OL Organic Letters

pubs.acs.org/OrgLett Letter

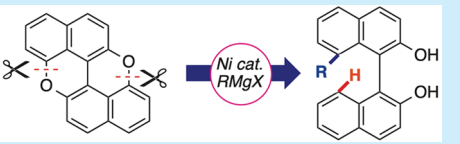
Nickel-Catalyzed Ring-Opening C−O Functionalization of *peri*-Xanthenoxanthenes for 8-Substituted Binaphthol Synthesis

Naoki Matsuyama, Naoto Minamino, Toyoshi Shimada, and Toshiyuki Kamei*

Cite This: https://doi.org/10.1021/acs.orglett.1c01053 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

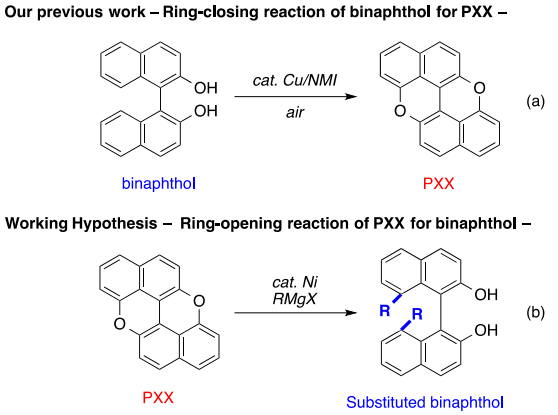
ABSTRACT: Herein, we disclose the Ni-catalyzed ring-opening C−O functionalization of *peri*-xanthenoxanthenes using Grignard reagents that forms 8-monofunctionalized binaphthols. 1,2-Bis(dicyclohexylphosphino)ethane was the best ligand for alkylations and ICy for arylation. After mechanistic investigations, we assumed that the reaction proceeds via C−O reduction and subsequent C−O functionalization. To verify the mechanism, the intermediate after reduction was isolated. Moreover, the asymmetric addition, using 8-octylbinaphthol after optical resolution, was studied.



Binaphthyl derivatives are widely applied as chiral ligands and catalysts in many asymmetric transformations.[1] Preferred synthetic strategies for these reagents are modifications of binaphthol (1,1′-bi-2-naphthol) using electrophilic substitutions at 6,6′-positions[2] and directed metalations at 3,3′-positions.[3] Although homocoupling reactions of 2-naphthol derivatives are also available for the synthesis of binaphthol with substituents in other positions,[4] the synthesis of 8,8′-functionalized binaphthols has not been fully developed because of the steric hindrance of the 8-position of binaphthol.[5]

In our laboratory, we applied Cu-catalyzed ring-closing reactions of binaphthol to produce *peri*-xanthenoxanthene (PXX) derivatives (Scheme 1a), which are used as p-type transistors for rollable displays by Kobayashi (Sony Corporation).[6,7] We think the reductive ring-opening reaction of PXX to introduce substituents could result in a novel synthetic strategy for binaphthol derivatives (Scheme 1b).

Scheme 1. Ring-Closing and Ring-Opening Strategy to Functionalize Binaphthols

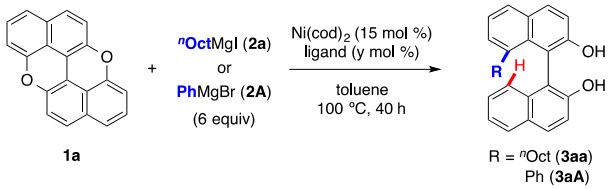


To prove this hypothesis, we applied the Ni-catalyzed C−O functionalization, which experienced considerable attention in this past decade.[8,9] There have been a few reports on C−O bond activation of diaryl ethers.[10] Martin reported the C−O silylation of dibenzofuran with silylborane,[10a] and Yorimitsu and Osuka disclosed the C−O arylation of dibenzofuran with ArMgBr.[10b] Tobisu and Chatani developed the C−O bond alkylation of diaryl ethers and dibenzofuran with Grignard reagents.[10c]

