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Articles

Catalytic Asymmetric Oxidation of Sulfides to Sulfoxides with *tert*-Butyl Hydroperoxide Using Binaphthol as a Chiral Auxiliary

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The asymmetric oxidation of sulfides to chiral sulfoxides in moderate yield with *tert*-butyl hydroperoxide (TBHP) was catalyzed very effectively by a titanium complex produced *in situ* from a titanium alkoxide and a chiral binaphthol. The highest enantioselectivities (up to 96% ee) were obtained with commercial aqueous 70% TBHP under atmospheric conditions at 25 °C with 2.5 mol % of the catalyst. The presence of more than 1.0 mol equiv of water relative to sulfide was essential for the oxidation, and it was found that the water was necessary not only to produce an effective catalyst for the highly enantioselective oxidation but also to maintain the catalytic activity of the titanium–binaphthol complex for a longer time. The nature of the solvent had a remarkable effect upon the ee of the sulfoxide. Carbon tetrachloride was proven to be the solvent of choice; the use of other chlorinated solvents resulted in low enantioselectivity. A moderate level of asymmetric amplification was observed in this catalytic system. From a mechanistic standpoint, it was revealed that the initial asymmetric oxidation to the chiral sulfoxide (~50% ee) is followed by the kinetic resolution of the sulfoxide; that is, the titanium–binaphthol complex catalyzes not only the asymmetric oxidation but also the subsequent kinetic resolution.

Introduction

Because chiral sulfoxides are useful chiral synthons,[1] their preparation has been studied for many years and is still of great interest. The following two types of procedures have been most commonly employed for the preparation of chiral sulfoxides: (1) the optical resolution of diastereomeric sulfinates or their analogues and (2) the direct asymmetric oxidation of prochiral sulfides to sulfoxides.

The former procedure is represented by the Andersen synthesis,[2] in which organometallic reagents are allowed to react with resolved diastereomeric sulfinates to give chiral sulfoxides. Althought this traditional procedure has been limited by the number of applicable compounds, improved Andersen procedures have been used recently to accomplish the almost completely asymmetric syntheses of various kinds of sulfoxides from diastereomeric sulfites,[1e,3] sulfinyloxazolidinones,[4] and sulfinates of diacetone-D-glucose.[5]

The latter procedure is very attractive for the preparation of sulfoxides with high ee because of its simplicity; however, the applicable sulfides are still limited mainly to alkyl aryl sulfides. Two approaches were reported recently: (1) a modified Sharpless oxidation of sulfides reported by Kagan, which uses diethyl tartrate (DET)/$Ti(O\text{-}i\text{-}Pr)_4/H_2O$/*tert*-butyl hydroperoxide (TBHP),[1e,6] and (2) Davis oxidation of sulfides using chiral oxaziridine derivatives[7] with a camphor skeleton.[8] Both reactions, however, are stoichiometric. Attempted asymmetric oxidation with a catalytic amount of the titanium complex resulted in a slower reaction with diminished enantioselectivity.[6b,9]

Herein, we describe a catalytic asymmetric oxidation of sulfides to sulfoxides with excellent enantioselectivity (up to 96% ee) by means of a facile synthetic procedure using a chiral binaphthol as an effective chiral auxiliary.[10] Because of the extraordinary chiral recognition properties of binaphthyl derivatives,[11] they have recently been used

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(1) For excellent reviews on the synthesis and application of chiral sulfoxides, see: (a) Andersen, K. K. In *The Chemistry of Sulfones and Sulfoxides*; Patai, S., Rappoport, Z., Stirling, C. J. M., Eds.; John Wiley & Sons, Ltd.: Chichester, England, 1988; Chapter 3, pp 55–94. (b) Posner, G. H. In *The Chemistry of Sulfones and Sulfoxides*; Patai, S., Rappoport, Z., Stirling, C. J. M., Eds.; John Wiley & Sons, Ltd.: Chichester, England, 1988; Chapter 16, pp 823–849. (c) Posner, G. H. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: New York, 1983; Vol. 2, Chapter 8, pp 225–241. (d) Barbachyn, M. R.; Johnson, C. R. In *Asymmetric Synthesis*; Morrison, J. D., Scott, J. W., Eds.; Academic Press: New York, 1984; Vol. 4, Chapter 2, pp 227–261. (e) Kagan, H. B.; Rebiere, F. *Synlett* **1990**, 643. (f) Posner, G. H. *Acc. Chem. Res.* **1987**, *20*, 72. (g) Mikolajczyk, M.; Drabowicz, J. *Top. Stereochem.* **1982**, *13*, 333. (h) Solladié, G. *Synthesis* **1981**, 185.

