Organic LETTERS

Letter

Cite This: Org. Lett. XXXX, XXX, XXX−XXX

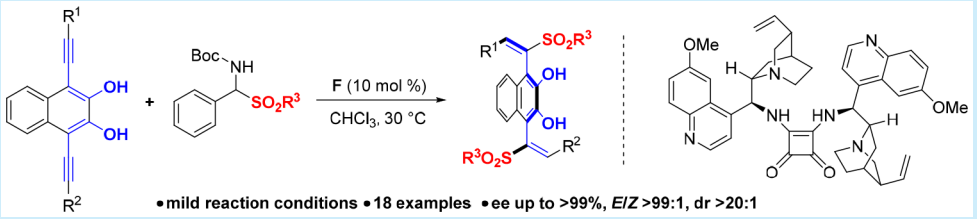
pubs.acs.org/OrgLett

Organocatalytic Asymmetric Atroposelective Construction of Axially Chiral 1,4-Distyrene 2,3-Naphthalene Diols

Shan Li, Da Xu, Fangli Hu, Dongmei Li, Wenling Qin, and Hailong Yan*

Chongqing Key Laboratory of Natural Product Synthesis and Drug Research, School of Pharmaceutical Sciences, Chongqing University, Chongqing 401331, P. R. China

Supporting Information

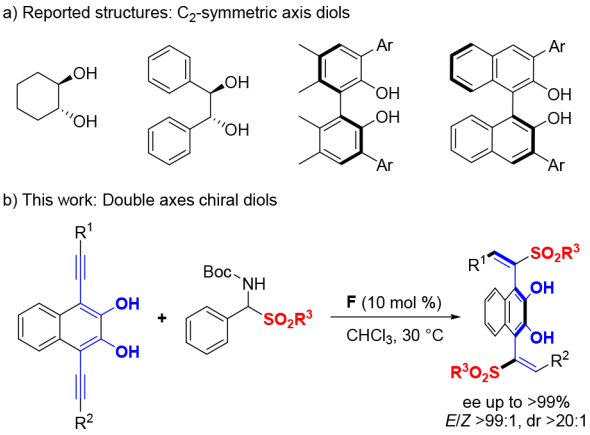


ABSTRACT: An efficient organocatalytic construction of enantioenriched axially chiral 1,4-distyrene 2,3-naphthalene diols through the nucleophilic addition of α-amido sulfone to in situ generated vinylidene *o*-quinone methide is described. The reaction pathway was investigated by isolating reaction intermediates and performing a kinetic resolution process. Axially chiral 1,4-distyrene 2,3-naphthalene diol was used as the chiral ligand for the enantioselective addition of diethylzinc to naphthalene formaldehyde. The preliminary results revealed that these adducts could be potentially used as ligands in asymmetric synthesis.

Diols are prominent feature of a number of biologically active natural products such as Taxol, isolobophytolide, and TAN-1085.[1] In addition, chiral diols are also widely used as chiral ligands and auxiliaries in stereoselective synthesis such as cyclohexyl glycol, hydrobenzoin, and axially chiral diaryl diols.[2] As a result, synthetic approaches toward the construction of these scaffolds have attracted considerable attention, and many practical methods have already been achieved.[3] The chiral diols commonly used as catalysts or ligands are C_2-symmetric diols that bear two hydroxyl groups in a tunable dihedral angle to meet the coordination requirements and one rigid C_2-symmetric axis to play a fundamental cooperative role in the stereochemical control (Scheme 1a).[4] To our knowledge, chiral diols bearing two hydroxyl groups in a single plane (no angle) along with two chiral axes remain largely unaddressed, probably due to a lack of reliable synthetic routes to atroposelectively construct two contiguous enantioenriched chiral axes. Therefore, it is necessary to develop a synthetic approach to construct two chiral axes surrounding the diols to afford novel axial chirality compounds.

In order to develop new and practical organocatalytic atroposelective methods for the preparation of highly functionalized axially chiral styrene, we envisaged that two units of axially chiral styrene could be installed into the positions 1 and 4 of naphthalene 2,3-diols to accomplish the introduction of chiral circumvents to vicinal diols. The key to this scenario is the construction of the axially chiral styrene skeleton, which represents a formidable challenge in asymmetric synthesis due to the relatively low-rotation energy to racemization and the difficulty in controlling the enantioselectivity.[5] Consequently, few methods are available for their atroposelective synthesis in an operationally simple and scalable fashion. The current strategies include palladium-catalyzed enantioselective arylation of hydrazones and aryl bromide,[6] organocatalytic atroposelective direct Michael reaction of diones to alkynals,[7] and organocatalytic nucleophilic addition of the vinylidene *o*-quinone methide (VQM)[8] intermediate by sulfone. However, all of the reported methods afforded products bearing only a single chiral styrene axis. A method for constructing two continuous chiral styrene axes has not yet been reported. Our research group has been engaged in developing new and