We started our investigation to achieve the Ni-catalyzed ring-opening reaction of PXX **1a** employing Tobisu's reaction conditions (Table 1). Surprisingly, the reaction of **1a** with $Ni(cod)_2$ (15 mol %), 1,2-bis(dicyclohexylphosphino)ethane (dcype) (15 mol %), and *n*-octylmagnesium iodide (**2a**, 6 equiv) in toluene for 40 h gave 8-*n*-octylbinaphthol (**3aa**) in 71% yield, accompanied by small amounts of binaphthol **4** (~9%, Table 1, entry 1), not 8,8′-di(*n*-octyl)binaphthol.[11] No reaction occurred with the addition of other bidentate cyclohexylphosphine ligands, such as 1,3-bis(dicyclohexylphosphino)propane (dcypp), 1,1′-bis(dicyclohexylphosphino)ferrocene (dcypf), bipyridine, monodentate, and carbene ligands (entries 2−8). The reaction of **1a** with PhMgBr **2A**, adding $Ni(cod)_2$ and dcype, was unsuccessful, with no recovery of starting materials (Table 1, entry 1). After optimization of the ligands, addition of carbene ligand ICy effectively produced 8-phenylbinaphthol **3aA** in 58% yield (entry 6).[11] No reactions occurred with **2A** using other ligands listed in Table 1 (entries 2−5, 7, and 8). Alternative ligands, nickel precursors, Grignard reagents, and temperature variations were also studied (see Tables S1−S4).

Received: March 27, 2021

Table 1. Ligand Optimizations of Ni-Catalyzed Ring Opening of PXX

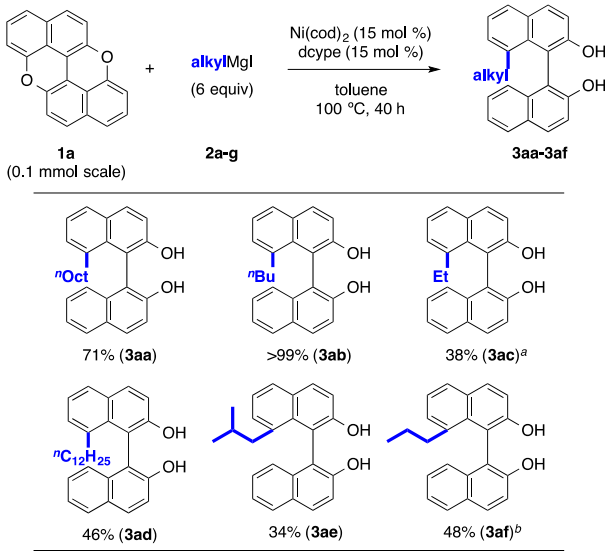


entry	ligand (y mol %)	3aa (%)[a]	3aA (%)[a]
1	dcype (15)	71[b,c]	0
2	dcypp (15)	0	0
3	dcypf[d] (15)	trace	0
4	dppe (15)	0	0
5	PCy_3 (30)	0	0
6	Icy·HCl (30)	0	58
7	I(1-Ad)·HBF_4 (30)	0	0
8	bipyridine (15)	0	0

[a]^{1}H NMR yield. [b]Isolated yield. [c]Binaphthol (R = H) **4** was obtained (9%). [d]1,1′-Bis(dicyclohexylphosphino)ferrocene.

We applied this reaction further using other Grignard reagents (Scheme 2). Butylmagnesium iodide produced **3ab** in high yields. Ethylmagnesium bromide was, together with MgI_2, the most suitable reagent to obtain **3ac** in low yields (38%).[10c] Addition of *n*-dodecylmagnesium iodide **2d** and isobutylmagnesium iodide **2e** formed **3ad** and **3ae** also in low yields. Using isopropylmagnesium iodide **2f**, isomerization to *n*-propylnickel occurred to produce 8-*n*-propylbinaphthol in 48% yield. Probing the β-H elimination of alkylnickel was included in the later reaction mechanism study.

