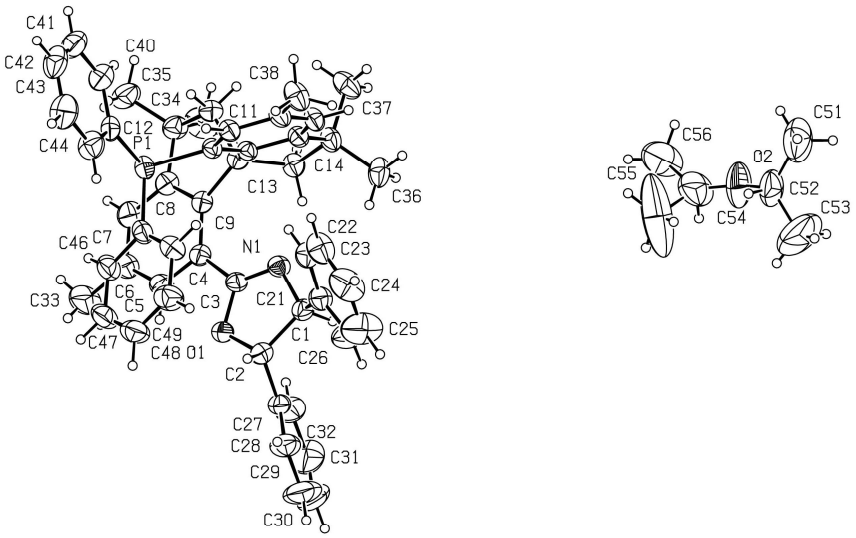
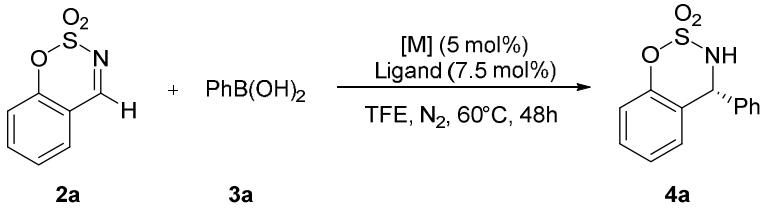


Figure 1. X-ray crystal structure of the complex of (S_a,*S*,*S*)-1d and diisopropyl ether

With the new chiral HMSI-PHOX ligands (**1**) in hand, we next evaluated the enantioselective arylation of cyclic N-sulfonyl imines with arylboronic acids. Highly efficient transition-metal-catalyzed asymmetric addition of arylboron reagents to imines to generate chiral amines is a current topic of interest,[16] and many excellent examples have been reported using Rh[17] or Pd[18] catalysts. The development of nickel catalyst which is cheap and abundant remains at the forefront and desirable, only one nice Ni-catalyzed example for such asymmetric transformation has been realized recently by the group of Zhang.[19] To our delight, with the newly synthesized (R_a,*S*)-**1a** (7.5 mol %) as the ligand and $Ni(ClO_4)_2 \cdot 6H_2O$ (5 mol %) as the catalyst precursor, the model reaction between **2a** and **3a** was initially performed in trifluoroethanol (TFE) at 60 ^oC to give the desired chiral amine **4a** with 97% ee despite in low yield (Table 1, entry 1). To our delight, when the ligand was replaced with (R_a,*S*)-**1b**, the model reaction proceeded smoothly to afford the addition product **4a** with 99% ee and in 80% yield, indicating the high efficiency of this novel chiral HMSI-PHOX ligand (Table 1, entry 2). After screening of these new chiral ligands, we found that the chirality at the spiro backbone of **1** had a significant impact on the

reactivity and asymmetric induction of the catalysis (Table 1, entries 1-8). The combination of a R_a configuration of the spiro backbone and the *S* configuration of the oxazoline moiety was revealed as the well matched case, such as in (R_a,*S*)-**1a-c** and (R_a,*S*,*S*)-**1d**. Furthermore, investigation of the substituent effect of the oxazoline moiety of ligands with a R_a configuration of the spiro backbone on the catalysis disclosed that the ligand (R_a,*S*,*S*)-**1d**, bearing two Ph group in the oxazoline moiety, was the best choice in terms of both reactivity and enantioselectivity (Table 1, entries 1-4). With the best ligand (R_a,*S*,*S*)-**1d**, the corresponding product **4a** was afforded in 88% yield and 99% ee (Table 1, entry 4). On the basis of this result, different nickel and iron salts were exampled instead of $Ni(ClO_4)_2 \cdot 6H_2O$ to give only low yield and low enantioselectivity or trace amounts of the product (Table 1, entries 9-13). Further evalutation of solvents indicated that the solvent had a remarkable impact on the reactivity and asymmetric induction of the catalysis (Table 1, entries 14-18). The experiments showed that dichloromethane, toluene, chloroform, acetonitrile and ethanol all gave a poor result with low reactivity and only moderate enantioselectivity, and trifluoroethanol was the best solvent for the Ni/HMSI-PHOX-catalyzed enantioselective arylation reaction. As a comparison, we tested the known spiro ligand (R_a,S)-Ph-Bn-SIPHOX[8] in the Ni-catalyzed asymmetric reaction with the model reaction under the current standard conditions to give the desired product in 85% yield and 97%.

Table 1. Optimization of reaction parameters[a]



2a **3a** **4a**

Entry	Ligand	[M]	Solvent	Yield [%][b]	*ee* [%][c]
1	(R_a,*S*)-**1a**	$Ni(ClO_4)_2 \cdot 6H_2O$	TFE	30	97
2	(R_a,*S*)-**1b**	$Ni(ClO_4)_2 \cdot 6H_2O$	TFE	80	99
3	(R_a,*S*)-**1c**	$Ni(ClO_4)_2 \cdot 6H_2O$	TFE	55	99

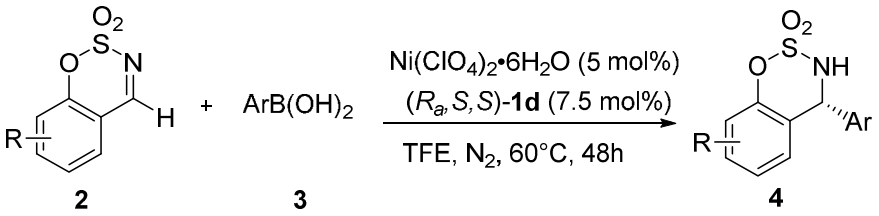
4	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	TFE	88	99
5	(S_a,*S*)-**1a**	$Ni(ClO_4)_2·6H_2O$	TFE	<10	-20
6	(S_a,*S*)-**1b**	$Ni(ClO_4)_2·6H_2O$	TFE	<10	-5
7	(S_a,*S*)-**1c**	$Ni(ClO_4)_2·6H_2O$	TFE	<10	-65
8	(S_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	TFE	trace	---
9	(R_a,*S*,*S*)-**1d**	$NiCl_2·6H_2O$	TFE	25	39
10	(R_a,*S*,*S*)-**1d**	$Ni(OAc)_2·4H_2O$	TFE	trace	---
11	(R_a,*S*,*S*)-**1d**	$FeCl_2·4H_2O$	TFE	trace	---
12	(R_a,*S*,*S*)-**1d**	$Fe(ClO_4)_2$	TFE	trace	---
13	(R_a,*S*,*S*)-**1d**	$Fe(ClO_4)_3$	TFE	trace	---
14	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	DCE	10	47
15	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	toluene	8	56
16	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	$CHCl_3$	15	61
17	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	MeCN	7	22
18	(R_a,*S*,*S*)-**1d**	$Ni(ClO_4)_2·6H_2O$	EtOH	trace	---

[a]Reactions conditions: 0.1 mmol **2a**, 0.15 mmol **3a**, 5 mol % [M], and 7.5 mol % ligand in 1 mL of solvent at 60 °C at N_2 atmosphere for 48 h. [b]Isolated yields. [c]Determined by chiral HPLC analysis.