(2) (a) Andersen, K. K. *Tetrahedron Lett.* **1962**, *3*, 93. (b) Andersen, K. K.; Gaffield, W.; Papanikolaou, N. E.; Foley, J. W.; Perkins, R. I. *J. Am. Chem. Soc.* **1964**, *86*, 5637.

(3) (a) Rebiere, F.; Kagan, H. B. *Tetrahedron Lett.* **1989**, *30*, 3659. (b) Rebiere, F.; Samuel, O.; Richard, L.; Kagan, H. B. *J. Org. Chem.* **1991**, *56*, 5991.

(4) Evans, D. A.; Faul, M. M.; Colombo, L.; Bisaha, J. J.; Clardy, J.; Cherry, D. *J. Am. Chem. Soc.* **1992**, *114*, 5977.

(5) Ferández, I.; Khiar, N.; Llera, J. M.; Alcudia, F. *J. Org. Chem.* **1992**, *57*, 6789.

(6) (a) Zhao, S. H.; Samuel, O.; Kagan, H. B. *Org. Synth.* **1989**, *68*, 49. (b) Zhao, S. H.; Samuel, O.; Kagan, H. B. *Tetrahedron* **1987**, *43*, 5135. (c) Kagan, H. B.; Duñach, E.; Nemecck, C.; Pitchen, P.; Samuel, O.; Zhao, S. H. *Pure Appl. Chem.* **1985**, *57*, 1911. (d) Duñach, E.; Kagan, H. B. *Nouv. J. Chim.* **1985**, *9*, 1. (e) Pitchen, P.; Duñach, E.; Deshmukh, M. N.; Kagan, H. B. *J. Am. Chem. Soc.* **1984**, *106*, 8188. (f) Pitchen, P.; Kagan, H. B. *Tetrahedron Lett.* **1984**, *25*, 1049.

(7) For a review, see: Davis, F. A.; Sheppard, A. C. *Tetrahedron* **1989**, *45*, 5703.

(8) (a) Davis, F. A.; Reddy, R. T.; Han, W.; Carroll, P. J. *J. Am. Chem. Soc.* **1992**, *114*, 1428. (b) Davis, F. A.; Reddy, R. T.; Weismiller, M. C. *J. Am. Chem. Soc.* **1989**, *111*, 5964.

(9) Nakajima, K.; Sasaki, C.; Kojima, M.; Aoyama, T.; Ohba, S.; Saito, Y.; Fujita, J. *Chem. Lett.* **1987**, 2189.

(10) Preliminary communication: Komatsu, N.; Nishibayashi, Y.; Sugita, T.; Uemura, S. *Tetrahedron Lett.* **1992**, *33*, 5391.

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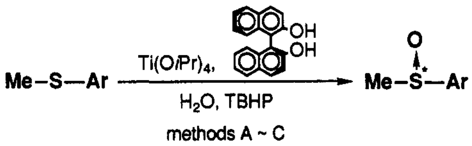
Scheme I



for several catalytic asymmetric C–C bond forming reactions such as the aldol,[11a,12] Diels–Alder,[11a,13] and ene reactions,[14] but there have been no successful examples of the application of these compounds to asymmetric oxidation.[15]

Results and Discussion

The following three methods (A–C) were employed in our catalytic asymmetric oxidation (Scheme I): method A, a sulfide (0.50 mmol) and then 2.0 mol equiv of a TBHP toluene solution[16] were added to the standard catalytic system ((*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H$_2$O = 0.20/0.10/2.0 mol equiv relative to the sulfide) under an argon atmosphere at 0 to 20 °C; method B, 70% aqueous TBHP was used (instead of the TBHP toluene solution used in method A) under aerial conditions at 0 °C; and method C, a smaller amount of catalyst ((*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H$_2$O = 0.050/0.025/0.50 mol equiv relative to the sulfide) was employed instead of the standard catalytic system used in method B at 25 °C. After an appropriate reaction time, the mixture was directly submitted to either column chromatography on silica gel or preparative TLC to isolate the produced sulfoxide. The ee values and the configurations of the sulfoxides were determined by HPLC on a Daicel Chiralcel OB column and by optical rotation,[6e] respectively. Typical results and reaction conditions are summarized in Table I.