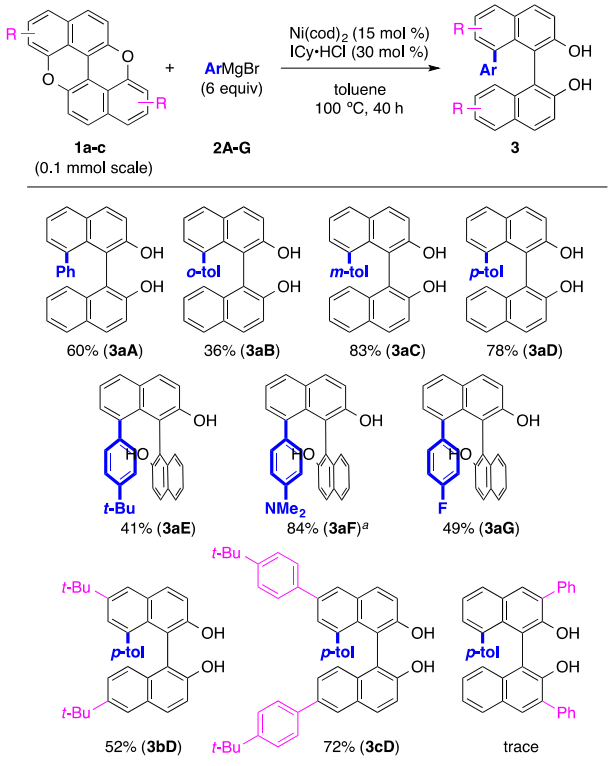
Scheme 2. Ni-Catalyzed Alkylative Ring Opening of PXX



[a]EtMgBr (6 equiv) and MgI_2 (2.2 equiv) were added. [b]^{i}PrMgI was used.

The results using aryl Grignard reagents are shown in Scheme 3. The reaction with *o*-tolylmagnesium bromide produced the corresponding product **3aB** in low yields (36%), related to the steric hindrance of the *o*-methyl group. Addition of *m*- and *p*-tolylmagnesium bromide successfully formed **3aC** and **3aD** in high yields. The reaction of *p*-*tert*-butylphenylmagnesium bromide yielded 84% **3aE**. The presence of electron-donating groups in the Grignard reagent enhanced the reactivity, and **3aF** was also obtained in 84% yield. Electron-withdrawing fluoro groups reduced the reactivity to give **3aG** in 49% yield. When the substituents on PXX were examined, the reaction with 2,8-di(*t*-butyl)PXX and 2,8-di(*p*-*t*-butylphenyl)PXX produced the corresponding products **3bD** and **3cD**, but the phenyl groups at the 5- and 11-positions prevented the ring-opening reaction.

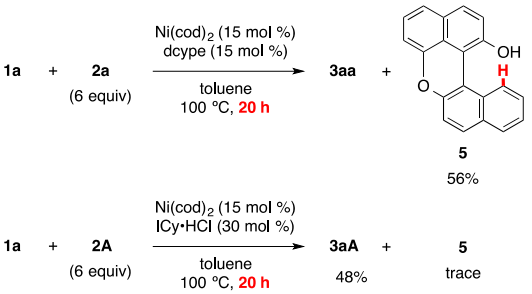
Scheme 3. Ni-Catalyzed Arylative Ring Opening of PXX



[a]120 °C.

To gain further insight on the mechanism of the transformation, we analyzed the products of the reaction prior to full conversion (Scheme 4). The alkylation with **2a** formed the half-ring-opening product **5** as the main product (56% yield), with **3aa** in 24% yield. Regarding the arylation, trace amounts of **5** were detected with ^{1}H NMR in the crude products, and the main product **3aA** was isolated in 48% yield. These results proved that the reaction proceeds via reductive ring-opening and alkylative/arylative binaphthol formation.

Scheme 4. Half-Time Reactions to Capture Intermediates

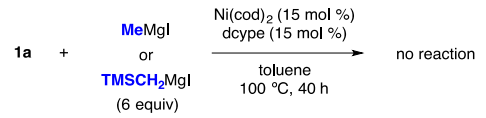


Next, we investigated the hydrogen source of the reduction. The β-H elimination of alkylnickel intermediates was observed

