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Asymmetric Synthesis of β-Hydroxy Sulfonic Acids by BINAP/Ru-Catalyzed Hydrogenation†

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Abstract: BINAP/Ru(II) complexes catalyze enantioselective hydrogenation of sodium β-keto sulfonates in acidic methanol under atmospheric pressure of hydrogen at 50 °C to give the corresponding β-hydroxy sulfonates with up to 97% ee in a quantitative yield. The sense of asymmetric induction is predictable. The low-pressure hydrogenation process allows the hectogram-scale synthesis of a variety of optically active β-hydroxy sulfonates, which attract attention in connection with their functions as surfactants, catalysts, enzyme inhibitors, etc.

1. BACKGROUND

β-Hydroxy sulfonates and their derivatives are widely utilized in electroplating of copper[1] and tin–lead alloy,[2] electrolytic pigmentation coatings of aluminum,[3] stabilization of disperse dyes,[4] and synthesis of domestic cleaning materials,[5] and also as acid catalysts.[6] Substitution of various surfactants affects both the interfacial and bulk properties of surfactant systems by changing their location and delivery rate in a given medium, and thereby significantly influences such phenomena as wetting, foaming, detergency, and solubilization. And changes in chirality would affect the type of function and the efficiency of systems by altering the assembly modes of constituent molecules. Most of the above surfactants, however, are now used in a racemic form. Furthermore, the sulfonic function with a tetrahedrally arranged sp^3 sulfur atom brings about characteristic binding features in metabolic processes due to its inherent competition with the carboxylic function.[7] The fact that the biological activity is dependent on their absolute configuration has increased the importance of optically active β-hydroxy sulfonates in bioorganic and medicinal chemistry. However, there have been only a few reports on the asymmetric synthesis of β-hydroxy sulfonates.[7a,8] Accordingly, we here describe a general synthetic method using asymmetric hydrogenation of β-keto sulfonates.

† In honor of Professors David A. Evans and Teruaki Mukaiyama on the occasion of their award of the prestigious Tetrahedron Prize.

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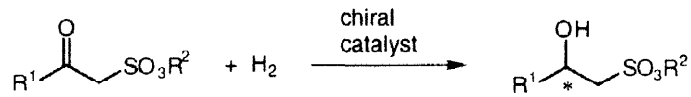
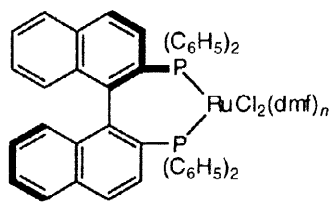
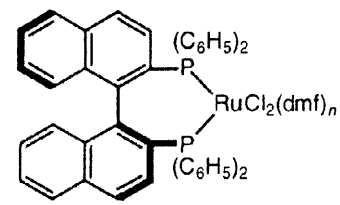
2. RESULTS AND DISCUSSION





(*R*)-**1**

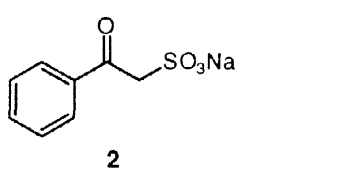


(*S*)-**1**

Reaction Conditions

The (*R*)- or (*S*)-BINAP/Ru dichloride complex, (*R*)- or (*S*)-**1**, (oligomeric structure) was selected as a catalyst candidate, because it is known to effect asymmetric hydrogenation of analogous β-keto carboxylic and phosphonic esters.[9,10] The BINAP/Ru complexes were prepared by reaction of $[RuCl_2(benzene)]_2$ and BINAP in DMF at 100 °C followed by removal of all the volatiles.[11] The residual yellow solid was used for hydrogenation. Sodium 2-oxo-2-phenylethanesulfonate (**2**), a model substrate, was quantitatively synthesized from phenacyl chloride and sodium sulfite according to the reported method.[12] Pure sodium 2-oxo-2-phenylethanesulfonate (**2**), obtained in 66% isolated yield after recrystallization from boiling ethanol, was subjected to hydrogenation under various conditions.