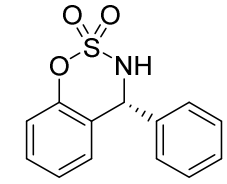
With the optimized conditions in hand, the scope of arylboronicacids was firstly examined, and the results were summarized as shown in Table 2. Notably, excellent enantioselectivity could be achieved in all case. Arylboronic acids with both electron-withdrawing (Table 2, **4b**-**4f**) and electron-donating groups (Table 2, **4g**-**4i**) afforded the corresponding products with excellent enantioselectivities (93%-99% ee). Meanwhile, the different substitution position on the benzene ring gave excellent enantioselectivities with all examples, but had significant influence on the yield. The *meta*- and *para*-substituted arylboronic acids showed outstanding performance in good to excellent yields (76%-93%), and *ortho*-substituted arylboronic acids disclosed moderate reactivity (51% yield, Table 2, **4d**).

Furthermore, biphenyl, fused-ring aryl and hetero aryl boronic acids could also afford their corresponding products with high yields and excellent enantioselectivities (Table 2, **4j**-**4l**). Besides, the scope of N-sulfonyl imine derivatives was also examined, and the results were also satisfying because the substrates possessing methyl, group on the chlorine or brominephenyl ring all gave the corresponding products in good yields (85%-94%) with 99% ee (Table 2, **4m**-**4o**). The use of acyclic imine and alkylboronic acid under the current standard reaction conditions, however, these substrates showed hydrolyzed or very low reactivity under our conditions, respectively.

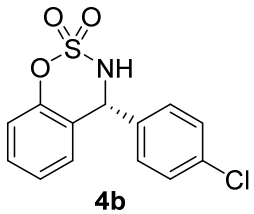
Table 2. Substate scope[a]



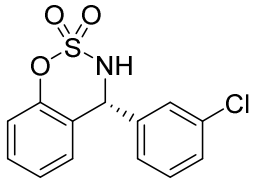
2 **3** **4**



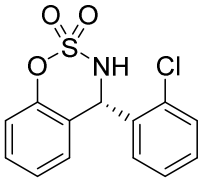
4a
88% yield, 99% *ee*



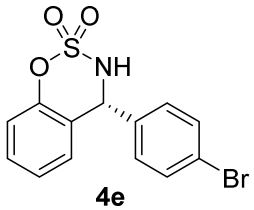
4b
93% yield, 99% *ee*



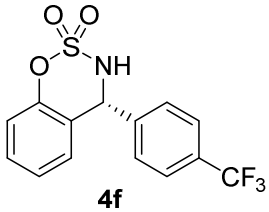
4c
91% yield, 99% *ee*



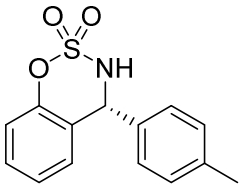
4d
51% yield, 93% *ee*



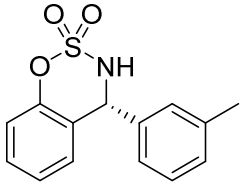
4e
91% yield, 99% *ee*



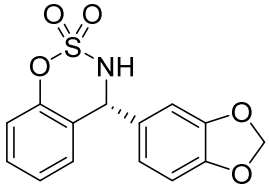
4f
76% yield, 98% *ee*



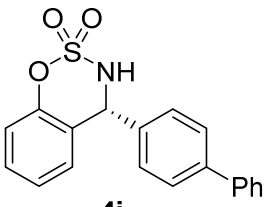
4g
87% yield, 93% *ee*



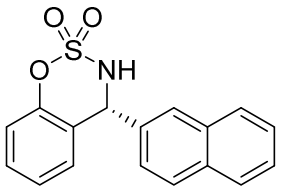
4h
91% yield, 99% *ee*



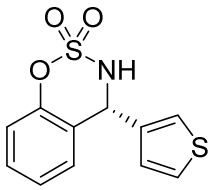
4i
88% yield, 95% *ee*



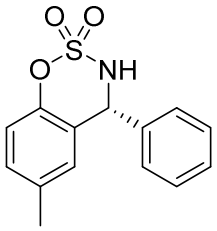
4j
92% yield, 99% *ee*



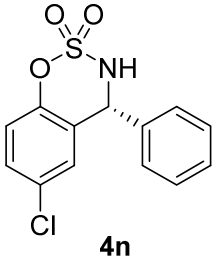
4k
90% yield, 98% *ee*



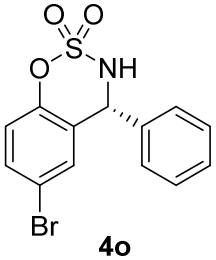
4l
82% yield, 95% *ee*



4m
94% yield, 99% *ee*



4n
88% yield, 99% *ee*



4o
85% yield, 99% *ee*

[a]Reactions conditions: 0.1 mmol of **2**, 0.15 mmol of **3**, 5 mol % $Ni(ClO_4)_2 \cdot 6H_2O$, and 7.5 mol % *(R_a,S,S)*-**1d** in 1 mL TFE at 60 °C at N_2 atmosphere for 48 h. Yields are of isolated products. Enantioselectivity was determined by chiral HPLC.

CONCLUSION

In summary, a new class of chiral phosphine-oxazoline ligands (HMSI-PHOX, **1**) based on the hexamethyl-1,1'-spirobiindanebackbone has been developed from industrially available Bisphenol C. The optimal ligand (*R_a*,*S*,*S*)-**1d** provided high yields and excellent enantioselectivities for the Ni-catalyzed asymmetric arylation of cyclic N-sulfonyl imines with a broad range of arylboronic acids leading to optically active amines. Expanding the applications of HMSI-PHOX ligands to other synthetically useful catalytic enantioselective transformations is currently under investigation in our laboratory.

Experimental Section

General information. ^{1}H NMR, ^{13}C NMR, ^{31}P NMR and ^{19}F NMR spectra were measured at 400, 100, 162 and 376 MHz spectrometer, respectively. The chemical shifts were reported relative to internal standard TMS (0) in $CDCl_3$ or DMSO. Infrared spectra were recorded on an ATR-FTIR spectrometer. HRMS were obtained using EI or ESI ionization. Optical rotation values were measured with instruments operating at λ = 589 nm, corresponding to the sodium D line at 20 °C. Enantiomeric

excesses (ee) were determined by chiral high-performance liquid chromatography. Analytical grade solvents for the column chromatography and commercially available reagents were used as received.

Synthesis of 3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene]-6,6'-diol (5).[10b] A 500 mL round bottom flask was charged with Bisphenol C (BPC, 50 g, 195 mmol) and methanesulfonic acid (250 mL). After stirring at room temperature for 3 days, additional 100 mL methanesulfonic acid was added to the mixture and the solution was allowed to stir for another 1 day. Then the mixture was directly poured into a large amount of crushed ice and filtered. The filter cake was washed with saturated $NaHCO_3$ and water. The crude product was recrystallized sequentially with ethylacetate/petroleum ether and ethanol/water to give the compound **5** (20.1 g, 92% yield) as a white solid. M.p. 249-250 ^oC; ^1H NMR (400 MHz, $CDCl_3$) δ 6.91 (s, 2H), 5.84 (s, 2H), 3.93 (s, 2H), 2.29 (d, *J* = 13.0 Hz, 2H), 2.20 (s, 6H), 2.15 (d, *J* = 13.0 Hz, 2H), 1.37 (s, 6H), 1.28 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.2, 150.1, 144.5, 123.5, 122.9, 110.5, 59.4, 57.00 43.1, 31.9, 30.1, 16.0; IR (film): γ = 3515, 2952, 2862, 1615, 1497, 1361, 1313, 858 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{23}H_{28}O_2$ [M^+] 336.2089, found 336.2085.

