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Acid promoted enantioselective oxygen-atom transfer from *N*-alkyl binaphthyl-derived oxaziridines onto sulfides

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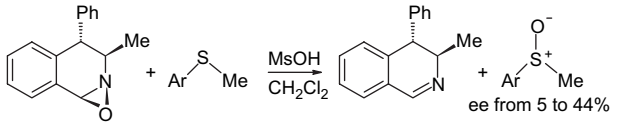
Abstract—Acid-promoted asymmetric sulfoxidations of prochiral sulfides using binaphthyl-derived oxaziridines have been studied. The reactions of dialkyl or aryl-alkyl sulfides gave good yields of the corresponding sulfoxides with enantiopurities ranging from 20% to 80%. The influence of temperature and strength of the acid catalyst on enantioselectivity was studied. The absolute configuration of the resulting major enantiomer varied with the structure of the sulfide.

1. Introduction

The exceptional ability of oxaziridines to transfer an amine group or an oxygen atom to a nucleophile originates from the incorporation of the relatively weak N–O bond into a strained ring. Although oxygen-atom transfer from structurally particular oxaziridine to phosphines or sulfides to give the corresponding oxides have been reported,[1–3] amino group transfer is the most common reaction with most nucleophilic reagents.[4] Sulfoxidations with oxaziridines are sluggish except with those carrying an electron-withdrawing group on either the nitrogen atom or both nitrogen and carbon atoms of the three-membered ring.[2,3] Enantioselective sulfoxidations have been performed with enantiopure *N*-sulfonyl-,[5] *N*-sulfamyl-,[6] and *N*-phosphinoyloxaziridines.[7] Examples of catalytic enantioselective sulfoxidations by oxaziridines have recently been reported.[8] In both cases, enantioselectivities vary from low to high according to the structure of the sulfides.[9]

Interestingly, it was found that, in the presence of Brönsted acids, *N*-alkyl oxaziridines derived from 3,4-dihydroisoquinoline oxidized sulfides to sulfoxides without over-oxidation to sulfones even in the presence of excess reagent.[10,12,13] Oxygen transfer probably occurred from a highly electrophilic oxaziridinium intermediate formed by protonation of oxaziridine. Oxaziridinium salts have indeed been shown to be highly reactive in oxygen-transfer reactions to a variety of nucleophilic functional groups.[11]

Acid-catalyzed oxidations of prochiral sulfides by a chiral oxaziridine have also been reported (Scheme 1).[12] The corresponding sulfoxides were formed with low to moderate enantioselectivities. Also Lewis acid-catalyzed enantioselective sulfoxidations using an otherwise inert oxaziridine have also been recently reported.[14]



Scheme 1.

Since 1996, enantiopure binaphthyl-containing iminium salts have emerged as potential catalysts for enantioselective oxygen transfer onto olefins with ee's varying with the structure of the olefin.[8,15] These reactions also involve oxaziridinium intermediates. However, no examples of enantioselective sulfoxidations using these binaphthyl-derived reagents have been reported so far.

This paper reports a detailed study of acid-promoted asymmetric oxidations of sulfides by oxaziridines derived from chiral dinaphthazepines (S_a atropisomers).

2. Results

2.1. Synthesis of oxaziridines 1 and 2

Enantiopure oxaziridines **1** and **2** have respectively been prepared from enantiopure azepine **3** and dibromide **4** (Scheme 2).[16] Dibromide **4** was easily converted into the new azepine

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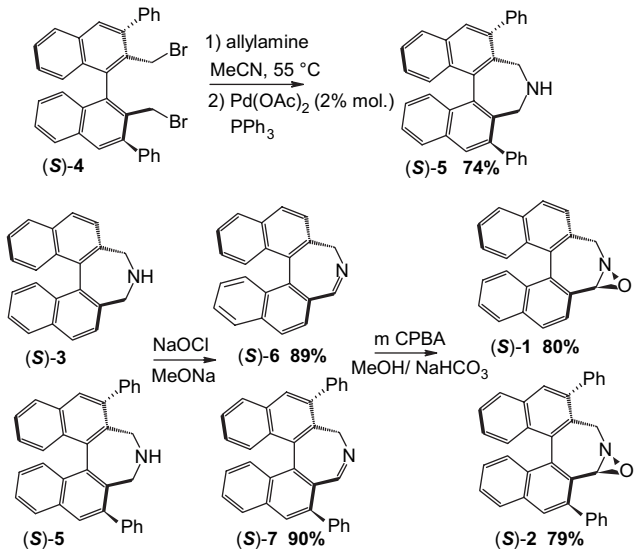


Scheme 2. Preparation of oxaziridines (*S*)-**1** and (*S*)-**2**.

5 after a double substitution reaction with allylamine followed by deallylation of the amine group. Ruschig oxidation[17] of compounds **3** and **5** yielded imines **6** and **7**, which were further oxidized by *meta*-chloroperbenzoic acid in methanol under basic conditions. Oxaziridines (*S*)-**1** and (*S*)-**2** were obtained as single diastereoisomers in 78% (from **3**) and 68% (from **4**) yields.

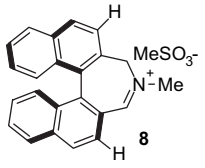


Figure 1.

