Inorganic Chemistry

Article

pubs.acs.org/IC

Enantioselective Syntheses of Sulfoxides in Octahedral Ruthenium(II) Complexes via a Chiral-at-Metal Strategy

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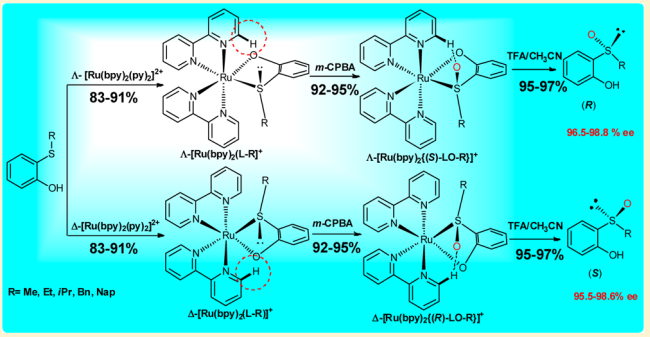
Supporting Information

ABSTRACT: The preparation of chiral 2-(alkylsulfinyl)-phenol compounds by enantioselective coordination−oxidation of the thioether ruthenium complexes with a chiral-at-metal strategy has been developed. The enantiomerically pure sulfoxide complexes Δ-$[Ru(bpy)_2\{(R)\text{-LO-R}\}](PF_6)$ (bpy is 2,2′-bipyridine, HLO-R is 2-(alkylsulfinyl)phenol, R = Me (Δ-**1a**), Et (Δ-**2a**), *i*Pr (Δ-**3a**), Bn (Δ-**4a**), and Nap (Δ-**5a**)) and Λ-$[Ru(bpy)_2\{(S)\text{-LO-R}\}](PF_6)$ (R = Me (Λ-**1a**), Et (Λ-**2a**), *i*Pr (Λ-**3a**), Bn (Λ-**4a**), and Nap (Λ-**5a**)) have been synthesized by the reaction of Δ-$[Ru(bpy)_2(py)_2]^{2+}$ or Λ-$[Ru(bpy)_2(py)_2]^{2+}$ with the prochiral thioether ligands 2-(alkylthio)phenol (HL-R), followed by enantioselective oxidation with *m*-CPBA as oxidant. The X-ray crystallography was used to verify the stereochemistry of ruthenium complexes and sulfur atoms. The configurations of the ruthenium complexes are stable during the coordination and oxidation reactions. Moreover, the chiral sulfoxide ligands are enantioselectively generated by controlling of the configuration of ruthenium centers in the course of oxidation reaction. That is, the Λ configuration at the ruthenium center generates the *S* sulfoxide ligand; on the contrary, the Δ configuration of the ruthenium complex originates the *R* sulfoxide ligand. Acidolysis of Λ-$[Ru(bpy)_2\{(R)\text{-LO-R}\}](PF_6)$ and Δ-$[Ru(bpy)_2\{(S)\text{-LO-R}\}](PF_6)$ complexes in the presence of TFA−MeCN afforded the chiral ligands (*R*)-HLO-R and (*S*)-HLO-R in 96−99% ee values, respectively. Importantly, the chiral ruthenium complexes can be recycled as Δ/Λ-$[Ru(bpy)_2(MeCN)_2](PF_6)_2$ and reused in a next reaction cycle with complete retention of the configurations at ruthenium centers.



INTRODUCTION

Enantiomerically pure sulfoxides are of great importance in synthetic and medicinal chemistry.[1,2] Two classical methods have been developed for the synthesis of chiral sulfoxide. One is the Andersen method.[1a,b,3] However, this synthetic approach was experimentally tedious and an organometallic reagent needs to be used. The second approach is the enantioselective oxidation of thioethers to sulfoxides using either chiral oxidant or achiral oxidant under an asymmetric environment such as the well-known Sharpless reagent.[4] The oxidation of thioethers, considered as the most direct and practical approach for the preparation of sulfoxides, has attracted much attention over the years.[5,6] Nevertheless, these methods suffered from the low turnover numbers and enantiomeric excess (ee) value, and overoxidation to sulfone. In particular, the enantioselective oxidation of dialkyl sulfides is still not well resolved. Therefore, it is still highly desirable to develop new approaches to supplement the existing methodologies for synthesis of chiral sulfoxides.

Chiral sulfoxide ligands have been found to be efficiently enantioselective recognition with an octahedral $[Ru(bpy)_2Cl_2]$ (bpy is 2,2′-bipyridine) complex.[7] We believe that the octahedral stereocenters allow the straightforward generation the Δ and Λ enantiomers in the presence of chiral sulfoxides. Therefore, the chiral-at-metal framework may be used to recognize and originate the enantiomeric sulfoxides. Indeed, a literature survey revealed that the first chiral sulfoxide compound oxidated enantioselectively from thioether in the presence of Δ-$[Ru(dmp)_2(MeCN)_2](\Lambda\text{-Trisphat})_2$ complex (where dmp is 2,9-dimethyl-1,10-phenanthroline) has been reported by Fontecave and co-workers.[8] However, the enantiomeric excess (ee) values are low in 7−18%. In the previous work, we have developed an approach for the preparation of chiral 2-alkylsulfinylbenzonate compounds up to 93% ee value by means of oxidation of the thioether complexes to sulfoxide complexes in a chiral-at-metal asymmetric envionment, followed by release of the oxidated ligand.[9] The configurations of the ruthenium centers are stable during the coordinated reaction of the thioether ligand to the ruthenium center, followed by oxidation of the thioether complexes to the corresponding sulfoxide complexes. Moreover, the chirality of the sulfoxide ligand is controlled by the chirality of the ruthenium complexes in the oxidation reaction;

Received: December 4, 2014

DOI: 10.1021/ic502898e
Inorg. Chem. XXXX, XXX, XXX−XXX

therefore, the predetermined chirality of sulfoxide is originated. To the best of our knowledge, though the asymmetric catalysis based on chiral ligands have been well documented,[10] the report for the asymmetric synthesis using a chiral-at-metal complex as the unique source is still rare.[11,12] On the other hand, the oxidation of thiolato and thioether complexes has been observed;[13,14] however, the enantioselective oxidation in situ of the thioether ligands generation of the predetermined chirallty of the sulfoxide ligands is unexplored.[9] As part of an ongoing study, we extend the approach of "*coordination oxidation in situ*" to synthesize the chiral *ortho* hydroxyl phenyl sulfoxides which have been used as chiral auxiliaries for asymmetric synthesis.[12g] In this paper, the synthesis of 15 Ru(II)-bpy-thioether complexes, rac-[Ru(bpy)$_2$(L-R)](PF$_6$) (HL-R is 2-(alkylthio)phenol, R = Me (rac-**1**), Et (rac-**2**), *i*Pr (rac-**3**), Bn (rac-**4**), and Nap (rac-**5**)), Δ/Λ-[Ru(bpy)$_2$(L-R)](PF$_6$) (R = Me (Δ-**1** and Λ-**1**), Et (Δ-**2** and Λ-**2**), *i*Pr (Δ-**3** and Λ-**3**), Bn (Δ-**4** and Λ-**4**), and Nap (Δ-**5** and Λ-**5**)), and the oxidated products rac-[Ru(bpy)$_2$(LO-R)](PF$_6$) (HLO-R is 2(alkylsulfinyl)phenol, R = Me (rac-**1a**), Et (rac-**2a**), *i*Pr (rac-**3a**), Bn (rac-**4a**), and Nap (rac-**5a**)), Δ-[Ru(bpy)$_2${(*R*)-LO-R}](PF$_6$) (R = Me (Δ-**1a**), Et (Δ-**2a**), *i*Pr (Δ-**3a**), Bn (Δ-**4a**), and Nap (Δ-**5a**)), and Λ-[Ru(bpy)$_2${(*S*)-LO-R}](PF$_6$) (R = Me (Λ-**1a**), Et (Λ-**2a**), *i*Pr (Λ-**3a**), Bn (Λ-**4a**) and Nap (Λ-**5a**)), have been reported. Moreover, the chiral *ortho* hydroxyl phenyl sulfoxides ((*R*/*S*)-**HLO-R**) afford by acidolysis of the chiral sulfoxide complexes in the presence of TFA−MeCN in 95−97% yields with an ee value up to 98.8%. In the meantime, the chirality of the ruthenium complex completely retains; it can be recovered and reused in a new synthetic cycle. The method reported here may offer a new choice for the synthesis of chiral sulfoxide compounds.