Synthesis of 7,7'-dibromo-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene]-6,6'-diol (6).[20] To a solution of **5** (10.1 g, 30 mmol) in CH_2Cl_2 (200 mL) was added *N*-bromosuccinimide (NBS, 11.2 g, 63 mmol) slowly and the mixture was stirred at room temperature for 4 hours. Then saturated $NaHSO_3$ (100 mL) was added and the solution was stirred for additional 30 minutes. The organic phase was washed twice with saturated brine and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure to afford a light yellow solid **6** (14.5 g, 98% yield) with enough purity for next step without further purification. M.p. 228-229 ^oC; ^1H NMR (400 MHz, $CDCl_3$) δ 6.87 (s, 2H), 5.57 (s, 2H), 2.46 (d, *J* = 13.1 Hz, 2H), 2.31 (s, 6H), 2.25 (d, *J* = 13.0 Hz, 2H), 1.39 (s, 6H), 1.32 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.2, 145.6, 142.7, 124.5, 123.6, 107.1, 60.8, 55.6, 43.1, 32.6, 29.3, 17.1; IR (film): γ = 3506, 2958, 2861, 1610, 1466, 1360, 1313, 864 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{23}H_{26}Br_2O_2$ [M^+] 492.0300, found 492.0302.

Synthesis of 7,7'-dibromo-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene]-6,6'-diyl bis(trifluoromethanesulfonate) (7). The compound **6** (12.3 g, 25 mmol) was dissolved in CH_2Cl_2 (150 mL) under nitrogen, and pyridine (8.1 mL, 100 mmol) was added in one portion. After

cooling to 0 °C, triflic anhydride (10.5 mL, 62.5 mmol) was added dropwise. The resulting mixture was naturally warmed to room temperature and stirred for 3 hours. The reaction solution was then washed with aqueous HCl (4 M), saturated $NaHCO_3$ and brine. The organic layer was dried over anhydrous Na_2SO_4 and concentrated in vacuum to obtain product **7** (18.6 g, 98% yield) as a yellow solid without further purification. M.p. 206-207 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.02 (s, 2H), 2.55 (d, *J* = 13.2 Hz, 2H), 2.45 (s, 6H), 2.30 (d, *J* = 13.2 Hz, 2H), 1.42 (s, 6H), 1.36 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.7, 145.1, 144.5, 132.6, 124.8, 118.5 (d, *J* = 320.7 Hz), 113.4, 61.3, 54.9, 43.4, 32.4, 28.8, 18.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -72.18; IR (film): γ = 2962, 2868, 1609, 1555, 1418, 1365, 1318, 846 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{25}H_{24}Br_2F_6O_6S_2$ [M^+] 755.9285, found 755.9285.

Synthesis of 7,7'-dibromo-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene] (8). To a solution of triflate **7** (15.2 g, 20 mmol), bis(triphenylphosphine) palladium dichloride (633.5 mg, 0.9 mmol), and 1,3-bis(diphenylphosphino)propane (dppp, 412.4 mg, 1 mmol) in 180 mL of DMF under nitrogen, triethylamine (33.3 mL, 240 mmol) was added in one portion at 0 °C. Then the formic acid (6.0 mL, 160 mmol) was added slowly under the ice bath, and the resulting solution was heated at 80 °C for 2 hours. The reaction system was diluted with water and extracted with ethyl acetate. The organic phase was washed with 30% aqueous H_2O_2, 10% aqueous HCl, saturated $NaHCO_3$ and brine, and dried over anhydrous Na_2SO_4. After removal of the solvent, the residue was purified by flash chromatography (ethyl acetate/petroleum ether = 1/50) to give the hexamethyl sprio dibromide **8** (8.9 g, 96% yield). White solid, m.p. 199-200 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12 (s, 2H), 6.92 (s, 2H), 2.51 (d, *J* = 13.0 Hz, 2H), 2.32 (s, 6H), 2.23 (d, *J* = 13.0 Hz, 2H), 1.41 (s, 6H), 1.33 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 142.5, 138.9, 131.9, 122.3, 119.1, 59.8, 55.4, 43.4, 32.6, 28.9, 21.0; IR (film): γ = 2954, 2861, 1602, 1558, 1459, 1360, 1316, 852 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{23}H_{26}Br_2$ [M^+] 460.0401, found 460.0404.

Synthesis of (7'-bromo-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)diphenylphosphine oxide (9). A mixture of dibromide **8** (4.62 g, 10 mmol), diphenylphosphine

oxide (4.02 g, 20 mmol), palladium acetate (224.5 mg, 1 mmol), 1,4-bis(diphenylphosphino)butane (dppb, 426.5 mg, 1 mmol), and N,N-diisopropylethylamine (7.0 mL, 40 mmol) in degassed DMSO (40 mL) was stirred at 100 ^{o}C under a dry nitrogen atmosphere for 24 hours. After cooling to room temperature, the reaction solution was diluted with water, and the aqueous phase was extracted with ethyl acetate. The organic layer was washed sequentially with 5% aqueous HCl, saturated $NaHCO_3$ and brine, and dried over anhydrous Na_2SO_4, and concentrated under reduced pressure. The resulting residue was purified by flash chromatography (ethyl acetate/petroleum ether = 1/4) to give the product **9** (2.1 g, 81% yield based of consumable **8**). White solid, m.p. 251-252 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 – 7.27 (m, 10H), 7.12 (s, 1H), 6.87 (s, 1H), 6.80 (d, *J* = 15.0 Hz, 1H), 6.27 (s, 1H), 3.45 (d, *J* = 12.2 Hz, 1H), 2.48 (d, *J* = 13.1 Hz, 1H), 2.24 (dd, *J* = 20.6, 10.4 Hz, 8H), 1.63 (s, 3H), 1.40 (s, 3H), 1.35 (s, 3H), 1.27 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.6, 155.3 (d, *J* = 10.8 Hz), 151.5 (d, *J* = 7.0 Hz), 143.6, 137.9, 137.1, 136.1, 135.5 (d, *J* = 13.2 Hz), 134.6 (d, *J* = 14.1 Hz), 131.9 (d, *J* = 3.6 Hz), 131.8 (d, *J* = 3.9 Hz), 131.4, 130.8 (dd, *J* = 16.3, 2.5 Hz), 128.1, 128.0, 127.5, 127.4, 126.7 (d, *J* = 2.7 Hz), 121.6, 119.2, 59.9 (d, *J* = 1.6 Hz), 57.0, 55.9, 44.2, 42.8, 33.4, 33.0, 28.8, 28.0, 21.4, 20.9; ^{31}P NMR (162 MHz, $CDCl_3$) δ 31.29; IR (film): γ = 2952, 2862, 1607, 1436, 1360, 1203, 1113 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{35}H_{36}OPBr$ [M^+] 582.1687, found 582.1672.

Synthesis of (7'-bromo-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)diphenylphosphane (10). To a stirred solution of phosphine oxide **9** (3.50 g, 6 mmol) in ethylene glycol dimethyl ether (DME, 40 mL) was added methyltrifluoromethanesulfonate (747 μL, 6.6 mmol) at room temperature under nitrogen. After 3 hours, the flask was immersed in an ice and lithium aluminum hydride (6 mL, 15 mmol, 2.5 mol/L in THF) was added dropwise. The resulting mixture was naturally warmed to room temperature and the mixture was stirred for 5 h, and then quenched by 1 M aqueous HCl. The organic phase was separated, and the aqueous layer was extracted with ethyl acetate. The combined extracts were washed by saturated brine and dried over anhydrous Na_2SO_4, and evaporated under reduced pressure. The residue was purified by flash chromatography (ethyl acetate/petroleum

ether = 1/50) to afford **10** (3.13 g, 92%) . White solid, m.p. 212-213 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23 – 7.14 (m, 6H), 7.07 – 6.99 (m, 4H), 6.97 (s, 1H), 6.87 (s, 1H), 6.72 (d, *J* = 4.6 Hz, 1H), 6.64 (s, 1H), 2.76 (d, *J* = 11.9 Hz, 1H), 2.55 (d, *J* = 13.1 Hz, 1H), 2.31 (d, *J* = 13.1 Hz, 1H), 2.24 (d, *J* = 5.8 Hz, 7H), 1.42 (s, 3H), 1.37 (s, 3H), 1.35 (s, 3H), 1.28 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.3 (d, *J* = 2.9 Hz), 152.9 (d, *J* = 7.7 Hz), 151.3 (d, *J* = 24.6 Hz), 144.9 (d, *J* = 4.1 Hz), 139.3 (d, *J* = 14.1 Hz), 138.6, 136.7, 136.5 (d, *J* = 13.5 Hz), 135.7 (d, *J* = 3.1 Hz), 134.1, 133.8, 133.6, 133.1, 132.9, 131.9, 131.5 (d, *J* = 20.8 Hz), 128.1 – 128.0 (m), 127.7 – 127.4 (m), 124.1, 121.9, 119.5 (d, *J* = 2.4 Hz), 59.5 (d, *J* = 3.3 Hz), 58.5 (d, *J* = 5.9 Hz), 55.7, 43.7, 42.9, 33.1, 28.9, 28.2 (d, *J* = 2.4 Hz), 21.4, 20.9; ^{31}P NMR (162 MHz, $CDCl_3$) δ -22.66; IR (film): γ = 2952, 2862, 1585, 1434, 1360, 1313, 1140 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{35}H_{36}PBr$ [M^+] 566.1738, found 566.1756.