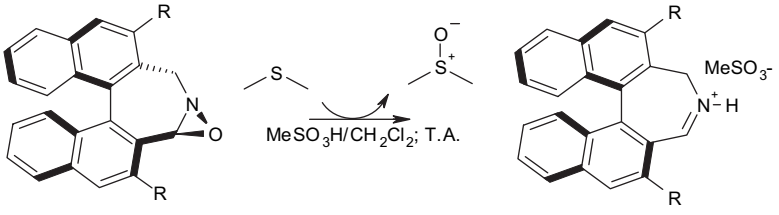
The S_c,R_N configuration of the new stereogenic centers of compounds **1** and **2** were assigned on the basis of Houk's[18] hypothesis, which is consistent with both calculations and experimental observations on the corresponding iminium salt **8** (Fig. 1) used for catalysis of epoxidation reactions. Calculations showed that the energy of R_c,S_N intermediate formed by nucleophilic attack of a peracid anion on the iminium salt **8** corresponding to imine **6** was 8.1 kcal/mol higher than that of the S_c,R_N isomer as a result of steric repulsions between the *ortho*-aromatic hydrogens and the oxygen atom. It should be expected that such repulsive interactions should be dramatically enhanced by the substitution of hydrogen by a phenyl group as in imine **7**.

2.2. Oxidation of sulfides to sulfoxides

Oxidations of sulfides with (*S*)-**1** or (*S*)-**2** were first performed under the previously[12] described conditions, i.e., at room temperature in the presence of a slight excess of methanesulfonic acid (MsOH) in dichloromethane (Table 1). Ee's of the sulfoxides were determined by ^{1}H NMR spectroscopy in the presence of (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide[19] as a chiral shift reagent. The absolute configuration of the major enantiomer was determined by comparison of the sign of optical rotation with that reported in the literature.[20]

Reactions were instantaneous: no active oxygen was detected (potassium iodide test) immediately after the addition of sulfides to (*S*)-**1** or (*S*)-**2**. In all cases, the conversion to sulfoxides was quantitative and no over-oxidation to sulfones was observed. Imines (*S*)-**6** and (*S*)-**7** resulting from

Table 1. Oxidation of sulfides with (*S*)-**1** and (*S*)-**2** in the presence of methanesulfonic acid



Entry	Sulfides	Oxaziridine	Time	Yield of sulfoxides[a] (%)	ee[c] (%)	Absolute configuration
1	t-Bu, S, Me	(*S*)-**1**	<1 min	84	33	*S*
2		(*S*)-**2**	<1 min	86	17	*S*
3	S, Me	(*S*)-**1**	<1 min	78	22	*R*
4		(*S*)-**2**	<1 min	77	22	*R*
5	MeO, S, Me	(*S*)-**1**	<1 min	74	16	*R*
6		(*S*)-**2**	<1 min	77	27	*R*
7	O_2N, S, Me	(*S*)-**1**	<1 min	66	11	*R*
8		(*S*)-**2**	<1 min	64	<5	[b]

[a] Isolated by preparative TLC.
[b] Enantiomeric excess too low to allow a safe assignment of the absolute configuration.
[c] Determined by ^{1}H NMR spectroscopy using (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide[19] as a chiral shift reagent.

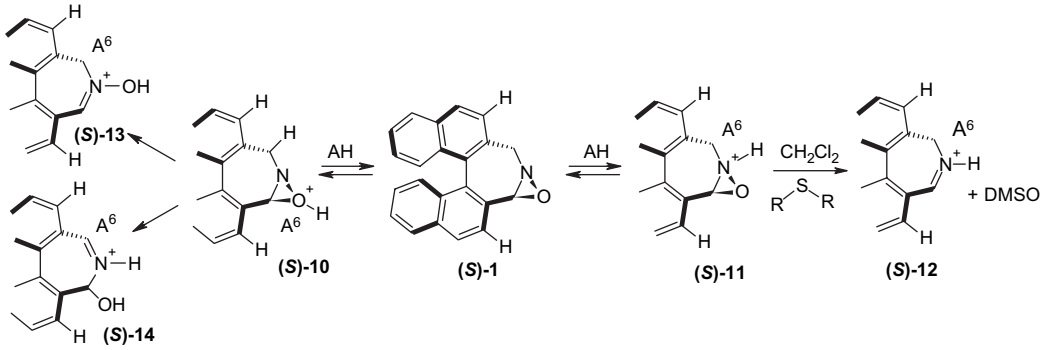
the oxygen-atom transfer reaction were recovered, respectively, in 80–90% yield after purification.

Oxidations took place with low to modest enantioselectivities. *tert*-Butyl methyl sulfoxide (entries 1 and 2) and aryl-alkyl sulfoxides (entries 3–7) formed, respectively, from (*S*)-**1** or (*S*)-**2** showed opposite configurations. To our knowledge, such result has never been observed with other oxaziridines.

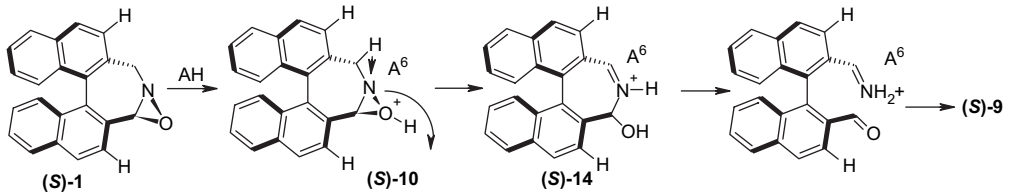
Following a mechanism proposed earlier[10,11] to rationalize the oxygen-atom transfer from an oxaziridine derived from a dihydroisoquinoline to dimethyl sulfide, we propose an equilibrium between oxaziridine (*S*)-**1** and its two protonated forms (*S*)-**10** and (*S*)-**11** (Scheme 3). The latter is able to transfer its oxygen to the dimethylsulfide leading to the protonated imine (*S*)-**12** and dimethylsulfoxide. In the absence of sulfide, the *O*-protonated form (*S*)-**10** leads to the corresponding nitrone (*S*)-**13** with eventually concomitant formation of the iminium carbinol (*S*)-**14**.