Scheme 1. Reported C_2-Symmetric Axis Diols and This Work



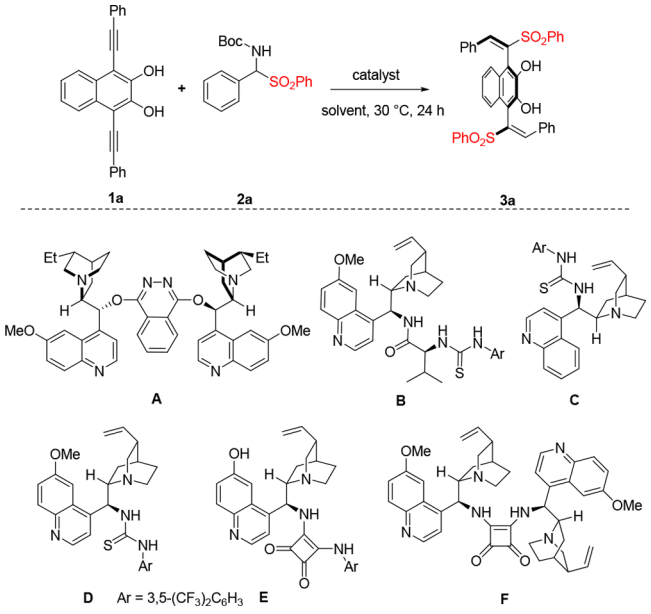
Received: October 23, 2018

DOI: 10.1021/acs.orglett.8b03398
Org. Lett. XXXX, XXX, XXX−XXX

practical methods for the construction of axially chiral compounds based on VQM intermediate.[8c−f] We presumed that two moieties of VQM could be generated in one naphthalene, followed by a formal stereoselective nucleophilic addition to install two chiral styrene units. Thus, a new kind of chiral axis skeleton bearing two continuous chiral styrene axes arose. Herein, we describe an organocatalytic atroposelective synthesis of 1,4-distyrene compounds bearing a 2,3-diol motif allowing the construction of novel axial chiral scaffolds for the development of chiral ligands or catalysts for asymmetric synthesis.

Initially, we began our studies with 1,4-bis(phenylethynyl)-naphthalene 2,3-diol **1a** and α-amido sulfone **2a** as model substrates. In the presence of dimeric cinchona alkaloid derivative catalyst **A**, the reaction proceeded smoothly with good yield, while the enantioselectivity (ee = 7%) (Table 1, entry 1) and diastereoselectivity were quite poor (Table 1, entry 1). This might be ascribed to a lack of hydrogen-bonding donors. Therefore, we turned our attention to cinchona-derived catalysts with hydrogen-bonding donors. Thiourea-based catalysts **B**−**D** were selected for further screening. The enantioselectivities of the reactions were dramatically increased compared to catalyst **A**. Both catalysts **C** and **D** showed excellent stereoselectivity. Nevertheless, the yields of reactions catalyzed by thiourea-based catalysts were generally low. Quinine-derived squaramides, which had a longer distance between the two donor hydrogen atoms than that of thioureas, had been successfully employed in a wide range of asymmetric reactions as hydrogen-bonding donor catalysts.[9] Cinchona squaramide catalysts **E** and **F** gave excellent enantiocontrol and afforded **3a** in higher yields. Eventually, biscinchona squaramide catalyst **F** afforded an improved chemical yield while retaining the stereoselectivity under the same conditions (88%, ee >99%, dr >20:1) (Table 1, entry 6). All of the solvents tested for the reaction were catalyzed by catalyst **F** (Table 1, entries 6−11), and chloroform was proven to be the optimal solvent with respect to enantioselectivity and yield (Table 1, entry 6). Finally, the reaction proceeded smoothly with retained enantioselectivity by using 10 mol % of catalyst **F** in chloroform at 30 °C.