The conversion was determined by ^{1}H-NMR analysis of a crude mixture obtained by removal of solvent. The enantiomeric excess (ee) value of the product **3** was measured by ^{1}H-NMR analysis of the diastereomeric Mosher's esters, (*R*,*R*)- and (*R*,*S*)-**4**, obtained by esterification of the alcoholic product with (*S*)-β,β,β-trifluoro-α-methoxy-α-phenylpropionyl chloride [(*S*)-MTPACl] and pyridine.



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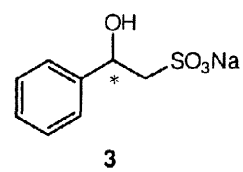

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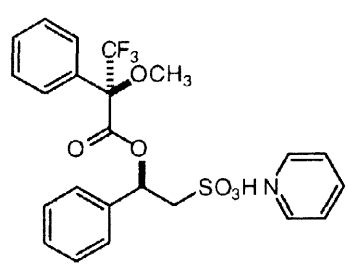
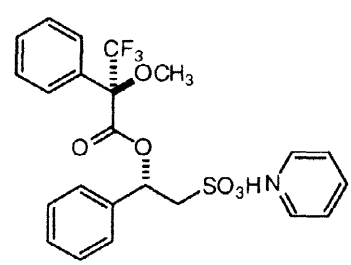


(*R*,*R*)-**4**



(*R*,*S*)-**4**

The results of optimization are listed in Table 1. Hydrogenation was first performed in methanol for 20 h under the conditions of [(*R*)-**1**] = 0.5 mM, [**2**] = 100 mM, 1 atm H_2, 50 °C, and converted less than 10% of **2** to **3** (entry 1). With an increase of H_2 pressure to 100 atm, reaction started and gave, after 20 h, (*R*)-**3** in 96% ee but with only 42% conversion (entry 2). The presence of 5 mM HCl in the standard system, however, greatly accelerated the hydrogenation.[13] Even under atmospheric pressure of H_2, (*R*)-**3** was obtained with an ee of 96% in quantitative yield (entry 3). The reaction was ca. ten times faster than that in the absence of HCl. The rate was further enhanced by increasing the HCl concentration to 25 mM, resulting in a completed reaction after 3 h (entry 5). This significant HCl effect is illustrated in Figure 1. At 80 °C, the reaction period was ca. 1.5 times shorter without a decrease of enantioselectivity (entry 6). When the reaction was performed with a 1 M suspension of **2** in methanol under 1 atm of H_2 for 72 h, (*R*)-**3** was obtained almost quantitatively in 96% ee (entry 7). The catalyst to substrate mol ratio (S/C) could be reduced to 1:1000. Thus, under the conditions of [(*R*)-**1**] = 0.1 mM, [HCl] = 5 mM, [**2**] = 100 mM, 80 °C, and 1 atm of H_2, **2** was converted to (*R*)-**3** in 96% ee in 84% yield after 168 h (entry 8). A similar rate enhancement was observed with H_2SO_4 and CF_3SO_3H, while CH_3COOH was ineffective (entries 9–11). The best-choice solvents were methanol and ethanol (entries 12–17). In acetone under the standard conditions, **2** was converted to **3** with 90% ee but in 50% yield. In THF, benzene, dichloromethane, or acetonitrile, the reaction was seriously retarded. [$RuCl(C_6H_6)$((*R*)-binap)]Cl and $Ru(CH_3COO)_2$[(*R*)-binap] were also usable with added HCl (entries 18–20). Both cationic and neutral BINAP/Rh complexes, [Rh((*R*)-binap)$(CH_3OH)_2$]ClO_4 and RhCl((*R*)-binap)(cod), were not effective under the standard conditions (entries 21 and 22).