Surprisingly, oxaziridine (*S*)-**1** led quantitatively to dialdehyde (*S*)-**9**[20,22] in the presence of 1.1 equiv of trifluoroacetic acid. No nitrone (*S*)-**13** was observed (Scheme 4). Dialdehyde (*S*)-**9** resulted probably from ring opening and subsequent hydrolysis of the iminium carbinol (*S*)-**14** obtained from *O*-protonated oxaziridine (*S*)-**10**.

Oxidation of *tert*-butyl methyl sulfide by oxaziridine (*S*)-**1** was then investigated as a probe reaction to study the influence of temperature and strength of the acid on the stereochemical course of the reaction (Table 2).

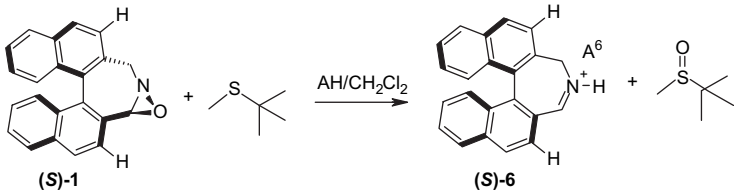


Scheme 3. Expected reactivity of (*S*)-**1** in acidic medium with or without dimethyl sulfide.



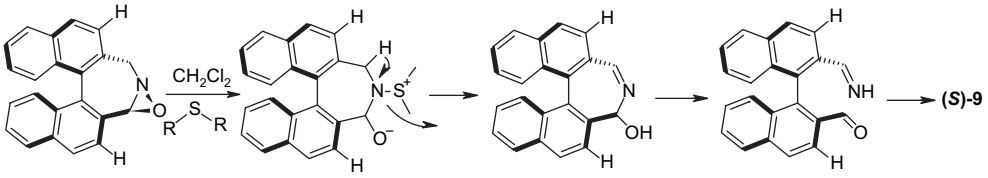
Scheme 4. Formation of dialdehyde (*S*)-**9** from oxaziridine (*S*)-**1** in acidic medium.

Table 2. Influence of temperature and acid strength on oxidation of *tert*-butyl methyl sulfide by (*S*)-**1**



Entry	Acid	Temperature (°C)	Time	Conversion[a] (yield[b] %)	ee[c] % (config.[d])
1	MsOH	20	<1 min	100 (82)	33 (*S*)
2	MsOH	−45	<1 min	100 (79)	52 (*S*)
3	MsOH	−78	<5 min	100 (80)	60 (*S*)
4	MsOH	−100	<5 min	100 (82)	80 (*S*)
5	CF_3COOH	20	<1 min	100 (78)	51 (*S*)
6	CF_3COOH	−45	40 min	100 (76)	66 (*S*)
7	AcOH	20	4 h	72 (61)	59 (*S*)
8	No	20	24 h	65 (42)	70 (*S*)

[a] Calculated using triphenylmethane as an internal standard.
[b] Isolated yields after preparative TLC.
[c] Determined by ^1H NMR spectroscopy using (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide[19] as a chiral shift reagent.
[d] Determined by comparison of optical rotation with that of an authentic sample.



Scheme 5. Formation of dialdehyde (*S*)-**9** from oxaziridine (*S*)-**1** in the presence of a thioether.

As expected, for a given acid, enantioselectivities increased as temperature decreases (entries 1–4 and 5 and 6). The highest ee (80%) was obtained with methanesulfonic acid at −100 °C (entry 4). Even at this low temperature, the reaction was over after a few minutes. As previously shown,[12] the rate of oxidation increased with the strength of the acid (entries 1, 7, and 8). Enantioselectivity increased with the pK_a of the acid (entries 1, 5, and 7) and an even higher ee was observed in the absence of acid (entry 8). Oxaziridine (*S*)-**1** is thus a more selective oxygen-transfer reagent than its conjugate acid. However, it is much less reactive: the reaction was slow and the sulfoxide was obtained in moderate (65%) yield only, even after 1 day at room temperature (entry 8). The mixture also contained ∼35% *tert*-butyl methyl sulfide, 70% imine (*S*)-**6**, and 30% dialdehyde (*S*)-**9** resulting probably from the nucleophilic attack of the sulfide on the nitrogen atom as depicted in Scheme 5.[2]

The higher rate of oxygen versus nitrogen atom transfer from an oxaziridine to a sulfide in the absence of acid is unprecedented and has been observed for all sulfides. Such behavior is only observed for special types of substituted oxaziridines[1] reacting with very strong nucleophiles (i.e., *N-tert*-butyl-oxaziridines on dialkylphosphines).

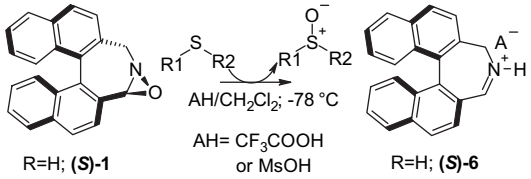
Table 3 shows oxidations of various sulfides with (*S*)-**1** in the presence of TFA or triflic acid. The best enantioselectivities were obtained with TFA. However, even in the best cases, ee's were only moderate except for *tert*-butyl methyl sulfide (entry 1) where the two substituents on sulfur are very different in size. Interestingly, ee's for aryl methyl sulfide carrying an electron-donating and an electron-withdrawing group on the phenyl group were significantly different although the sizes of these substituents are comparable. It appears thus that electronic factors also play a role on the facial discrimination.