Table 1. Optimization of Reaction Conditions[a]



entry	catalyst	solvent	yield[b] (%)	ee[c] (%)	dr[d]
1	**A**	$CHCl_3$	85	7	1:1
2	**B**	$CHCl_3$	30	90	1:1
3	**C**	$CHCl_3$	36	>−99	10:1
4	**D**	$CHCl_3$	50	>99	>20:1
5	**E**	$CHCl_3$	75	>99	>20:1
6	**F**	$CHCl_3$	**88**	**>99**	**>20:1**
7	**F**	CH_2Cl_2	77	>99	>20:1
8	**F**	toluene	79	>99	>20:1
9	**F**	CH_3CN	72	99	>20:1
10	**F**	Et_2O	<5		
11	**F**	THF	<5		

[a]Reaction conditions: **1a** (0.05 mmol), **2a** (0.1 mmol), catalyst (10 mol %) in solvent (1.0 mL) at 30 °C for 24 h, unless otherwise specified. [b]Isolated yield. [c]The ee value was determined by HPLC analysis. [d]Diastereomeric ratio (dr) was determined by ^{1}H NMR.

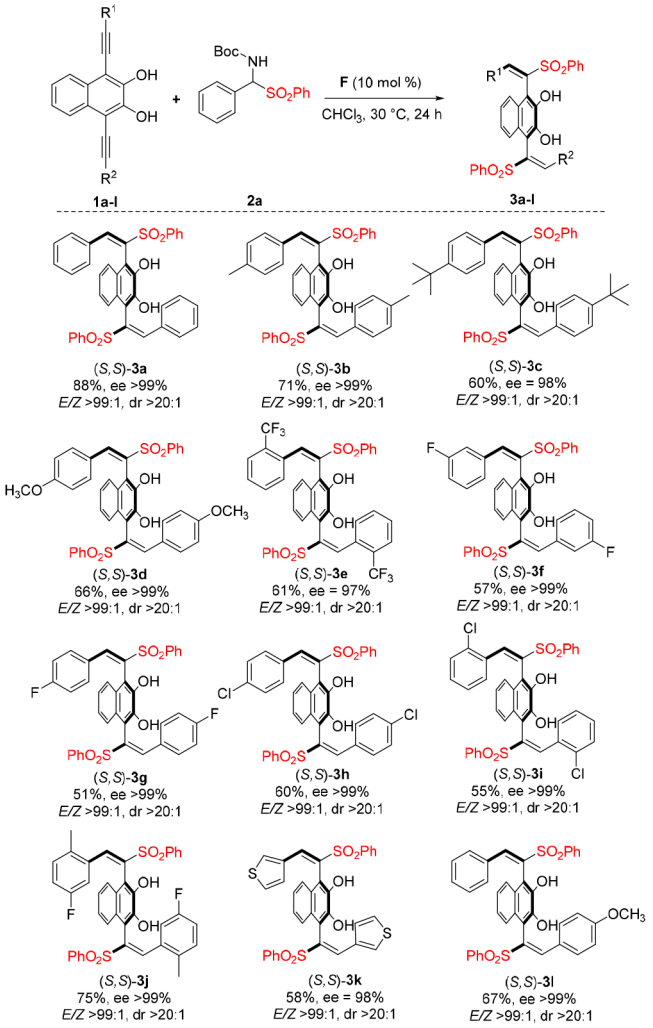
After establishing the optimal catalyst **F** and experimental procedure, we expanded **1** toward the nucleophilic addition of **2a**. Substrates with electron-donating groups on the *para* position of the R group proceeded smoothly to give the desired adducts **3b**, **3c**, and **3d** in excellent stereoselectivity (ee up to 99%, dr >20:1) with moderate yields. The electron-withdrawing groups at different positions of R appeared to have a limited effect on stereoselectivity (**3e**−**i**) (Scheme 2). All of the substrates gave excellent enantioselectivities, and a significantly lower reaction rate was observed. The absolute configuration of product **3h** was determined by X-ray crystallographic analysis, while others were assigned by analogue. The substrate with 5-fluoro-2-methyl-disubstituted R also afforded the desired product **3j** with excellent stereocontrol (ee >99%) under the standard reaction conditions, demonstrating that the substrate scope was not limited to monosubstituted substrates. Changing the phenyl group into a more useful heterocyclic ring, such as thiophene, almost had no influence on the reaction stereoselectivity and still gave excellent results (**3k**) (Scheme 2). When the substrate was asymmetric (R^1 = C_6H_5, R^2 = 4-$MeOC_6H_4$), the reaction also proceeded smoothly to afford the desired product with good results (**3l**) (Scheme 2).

To further evaluate the substrate scope, we then investigated a series of substitution groups on the sulfone moiety of α-amido sulfones. The results are outlined in Scheme 3. Regardless of the type of substituents on the aromatic rings of sulfone, bearing electron-donating (**3m**) (Scheme 3) or electron-withdrawing (**3n**−**p**) (Scheme 3) groups on the *para* position, the reactions of these α-amido sulfones gave axially chiral distyrene diols with high stereoselectivities and good reactivities. Notably, 3-chloro-4-methyl-disubstituted α-amido sulfone also led to the desired adduct with excellent stereoselectivity and good yield (**3q**) (Scheme 3). An aliphatic substitution group on the sulfone moiety also is tolerated to our reaction system. A high enantioselectivity of 99% ee was also obtained, although the diastereoselectivity and chemical yield were decreased.