The enantioselectivities obtained with 70% aqueous TBHP (methods B and C, runs 2–5) were higher than those obtained with the TBHP toluene solution (method A, run 1), and the ee's were higher under aerial conditions (run 2) than under an argon atmosphere (run 3). The smaller amount (2.5 or 5.0 mol %) of catalyst (method C, runs 4 and 5) gave the highest enantioselectivities. That is, method C was revealed to be the method of choice for this catalytic asymmetric oxidation.

As far as the substrate is concerned, all the alkyl aryl sulfides afforded satisfactory enantioselectivities (80–96% ee) with both methods B and C, but the selectivity was unsatisfactory for a dialkyl sulfide (69% ee, run 23).

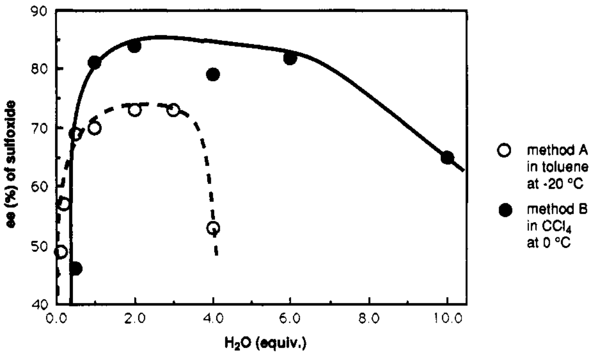


Figure 1. Effect of water on the asymmetric oxidation of methyl *p*-tolyl sulfide: method A, in toluene at −20 °C (– –); method B, in CCl$_4$ at 0 °C (—).

The Effect of Solvent. The nature of the solvent was revealed to have a remarkable effect upon the ee and the chemical yield. Of the chlorinated solvents (runs 1 and 6–8), CCl$_4$ gave high ee values and moderate chemical yields, but CH$_2$Cl$_2$, which is usually a good solvent for Sharpless type reactions,[6,16,17] CHCl$_3$, and ClCH$_2$CH$_2$Cl gave low ee values and high chemical yields. The reactions run in aromatic solvents gave slightly lower selectivities than those in CCl$_4$, but the yields in aromatic solvents were comparable to those in CCl$_4$ (runs 9–11). In ether solvents, the stereoselectivities were similar to those in the aromatic solvents, but the chemical yields were lower in the ether solvents (runs 12 and 13). These results revealed that nonpolar solvents were generally suitable for this catalytic reaction, and CCl$_4$, in particular, was proven to be the solvent of choice.

The Effect of Water (Figure 1). Figure 1 illustrates the correlation between the ee value of the methyl *p*-tolyl sulfoxide and the amount of added water for method B at 0 °C in CCl$_4$ and for method A at −20 °C in toluene. High ee values were maintained over a range of 1.0–6.0 mol equiv of water in CCl$_4$ and 0.5–3.0 mol equiv of water in toluene. In contrast to the case of the modified Sharpless oxidation,[6e] our catalytic oxidation tolerates a wide range of amounts of water, including large amounts of water, and still maintains the high enantioselectivity. This water tolerance allows the direct injection of 70% aqueous TBHP (methods B and C), 0.15 mL of which contains 5.7 mol equiv of water relative to the sulfide. Because 1.0–6.0 and 0.5–3.0 mol equiv of water relative to the sulfide correspond to 10–60 and 5–30 mol equiv relative to the catalyst, respectively, it is apparent that a large excess of water relative to the catalyst is required for obtaining a high ee.

Positive Nonlinear Effect (Figure 2).[18] Figure 2 illustrates the asymmetric amplification observed for method A in CCl$_4$ at −20 °C and method B in CCl$_4$ at 0

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(11) For example: (a) Reetz, M. T.; Kyung, S.-H.; Bolm, C.; Zierke, T. *Chem. Ind.* **1986**, 824. (b) Naruse, Y.; Esaki, T.; Yamamoto, H. *Tetrahedron Lett.* **1988**, *29*, 1417. (c) Seebach, D.; Beck, A. K.; Roggo, S.; Wonnacott, A. *Chem. Ber.* **1985**, *118*, 3673. (d) Maruoka, K.; Yamamoto, H. *Synlett* **1991**, 793.

(12) Mukaiyama, T.; Inubushi, A.; Suda, S.; Hara, R.; Kobayashi, S. *Chem. Lett.* **1990**, 1015.