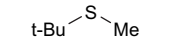
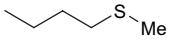
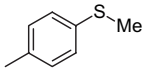
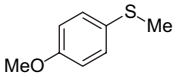
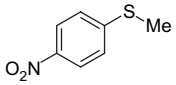
We next turned our attention to oxidations with oxaziridine (*S*)-**2**. These reactions were carried out with slight excess of acid in dichloromethane. As the reaction rates were lower than those observed using oxaziridine (*S*)-**1** we did not test weaker acid than TFA. Once again enantioselectivities were higher at lower temperatures. However, here, we did not observe a significant improvement of enantioselectivity in the presence of trifluoroacetic acid. Overall enantioselectivity was not improved by the presence of the two phenyl substituents on the binaphthyl skeleton.

3. Discussion

Oxygen transfer from electrophilic reagents to sulfides are thought to be S_N2 displacements and have been rationalized

Table 3. Oxidation of sulfides with (*S*)-**1** at −78 °C



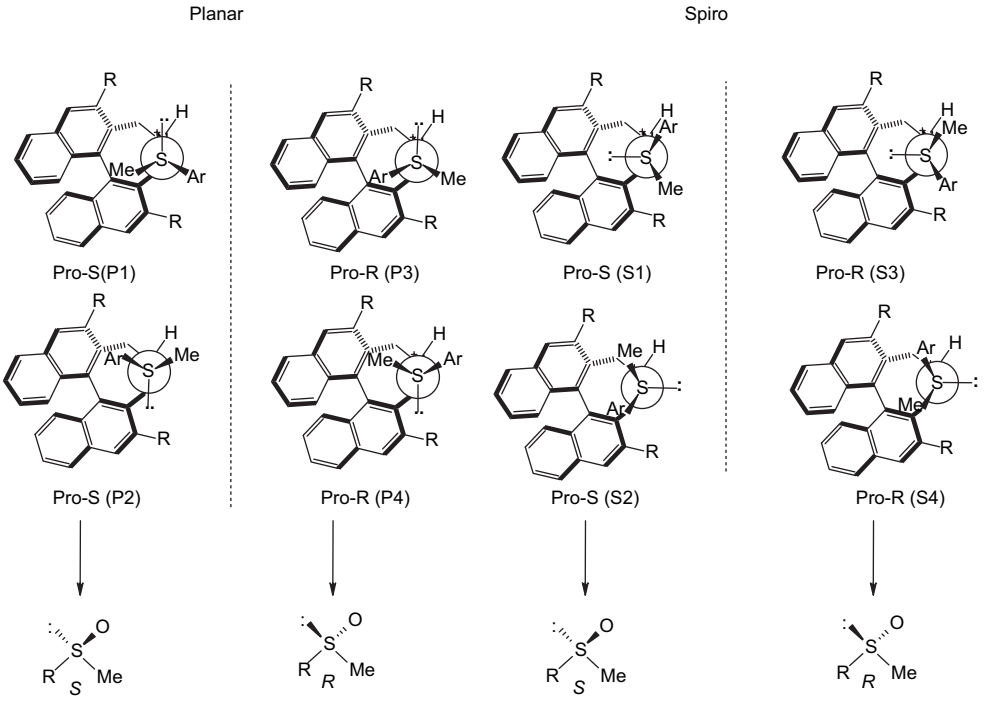
Entry	Sulfides	Time		Conversion[b] (yield[a] %)		ee[c] (%)		Absolute configuration[d]
		TFA	MsOH	TFA	MsOH	TFA	MsOH	
1		1 h 30 min	<5 min	100% (78)	100% (80)	80	60	*S*
2		1 h	<5 min	100% (65)	100% (62)	24	14	*S*
3		2 h 30 min	<5 min	100% (77)	100% (72)	70	47	*R*
4		2 h	<5 min	100% (74)	100% (69)	64	40	*R*
5		5 h	5 min	92% (51)	100% (65)	26	20	*R*

[a] Isolated by preparative TLC.
[b] Calculated using triphenylmethane as an internal standard.
[c] Determined by ^{1}H NMR spectroscopy using (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide as a chiral shift reagent.[19]
[d] Determined by comparison of optical rotations with that of an authentic sample.