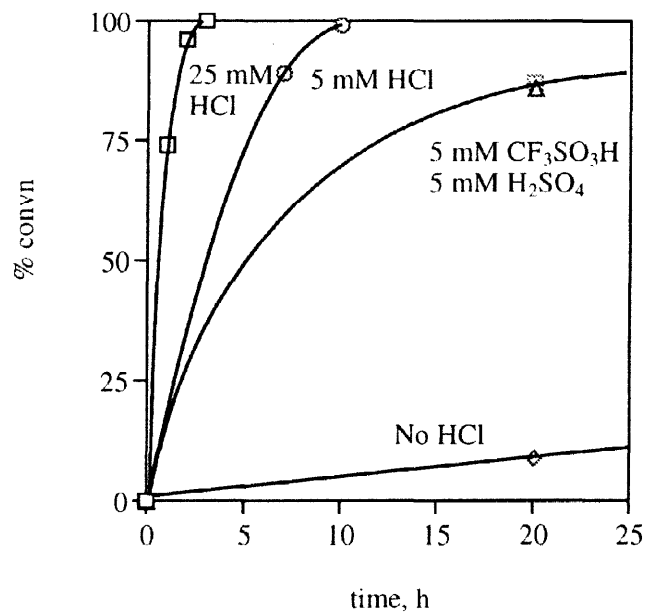


Figure 1. Acceleration effect of HCl in the 1-atm hydrogenation of β-keto sulfonate **2**.

Asymmetric Synthesis

The scope and limitations of the BINAP/Ru method were examined under the optimized conditions. The results are shown in Table 2. The ee values of β-hydroxy sulfonates were determined by ^{1}H-NMR analysis of

Table 1. Asymmetric hydrogenation of sodium 2-oxo-2-phenylethanesulfonate (**2**).[a]

								product	
entry	substrate, mM	catalyst (mM)	additive (mM)	S/C[b]	solvent	time, h	% convn	% ee	confign
1	100	$RuCl_2$[(*R*)-binap](dmf)$_n$ [(*R*)-**1**] (0.5)	—	200	CH_3OH	20	9	—	—
2[c]	100	(*R*)-**1** (0.5)	—	200	CH_3OH	20	42	96	*R*
3	100	(*R*)-**1** (0.5)	HCl (5)	200	CH_3OH	10	99	96	*R*
4	100	(*S*)-**1** (0.5)	HCl (5)	200	CH_3OH	10	99	96	*S*
5	100	(*R*)-**1** (0.5)	HCl (25)	200	CH_3OH	3	100	96	*R*
6[d]	100	(*R*)-**1** (0.5)	HCl (5)	200	CH_3OH	7	99	96	*R*
7	1000	(*R*)-**1** (5)	HCl (250)	200	CH_3OH	72	100	96	*R*
8[d]	100	(*R*)-**1** (0.1)	HCl (5)	1000	CH_3OH	168	84	96	*R*
9	100	(*R*)-**1** (0.5)	H_2SO_4 (5)	200	CH_3OH	20	86	96	*R*
10	100	(*R*)-**1** (0.5)	CF_3SO_3H (5)	200	CH_3OH	20	87	96	*R*
11	100	(*R*)-**1** (0.5)	CH_3CO_2H (5)	200	CH_3OH	20	27	—	—
12	100	(*R*)-**1** (0.5)	HCl (5)	200	C_2H_5OH	10	99	96	*R*
13	100	(*R*)-**1** (0.5)	HCl (5)	200	acetone	10	50	90	*R*
14	100	(*R*)-**1** (0.5)	HCl (5)	200	THF	10	10	—	—
15	100	(*R*)-**1** (0.5)	HCl (5)	200	C_6H_6	10	2	—	—
16	100	(*R*)-**1** (0.5)	HCl (5)	200	CH_2Cl_2	10	10	—	—
17	100	(*R*)-**1** (0.5)	HCl (5)	200	CH_3CN	10	1	—	—
18	100	[$RuCl(C_6H_6)$((*R*)-binap)]Cl (0.5)	HCl (5)	200	CH_3OH	10	99	96	*R*
19	100	$Ru(CH_3COO)_2$[(*R*)-binap] (0.5)	—	200	CH_3OH	10	5	—	—
20	100	$Ru(CH_3COO)_2$[(*R*)-binap] (0.5)	HCl (5)	200	CH_3OH	10	97	96	*R*
21	100	[Rh((*R*)-binap)$(CH_3OH)_2$]ClO_4 (0.5)	HCl (5)	200	CH_3OH	10	11	—	—
22	100	RhCl((*R*)-binap)(cod) (0.5)	HCl (5)	200	CH_3OH	10	3	—	—