(13) (a) Seebach, D.; Beck, A. K.; Imwinkelried, R.; Roggo, S.; Wonnacott, A. *Helv. Chem. Acta* **1987**, *70*, 954. (b) Chapuis, C.; Jurczarc, J. *Ibid.* **1987**, *70*, 436. (c) Maruoka, K.; Itoh, T.; Shirasaka, T.; Yamamoto, H. *J. Am. Chem. Soc.* **1988**, *110*, 310. (d) Kelly, T. R.; Whiting, A.; Chandrakumar, N. S. *J. Am. Chem. Soc.* **1986**, *108*, 3510.

(14) (a) Sakane, S.; Maruoka, K.; Yamamoto, H. *Tetrahedron Lett.* **1985**, *26*, 5535; *Tetrahedron* **1986**, *42*, 2203. (b) Maruoka, K.; Hoshino, Y.; Shirasaka, T.; Yamamoto, H. *Tetrahedron Lett.* **1988**, *29*, 3967. (c) Mikami, K.; Terada, M.; Nakai, T. *J. Am. Chem. Soc.* **1990**, *112*, 3949; *Ibid.* **1989**, *111*, 1940. (d) Terada, M.; Mikami, K.; Nakai, T. *J. Chem. Soc., Chem. Commun.* **1990**, 1623. (e) Mikami, K.; Sawa, E.; Terada, M. *Tetrahedron: Asymmetry* **1991**, *2*, 1403.

(15) Finn, M. G. and Sharpless, K. B. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: New York, 1985; Vol. 5, Chapter 8, pp 247–308.

(16) (a) Gao, Y.; Hanson, R. M.; Klunder, J. M.; Ko, S. Y.; Masamune, H.; Sharpless, K. B. *J. Am. Chem. Soc.* **1987**, *109*, 5765. (b) Hanson, R. M.; Sharpless, K. B. *J. Org. Chem.* **1986**, *51*, 1922.

(17) (a) Katsuki, T.; Sharpless, K. B. *J. Am. Chem. Soc.* **1980**, *102*, 5976. (b) Hill, J. G.; Sharpless, K. B.; Exon, C. M.; Regenye, R. *Org. Synth.* **1984**, *63*, 66.

(18) (a) Puchot, C.; Samuel, O.; Duñach, E.; Zhao, S. H.; Agami, C.; Kagan, H. B. *J. Am. Chem. Soc.* **1986**, *108*, 2353. (b) Oguni, N.; Matsuda, Y.; Kaneko, T. *J. Am. Chem. Soc.* **1988**, *110*, 7877. (c) Noyori, R.; Kitamura, M. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 49. (d) Kitamura, M.; Okada, S.; Suga, S.; Noyori, R. *J. Am. Chem. Soc.* **1989**, *111*, 4028. (e) Terada, M.; Mikami, K.; Nakai, T. *J. Chem. Soc., Chem. Commun.* **1990**, 1623. (f) Mikami, K.; Terada, M.; Narisawa, S.; Nakai, T. *Synlett* **1992**, 255.

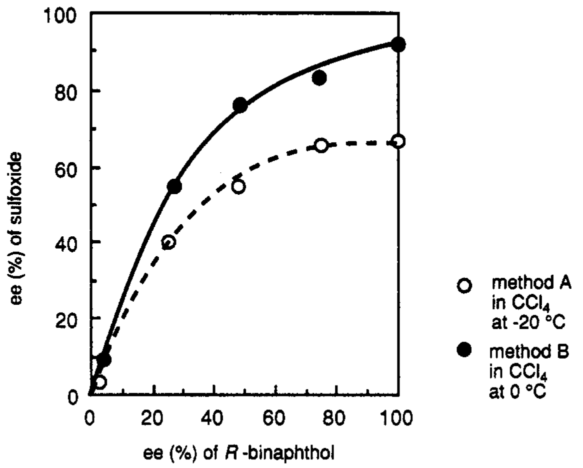


Figure 2. Positive nonlinear effects in the asymmetric oxidation of methyl *p*-tolyl sulfide: method A, in CCl_4 at −20 °C (− −); method B, in CCl_4 at 0 °C (—).