in terms of two transition states, planar or spiro.[21] In the planar TS, both electron pairs on the sulfur atom are in the plane containing the oxaziridine ring while, in the spiro TS, the two electron pairs are in a plane orthogonal to the oxaziridine ring. Considering the absolute configuration of oxaziridines (*S*)-**1** and (*S*)-**2** as (S_a,S_c,R_N), eight transition states can be envisaged (Scheme 6). A qualitative evaluation of the steric interactions favors a planar transition state. The large and the small groups of the sulfide lie both on the same side of the oxaziridine ring. In the pro-(*R*)/pro-(*S*) pair of arrangements S_2 and S_4 both sulfur-attached groups lie on the hindered side of the oxaziridines (maximum of repulsion). The corresponding rotamers S_1 and S_3 have the sulfur-attached group on the unhindered side of the oxaziridine ring and should have the weaker steric repulsions. But if such transition states involving weak and quite similar steric repulsions are considered, it appears clearly that no or very low asymmetric induction should result. On the contrary, in each pair P_1–P_3 and P_2–P_4 of the planar transition states, the small and the large groups of the sulfide lie, respectively, on the opposite sides of the oxaziridine ring. In these pairs the pro-(*S*) and the pro-(*R*) geometries involve clearly distinct steric interactions. The pro-(*S*) P_1 and the pro-(*R*) P_3 arrangements are clearly sterically more favorable since the sulfur substituents are on the less hindered side of the oxaziridine. However, P_1 and P_3 differ from each other regarding the relative position of the sulfide-methyl group and the upper oxaziridine naphthyl group, with less steric hindrance in the case of P_1. From this analysis, the (*S*) sulfoxide should be formed predominantly, which is in agreement with the experimental results and the absolute configuration observed with *tert*-butyl methyl sulfide and *n*-butyl methyl sulfide. Following this hypothesis, increasing the size of the naphthyl substituents of the oxaziridine (substitution of a hydrogen atom by a phenyl group) should not influence the facial selectivity. This was indeed observed as ee's did not significantly increase (63%, 14% to 60%, 20%) in going from oxaziridine (*S*)-**1** to oxaziridine (*S*)-**2** (Table 3, entries 1, 2 and Table 4, entries 1, 3).

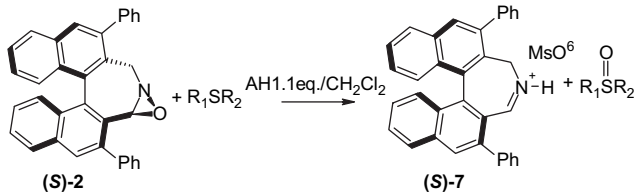
It should be noted that the quite high level of asymmetric induction observed in the absence of acid (Table 2, entry 8) results probably from a slight different topology of the transition state due to the geometry of the oxaziridine core, which should differ from the corresponding protonated form.

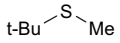
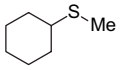
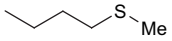
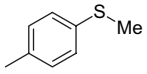
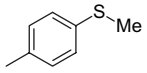
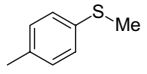
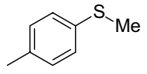
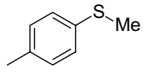
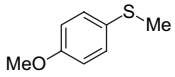
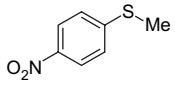
The opposite absolute configuration of the aryl-alkyl sulfoxides (*R*) obtained and the drop in the enantioselectivity of the oxygen transfer observed as the *para* substituent of the phenyl group is a weak electron donor may be rationalized considering electronic interactions. As the binaphthyl aromatic ring of (*S*)-**1** and (*S*)-**2** is electron-demanding while *p*-tolyl and *p*-anisyl are more electron rich, it may be thought that donor–acceptor interaction should favor the pro-(*R*) P_3 and the pro-(*S*) S_2 geometries over the other possible arrangements. Thus, considering steric interactions, the preference for the planar pro-(*R*) arrangement leading to (*R*) sulfoxides is obvious as the sulfide-methyl group lies on the unhindered side of the oxaziridine ring and should have the weaker steric repulsions. In this context, the better enantioselectivity observed for the sulfoxidation of electron-rich aryl-alkyl sulfides using (*S*)-**2** as compared to (*S*)-**1** is quite surprising. This hypothesis was reinforced by MsOH-promoted oxygen-atom transfers performed on *p*-tolyl-methyl sulfide using (*S*)-**1** and (*S*)-**2** in toluene at −78 °C,



Scheme 6. Hypothetical transition states involved in the enantioselective oxidation of sulfides by oxaziridines (*S*)-**1** and (*S*)-**2** in the presence of 1 equiv of strong acid.

Table 4. Oxidation of sulfides with (*S*)-**2**



Entry	Sulfide	Acid	Temperature (°C)	Time[a]	Conversion[b] (yield[c] %)	ee[d] (%) absolute configuration[e]
1		MsOH	−100	<5 min	100% (71)	63 (*S*)
2		MsOH	−100	<5 min	100% (66)	10[f]
3		MsOH	−100	<5 min	100% (61)	20 (*S*)
4		CF_3COOH	20	<1 min	100% (78)	20 (*R*)
5		CF_3COOH	−78	3 h 30 min	100% (77)	62 (*R*)
6		MsOH	20	<1 min	100% (77)	22 (*R*)
7		MsOH	−78	<1 min	100% (80)	68 (*R*)
8		MsOH	−100	<5 min	100% (76)	71 (*R*)
9		MsOH	−100	<5 min	100% (68)	72 (*R*)
10		MsOH	−100	<5 min	100% (62)	<5 (*R*)

[a] Potassium iodide test negative.
[b] Calculated using triphenylmethane as an internal standard.
[c] Sulfoxides isolated by preparative TLC.
[d] Ee's were determined by ^1H NMR spectroscopy using (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide[19] as a chiral shift reagent.
[e] Determined by polarimetry.
[f] Enantiomeric excess too low to allow a precise determination of the absolute configuration.

which give respectively the (*R*)-*p*-tolyl methyl sulfoxide as major enantiomer with only 26% and 34% ee (instead of 47% and 68% when the reaction was performed in CH_2Cl_2).