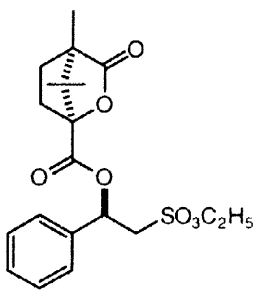
[a] Reactions were carried out under atmospheric pressure of H_2 at 50 °C unless otherwise specified. [b] Substrate/catalyst molar ratio. [c] 100 atm H_2. [d] 80 °C.

the diastereomeric Mosher's esters. Introduction of a long alkyl substituent to the phenyl group of **2** exerted little influence on either reactivity or stereoselectivity. Alkyl ketones were also usable as substrates. Sodium (*R*)-2-hydroxypropanesulfonate in 97% ee was obtained quantitatively by the (*R*)-BINAP/Ru-catalyzed hydrogenation of the methyl ketone **6**. Hydrogenation of the higher analogues **7** and **9** proceeded in the same manner. Reaction of the ethyl ester **8** gave quantitatively the β-hydroxy sulfonic acid with 95% ee. Under these reaction conditions, ethyl ester may undergo methanolysis. The reactivity of the *tert*-butyl ketone **10**, however, was significantly low, giving the alcoholic product in 2% yield after 168 h. Even at 10 atm of H_2, the alcohol with 47% ee was obtained in only 66% yield.

The present method also can be applied to hectogram-scale synthesis of optically active β-hydroxysulfonic acids. For example, when a suspension of 100 g of **2** in 900 mL of methanol containing 1.79 g of (*R*)-**1** and 9.38 mL of a 12 M aqueous solution of HCl was vigorously stirred under atmospheric pressure of H_2 for 72 h at 50 °C and then the mixture was cooled to 0 °C, 95.6 g of sodium hydroxy sulfonate (*R*)-**3** with 96% ee was obtained as a white solid.

Structure Determination

The absolute configuration of **3** was determined by X-ray diffraction study of a single crystal of the camphanate **11**. The ester was obtained by acylating the (*R*)-BINAP/Ru-derived β-hydroxy sulfonate **3** with (*S*)-camphanic chloride. The compound crystallized in the orthorhombic space group $P2_12_12_1$ with a = 15.5(1) Å , b = 20.00(10) Å, c = 6.88(6) Å, V = 2125(21) Å^3, Z = 4. The diffraction data were collected at room temperature on a crystal with an approximate volume of 0.02 mm^3. The structural refinement yielded final agreement factors of R = 0.060 and R_W = 0.046, and the structure indicated that the absolute configuration of the hydroxy sulfonic acid is *R*. Crystallographic details and the molecular structure are given in the Experimental section.



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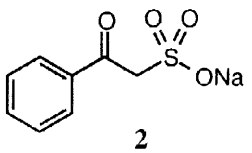
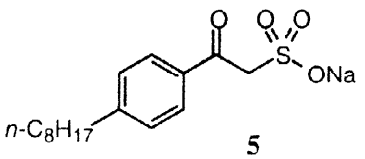
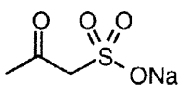
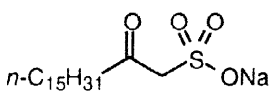
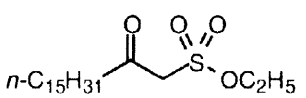
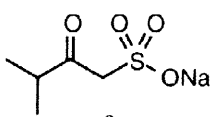
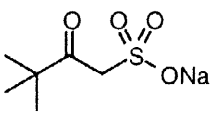
The absolute configurations of other hydrogenation products obtained from the alkyl ketones **6–9** were determined by the Kakisawa–Kashman modification of the Mosher NMR method.[14] This empirical method was reliable in the structual determination of related β-hydroxy phosphonates.[10] With the *R*-configurated alcohols, owing to the diamagnetic shielding effect of the MTPA benzene ring, the proton signals at C(n) ($n \geq 3$) in the (*R*)-MTPA ester should appear upfield relative to the (*S*)-MTPA ester. The ^{1}H $\Delta\delta$ values for β-hydroxy sulfonates, shown in Figure 2, indicated that the absolute configuration of C(2) of products obtained by use of (*R*)-BINAP/Ru complex was consistently *R*. This method can not be applied to the products derived

