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Organocatalytic Asymmetric Synthesis of Sulfoxides from Sulfenic Acid Anions Mediated by a *Cinchona*-Derived Phase-Transfer Reagent

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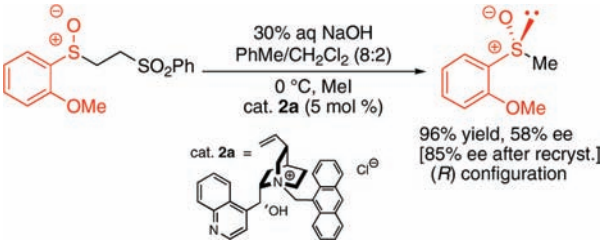
ABSTRACT



Preliminary results concerning a conceptually novel route to chiral sulfoxides based on the asymmetric alkylation of sulfenate salts with alkyl halides mediated by a chiral phase-transfer catalyst are described. As a representative example, *o*-anisyl methyl sulfoxide was produced in 96% yield and with an enantiomeric excess of 58% using commercial cinchonidinium derivative 2a.

Enantiopure sulfoxides represent an important class of compounds that find increasing use as chiral auxiliaries or ligands in asymmetric catalysis.[1] Moreover, this sulfur subunit is present in natural products[2] or some biologically significant molecules,[3] the most relevant one being probably the antiulcer agent esomeprazole. Conventional methods for preparing optically active sulfoxides consist of the creation of the sulfur−oxygen bond by asymmetric oxidation of the parent thioether or formation of the carbon−sulfur bond by treatment of an organometallic reagent with an enantiopure sulfinyl derivative, namely the Andersen approach, according to an S_N2 mechanism. Despite high synthetic values, these two methods still suffer from limitations.[4,5] Therefore, the development of complementary and conceptually different routes to chiral sulfoxides remains a subject of both relevant synthetic and fundamental interest. Crucial criteria to fulfill include,

(1) (a) Fernández, I.; Khiar, N. *Chem. Rev.* **2003**, *103*, 3651–3705. (b) Senanayake, C. H.; Krishnamurthy, D.; Lu, Z.-H.; Han, Z.; Gallou, I. *Aldrichim. Acta* **2005**, *38*, 93–104. (c) Legros, J.; Dehli, J. R.; Bolm, C. *Adv. Synth. Catal.* **2005**, *347*, 19–31. (d) Pellissier, H. *Tetrahedron* **2006**, *62*, 5559–5601. (e) Mellah, M.; Voituriez, A.; Schulz, E. *Chem. Rev.* **2007**, *107*, 5133–5209. (f) Kagan, H. B. In *Organosulfur Chemistry in Asymmetric Synthesis*; Toru, T., Bolm, C., Eds; Wiley VCH: Weinheim, 2008; pp 1−29. (g) Carreño, M. C.; Hernández-Torres, G.; Ribagorda, M.; Urbano, A. *Chem. Commun.* **2009**, 6129–6144. (h) Wojaczynska, E.; Wojaczynski, J. *Chem. Rev.* **2010**, *110*, 4303–4356. (i) O'Mahony, G. E.; Kelly, P.; Lawrence, S. E.; Maguire, A. R. *ARKIVOC* **2011**, 1–110.

(2) (a) Meyer, S. V.; Mordhorst, T. F.; Lee, C.; Jensen, P. R.; Fenical, W.; Köck, M. *Org. Biomol. Chem.* **2010**, *8*, 2158–2163. (b) Kusterer, J.; Vogt, A.; Keusgen, M. *J. Agric. Food Chem.* **2010**, *58*, 520–526. (c) Park, H.-S.; Yoda, N.; Fukaya, H.; Aoyagi, Y.; Takeya, K. *Tetrahedron* **2004**, *60*, 171–177.

(3) Esomeprazole was the second largest selling drug in 2009 ($5.0 billion U.S.): 2009 Top 200 Branded Drugs by Retail Dollars, Drug Topics, the Newsmagazine for Pharmacists; 2010: 1−3. Source: SDI/Verispan, VONA, full year 2009. http://drugtopics.modernmedicine.com/drugtopics/data/articlestandard//drugtopics/252010/674969/article.pdf (accessed 2010 June 17).

(4) High substrate-dependency and also formation of variable amounts of sulfone impurity are generally observed for the oxidation process. Drawbacks for the Andersen reaction include the limited availability of the required sulfinic acid derivatives in stereochemically pure form and use of these reagents in stoichiometric quantity.