Synthesis of 7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene]-7-carbonitrile (11). A mixture of the reduction product **10** (2.84 g, 5 mmol), $Zn(CN)_2$ (645.7 mg, 5.5 mmol), and $Pd(PPh_3)_4$ (577.8 mg, 0.5 mmol) in DMF (50 mL) was stirred at 130 ^{o}C for 36 hours under nitrogen. The reaction solution was diluted with ethyl acetate, washed sequentially with saturated $NaHCO_3$ and brine, and dried over by anhydrous Na_2SO_4. The solvent was removed in vacuum to give a product **11** (1.67 g, 65%) for next step without further purification. White solid, m.p. 220-221 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26 (dd, *J* = 12.3, 4.6 Hz, 1H), 7.23 – 7.15 (m, 5H), 7.06 (s, 1H), 7.02 (s, 1H), 6.97 (td, *J* = 9.2, 3.9 Hz, 4H), 6.69 (d, *J* = 4.1 Hz, 1H), 6.41 (s, 1H), 3.06 (dd, *J* = 13.1, 2.5 Hz, 1H), 2.44 – 2.39 (m, 1H), 2.36 (d, *J* = 1.8 Hz, 2H), 2.23 (s, 3H), 2.20 (s, 3H), 1.55 (s, 3H), 1.47 (s, 3H), 1.36 (s, 3H), 1.29 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.0 (d, *J* = 3.2 Hz), 153.3 (d, *J* = 7.6 Hz), 151.2 (d, *J* = 4.1 Hz), 150.3, 150.1, 139.2 (d, *J* = 13.5 Hz), 137.6, 137.1, 136.0 (d, *J* = 2.5 Hz), 135.3 (d, *J* = 11.2 Hz), 133.9, 133.7, 132.9 (d, *J* = 19.0 Hz), 131.5, 131.1 (d, *J* = 19.5 Hz), 128.4, 128.1 (d, *J* = 6.0 Hz), 127.9 – 127.5 (m), 127.0, 124.3, 117.2, 107.7, 58.4, 58.2 (d, *J* = 3.0 Hz), 43.6, 43.3, 33.1 (d, *J* = 2.6 Hz), 32.7, 28.6, 27.7 (d, *J* = 3.3 Hz), 21.5, 20.9; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.87; IR (film): γ = 2951, 2852, 1721, 1435, 1381, 1262, 1096, 862 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{36}H_{36}NP$ [M^+] 513.2585, found 513.2584.

Synthesis of 7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[indene]-7-carboxylic acid (12). The cyanide **11** (1.03 g, 2 mmol) was added to a solution of H_2O (15 mL), H_2SO_4 (10 mL), and AcOH (5 mL) under a nitrogen atmosphere, and the suspension was allowed to stir at 145 ^oC for 48 hours. The resulting mixture was then cooled to room temperature, diluted with water, and extracted with ethyl acetate. The organic phase was washed with brine and dried over anhydrous Na_2SO_4. After removal of the solvent, the residue was purified by flash chromatography (ethyl acetate/petroleum ether = 1/10) to afford the carboxylic acid **12** (0.80 g, 75%). White solid, m.p. 237-238 ^oC; ^1H NMR (400 MHz, DMSO) δ 12.13 (s, 1H), 7.30 (d, *J* = 6.5 Hz, 4H), 7.24 – 7.14 (m, 4H), 7.00 – 6.91 (m, 3H), 6.86 (dd, *J* = 10.9, 4.1 Hz, 2H), 6.48 (d, *J* = 4.0 Hz, 1H), 2.74 (d, *J* = 12.3 Hz, 1H), 2.32 (s, 3H), 2.21 (s, 2H), 2.18 – 2.10 (m, 4H), 1.40 (s, 3H), 1.30 (s, 3H), 1.25 (s, 3H), 1.14 (s, 3H); ^{13}C NMR (100 MHz, DMSO) δ 167.79, 153.9 (d, *J* = 2.8 Hz), 153.3 (d, *J* = 8.0 Hz), 152.6, 152.3, 147.5 (d, *J* = 3.4 Hz), 137.8 (dd, *J* = 29.7, 14.9 Hz), 136.0, 135.2, 134.4 (d, *J* = 2.6 Hz), 132.7 (d, *J* = 11.9 Hz), 132.5 877, 127.6 (d, *J* = 3.0 Hz), 126.2, 123.7, 58.8 (d, *J* = 3.5 Hz), 58.7 (d, *J* = 4.4 Hz), 56.1, 42.5, 42.1, 33.1, 32.2, 28.8, 28.6, 20.9, 20.7; ^{31}P NMR (162 MHz, DMSO) δ -23.06; IR (film): γ = 2951, 2856, 1694, 1607, 1434, 1360, 1307, 1256 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{36}H_{37}O_2P$ [M^+] 532.2531, found 532.2531.

General procedure for synthesis of HMSI-PHOX ligands (1). A solution of acid **12** (532.7 mg, 1.0 mmol), chiral amino alcohol (3.0 mmol), 1-ethyl-3-[3-(dimethylamino)propyl]carbodiimide (EDCI, 575.2 mg, 3.0 mmol) and benzotriazol-1-ol (HOBt, 405.4 mg, 3.0 mmol) in DMF (40 mL) was stirred at room temperature under nitrogen. The mixture was monitored by TLC for a complete conversion. Then the resulting solution was diluted with water and extracted with ethyl acetate. The organic layer was washed with saturated brine and dried over anhydrous Na_2SO_4. After evaporation in vacuum, the crude product **13** which could be used directly in the next step was obtained. To a solution of amide **13** (1.0 mmol) and 4-dimethlaminopridine (DMAP, 12.2 mg, 0.1 mmol) in CH_2Cl_2 (30 mL) was added triethylamine (1.1 mL, 8 mmol) and methanesulfonyl chloride (310 μL, 4 mmol) sequentially at 0 ^oC

under a nitrogen atmosphere. Then the resulting mixture was allowed to warm up to room temperature and stirred overnight. The reaction was quenched with water and extracted with CH_2Cl_2. The combined extracts were washed with brine, dried over anhydrous Na_2SO_4, and evaporated under reduced pressure. The residue was purified by silica gel column chromatography (ethyl acetate/petroleum ether = 1/20-1/10) to give a pair of diastereomers **1** as white solids.