4. Conclusion

In conclusion, two enantiomerically pure binaphthyl-based oxaziridines have been prepared. Asymmetric acid-promoted oxidation of dialkyl or aryl-alkyl sulfides by these oxaziridines gave good yields of the corresponding sulfoxides with enantioselectivities ranging from 20% to 80%. Enantiomerically pure imines resulting from the oxygen transfer are generally recovered (90%) and can be reused for the preparation of the corresponding oxaziridines for further asymmetric sulfoxidations. A planar transition state geometry is consistent with the observed stereochemical course of the reactions with both steric or stereoelectronic interactions controlling the approach of the reactants.

5. Experimental section

5.1. General

Reagents and solvents (reagent grade) were used without further purification. THF was distilled over sodium benzophenone ketyl. Dichloromethane was distilled over CaH_2. Column chromatography: silica gel 60 (230–400 mesh, 0.040–0.063 mm) was purchased from E. Merck. Thin layer chromatography (TLC) was performed on glass sheets coated with silica gel 60 F_{254} (otherwise stated) purchased from E. Merck, visualization by UV light or stained with Draggendorf reagent. IR (cm^{-1}) measurements were performed using Universal ATR sampling accessories. The presence of oxaziridine species in the reaction mixtures was determined by potassium iodide test. All sulfides were commercially available. NMR spectra (^1H and ^{13}C) were recorded on a 200 or 300 or 400 MHz. Chemical shifts are reported in parts per million relative to the central $CHCl_3$ resonance (δ=7.16 ppm) in ^1H NMR spectra, and

(δ=7.77 ppm) in ^{13}C NMR spectra. Data reported as follows: s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet, br s=broad singlet; integration; coupling constant(s) in hertz. Enantiomeric excesses (ee's) of sulfoxides were determined by ^{1}H NMR (400 MHz) using (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide[17] as a chiral shift reagent versus racemic compounds resulting from peracidic (*m*-CPBA) oxidation. Optical rotations were measured on a polarimeter with a sodium lamp and are reported as follows: $[\alpha]_D^{\circ T}$ (*c* g/100 mL, solvent). The mass spectrum was performed at 70 eV, mass range 35–400. Azepine **3** and dibromide **4** were synthetized following a known procedure.[16]

5.2. Synthesis of oxaziridine (*S*)-1

5.2.1. (*S*)-1*H*-Dinaphtho[2,1-*c*:1′,2′-*e*]azepine 6. Small portions of an aqueous solution of NaOCl at 15 °C were added to a solution of amine (*S*)-**3** (450 mg, 1.52 mmol) in dichloromethane (6 mL) until disappearance of the starting amine and the quantitative formation of chloramine. The organic phase was treated at 0 °C under stirring, with 1 M sodium hydroxide in methanol until disappearance of chloramine. The aqueous phase was extracted with dichloromethane and the organic phases were combined and dried with magnesium sulfate. Removal of the solvent left an oil, which was purified by chromatography (silica gel, dichloromethane) to give 394 mg of pure imine (*S*)-**6** (white foam). Yield 89%.

R_f(CH_2Cl_2/NH_4OH): 0.4; mp 144.5–146 °C; $[\alpha]_D^{20}$ +238.5 (*c* 10, CH_2Cl_2); IR (neat) 1613.2 cm^{-1} (ν C=N); ^{1}H NMR (200 MHz, $CDCl_3$): δ 8.58–8.57 (d, 1H, J_1=2.15 Hz, Ar-C*H*=N), 8.02–7.1 (m, 12H, Ar-H), 5.01–4.95 (d, 1H, J_2=10.74 Hz, Ar-CH_2N), 3.98–3.91 (dd, 1H, J_1=2.15 Hz, J_2=10.74 Hz, Ar-CH_2N); ^{13}C NMR (75 MHz, $CDCl_3$): δ 162.4 (*C*=N), 141.0, 136.9, 133.1, 132.9, 132.3, 131.7, 129.2, 128.9, 128.5, 128.2, 128.0, 127.1, 126.3, 126.0, 125.8, 125.3, 124.3, 56.0 (Ar-*C*H_2N). Anal. Calcd for $C_{22}H_{15}N$: C, 90.07; H, 5.15; N, 4.77. Found: C, 89.43; H, 5.27; N, 4.75.

5.2.2. (*S*)-1*H*-1,2-Oxydo-dinaphtho[2,1-*c*:1′,2′-*e*]azepine 1. *m*-Chloroperbenzoic acid (230 mg, 1.5 mmol, 1.1 equiv of active oxygen) was added in small portions at 0 °C to a solution of imine **6** (364 mg, 1.24 mmol, 1 equiv) in 3 mL of dichloromethane and 15 mL of methanol. After completion of the addition, sodium hydrogen carbonate (104 mg, 1 equiv) was added and the reaction was left until complete disappearance of the imine. The reaction mixture was diluted with dichloromethane, washed with a saturated solution of sodium thiosulfate, sodium hydrogen carbonate, and finally with brine. The collected organic phases were dried with magnesium sulfate, filtered, and concentrated. The resulting yellow foam was purified by flash chromatography (dichloromethane) to give pure oxaziridine (*S*)-**1** as an amorphous solid (307 mg, 80%).