In order to gain insight into the reaction process, we performed an experiment to monitor the reaction with thin-layer chromatography (TLC). We found that, at an early stage of the reaction, two new spots appeared simultaneously. At the beginning of the reaction, intermediate (*S*)-**3aa** with high enantioselectivity (ee = 97%) was isolated, and product (*S*,*S*)-**3a** was also formed with excellent enantioselectivity (ee >99%)

DOI: 10.1021/acs.orglett.8b03398
Org. Lett. XXXX, XXX, XXX−XXX

Scheme 2. Substrate Scope[a]

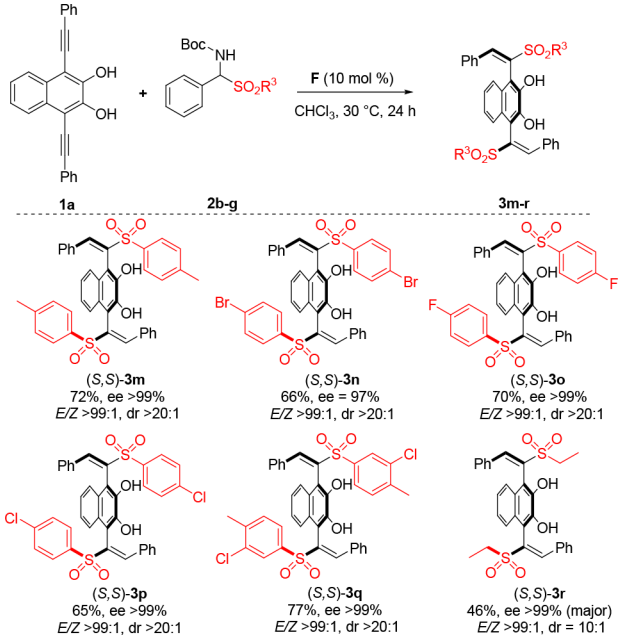


[a]Reaction conditions: **1** (0.2 mmol), **2a** (0.4 mmol), **F** (10 mol %) in $CHCl_3$ (2.0 mL) at 30 °C for 24 h, unless otherwise specified.

(Scheme 4a). In the later stage, the reaction experienced a change in two different trends. The intermediate (*S*)-**3aa** disappeared with the increase in final product (*S,S*)-**3a**. To further understand the reaction process of the second step, we performed a kinetic resolution reaction with racemic (±)-**3aa** as substrate. As shown in Scheme 4b, the racemic (±)-**3aa** was treated with 0.5 equiv of **2a** under the standard reaction conditions. After 40 min, optically pure (*S,S*)-**3a** (ee = 94%) was successfully formed. The *s* value of this kinetic resolution process was 50 (see the Supporting Information (SI) for details). This observation indicated that this reaction could be explored as a kinetic resolution process. Our catalytic system has a strong stereocontrol even in the second reaction step.

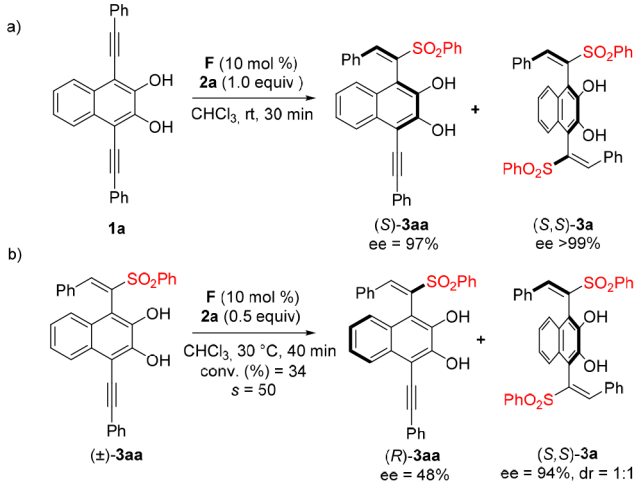
Mechanistically, we assume a stepwise process initiated by a conjugate addition of the in situ generated sulfone anion to the VQM which is generated through an enantioselective prototropic rearrangement (tautomerization) in the presence of quinine-derived squaramide catalyst **F** (Scheme 5). The activation of the α-amido sulfone with quinine-derived squaramide catalyst **F** appears necessary for increasing its nucleophilicity and facilitating the conjugate addition. Next, repeating the above-mentioned reaction pathway gives the final product (*S,S*)-**3a** with excellent enantioselectivity.