https://doi.org/10.1021/acs.orglett.1c01053
Org. Lett. XXXX, XXX, XXX−XXX

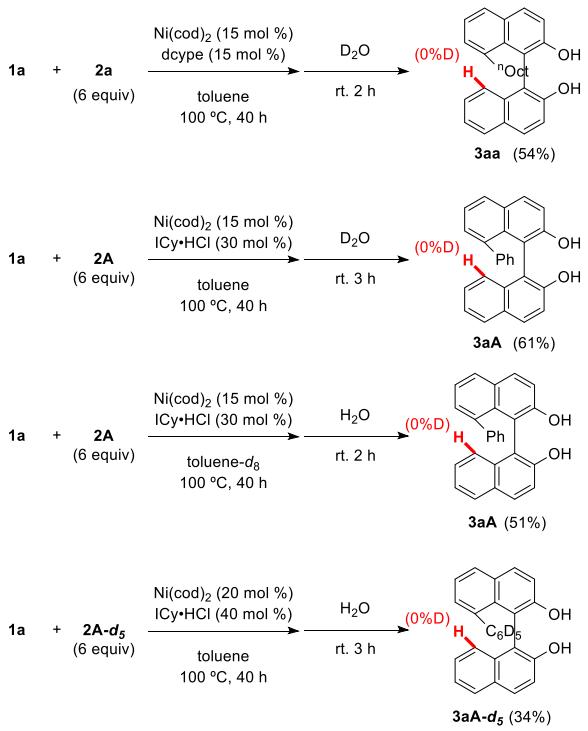
during the reaction with isopropylmagnesium iodide (**3f**). Therefore, we subjected Grignard reagents with no hydrogen in the β-position, such as methylmagnesium iodide and trimethylsilylmethylmagnesium iodide, to ring-opening conditions to recover the starting materials (Scheme 5).[12]

Scheme 5. Reaction with Grignard Reagent without β-Hydrides



To identify the hydrogen source, the reaction was quenched with D_2O (Scheme 6). The addition of D_2O to **1a** and **2a** did not

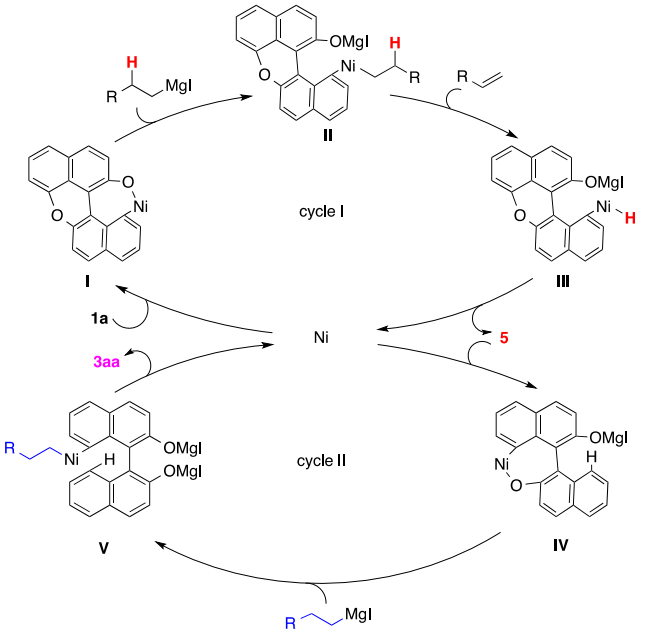
Scheme 6. Deuterium-Labeled Experiments



result in incorporation of deuterium (D) into **3aa**. Adding D_2O to the mixture of **1a** and **2A** also did not produce **3aA** with D atoms included. Furthermore, the reaction of **1a** and **2A** performed in toluene-d_8 afforded **3aA** without D atoms. The D-incorporated Grignard reagent (**2A**-d_5) was subjected to the reaction to result in 0% D at the 8-position. Mechanism of the reaction with aryl magnesium bromide did not include β-hydride elimination.

A possible reaction mechanism is shown in Scheme 7. The oxidative addition of a Ni catalyst into the C−O bond, using the Grignard reaction, is followed by the transmetalation with Grignard reagents to produce complex **II**. Oxidative addition of Ni(0) species was well examined on Ni-catalyzed reduction of diphenyl ether. Oxidative addition proceeded via the η^6-benzene complex.[13] Ni(0) complex might be slightly sterically accessible to the benzene structure, including a C_α−O atom to form the η^6-complex. The inhibition of free rotation of the axial bond caused steric congestion and was strict with the reductive elimination, and β-H elimination is preferred, forming a nickel hydride

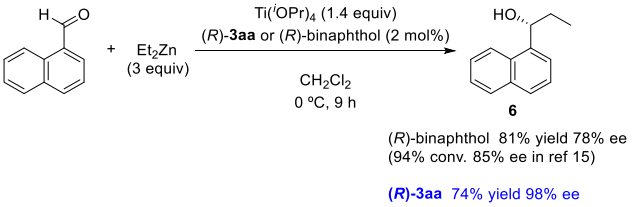
Scheme 7. Possible Mechanisms of Ni-Catalyzed Ring Opening with Alkyl Grignard Reagent



complex. Reductive elimination yields half-ring-opening product **5** (cycle I).[14] The oxidative addition of Ni to another C−O bond, followed by transmetalation and reductive elimination, results in the products shown in cycle II. In the case of aryl Grignard reagents, **5** is produced similarly to that with alkyl Grignard reagents, following a cross-coupling sequence to obtain the corresponding products; however, the hydrogen source could not be determined.