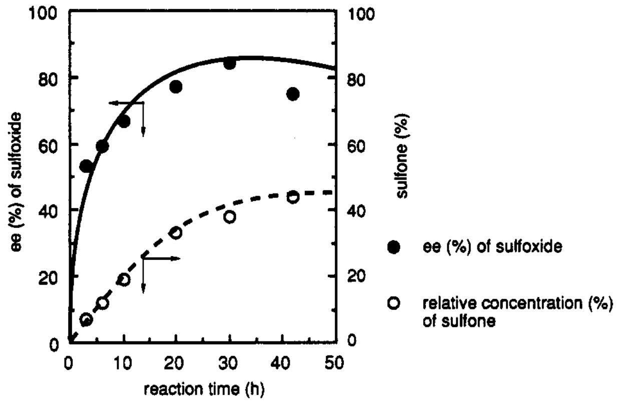


Figure 3. Time course of the ee (%) of the sulfoxide (—) and relative concentration (%) of the sulfone (− −) in method A in CCl_4 at 0 °C.

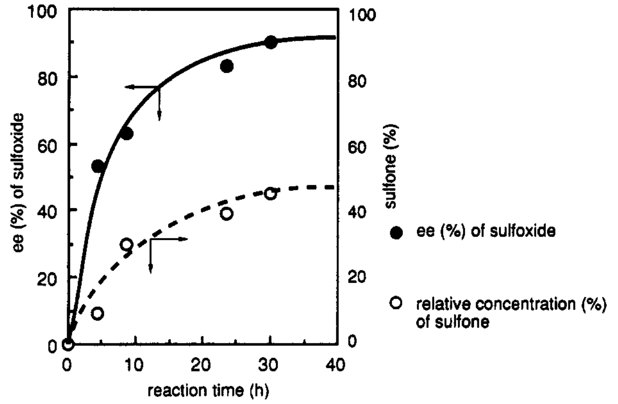


Figure 4. Time course of the ee (%) of the sulfoxide (—) and relative concentration (%) of the sulfone (− −) in method B in CCl_4 at 0 °C.

°C with methyl *p*-tolyl sulfide as the substrate. Under both conditions, the catalytic oxidation system exhibits a high level of asymmetric amplification; that is, the ee value of the produced methyl *p*-tolyl sulfoxide highly exceeds the ee value of the (*R*)-(+)-binaphthol over a wide range. Since a negative nonlinear effect was observed for a modified Sharpless oxidation reported by Kagan,[18a] these results indicate the fundamental difference in the catalyst structure for the modified Sharpless oxidation system (or Kagan system) and our oxidation system.

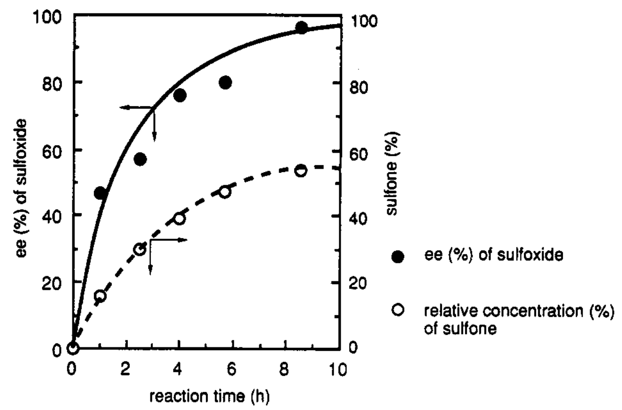
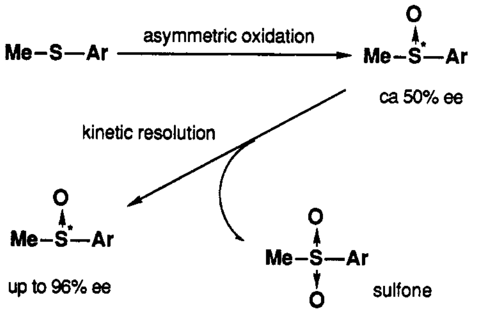
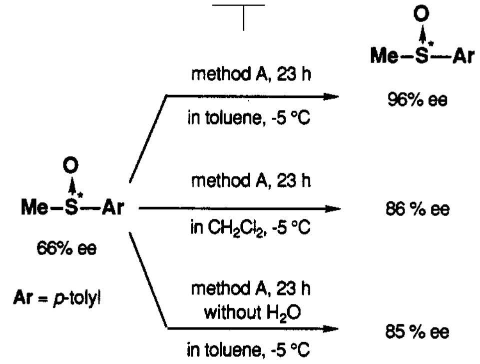


Figure 5. Time course of the ee (%) of the sulfoxide (—) and relative concentration (%) of the sulfone (− −) in method C in CCl_4 at 25 °C.