Table 2. Asymmetric hydrogenation of β-keto sulfonates catalyzed by an (*R*)-BINAP/Ru complex with S/C = 200.[a]

substrate	time, h	product		
		% yield	% ee	confign
 **2**	3	100	96	*R*
 **5**	12	99	95	—[b,c]
 **6**	24	100	97	*R*
 **7**	24	100	96	*R*
 **8**	92	100[d]	95	*R*
 **9**	24	100	97	*R*
 **10**	168 168[e]	2 66	— 47	— —[b]

[a] Conditions: [substrate] = 100 mM; [(*R*)-**1**] = 0.5 mM; [HCl] = 25 mM; solvent, CH_3OH; H_2, 1 atm; temperature, 50 °C. [b] Not determined. [c] The sign of optical rotation was the same as that of sodium (*R*)-2-hydroxy-2-phenylethanesulfonate. [d] 2-Hydroxyheptadecanesulfonic acid was obtained. [e] Reaction under 10 atm of H_2.

from aryl ketone **5** because of signal overlapping in the aromatic region. The alcohol obtained from the *tert*-butyl ketone **10** was not esterified with MTPA chloride. The absolute configurations of these hydrogenation products remain unknown.

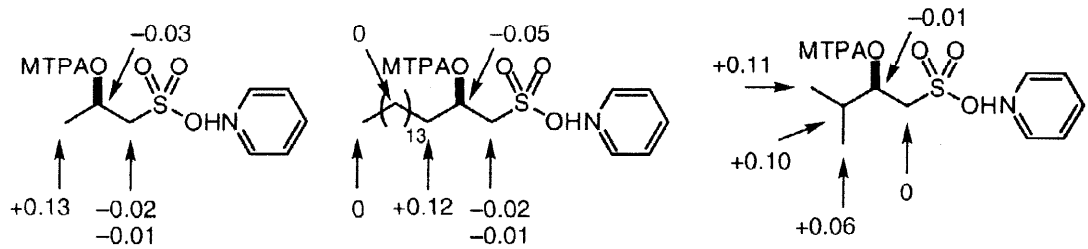
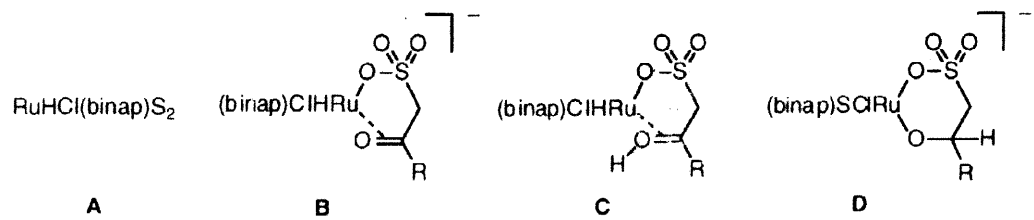


Figure 2. Chemical shift differences between (*R*)- and (*S*)-MTPA esters of (*R*)-β-hydroxy sulfonates in $CDCl_3$ at 27 °C. The values correspond to δ [((*S*)-MTPA ester) − ((*R*)-MTPA ester)].

