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Stereoselective Synthesis of Chiral Sulfilimines from *N*-Mesyloxycarbamates: Metal-Nitrenes versus Metal-Nitrenoids Species

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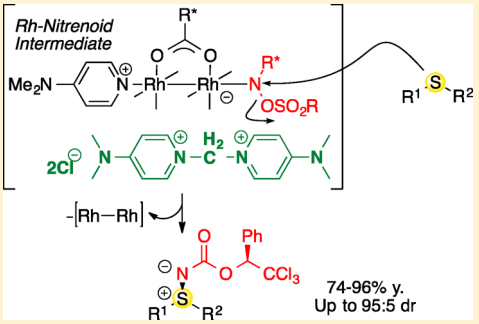
Supporting Information

ABSTRACT: The synthesis of a variety of chiral sulfilimines and sulfoximines is described. The amination of thioethers with a chiral *N*-mesyloxycarbamate was achieved in high yields and stereoselectivities using $Rh_2[(S)\text{-nttl}]_4$ as catalyst in the presence of 4-dimethylaminopyridine (DMAP) and a pyridinium salt, such as bis(DMAP)CH_2Cl_2 or a viologen salt. These additives proved instrumental to enhance both the yield and the stereochemical discrimination of the reaction. Mechanistic studies and control experiments have elucidated the role of these additives. DMAP served as an apical ligand for the rhodium catalyst: an X-ray crystal structure of the $(DMAP)_2\cdot[Rh_2\{(S)\text{-nttl}\}_4]$ complex was obtained. This complex displayed a lower and irreversible redox potential. Control experiments with preformed Rh(II)−Rh(III) complex suggested such a catalytically active species in the thioether amination process. Diastereoselectivities were influenced by the sulfonyloxy leaving group, ruling out the possibility of a common metal nitrene species and instead suggesting a rhodium-nitrenoid complex. It is believed that the bispyridinium salt played the role of a phase transfer catalyst, influencing both the yield and the diastereoselectivity of the reaction.



INTRODUCTION

Sulfilimines[1] (or sulfimides)[2] and sulfoximines[3] are biologically interesting molecules that have a high potential as therapeutic agents.[4] They have also been used as synthetic intermediates in a few transformations[5,6] and as chiral ligands for metal asymmetric catalysis due to the chirality at the sulfur atom.[7] Despite their relevance, the chemistry of sulfilimines remains largely underdeveloped. This is likely due to the limited synthetic and stereoselective methods available in their preparation. The amination of thioethers with electrophilic nitrogen reagents is the oldest and most widely reported method to prepare sulfilimines.[1a,8] Resolution of the resulting sulfilimine product was the first reported strategy to prepare optically active variants.[9] The amination of chiral thioethers possessing inherent stereocenters has been also described.[10] An alternative strategy is to use chiral sulfoxides as starting materials, but not all reagents result in complete retention or inversion of configuration at the sulfur center.[11] A number of transition metal complexes have been reported to catalyze the amination of thioethers presumably via the formation of metal nitrene species.[8f,12] Metal-catalyzed diastereoselective reactions with chiral substrates[13] or chiral reagents[14] have been reported, but proceed with limited substrate scope. The first catalytic enantioselective amination of thioethers using Cu−bis(oxazoline) complexes was developed by Uemura and coworkers, producing the desired sulfilimine with a modest enantioselectivity.[15] The group of Katsuki later delineated Mn(salen),[16] Ru(salen),[17] and Ru(salalen)[18] catalysts that afforded aromatic sulfilimines with high levels of enantioselectivity.[19] A drawback associated with the latter methods is the multistep synthesis of the chiral ligands. Recently, Bolm and coworkers reported the enantioselective amination of thioethers with iminoiodinanes, catalyzed by an Fe−PyBOX complex.[20] This resulted in aromatic sulfilimines in high yields and excellent enantioselectivities. However, modest yields and enantiomeric ratios were obtained with sterically hindered and aliphatic substrates. An enzyme-catalyzed amination of aromatic thioethers has recently been disclosed to produce sulfilimines with modest enantioselectivities.[21]

We have recently reported the stereoselective amination of thioethers with *N*-mesyloxycarbamate **1** in the presence of catalytic amounts of $Rh_2[(S)\text{-nttl}]_4$, 4-dimethylaminopyridine (DMAP), and bis(DMAP)CH_2Cl_2 (**2**) (eq 1).[22] The latter additives were found crucial for the yields and the stereoinduction of the process. Herein, we report the full scope of this amination process, illustrating its functional group tolerance, in addition to the mechanistic investigation to elucidate the role of the additives. The oxidation of the sulfilimine, followed by the cleavage of the carbamate moiety, allowing the synthesis of N−H-sulfoximines in high yields and enantioselectivities is also described.

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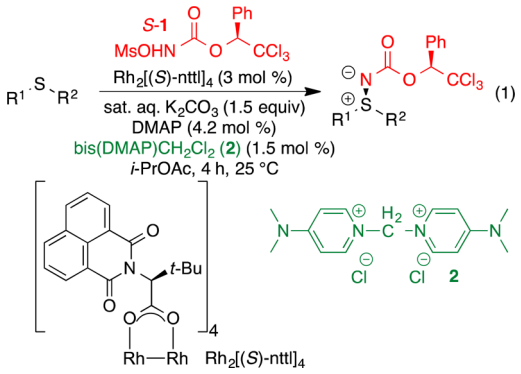
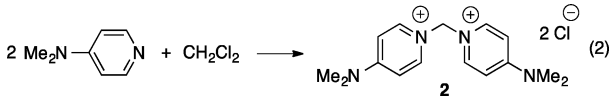


RESULTS AND DISCUSSION

Stereoselective Amination of Thioethers: Scope. Our group has been interested in the use of *N*-sulfonyloxycarbamates to produce metal nitrenes from rhodium dimers and copper catalysts. The resulting metal nitrene species readily undergo highly efficient C−H amination and aziridination reactions.[23] These reagents are practical alternatives to iminoiodinanes (typically used in metal nitrene chemistry), producing carbamate-protected amines and aziridines that are easy to cleave. Chiral *N*-sulfonyloxycarbamates, namely, **1**, have been disclosed to perform stereoselective aziridination and C−H amination reactions in the presence of chiral copper and rhodium catalysts.[24] More recently, we became interested in studying the stereoselective amination of thioethers with chiral *N*-mesyloxycarbamate **1** and $Rh_2[(S)\text{-nttl}]_4$ as catalyst. In our initial investigation, DMAP and the corresponding dichloromethane adduct **2**[25] (eq 2) were revealed as beneficial

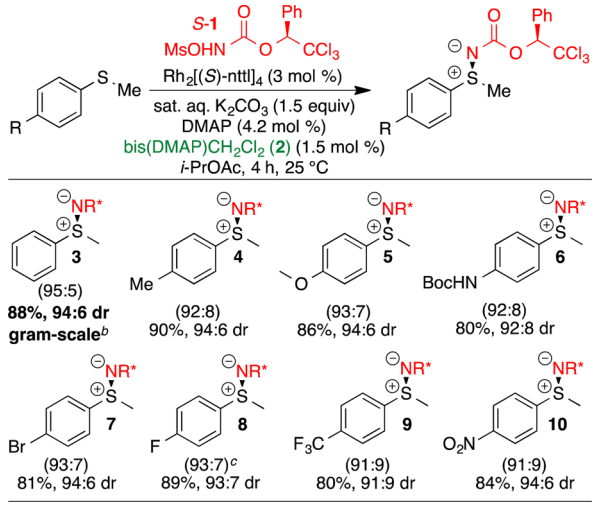


synergistic additives, enhancing both the yields and the diastereomeric ratio (dr) of the amination process.[22] The best results were achieved when both additives were present, the details of which will be discussed *vide infra*.

The amination of substituted thioanisoles was first studied under the optimal reaction conditions using a stoichiometric amount of thioether and *N*-mesyloxycarbamate **1**, 3 mol % of $Rh_2[(S)\text{-nttl}]_4$, 1.5 equiv of an aqueous saturated solution of potassium carbonate, 4.2 mol % of DMAP, and 1.5 mol % of **2**, in isopropyl acetate at rt (Scheme 1). The reaction was complete in 4 h, relative to the 12 h typically reported for other stereoselective methods.[19,20] A gram-scale reaction was performed with thioanisole, using 1 mol % of the rhodium catalyst and affording the desired sulfilimine **3** in 88% yield and 94:6 dr. The absolute configuration was established with an X-ray crystal structure of sulfilimine **4**.[22] Thioanisoles substituted with electron-donating groups were also reacted to produce the corresponding sulfilimines **5** and **6** in high yields and dr. Aryl halides were also compatible with the reaction conditions (sulfilimines **7** and **8**). Moreover, sulfilimines **9** and **10** derived from thioanisoles containing electron-withdrawing groups were produced in high yields and dr.

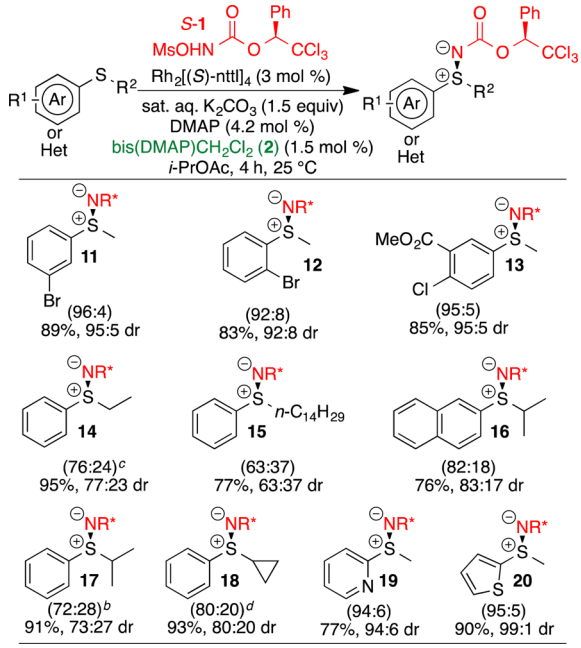
Similar results were observed with *meta*- and *ortho*-substituted aromatic sulfilimines **11**−**13** (Scheme 2). When the alkyl group of the aromatic thioether was bigger than a methyl, the diastereoselectivity of the reaction decreased significantly. For the synthesis of sulfilimines **14** and **15**,

Scheme 1. Synthesis of Sulfilimines Derived from *p*-Substituted Thioanisoles[a]



[a]Yields and dr (*S*,*S*:*S*,*R* ratio by ^{1}H NMR spectroscopy) of isolated product; in parentheses, crude *S*,*S*:*S*,*R* ratio by ^{1}H NMR spectroscopy. [b]$Rh_2[(S)\text{-nttl}]_4$ (1 mol %); DMAP (1.4 mol %), **2** (0.5 mol %). [c]$Rh_2[(S)\text{-4-NO}_2\text{-nttl}]_4$.