Finally, to ensure the suitability of the 8-alkyl substituent for asymmetric reactions, the enantioselective alkylation of carbonyl compounds with a zinc reagent was used as a model reaction (Scheme 8).[15] The enantiomerically pure binaphthol **3aa** was

Scheme 8. Enantioselective Alkylation of 1-Naphthaldehydes



resolved using camphor sulfonyl ester column chromatography (Scheme S2). The reaction of α-naphthaldehyde and diethyl zinc in the presence of Ti(O^{i}Pr)$_4$ and (*R*)-**3aa** produced 1-(α-naphthyl)-1-propanol **6** in 74% yield and 98% ee. The control experiment using (*R*)-binaphthol instead of (*R*)-**3aa** yielded the product in 81% yield and 78% ee (ref 15 reports products obtained in 94% yield and 85% ee). These results show that the 8-substituted binaphthol can control asymmetric reactions.

In conclusion, we achieved the Ni-catalyzed C−O bond activation of PXX to afford 8-substituted binaphthol derivatives in high yields. The reaction proceeds through the reductive half-ring-opening of PXX. Hydride is derived from β-H elimination of alkyl nickel intermediates. Cross-coupling with alkylation or arylation provides the 8-substituted binaphthol derivatives. The suitability of the products as ligands in asymmetric reactions was

https://doi.org/10.1021/acs.orglett.1c01053
Org. Lett. XXXX, XXX, XXX−XXX

examined using (*R*)-8-*n*-octylbinaphthol. Studies to determine the hydrogen source in the case of arylations and apply the 8-substituted binaphthol in other asymmetric reactions are ongoing.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.1c01053.

Experimental procedures and compound characterization (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Toshiyuki Kamei − *Department of Chemical Engineering, National Institute of Technology, Nara College, Yamatokoriyama, Nara 639-1080, Japan;* orcid.org/0000-0001-8435-3767; Email: kamei@chem.nara-k.ac.jp

Authors

Naoki Matsuyama − *Department of Chemical Engineering, National Institute of Technology, Nara College, Yamatokoriyama, Nara 639-1080, Japan*

Naoto Minamino − *Department of Chemical Engineering, National Institute of Technology, Nara College, Yamatokoriyama, Nara 639-1080, Japan*

Toyoshi Shimada − *Department of Chemical Engineering, National Institute of Technology, Nara College, Yamatokoriyama, Nara 639-1080, Japan*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.orglett.1c01053

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful to Prof. Mamoru Tobisu (Osaka University) for his helpful advice. This work was supported by Grant-in-Aid for Young Scientists (B) JP15K17859. We would like to thank Editage (www.editage.com) for English language editing.

■ REFERENCES

(1) (a) Chen, Y.; Yekta, S.; Yudin, A. Modified BINOL Ligands in Assymmetric Catalysis. *Chem. Rev.* **2003**, *103*, 3155−3211. (b) Kočovský, P.; Vyskočil, Š.; Smrčina, M. Non-Symmetrically Substituted 1,1'-Binaphthyls in Enantioselective Catalysis. *Chem. Rev.* **2003**, *103*, 3213−3245. (c) Berthod, M.; Mignani, G.; Woodward, G.; Lemaire, M. Modified BINAP: The How and the Why. *Chem. Rev.* **2005**, *105*, 1801−1836 and references therein.

(2) (a) Vondenhof, M.; Mattay, J. Sulfonic Acid Esters Derived from 1,1'-Binaphtharene as New Axially Chiral Photosensitizers. *Tetrahedron Lett.* **1990**, *31*, 985−988. (b) Kamei, T.; Shibaguchi, H.; Sako, M.; Toribatake, K.; Shimada, T. Scandium Triflate-Catalyzed 6,6'-Diiodination of 2,2'-Dimethoxy-1,1'-binaphthyl with 1,3-Diiodo-5,5-dimethylhydantoin. *Tetrahedron Lett.* **2012**, *53*, 3894−3896.