(*S*)-2-((*R*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4-isopropyl-4,5-dihydrooxazole [(R_a,*S*)-**1a**]: 258 mg, 44% yield; white solid, m.p. 199-200 ^oC; $[\alpha]_D^{20}$ = +131 (c 0.1, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 7.39 (s, 1H), 7.22 (dd, *J* = 6.8, 3.4 Hz, 3H), 7.20 – 7.16 (m, 3H), 7.09 (td, *J* = 7.0, 3.1 Hz, 2H), 7.04 (s, 1H), 6.98 – 6.92 (m, 3H), 6.57 (d, *J* = 4.4 Hz, 1H), 3.79 – 3.68 (m, 1H), 3.41 (dd, *J* = 17.7, 9.6 Hz, 1H), 2.84 (t, *J* = 9.2 Hz, 2H), 2.39 (s, 3H), 2.28 – 2.07 (m, 6H), 1.41 (s, 3H), 1.29 (s, 6H), 1.16 – 1.06 (m, 4H), 0.89 (d, *J* = 6.6 Hz, 3H), 0.56 (d, *J* = 6.7 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.58, 152.74 (dd, *J* = 5.1, 3.9 Hz), 150.43 (d, *J* = 24.7 Hz), 145.92 (d, *J* = 2.9 Hz), 137.4 (dd, *J* = 28.6, 14.9 Hz), 135.4, 134.9, 133.6 (d, *J* = 3.0 Hz), 133.2, 133.0, 132.3 (d, *J* = 19.0 Hz), 130.4 (d, *J* = 21.7 Hz), 129.0, 127.0 (d, *J* = 6.1 Hz), 126.7 (dd, *J* = 9.8, 5.6 Hz), 124.2, 123.7 (d, *J* = 2.9 Hz), 122.1, 76.3, 76.0, 75.6, 71.5, 68.7, 57.7 (d, *J* = 3.5 Hz), 57.0 (d, *J* = 5.2 Hz), 56.3, 42.0, 41.7, 32.6, 31.7, 31.3, 28.1, 27.2, 20.1, 19.1, 17.3; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.49; IR (film): γ = 2952, 2856, 1640, 1434, 1383, 1358, 1134 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{41}H_{46}NOP$ [M^+] 599.3317,found 599.3320.

(*S*)-2-((*S*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4-isopropyl-4,5-dihydrooxazole [(S_a,*S*)-**1a**]: 244 mg, 41% yield; white solid, m.p. 190-191 ^oC; $[\alpha]_D^{20}$ = -182 (c 0.1,CH_2Cl_2);^1H NMR (400 MHz, $CDCl_3$) δ 7.47 (s, 1H), 7.22 (dd, *J* = 4.0, 2.3 Hz, 3H), 7.17 (d, *J* = 4.6 Hz, 3H), 7.13 – 7.06 (m, 2H), 7.04 (s, 1H), 7.03 – 6.97 (m, 2H), 6.96 (s, 1H), 6.55 (d, *J* = 4.5 Hz, 1H), 3.64 – 3.54 (m, 1H), 3.45 (dt, *J* = 9.8, 6.3 Hz, 1H), 2.97 (dd, *J* = 9.8, 8.2 Hz, 1H), 2.66 (d, *J* = 12.6 Hz, 1H), 2.38 (s, 3H), 2.30 – 2.13 (m, 6H), 1.68 (dt, *J* = 13.0, 6.7 Hz, 1H), 1.38 (s, 3H), 1.32 (s, 3H), 1.29 (s, 3H), 1.08 (s, 3H), 0.87 (d, *J* = 6.8 Hz, 3H), 0.77 (d, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz,

$CDCl_3$) δ 164.5, 153.7 (d, *J* = 2.6 Hz), 153.3 (d, *J* = 7.6 Hz), 151.7, 151.5, 146.1 (d, *J* = 2.9 Hz), 138.7 – 138.3 (m), 136.4, 135.7, 134.6 (d, *J* = 2.6 Hz), 133.6 (dd, *J* = 26.9, 19.6 Hz), 131.3, 131.1, 130.1, 128.0 (d, *J* = 6.3 Hz), 127.9 – 127.4 (m), 125.6, 124.5 (d, *J* = 3.5 Hz), 123.5, 77.3, 77.0, 76.7, 71.1, 68.8, 59.2 (d, *J* = 3.6 Hz), 58.0 (d, *J* = 4.3 Hz), 57.4, 42.8, 42.4, 33.3, 32.5 – 32.1 (m), 29.3, 28.9, 21.2 (d, *J* = 14.4 Hz), 18.9, 17.7; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.19; IR (film): γ = 2953, 2860, 1646, 1434, 1384, 1358, 1132 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{41}H_{46}NOP$ [M^+] 599.3317, found 599.3322.

(*S*)-2-((*R*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4-phenyl-4,5-dihydrooxazole [(R_a,*S*)-**1b**]: 250 mg, 40% yield; white solid, m.p. 67-68°C; $[\alpha]_D^{20}$ = +74 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (s, 1H), 7.24 – 7.19 (m, 3H), 7.13 – 6.94 (m, 11H), 6.90 (s, 1H), 6.73 (dd, *J* = 8.0, 6.8 Hz, 3H), 4.83 (t, *J* = 10.5 Hz, 1H), 4.21 (dd, *J* = 9.9, 8.3 Hz, 1H), 3.14 – 2.87 (m, 2H), 2.41 (s, 3H), 2.27 (d, *J* = 12.7 Hz, 2H), 2.19 (d, *J* = 13.6 Hz, 1H), 2.08 (s, 3H), 1.37 (s, 3H), 1.32 (s, 3H), 1.30 (s, 3H), 1.13 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 154.2 (d, *J* = 2.8 Hz), 153.9 (d, *J* = 7.4 Hz), 151.7 (d, *J* = 25.0 Hz), 147.7 (d, *J* = 3.0 Hz), 141.2, 138.7 (d, *J* = 13.7 Hz), 137.9 (d, *J* = 15.6 Hz), 136.6, 136.2, 135.0 (d, *J* = 2.8 Hz), 134.4, 134.2, 133.2, 133.0, 130.8, 128.0, 128.0, 127.9, 127.8, 127.6, 127.4, 127.0, 125.8, 123.9 (d, *J* = 3.0 Hz), 123.2, 73.9, 69.7, 58.8 (d, *J* = 3.4 Hz), 58.56 (d, *J* = 5.5 Hz), 57.2, 43.2, 42.8, 33.8, 32.4, 29.0, 28.0, 21.2; ^{31}P NMR (162 MHz, $CDCl_3$) δ -22.22; IR (film): γ=2950, 2856, 1635, 1434, 1381, 1359, 1266, 1137 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{44}H_{44}NOP$ [M^+] 633.3161, found 633.3161.

(*S*)-2-((*S*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4-phenyl-4,5-dihydrooxazole [(S_a,*S*)-**1b**]: 238 mg, 38% yield; white solid, m.p. 38-39°C; $[\alpha]_D^{20}$ = -138 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (s, 1H), 7.30 – 7.08 (m, 12H), 7.07 – 6.95 (m, 4H), 6.94 (s, 1H), 6.63 (d, *J* = 2.3 Hz, 1H), 4.90 – 4.56 (m, 1H), 3.82 – 3.65 (m, 1H), 3.42 – 3.30 (m, 1H), 2.84 – 2.70 (m, 1H), 2.40 (s, 3H), 2.33 – 2.16 (m, 6H), 1.33 (d, *J* = 6.0 Hz, 6H), 1.26 (s, 3H), 1.15 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.7, 154.1, 153.3 (d, *J* = 7.6 Hz), 152.1 (d, *J* = 25.3 Hz), 146.7, 142.7, 138.6 (d, *J* = 14.5 Hz), 138.0 (d, *J* = 15.1 Hz), 136.6, 135.7, 134.7, 134.0, 133.8, 133.4,

133.2, 130.5, 128.5, 128.0, 128.0, 127.8, 127.8, 127.7, 127.2, 126.6, 126.1, 123.7, 73.9, 68.6, 59.4 (d, *J* = 3.7 Hz), 58.4 (d, *J* = 4.3 Hz), 57.1, 42.9, 42.5, 33.3, 32.4, 29.2, 28.9, 21.4; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.71; IR (film): γ = 2955, 2856, 1641, 1436, 1383, 1356, 1263, 1132 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{44}H_{44}NOP$ [M^+] 633.3161, found 633.3162.