EXPERIMENTAL SECTION

Materials. RuCl$_3$·3H$_2$O, 2,2′-bipyridine, 2-hydroxythiophenol, 2-(methylthio)phenol, bromoethane, 2-bromopropane, benzyl bromide, 2-(bromomethyl)naphthalene, 3-chloroperoxybenzoic acid (*m*-CPBA), and other chemicals were purchased from commercial sources. [Ru(bpy)$_2$Cl$_2$]·2H$_2$O,[15] Λ-[Ru(bpy)$_2$(py)$_2$][*O*,*O*′-dibenzoyl-*D*-tartrate]·12H$_2$O (Λ-**Ru**), and Δ-[Ru(bpy)$_2$(py)$_2$][*O*,*O*′-dibenzoyl-*L*-tartrate]·12H$_2$O (Δ-**Ru**) were prepared by the literature procedures.[16]

Syntheses of Thioether Ligands. The ligands were synthesized according to the reported procedure.[17]

*2-(Ethylthio)phenol (**HL-Et**).* Yield 85% (reaction in 0.5 h). ESI-MS: m/z = 153 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 7.46 (d, 1H), 7.26 (t, 1H), 6.99 (d, 1H), 6.87 (t, 1H), 6.77 (s, 1H), 2.43 (q, 2H), 1.24 (d, 3H).

*2-(Isopropylthio)phenol (**HL-iPr**).* Yield 86% (reaction in 3 h). ESI-MS: m/z = 167 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 7.47 (d, 1H), 7.30 (t, 1H), 7.02 (d, 1H), 6.90 (m, 2H), 3.12 (m, 1H), 1.28 (d, 6H).

*2-(Benzylthio)phenol (**HL-Bn**).* Yield 83% (reaction overnight). ESI-MS: m/z = 215 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 7.29 (m, 5H), 7.11 (m, 2H), 6.95 (d, 1H), 6.83 (t, 1H), 6.57 (s, 1H), 3.87 (s, 2H).

*2-(Naphthalthio)phenol (**HL-Nap**).* Yield 82% (reaction overnight). ESI-MS: m/z = 265 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 7.79 (m, 2H), 7.67 (m, 1H), 7.45 (m, 2H), 7.38 (s, 1H), 7.33 (d, 1H), 7.24 (m, 2H), 6.92 (d, 1H), 6.76 (t, 2H), 4.01 (s, 2H).

Syntheses of Thioether Complexes. The thioether complexes were synthesized by the similar procedure of our previous report.[9]

*[Ru(bpy)$_2$(L-Me)](PF$_6$) (rac-**1**).* Yield 98% based on *cis*-Ru(bpy)$_2$Cl$_2$. The reactants were added to 18 mL of EtOH and 2 mL of H$_2$O, and stirred at 90 °C for 6 h. Anal. Calcd for C$_{27}$H$_{23}$F$_6$N$_4$OPRuS: C 46.49, H 3.32, N 8.03, S 4.60. Found: C 46.41, H 3.33, N 8.00, S 4.55; ESI-MS: m/z = 553 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 9.20 (d, 1H), 8.84 (d, 1H), 8.41(m, 3H), 8.31 (d, 3H), 8.12 (t, 1H), 7.94 (m, 3H), 7.81 (t, 1H), 7.64 (m, 2H), 7.52 (t, 1H), 7.29 (m, 2H), 7.16 (t, 1H), 6.92 (t, 1H), 6.51 (d, 1H), 6.44 (t, 1H), 1.41 (s, 3H). Λ-[Ru(bpy)$_2$(L-Me)](PF$_6$) (Λ-**1**). Yield 90% based on Λ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (−66), 297 nm (+122), 362 nm (+16). Δ-[Ru(bpy)$_2$(L-Me)](PF$_6$) (Δ-**1**). Yield 91% based on Δ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (+70), 297 nm (−128), 362 nm (−17).

*[Ru(bpy)$_2$(L-Et)](PF$_6$) (rac-**2**).* Yield 94% (reaction conditions are similar to rac-**1**). Anal. Calcd for C$_{28}$H$_{25}$F$_6$N$_4$OPRuS: C 47.26, H 3.54, N 7.87, S 4.51. Found: C 47.20, H 3.57, N 7.81, S 4.49; ESI-MS: m/z = 567 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 9.22 (d, 1H), 8.89 (d, 1H), 8.48(d, 1H), 8.36 (m, 3H), 8.13 (t, 1H), 7.95 (m, 3H), 7.80 (t, 1H), 7.68 (t, 1H), 7.50 (m, 2H), 7.34 (d, 1H), 7.26 (t, 1H), 7.17 (t, 1H), 6.91 (t, 1H), 6.51 (d, 1H), 6.43 (t, 1H), 2.21 (m, 1H), 1.64 (m, 1H), 0.65 (t, 3H). Λ-[Ru(bpy)$_2$(L-Et)](PF$_6$) (Λ-**2**). Yield, 85% based on Λ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (−83), 298 nm (+152), 362 nm (+23). Δ-[Ru(bpy)$_2$(L-Et)](PF$_6$) (Δ-**2**). Yield 85% based on Δ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (+79), 297 nm (−142), 362 nm (−20).

*[Ru(bpy)$_2$(L-iPr)](PF$_6$) (rac-**3**).* Yield 93% (reaction conditions are similar to rac-**1**). Anal. Calcd for C$_{29}$H$_{27}$F$_6$N$_4$OPRuS: C 48.00, H 3.75, N 7.72, S 4.42. Found: C 47.95, H 3.75, N 7.70, S 4.38; ESI-MS: m/z = 581 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 9.24 (d, 1H), 9.01 (d, 1H), 8.50(d, 1H), 8.34 (m, 3H), 8.13 (t, 1H), 8.05 (d, 1H), 7.94 (t, 1H), 7.86 (t, 1H), 7.80 (t, 1H), 7.70 (t, 1H), 7.49 (t, 1H), 7.28 (m, 3H), 7.16 (t, 1H), 6.90 (t, 1H), 6.48 (d, 1H), 6.40 (t, 1H), 2.58 (m, 1H), 0.87 (d, 3H), 0.32 (d, 3H). Λ-[Ru(bpy)$_2$(L-*i*Pr)](PF$_6$) (Λ-**3**). Yield, 87% based on Λ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 280 nm (−77), 298 nm (+140), 360 nm (+24). Δ-[Ru(bpy)$_2$(L-*i*Pr)](PF$_6$) (Δ-**3**). Yield 88% based on Δ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 280 nm (+76), 298 nm (−135), 360 nm (−23).