Reaction Pathway and Enantioface Selection

This Ru-catalyzed hydrogenation probably proceeds by a monohydride mechanism.[15,16] The catalyst precursor, $RuCl_2(binap)(dmf)_n$ (**1**), exists in the form of aggregates, and these would be partly dissociated to monomeric $RuCl_2(binap)S_2$ by the influence of donor molecules (S), such as those of solvent, substrates, and products. The Ru(II) species then splits molecular hydrogen heterolytically to form $RuHCl(binap)S_2$ (**A**) with elimination of HCl.[17] The monohydride species reacts reversibly with a β-keto sulfonate to form **B**, which undergoes intramolecular hydride transfer via the protonated species **C**. The carbonyl protonation greatly stabilizes the transition state by increasing the electrophilicity of the carbon center. This pathway in an alcoholic medium gives a β-hydroxy sulfonate product and $[RuCl(binap)S_n]^+$. The latter cationic Ru(II) species readily reacts with H_2 to regenerate the catalyst **A**. HCl is already present in the reaction system, but in insufficient quantity to effect the facile hydrogenation by this mechanism. Addition of a strong acid results in a marked acceleration effect (Figure 1), allowing smooth hydrogenation under atmospheric pressure of H_2. $Ru(CH_3COO)_2(binap)$ without added HCl is totally inactive, because its hydrogenolysis liberates weakly acidic acetic acid in addition to a RuH species.[9a] The presence of a strong acid promotes the reaction equally well. This is the simplest mechanism. Alternatively, as postulated in hydrogenation of functionalized olefins,[18] the RuH species **B** may be converted to the cyclic product **D**. Hydrogenolysis of the alkoxy–Ru bond of **D**[16] gives the hydroxy sulfonate product and the catalyst **A**. Furthermore, the alkoxide **D** may undergo ligand exchange with solvent alcohol, ROH, to form the hydroxy sulfonate and $RuCl(OR)(binap)S_2$.



This step could be facilitated by an acid. Finally, reaction of RuCl(OR)(binap)S_2 and H_2 regenerates the Ru hydride **A**, completing the catalytic cycle.

The sense of asymmetric induction is the same as that observed earlier in the BINAP/Ru-catalyzed hydrogenation of other functionalized ketones.[9b] This is understood by considering the relative stabilities of the diastereomeric structures of Figure 3, which approximate the transition states of the proton-aided hydride transfer. The characteristic chiral structure of the BINAP ligand clearly develops two spatially different quadrants in a hypothetical "Ru(binap)" template that accommodates an additional four ligands.[18] The sites out of the P–Ru–P plane are occupied by small hydride and chloride ligands. When (*R*)-BINAP ligand is used, the first and third quadrants of the RuHCl(binap) element are relatively uncrowded, while the second and fourth quadrants are sterically congested because of the steric effects of the "equatorial" P-phenyl rings indicated in gray. Then a carbonyl-protonated β-keto sulfonate occupies the remaining coordination sites in the P–Ru–P plane to lead to the two diastereomeric octahedral structures, **Ru**$_R$ and **Ru**$_S$. This bidentate ligation takes place so as to minimize the unfavored nonbonded repulsion with the equatorial phenyl rings. Obviously, **Ru**$_R$ generating an (*R*)-β-hydroxy sulfonate is more stable than the *S* alcohol-forming structure **Ru**$_S$, which suffers a substantial nonbonded repulsion between the R group and the equatorial phenyl group in the fourth quadrant. In diastereomeric **Ru**$_R$, the R group is well suited in the uncrowded third quadrant and the sulfonyl oxygens are far away from the phenyl group in the fourth quadrant. The direction of asymmetric hydrogenation is simply determined by the relative stabilities of these diastereomers (**Ru**$_R$ > **Ru**$_S$). Thus this stereo-complementary model consistently explains the sense of asymmetric induction, *R* to *R* or *S* to *S*, of the BINAP/Ru-catalyzed hydrogenation of β-keto sulfonates.