R_f (CH_2Cl_2): 0.65; mp: 132–134 °C. MS (ESI positive): 309.1 [M$^+$]. MS (EI +Q1MS): 309.0 (M$^{+\bullet}$, 100%), 293.2 [(M$^{+\bullet}$ –O), 69%], 310 [(M$^{+\bullet}$+1), 26%];^{1}H NMR (200 MHz, $CDCl_3$): δ 8.1–7.1 (m, 12H, Ar-H), 5.17 (s, 1H, Ar-C*H*(O)N), 4.63–4.55 (d, 1H, *J*=12.2 Hz, Ar-CH_2N), 3.94–3.88 (d, 1H, *J*=11.88 Hz, Ar-CH_2N); ^{13}C NMR (75 MHz, $CDCl_3$): δ 134.6, 130.3, 129.7, 129.2, 129.9, 128.6, 128.5, 128.2, 128.1, 128.1, 128.0, 127.7, 127.5, 127.3, 126.9, 126.8, 126.3, 125.9, 125.7, 124.7, 80.3 (Ar-*C*H(O)N), 56.26 (Ar-*C*H_2N); $[\alpha]_D^{20}$ +601 (*c* 0.5, CH_2Cl_2).

5.2.3. (*S*)-4,15-Diphenyl-2,3-dihydro-1*H*-dinaphtho[2,1-*c*;1′,2′-*e*]azepine 5. (*S*)-*3,3′-Diphenyl-3,5-dihydro-1H-(3-propenyl)dinaphth[2,1-c;1′,2′-e]azepine*. To a degassed acetonitrile solution (25 mL) of (*S*)-(−)-2,2′-bis(bromomethyl)-1,1′-binaphthyl **4** (5.56 g, 12.6 mmol, 1 equiv) was added (2.9 mL, 3 equiv) of allylamine at room temperature and under argon. The reaction mixture was heated at 55 °C for 5 h but remained heterogeneous. The reaction mixture was brought to room temperature, poured into a saturated solution of sodium hydrogen carbonate. After extraction with dichloromethane, the collected organic phases were dried over magnesium sulfate, filtered, and concentrated. The resulting oil was purified by flash chromatography (gradient CH_2Cl_2–CH_2Cl_2/MeOH 30:1) to yield 4.9 g of a white solid (96%).

R_f(CH_2Cl_2): 0.25; MS (ESI positive): 487.2 [M$^+$], calculated 487.6; ^{1}H NMR (200 MHz, $CDCl_3$):δ 7.99–7.95 (m, 4H, Ar-H), 7.66–7.63 (d, 4H, 6.18 Hz, Ar-H), 7.51–7.26 (m, 12H, Ar-H), 5.58–5.47 (m, 1H, C*H*=CH_2), 4.76–4.71 (d, 1H, 10.2 Hz, *cis*-CH=CH_2), 4.61–4.52 (d, 1H, 17.18 Hz, *trans*-CH=CH_2), 4.02–3.96 (d, 2H, 12.36 Hz, Ar-CH_2), 3.12–3.05 (d, 2H, 12.62 Hz, Ar-CH_2), 2.76–2.45 (m, 2H, NCH_2C=C); ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.3, 141.3, 137.3, 136.8, 133.5, 132.6, 131.6, 131.0, 130.2, 129.2, 129.0, 128.5, 127.9, 126.7, 126.5, 116.8, 56.07, 51.03.

Under nitrogen atmosphere, a degassed dichloromethane solution (30 mL) of -(*S*)-3,3′-diphenyl-3,5-dihydro-1*H*-(3-propenyl)-dinaphth[2,1-*c*;1′,2′-*e*]azepine (3 g, 6.15 mmol, 1 equiv), *N*,*N*-dimethylbarbituric acid (2.88 g, 18.46 mmol, 3 equiv), $Pd(OAc)_2$ (83 mg, 0.123 mmol, 2 mol %), and PPh_3 (141 mg, 0.54 mmol, 4.3 equiv/$Pd(OAc)_2$) was stirred overnight at 35 °C. The reaction mixture was poured into a saturated hydrogen carbonate solution and extracted three times with dichloromethane. The collected organic phases were dried with magnesium sulfate, filtered, and concentrated in vacuo to yield a brown oil, which was purified on silica gel using (CH_2Cl_2/MeOH from 50:1 to 20:1) as an eluent and gave a white foam (74%).

$[\alpha]_D^{20}$ +248.4 (*c* 0.5, $CHCl_3$); MS (ESI positive): 447.2 [M] $C_{34}H_{25}N$, calculated 447.54; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.97–7.95 (m, 4H), 7.63–7.60 (m, 4H), 7.51–7.40 (m, 8H), 7.33–7.27 (m, 4H), 4.06–4.02 (d, 2H, 12.63 Hz), 3.42–3.38 (d, 2H, 12.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$): δ 141.17, 139.81, 136.07, 132.57, 130.83, 129.72, 128.30, 128.22, 127.52, 127.21, 125.91, 125.79, 44.35 (C2, C2′).

5.2.4. (*S*)-4,15-Diphenyl-1*H*-dinaphtho[2,1-*c*:1′,2′-*e*]azepine 7. Small portions of aqueous NaOCl were added at 15 °C to a solution of amine (*S*)-**5** (600 mg, 1.34 mmol) in dichloromethane (8 mL) until disappearance of the starting reagent and the quantitative formation of chloramine. The phases were separated, and the organic phase was added dropwise at 0 °C under stirring to a sodium hydroxide solution in methanol (NaOH=1 g; MeOH=18 mL). The

biphasic mixture was stirred until disappearance of chloramine after adding more NaOH if necessary. The aqueous phase was extracted with dichloromethane and the collected organic phases were dried with magnesium sulfate, filtered, and concentrated. The resulting oil was purified by chromatography on silica gel (dichloromethane) to give 530 mg of pure imine (*S*)-**7** as a pale yellow foam. Yield 90%.