(*S*)-4-benzyl-2-((*R*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4,5-dihydrooxazole [(R_a,*S*)-**1c**]: 249 mg, 39% yield; white solid, m.p. 57-58°C; $[\alpha]_D^{20}$ = +106 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (s, 1H), 7.23 (dd, *J* = 7.0, 4.8 Hz, 5H), 7.17 (dd, *J* = 7.4, 6.1 Hz, 6H), 7.07 (s, 1H), 6.97 (ddd, *J* = 17.5, 11.6, 6.8 Hz, 5H), 6.64 (d, *J* = 4.4 Hz, 1H), 4.10 (qd, *J* = 9.3, 4.1 Hz, 1H), 3.75 (t, *J* = 8.7 Hz, 1H), 3.04 (dd, *J* = 13.7, 4.1 Hz, 1H), 2.89 – 2.71 (m, 2H), 2.41 (s, 3H), 2.25 (d, *J* = 10.8 Hz, 4H), 2.20 – 2.06 (m, 2H), 1.73 (dd, *J* = 13.6, 10.7 Hz, 1H), 1.37 (s, 3H), 1.31 (d, *J* = 1.9 Hz, 6H), 1.08 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.6, 154.0 (d, *J* = 7.4 Hz), 153.87 151.3, 146.8, 138.6, 138.3, 138.2 (d, *J* = 3.0 Hz), 136.6, 136.0, 134.8 (d, *J* = 2.8 Hz), 134.3, 134.1, 133.4, 133.2, 131.6 (d, *J* = 21.8 Hz), 130.1, 128.7, 128.4, 128.1, 128.0, 127.8 (d, *J* = 2.0 Hz), 127.8, 126.2, 125.7, 124.2, 123.4, 71.7, 67.2, 58.9 (d, *J* = 3.6 Hz), 58.0 (d, *J* = 4.9 Hz), 57.3, 43.0, 42.7, 41.8, 33.6, 32.2, 29.2, 28.4, 21.4, 21.2; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.80; IR (film): γ = 2950, 2856, 1646, 1434, 1379, 1359, 1132 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{45}H_{46}NOP$ [M^+] 647.3317, found 647.3313.

(*S*)-4-benzyl-2-((*S*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4,5-dihydrooxazole [(S_a,*S*)-**1c**]: 246 mg, 38% yield; white solid, m.p. 61-62°C; $[\alpha]_D^{20}$ = -125 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 (s, 1H), 7.29 – 7.23 (m, 2H), 7.23 – 7.14 (m, 7H), 7.07 (dd, *J* = 10.4, 3.3 Hz, 5H), 7.01 – 6.95 (m, 2H), 6.92 (s, 1H), 6.59 (d, *J* = 3.9 Hz, 1H), 4.05 – 3.91 (m, 1H), 3.52 (dd, *J* = 8.3, 6.2 Hz, 1H), 3.12 (t, *J* = 8.8 Hz, 1H), 2.87 (dd, *J* = 13.9, 4.3 Hz, 1H), 2.75 (d, *J* = 12.5 Hz, 1H), 2.39 (s, 3H), 2.29 – 2.17 (m, 3H), 2.15 (s, 3H), 2.04 (dd, *J* = 13.8, 10.2 Hz, 1H), 1.39 (s, 3H), 1.33 (s, 3H), 1.30 (s, 3H), 1.13 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.3, 154.0 (d, *J* = 2.6 Hz), 153.4 (d, *J* = 8.1 Hz), 152.2 (d, *J* = 25.1 Hz), 146.5 (d, *J* = 3.4 Hz), 138.7 (d, *J* =

14.3 Hz), 138.5, 138.2 (d, J = 15.4 Hz), 136.4, 135.7, 134.7 (d, J = 2.7 Hz), 133.9, 133.7, 133.3, 133.2, 130.8 (d, J = 20.9 Hz), 130.1, 129.0, 128.4, 128.0, 128.0, 127.8 – 127.7 (m), 127.6, 126.2, 125.8, 124.1 (d, J = 2.9 Hz), 123.7, 70.5, 66.8, 59.3 (d, J = 3.9 Hz), 58.3 (d, J = 4.2 Hz), 57.0, 42.8, 42.4, 41.1, 33.2, 32.4, 29.2, 28.9, 21.2, 21.1; ^{31}P NMR (162 MHz, $CDCl_3$) δ -21.96; IR (film): γ = 2950, 2856, 1652, 1434, 1381, 1356, 1132 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{45}H_{46}NOP$ [M^+] 647.3317, found 647.3318.

(4*S*,5*S*)-2-((*R*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4,5-diphenyl-4,5-dihydrooxazole [(R_a,*S*,*S*)-**1d**]: 258 mg, 36% yield; white solid, m.p. 213-214°C; $[\alpha]_D^{20}$ = +94 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (s, 1H), 7.25 – 7.18 (m, 6H), 7.11 (ddd, J = 12.0, 7.4, 4.6 Hz, 5H), 7.05 – 6.90 (m, 8H), 6.87 (s, 1H), 6.81 (d, J = 4.5 Hz, 1H), 6.64 (s, 1H), 6.62 (s, 1H), 4.62 (d, J = 10.5 Hz, 1H), 4.14 (d, J = 10.5 Hz, 1H), 3.03 (d, J = 12.4 Hz, 1H), 2.45 (s, 3H), 2.29 – 2.16 (m, 3H), 2.10 (s, 3H), 1.33 (s, 3H), 1.22 (s, 3H), 1.13 (s, 3H), 1.00 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.5, 154.4, 154.4, 154.3, 151.6 (d, J = 24.6 Hz), 148.1 (d, J = 2.9 Hz), 140.4, 139.4, 138.8, 138.7, 137.8, 137.6, 136.7, 136.3, 135.1, 135.0, 133.2, 133.0, 131.1, 130.8 (d, J = 22.0 Hz), 128.4, 128.1, 128.0, 128.0, 127.9, 127.6, 127.4, 127.0, 126.3, 126.0, 124.1 (d, J = 2.9 Hz), 123.1, 89.2, 78.7, 58.7, 58.7, 58.4, 58.4, 57.1, 43.3, 42.9, 34.1, 32.3, 29.1, 27.3, 21.2; ^{31}P NMR (162 MHz, $CDCl_3$) δ -22.26; IR (film): γ = 2950, 2852, 1639, 1605, 1454, 1384, 1264, 1136 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{50}H_{48}NOP$ [M^+] 709.3474, found 709.3478.

(4*S*,5*S*)-2-((*S*)-7'-(diphenylphosphanyl)-3,3,3',3',5,5'-hexamethyl-2,2',3,3'-tetrahydro-1,1'-spirobi[inden]-7-yl)-4,5-diphenyl-4,5-dihydrooxazole [(S_a,*S*,*S*)-**1d**]: 256 mg, 36% yield; white solid, m.p. 167-168°C; $[\alpha]_D^{20}$ = -43 (c 0.1, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, J = 0.9 Hz, 1H), 7.25 – 7.05 (m, 15H), 6.97 (ddd, J = 11.2, 7.9, 2.8 Hz, 4H), 6.77 – 6.53 (m, 4H), 4.85 (d, J = 9.8 Hz, 1H), 4.67 (d, J = 9.8 Hz, 1H), 2.90 (d, J = 12.5 Hz, 1H), 2.56 (d, J = 12.9 Hz, 1H), 2.41 (d, J = 12.4 Hz, 4H), 2.18 (d, J = 12.5 Hz, 1H), 2.07 (s, 3H), 1.32 (d, J = 11.3 Hz, 9H), 1.13 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.2, 154.0 (d, J = 3.0 Hz), 153.3, 153.0, 151.3 (d, J = 8.0 Hz), 145.7 (d, J = 4.2 Hz), 140.2, 138.7, 135.5,

134.6, 134.0 (d, J = 3.1 Hz), 133.4, 133.2, 131.8, 131.6, 129.6, 129.0 (d, J = 20.1 Hz), 127.3, 127.2, 127.0, 126.9, 126.9, 126.8, 126.6, 126.5, 126.2, 125.9, 125.8, 125.3, 125.2, 123.1, 122.7, 86.9, 77.7, 58.7, 58.7, 54.5, 41.7, 41.4, 32.2, 32.1, 27.7, 27.6, 27.6, 20.3, 20.1; ^{31}P NMR (162 MHz, $CDCl_3$) δ -22.33; IR (film): γ = 2951, 2852, 1646, 1605, 1454, 1384, 1260, 1130 cm^{-1}; HRMS (GC-TOF, EI) *m/z* calcd for $C_{50}H_{48}NOP$ [M^+] 709.3474, found 709.3467.