Scheme 3. Substrate Scope[a]



[a]Reaction conditions: **1a** (0.2 mmol), **2** (0.4 mmol), **F** (10 mol %) in $CHCl_3$ (2.0 mL) at 30 °C for 24 h, unless otherwise specified.

Scheme 4. Mechanistic Experiments[a]

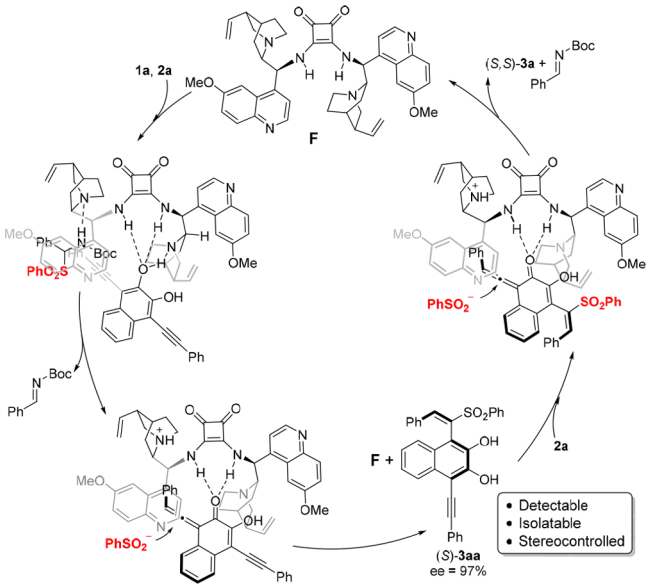


[a]For reaction conditions, see the SI. The ee value was determined by HPLC analysis.

Additionally, to further demonstrate the utility of the obtained chiral 1,4-distyrene 2,3-naphthalene diols in synthesis, especially used as organocatalysts or ligands, we first performed a scaled-up experiment (see the SI for details). The reaction proceeded smoothly to give the product on gram scale without the loss of stereoselectivity and yield. Next, we tested the configurational stability of the product by heating a solution of (*S,S*)-**3a** in DCE at 80 °C for 24 h. Chiral HPLC analysis showed that the ee was unaffected (see the SI for details). Thus, we further investigated the obtained chiral 1,4-distyrene 2,3-naphthalene diol (*S,S*)-**3a** as a ligand for the enantioselective addition of diethylzinc to naphthalene formaldehyde, which was considered to be one of standard reactions to test the reactivity and enantioselectivity of newly designed chiral ligands.[10] As a result, product (*S,S*)-**3a** showed

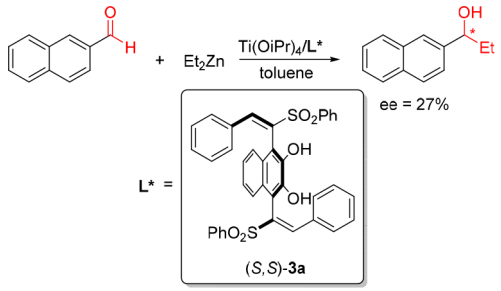
DOI: 10.1021/acs.orglett.8b03398
Org. Lett. XXXX, XXX, XXX−XXX

Scheme 5. Proposed Mechanism



the role as ligand in this reaction and gave chiral *sec*-alcohols with an enantiomeric excess of 27% under unmodified reaction conditions (Scheme 6).

Scheme 6. Preliminary Application in Addition of Diethylzinc to Aldehyde[a]



[a]For reaction conditions, see the SI. The ee value was determined by HPLC analysis.

In conclusion, we have developed an organocatalytic atroposelective approach for the construction of axially chiral 1,4-distyrene 2,3-naphthalene diols with excellent stereoselectivities (ee up to 99%, dr >20:1). The reaction proceeded through nucleophilic addition of α-amido sulfone to VQM and gave 1,4-distyrene 2,3-naphthalene diols with high atroposelectivity. The reaction process was demonstrated by isolating and identifying the reaction intermediates and performing kinetic resolution experiments. The preliminary investigation indicated the potential of axially chiral 1,4-distyrene 2,3-naphthalene diols as ligands for asymmetric synthesis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b03398.

Experimental procedures and characterization data for all of the products (PDF)

Accession Codes

CCDC 1864091 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.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: yhl198151@cqu.edu.cn.

ORCID

Hailong Yan: 0000-0003-3378-0237

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study was supported by the Scientific Research Foundation of China (Grant No. 21772018) and the Chongqing Science and Technology Commission (cstc2017jcyjAX0389).