Scheme 2. Synthesis of Sulfilimines Derived from Aromatic and Heteroaromatic Thioethers[a]



[a]Yields and dr of isolated product; in parentheses, crude *S*,*S*:*S*,*R* ratio determined by ^{1}H NMR spectroscopy. [b]$Rh_2[(S)\text{-4-NO}_2\text{-nttl}]_4$, Me-viologen$(PF_6)_2$ (3 mol %). [c]Me-viologen$(PF_6)_2$ (3 mol %) [d]$Rh_2[(S)\text{-4-NO}_2\text{-nttl}]_4$.

other previously reported amination methods provided improved results.[19,20] However, in comparison with literature results,[20] higher yields were obtained for the reaction of chiral *N*-mesyloxycarbamate **1** with sterically hindered thioethers; sulfilimines **16**−**18** were produced in 76−93% yields. The dr was slightly improved compared to sulfilimines **14** and **15**, but remained modest, though at a level similar to other methods.[20] The reaction conditions are compatible with a pyridine and a

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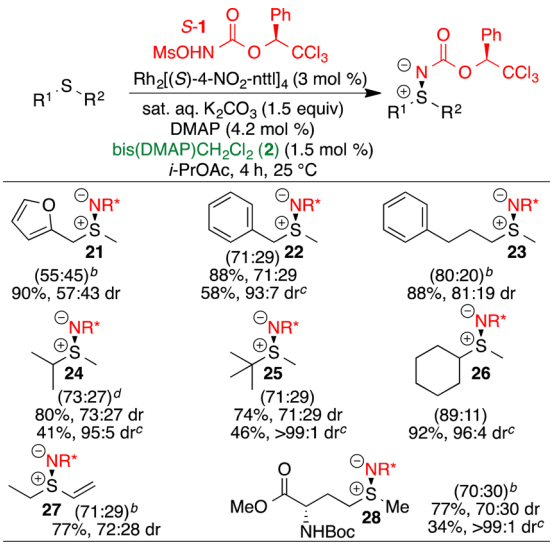
thiophene group. Only the amination at the thioether position was observed, affording sulfilimines **19** and **20** in good to excellent yields with high levels of stereoinduction.

The stereoselective amination of aliphatic thioethers proved problematic with previously reported methods.[19,20] Not only were modest selectivities observed but also yields were compromised. We were pleased to find that excellent yields were obtained when using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ as catalyst with aliphatic thioethers (Scheme 3).[26] Modest to good

Scheme 3. Synthesis of Sulfilimines Derived from Aliphatic Thioethers[a]



[a]Yields and dr of isolated product; in parentheses, crude *S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy. [b]DMAP (3 mol %), Me-viologen$(PF_6)_2$ (3 mol %). [c]Isolated yield and *S,S*:*R,S* ratio after recrystallization in $CHCl_3$/hexanes. [d]$Rh_2[(S)\text{-}4\text{-}Br\text{-}nttl]_4$.

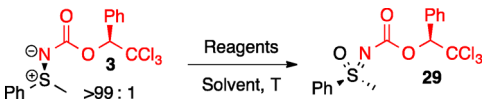
diastereoselectivities were observed with a variety of diversely substituted aliphatic thioethers. In many cases, it is possible to enhance the dr of the sulfilimine by a simple recrystallization. Using such a strategy, sulfilimines **22**, **24**, and **25** were isolated in 41−58% yields and >90:10 dr. The absolute configuration was established with an X-ray crystal structure of sulfilimine **25**. The best chiral discrimination was observed with cyclohexylmethyl thioether, producing sulfilimine **26** in 92% yield and 96:4 dr, after recrystallization. The reaction conditions displayed a very good functional group tolerance. Furan, alkene, ester, and protected nitrogen groups were found to be compatible, and the amination was highly chemoselective for the thioether moiety. For instance, sulfilimine **27** was isolated in good yields and no trace of the corresponding aziridination product was observed. The amination of a protected methionine derivative also proceeded in good yields. The resulting sulfilimine **28** was recrystallized, and a single diastereomer was isolated in 34%. To date, this is the best method to access such a stereoenriched aliphatic sulfilimine.

Synthesis of NH-sulfoximines. Sulfoximines are accessible by the oxidation of sulfilimines.[27] In most cases, the reaction proceeds without racemization.[3,12i,14b,20] A number of reaction conditions were tested with sulfilimine **3** (Table 1). Whereas no conversion was observed with peroxide reagent, sodium hypochlorite or sodium perborate (entries 1−6), the use of an excess of *m*-CPBA in ethanol afforded 83% of desired sulfoximine **29** without any traceable racemization (entry 7). Better yields and faster reactions were observed with ruthenium-catalyzed oxidation in the presence of sodium periodate; 98% of the desired sulfoximine **29** was isolated, again without any detectable racemization (entry 9).

These reaction conditions were applied to the synthesis of aromatic sulfoximines **30** and **31** (Table 2, entries 1 and 2), containing, respectively, an electron-withdrawing and a halide group. Aliphatic sulfoximine **32** was also produced in high yield and diastereoselectivity (entry 3). Methionine sulfoximine was the very first isolated and fully characterized sulfoximine.[28] Several biological studies have established the physiological properties of methionine sulfoximine.[4e] The oxidation of methonine-derived sulfilimine **28** afforded the corresponding protected sulfoximine **33** in high yield and as a single diastereomer (Scheme 4). Orthogonal cleavage of the phenyl-Troc protecting group ((O)COCH(Ph)CCl_3) was achieved with zinc in acetic acid, producing methionine *NH*-sulfoximine **34** in a good yield as a single diastereomer. These deprotection reaction conditions are also compatible with other sulfoximine substrates.[22]

Stereoselective Amination of Thioethers: Mechanistic Studies. Many aspects of the rhodium-catalyzed amination of thioethers are puzzling; thus, a number of control experiments and kinetic studies were conducted to attempt to elucidate the mechanism. Furthermore, there is a discrepancy between the amination of thioethers versus the amination of C−H bonds

Table 1. Oxidation of Sulfilimine 3 under Various Reaction Conditions



entry	reagents	conditions	yield (%)[a]
1	H_2O_2 (10 equiv), $FeCl_2$ (5 mol %)	CH_3CN, 25 °C, 24 h	0
2	NaOCl (10 equiv)	MeOH, 25 °C, 24 h	<5
3	*t*-BuOOH (5 equiv)	CH_3CN, 25 °C, 24 h	<5
4	$NaBO_3{\cdot}4H_2O$ (10 equiv), AcOH (3 equiv)	CH_2Cl_2, 25 °C, 24 h	0
5	$NaBO_3{\cdot}4H_2O$ (5 equiv)	H_2O/MeOH (9:1), 90 °C, 12 h	0
6	$NaBO_3{\cdot}4H_2O$ (3 equiv)	H_2O/MeOH (9:1), MW (30W), 1 h	0
7	*m*-CPBA (5 equiv), K_2CO_3 (5 equiv)	EtOH, 25 °C, 24 h	83
8	*m*-CPBA (5 equiv), K_2CO_3 (5 equiv)	CH_2Cl_2, 25 °C, 24 h	38
9	$NaIO_4$ (1.5 equiv), $RuCl_3$ (2 mol %)	CH_3CN/CCl_4 (1:1), H_2O, 23 °C, 1 h	98 (>99:1)[b]

[a]Yields of isolated product. [b]*S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy.

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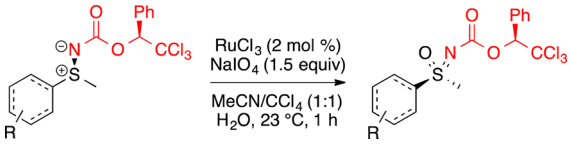
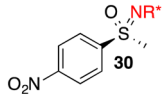
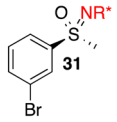
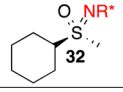
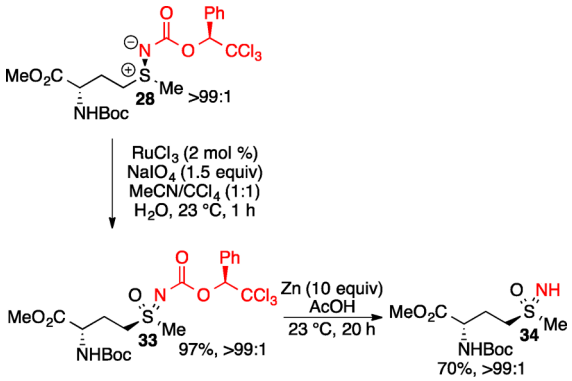
Table 2. Synthesis of Aromatic and Aliphatic Sulfoximines



Entry	Sulfilimine	Sulfoximine	Yield (%)[a]	dr[b]
1	**10**, 94:6 dr	 **30**	92	94:6
2	**11**, 96:4 dr	 **31**	98	96:4
3	**26**, 96:4 dr	 **32**	95	96:4

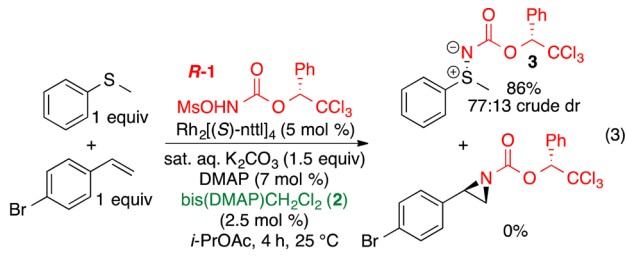
[a]Yields of isolated product. [b]*S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy.

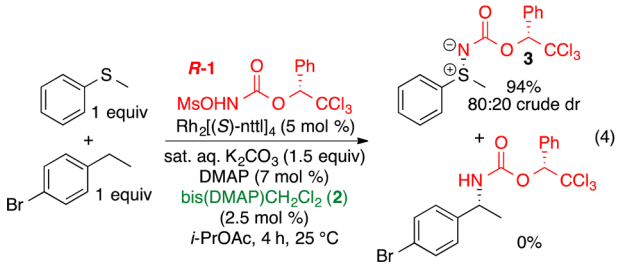
Scheme 4. Synthesis of Protected-Methionine *NH*-Sulfoximine 34



and the aziridination reaction with *N*-mesyloxycarbamate **1**. For instance, the match case in between *N*-mesyloxycarbamate **1** and the chiral catalyst for the amination of thioethers is not the same as that for the amination of C−H bonds and the aziridination reaction. Whereas the *S* enantiomer of *N*-mesyloxycarbamate **1** was used with $Rh_2[(S)\text{-nttl}]_4$ for the amination of thioethers, the *R* enantiomer of *N*-mesyloxycarbamate **1** was used for the C−H amination of ethylbenzene derivatives and the aziridination of styrene derivatives (with the same enantiomer of the catalyst ($Rh_2[(S)\text{-nttl}]_4$)). In addition, the difference in rate in between the match and mismatch cases for the amination of thioethers was not as important as that for the amination of C−H bonds and the aziridination reaction. We have also noticed that the amination of thioethers proceeded much faster than the amination of C−H bonds and the aziridination reaction. In a competitive study in which we use the mismatch pair for the amination of thioethers and the match pair for the amination of C−H bonds and the aziridination reaction (thus *R*-**1** with $Rh_2[(S)\text{-nttl}]_4$), we observed exclusively the amination of thioanisole and no reaction with the ethylbenzene or the styrene derivative (eqs 3 and 4).[29]

The role of the additives was initially elusive. In the absence of an additive, in isopropyl acetate, sulfilimine **3** was isolated in 85% yield and 75:25 dr (Table 3, entry 1). The





diastereoselectivity was slightly improved upon addition of a catalytic amount of DMAP; however, the yield was compromised (entry 2). In the presence of DMAP and bis(DMAP)CH_2Cl_2 (**2**), both the yield and the dr of sulfilimine **3** were excellent (entry 3). The role of the bispyridinium **2** alone was difficult to establish, as bis(DMAP)CH_2Cl_2 (**2**) partially reverts to form DMAP and CH_2Cl_2 in solution.[22,25] However, another stable bispyridinium, Me-viologen$(PF_6)_2$ (see Scheme 5 for chemical structures of the additives), was successfully used with DMAP, producing sulfilimine **3** with high yields and dr (entry 4). When DMAP was replaced by other donor ligands such as *N*-methylimidazole (NMI) and IPr, similar high yields and dr were obtained in the presence of Me-viologen$(PF_6)_2$ for the synthesis of sulfilimine **3** (entries 6 and 8). However, the use of an excessively strong coordinating ligand, such as triphenylphosphine, was detrimental for both the yield and the diastereoselectivity, even in the presence of Me-viologen$(PF_6)_2$ (entries 9−10). In the absence of DMAP, Me-viologen$(PF_6)_2$ still provided the desired sulfilimine **3** with good yields and dr, though lower than those obtained when DMAP is used (entry 11). The diastereoselectivity of the rhodium-catalyzed amination of thioethers was strongly influenced by the chemical structure of the bispyridinium. For instance, octyl-viologen$(PF_6)_2$ afforded the desired sulfilimine **3** in lower dr, with or without DMAP (entries 12 and 16). Good results were observed with bis(DMAP)CH_2Br_2 and bis(DMAP)$EtCl_2$, whereas bis(Pyrrpy)CH_2Cl_2 afforded modest dr (entries 13−15). We initially postulated that the bispyridinium salt was acting as a mild oxidant for the Rh catalyst to generate a Rh(II)−Rh(III) species as the active catalyst (*vide infra* for discussion on the oxidation state of the catalyst).[22] To validate this hypothesis, the bispyridinium salt was replaced by other mild oxidants, such as *N*-chlorosuccinimide (NCS), TEMPO, and benzoquinone. In all cases, these additives provided better yields than that obtained with only DMAP as additive (entries 2 vs 17−19). However, the diastereoselectivity was not significantly improved, except in the presence of bis(DMAP)CH_2Cl_2 (**2**) (entry 20).