General Procedure for Asymmetric Arylation. A Schlenk tube was charged with $Ni(ClO_4)_2 \cdot 6H_2O$ (1.8 mg, 0.005 mmol), (R_a,*S*,*S*)-**1d** (5.3 mg, 0.0075 mmol), and TFE (0.5 mL) under a nitrogen atmosphere. The mixture was stirred at 60 °C for 30 minutes. Then the substrate **2** (0.1 mmol) and aryl boronic acid **3** (0.15 mmol) were added and the wall of the tube was rinsed with additional 0.5 mL of TFE. The reaction mixture was stirred at 60 °C for 48 hours monitored by TLC. After cooling to room temperature, the solution was concentrated under reduced pressure, and the residue was purified by flash chromatography on silica gel (ethyl acetate/petroleum ether = 1/6) to obtain the corresponding product **4**. (*R*)-4-phenyl-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4a**)[21]: 23 mg, 88% yield; white solid; m.p. 131-132°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 10.2 min, t_R (minor) 11.7 min; $[\alpha]_D^{20}$ = +28.2 (*c* 0.10, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (dd, J = 6.5, 3.7 Hz, 3H), 7.39 – 7.29 (m, 3H), 7.10 (t, J = 7.7 Hz, 2H), 6.83 (d, J = 7.6 Hz, 1H), 5.91 (s, 1H), 4.70 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.4, 136.8, 128.7, 128.5, 128.4, 127.8, 127.5, 124.2, 120.9, 117.8, 60.9; IR (film): γ = 3282, 1580, 1423, 1203, 1171, 1101, 846 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_{10}NO_3S^-$ [M-H]$^-$ 260.0381, found 260.0397.

(*R*)-4-(4-chlorophenyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4b**)[19]: 28 mg, 93% yield; white solid; m.p. 139-140°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 7.3 min, t_R (minor) 9.8 min; $[\alpha]_D^{20}$ = +8.5 (*c* 0.20, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.27 (m, 5H), 7.15 – 7.03 (m, 2H), 6.80 (d, J = 7.8 Hz, 1H), 5.88 (d, J = 8.4 Hz, 1H), 4.86 (d, J = 8.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.4, 136.29, 135.6, 130.2, 130.0, 129.7,

128.4, 125.4, 121.4, 119.0, 61.2; IR (film): γ = 3274, 1581, 1425, 1202, 1170, 1092, 849 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9ClNO_3S^-$ $[M-H]^-$ 293.9992, found 293.9997.

(*R*)-4-(3-chlorophenyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4c**)[21]: 27 mg, 91% yield; white solid; m.p. 104-105°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 95/5, 220 nm,1.0 mL/min), t_R (minor) 8.8 min, t_R (major) 11.5 min; $[\alpha]_D^{20}$ = +16.6 (*c* 0.28, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.32 (m, 4H), 7.28 – 7.23 (m, 1H), 7.11 (ddd, *J* = 23.4, 11.7, 4.6 Hz, 2H), 6.83 (d, *J* = 7.8 Hz, 1H), 5.87 (s, 1H), 4.79 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.4, 139.6, 135.3, 130.8, 130.0, 129.8, 129.0, 128.4, 127.1, 125.4, 121.2, 119.0, 61.4; IR (film): γ = 3276, 1581, 1425, 1203, 1172, 1101, 857cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9ClNO_3S^-$ $[M-H]^-$ 293.9992, found 293.9997.

(*S*)-4-(2-chlorophenyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4d**)[21]: 15 mg, 51% yield; light yellow solid; m.p. 114-115°C; 93% ee; HPLC analysis: Chiralpak IF-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 6.2 min, t_R (minor) 7.6 min; $[\alpha]_D^{20}$ = +29.8 (*c* 0.08, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 7.51 – 7.45 (m, 1H), 7.44 – 7.29 (m, 4H), 7.15 – 7.05 (m, 2H), 6.78 (d, *J* = 7.7 Hz, 1H), 6.30 (s, 1H), 5.09 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.4, 134.9, 134.0, 131.3, 130.9, 130.8, 129.8, 127.8, 127.6, 125.4, 121.1, 118.9, 59.6; IR (film): γ = 3280, 1581, 1427, 1374, 1203, 1172, 1101, 847cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9ClNO_3S^-$ $[M-H]^-$ 293.9992, found 293.9999.

(*R*)-4-(4-bromophenyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4e**)[19]: 31 mg, 91% yield; white solid; m.p. 126-127°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 7.6 min, t_R (minor) 10.2 min; $[\alpha]_D^{20}$ = +10.2 (*c* 0.23, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 7.61 – 7.55 (m, 2H), 7.35 (td, *J* = 7.9, 0.8 Hz, 1H), 7.25 – 7.20 (m, 2H), 7.11 (ddd, *J* = 9.1, 6.8, 1.0 Hz, 2H), 6.81 (d, *J* = 7.8 Hz, 1H), 5.88 (s, 1H), 4.70 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.4, 135.8, 131.6, 129.5, 128.9, 127.4, 124.3, 122.8, 120.3, 117.9, 60.3; IR (film): γ= 3276, 1581, 1426, 1371, 1203, 1170, 1099, 849 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9BrNO_3S^-$ $[M-H]^-$ 337.9487, found 337.9493.

(*R*)-4-(4-(trifluoromethyl)phenyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4f**)[19]: 25 mg, 76% yield; light yellow solid; m.p. 119-120°C; 98% ee; HPLC analysis: Chiralpak IF-3 (hexane/i-PrOH = 90/10, 220 nm,0.8 mL/min), t_R (minor) 5.9 min, t_R (major) 6.8 min; $[\alpha]_D^{20}$ = +34.3 (*c* 0.07, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, *J* = 8.2 Hz, 2H), 7.43 (d, *J* = 8.1 Hz, 2H), 7.30 (dd, *J* = 11.5, 4.2 Hz, 1H), 7.12 – 7.00 (m, 2H), 6.73 (d, *J* = 7.7 Hz, 1H), 5.91 (s, 1H), 4.72 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.5, 140.6, 130.8 (d, *J* = 32.8 Hz), 129.1, 128.3, 127.3, 125.4 (d, *J* = 3.7 Hz), 124.4, 122.6 (d, *J* = 272.4 Hz), 120.0, 118.1, 60.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.80 (s, 3F); IR (film): γ = 3274, 1582, 1427, 1326, 1205, 1171, 853 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{14}H_9F_3NO_3S^-$ $[M-H]^-$ 328.0255, found 328.0268.

(*R*)-4-(*p*-tolyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4g**)[21]: 24 mg, 87% yield; white solid; m.p. 120-121°C; 93% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 95/5, 220 nm,1.0 mL/min), t_R (major) 16.0 min, t_R (minor) 17.4 min; $[\alpha]_D^{20}$ = +18.7 (*c* 0.12, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 (t, *J* = 7.7 Hz, 1H), 7.27 – 7.17 (m, 4H), 7.07 (dd, *J* = 15.6, 8.0 Hz, 2H), 6.82 (d, *J* = 7.8 Hz, 1H), 5.86 (s, 1H), 4.73 (s, 1H), 2.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.4, 138.6, 133.9, 129.1, 128.6, 127.64, 127.5, 124.1, 121.2, 117.7, 60.7, 20.2; IR (film): γ = 3276, 1580, 1424, 1370, 1203, 1170, 1100, 850 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{14}H_{12}NO_3S^-$ $[M-H]^-$ 274.0538, found 274.0540.

(*R*)-4-(*m*-tolyl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4h**)[21]: 25 mg, 91% yield; white solid; m.p. 83-84°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 95/5, 220 nm,1.0 mL/min), t_R (major) 15.0 min, t_R (minor) 17.4 min; $[\alpha]_D^{20}$ = +12.1 (*c* 0.31, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (dd, *J* = 12.2, 4.8 Hz, 2H), 7.27 – 7.20 (m, 1H), 7.09 (ddd, *J* = 15.0, 10.9, 2.6 Hz, 4H), 6.82 (d, *J* = 7.8 Hz, 1H), 5.85 (s, 1H), 4.72 (s, 1H), 2.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.5, 139.4, 137.8, 130.3, 129.7, 129.4, 129.3, 128.6, 125.8, 125.2, 122.1, 118.8, 62.0, 21.4; IR (film): γ = 3277, 1581, 1421, 1370, 1198, 1170, 1101, 879 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{14}H_{12}NO_3S^-$ $[M-H]^-$ 274.0538, found 274.0541.