*[Ru(bpy)$_2$(L-Bn)](PF$_6$) (rac-**4**).* Yield 91% (reaction conditions are similar to rac-**1**). Anal. Calcd for C$_{33}$H$_{27}$F$_6$N$_4$OPRuS: C 51.23, H 3.52, N 7.24, S 4.14. Found: C 51.02, H 3.60, N 7.18, S 4.10; ESI-MS: m/z = 629 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 9.26 (d, 1H), 8.92 (d, 1H), 8.34(m, 2H), 8.24 (d, 1H), 8.14 (t, 1H), 7.95 (t, 1H), 7.87 (m, 3H), 7.75 (t, 1H), 7.54 (m, 2H), 7.34 (d, 1H), 7.21 (m, 2H), 6.98 (m, 5H), 6.63 (d, 2H), 6.53 (d, 1H), 6.39 (t, 1H), 3.83 (d, 1H), 3.06 (d, 1H). Λ-[Ru(bpy)$_2$(L-Bn)](PF$_6$) (Λ-**4**). Yield, 83% based on Λ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 280 nm (−61), 299 nm (+121), 364 nm (+20). Δ-[Ru(bpy)$_2$(L-Bn)](PF$_6$) (Δ-**4**). Yield 83% based on Δ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 280 nm (+65), 299 nm (−128), 362 nm (−21).

*[Ru(bpy)$_2$(L-Nap)](PF$_6$) (rac-**5**).* Yield 91% (reaction conditions are similar to rac-**1**). Anal. Calcd for C$_{37}$H$_{29}$F$_6$N$_4$OPRuS: C 53.95, H 3.55, N 6.80, S 3.89. Found: C 53.75, H 3.65, N 6.75, S 3.78; ESI-MS: m/z = 679 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 9.34 (d, 1H), 8.92 (d, 1H), 8.34(d, 1H), 8.28 (d, 1H), 8.17 (t, 1H), 8.04 (d, 1H), 7.95 (t, 1H), 7.81 (m, 3H), 7.70 (m, 1H), 7.48 (m, 5H), 7.34 (d, 1H), 7.19 (m, 3H), 6.90 (m, 5H), 6.56 (d, 1H), 6.43 (t, 1H), 4.24 (d, 1H), 3.30 (d, 1H). Λ-[Ru(bpy)$_2$(L-Nap)](PF$_6$) (Λ-**5**). Yield 88% based on Λ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (−55), 299 nm (+107), 368 nm (+21). Δ-[Ru(bpy)$_2$(L-Nap)](PF$_6$) (Δ-**5**). Yield 88% based on Δ-**Ru**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (+59), 299 nm (−109), 368 nm (−22).

Synthesis of Sulfoxide Complexes. ***Caution!*** *m-CPBA is potentially explosive beyond 85% purity and irritates the mucous membranes, respiratory tract, eyes, and skin. Moreover, skin contact with m-CPBA causes burns and blisters. Therefore, it is recommended that m-CPBA should only be used in a chemical fume hood.*

Method A. The sulfoxide complexes were sprepared by the similar procedure of our previous report.[9]

*[Ru(bpy)$_2$(LO-Me)](PF$_6$) (rac-**1a**).* Yield 95% based on rac-**1**. Anal. Calcd for C$_{27}$H$_{23}$F$_6$N$_4$O$_2$PRuS: C 45.44, H 3.25, N 7.85, S 4.49. Found: C 45.31, H 3.29, N 7.80, S 4.45; ESI-MS: m/z = 569 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 10.05 (d, 1H), 8.51 (d, 1H), 8.43(m, 3H), 8.38 (d, 1H), 8.20 (t, 1H), 8.06 (m, 2H), 7.94 (m, 2H), 7.67 (t, 1H), 7.58 (m, 2H), 7.38 (m, 2H), 7.28 (t, 1H), 7.10 (t, 1H), 6.60 (m, 2H), 2.30 (s, 3H). Λ-[Ru(bpy)$_2${(*S*)-LO-Me}](PF$_6$)

DOI: 10.1021/ic502898e
Inorg. Chem. XXXX, XXX, XXX−XXX

Table 1. Crystallographic Data for rac-2a·CH_2Cl_2, Λ-2a·CH_2Cl_2, Δ-2a·CH_2Cl_2, and (*R*)-HLO-Bn

complex	rac-**2a**·CH_2Cl_2	Λ-**2a**·CH_2Cl_2	Δ-**2a**·CH_2Cl_2	(*R*)-**HLO-Bn**
molecular formula	$C_{29}H_{27}Cl_2F_6N_4O_2PRuS$	$C_{29}H_{27}Cl_2F_6N_4O_2PRuS$	$C_{29}H_{27}Cl_2F_6N_4O_2PRuS$	$C_{13}H_{12}O_2S$
M_r	812.55	812.55	812.55	232.29
crystal system	monoclinic	monoclinic	monoclinic	orthorhombic
space group	$P2_1/c$	$C2$	$C2$	$P2_12_12_1$
a/Å	10.9404(2)	21.5650(2)	21.6534(3)	6.7450(2)
b/Å	14.2532(2)	8.79600(10)	8.84210(10)	7.3199(2)
c/Å	20.8005(4)	17.9140(2)	17.9476(2)	23.9210(9)
β/deg	101.441(2)	105.1050(10)	105.063(2)	90
V/Å^3	3179.09(10)	3280.63(6)	3318.21(8)	1181.04(7)
Z	4	4	4	4
D_c (g cm^{-3})	1.698	1.645	1.626	1.306
μ (mm^{-1})	7.265	7.040	6.961	2.288
data/restraints/para	6265/0/416	6215/1/418	6458/1/418	1806/0/146
$^aR_1[I > 2\sigma(I)]$	0.0480	0.0416	0.0301	0.0323
$^bwR_2$ (all data)	0.1367	0.1155	0.0772	0.0760
Flack parameter		−0.015(9)	−0.030(7)	0.00(2)
GOF on F^2	1.027	1.103	1.035	1.087
$\Delta\rho_{max}/\Delta\rho_{min}$ (e Å^{-3})	1.109/−1.043	0.886/−0.881	0.521/−0.426	0.115/−0.205

$^aR_1 = \sum||F_o| - |F_c||/\sum|F_o|$. $^bwR_2 = [\sum w(F_o^2 - F_c^2)^2/\sum w(F_o^2)^2]^{1/2}$.

(Λ-**1a**). Yield 95% based on Λ-**1**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 274 nm (−112), 290 nm (+142). Δ-[Ru(bpy)$_2${(*R*)-LO-Me}](PF$_6$) (Δ-**1a**). Yield 95% based on Δ-**1**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 274 nm (+120), 290 nm (−145).