The effect of donor ligands, namely, DMAP, with chiral dirhodium(II) complexes has been previously reported in enantioselective processes.[30] The spectacular color change observed, in between the green $Rh_2[(S)\text{-nttl}]_4$ solution, the purple thioanisole-$Rh_2[(S)\text{-nttl}]_4$ complex solution and the red

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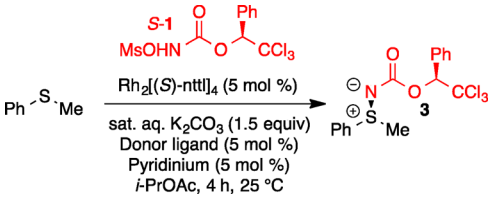
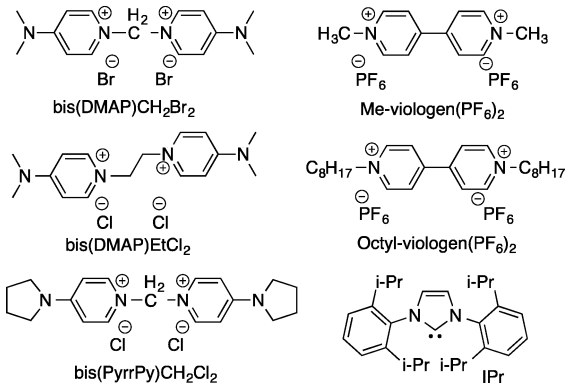
Table 3. Additives in Rhodium-Catalyzed Amination of Thioanisole



entry	donor ligand	pyridinium	yield (%)[a]	dr[b]
1			85	75:25
2	DMAP[c]		52	80:20
3	DMAP[c]	bis(DMAP)CH_2Cl_2[d]	87	95:5
4	DMAP[c]	Me-viologen$(PF_6)_2$	85	94:6
5	NMI		85	81:19
6	NMI	Me-viologen$(PF_6)_2$	92	96:4
7	IPr		69	72:28
8	IPr	Me-viologen$(PF_6)_2$	92	95:5
9	PPh_3		41	76:24
10	PPh_3	Me-viologen$(PF_6)_2$	56	73:27
11		Me-viologen$(PF_6)_2$	82	90:10
12		octyl-viologen$(PF_6)_2$	70	88:12
13	DMAP[c]	bis(DMAP)CH_2Br_2[d]	85	95:5
14	DMAP[c]	bis(DMAP)$EtCl_2$[d]	89	92:8
15	DMAP[c]	bis(PyrrPy)CH_2Cl_2[d]	70	85:15
16	DMAP[c]	octyl-viologen$(PF_6)_2$	60	84:16
17	DMAP[c]	NCS	90	82:18
18	DMAP	TEMPO	84	83:17
19	DMAP	benzoquinone	96	85:15
20	DMAP	benzoquinone, bis(DMAP)CH_2Cl_2[d]	95	95:5

[a]Yields of isolated product. [b]Crude *S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy. [c]7 mol %. [d]2.5 mol %.

Scheme 5. Chemical Structures of Additives



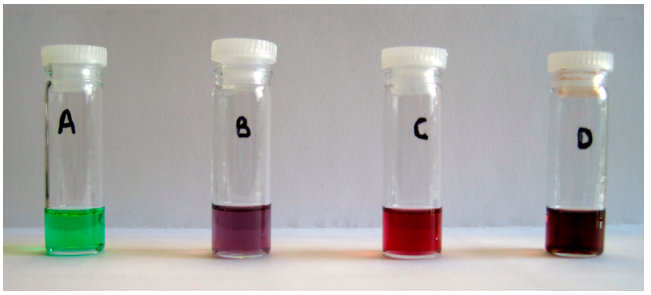


Figure 1. Solution color of (A) $Rh_2[(S)\text{-nttl}]_4$ in DCM; (B) $Rh_2[(S)\text{-nttl}]_4$ (5 mol %) and thioanisole (1 equiv) in DCM; (C) $Rh_2[(S)\text{-nttl}]_4$ (5 mol %), DMAP (10 mol %), and thioanisole (1 equiv) in DCM; (D) $Rh_2[(S)\text{-nttl}]_4$ (5 mol %), DMAP (10 mol %), $NOBF_4$ (5 mol %), and thioanisole (1 equiv) in DCM.

thioanisole, DMAP-$Rh_2[(S)\text{-nttl}]_4$ complex solution, suggested a strong binding of both the thioanisole and the DMAP to the rhodium (Figure 1). These visual observations were correlated by UV/vis spectra measurements.[22]

Red crystals suitable for X-ray crystal analysis were obtained from a chloroform/hexanes solution of $Rh_2[(S)\text{-nttl}]_4$ with 2 equiv of DMAP. The crystal structure of the $(DMAP)_2\cdot Rh_2[(S)\text{-nttl}]_4$ complex exhibited a DMAP molecule bound to each atom of rhodium (Figure 2).[22] Importantly, the all-up (or chiral crown) conformation typically observed for these types of complexes was preserved.[31] In comparison with the crystal structure of $Rh_2[(S)\text{-nttl}]_4$,[31c] a π-stacking interaction was observed between one of the bound DMAP and two of the naphthalimide units, resulting in a distortion of the all-up conformation.

Redox potentials of $Rh_2[(S)\text{-nttl}]_4$ and $(DMAP)_2\cdot Rh_2[(S)\text{-nttl}]_4$ complexes were measured by cyclic voltammetry. $Rh_2[(S)\text{-nttl}]_4$ displayed a typical quasi-reversible oxidation at 1070 mV for the redox couple Rh(II)−Rh(II)/Rh(II)−Rh(III) (Figure 3). The electrochemical properties of the complex were dramatically changed for the $(DMAP)_2\cdot Rh_2[(S)\text{-nttl}]_4$ complex. Redox potential changes by axial ligand coordination on achiral rhodium(II) dimer complexes have been previously observed.[30a,32] In the case of the $(DMAP)_2\cdot Rh_2[(S)\text{-nttl}]_4$ complex, not only was the observed redox potential ($E_{1/2}$ = 570 mV) much lower than expected but also the oxidation became irreversible. The same irreversible species was also observed from a mixture of 5 equiv of thioanisole, 1.4 equiv of DMAP and $Rh_2[(S)\text{-nttl}]_4$.[22] Considering the known oxidizing properties of nitrene precursors and nitrene species,[33] it thus strongly

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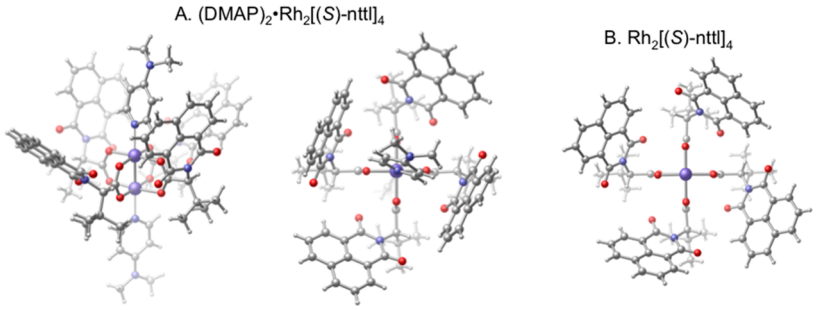


Figure 2. (A) Crystal structure of $(DMAP)_2{\cdot}Rh_2[(S)\text{-nttl}]_4$ complex. Thermal ellipsoids were shown at 50% probability. Co-crystallized solvent molecules were removed for clarity. One naphthalimide moiety was found disordered over two positions of which only the one with higher occupancy is shown. (B) Crystal structure of the $Rh_2[(S)\text{-nttl}]_4$ complex.[31c]

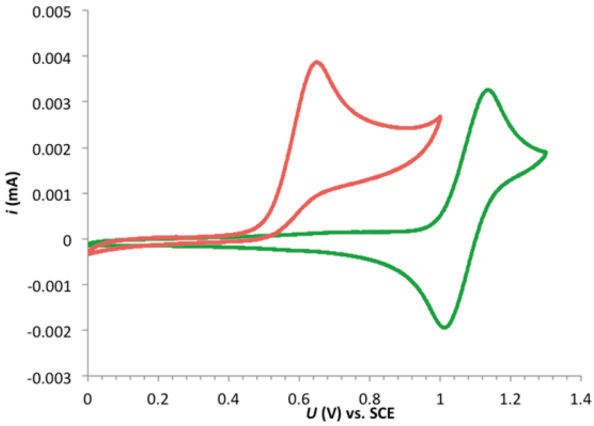
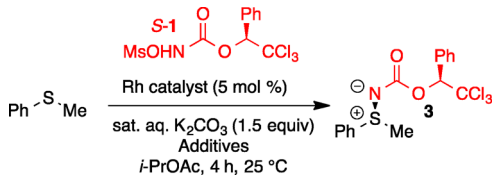


Figure 3. Cyclic voltammetric curves for the oxidation of $Rh_2[(S)\text{-nttl}]_4$ (green, quasi-reversible, $E_{1/2}$ = 1070 mV) and of $(DMAP)_2{\cdot}Rh_2[(S)\text{-nttl}]_4$ (red, irreversible, $E_{1/2}$ = 570 mV).

suggested that the catalytically active species was a Rh(II)−Rh(III) complex when DMAP was used as an additive. Many rhodium(II) carboxamidates have been reported to display low oxidation potentials and were thus studied in the amination of thioethers (Table 4).[30a,34] $Rh_2[(S)\text{-nap}]_4$ ($E_{1/2}$ = 330 mV, quasi-reversible) has been reported for the enantioselective intramolecular amination of sulfamates.[35] However, modest yields and no selectivity were observed with this catalyst in the amination of thioanisole (entries 1−2). Conversely, $Rh_2(cap)_4$ ($E_{1/2}$ = 11 mV, quasi-reversible) produced sulfilimine **3** in good yields, albeit with no selectivity (entry 3). Interestingly, the use of a mixture of $Rh_2(cap)_4$ and NBS, previously reported to produce the corresponding Rh(II)−Rh(III) complex,[36] afforded the same yield of sulfilimine **3** (entry 4). Such a result strongly suggests a common active species for both reactions, or that Rh(II)−Rh(II) and Rh(II)−Rh(III) complexes display the same reactivity. The use of the additives (DMAP and bis(DMAP)CH_2Cl_2 (**2**)) was not beneficial in the case of $Rh_2(cap)_4$ (entry 5). As shown in Table 3 (entries 17−19), external oxidants have been tested with $Rh_2[(S)\text{-nttl}]_4$ in the amination of thioanisole and have positively affected the yield (but not the dr), supporting the hypothesis of catalytically active Rh(II)−Rh(III) active species. Doyle and co-workers had previously demonstrated that nitrosonium salts could efficiently be used to oxidize rhodium(II) carboxamidates.[37] This approach was tested with $Rh_2[(S)\text{-nttl}]_4$ (Table 4, entries 6−8). A mixture of $Rh_2[(S)\text{-nttl}]_4$ and $NOBF_4$ produced a dark brown complex (see Figure 1, vial D) that is silent by NMR and exhibits an electronic absorption near 550 nm. Using that complex, sulfilimine **3** was isolated with 74% yield and 74:26 dr (entry 6). The yield was improved to 93% when DMAP was used as an additive, suggesting that DMAP might stabilize the Rh(II)−Rh(III) species (entry 7). The dr was significantly increased when bis(DMAP)CH_2Cl_2 (**2**) was added to the reaction mixture (entry 8).