(5) As an interesting example, the Andersen approach failed to give hetaryl sulfoxides: (a) Colobert, F.; Ballesteros-Garrido, R.; Leroux, F. R.; Ballesteros, R; Abarca, B. *Tetrahedron Lett.* **2007**, *48*, 6896–6899. (b) Abarca, B.; Ballesteros, R.; Ballesteros-Garrido, R.; Collobert, F.; Leroux, F. R. *Tetrahedron* **2008**, *64*, 3794–3801.

(6) (a) Ikemoto, T.; Nishiguchi, A.; Ito, T.; Tawada, H. *Tetrahedron* **2005**, *61*, 5043–48. (b) Stingl, K. A.; Tsogoeva, S. B. *Tetrahedron: Asymmetry* **2010**, *21*, 1055–1074.

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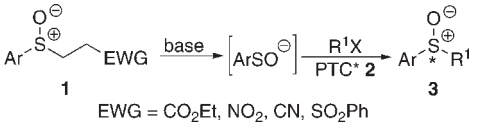
Scheme 1



if possible, proceeding with only a catalytic amount of the chiral inducer and avoiding the use of transition metals.[6] With this goal in mind, an alternative disconnection for the C−S bond was envisaged inverting the polarity of the reaction partners and hence starting with a prochiral and unusual sulfur nucleophile, i.e., a sulfenate salt[7] (Scheme 1).

Quenching with alkyl halides to afford racemic compounds is well established.[7,8] Diastereoselective versions involving sulfenates possessing a stereogenic center or planar chirality have been described with a high degree of success.[9] In contrast, enantioselective variants are limited to a single precedent from our group,[10] in which the chiral influence of (−)-sparteine was evaluated and furnished a low 29% ee.[11,12] We anticipated that the use of a chiral phase-transfer catalyst **2** (PTC*) could be an alternative. Phase-transfer catalysis has already been successfully employed for various C−C and C−O bond-forming reactions.[13] However, applications to the creation of carbon−sulfur bonds have been surprisingly neglected, and

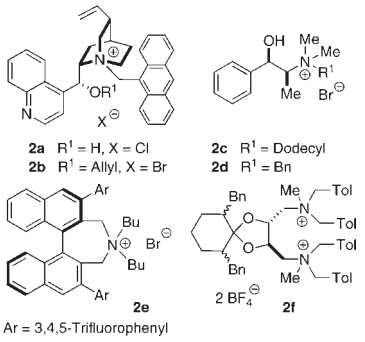


Figure 1. Commercial phase-transfer catalysts used in this study.

none of them exploit sulfenate species as nucleophile.[14] We wish to describe herein our preliminary results concerning the development of this unprecedented reaction combining sulfenate salt chemistry and phase-transfer catalysis.

Sulfenate salts being highly reactive, it is necessary to generate them in situ. We decided to exploit a methodology previously developed by us, which is based on a retro-Michael reaction initiated by a base (Scheme 1).[10] The mechanistic proposal we suggest for the overall process in the presence of PTC* involves the following cascade reactions: (i) upon treatment with an inorganic base, deprotonation of precursor **1** at the interface of the two immiscible phases followed by β-fragmentation and liberation of the sulfenate, (ii) cation exchange with the chiral ammonium salt to afford a lipophilic species with extraction to the organic layer, (iii) and finally reaction with the alkyl halide to give the sulfoxide **3**. If a tight ion pair with the quaternary ammonium salt is formed, we can envision discrimination of the two enantiotopic lone pairs of the sulfenate during the final alkylation step and hence formation of an enantioenriched sulfoxide product. Worthy of note is that all examples already investigated concern enantiofacial differentiation of double bonds in enolates or enones.[13] The formation of an effective chiral ion pair in our case remained questionable but is required to prevent a racemic background pathway.

Accordingly, a model study was initiated with the synthesis of tolyl methyl sulfoxide **3aa**. Optimization was carried out on a 0.08 mmol scale using 10 mol % of a commercially available cinchonidinium salt **2a**, possessing a free OH group, and an anthracenylmethyl substituent on the quinuclidine moiety (Figure 1). The influence of a range of reaction parameters was examined, including the nature of the precursor, base, solvent, dilution, and temperature. Representative results of this thorough screening are given in Table 1.

A preliminary set of experiments was arbitrarily carried out at −20 °C with 33% aqueous NaOH solution in toluene, thus allowing identification of sulfinyl sulfone **1aa** (EWG = SO_2Ph) as the most appropriate starting material.[15] The anticipated sulfoxide product **3aa** was obtained in 50% yield and 20% ee in favor of the (*R*)-enantiomer (entry 1). Although this result is far from

(7) O'Donnell, J. S.; Schwan, A. L. *J. Sulfur Chem.* **2004**, *25*, 183–211.