*[Ru(bpy)$_2$(LO-Et)](PF$_6$) (rac-**2a**).* Yield 94% based on rac-**2**. Anal. Calcd for $C_{28}H_{25}F_6N_4O_2PRuS$: C 46.22, H 3.46, N 7.70, S 4.41. Found: C 46.21, H 3.45, N 7.64, S 4.35; ESI-MS: m/z = 583 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 10.15 (d, 1H), 8.45 (m, 5H), 8.23(t, 1H), 7.98 (m, 4H), 7.70 (t, 1H), 7.59 (t, 1H), 7.52 (d, 1H), 7.34 (t, 1H), 7.28 (t, 1H), 7.23 (d, 1H), 7.09 (t, 1H), 6.58 (m, 2H), 3.07 (m, 1H), 2.10 (m, 1H), 0.64 (t, 3H). Λ-[Ru(bpy)$_2${(*S*)-LO-Et}](PF$_6$) (Λ-**2a**). Yield 95% based on Λ-**2**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 277 nm (−117), 291 nm (+154) Δ-[Ru(bpy)$_2${(*R*)-LO-Et}](PF$_6$) (Δ-**2a**): Yield 94% based on Δ-**2**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 277 nm (+109), 291 nm (−136).

*[Ru(bpy)$_2$(LO-iPr)](PF$_6$) (rac-**3a**).* Yield 95% based on rac-**3**. Anal. Calcd for $C_{29}H_{27}F_6N_4O_2PRuS$: C 46.96, H 3.67, N 7.55, S 4.32. Found: C 46.91, H 3.65, N 7.54, S 4.35; ESI-MS: m/z = 597 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 10.15 (d, 1H), 8.72 (d, 1H), 8.55(d, 1H), 8.39 (d, 3H), 8.24 (t, 1H), 7.96 (m, 4H), 7.74 (t, 1H), 7.54 (t, 1H), 7.48 (d, 1H), 7.30 (m, 2H), 7.04 (m, 2H), 6.54 (m, 2H), 2.87 (m, 1H), 1.02 (d, 3H), 0.34 (d, 3H). Λ-[Ru(bpy)$_2${(*S*)-LO-*i*Pr}](PF$_6$) (Λ-**3a**). Yield 94% based on Λ-**3**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 278 nm (−105), 293 nm (+148). Δ-[Ru(bpy)$_2${(*R*)-LO-*i*Pr}](PF$_6$) (Δ-**3a**). Yield 95% based on Δ-**3**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 278 nm (+106), 293 nm (−143).

*[Ru(bpy)$_2$(LO-Bn)](PF$_6$) (rac-**4a**).* Yield 93% based on rac-**4**. Anal. Calcd for $C_{33}H_{27}F_6N_4O_2PRuS$: C 50.19, H 3.45, N 7.09, S 4.06. Found: C 50.21, H 3.35, N 7.14, S 4.15; ESI-MS: m/z = 645 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 10.14 (d, 1H), 8.55 (d, 1H), 8.39(d, 1H), 8.36 (d, 1H), 8.20 (m, 2H), 8.00 (m, 2H), 7.83 (m, 2H), 7.77 (m, 1H), 7.67 (t, 1H), 7.59 (t, 1H), 7.40 (d, 1H), 7.30 (t, 1H), 7.11 (m, 3H), 6.90 (d, 1H), 6.88 (t, 2H), 6.67 (d, 2H), 6.61 (d, 1H), 6.56 (t, 1H), 4.68 (d, 3H), 3.66 (d, 1H). Λ-[Ru(bpy)$_2${(*S*)-LO-Bn}](PF$_6$) (Λ-**4a**). Yield 93% based on Λ-**4**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 278 nm (−116), 294 nm (+118). Δ-[Ru(bpy)$_2${(*R*)-LO-Bn}](PF$_6$) (Δ-**4a**). Yield 93% based on Δ-**4**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 278 nm (+126), 294 nm (−123).

*[Ru(bpy)$_2$(LO-Nap)](PF$_6$) (rac-**5a**).* Yield 92% based on rac-**5**. Anal. Calcd for $C_{37}H_{29}F_6N_4O_2PRuS$: C 52.92, H 3.48, N 6.67, S 3.82. Found: C 53.01, H 3.25, N 6.64, S 3.89; ESI-MS: m/z = 695 [M − PF$_6$]$^+$; ^{1}H NMR (300.1 MHz, CD$_3$CN): δ 10.21 (d, 1H), 8.55 (d, 1H), 8.35(t, 2H), 8.23 (t, 1H), 8.02 (t, 1H), 7.94 (m, 2H), 7.80 (m, 2H), 7.71 (d, 1H), 7.60 (m, 2H), 7.48 (m, 3H), 7.34 (d, 1H), 7.26 (t, 1H), 7.13 (m, 2H), 6.97 (m, 4H), 6.85 (d, 1H), 6.63 (m, 2H), 5.06 (d, 1H), 3.86 (d, 1H). Λ-[Ru(bpy)$_2${(*S*)-LO-Nap}](PF$_6$) (Λ-**5a**). Yield 92% based on Λ-**5**; ee, 98%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 279 nm (−100), 295 nm (+75). Δ-[Ru(bpy)$_2${(*R*)-LO-Nap}](PF$_6$) (Δ-**5a**). Yield 92% based on Δ-**5**; ee, 98%; CD ($\Delta\varepsilon$/ M^{-1} cm^{-1}, MeCN): 279 nm (+99), 295 nm (−66).

Mothod B (One-Pot Method). The one-pot synthesis of sulfoxide complexes was carried out with the similar procedure of ours.[9] The yield of Λ-**3a** is 81%. Its enantiomeric excess is determined by ^{1}H NMR and found to be larger than 98%.

Syntheses of Sulfoxide Compounds and Recovery of the Chiral Complex. A sulfoxide complex (0.1 mmol) was added to the solution of CH_3CN (3 mL) containing 1.0 mmol of TFA. The solution was stirred at 80 °C for 2 h. After cooling to room temperature, the solvent was removed under reduced pressure and subjected to silica gel chromatography with EtOAc, and then MeCN−H_2O (10:1) as eluents. After removal of the solvent and drying in a desiccator with silica gel, chiral sulfoxide compounds and Λ/Δ-[Ru(bpy)$_2$(MeCN)$_2$](CF$_3$COO)(PF$_6$) were obtained. To convert into PF$_6$ salt, 20 mL of water was used to dissolve [Ru(bpy)$_2$(MeCN)$_2$]-(CF$_3$COO)(PF$_6$), and then solid KPF$_6$ was added. Furthermore, 15 mL and 2 × 10 mL of CH_2Cl_2 were used to extract the product from the aqueous phase, and the CH_2Cl_2 phase was combined and dried over $MgSO_4$. After filtration and concentration, Λ/Δ-[Ru(bpy)$_2$-(MeCN)$_2$](PF$_6$)$_2$ was obtained in the yield of 94%.