Table 4. Catalysts in Rhodium-Catalyzed Amination of Thioanisole



entry	Rh catalyst	additives (mol %)	yield (%)[a]	dr[b]
1	$Rh_2[(S)\text{-nap}]_4$		48	56:44
2	$Rh_2[(S)\text{-nap}]_4$	DMAP (7), bis(DMAP)CH_2Cl_2 (2.5)	55	55:45
3	$Rh_2(cap)_4$		85	53:47
4	$Rh_2(cap)_4$	NBS (5)	85	50:50
5	$Rh_2(cap)_4$	DMAP (7), bis(DMAP)CH_2Cl_2 (2.5)	63	55:45
6	$Rh_2[(S)\text{-nttl}]_4$	$NOBF_4$ (5)[c]	74[d]	74:26
7	$Rh_2[(S)\text{-nttl}]_4$	$NOBF_4$ (5)[c], DMAP (7)	93[d]	81:19
8	$Rh_2[(S)\text{-nttl}]_4$	$NOBF_4$ (5)[c], DMAP (7), bis(DMAP)CH_2Cl_2 (2.5)	91[d]	93:7

[a]Yields of isolated product. [b]Crude *S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy. [c]Added with 20 mol % of acetonitrile to improve solubility. [d]Average of two independently run reactions.

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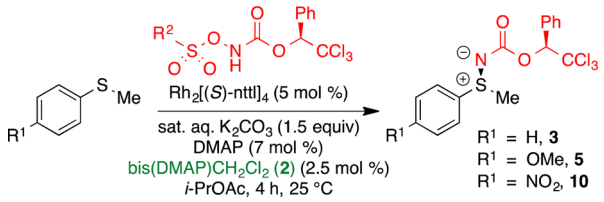
Having established the role of DMAP and the catalytically active rhodium species, we then studied the role of the bispyridinium salt. At the outset, we hypothesized that the bispyridinium salt could be involved in helping the formation of the catalytically active Rh(II)−Rh(III) complex, as bispyridinium salts are known as mild oxidants.[22,38] However, the strong influence of the bispyridinium salt on the diastereoselectivity of the thioether amination suggested another role. The key experiment was to study the influence of the sulfonyl group of the chiral sulfonyloxycarbamate reagent (Table 5).

Table 5. Sulfonyl Group in Rhodium-Catalyzed Amination of Thioanisole



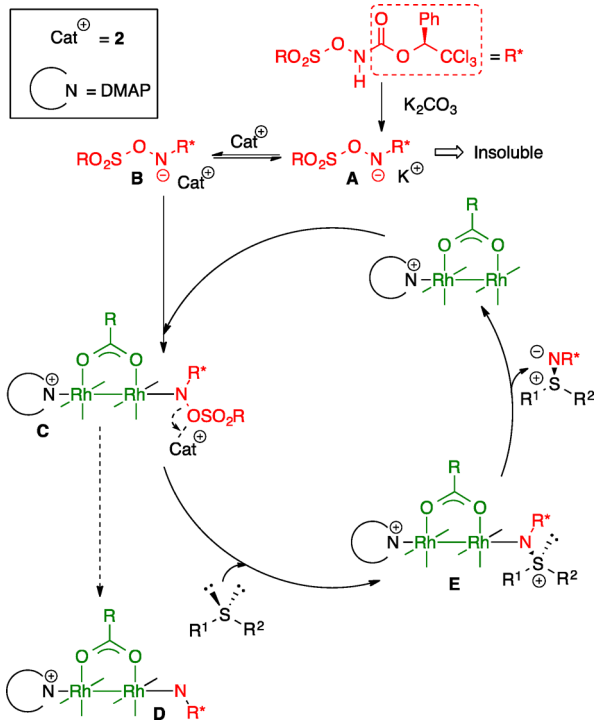
entry	R^1	R^2	yield (%)[a]	dr[b]
1	H	Me	86	95:5
2	H	4-NO_2Ph	69	85:15
3	H	2-BrPh	32	85:15
4	OMe	Me	88	94:6
5	OMe	4-NO_2Ph	64	84:16
6	OMe	2-BrPh	28	83:17
7	NO_2	Me	87	93:7
8	NO_2	4-NO_2Ph	76	81:19
9	NO_2	2-BrPh	25	83:17

[a]Yields of isolated product. [b]Crude *S,S*:*S,R* ratio determined by ^{1}H NMR spectroscopy.

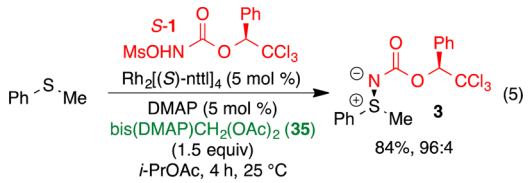
In rhodium-catalyzed C−H amination reactions, it has been established that the selectivity of the reaction is not affected by the sulfonyl group, suggesting a metal nitrene species as the common intermediate.[23d,24c] In sharp contrast, the diastereoselectivity of the rhodium-catalyzed amination of thioethers was impacted by the sulfonyl group. *N*-Mesyloxycarbamate **1** afforded the highest yields and dr for sulfilimines **3**, **5**, and **10** (Table 5, entries 1, 4, and 7). When using arylsulfonyloxycarbamates, not only the yields dropped but also the diastereoselectivity was affected, producing sulfilimines with 81:19 to 85:15 (entries 2−3, 5−6, 8−9).[39]

Such results clearly indicate that the sulfonyl group was still present on the reactive species, when the *S*−*N* bond was formed. As a result, the addition of the thioether must occur on a rhodium nitrenoid species, such as **C**, rather than on a rhodium nitrene species (**D**) (Scheme 6). So far, only metal nitrene species such as **D** have been proposed as intermediates to react with thioethers. There are stereochemical consequences associated with this revised mechanism: not only will the stereoselectivity be affected by the sulfonyl group (as shown in Table 5) but also the stereoselectivity might be impacted by the nature of the cation associated with the anion of the sulfonyloxcarbamate (cat^+). Upon deprotonation with potassium carbonate, the formation of insoluble potassium sulfonyloxcarbamate anion **A** was observed. The bispyridinium salt might play the role of a phase transfer catalyst to form the more soluble species **B** in which the pyridinium has replaced the potassium cation. To validate this hypothesis, we performed a reaction in which the potassium carbonate base was replaced

Scheme 6. Proposed Catalytic Cycle for the Rhodium-Catalyzed Amination of Thioethers with Sulfonyloxycarbamate Reagents



by bis(DMAP)$CH_2(OAc)_2$ (**35**) (eq 5). We were pleased to observe that sulfilimine **3** was isolated in yields and dr similar to



the ones obtained with the additives (Table 5, entry 1). The species **B** obtained from *N*-mesyloxycarbamate **1** and bis(DMAP)$CH_2(OAc)_2$ (**35**) was characterized by ^{1}H NMR.[40] We also demonstrated that the same species **B** was obtained, if the *N*-mesyloxycarbamate **1** was deprotonated with another base, in the presence of bis(DMAP)CH_2Cl_2 (**2**). These experiments strongly suggested the formation of sulfonyloxcarbamate anion **B**, which could coordinate with the rhodium catalyst (presumably a DMAP-bound Rh(II)−Rh(III) species) to form species **C** (Scheme 6).[41] The addition of the thioether then displaced the sulfonate anion to form species **E**, which then fragmented to release the sulfilimine and the catalyst.

The rate-determining step was then investigated. Previously, for the rhodium-catalyzed C−H amination reactions with *N*-sulfonyloxycarbamates, it was suggested that the formation of the metal nitrene species was the rate-limiting step.[23d] As metal nitrene species appear not to be formed in the thioether amination process, a Hammett study was undertaken to establish the rate-limiting step of the reaction. First-order rate constants for the amination of various *para*-substituted thioanisoles were measured by fitting the monoexponential increase in product over 3−5 half-lives to a monoexponential equation.[40] The log values of these rate constants were then plotted against the respective σ^+ Hammett parameters (Figure

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4).[42] With thioanisole substituted with strong electron-donating groups, the reaction rate was slightly slower compared to

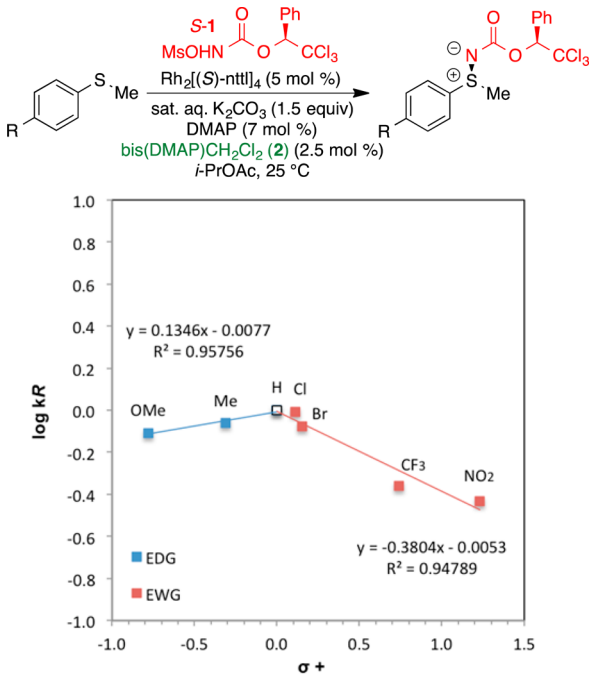

Figure 4. Hammett plot for the rhodium-catalyzed amination of *para*-substituted thioanisole with chiral *N*-mesyloxycarbamate **1**.

unsubstituted thioanisole, but the variation is rather small. Conversely, with thioanisoles containing *para*-substituted strong electron-withdrawing groups, the rate was decreased significantly. The shape of the Hammett curve suggests a change in the rate-limiting step in between electron-donating groups and electron-withdrawing groups. There was probably a competition between anion **B** and the thioether for the catalyst, explaining why the rate is decreased with a thioether substituted with an electron-donating group. In the case of electron-withdrawing group substitution, the competition for the catalyst appears to no longer be problematic and attack of the thioether on species **C** (to form **E**) is probably rate-limiting.