(8) See, for example: (a) Foucoin, F.; Caupène, C.; Lohier, J.-F.; Sopková−de Oliveira Santos, J.; Perrio, S.; Metzner, P. *Synthesis* **2007**, 1315–1324. (b) Singh, S. P.; O'Donnell, J. S.; Schwan, A. L. *Org. Biomol Chem.* **2010**, *8*, 1712–1717.

(9) (a) Sandrinelli, F.; Perrio, S.; Averbuch-Pouchot, M.-T. *Org. Lett.* **2002**, *4*, 3619–3622. (b) Maezaki, N.; Yagi, S.; Yoshigami, R.; Maeda, J.; Suzuki, T.; Ohsawa, S.; Tsukamoto, K.; Tanaka, T. *J. Org. Chem.* **2003**, *68*, 5550–5558. (c) Schwan, A. L.; Verdu, M. J.; Singh, S. P.; O'Donnell, J. S.; Ahmadi, A. M. *J. Org. Chem.* **2009**, *74*, 6851–6854.(d) Lohier, J.-F.; Foucoin, F.; Jaffrès, P.-A.; Garcia, J. I.; Sopková−de Oliveira Santos, J.; Perrio, S.; Metzner, P. *Org. Lett.* **2008**, *10*, 1271–1274.

(10) Caupène, C.; Boudou, C.; Perrio, S.; Metzner, P. *J. Org. Chem.* **2005**, *70*, 2812–2815.

(11) Alkylation of anthraquinone-1-sulfenate with a stoichiometric amount of an enantiopure sulfonium salt was also reported and afforded a modest 24% ee: Kobayashi, M.; Manabe, K.; Umemura, K.; Matsuyama, H. *Sulfur Lett.* **1987**, *6*, 19–24.

(12) For the related asymmetric palladium-catalyzed arylation, see: (a) Maitro, G.; Vogel, S.; Sadaoui, M.; Prestat, G.; Madec, G.; Poli, G. *Org. Lett.* **2007**, *9*, 5493–5496. (b) Maitro, G.; Prestat, G.; Madec, D.; Poli, G. *Tetrahedron: Asymmetry* **2010**, *21*, 1075–1084.

(13) (a) Maruoka, K., Ed. *Asymmetric Phase Transfer Catalysis*; Wiley-VCH: Weinheim, 2008. (b) Hashimoto, T.; Maruoka, K. *Chem. Rev.* **2007**, *107*, 5656–5682. (c) Ooi, T.; Maruoka, K. *Angew. Chem., Int. Ed.* **2007**, *46*, 4222–4266. (d) Jew, S.-s.; Park, H.-g. *Chem. Commun.* **2009**, 7090–7103. (e) Yeboah, E. M. O.; Yeboah, S. O.; Singh, G. S. *Tetrahedron* **2011**, *67*, 1725–1762.

(14) Introduction of the sulfur atom was achieved by reaction of a thiol or a thiosulfonate: (a) Juliá, S.; Ginebreda, A.; Guixer, J.; Tomás, A. *Tetrahedron Lett.* **1980**, *21*, 3709–3712. (b) Colonna, S.; Re, A.; Wynberg, H. *J. Chem. Soc., Perkin Trans. 1* **1981**, 547–552. (c) Wladislaw, B.; Marzorati, L.; Biaggio, F. C.; Vargas, R. R.; Bjorklund, M. B.; Zukerman-Schpector, J. *Tetrahedron* **1999**, *55*, 12023–12030. (d) Rodrigues, A.; Wladislaw, B.; Di Vitta, C.; Pandini Cardhoso Filho, J. E.; Marzorati, L.; Bueno, M. A.; Olivato, P. R. *Tetrahedron Lett.* **2010**, *51*, 5344–5348.

(15) The EWG activating group plays a critical role in the efficiency of this organocatalytic process. A pK_a value around 31 (value in DMSO) for the α-hydrogen seems to ensure a smooth and efficient release of the sulfenate, along with the best ee. Use of the more acidifying nitro substituent (pK_a of 17) furnished a faster reaction but with almost no enantioinduction. See the Supporting Information.