*2-(Methylsulfinyl)phenol (**HLO-Me**).* Yield, 95%. ESI-MS: m/z = 155 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 10.25 (s, 1H), 7.37 (t, 1H), 7.07 (d, 1H), 6.93 (m, 2H), 2.97 (s, 3H). For (*R*)-**HLO-Me**, yield 95% based on Λ-**1a**; ee, 97.0% (mobile phase: hexane/(EtOH:MeOH)/TFA = 90/(3:1)10/0.1); CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 219 nm (−23), 243 nm (+52). For (*S*)-**HLO-Me**, yield 95% based on Δ-**1a**; ee, 97.6%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 219 nm (+23), 243 nm (−52).

*2-(Ethylsulfinyl)phenol (**HLO-Et**).* Yield 95%. ESI-MS: m/z = 169 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 10.46 (s, 1H), 7.36 (t, 1H), 7.01 (d, 1H), 6.76 (m, 1H), 3.13 (m, 2H), 1.33 (t, 3H). For (*R*)-**HLO-Et**, yield 93% based on Λ-**2a**; ee, 96.7% (mobile phase: hexane/(EtOH:MeOH)/TFA = 95.5/(3:1)4.5/0.1); CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 221 nm (−26), 245 nm (+47). For (*S*)-**HLO-Et**, yield 94% based on Δ-**2a**; ee, 95.5%; CD ($\Delta\varepsilon$/M^{-1} cm^{-1}, MeCN): 221 nm (+27), 245 nm (−49)

*2-(Isopropylsulfinyl)phenol (**HLO-iPr**).* Yield 96%. ESI-MS: m/z = 183 [M − H]$^-$; ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 10.63 (s, 1H), 7.36 (t, 1H), 6.98 (d, 1H), 6.89 (m, 1H), 3.21 (m, 1H), 1.37 (d, 3H), 1.27 (d, 3H). For (*R*)-**HLO-*i*Pr**, yield 96% based on Λ-**3a**; ee, 98.8%

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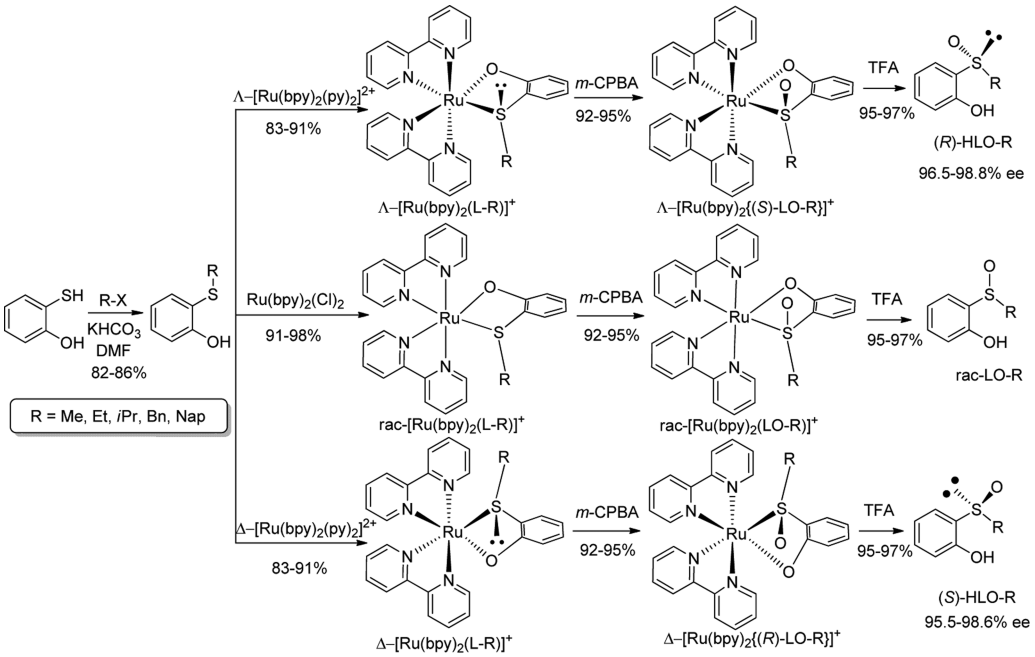
Scheme 1. Synthetic Pathway for Complexes and Chiral Sulfoxides



(mobile phase: hexane/(EtOH:MeOH)/TFA = 92/(3:1)8/0.1); CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 214 nm (−36), 222 nm (−39), 248 nm (+55). For (*S*)-**HLO-*i*Pr**, yield 97% based on Δ-**3a**; ee, 98.6%; CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 213 nm (+39), 222 nm (+40), 248 nm (−53).

*2-(Benzylsulfinyl)phenol (**HLO-Bn**).* Yield 97%. ESI-MS: m/z = 231 $[M - H]^-$; ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 10.20 (s, 1H), 7.30 (m, 4H), 7.02 (d, 2H), 6.89 (d, 1H), 6.76 (t, 1H), 6.66 (d, 1H), 4.37 (d, 1H), 4.30 (d, 1H). For (*R*)-**HLO-Bn**, yield 97% based on Λ-**4a**; ee, 96.5% (mobile phase: hexane/(EtOH:MeOH)/TFA = 92/(3:1)8/0.1). CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 224 nm (−27), 251 nm (+51). For (*S*)-**HLO-Bn**, yield 98% based on Δ-**4a**; ee, 97.4%; CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 225 nm (+27), 251 nm (−48) .

*2-(Naphthalsulfinyl)phenol (**HLO-Nap**).* Yield 97%. ESI-MS: m/z = 281 $[M - H]^-$; ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 10.25 (s, 1H), 7.76 (m, 3H), 7.48 (m, 3H), 7.34 (t, 1H), 7.13 (d, 1H), 6.90 (d, 1H), 6.71 (t, 1H), 6.62 (d, 1H), 4.56 (d, 1H), 4.45 (d, 1H). For (*R*)-**HLO-Nap**, yield 97% based on Λ-**5a**; ee, 96.7% (mobile phase: hexane/(EtOH:MeOH)/TFA = 80/(3:1)20/0.1); CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 230 nm (−16), 254 nm (+48). For (*S*)-**HLO-Nap**, yield 97% based on Δ-**5a**; ee, 97.4%; CD ($\Delta\varepsilon/M^{-1}$ cm^{-1}, MeCN): 230 nm (+17), 254 nm (−51).

Single-Crystal X-ray Crystallography. The data collection and the structure resolution for rac-**2a**·CH_2Cl_2, Δ-**2a**·CH_2Cl_2, Λ-**2a**·CH_2Cl_2, and (*R*)-**HLO-Bn** were carried out as the previous report.[9] The crystal data and parameters for the complexes are presented in Table 1. CCDC reference numbers 1036023 ((*R*)-**HLO-Bn**), 1036024 (for rac-**2a**), 1036025 (for Δ-**2a**), and 1036026 (for Λ-**2a**) contain the supplementary crystallographic data for the compounds. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