Mp 145–146 °C; $[\alpha]_D^{20}$ +338 (*c* 0.5, CH_2Cl_2); IR (neat) 1605.61 cm^{-1} (ν C=N); ^1H NMR (300 MHz, $CDCl_3$): δ 8.39–8.38 (d, 1H, J_1=2.28 Hz, Ar-C*H*=N), 8.0–7.09 (m, 20H, Ar-H), 5.21–5.18 (d, 1H, J_2=10.35 Hz, Ar-CH_2N), 3.89–3.84 (dd, 1H, J_1=2.28 Hz, J_2=10.35 Hz, Ar-CH_2N); ^{13}C NMR (75 MHz, $CDCl_3$): δ 161.2 (*C*=N), 140.34, 138.81, 137.43, 136.9, 132.08, 131.7, 130.88, 130.56, 129.97, 129.4, 129.3, 129.2, 129.17, 128.9, 128.69, 127.86, 127.77, 127.73, 127.68, 127.29, 127.2, 127.01, 126.83, 125.64, 125.24, 125.11, 51.37 (Ar-*C*H_2N). Anal. Calcd for $C_{34}H_{23}N$: C, 91.65; H, 5.20; N, 3.14. Found: C, 91.08; H, 5.36; N, 2.98.

5.2.5. (*S*)-1*H*-1,2-Oxydo-4,15-diphenyl-dinaphtho[2,1-*c*:1′,2′-*e*]azepine 2. Imine **7** (500 mg, 1.12 mmol, 1 equiv) was dissolved in a mixture of 6 mL of dichloromethane and 20 mL of methanol. The resulting solution was cooled to 0 °C, and *m*-chloroperbenzoic acid (260 mg, 1.5 mmol, 1.1 equiv of active oxygen) was added in small portions. When the addition was complete, sodium hydrogen carbonate (103 mg, 1.1 equiv) was added. The reaction was followed by TLC until complete disappearance of the imine. The reaction mixture was diluted with dichloromethane, washed with a saturated solution of sodium thiosulfate, sodium hydrogen carbonate, and finally with brine. The collected organic phases were dried with magnesium sulfate, filtered, and concentrated. The resulting white foam was purified by flash chromatography (dichloromethane) to give pure oxaziridine (*S*)-**2** as an amorphous solid (410 mg, 79%).

Mp 134–136 °C; IR (CH_2Cl_2, cm^{-1}) 1698 (N–O), 1264 (C–O), 754 (C–N); ^1H NMR (300 MHz, $CDCl_3$) δ 8.0–7.1 (m, 20H, Ar-H), 5.37 (s, 1H, Ar-C*H*(O)N), 4.83–4.79 (d, 1H, *J*=12 Hz, Ar-CH_2N), 3.77–3.71 (d, 1H, *J*=12 Hz, Ar-CH_2N); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.6–125.7 ($C_{arom.}$), 77.3 (Ar-*C*H(O)N), 51.6 (Ar-*C*H_2N); SM (HR): *m*/*z* found 461.2, for $C_{34}H_{23}NO$ *m*/*z* calculated 461.1780. MS (EI +Q1MS): 461.2 ($M^{+\bullet}$, 100%), 445.2 [($M^{+\bullet}$ –O, 81%], 430.2 [($M^{+\bullet}$ –CH_2OH), 48%], 462.2 [($M^{+\bullet}$+1), 40%], 418.2 [($M^{+\bullet}$ –CH_2CHOH), 28%]; $[\alpha]_D^{20}$ +592.2 (*c* 0.5, CH_2Cl_2).

5.2.6. (*S*)-1,1-Dinaphtalene-2,2′-dicarboxaldehyde 9.[20] R_f (CH_2Cl_2): 0.48; ^1H NMR (300 MHz, $CDCl_3$): δ 9.62 (d, 2H, *J*=1 Hz, CHO); 8.23–7.25 (m, 12H, Ar-H). ^{13}C NMR (50 MHz, $CDCl_3$): δ 191.1 (CO); 140–121; SM (Cl/CH_4-NO_2)=310.0 ($M^{+\bullet}$, 100%); 311.4 ($M^{+\bullet}$+1, 12%); IR (CH_2Cl_2, cm^{-1}): 3060, 2932, 2852.

5.3. Standard conditions for sulfoxidations using oxaziridines (*S*)-1 and (*S*)-2

Into a 5 mL, round-bottomed flask equipped with magnetic stir bar and argon inlet was placed 0.5 mmol of oxaziridine (*S*)-**1** or (*S*)-**2** dissolved in 6 mL of dichloromethane. To this mixture was added an equimolar amount of sulfides. The mixture was stirred for 15 min at rt, −20 °C, −78 °C or −100 °C and 1.1 equiv of the selected acid (CF_3COOH, $MeSO_3H$, AcOH) was rapidly added. The reaction was monitored by TLC until complete disappearance of starting materiel (sulfide). Dichloromethane (20 mL) was then added and the mixture was transferred to a separating funnel. The organic layer was washed with water and brine, dried over $MgSO_4$, and evaporated in vacuo. Separation of the imine and sulfoxide was achieved by preparative TLC (silica gel).

The ee's were determined by ^1H NMR in $CDCl_3$ for the purified products as follows: 0.5–2 equiv of (*R*)-(−)-(3,5-dinitrobenzoyl)-α-phenylethylamide was added by small portions until a good splitting of the CH_3 singlet (between 2.7 and 2.9 ppm) was obtained.[19] The ee was calculated from the deconvolution of these two peaks.

Absolution configurations of the major sulfoxides were determined by comparison of the sign of specific rotation with the literature data.[23]

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