CONCLUSION

In conclusion, we have described the scope of the rhodium-catalyzed amination of thioethers with chiral *N*-mesyloxycarbamate **1** to produce chiral sulfilimines in high yields and selectivities. The beneficial effect of DMAP and bis(DMAP)-CH_2Cl_2 (**2**) was studied in detail. DMAP is an apical ligand for the $Rh_2[(S)\text{-nttl}]_4$ that stabilizes the Rh(II)−Rh(III) complex, which is presumably the active species. The pyridinium salt is acting as a phase transfer catalyst and was shown to be instrumental to obtain high selectivities. The key mechanistic aspect of the process is the absence of metal nitrene species as intermediates. The intermediate formed from the anion of the *N*-sulfonyloxycarbamates and the rhodium dimer; a rhodium nitrenoid species is reacting with the thioether prior to the release of the leaving group to form the metal nitrene species. A Hammett plot revealed that the attack of the thioether on the rhodium nitrenoid species is probably rate-determining with thioanisoles substituted with electron-withdrawing groups. Conversely, the formation of the rhodium nitrenoid species appeared to be rate-determining for thioanisole substituted with electron-donating groups.

EXPERIMENTAL SECTION

General Information. (*S*)-1-Phenyl-2,2,2-trichloroethyl-*N*-mesyloxycarbamate (**1**) was prepared according to a literature procedure.[22] $Rh_2[(S)\text{-nttl}]_4$, $Rh_2[(S)\text{-4-Br-nttl}]_4$, and $Rh_2[(S)\text{-4-NO}_2\text{-nttl}]_4$ catalysts,[43] free IPr,[44] Me-viologen$(PF_6)_2$, and octyl-viologen$(PF_6)_2$[45,46] were prepared according to literature procedures. The synthesis of sulfilimines **3**, **4**, **5**, **7**, **8**, **10**, **11**, **12**, **16**, **19**, **20**, **22**, and **26** and sulfoximine **29** has been previously described.[22] Analytical thin-layer chromatography (TLC) was performed using 0.25 mm silica gel 60-F plates. Visualization of the developed chromatogram was performed by UV absorbance, ethanolic phosphomolybdic acid, or aqueous potassium permanganate. Flash chromatography was performed using silica gel (230−400 mesh) with the indicated solvent system. Optical rotations data are reported as follows: $[\alpha]_\lambda^{temp}$, concentration (*c* g/100 mL), and solvent. Infrared spectra are reported in reciprocal centimeters (cm^{-1}). Only the most important and relevant frequencies are reported. ^1H NMR spectra were recorded in benzene-d_6, unless otherwise noted. Chemical shifts are reported in ppm on the δ scale from an internal standard of residual benzene (7.15 ppm), $CHCl_3$ (7.26 ppm), water (4.79 ppm), or DMSO-d_6 (2.50 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, qn = quintet, sept = septuplet, m = multiplet and br = broad), coupling constant in Hz, integration. ^{13}C NMR spectra were recorded in $CDCl_3$, unless otherwise noted with complete proton decoupling. Chemical shifts are reported in ppm from the central peak of benzene-d_6 (128.06 ppm), $CDCl_3$ (77.16 ppm), or DMSO-d_6 (39.52 ppm) on the δ scale. Mass spectra were obtained on a LC-MSD TOF (ESI).

General Procedure for the Amination of Thioethers with *N*-Mesyloxycarbamate 1. To a solution of the thioether (1.05 mmol, 1.05 equiv) in isopropyl acetate (10 mL) at rt, were successively added $Rh_2[(S)\text{-nttl}]_4$ (45.6 mg, 0.032 mmol, 3 mol %) and an aqueous saturated potassium carbonate solution (0.19 mL, 1.5 mmol, 1.5 equiv). To the resulting purple mixture were successively added dimethylaminopyridine (DMAP) (5.1 mg, 0.042 mmol, 4.2 mol %), 1,1′-methylenebis(4-dimethylaminopyridinium) dichloride (bis-(DMAP)CH_2Cl_2, **2**) (4.9 mg, 0.015 mmol, 1.5 mol %), and (*S*)-1-phenyl-2,2,2-trichloroethyl-*N*-mesyloxycarbamate (**1**) (362 mg, 1.00 mmol, 1.00 equiv). The heterogeneous reddish reaction mixture was vigorously stirred at rt for 4 h, then filtered over a Celite pad, washing with EtOAc. The solvent was removed under reduced pressure. To the resulting oily solid residue were added dichloromethane (10 mL) and 4-vinylpyridine cross-linked polymer (~500 mg), and the resulting mixture was stirred overnight. The heterogeneous mixture, containing the polymer bound rhodium complex, was filtered over a Celite pad washing with EtOAc. The solvent was removed under reduced pressure, and the crude residue was purified by flash chromatography on silica gel (EtOAc/hexanes).

Gram-Scale Procedure for the Synthesis of Sulfilimine 3. To a solution of thioanisole (522 mg, 4.20 mmol, 1.05 equiv) in isopropyl acetate (20 mL) at rt were successively added, $Rh_2[(S)\text{-nttl}]_4$ (60 mg, 0.042 mmol, 1 mol %) and an aqueous saturated potassium carbonate solution (0.74 mL, 1.5 mmol, 1.5 equiv). To the resulting purple mixture were successively added dimethylaminopyridine (DMAP) (6.8 mg, 0.056 mmol, 1.4 mol %), 1,1′-methylenebis(4-dimethylamino-pyridinium) dichloride (bis(DMAP)CH_2Cl_2, **2**) (6.6 mg, 0.020 mmol, 0.5 mol %), and (*S*)-1-phenyl-2,2,2-trichloroethyl-*N*-mesyloxy-carbamate (**1**) (1.45 g, 4.00 mmol, 1.00 equiv). The heterogeneous reddish reaction mixture was vigorously stirred at rt for 4 h, then filtered over a Celite pad, washing with EtOAc. The solvent was removed under reduced pressure. To the resulting oily solid residue were added dichloromethane (15 mL) and 4-vinylpyridine cross-linked polymer (~700 mg), and the resulting mixture was stirred overnight. The heterogeneous mixture, containing the polymer bound rhodium complex, was filtered over a Celite pad washing with EtOAc. The solvent was removed under reduced pressure, and the crude residue

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was purified by flash chromatography on silica gel (50:50 EtOAc/hexanes, then 100%) to afford sulfilimine **3** as a white solid (1.38 g, 88%).

(*S*)-*S*-Methyl-*S*-(4-*tert*-butoxycarbonylaminophenyl)-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (6). The title compound was prepared from *tert*-butyl-[4-(methylthio)phenyl] carbamate (251 mg, 1.05 mmol) according to the general procedure. The crude dr was determined prior to purification to be 92:8 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 2.83 ppm). The desired protected sulfilimine was obtained as a pale yellow solid (405 mg, 80%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 92:8 diastereomeric mixture (determined using the same method described above). R_f 0.19 (hexanes/EtOAc 1:1); mp 151.5−152.8 °C; $[\alpha]_D^{25}$ = −154.4 (*c* = 0.975, $CHCl_3$). Major diastereomer: ^{1}H NMR (400 MHz, C_6D_6) δ 7.66 (dd, *J* = 7.1, 1.9 Hz, 2H), 7.57 (d, *J* = 8.8 Hz, 2H), 7.41 (d, *J* = 8.8 Hz, 2H), 7.36−7.31 (m, 3H), 6.96 (s, 1H), 6.29 (s, 1H), 2.83 (s, 3H), 1.51 (s, 9H) ; ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.1, 152.3, 142.9, 134.4, 130.0, 129.3, 128.3, 127.8, 127.7, 119.2, 100.3, 84.4, 81.6, 36.0, 28.4; IR (neat) 3276, 2978, 2236, 20803, 1726, 1645, 1591, 1527, 1314, 1233, 1153, 1088, 1047, 818, 698 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{21}H_{24}Cl_3N_2O_4S$ $[M + H]^+$ 505.0517; Found 505.0517.

(*S*)-*S*-Methyl-*S*-4-trifluoromethylphenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (9). The title compound was prepared from 4-trifluoromethylthioanisole (50.5 mg, 0.260 mmol) according to the general procedure. The crude dr was determined prior to purification to be 92:8 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 6.82 ppm). The desired protected sulfilimine was obtained as an off-white solid (92 mg, 80%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 92:8 diastereomeric mixture (determined using the same method described above). R_f 0.20 (hexanes/EtOAc 1:1); mp 64−65 °C; $[\alpha]_D^{25}$ = −121 (*c* = 0.80, $CHCl_3$). Major diastereomer: ^{1}H NMR (400 MHz, C_6D_6) δ 7.74 (dd, *J* = 8.6, 1.9 Hz, 2H), 7.10−7.02 (m, 3H) 7.01−6.93 (m, 4H), 6.82 (s, 1H), 1.75 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.2, 140.5, 134.6, 134.2; 129.9, 129.5, 127.8, 127.2, 126.7, 100.1, 84.6, 35.9; IR (neat) 3094, 3036, 2949, 1646, 1403, 1323, 1248, 1171, 1131, 1061, 835, 699 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{17}H_{14}Cl_3F_3NO_2S$ 457.9757; Found 457.9768.

(*S*)-*S*-Methyl-*S*-(3-methoxycarbonyl-4-chlorophenyl)-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (13). The title compound was prepared from methyl 2-chloro-5-(methylthio)-benzoate (185 mg, 0.860 mmol) according to the general procedure. The crude dr was determined prior to purification to be 95:5 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 2.89 ppm). The desired protected sulfilimine was obtained as a white powder (333 mg, 85%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 95:5 diastereomeric mixture (determined using the same method described above). R_f 0.22 (hexanes/EtOAc 1:1); mp 53.7−55 °C; $[\alpha]_D^{20}$ = −174.4 (*c* = 1.025, $CHCl_3$). Major diastereomer: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.17 (d, *J* = 2.4 Hz, 1H), 7.76 (dd, *J* = 8.4, 2.3 Hz, 1H), 7.65 (dd, *J* = 7.3, 1.7 Hz, 2H), 7.58 (d, *J* = 8.5 Hz, 1H), 7.37−7.32 (m, 3H), 6.26 (s, 1H), 3.92 (s, 3H), 2.89 (s, 3H) ; ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.3, 162.0, 138.6, 135.1, 134.1, 133.0, 131.7, 129.9, 129.8, 129.5, 129.4, 127.8, 100.1, 84.6, 53.0, 35.8; IR (neat) 3028, 2951, 1736, 1642, 1295, 1240, 1119, 1074, 961, 818, 779, 698 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{18}H_{16}Cl_4NO_4S$ 483.9521; Found 483.9533.

(*S*)-*S*-Ethyl-*S*-phenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)-carbonyl)sulfilimine (14). The title compound was prepared from ethyl phenyl sulfide (145 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-nttl}]_4$ (43.5 mg, 0.03 mmol, 3 mol %) and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 76:24 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 0.65 ppm). The desired protected sulfilimine was obtained as a pale yellow syrup (383 mg, 95%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 77:23 diastereomeric mixture (determined using the same method described above). R_f 0.30 (hexanes/EtOAc 1:1); $[\alpha]_D^{20}$ = −86.3 (*c* = 0.76, $CHCl_3$). Major (maj) and minor (min) diastereomers: ^{1}H NMR (400 MHz, C_6D_6) δ 7.74 (dd, *J* = 8 Hz, 1.8 Hz, 2H maj and 2H min), 7.38 (dd, *J* = 7.1, 1.7 Hz, 2H min), 7.32 (dd, *J* = 7.8, 1.3 Hz, 2H maj), 7.10−7.02 (m, 3H maj and 3H min), 6.94−6.81 (m, 4H maj and 4H min), 2.37 (q, *J* = 7.3 Hz, 2H maj), 2.29 (q, *J* = 7.7 Hz, 2H min), 0.66 (t, *J* = 7.3 Hz, 3H maj), 0.59 (t, *J* = 7.2 Hz, 3H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.3 (maj and min), 134.4 (maj), 134.3 (min), 134.1 (maj and min), 132.5 (maj and min), 129.9 (maj and min), 129.9 (maj and min), 129.2 (maj and min), 127.6 (maj and min), 126.9 (maj), 126.8 (min), 100.4 (maj and min), 84.4 (maj and min), 45.4 (maj), 45.2 (min), 8.1 (min), 8.0 (maj); IR (neat) 2980, 2938, 1643, 1240, 1088, 1074, 784, 697, 687 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{17}H_{17}Cl_3NO_2S$ 404.0040; Found 404.0041.