RESULTS AND DISCUSSION

Syntheses and Characterization of the Ligands and Thioether Complexes. Scheme 1 presents the pathway for the synthesis of the ligands and complexes. The 2-(alkylthio)-phenol (HL-R) ligands were smoothly synthesized by the reaction of 2-hydroxythiophenol and alkyl bromide in the presence of $KHCO_3$ as a base at room temperature.[17] The bulky substituents such as Bn and Nap need to extend the reaction time to afford the satisfactory results. No hydroalkylation product was observed in the experiment conditions, indicating that the alkylation reaction was high chemical selectivity. The products were confirmed by MS and NMR spectra. For the complexes, the racemic thioether complexes rac-**1** to rac-**5** were obtained when *cis*-$Ru(bpy)_2Cl_2$ reacted with the corresponding thioether ligands in EtOH−H_2O at 90 °C for 6 h. When the chiral precursors Δ/Λ-$[Ru(bpy)_2(py)_2]^{2+}$ were used to react with the prochiral thioethers at 120 °C in ethylene glycol, the corresponding chiral complexes Δ/Λ-$[Ru(bpy)_2(L\text{-}R)](PF_6)$ (Δ/Λ-**1**, Δ/Λ-**2**, Δ/Λ-**3**, Δ/Λ-**4**, and Δ/Λ-**5**) were obtained in yields of 83−91% after chromatography column separation. They were characterized by ^{1}H NMR, and positive ESI-MS spectroscopy. CD spectra were employed to observe the optical activity of the thioether complexes. As expected, the racemic complexes are all optically silent, whereas Δ/Λ-**1**, Δ/Λ-**2**, Δ/Λ-**3**, Δ/Λ-**4**, and Δ/Λ-**5** are optically active. As shown in Figure 1, Λ-**1** and Δ-**1** have an intensive Cotton effect at 279 and 297 nm. They are almost mirror images. The analogous cases were also observed for Δ/Λ-**2**, Δ/Λ-**3**, Δ/Λ-**4**,

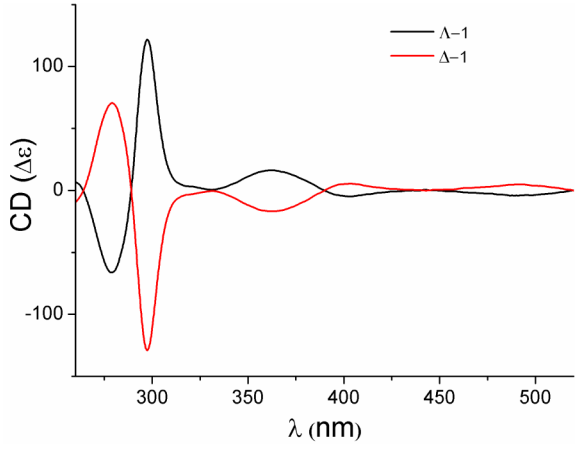


Figure 1. CD spectra of Δ-**1** and Λ-**1** in MeCN (50 μM).

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and Δ/Λ-**5** (see Figures S1−S4 in the Supporting Information and the Experimental Section).

The enantiopurities of the thioether complexes were measured by ^{1}H NMR spectra, because the Δ and Λ isomers have different chemical shifts when *S*-binol was added.[18] As shown in Figure 2, the resonance peak at 8.84 ppm in rac-**1**,

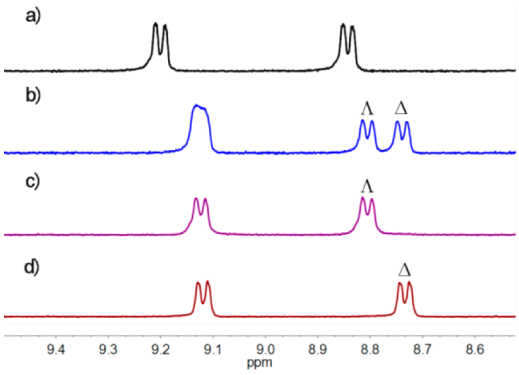

Figure 2. ^{1}H NMR spectra of rac-**1** (a), rac-**1** and 40 equiv of *S*-binol (b), Λ-1 and 40 equiv of *S*-binol (c), Δ-**1** and 40 equiv of *S*-binol (d) in CD_3CN.

assigned to the H_6 of bpy, is split into 8.81 and 8.73 ppm when 40 equiv of *S*-binol was added. They have the same chemical shifts with the corresponding Λ and Δ enantiomers. Thereby, the enantiopurities of Δ and Λ enantiomers can be calculated from the integrals of these peaks and were found to be larger than 98%. The same approach is used to examine the enantiopurities of the other thioether complexes (see Figures S5−S8 in the Supporting Information). Their enantiopurities were found to be larger than 98%. The above results indicate that the configurations of ruthenium complexes are stable in the coordination reaction.

Syntheses and Structural Characterization of Sulfoxide Complexes. Sulfoxide complexes were obtained by the directed oxidation of the thioether complexes in the presence of *m*-CPBA in methanol at room temperature. The yields are excellent in 93−95%. It was noteworthy that no sulfone product was detected. The sulfoxide complexes were characterized by NMR and MS spectroscopy. CD spectra were used to examine the optical activity of the corresponding complexes. As shown in Figure 3, Λ-**1a** and Δ-**1a** have a strong

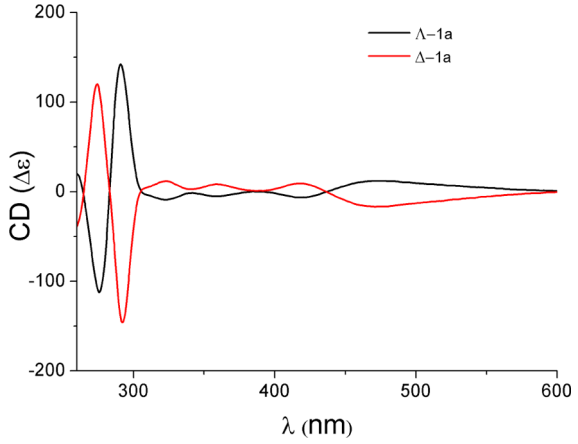

Figure 3. CD spectra of complexes Δ-**1a** and Λ-**1a** in MeCN (50 μM).

Cotton effect at 274 and 290 nm. The similar cases were also observed for Δ/Λ-**2a**, Δ/Λ-**3a**, Δ/Λ-**4a**, and Δ/Λ-**5a** (see Figures S8−S12 in the Supporting Information and the Experimental Section).

The chemical shifts of the H_6 of bpy at 10.05 ppm in **1a**, 10.15 ppm in **2a**, 10.15 ppm in **3a**, 10.14 ppm in **4a**, and 10.21 ppm in **5a** are markedly low-field shifted in comparison with those of the corresponding thioether complexes (9.20, 9.22, 9.24, 9.26, and 9.34 ppm). These may be attributed to the hydrogen bonding between the α-H and sulfoxide oxygen atom (*vide infra*). The ^{1}H chemical shifts at 1.41 ppm in **1**, 2.21 and 1.64 ppm in **2**, 2.58 ppm in **3**, 3.83 and 3.06 ppm in **4**, and 4.24 and 3.30 ppm in **5**, assigned to the methyl or methylene (−S-*CH*−) in the thioether ligands, are low-field shifted to the corresponding 2.30 ppm in **1a**, 3.07 and 2.10 ppm in **2a**, 2.87 ppm in **3a**, 4.68 and 3.66 ppm in **4a**, and 5.06 and 3.86 ppm in **5a**, demonstrating that the oxidation reaction indeed occurs because sulfoxide is an electron-withdrawing group. The ^{1}H NMR spectra of rac-**3a**, Λ-**3a**, and Δ-**3a** in the absence or presence of *S*-binol in CD_3CN are presented in Figure 4. The