■ REFERENCES

(1) (a) Marshall, J. A.; Andrews, R. C. Stereoselective Total Synthesis of (±)-Isolobophytolide, A Marine Cembranolide Natural Product. *Tetrahedron Lett.* **1986**, *27*, 5197−5200. (b) Nicolaou, K. C.; Yang, Z.; Liu, J. J.; Ueno, H.; Nantermet, P. G.; Guy, R. K.; Claiborne, C. F.; Renaud, J.; Couladouros, E. A.; Paulvannan, K.; Sorensen, E. J. Total Synthesis of Taxol. *Nature* **1994**, *367*, 630−634. (c) Nicolaou, K. C.; Yang, Z.; Liu, J.-J.; Nantermet, P. G.; Claiborne, C. F.; Renaud, J.; Guy, R. K.; Shibayama, K. Total Synthesis of Taxol. 3. Formation of Taxol's ABC Ring Skeleton. *J. Am. Chem. Soc.* **1995**, *117*, 645−652. (d) Fu, G. C. Pinacol Coupling. *Modern Carbonyl Chemistry* **2000**, 69−91. (e) Shen, X.; Jones, G. O.; Watson, D. A.; Bhayana, B.; Buchwald, S. L. Enantioselective Synthesis of Axially Chiral Biaryls by the Pd-Catalyzed Suzuki-Miyaura Reaction: Substrate Scope and Quantum Mechanical Investigations. *J. Am. Chem. Soc.* **2010**, *132*, 11278−11287. (f) Ohmori, K.; Mori, K.; Ishikawa, Y.; Tsuruta, H.; Kuwahara, S.; Harada, N.; Suzuki, K. Concise Total Synthesis and Structure Assignment of TAN-1085**. *Angew. Chem., Int. Ed.* **2004**, *43*, 3167−3171.

(2) (a) Pu, L. 1.1′-Binaphthyl Dimers, Oligomers, and Polymers: Molecular Recognition, Asymmetric Catalysis, and New Materials. *Chem. Rev.* **1998**, *98*, 2405−2494. (b) Chen, Y.; Yekta, S.; Yudin, A. K. Modified BINOL Ligands in Asymmetric Catalysis. *Chem. Rev.* **2003**, *103*, 3155−3211. (c) Brunel, J. M. BINOL: A Versatile Chiral Reagent. *Chem. Rev.* **2005**, *105*, 857−897. (d) Brunel, J. M. Update 1 of: BINOL: A Versatile Chiral Reagent. *Chem. Rev.* **2007**, *107*, PR1−PR45. (e) Rauniyar, V.; Zhai, H.; Hall, D. G. Catalytic Enantioselective Allyl- and Crotylboration of Aldehydes Using Chiral Diol•$SnCl_4$ Complexes. Optimization, Substrate Scope and Mechanistic Investigations. *J. Am. Chem. Soc.* **2008**, *130*, 8481−8490.

(3) (a) Jacobsen, E. N.; Markó, I.; Mungall, W. S.; Schröder, G.; Sharpless, K. B. Asymmetric Dihydroxylation via Ligand-Accelerated Catalysis. *J. Am. Chem. Soc.* **1988**, *110*, 1968−1970. (b) Zhang, W.; Loebach, J. L.; Wilson, S. R.; Jacobsen, E. N. Enantioselective Epoxidation of Unfunctionalized Olefins Catalyzed by (Salen)-manganese Complexes. *J. Am. Chem. Soc.* **1990**, *112*, 2801−2803. (c) Kolb, H. C.; VanNieuwenhze, M. S.; Sharpless, K. B. Catalytic Asymmetric Dihydroxylation. *Chem. Rev.* **1994**, *94*, 2483−2547. (d) Li, X.; Yang, J.; Kozlowski, M. C. Enantioselective Oxidative Biaryl Coupling Reactions Catalyzed by 1,5-Diazadecalin Metal Complexes. *Org. Lett.* **2001**, *3*, 1137−1140. (e) Ishihara, K.; Nakashima, D.; Hiraiwa, Y.; Yamamoto, H. The Crystallographic Structure of a Lewis Acid-Assisted Chiral Brønsted Acid as an