(*S*)-*S*-Tetradecyl-*S*-phenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenyl-ethoxy)carbonyl)sulfilimine (15). The title compound was prepared from phenyl tetradecyl sulfide (322 mg, 1.05 mmol) according to the general procedure. The crude dr was determined prior to purification to be 63:37 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 6.33 ppm). The desired protected sulfilimine was obtained as a pale yellow oil (440 mg, 77%) after flash chromatography (hexanes/EtOAc 7:3, then 1:1) as a 63:37 diastereomeric mixture (determined using the same method described above). R_f 0.34 (hexanes/EtOAc 7:3); $[\alpha]_D^{25}$ = −14.95 (*c* = 0.99, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.73−7.66 (m, 3H maj and 3H min), 7.62−7.46 (m, 4H maj and 4H min), 7.36−7.30 (m, 3H maj and 3H min), 6.33 (s, 1H maj), 6.31 (s, 1H min), 3.22−3.14 (m, 1H maj and 1H min), 2.99−2.90 (m, 1H maj and 1H min), 1.68−1.60 (m, 2H maj and 2H min), 1.39−1.22 (m, 22H maj and 22H min), 0.87 (t, *J* = 6.5 Hz, 3H maj and 3H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.5 (maj and min), 135.1 (min), 134.8 (maj), 134.5 (maj and min), 132.5 (maj and min), 130.0 (min); 130.0 (maj and min), 130.0 (maj), 129.2 (maj and min), 127.7 (min), 127.7 (maj), 126.9 (maj), 126.8 (min), 100.5 (maj), 100.4 (min), 84.4 (maj and min), 51.7 (maj), 51.4 (min), 32.0 (maj and min), 29.8 (maj and min), 29.8 (maj and min), 29.8 (maj and min), 29.7 (maj), 29.7 (min), 29.6 (maj), 29.6 (min), 29.5 (maj and min), 29.4 (maj), 29.4 (min), 29.1 (maj), 29.1 (min), 28.4 (maj and min), 23.5 (min), 23.5 (maj), 22.8 (maj and min), 14.3 (maj and min); IR (neat) 2923, 2853, 1651, 1244, 1090, 1073, 820, 698, 609 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{29}H_{41}Cl_3NO_2S$ 572.1918; Found 572.1922.

(*S*)-*S*-Isopropyl-*S*-phenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenyl-ethoxy)carbonyl)sulfilimine (17). The title compound was prepared from isopropyl phenyl sulfide (160 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-4-NO}_2\text{-nttl}]_4$ (49 mg, 0.03 mmol, 3 mol %) and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 72:28 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 6.35 ppm). The desired protected sulfilimine was obtained as a sticky translucent oil (380 mg, 91%) after flash chromatography (hexanes/EtOAc 7:3 then 1:1) as a 73:27 diastereomeric mixture (determined using the same method described above). R_f 0.2 (hexanes/EtOAc 7:3); $[\alpha]_D^{20}$ = −75.7 (*c* = 0.65, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.73−7.52 (m, 5H maj and 5H min), 7.51−7.48 (m, 2H maj and 2H min), 7.36−7.30 (m, 3H maj and 3H min), 6.35 (s, 1H maj), 6.31 (s, 1H min), 3.30 (sept, *J* = 6.6 Hz, 1H maj and 1H min), 1.34 (d, *J* = 7.0 Hz, 3H min), 1.33 (d, *J* = 6.8 Hz, 3H maj), 1.17 (d, *J* = 7.0 Hz, 3H min), 1.15 (d, *J* = 6.8 Hz, 3H maj); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.5 (maj and min), 134.6 (min), 134.6 (maj), 132.6 (maj), 132.6 (min), 132.5 (maj and min), 130.0 (maj), 130.0 (min), 129.7 (min), 129.7 (maj), 129.2 (maj), 129.2 (min), 128.0 (maj and min), 127.8 (min), 127.7 (maj), 100.5 (maj), 100.4 (min), 84.5 (min), 84.5 (maj), 52.5 (maj), 52.1 (min), 16.9 (min), 16.7 (maj), 16.7 (min), 16.6 (maj); IR (neat) 3062, 2972, 2934, 1649, 1241, 1089, 1073, 820, 747, 700 cm^{-1}; HRMS (ESI-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{18}H_{19}Cl_3NO_2S$ 418.0197; Found 418.0201.

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(*S*)-*S*-Cyclopropyl-*S*-phenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (18). The title compound was prepared from cyclopropyl phenyl sulfide (158 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 86:14 (determined by quantitative ^{1}H NMR evaluation based on ^{1}H signal at 6.31 ppm). The desired protected sulfilimine was obtained as a pale yellow syrup (400 mg, 96%) after flash chromatography (hexanes/EtOAc 1:1 then 100% EtOAc) as a 86:14 diastereomeric mixture (determined using the same method described above). R_f 0.36 (hexanes/EtOAc 1:1); $[\alpha]_D^{20} = -84.5$ (c = 0.755, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.76−7.73 (m, 2H maj and 2H min), 7.69−7.65 (m, 2H maj), 7.64−7.60 (m, 2H min), 7.56−7.47 (m, 3H maj and 3H min), 7.37−7.31 (m, 3H maj and 3H min), 6.31 (s, 1H maj), 6.30 (s, 1H min), 2.61−2.54 (m, 1H maj and 1H min), 1.38−1.25 (m, 1H maj and 1H min), 1.14−1.05 (m, 3H maj and 3H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.4 (maj and min), 136.0 (min), 135.8 (maj), 134.4 (maj and min), 132.3 (min), 132.3 (maj), 130.0 (maj and min), 129.9 (min), 129.8 (maj), 129.3 (maj and min), 127.7 (maj and min), 126.7 (maj), 126.5 (min), 100.4 (maj and min), 84.4 (maj and min), 29.1 (min), 29.0 (maj), 5.8 (min), 5.3 (maj), 5.1 (maj and min); IR (neat) 3060, 2949, 1642, 1237, 1088, 1073, 838, 784, 727, 698 cm^{-1}; HRMS (ESI-TOF) m/z: $[M + H]^+$ Calcd for $C_{18}H_{17}Cl_3NO_2S$ 418.0012; Found 418.0028.

(*S*)-*S*-Methyl-*S*-furfuryl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (21). The title compound was prepared from 2-((methylthio)methyl)furan (135 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %), DMAP (3.7 mg, 0.03 mmol, 3 mol %), and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 55:45 (determined by quantitative ^{1}H NMR evaluation and based on ^{1}H signal at 1.73 ppm). The desired protected sulfilimine was obtained as a pale yellow oil (330 mg, 90%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 57:43 diastereomeric mixture (determined using the same method described above). R_f 0.20 (hexanes/EtOAc 1:1); $[\alpha]_D^{25} = -58.2$ (c = 0.96, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (400 MHz, C_6D_6) δ 7.68−7.66 (m, 2H maj and 2H min), 7.43−7.35 (m, 4H maj and 4H min), 6.43 (d, J = 3.3 Hz, 1H maj and 1H min), 6.38 (dd, J = 1.8, 3.3 Hz, 1H maj), 6.32 (dd, J = 1.9, 3.3 Hz, 1H min), 6.30−6.28 (m, 1H maj and 1H min), 4.37 (d, J = 13.9 Hz 1H min), 4.32 (d, J = 13.9 Hz 1H maj), 4.27 (d, J = 13.9 Hz, 1H min), 4.23 (d, J = 13.9 Hz, 1H maj), 2.62 (s, 3H maj), 2.61 (s, 3H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.5 (maj), 162.2 (min), 144.5 (min), 144.5 (maj), 142.1 (min), 141.1 (maj), 134.4 (maj), 134.4 (min), 130.0 (maj), 130.0 (min), 129.4 (maj and min), 127.8 (min), 127.8 (maj), 113.3 (min), 113.3 (maj), 111.6 (min), 111.6 (maj), 100.3 (min), 100.2 (maj), 84.4 (maj), 84.4 (min), 45.6 (min), 45.6 (maj), 29.5 (maj and min); IR (neat) 3034, 2939, 1631, 1239, 1089, 1070, 817, 742, 697, 679, 598 cm^{-1}; HRMS (ESI-TOF) m/z: $[M + H]^+$ Calcd for $C_{15}H_{15}Cl_3NO_3S$ 393.9833; Found 393.9813.

(*S*)-*S*-Methyl-*S*-3-Phenylpropyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (23). The title compound was prepared from methyl(3-phenylpropyl)sulfide (140 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %), DMAP (3.7 mg, 0.03 mmol, 3 mol %), and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 80:20 (determined by quantitative ^{1}H NMR evaluation and based on ^{1}H signal at 2.61 ppm). The desired protected sulfilimine was obtained as a pale yellow oil (307 mg, 88%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 81:19 diastereomeric mixture (determined using the same method described above). R_f 0.10 (hexanes/EtOAc 1:1); $[\alpha]_D^{20} = +35.9$ (c = 0.88, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.68 (m, 1H maj and 1H min), 7.38−7.33 (m, 3H maj and 3H min), 7.31−7.18 (m, 3H maj and 3H min), 7.15 (d, J = 7.8 Hz, 2H min), 7.09 (d, J = 7.8 Hz, 2H maj), 6.32 (s, 1H min), 6.30 (s, 1H maj), 3.04−2.96 (m, 1H maj and 1H min), 2.85−2.68 (m, 3H maj and 3H min), 2.61 (s, 3H maj), 2.58 (s, 3H min), 2.09−1.94 (m, 1H maj and 1H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.7 (maj and min), 139.7 (min), 139.7 (maj), 134.4 (maj), 134.4 (min), 130.0 (min), 129.9 (maj), 129.3 (maj and min), 128.8 (min), 128.8 (maj), 128.4 (min), 128.4 (maj), 127.7 (maj and min), 126.6 (min), 126.6 (maj), 100.4 (min), 100.4 (maj), 84.2 (maj), 84.2 (min), 47.9 (min), 47.6 (maj), 34.2 (maj and min), 31.4 (min), 31.2 (maj), 24.7 (maj and min); IR (neat) 3028, 2946, 1639, 1240, 1200, 1088, 1073, 950, 817, 743, 696, 634, 606 cm^{-1}; HRMS (ESI-TOF) m/z: $[M + H]^+$ Calcd for $C_{19}H_{21}Cl_3NO_2S$ 432.0353; Found 432.0367.

(*S*)-*S*-Methyl-*S*-isopropyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (24). The title compound was prepared from isopropyl(methyl)sulfide (94.7 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}Br\text{-}nttl]_4$ (106 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 73:27 (determined by quantitative ^{1}H NMR evaluation and based on ^{1}H signal at 1.61 ppm). The desired protected sulfilimine was obtained as an off-white solid (363 mg, 80%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc). Recrystallization from $CHCl_3$/hexanes afforded 292 mg, 41% yield, as a 95:5 diastereomeric mixture (determined using the same method described above). R_f 0.10 (hexanes/EtOAc 1:1); mp 96.5−97.2 °C; $[\alpha]_D^{25} = -2.3$ (c = 1.05, $CHCl_3$). Major diastereomer: ^{1}H NMR (400 MHz, C_6D_6) δ 7.75 (dd, J = 7.9, 1.8 Hz, 2H), 7.11−7.03 (m, 3H), 6.83 (s, 1H), 2.38 (sept, J = 7 Hz, 1H), 1.61 (s, 1H), 0.65 (d, J = 6.9 Hz, 3H), 0.54 (d, J = 6.9 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.8, 134.5. 129.9. 129.2, 127.7, 100.4, 84.2, 49.1, 27.2, 16.6, 15.9; IR (neat) 2873, 1638, 1241, 1097, 1064, 824, 779, 737, 699, 612 cm^{-1}; HRMS (ESI-TOF) m/z: $[M + H]^+$ Calcd for $C_{13}H_{17}Cl_3NO_2S$ 356.0040; Found 356.0048.