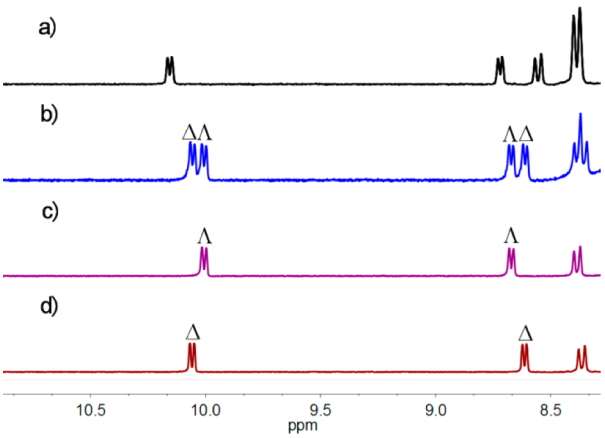

Figure 4. ^{1}H NMR spectra of rac-**3a** (a), rac-**3a** with 40 equiv of *S*-binol (b), Λ-**3a** with 40 equiv of S-binol (c), Δ-**3a** with 40 equiv of *S*-binol (d) in CD_3CN.

resonance peak at 10.15 ppm is split into two peaks at 10.06 and 10.01 ppm, which are in accord with those of Δ and Λ enantiomers. Moreover, the peak at 8.72 ppm is also split and shifted to 8.67 and 8.61 ppm, which are consistent with those of Λ and Δ enantiomers. The similar cases are also observed in the other complexes (see Figures S13−S16 in the Supporting Information): the peak at 10.05 ppm for rac-**1a** is split into 10.00 and 9.94 ppm, that at 10.15 ppm for rac-**2a** is split into 10.08 and 10.03 ppm, those at 10.14 and 8.55 ppm for rac-**4a** are split into 10.09 and 10.04 ppm, and 8.51 and 8.44 ppm, and those at 10.21 and 8.53 ppm for rac-**5a** are split into 10.15 and 10.11 ppm, and 8.51 and 8.45 ppm. The enantiopurities of Δ and Λ enantiomers are calculated from the integrals of these peaks and are found to be larger than 98%. The experiments also demonstrated that the ruthenium complexes are stable in the oxidation reaction under the experimental conditions.

The racemic complex rac-**2a** crystallizes in the $P2_1/c$ space group. As shown in Figure 5, the sulfoxide ligand is indeed generated *in situ*. Each Ru(II) ion is coordinated by two bpy and one **LO-Et** ligand in a distorted octahedral geometry. The sulfur atom is bound to the Ru(II) ion with a distance of 2.250(1) Å; the Ru1−S1 bond length is comparable with those of the ruthenium sulfoxide complexes.[7c,9,14] The bond distance

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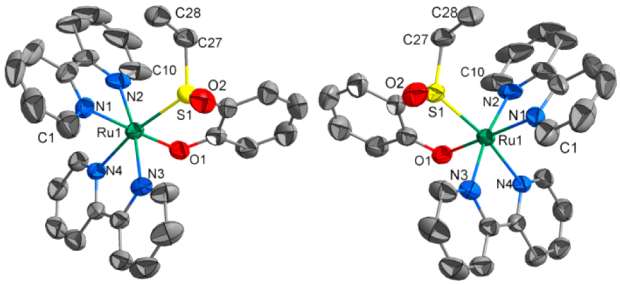

Figure 5. View of the structures of a pair of cations in rac-**2a** (left, Δ-*R*; and right, Λ-*S*). Selected bond angles (deg) and distances (Å): Ru1−O1 = 2.076(3), Ru1−S1 = 2.250(1), Ru1−N1 = 2.060(4), Ru1−N2 = 2.058(4), Ru1−N3 = 2.070(4), Ru1−N4 = 2.105(3), S1−O2 = 1.487(4), N4−Ru1−S1 = 168.5(1). ORTEP drawing with 50% probability thermal elipsoids.[19]

of Ru1−N4 (2.105(3) Å) is slightly longer than those of Ru−N(1−3) (2.058−2.070 Å), indicating the stronger *trans* effect of the coordination sulfur atom.[7c] The S−O bond length (1.487(4) Å) is in the range of those reported.[9,14] The bulk ethyl group of the **LO-Et** ligand is away from the H_6 of bpy to relieve the repulsion. Moreover, the sulfoxide oxygen atom generated *in situ* indeed anchors on the other side and further forms a hydrogen bond with the H_6 of bpy (C11···O2 = 3.080 Å, H···O2 = 2.227 Å, ∠C11−H−O2 = 150.5°). Only a pair of enantiomeric cations Δ-*R* and Λ-*S* are found in each asymmtric unit, though two pairs of diasteromeric cations (Δ-*S* and Δ-*R*, Λ-*S* and Λ-*R*) would be produced theoretically during the oxidation process. Upon careful examination of the crystal structure, the fact that enantioselective origination of the absolute configuration at the sulfur atom mediated by the chiral ruthenium center is found, namely, the *R* configuration at the sulfur atom is generated by the **Δ** metal-centered parent, whereas the *S* configuration at the sulfur atom is produced by the **Λ** metal-centered environment. This also inspires us to observe the oxidation reaction in an asymmetric environment. Indeed, the cases were also found in the chiral sulfoxide complexes Δ-**2a** and Λ-**2a**, which were generated by the oxidation of the chiral thioether complexes Δ-**2** and Λ-**2**, respectively. The absolute configurations of sulfur atoms and ruthenium centers in complexes Δ-**2a** and Λ-**2a** were measured by single-crystal X-ray diffraction (see Figures S17 and S18 in the Supporting Information). The structures verify that the Δ and **Λ** configurations are at the ruthenium centers of Δ-**2a** and Λ-**2a**, respectively, which are consistent with the configurations of their parents, indicating that the configurations of ruthenium complexes are retained during the oxidation reaction. The Flack parameters of Δ-**2a** (−0.030(7)) and Λ-**2a** (−0.015(9)) demonstrate that the chiral assignments at the complexes are correct. Most important, only the *R* configuration of the **LO-Et** ligand is found in Δ-**2a**; on the contrary, only the *S* configuration of the **LO-Et** ligand is observed in Λ-**2a**. These further demonstrate that the configuration at the ruthenium center mediates the sulfoxide chirality during the oxidation process. Therefore, this strategy can be employed to originate the predetermined chirality of sulfoxide compounds.

One-pot method for the synthetic sulfoxide complex Λ-**3a** was also developed. The total yield of the sulfoxide complex was 81% (see the Experimental Section). The enantiopurity of the one-pot product was measured by NMR spectra, and the ee value is larger than 98%. The result also proves that the ruthenium-centered configuration is stable in the course of reaction under the experiment conditions and mediates the chirality of sulfoxide *in situ* oxidation.