Scheme II



Scheme III



Time Course of the ee Value and the Mechanism for the High Enantioselectivity (Figures 3–5 and Schemes II and III). The ee of the sulfoxide produced by our oxidation system depends on the reaction time rather than the reaction temperature. Figures 3–5 illustrate the time dependence of the ee values of the methyl *p*-tolyl sulfoxide and the relative concentrations of methyl *p*-tolyl sulfone for the oxidation of methyl *p*-tolyl sulfide in CCl_4 by means of methods A and B at 0 °C and method C at 25 °C. For all three methods, the ee of the sulfoxide as well as the concentration of the sulfone increased as the reaction proceeded. The ~50% ee obtained at the initial stage of the reaction improved over time to 84% for method A, 93% for method B, and 96% for method C, respectively. This fact indicates that kinetic resolution may follow the asymmetric oxidation, thus enhancing the ee of the sulfoxide (Scheme II).[19] In order to confirm that kinetic

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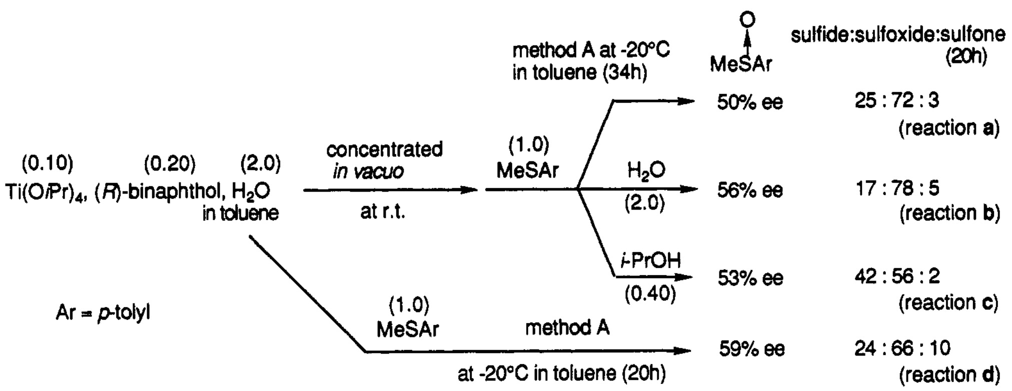
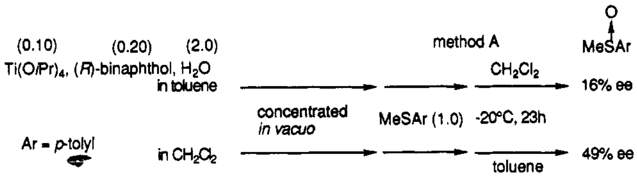
[19] (a) Kagan, H. B.; Fiaud, J. C. *Top. Stereochem.* **1988**, *18*, 249. (b) Sugimoto, T.; Miyazaki, J.; Tanimoto, S.; Okano, M. *Bioorg. Chem.* **1981**, *10*, 311.

Scheme IV



Scheme V



resolution of the produced sulfoxide was occurring under our oxidation conditions, (*R*)-methyl *p*-tolyl sulfoxide of 66% ee was subjected to the following three conditions at −5 °C: method A in toluene, method A in CH_2Cl_2, and method A without water in toluene (Scheme III). The fact that the *R*-isomer was obtained with a higher ee under all the conditions after 23 h confirmed that our oxidation catalyst works as a catalyst for the kinetic resolution of the sulfoxide. Furthermore, the combination of water and toluene was revealed to be the preferred solvent for the kinetic resolution on the basis of the comparison of the three reactions. The asymmetric oxidation of the sulfide gave the chiral (*R*)-sulfoxide in ~50% ee at the initial stage of the reaction, and then selective oxidation of the minor component, the *S*-sulfoxide, to the sulfone resulted in an enhancement of the concentration of the *R*-isomer of the sulfoxide. Thus, the complex derived from $Ti(O\text{-}i\text{-}Pr)_4$ and binaphthol catalyzes the kinetic resolution of sulfoxides as well as the asymmetric oxidation of sulfides.