(*R*)-4-(benzo[*d*][1,3]dioxol-5-yl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4i**)[19]: 27 mg, 88% yield; white solid; m.p. 127-128°C; 95% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (minor) 17.3 min, t_R (major) 18.1 min; $[\alpha]_D^{20}$ = +21.0 (*c* 0.10, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (t, *J* = 7.7 Hz, 1H), 7.17 – 6.98 (m, 2H), 6.92 – 6.79 (m, 3H), 6.73 (s, 1H), 6.00 (s, 2H), 5.80 (t, *J* = 8.2 Hz, 1H), 4.73 (d, *J* = 8.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.4, 148.6, 148.5, 131.5, 129.7, 128.6, 125.2 , 122.9 , 122.0, 118.8, 108.8, 108.7, 101.6, 61.8; IR (film): γ = 3277, 1580, 1423, 1370, 1202, 1170, 1096, 836 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{14}H_{10}NO_5S^-$ $[M-H]^-$ 304.0280, found 304.0286.

(*R*)-4-([1,1'-biphenyl]-4-yl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4j**)[19]: 31 mg, 92% yield; white solid; m.p. 167-168°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 12.5 min, t_R (minor) 14.4 min; $[\alpha]_D^{20}$ = +17.0 (*c* 0.10, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, *J* = 8.2 Hz, 2H), 7.62 – 7.54 (m, 2H), 7.46 (dd, *J* = 10.3, 4.7 Hz, 2H), 7.38 (ddd, *J* = 24.0, 11.4, 6.0 Hz, 4H), 7.10 (dd, *J* = 14.8, 7.9 Hz, 2H), 6.89 (d, *J* = 7.7 Hz, 1H), 5.95 (d, *J* = 8.5 Hz, 1H), 4.77 (d, *J* = 8.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.5, 142.5, 140.0, 136.7, 129.82, 129.2, 128.9, 128.6, 128.1, 127.9, 127.1, 125.3, 121.9, 118.9, 61.7; IR (film): γ = 3278, 1580, 1423, 1371, 1204, 1170, 1100, 851 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for$C_{19}H_{14}NO_3S^-$ $[M-H]^-$ 336.0694, found 336.0705

(*R*)-4-(naphthalen-2-yl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4k**)[21]: 28 mg, 90% yield; white solid; m.p. 138-139°C; 98% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 90/10, 220 nm,1.0 mL/min), t_R (major) 11.4 min, t_R (minor) 18.3 min; $[\alpha]_D^{20}$ = -48.3 (*c* 0.10, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.81 (m, 4H), 7.61 – 7.50 (m, 2H), 7.40 – 7.30 (m, 2H), 7.17 – 7.03 (m, 2H), 6.85 (d, *J* = 7.8 Hz, 1H), 6.09 (d, *J* = 11.3 Hz, 1H), 4.79 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.5, 134.9, 133.5, 133.1, 129.8, 129.7, 128.8, 128.6, 128.1, 127.9, 127.2, 127.0, 125.3, 125.2, 122.0, 118.9, 62.2; IR (film): γ = 3276, 1580, 1421, 1365, 1204, 1171, 1099, 865 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{17}H_{12}NO_3S^-$ $[M-H]^-$ 310.0538, found 310.0544.

(*S*)-4-(thiophen-3-yl)-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4l**)[19]: 22 mg, 82% yield; white solid; m.p. 130-131°C; 95% ee; HPLC analysis: Chiralpak IF-3 (hexane/i-PrOH = 90/10, 220 nm,0.8 mL/min), t_R (minor) 9.9 min, t_R (major) 12.9 min; $[\alpha]_D^{20}$ = +59.2 (*c* 0.07, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (ddd, *J* = 4.3, 3.9, 2.3 Hz, 2H), 7.37 – 7.30 (m, 1H), 7.12 (td, *J* = 7.7, 1.0 Hz, 1H), 7.05 (dd, *J* = 8.3, 0.8 Hz, 1H), 7.01 (dd, *J* = 4.9, 1.4 Hz, 1H), 6.94 (d, *J* = 7.8 Hz, 1H), 6.04 (d, *J* = 8.7 Hz, 1H), 4.79 (d, *J* = 8.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.1, 138.0, 129.8, 128.2, 127.9, 126.6, 125.9 , 125.2, 121.6, 118.8, 56.9; IR (film): γ = 3275, 1580, 1423, 1368, 1195, 1170, 1100, 863 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{11}H_8NO_3S_2^-$ $[M-H]^-$ 265.9946, found 265.9943.

(*R*)-6-methyl-4-phenyl-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4m**)[21]: 26 mg, 94% yield; white solid; m.p. 125-126°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 95/5, 220 nm,1.0 mL/min), t_R (major) 20.1 min, t_R (minor) 21.9 min; $[\alpha]_D^{20}$ = +57.0 (*c* 0.10, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.42 (m, 1H), 7.39 – 7.31 (m, 1H), 7.12 (dd, *J* = 8.4, 1.9 Hz, 1H), 6.97 (d, *J* = 8.4 Hz, 1H), 6.60 (s, 1H), 5.86 (s, 1H), 4.65 (s, 1H), 2.21 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.4, 137.0, 134.0, 129.3, 128.5, 128.4, 127.8, 127.5, 120.4, 117.5, 60.9, 19.7; IR (film): γ = 3276, 1488, 1422, 1370, 1176, 1109, 856 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{14}H_{12}NO_3S^-$ $[M-H]^-$ 274.0538, found 274.0530.

(*R*)-6-chloro-4-phenyl-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4n**)[21]: 26 mg, 88% yield; white solid; m.p. 137-138°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 98/2, 220 nm,0.8 mL/min), t_R (major) 34.6 min, t_R (minor) 40.7 min; $[\alpha]_D^{20}$ = +33.9 (*c* 0.22, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 2.9 Hz, 3H), 7.38 – 7.28 (m, 3H), 7.04 (d, *J* = 8.8 Hz, 1H), 6.81 (d, *J* = 1.3 Hz, 1H), 5.86 (s, 1H), 4.71 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.9, 135.9, 129.5, 128.9 (d, *J* = 1.5 Hz), 128.6, 127.7, 127.2, 122.5, 119.2, 60.7; IR (film): γ = 3279, 1473, 1426, 1371, 1204, 1169, 1111, 847 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9ClNO_3S^-$ $[M-H]^-$ 293.9992, found 293.9994.

(*R*)-6-bromo-4-phenyl-3,4-dihydrobenzo[*e*][1,2,3]oxathiazine-2,2-dioxide (**4o**)[19]: 29 mg, 85% yield; white solid; m.p. 154-155°C; 99% ee; HPLC analysis: Chiralpak IC-3 (hexane/i-PrOH = 98/2, 220

nm,0.8 mL/min), t_R (major) 40.3 min, t_R (minor) 45.3 min; $[\alpha]_D^{20}$ = +37.8 (*c* 0.23, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 7.52 – 7.41 (m, 4H), 7.33 (dd, *J* = 6.3, 3.2 Hz, 2H), 6.96 (dd, *J* = 11.0, 5.4 Hz, 2H), 5.87 (s, 1H), 4.75 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.5, 137.0, 132.8, 131.2, 129.9, 129.7, 128.7, 124.0, 120.7, 118.0, 61.7; IR (film): γ = 3266, 1471, 1417, 1368, 1200, 1167, 1111, 845 cm^{-1}; HRMS (ESI-TOF) *m/z* calcd for $C_{13}H_9BrNO_3S^-$ $[M-H]^-$ 337.9487, found 337.9486.

ASSOCIATED CONTENT

Supporting Information

This Supporting Information is available free of charge via the Internet at http://pubs.acs.org.

copies of ^1H, ^{13}C, ^{19}F NMR and HPLC traces; crystallographic data for the complex of (*S*$_a$,*S*,*S*)-**1d** and diisopropyl ether (CIF).

Accession Codes

CCDC 1814373 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

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