(3) (a) Cox, P. J.; Wang, W.; Snieckus, V. Expedient route to 3- and 3,3′-substituted 1,1'-bi-2-naphthols by directed ortho metalation and Suzuki cross coupling methods. *Tetrahedron Lett.* **1992**, *33*, 2253−2256. (b) Ahmed, I.; Clark, D. A. Rapid Synthesis of 3,3′ Bis-Arylated BINOL Derivatives Using a C−H borylation *in Situ* Suzuki−Miyaura Coupling Sequence. *Org. Lett.* **2014**, *16*, 4332−4335. (c) Yang, J.-F.; Wang, R.-H.; Wang, Y.-X.; Yao, W.-W.; Liu, Q.-S.; Ye, M. Ligand-Accelerated Direct C−H Arylation of BINOL: A Rapid One-Step Synthesis of Racemic 3,3′-Diaryl BINOLs. *Angew. Chem., Int. Ed.* **2016**, *55*, 14116−14120.

(4) For example, see: (a) Noji, M.; Nakajima, M.; Koga, K. A New Catalytic System for Aerobic Oxidative Coupling of 2-Naphthol Derivatives by the Use of CuCl-amine Complex: A Practical Synthesis of Binaphthol Derivatives. *Tetrahedron Lett.* **1994**, *35*, 7983−7984. (b) Egami, H.; Katsuki, T. Iron-Catalyzed Asymmetric Aerobic Oxidation: Oxidative Coupling of 2-Naphthols. *J. Am. Chem. Soc.* **2009**, *131*, 6082−6083. (c) Liu, Q.-Z.; Xie, N.-S.; Luo, Z.-B.; Cui, X.; Cun, L.-F.; Gong, L.-Z.; Mi, A.-Q.; Jiang, Y.-Z. Facile Preparation of Optically Pure 7,7′-Disubstituted BINOLs and Their Application in Asymmetric Catalysis. *J. Org. Chem.* **2003**, *68*, 7921−7924. (d) Dewar, M. J.; Nakaya, T. Oxidative Coupling of Phenols. *J. Am. Chem. Soc.* **1968**, *90*, 7134−7135.

(5) 8,8'-Disubstituted binaphthols: (a) Katsuki, N.; Isshiki, S.; Fukatsu, D.; Okamura, J.; Kuramochi, K.; Kawabata, T.; Tsubaki, K. Total Synthesis of Dendrochrysanene through a Frame Rearrangement. *J. Org. Chem.* **2017**, *82*, 11573−11584. (b) Podlesny, E. E.; Carroll, P. J.; Kozlowski, M. C. Selective Oxidation of 8,8'-Hydroxylated Binaphthols to Bis-spironaphthalenones or Binaphtho-*para*- and Binaphtho-*ortho*-quinones. *Org. Lett.* **2012**, *14*, 4862−4865. (c) Terrasson, V.; Roy, M.; Moutard, S.; Lafontaine, M.-P.; Pèpe; Fèlix, G.; Gingras, M. Benzylic-type couplings provide an important asymmetric entry to functionalized, non-racemic helicenes. *RSC Adv.* **2014**, *4*, 32412−32414. (d) Vesely, V.; Stursa, F. 1-Methyl-7-naphthol. *Collect. Czech. Chem. Commun.* **1933**, *5*, 170−178.

(6) (a) Kamei, T.; Uryu, M.; Shimada, T. Cu-Catalyzed Aerobic Oxidative C−H/C−O Cyclization of 2,2'-Binaphthols: Practical Synthesis of PXX Derivatives. *Org. Lett.* **2017**, *19*, 2714−2717. (b) Kamei, T.; Nishino, S.; Yagi, A.; Segawa, Y.; Shimada, T. Ni-Catalyzed α-Selective C−H Borylation of Naphthalene-Baseed Aromatic Compounds. *J. Org. Chem.* **2019**, *84*, 14354−14359.

(7) Kobayashi, N.; Sasaki, M.; Nomoto, K. Stable *peri*-Xanthenoxanthene Thin-Film Transistors with Efficient Carrier Injection. *Chem. Mater.* **2009**, *21*, 552−556.