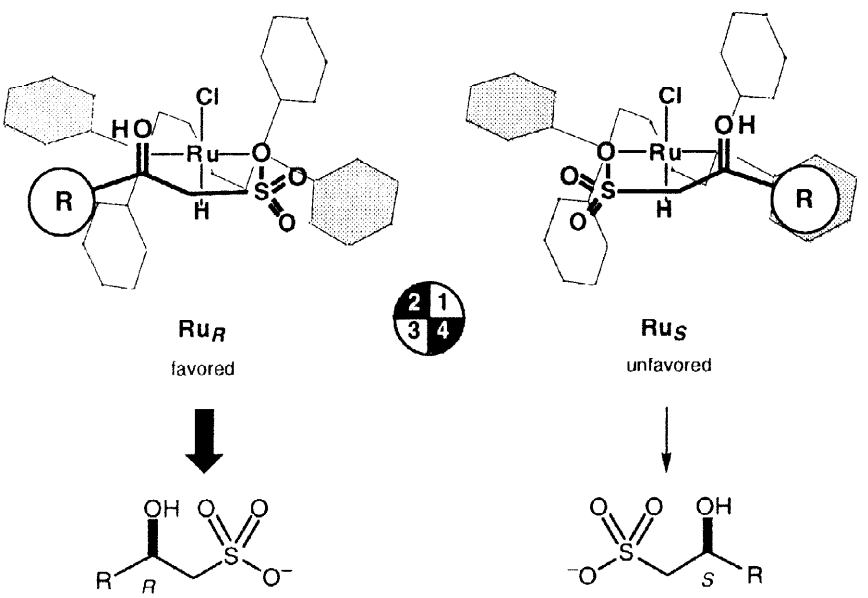


Figure 3. Stereo-complementary model explaining the sense of enantioface selection.

Conclusion

Chemical substances such as drug candidates, domestic detergents, and industrial surfactants often incorporate a functionality of chiral hydroxy sulfonates or their derivatives. These are now utilized in a racemic form, even in the case of domestic applications wherein direct skin contact is possible. The enantiomerically pure compounds are apparently important not only in terms of biological activity but also for the design and preparation of new functional surface-active species. The present method provides a practical solution to this problem. The readily accessible β-keto sulfonates can be hydrogenated in the presence of BINAP/Ru complex catalysts under 1 atm of H_2 to give β-hydroxy sulfonates in high chemical and optical yield.

3. EXPERIMENTAL

Chemicals for Hydrogenation

Solvents for hydrogenation were distilled under an argon stream from Mg (CH_3OH and C_2H_5OH), Na–K alloy (THF and C_6H_6), or CaH_2 (CH_2Cl_2 and CH_3CN), or passed through a molecular sieve 4 A (acetone), and kept in Schlenck flasks. These were degassed by three freeze-thaw cycles before hydrogenation.

H_2 gas of a 99.99999% grade was purchased from Nippon Sanso and used without purification. Ar obtained from Nippon Sanso was purified by passing through a column of the BASF catalyst R3-11 at 80 °C and then through a molecular sieve 4A.

Chiral catalysts, $RuCl_2$[(*R*)-binap](dmf)$_n$ ((*R*)-**1**), (*S*)-**1**),[11] $Ru(CH_3COO)_2$((*R*)-binap),[19] [Rh((*R*)-binap)$(CH_3OH)_2$]ClO_4, and RhCl((*R*)-binap)(cod),[20] were prepared according to the reported methods.

Sodium β-keto sulfonates were synthesized with reference to the reported procedures.[12] Synthetic operation of sodium 2-oxo-2-phenylethanesulfonate was represented in the section of Synthesis of β-Hydroxy Sulfonates. The same process was applied to the synthesis of sodium 2-oxopropanesulfonate (**6**), sodium 3-methyl-2-oxobutanesulfonate (**9**), and sodium 3,3-dimethyl-2-oxobutanesulfonate (**10**). Sodium 2-oxo-2-(4-*n*-octylphenyl)ethanesulfonate (**5**) was obtained by neutralization of the corresponding sulfonic acid, which was obtained by reaction of 4-*n*-octylphenyl methyl ketone and SO_3–dioxane.[21] Sodium 2-oxoheptadecanesulfonate (**7**) was obtained by treatment of ethyl 2-oxoheptadecanesulfonate (**8**) with sodium iodide,[22] which was synthesized from ethyl lithiomethansulfonate and ethyl palmitate. All sulfonates were purified by recrystallization. **6**: mp 166–168 °C. Anal. Calcd for $C_3H_5O_4SNa$: C, 22.50; H, 3.15. Found: C, 22.55; H, 3.05. **9**: mp 195–197 °C. Anal. Calcd for $C_5H_9O_4SNa$: C, 31.91; H, 4.82. Found: C, 31.63; H, 4.63. **10**: mp 213–215 °C. Anal. Calcd for $C_6H_{11}O_4SNa$: C, 35.64; H, 5.48. Found: C, 35.66; H, 5.45. **5**: mp 182–183 °C. Anal. Calcd for $C_{16}H_{23}O_4SNa$: C, 57.47; H, 6.93. Found: C, 57.45; H, 6.83. **7**: mp 168–170 °C. Anal. Calcd for $C_{17}H_{33}O_4SNa$: C, 57.27; H, 9.33. Found: C, 57.31; H, 9.19.