Table 1. Optimization of the Reaction with Catalyst **2a** According to Scheme 1 (EWG = SO_2Ph, Ar = Tol and R^1 = Me)[a]

entry	base/temp (°C)	solvent	time[b] (h)	yield[c] (%)	ee[d] (%)
1	NaOH/−20	PhMe	38	50	20 (*R*)
2	NaOH/−20	CH_2Cl_2	96	76	0
3	NaOH/−20	THF	72	72	5 (*R*)
4	NaOH/−20	PhCl	72	81	42 (*R*)
5	NaOH/−20	7:3 PhMe/CH_2Cl_2	72	80	47 (*R*)
6	NaOH/−10	7:3 PhMe/CH_2Cl_2	6	83	49 (*R*)
7	NaOH/0	7:3 PhMe/CH_2Cl_2	1	86	48 (*R*)
8	NaOH/10	7:3 PhMe/CH_2Cl_2	0.5	90	46 (*R*)
9	NaOH/20	7:3 PhMe/CH_2Cl_2	0.5	80	41 (*R*)
10	LiOH/0	7:3 PhMe/CH_2Cl_2	48	65	50 (*R*)
11	K_3PO_4/0	7:3 PhMe/CH_2Cl_2	48	49	46 (*R*)
12	K_2CO_3/0	7:3 PhMe/CH_2Cl_2	72	0	
13	Cs_2CO_3/0	7:3 PhMe/CH_2Cl_2	72	0	
14	K_2CO_3/0	7:3 PhMe/CH_2Cl_2	72	0	
15[e]	NaOH/0	7:3 PhMe/CH_2Cl_2	5	80	55 (*R*)
16[e]	NaOH/0	8:2 PhMe/CH_2Cl_2	5	88	59 (*R*)
17[e,f]	NaOH/0	8:2 PhMe/CH_2Cl_2	8	77	57 (*R*)

[a] Reactions performed on 0.08 mmol scale using 5 equiv of MeI and 10 equiv of base in the presence of 10 mol % of catalyst **2a** in 1 mL of solvent, unless otherwise indicated. [b] Consumption of the starting material was monitored by TLC, and the reaction mixture was then quenched with aqueous HCl solution. [c] Isolated yield. [d] Determined by HPLC analysis using a chiral stationary phase column (Daicel Chiralpak OB-H) with 3:7 2-propanol/heptane as the eluent. [e] With 3 mL of solvent. [f] With 5 mol % of catalyst **2a**.

satisfactory, it validates our working hypothesis of asymmetric induction. Variation of the solvent showed a dramatic impact over the process. Use of dichloromethane afforded **3aa** in an improved 76% yield but in a racemic form (entry 2). The stereochemical outcome was almost similar in THF (entry 3). A 42% ee was observed in chlorobenzene (entry 4), while an improvement to 47% was obtained in a 7:3 mixture of toluene and CH_2Cl_2 (entry 5).[16] Elevation of the temperature above −20 °C allowed the reactions to be completed within a few hours, instead of a few days (entries 6−9). A balance between reaction time and enantioselectivity was obtained at 0 °C, **3aa** being isolated in 86% yield and 48% ee (entry 7). Subsequent survey revealed that NaOH is still the base of choice (entries 10−14). Higher dilution (3 mL of organic solvent) furnished an improved ee of 55% (entry 15). A slight adjustment of the solvent combination to an 8:2 ratio led to a 59% ee (entry 16). Gratifyingly, the catalyst loading could be limited to 5 mol % without significantly affecting the process efficiency (entry 17).

Other commercially available catalysts (10 mol %) displaying various structural types were tested under the conditions mentioned above (Figure 1 and Table 2). Use of ephedra derivatives **2c** and **2d** led to the desired sulfoxide in reasonable 64% yields but in poor enantiomeric excesses (3−4%, entries 2−3). The case is even worse with the binaphthyl catalyst **2e** developed by Maruoka (entry 4). Reduced ee's (18%) were also obtained using the tartrate derivative **2f** (entry 5) and also the *O*-allyl cinchonidinium salt **2b** (entry 6).

Table 2. Influence of Catalyst **2** According to Scheme 1 (EWG = SO_2Ph, Ar = Tol and R^1 = Me)[a]

entry	catalyst	time[b] (h)	yield[c] (%)	ee[d] (%)
1	**2a**	5	88	59 (*R*)
2	**2c**	18	64	3 (*R*)
3	**2d**	42	64	4 (*R*)
4	**2e**	84	80	0
5	**2f**	24	60	18 (*R*)
6	**2b**	17	56	18 (*R*)

[a] The reactions were performed at 0 °C on 0.08 mmol scale using 5 equiv of MeI and 10 equiv of 33% aqueous NaOH in the presence of 10 mol % of catalyst **2** in 8:2 PhMe/CH_2Cl_2 (3 mL). [b] Consumption of the starting material was monitored by TLC, and the reaction mixture was then quenched at 0 °C with aqueous HCl solution. [c] Isolated yield. [d] Determined by HPLC analysis using a chiral stationary-phase column (Daicel Chiralpak OB-H) with 3:7 2-propanol/heptane as the eluent.