The Influence of Water, 2-Propanol, and Solvent on the Catalyst (Schemes IV and V). In order to determine the influence of the added water and the 2-propanol generated *in situ*, the reactions shown in Scheme IV were carried out. After the catalyst was prepared by the standard method in toluene, it was dried *in vacuo*, and then dry toluene and methyl *p*-tolyl sulfide were added. With these toluene solutions, three oxidations were carried out at −20 °C. A TBHP toluene solution was added under an argon atmosphere (**a**) without any additive, (**b**) after the addition of 2.0 mol equiv of water, and (**c**) after the addition of 0.40 mol equiv of 2-propanol. The 50–56% ee value obtained was quite similar to that (59% ee) obtained with method A in toluene at −25 °C (reaction **d**). The results of reaction **a** together with the fact that 0.50–3.0 mol equiv of water is necessary to obtain a high ee value (Figure 1) shows that water is required for the preparation of the active catalyst and is not necessarily required for the asymmetric oxidation step. Comparison of the results of reactions **a** and **b** shows that water also plays a role in increasing the oxidation rate, probably by maintaining the activity of the catalyst. In contrast, 2-propanol decreased the oxidation rate (reaction **c**). Thus, water also dissolves the 2-propanol, which may deactivate the catalyst. Since the catalyst in this reaction not only catalyzes the asymmetric oxidation but also catalyzes the subsequent kinetic resolution, it is very important that the catalytic activity is maintained for the latter resolution step so that a highly enantioselective synthesis of the sulfoxide can be achieved. As discussed above, water keeps the catalyst active, and a large ratio of water to catalyst is required for this asymmetric oxidation.

When this reaction was carried out in a solvent different from that used for the catalyst preparation (see Scheme V), it was revealed that the ee of the product depends on the solvent at the oxidation step. When the solvent was changed from toluene to CH_2Cl_2, the ee value was 16%, a value quite similar to that obtained in run 8 of Table I. In contrast, the reverse combination of these solvents gave a 49% ee, which is similar to the value obtained in reaction **a** of Scheme IV.

Experimental Section

General Procedures. HPLC analyses were performed on a HLC-803A instrument (Tosoh) with a UV-8011 detector (Tosoh) and 25% 2-propanol/hexane as an eluent at 40 °C. GLC analyses were performed on a Shimadzu GC-14A (3-mm × 2-m glass column packed with either 10% SE-30 on Chromosorb W or 5% OV-17 on Chromosorb W) with flame-ionization detectors and N_2 as the carrier gas. Optical rotations were measured on a JASCO DIP-360 polarimeter.

Materials. CCl_4 was distilled from $CaCl_2$ and stored over 4-Å molecular sieves under nitrogen. The other chlorinated solvents and the aromatic solvents were distilled from CaH_2 and stored similarly. The ether solvents were distilled from $LiAlH_4$ and stored similarly. A toluene solution of *tert*-butyl hydroperoxide (TBHP) was prepared according to the reported method.[17] The commercially available 70% aqueous TBHP and $Ti(O\text{-}i\text{-}Pr)_4$ were used without any purification. The (*R*)-(+)- and (*S*)-(−)-1,1′-binaphthols were purchased from Wako Chemicals and used without further purification. The methyl 2-naphthyl sulfide was prepared according to the reported method.[20]

The Catalytic Asymmetric Oxidation of Sulfides to Sulfoxides (Methods A–C). The following three procedures, methods A–C, were employed for this catalytic oxidation.

Method A. To a solution of binaphthol (0.10 mmol) in a suitable solvent were introduced $Ti(O\text{-}i\text{-}Pr)_4$ (0.050 mmol) and H_2O (1.0 mmol) by means of a syringe under an argon atmosphere at room temperature. After the resulting brown solution was stirred magnetically at rt for 1 h, the sulfide (0.50 mmol) was introduced by means of a syringe, and the mixture was cooled to the appropriate temperature. After 0.5 h, TBHP in toluene (1.0 mmol) was introduced by means of a syringe, and the mixture was stirred. The reaction mixture was directly submitted to either

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(20) Engman, L.; Hellberg, J. S. E. *J. Organomet. Chem.* **1985**, *296*, 357.