DOI: 10.1021/acs.orglett.8b03398
Org. Lett. XXXX, XXX, XXX−XXX

Enantioselective Protonation Reagent for Silyl Enol Ethers. *J. Am. Chem. Soc.* **2003**, *125*, 24−25. (f) Shi, Y. Organocatalytic Asymmetric Epoxidation of Olefins by Chiral Ketones. *Acc. Chem. Res.* **2004**, *37*, 488−496. (g) Egami, H.; Matsumoto, K.; Oguma, T.; Kunisu, T.; Katsuki, T. Enantioenriched Synthesis of C_1-Symmetric BINOLs: Iron-Catalyzed Cross-Coupling of 2-Naphthols and Some Mechanistic Insight. *J. Am. Chem. Soc.* **2010**, *132*, 13633−13635. (h) Guo, F.; Konkol, L. C.; Thomson, R. J. Enantioselective Synthesis of Biphenols from 1,4-Diketones by Traceless Central-to-Axial Chirality Exchange. *J. Am. Chem. Soc.* **2011**, *133*, 18−20. (i) Ma, G.; Sibi, M. P. Catalytic Kinetic Resolution of Biaryl Compounds. *Chem. - Eur. J.* **2015**, *21*, 11644−11657. (j) Chen, Y.-H.; Cheng, D.-J.; Zhang, J.; Wang, Y.; Liu, X.-Y.; Tan, B. Atroposelective Synthesis of Axially Chiral Biaryldiols via Organocatalytic Arylation of 2-Naphthols. *J. Am. Chem. Soc.* **2015**, *137*, 15062−15065. (k) Wang, J.-Z.; Zhou, J.; Xu, C.; Sun, H.; Kürti, L.; Xu, Q.-L. Symmetry in Cascade Chirality-Transfer Processes: A Catalytic Atroposelective Direct Arylation Approach to BINOL Derivatives. *J. Am. Chem. Soc.* **2016**, *138*, 5202−5205.

(4) (a) Quallich, G. J.; Keavey, K. N.; Woodall, T. M. Enantioselective Synthesis of C_2-Symmetric Diols. *Tetrahedron Lett.* **1995**, *36*, 4729−4732. (b) Burda, E.; Bauer, W.; Hummel, W.; Gröger, H. Enantio- and Diastereoselective Chemoenzymatic Synthesis of C2-Symmetric Biaryl-Containing Diols. *ChemCatChem* **2010**, *2*, 67−72. (c) Gabrieli, S.; Cirilli, R.; Benincori, T.; Pierini, M.; Rizzo, S.; Rossi, S. BITHIENOLs: Promising C_2-Symmetric Biheteroaromatic Diols for Organic Transformation. *Eur. J. Org. Chem.* **2017**, *2017*, 861−870.

(5) (a) Kawabata, T.; Yahiro, K.; Fuji, K. Memory of Chirality: Enantioselective Alkylation Reactions at an Asymmetric Carbon Adjacent to a Carbonyl Group. *J. Am. Chem. Soc.* **1991**, *113*, 9694−9696. (b) Baker, R. W.; Hambley, T. W.; Turner, P.; Wallace, B. J. Central to Axial Chirality Transfer *via* Double Bond Migration: Asymmetric Synthesis and Determination of the Absolute Configuration of Axially Chiral 1-(3′-Indenyl)Naphthalenes. *Chem. Commun.* **1996**, 2571−2572. (c) Kumarasamy, E.; Raghunathan, R.; Sibi, M. P.; Sivaguru, J. Nonbiaryl and Heterobiaryl Atropisomers: Molecular Templates with Promise for Atropselective Chemical Transformations. *Chem. Rev.* **2015**, *115*, 11239−11300. (d) Jolliffe, J. D.; Armstrong, R. J.; Smith, M. D. Catalytic Enantioselective Synthesis of Atropisomeric Biaryls by a Cation-Directed *O*-Alkylation. *Nat. Chem.* **2017**, *9*, 558−562.

(6) (a) Feng, J.; Li, B.; He, Y.; Gu, Z. Enantioselective Synthesis of Atropisomeric Vinyl Arene Compounds by Palladium Catalysis: A Carbene Strategy. *Angew. Chem., Int. Ed.* **2016**, *55*, 2186−2190. (b) Pan, C.; Zhu, Z.; Zhang, M.; Gu, Z. Palladium-Catalyzed Enantioselective Synthesis of 2-Aryl Cyclohex-2-enone Atropisomers: Platform Molecules for the Divergent Synthesis of Axially Chiral Biaryl Compounds. *Angew. Chem., Int. Ed.* **2017**, *56*, 4777−4781. (c) Feng, J.; Li, B.; Jiang, J.; Zhang, M.; Ouyang, W.; Li, C.; Fu, Y.; Gu, Z. Visible Light Accelerated Vinyl C-H Arylation in Pd-Catalysis: Application in the Synthesis of ortho Tetra-substituted Vinylarene Atropisomers. *Chin. J. Chem.* **2018**, *36*, 11−14.