To summarize, best results were obtained so far using sulfinyl sulfone as sulfenate surrogate, aqueous sodium hydroxide, and a mixture of toluene and CH_2Cl_2 in a 8:2 ratio at 0 °C. The sulfoxide **3aa** is obtained after an overnight reaction in a good 88% chemical yield and 59% ee in favor of the (*R*)-enantiomer (Table 2, entry 1).[17] Further control experiments indicated that (i) the sulfoxide target is configurationally stable under the reaction conditions, (ii) the ee is constant from the beginning until completion of the reaction, and (iii) no background reaction[18] is taking place.

To examine the scope of the methodology, a collection of arylsulfinyl sulfones **1** was then prepared. Structural modifications comprise variations of the electronic character, steric demand, and also position of the substituents on the arene (Table 3). A naphthyl derivative **1d** was also prepared. The two-step synthesis of these precursors involves a 1,4-addition of the requisite thiophenol on phenyl vinyl sulfone, followed by oxidation of the sulfur center.[19]

All substrates were subjected to the optimized conditions (5 mol % of catalyst), and various alkyl halides were also employed. The results obtained are collected in Table 3. In all cases, the corresponding sulfenates were released and efficiently converted into the anticipated sulfoxides. A larger excess of electrophile (10 equiv instead of 5) is required with ethyl iodide to reach a 63% yield (entry 2). The enantioselectivity level depends dramatically on the nature of the halide. Whereas reduced but still acceptable ees of 35 and 42%[20] were measured,

(16) A slight erosion of enantioselectivity (41%) and also a slower reaction rate (48% yield after 72 h of reaction) were observed when powdered NaOH was used in a similar PhMe/CH_2Cl_2 solvent system.

(17) A comparable result with an ee of 58% and a chemical yield of 81% was also obtained with sulfinyl nitrile **1af**. See the Supporting Information.

(18) Without the phase-transfer catalyst, no reaction took place. 96% of starting material was recovered after 12 h of reaction.

(19) *p*-Chlorophenylsulfinyl sulfone **1i** and also its sulfanyl congener **4i** provided crystals suitable for X-ray crystallography.

(20) Since allylic sulfoxide **3ac** is prone to epimerization via the Mislow−Braverman−Evans [2,3]sigmatropic rearrangement, rapid determination of ee from the crude product is required

Table 3. Scope of the Reaction According to Scheme 1 (EWG = SO_2Ph)[a]

entry	1	Ar	R^1	3	yield (%)[b]	ee (%)[c]
1	**1aa**	Tol	Me	**3aa**	77	57 (*R*)
2	**1aa**	Tol	Et	**3ab**	34 (63)[d]	35 (*R*)
3	**1aa**	Tol	Allyl	**3ac**	89	42 (*R*)[e]
4	**1aa**	Tol	Bn	**3ad**	92	19 (*R*)
5	**1aa**	Tol		**3ae**	92	21 (*R*)
6	**1b**	Ph	Me	**3b**	96	52 (*R*)
7	**1c**	4-*i*-PrC_6H_4	Me	**3c**	96	48 (*R*)
8	**1d**	2-Napht	Me	**3d**	88	42 (*R*)
9	**1e**	4-F_3C-C_6H_4	Me	**3e**	81	18 (*R*)
10	**1f**	4-$MeOC_6H_4$	Me	**3f**	81	48 (*R*)
11	**1g**	3-$MeOC_6H_4$	Me	**3g**	96	51 (*R*)
12	**1h**	2-$MeOC_6H_4$	Me	**3h**	88	54 (*R*)
13	**1i**	4-ClC_6H_4	Me	**3i**	79	40 (*R*)
14	**1j**	2-ClC_6H_4	Me	**3j**	72	37 (*R*)
15	**1k**	2-*t*-BuC_6H_4	Me	**3k**	89	50 (*R*)
16	**1l**	Mes	Me	**3l**	69	44 (*R*)
17[f]	**1a**	Tol	Me	**3aa**	95	54 (*R*)
18[f]	**1h**	2-$MeOC_6H_4$	Me	**3h**	96	58 (*R*)