(*S*)-*S*-Methyl-*S*-*tert*-butyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (25). The title compound was prepared from *tert*-butyl(methyl)sulfide (219 mg, 2.1 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 71:29 (determined by quantitative ^{1}H NMR evaluation and based on ^{1}H signal at 0.69 ppm). The desired protected sulfilimine was obtained as a yellowish solid (549 mg, 74%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc). Recrystallization from $CHCl_3$/hexanes afforded 342 mg, 46% yield, as a >99:1 diastereomeric mixture (determined using the same method described above). R_f 0.10 (hexanes/EtOAc 1:1); mp 134−135.4 °C; $[\alpha]_D^{25} = -37.5$ (c = 1.03, $CHCl_3$). Major diastereomer: ^{1}H NMR (400 MHz, C_6D_6) δ 7.74 (dd, J = 8.0, 1.8 Hz, 2H), 7.12−7.04 (m, 3H), 6.82 (s, 1H), 1.62 (s, 1H), 0.69 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 163.1, 134.8. 130.0. 129.2, 127.8, 100.4, 84.4, 54.8, 25.7, 23.8; IR (neat) 2928, 2901, 1652, 1236, 1090, 1073, 832, 781, 699, 610 cm^{-1}; HRMS (ESI-TOF) m/z: $[M + H]^+$ Calcd for $C_{14}H_{19}Cl_3NO_2S$ 370.0197; Found 370.0204.

(*S*)-*S*-Ethyl-*S*-vinyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (27). The title compound was prepared from ethyl(vinyl)sulfide (92.6 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %), DMAP (3.7 mg, 0.03 mmol, 3 mol %), and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 71:29 (determined by quantitative ^{1}H NMR evaluation and based on ^{1}H signal at 0.65 ppm). The desired protected sulfilimine was obtained as a pale yellow oil (273 mg, 77%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc) as a 72:28 diastereomeric mixture (determined using the same method described above). R_f 0.20 (hexanes/EtOAc 1:1); $[\alpha]_D^{20} = -53.6$ (c = 1.4, $CHCl_3$). Major (maj) and Minor (min) diastereomers: ^{1}H NMR (400 MHz, C_6D_6) δ 7.73 (dd, J = 8.0, 2.0 Hz, 2H maj and 2H min), 7.11−7.03 (m, 3H maj and 3H min), 6.81 (s, 1H maj and 1H min), 5.76 (d, J = 16.4 Hz, 1H min), 5.64 (d, J = 16.4 Hz, 1H maj), 5.57−5.46 (m, 1H maj and 1H min), 5.19 (d, J = 9 Hz, 1H min), 5.11 (d, J = 9 Hz, 1H maj), 2.20−2.06 (m, 2H maj and 2H min), 0.65 (t, J = 7.2 Hz, 3H maj), 0.60 (t, J = 7.2 Hz, 3H min); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.7 (maj and min), 134.4 (maj and min), 130.1 (maj), 130.1 (min), 130.0 (maj and min), 129.3 (maj and min), 128.5 (maj), 128.3 (min), 127.8 (maj and min), 100.4 (maj and min), 84.3 (maj and min), 42.4 (maj), 42.2

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(min), 7.8 (min), 7.7 (maj); IR (neat) 3035, 2935, 1640, 1229, 1200, 1088, 1073, 816, 781, 634, 603 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{13}H_{15}Cl_3NO_2S$ 353.9884; Found 353.9888.

(*S*)-*S*-L-*tert*-Butoxycarbonyl Methionine Methyl Ester-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfilimine (28). The title compound was prepared from L-Boc-methionine methyl ester (276 mg, 1.05 mmol) according to the general procedure using $Rh_2[(S)\text{-}4\text{-}NO_2\text{-}nttl]_4$ (49 mg, 0.03 mmol, 3 mol %), DMAP (3.7 mg, 0.03 mmol, 3 mol %), and Me-viologen$(PF_6)_2$ (14.3 mg, 0.03 mmol, 3 mol %). The crude dr was determined prior to purification to be 70:30 (determined by quantitative ^1H NMR evaluation and based on ^1H signal at 3.69 ppm). The desired protected sulfilimine was obtained as a pale yellow powder (406 mg, 77%) after flash chromatography (hexanes/EtOAc 1:1, then 100% EtOAc). Recrystallization from $CHCl_3$/hexanes afforded 173 mg of yellow crystals, 34% yield, as a >99:1 diastereomeric mixture (determined using the same method described above). R_f 0.10 (hexanes/EtOAc 1:1); $[\alpha]_D^{20}$ = +65.7 (*c* = 1.00, $CHCl_3$). Major diastereomer: ^1H NMR (500 MHz, $CDCl_3$) δ 7.65 (dd, *J* = 7.6 Hz, 1.8 Hz, 2H), 7.37−7.32 (m, 3H), 6.27 (s, 1H), 5.29−5.25 (m, 1H), 4.39−4.32 (m, 1H), 3.67 (s, 3H), 3.13−2.91 (m, 2H), 2.66 (s, 3H), 2.36−2.24 (m, 1H), 2.03−1.96 (m, 1H), 1.41 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.5, 162.6, 155.6, 134.4, 129.9, 129.3, 127.8, 100.3, 84.3, 80.6, 52.9, 52.7, 44.6, 31.3, 28.4, 26.4; IR (neat) 3351, 2978, 1706, 1638, 1511, 1246, 1160, 1089, 1073, 818, 746, 698, 634 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{20}H_{28}Cl_3N_2O_6S$ 531.0701; Found 531.0709.

General Procedure for the Oxidation of Chiral Ph-Troc Protected Sulfilimines. To a solution of chiral sulfilimine (0.72 mmol, 1 equiv) in MeCN (4 mL) and CCl_4 (4 mL) was added ruthenium(III) chloride hydrate ($RuCl_3{\cdot}xH_2O$, 40−49% Ru) (0.014 mmol, 2.0 mol %). The resulting brown mixture was stirred for 5 min, and then a solution of sodium periodate in water (*x* mL, 0.15 M, 1.5 equiv) was added. The resulting solution was stirred at rt for 1 h and monitored by TLC. When the reaction was finished (1 h), water (20 mL) was added. The two layers were separated, and the aqueous layer was extracted with dichloromethane (3 × 20 mL). The combined organic layers were successively washed with a saturated solution of $Na_2S_2O_3$ (2 × 20 mL) and NaCl (20 mL). The organic layer was dried over Na_2SO_4, then filtered over a pad of Celite and concentrated under reduced pressure. The crude product was purified by flash chromatography to afford the desired pure sulfoximine.

(*S*)-*S*-Methyl-*S*-4-nitrophenyl-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfoximine (30). The title compound was prepared from chiral sulfilimine **10** (77.1 mg, 0.180 mmol, 94:6 dr) according to the general oxidation procedure. The desired protected sulfoximine was obtained as a translucent syrup (73.5 mg, 92%) after flash chromatography (hexanes/EtOAc 7:3, then 1:1) as a 94:6 diastereomeric mixture (determined by quantitative ^1H NMR evaluation and based on ^1H signal at 6.49 ppm). R_f 0.46 (hexanes/EtOAc 1:1); $[\alpha]_D^{25}$ = −53 (*c* = 1.02, $CHCl_3$). Major diastereomer: ^1H NMR (400 MHz, C_6D_6) δ 7.60 (dd, *J* = 7.8, 2.1 Hz, 2H), 7.55 (d, *J* = 8.9 Hz, 2H), 7.39 (d, *J* = 8.9, 2H), 7.09−7.02 (m, 3H), 6.49 (s, 1H), 2.45 (s, 3H) ; ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.3, 151.1, 144.1, 133.0, 129.8, 129.7, 129.2, 127.9, 124.9, 99.1, 84.7, 44.6; IR (neat) 3104, 3032, 2955, 2928, 1714, 1682, 1530, 1233, 903, 852, 737, 700 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{16}H_{14}Cl_3N_2O_5S$ 452.9662; Found 452.9656.

(*S*)-*S*-Methyl-*S*-(3-bromophenyl)-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfoximine (31). The title compound was prepared from chiral sulfilimine **11** (235 mg, 0.500 mmol, 96:4 dr) according to the general oxidation procedure. The desired protected sulfoximine was obtained as a white solid (238 mg, 98%) after flash chromatography (hexanes/EtOAc 7:3, 1:1, then 100% EtOAc) as a 96:4 diastereomeric mixture (determined by quantitative ^1H NMR evaluation and based on ^1H signal at 6.48 ppm). R_f 0.45 (hexanes/EtOAc 1:1); mp 123−124.3 °C; $[\alpha]_D^{25}$ = −57.3 (*c* = 0.99, $CHCl_3$). Major diastereomer: ^1H NMR (400 MHz, C_6D_6) δ 8.02−8.01 (m, 1H), 7.60 (dd, *J* = 8.1, 2.0 Hz, 2H), 7.50 (d, *J* = 7.9 Hz, 1H), 7.13−7.04 (m, 6H), 6.62 (dd, *J* = 8.1 Hz 1H), 6,48 (s, 1H), 2.52 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.1, 139.9, 137.2, 133.0, 131.3, 130.3. 129.6, 129.5, 127.8, 126.0, 123,6, 99.1, 84.4, 44.8 ; IR (neat) 2930, 1686, 1233, 904, 725, 698, 568 501 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{16}H_{14}{}^{[79]}BrCl_3NO_3S$ 485.8910 ; Found 485.8920.

(*S*)-*S*-Methyl-*S*-(3-bromophenyl)-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfoximine (32). The title compound was prepared from chiral sulfilimine **26** (79.2 mg, 0.200 mmol, 96:4 dr) according to the general oxidation procedure. The desired protected sulfoximine was obtained as a colorless syrup (78.4 mg, 95%) after flash chromatography (hexanes/EtOAc 7:3, then 1:1) as a 96:4 diastereomeric mixture (determined by quantitative ^1H NMR evaluation and based on ^1H signal at 3.12 ppm). R_f 0.21 (hexanes/EtOAc 7:3); $[\alpha]_D^{25}$ = +19.4 (*c* = 1.04, $CHCl_3$). Major diastereomer: ^1H NMR (500 MHz, $CDCl_3$) δ 7.65 (dd, *J* = 7.2, 1.7 Hz, 2H), 7.40−7.34 (m, 3H), 6.27 (s, 1H), 3.42 (tt, *J* = 6.9, 3.4 Hz, 1H), 3.12 (s, 3H), 2.29 (d, *J* = 12 Hz, 1H), 2.17 (d, *J* = 12.2 Hz, 1H), 1.96−1.90 (m, 2H), 1.74 (d, *J* = 13 Hz), 1.53−1.42 (m, 2H), 1.35−1.14 (m, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 157.0, 133.6, 129.9, 129.6, 127.9, 99.8, 84.4, 62.4, 35.4, 26,1. 25.2 (2C), 25.1, 24.9 ; IR (neat) 2935, 2858, 1674, 1454, 1249, 1203, 860, 700; HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{16}H_{20}Cl_3NaNO_3S$: 434.0122; Found 434.0132.