Synthesis and Characterization of Sulfoxide Compounds. The sulfoxide ligands can be released from the corresponding sulfoxide complexes in the presence of TFA and displaced by the coordinated solvent CH_3CN.[9,20] Indeed, when the sulfoxide complexes were added to the TFA−CH_3CN solution, and then stirred at 80 °C for 2 h, the sulfoxide compounds HLO-R were obtained in 95−97% after a column separation. The sulfoxide compounds were characterized by MS and NMR spectroscopy. CD spectra was also used to examine their optical activity (see Figures S19−S23 in the Supporting Information). Furthermore, the enantiopurities of (*R*/*S*)-HLO-R were measured by means of chiral HPLC analyses (see Figure 6 and Figures S24−27, Supporting Information). The ee

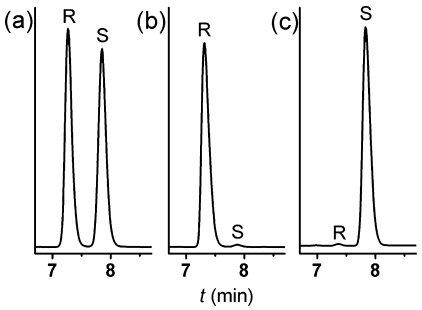

Figure 6. HPLC traces of racemic **HLO-*i*Pr** (a), (*R*)-**HLO-*i*Pr** with 98.8% ee value (b), and (*S*)-**HLO-*i*Pr** with 98.6% ee value (c).

values are 97.0% for (*R*)-**HLO-Me**, 96.7% for (*R*)-**HLO-Et**, 98.8% for (*R*)-**HLO-*i*Pr**, 96.5% for (*R*)-**HLO-Bn**, and 96.7% for (*R*)-**HLO-Nap**, and 97.6% for (*S*)-**HLO-Me**, 95.5% for (*S*)-**HLO-Et**, 98.6% for (*S*)-**HLO-*i*Pr**, 97.4% for (*S*)-**HLO-Bn**, and 97.4% for (*S*)-**HLO-Nap**. The experiment results show that no significant racemization occurred during the acidolysis reaction. It is noteworthy that the sulfur atom configuration converts from *R* to *S* upon release from the coordination. (*S*)-**HLO-*i*Pr** has been prepared by the Andersen method,[7c] involving nucleophilic substitution of 1,2:5,6-di-isopropylidene-α-D-glucofuranosyl-(+)-(*R*)-2-propanesulfinate[21] by the freshly prepared Grignard reagent and then deprotection of the methoxyl group. Here, we developed a new approach to synthesize the chiral sulfoxide compounds with high yields and enantiopurities. Importantly, the use of the organometallic reagent is avoided, and the procedures are easy to be controlled.

The absolute configuration of (*R*)-**HLO-Bn** was further identified by single-crystal X-ray diffraction. It crystallizes in the $P2_12_12_1$ space group. The molecular structure of (*R*)-**HLO-Bn** is presented in Figure 7. The sulfur atom is a *R* configuration. The Flack parameter 0.00(7) demonstrates that the chiral assignment at the sulfur atom is correct. The S1−O2 distance of 1.504(2) Å is compared to that reported.[9]

Recovery and Reuse of the Chiral Ruthenium Complex. The affording of chiral sulfoxide compounds with high yields and high enantiomeric excesses indicates that the configuration of the sulfur atom is retained during the acidolysis reaction. This prompts us to observe the configuration of the metal center upon removal of the chiral sulfoxide ligand, and to recycle and reuse the chiral ruthenium complex as a new precursor. When 10 equiv of TFA was added to the acetonitrile solution of Λ-**3a** at 80 °C in the dark, the new complex Λ-

DOI: 10.1021/ic502898e
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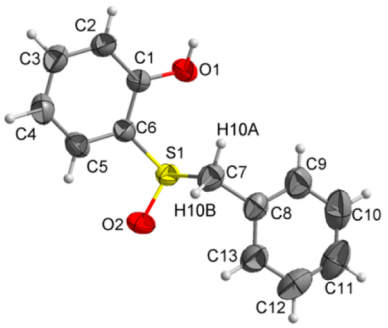


Figure 7. View of the structure of (*R*)-**HLO-Bn**. Selected bond distances (Å) and angles (deg): S1−O2 = 1.504(2), C6−S1 = 1.787(2), C7−S1 = 1.820(2), O2−S1−C6 = 104.9(1), C7−S1−C6 = 99.3(1), O2−S1−C7 = 104.4(1). ORTEP drawing with 50% probability thermal elipsoids.[19]

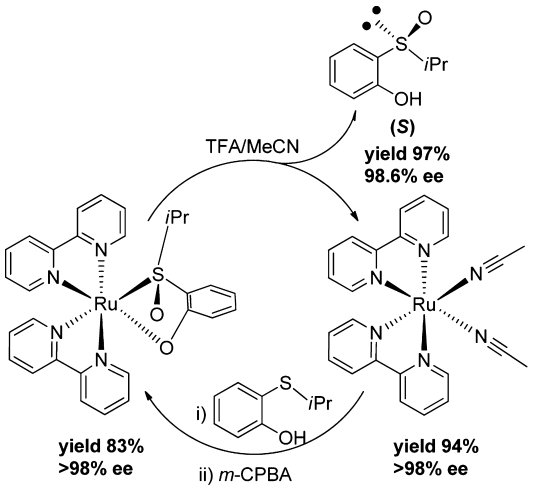
$[Ru(bpy)_2(CH_3CN)_2](PF_6)_2$[7d] was afforded in 94% yield after a facile silica gel chromatographic column separation. Its enantiopurity was examined by conversion into the corresponding thioether complex Λ-**3** (see the Experimental Section) and measured by ^{1}H NMR spectra. The ee value was found to be larger than 98% calculated from the integrals of H_6 peaks (see Figure S28, Supporting Information), indicating that the chiral ruthenium complex would be recyclable under the reaction conditions.

Moreover, the reusability of the recycled chiral ruthenium complex was also examined. Indeed, Δ-**3a** was obtained in a yield of 83% by the reaction of the recycled Δ-$[Ru(bpy)_2(MeCN)_2](PF_6)_2$ and **HL-*i*Pr** in EtOH at 80 °C for 0.5 h under an argon atmosphere, followed by oxidation using *m*-CPBA as an oxidant (see the Experimental Section, one-pot method). Its enantiopurity was determined by ^{1}H NMR spectra. The ee value was found to be larger than 98% (see Figure S29, Supporting Information). The results demonstrate that the chiral ruthenium complex is reusable under the reaction conditions, as shown in Scheme 2.

CONCLUSIONS

The preparation of chiral 2-(alkylsulfinyl)phenol compounds by means of enantioselective coordination−oxidation of the thioether ruthenium complexes with a chiral-at-metal strategy has been developed. The configurations of ruthenium complexes are stable during the coordination and oxidation processes. Moreover, the ruthenium centered configurations mediate the origination of sulfoxide chirality in the course of oxidation. The chiral sulfoxide can be released by the acidolysis of the corresponding sulfoxide complex with TFA in the presence of CH_3CN. Importantly, the chiral ruthenium complex can be recycled and reused in a next reaction cycle with complete retention of their configurations.

Scheme 2. Reaction Cycle for the Synthesis of Chiral Sulfoxide from Prochiral Thioether



ASSOCIATED CONTENT

Supporting Information

The detailed experiments. the CD, ^{1}H NMR, crystal structure, and HPLC figures for the compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the NSF of China (21272284) and the DPF of MOE of China (No. 0171110004).

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