Table I. Catalytic Asymmetric Oxidation of Aryl Methyl Sulfides (ArSMe) to the Corresponding Sulfoxides

run	Ar	solvent	method[a]	reactn condns temp (°C)/time (h)	yield[b] (%)	ee[c] (confign) (%)
1	*p*-tolyl	CCl_4	A	0/30	65	84 (*R*)
2	*p*-tolyl	CCl_4	B	0/30	67	93 (*R*)
3	*p*-tolyl	CCl_4	B[d]	0/30	64	88 (*R*)
4	*p*-tolyl	CCl_4	C	25/9	44	96 (*R*)
5	*p*-tolyl	CCl_4	C[e]	25/7	43	96 (*R*)
6	*p*-tolyl	$CHCl_3$	A	−20/19	74	23 (*R*)
7	*p*-tolyl	CH_2Cl_2	A	−20/19	84	16 (*R*)
8	*p*-tolyl	$ClCH_2CH_2Cl$	A	−20/28	86	25 (*R*)
9	*p*-tolyl	toluene	A	0/31	66	72 (*R*)
10	*p*-tolyl	*o*-xylene	A	−20/48	88	61 (*R*)
11	*p*-tolyl	cumene	A	−20/48	86	57 (*R*)
12	*p*-tolyl	THF	A	−20/71	46	72 (*R*)
13	*p*-tolyl	diethyl ether	A	−20/71	32	57 (*R*)
14	Ph	CCl_4	A	−20/48	80	65 (*R*)
15	Ph	toluene	A	−20/48	86	63 (*R*)
16	Ph	CCl_4	B	0/30	39	80 (*R*)
17	Ph	CCl_4	C	25/9	28	96 (*R*)
18	2-naphthyl	CCl_4	A	−20/66	73	51
19	2-naphthyl	toluene	A	−20/66	67	56
20	*p*-BrC_6H_4	CCl_4	A	0/24	62	68 (*R*)
21	*p*-BrC_6H_4	CCl_4	B	0/30	57	93 (*R*)
22	*p*-BrC_6H_4	CCl_4	C	25/10	39	96 (*R*)
23	*n*-octyl	CCl_4	B	0/31	64	69

[a] Method A: sulfide/(*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H_2O/TBHP (toluene solution) = 1.0/0.20/0.10/2.0/2.0 under an argon atmosphere. Method B: sulfide/(*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H_2O/$TBHP_{aq}$ = 1.0/0.20/0.10/2.0/2.0 under aerial conditions. Method C: sulfide/(*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H_2O/$TBHP_{aq}$ = 1.0/0.050/0.025/0.50/2.0 under aerial conditions. [b] Isolated yield. [c] Determined by HPLC on a Daicel Chiralcel OB column. [d] Carried out under an argon atmosphere. [e] Sulfide/(*R*)-(+)-binaphthol/Ti(O-*i*-Pr)$_4$/H_2O/$TBHP_{aq}$ = 1.0/0.10/0.050/1.0/2.0.

column chromatography with Wakogel C-200 or preparative TLC with 20 × 20 cm Kieselgel 60 HF_{254} (Merck) using diethyl ether as an eluent to isolate the sulfoxide. When the obtained sulfoxide was a pale yellow color, it was purified further by flash column chromatography. The ee and the configuration of the isolated sulfoxide were determined by HPLC on a Daicel Chiralcel OB column and by optical rotation, respectively.

Method B. A procedure similar to that used for method A was employed, except that the reaction was carried out open to the air throughout the reaction, and 70% aqueous TBHP (1.0 mmol, 0.15 mL) was used instead of the toluene TBHP solution.

Method C. A procedure similar to that used for method B was employed, except that the amounts of the reagents for preparing the catalyst were decreased by one half: binaphthol (0.025 mmol), Ti(O-*i*-Pr)$_4$ (0.0125 mmol), and H_2O (0.25 mmol).

The Monitoring of the ee Value (Figures 3–5). An aliquot of the reaction mixture removed by means of a microsyringe was directly submitted to TLC (Kieselgel 60 F_{254}), and the band corresponding to the sulfoxide was extracted with CH_2Cl_2. The solution was analyzed by HPLC to determine the ee of the sulfoxide. Another aliquot of the reaction mixture was analyzed by GLC to determine the relative concentrations of the sulfide, the sulfoxide, and the sulfone.

Experiments To Determine the Influence of Water, 2-Propanol, and Solvent upon the Effectiveness of the Catalyst (Schemes IV and V). After the preparation of the catalyst by a procedure similar to that used for method A, the mixture was concentrated *in vacuo* at room temperature for 0.5 h, and then an appropriate solvent and some additives were added under an argon atmosphere. After the reaction mixture was stirred at room temperature for 0.5 h, the sulfide was introduced by means of a syringe. A procedure similar to that used for method A was employed after the injection of the sulfide.

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