[a] Reactions performed at 0 °C on 0.08 mmol scale using 5 equiv of electrophile and 10 equiv of 33% aqueous NaOH in the presence of 5 mol % catalyst **2a** in 8:2 PhMe/CH_2Cl_2 (3 mL), unless otherwise noted. [b] Isolated yield. [c] Determined by HPLC analysis using chiral stationary phase columns. See the Supporting Information for the conditions. [d] With 10 equiv of EtI in parentheses. [e] Determined with the crude product. [f] Performed on 1 mmol scale.

respectively, with ethyl and allyl iodides (entries 2 and 3), substantial erosion to 20% was noticed with the more reactive benzyl agents (entries 4 and 5, to be compared with 57% with MeI). In contrast, alkylation with methyl iodide provided relatively homogeneous enantioselectivities. The exception concerns the strongly electron-deficient trifluoromethyl derivative **3** for which a drop to 18% ee is observed, despite an excellent 81% yield (entry 9). The position of the methoxy substituent on the aryl moiety has no impact on the enantioselectivity, as exemplified with the results obtained with the *ortho*, *meta*, and *para* isomers (entries 10–12). A similar conclusion is also obtained with the chloro compounds (entries 13 and 14). Interestingly, the bulky *tert*-butyl or mesityl derivatives still retain enantioselectivity (50 and 44% ee's, respectively, entries 15 and 16). An (*R*)-configuration is uniformly produced for the major enantiomers. This stereochemistry was unambiguously assigned by comparison with optical rotations and/or HPLC retention times with literature data. For the unknown enantioenriched *ortho-tert*-butyl sulfoxide **3k**, chemical correlation was investigated.[21]

The encouraging results on a small scale prompted an investigation into scaling up the reaction. Repeating the reaction with 1 mmol of substrate **1aa** under the same conditions (albeit an increase of the reaction time from 8 to 15 h) allowed the isolation of (*R*)-methyl tolyl sulfoxide **3aa** quantitatively with a 54% ee (entry 17). Similarly, the *o*-anisyl product **3h** was produced within 20 h in 96% yield and with a 58% ee (entry 18). In these two cases, the efficiency of the process was even higher than that observed on the smaller scale. Futhermore, sulfoxides are usually solid compounds, and a single crystallization allows ee to increase, an aspect that is of practical interest. For example, the sample of *o*-anisyl sulfoxide **3h** prepared above was enantiomerically enriched to 85% after crystallization (54% yield) in a CH_2Cl_2/pentane system.

In conclusion, we have reported an unprecedented and conceptually novel route to enantioenriched sulfoxides, based on the enantioselective alkylation of prochiral sulfenates with alkyl halides in the presence of a *Cinchona*-derived phase-transfer catalyst. Attractive features of the protocol include operational simplicity, mild and transition-metal-free conditions, inexpensive and readily available reagents, compatibility with only a catalytic amount of the chiral inducer (5 mol %), and ease in scale-up. Furthermore, it constitutes a unique example of a successful asymmetric C–S bond formation mediated by a chiral phase-transfer catalyst, along with lone pair discrimination.[22] Although the enantioselectivities (up to 58%) are still moderate, these preliminary results obtained with a classical and commercial cinchonidinium salt form the basis for further developments. We believe that increasing the electrostatic interaction between the sulfenate and the catalyst, through hydrogen bonding and π-stacking interactions, should lead to a better ion pairing and hence an improved induction. Screening of modified catalysts is currently in progress in our laboratory. Further studies to expand the methodology to chiral dialkyl sulfoxides are also ongoing.[23]

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Supporting Information Available. General methods of the experimental section, full spectroscopic data, additional experiments for the screening of the PTC* conditions, HPLC charts and X-ray crystal structures of **4i** and **1i**. This material is available free of charge via the Internet at http://pubs.acs.org.

(21) An enantioenriched reference of 79% ee in favor of the (*S*)-configuration was prepared by asymmetric oxidation of the corresponding thioether, as described in the Supporting Information.

(22) A low enantioselectivity of 17% was reported for the PTC* alkylation of phenylphosphine borane with MeI (creation of C–P bond): Lebel, H.; Morin, S.; Paquet, V. *Org. Lett.* **2003**, *5*, 2347–2349.

(23) Under the conditions used in the present paper, the reaction is too slow with aliphatic substrates for an immediate synthetic application. Revision of the conditions is consequently required.