(8) For selected reviews, see: (a) Tobisu, M.; Chatani, N. Cross-Couplings Using Aryl Ethers via C−O Bond Activation Enabled by Nickel Catalysts. *Acc. Chem. Res.* **2015**, *48*, 1717−1726. (b) Li, B.-J.; Yu, D.-G.; Sun, C.-L.; Shi, Z.-J. Activation of "Inert" Alkenyl/Aryl C−O Bond and Its Application in Cross-Coupling Reactions. *Chem. - Eur. J.* **2011**, *17*, 1728−1759. (c) Rosen, B. M.; Quasdorf, K. W.; Wilson, D. A.; Zhang, N.; Resmerita, A.-M.; Garg, N. K.; Percec, V. Nickel-Catalyzed Cross- Couplings Involving Carbon−Oxygen Bonds. *Chem. Rev.* **2011**, *111*, 1346−1416. (d) Cornella, J.; Zarate, C.; Martin, R. Metal-catalyzed activation of ethers via C−O bond cleavage: a new strategy for molecular diversity. *Chem. Soc. Rev.* **2014**, *43*, 8081−8097. (e) Qiu, Z.; Li, C.-J. Transformations of Less-Activated Phenols and Phenol Derivatives via C−O bond Cleavage. *Chem. Rev.* **2020**, *120*, 10454−10515.

(9) Wenkert, E.; Michelotti, E. L.; Swindell, C. S. Nickel-induced conversion of carbon-oxygen into carbon-carbon bonds. One-step transformations of enol ethers into olefins and aryl ethers into biaryls. *J. Am. Chem. Soc.* **1979**, *101*, 2246−2247.

(10) (a) Zarate, C.; Nakajima, M.; Martin, R. A Mild and Ligand Free Ni-Catalyzed Silylation via C−OMe Cleavage. *J. Am. Chem. Soc.* **2017**, *139*, 1191−1197. (b) Kurata, Y.; Otsuka, S.; Fukui, N.; Nogi, K.; Yorimitsu, H.; Osuka, A. Aromatic Metamorphosis of Dibenzofurans into Triphenylenes Starting with Nickel-Catalyzed Ring-Opening C−O Arylation. *Org. Lett.* **2017**, *19*, 1274−1277. (c) Tobisu, M.; Takahira, T.; Morioka, T.; Chatani, N. Nickel-Catalyzed Alkylative Cross-Coupling of Anisoles with Grignard Reagents via C−O Bond Activation. *J. Am. Chem. Soc.* **2016**, *138*, 6711−6714.

(11) The ring-opening product at another C−O bond, 8-hydroxy-1,1′-binaphthyl, was not observed.

(12) The reactions of **1a** with MeMgI or $TMSCH_2MgI$ using $Ni(cod)_2$/ICy·HCl also resulted in no reaction: Tobisu, M.; Takahira, T.; Chatani, N. Nickel-Catalyzed Cross-Coupling of Anisoles with Alkyl Grignard Reagents via C−O Bond Cleavage. *Org. Lett.* **2015**, *17*, 4352−4355.

(13) Oxidative addition mechanism in the reduction of the C−O bond via the η^6-complex: (a) Saper, N. I.; Hartwig, J. F. Mechanistic Investigations of the Hydrogenolysis of Diaryl Ethers Catalyzed by Nickel Complexes of *N*-Heterocyclic Carbene Ligands. *J. Am. Chem. Soc.* **2017**, *139*, 17667−17676. (b) Xu, L.; Chung, L. W.; Wu, Y.-D. Mechanism of Ni-NHC Catalyzed Hydrogenolysis of Aryl Ethers: Roles of the Excess Base. *ACS Catal.* **2016**, *6*, 483−493.
(14) Reduction via β-H elimination: Tobisu, M.; Morioka, T.; Ohtsuki, A.; Chatani, N. Nickel-catalyzed reductive cleavage of aryl alkyl ethers to arenes in absence of external reductant. *Chem. Sci.* **2015**, *6*, 3410−3414.
(15) Harada, T.; Kanda, K. Enantioselective Alkylation of Aldehydes Catalyzed by a Highly Active Titanium Complex of 3-Substituted Unsymmetric BINOL. *Org. Lett.* **2006**, *8*, 3817−3819.

https://doi.org/10.1021/acs.orglett.1c01053
Org. Lett. XXXX, XXX, XXX−XXX