(7) Zheng, S.-C.; Wu, S.; Zhou, Q.; Chung, L. W.; Ye, L.; Tan, B. Organocatalytic Atroposelective Synthesis of Axially Chiral Styrenes. *Nat. Commun.* **2017**, *8*, 15238−15246.

(8) (a) Furusawa, M.; Arita, K.; Imahori, T.; Igawa, K.; Tomooka, K.; Irie, R. Base-Catalyzed Schmittel Cycloisomerization of *o*-Phenylenediynelinked Bis(arenol)s to Indeno[1,2-c]chromenes. *Tetrahedron Lett.* **2013**, *54*, 7107−7110. (b) Beppu, S.; Arae, S.; Furusawa, M.; Arita, K.; Fujimoto, H.; Sumimoto, M.; Imahori, T.; Igawa, K.; Tomooka, K.; Irie, R. Stereoselective Intramolecular Dearomatizative [4 + 2] Cycloaddition of Linked Ethynylnaphthol-Benzofuran Systems. *Eur. J. Org. Chem.* **2017**, *2017*, 6914−6918. (c) Wu, X.; Xue, L.; Li, D.; Jia, S.; Ao, J.; Deng, J.; Yan, H. Organocatalytic Intramolecular [4 + 2] Cycloaddition between In Situ Generated Vinylidene *ortho*-Quinone Methides and Benzofurans. *Angew. Chem., Int. Ed.* **2017**, *56*, 13722−13726. (d) Jia, S.; Chen, Z.; Zhang, N.; Tan, Y.; Liu, Y.; Deng, J.; Yan, H. Organocatalytic Enantioselective Construction of Axially Chiral Sulfone-Containing Styrenes. *J. Am. Chem. Soc.* **2018**, *140*, 7056−7060. (e) Li, D.; Tan, Y.; Peng, L.; Li, S.; Zhang, N.; Liu, Y.; Yan, H. Asymmetric Mannich Reaction and Construction of Axially Chiral Sulfone-Containing Styrenes in One Pot from α-Amido Sulfones Based on the Waste-Reuse Strategy. *Org. Lett.* **2018**, *20*, 4959−4963. (f) Liu, Y.; Wu, X.; Li, S.; Xue, L.; Shan, C.; Zhao, Z.; Yan, H. Organocatalytic Atroposelective Intramolecular [4 + 2] Cycloaddition: Synthesis of Axially Chiral Heterobiaryls. *Angew. Chem., Int. Ed.* **2018**, *57*, 6491−6495. (g) Arae, S.; Beppu, S.; Kawatsu, T.; Igawa, K.; Tomooka, K.; Irie, R. Asymmetric Synthesis of Axially Chiral Benzocarbazole Derivatives Based on Catalytic Enantioselective Hydroarylation of Alkynes. *Org. Lett.* **2018**, *20*, 4796−4800.

(9) (a) Malerich, J. P.; Hagihara, K.; Rawal, V. H. Chiral Squaramide Derivatives are Excellent Hydrogen Bond Donor Catalysts. *J. Am. Chem. Soc.* **2008**, *130*, 14416−14417. (b) Alemán, J.; Parra, A.; Jiang, H.; Jørgensen, K. A. Squaramides: Bridging from Molecular Recognition to Bifunctional Organocatalysis. *Chem. - Eur. J.* **2011**, *17*, 6890−6899. (c) Chauhan, P.; Mahajan, S.; Kaya, U.; Hack, D.; Enders, D. Bifunctional Amine-Squaramides: Powerful Hydrogen-Bonding Organocatalysts for Asymmetric Domino/Cascade Reactions. *Adv. Synth. Catal.* **2015**, *357*, 253−281.

(10) (a) Mori, M.; Nakai, T. Asymmetric Catalytic Alkylation of Aldehydes with Diethylzinc Using a Chiral Binaphthol-Titanium Complex. *Tetrahedron Lett.* **1997**, *38*, 6233−6236. (b) Zhang, F.-Y.; Yip, C.-W.; Cao, R.; Chan, A. S. C. Enantioselective Addition of Diethylzinc to Aromatic Aldehydes Catalyzed by Ti(BINOL) Complex. *Tetrahedron: Asymmetry* **1997**, *8*, 585−589. (c) Pu, L.; Yu, H.-B. Catalytic Asymmetric Organozinc Additions to Carbonyl Compounds. *Chem. Rev.* **2001**, *101*, 757−824.

DOI: 10.1021/acs.orglett.8b03398
Org. Lett. XXXX, XXX, XXX−XXX