(*S*)-*S*-L-*tert*-Butoxycarbonyl Methionine Methyl Ester-*N*-(((*S*)-2,2,2-trichloro-1-phenylethoxy)carbonyl)sulfoximine (33). The title compound was prepared from chiral sulfilimine **28** (150 mg, 0.280 mmol, >99:1 dr) according to the general oxidation procedure. The desired protected sulfoximine was obtained as a white powder (150 mg, 97%) after flash chromatography (hexanes/EtOAc 7:3, then 1:1) as a >99:1 diastereomeric mixture (determined by quantitative ^1H NMR evaluation and based on ^1H signal at 3.24 ppm). R_f 0.43 (hexanes/EtOAc 1:1); $[\alpha]_D^{20}$ = +54.6 (*c* = 0.92, $CHCl_3$). Major diastereomer: ^1H NMR (500 MHz, $CDCl_3$) δ 7.64 (dd, *J* = 7.6 Hz, 1.4 Hz, 2H), 7.41−7.35 (m, 3H), 6.26 (s, 1H), 5.17 (d, *J* = 7.9 Hz, 1H), 4.45−4.31 (m, 1H), 3.73 (s, 3H), 3.60−3.40 (m, 2H), 3.23 (s, 3H), 2.50−2.39 (m, 1H), 2.22−2.07 (m, 1H), 1.43 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.4, 156.9, 155.5, 133.5, 129.9, 129.7, 128.0, 99.6, 84.5, 80.9, 53.1, 52.0, 50.6, 39.8, 28.4, 26.1; IR (neat) 3365, 2977, 1705, 1676, 1498, 1243, 1160, 860, 746, 698, 615 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{20}H_{27}Cl_3NaN_2O_7S$ 567.0497; Found 567.0490.

(*S*)-*S*-L-*tert*-Butoxycarbonyl Methionine Methyl Ester Sulfoximine (34). In a 25 mL round-bottom flask containing a magnetic stirring bar, Ph-Troc protected sulfoximine **33** (415 mg, 0.760 mmol, 1 equiv) was dissolved in glacial acetic acid (4 mL). To this solution, was added zinc dust (497 mg, 7.60 mmol, 10 equiv). The resulting mixture was then stirred at room temperature for 14 h. After completion, the reaction mixture was filtered over cotton to remove Zn residues, and washed with acetic acid. The filtrate was diluted with water (5 mL), and the pH of the solution was adjusted to 7−8 via addition of saturated aqueous $NaHCO_3$. The resulting mixture was then extracted with dichloromethane (3 × 20 mL), and the combined organic layers were dried over Na_2SO_4, filtered, and concentrated under reduced pressure. (*S*)-*S*-L-*tert*-Butoxycarbonyl methionine methyl ester sulfoximine was obtained as a translucent sticky oil (157 mg, 70%) after flash chromatography (100% EtOAc). R_f 0.11 (100% EtOAc); ^1H NMR (500 MHz, $CDCl_3$) δ 5.37−5.32 (m, 1H), 4.47−4.38 (m, 1H), 3.76 (s, 3H), 3.25−3.10 (m, 2H), 2.99 (s, 3H), 2.68 (br s, 1H), 2.45−2.38 (m, 1H), 2.21−2.13 (m, 1H), 1.43 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.0, 155.5, 80.6, 53.5, 52.9, 43.4, 28.4, 26.6. IR (neat) 3302, 2977, 1740, 1701, 1522, 1366, 1209, 1162, 1047, 1012, 727 cm^{-1}; HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{11}H_{23}N_2O_5S$ 295.1322; Found 295.1325.

1,1′-Methylenebis(4-dimethylaminopyridinium) Dichloride (bis(DMAP)CH_2Cl_2 (2)).[25] In a 20 mL scintillation vial containing 4-dimethylaminopyridine (2.00 g) was added dichloromethane (10−12 mL). The resulting clear mixture was capped and stored at room temperature until a white precipitate was formed (typically 2−3 weeks were necessary). The white precipitate was filtered through a glass frit and washed with CH_2Cl_2 (4 × 10 mL). The resulting white powder was dried under high vacuum to afford the desired compound (1.20 g, 20% yield). mp 305 °C dec (Lit. mp 295 °C dec);[25] ^1H NMR (500 MHz, D_2O) δ 8.20 (d, *J* = 8.1 Hz, 4H), 6.98 (d, *J* = 8.0 Hz, 4H), 6.32

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(s, 2H), 3.27 (s, 12H); ^{13}C NMR (125 MHz, D_2O) δ 157.1, 140.4, 108.3, 73.0, 40.0.

1,1′-Methylenebis(4-pyrrolidinylpyridinium) Dichloride (bis-(PyrrPy)CH_2Cl_2). The title compound was prepared from 4-pyrrolidinopyridine (1 g) and CH_2Cl_2 (5−7 mL) according to the procedure described for bis(DMAP)CH_2Cl_2 (**2**). The desired bispyridinium was obtained as a white powder (0.43 g, 17% yield). mp 307 °C dec; ^{1}H NMR (500 MHz, DMSO) δ 8.91 (d, J = 7.6 Hz, 4H), 7.00 (dd, J = 7.9 Hz, 4H), 6.70 (s, 2H), 3.54−3.51 (m, 8H), 2.00−1.97 (m, 8H); ^{13}C NMR (125 MHz, DMSO) δ 153.5, 141.3, 108.9, 71.0, 48.7, 24.6; IR (neat) 3328, 3043, 1638, 1562, 1439, 1163, 840 cm^{-1}; HRMS (ESI-TOF) m/z: $[M]^{2+}$ Calcd for $C_{19}H_{26}N_4$ 155.1073; Found 155.1066.

1,1′-Methylenebis(4-dimethylaminopyridinium) Dibromide (bis(DMAP)CH_2Br_2). In a 25 mL round-bottom flask, 4-dimethylaminopyridine (611 mg, 5.00 mmol, 2 equiv) was dissolved in acetonitrile (10 mL). To this solution was added CH_2Br_2 (0.18 mL, 2.5 mmol, 1 equiv). The resulting mixture was stirred at reflux for 48 h, under an argon atmosphere. The reaction mixture was then cooled to room temperature, and the white precipitate was filtered through a glass frit, washed with cold acetonitrile (2 × 10 mL), and dried under high vacuum, affording the desired product (904 mg, 43% yield) as a white powder. mp 320 °C dec; ^{1}H NMR (400 MHz, DMSO) δ 8.64 (d, J = 7.9, 4H), 7.15 (d, J = 7.9, 4H), 6.47 (s, 2H), 3.22 (s, 12H); ^{13}C NMR (125 MHz, DMSO) δ 156.5, 141.2, 108.3, 71.5, 40.2; IR (neat) 3406, 3300, 1639, 1576, 1269, 1378, 1156, 837 cm^{-1}; HRMS (ESI-TOF) m/z: $[M]^+$ Calcd for $C_{15}H_{22}N_4Br$ 337.1022; Found 337.1031.

1,1′-Methylenebis(4-dimethylaminopyridinium) Diacetate (bis(DMAP)$CH_2(OAc)_2$) (35). In a 25 mL round-bottom flask, bis(DMAP)CH_2Cl_2 (726 mg, 2.20 mmol, 1 equiv) was dissolved in dry MeOH (10 mL). To this solution was added anhydrous silver acetate (810 mg, 4.85 mmol, 2.2 equiv). The resulting mixture was stirred for 2 h at room temperature, in the dark. The precipitate was then filtered and washed with cold MeOH (2 × 10 mL). The filtrate was concentrated *in vacuo* and dried under high vacuum, affording a pasty brown oil that solidified over time (680 mg, 82% yield). mp 203 °C dec; ^{1}H NMR (400 MHz, DMSO) δ 9.18 (d, J = 7.6, 4H), 7.10 (d, J = 7.6, 4H), 7.03 (s, 2H), 3.20 (s, 12H), 1.61 (s, 6H); ^{13}C NMR (125 MHz, DMSO) δ 173.4, 156.4, 142.1, 108.2, 70.6, 40.0, 26.2; IR (neat) 3089, 2916, 1647, 1564, 1377, 1156, 905, 816 cm^{-1}; HRMS (ESI-TOF) m/z: $[M]^{2+}$ Calcd for $C_{15}H_{22}N_4$ 129.0917; Found 129.0923.

1,1′-(1,2-Ethanediyl)bis(4-dimethylaminopyridinium) Dichloride (bis(DMAP)$EtCl_2$). In a 25 mL round-bottom flask, 4-dimethylaminopyridine (611 mg, 5.00 mmol, 2.5 equiv) was dissolved in 10 mL of acetonitrile. To this solution was added 1,2-dichloroethane (0.16 mL, 2.0 mmol, 1 equiv). The resulting mixture was stirred at reflux for 72 h, under an argon atmosphere. The mixture was then cooled at room temperature, and diethyl ether was added to give a white precipitate. The solid was filtered through a glass frit, washed with diethyl ether (4 × 15 mL), and dried under high vacuum, affording the desired product (328 mg, 48% yield) as a white powder. mp 360 °C dec; ^{1}H NMR (400 MHz, DMSO) δ 8.30 (d, J = 7.6, 4H), 7.07 (d, J = 7.6, 4H), 4.70 (s, 4H), 3.19 (s, 12H); ^{13}C NMR (125 MHz, D_2O) δ 156.4, 141.0, 108.1, 56.7, 39.6; IR (neat) 3419, 3286, 3005, 1646, 1566, 1399, 1169, 1032, 853 cm^{-1}; HRMS (ESI-TOF) m/z: $[M]^+$ Calcd for $C_{16}H_{24}ClN_4$ 307.1684; Found 307.1690.

Bis-acetonitrile Complex of Dirhodium Tetrakis[(*S*)-*N*-1,8-naphthaloyl-*t*-leucinate] Tetrafluoroborate, $(MeCN)_2$·Rh_2[(*S*)-nttl]$_4BF_4$. A solution of $NOBF_4$ (2.0 mg, 0.017 mmol) in acetonitrile (1 mL) was slowly added by syringe to a solution of Rh_2[(*S*)-nttl]$_4$ (24.8 mg, 0.017 mmol) in CH_2Cl_2 (5 mL). The green solution turned purple and became heterogeneous during the addition. The resulting mixture was then stirred for 30 min at room temperature. Solvents were removed *in vacuo*, affording a pinky-purple powder that was dissolved in CH_2Cl_2 and filtered through cotton. The filtrate was concentrated to give a gray-brown powder dried under high vacuum (quantitative yield). NMR silent. HRMS (ESI-TOF) m/z: $[M - CH_3CN]^+$ Calcd for $C_{74}H_{67}N_5O_{16}Rh_2$ 1487.2687; Found 1487.2669. UV/Visible (CH_2Cl_2), λ (ε, M^{-1} cm^{-1}): 520 (170).

Bis-dimethylaminopyridine Complex of Dirhodium Tetrakis-[(*S*)-*N*-1,8-naphthaloyl-*t*-leucinate] Tetrafluoroborate, $(DMAP)_2$·Rh_2[(*S*)-nttl]$_4BF_4$. A solution of $NOBF_4$ (2.0 mg, 0.017 mmol) in acetonitrile (1 mL) was slowly added by syringe to a solution of Rh_2[(*S*)-nttl]$_4$ (24.8 mg, 0.017 mmol). The green solution turned purple and became heterogeneous during the addition. To the resulting mixture was added 4-dimethylaminopyridine (4.18 mg, 0.034 mmol, 2 equiv), The resulting brown-reddish mixture was then stirred for 30 min at room temperature. Solvents were removed *in vacuo*, affording a gray-green powder that was dried under high vacuum (quantitative yield). NMR silent. HRMS (ESI-TOF) m/z: $[M]^+$ Calcd for $C_{86}H_{84}N_8O_{16}Rh_2$ 1690.4110; Found 1690.4073. UV/Visible (CH_2Cl_2), λ (ε, M^{-1} cm^{-1}): 587 (195).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Complete optimization tables, Hammett data, characterization spectra (^{1}H and ^{13}C NMR) for new compounds, and X-ray data for sulfilimine **25**. 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.

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