Analytical Methods

Chemicals: $CHCl_3$ and CH_3OH purchased from Tokyo Kasei for measurement of optical rotation, and $CDCl_3$, CD_3OD, and DMSO-d_6 purchased from Aldrich Chemicals for NMR measurement were used without further purification. Guaranteed CH_2Cl_2 and CH_3OH were used for the preparation of (*R*)-MTPA esters (MTPA = β,β,β-trifluoro-α-methoxy-α-phenylpropionic acid), (*S*)-1-(1-naphthyl)ethylammonium salts and camphanic ester. (*S*)-1-(1-Naphthyl)ethyl amine and (*S*)-MTPACl were purchased from Aldrich Chemicals. Cation exchange resin Dowex 50W-X8 (H^+ form) was obtained from Dow Chemical Company.

Silica gel: Analytical thin-layer chromatography (TLC) was performed using Merck 5715 indicating plates precoated with silica gel 60 F254 (layer thickness, 0.25 mm). The product spots were visualized with a solution of *o*-anisaldehyde. Liquid chromatographic purifications were performed by flash column chromatography, using glass columns packed with Merck 9385 (230–400 mesh).

Instruments: Melting points (mp) measured with a YANACO apparatus are uncorrected. NMR spectra were measured on a JEOL JNM-EX270, JNM-A400, or Varian INOVA-500 spectrometer. The chemical shifts are expressed in parts per million (ppm) downfield from $Si(CH_3)_4$ or in ppm relative to $CHCl_3$, CH_3OH, and DMSO (δ 7.26, 3.31, and 2.50 in ^1H NMR and δ 77.0, 49.0, and 39.5 in ^{13}C NMR, respectively), and the coupling constants (*J*) are expressed in Hz. Signal patterns are indicated as s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; or br, broad peak. All deuterated solvents were purchased from Aldrich Chemicals and used without further purification. Optical rotations were determined on a JASCO P-1010-GT digital polarimeter using a 3 mm x 10 cm cell. X-ray crystallographic analysis was conducted on a Rigaku automated four-circle diffractometer. Elemental analyses were determined with a LECO-CHN900 instrument.

Conversion: The conversion of substrates was determined by 400-MHz ^1H-NMR analysis of a reaction mixture obtained by addition of a 50.6–55.0-mg quantity of mesitylene followed by evaporation of all the volatiles. The area of the methyl signal of mesitylene (δ 2.21) and the following signals of the β-hydroxy sulfonates were compared under the conditions: solvent, DMSO-d_6; mesitylene concentration, 40–45 mM; sample concentration, 41–43 mM; temperature, 27 °C. Sodium 2-hydroxy-2-phenylethanesulfonate (**3**), δ 4.95 (dd, 1, *J* = 2.4 Hz and 10.2 Hz, CH); sodium 2-hydroxy-2-(4-*n*-octylphenyl)ethanesulfonate, δ 4.87 (dd, 1, *J* = 2.3 and 10.2 Hz, CH); sodium 2-hydroxypropanesulfonate, δ 1.05 (d, 3, *J* = 6.3 Hz, CH_3); sodium 2-hydroxyheptadecanesulfonate, δ 3.77 (m, 1, CH); 2-hydroxyheptadecanesulfonic acid, δ 0.85 (t, 3, *J* = 6.6 Hz, CH_3); sodium 2-hydroxy-3-methylbutanesulfonate, δ 0.82 (d, 6, *J* = 6.5 Hz, 2 CH_3); sodium 2-hydroxy-3,3-dimethylbutanesulfonate, δ 0.90 (s, 9, $(CH_3)_3$).

Enantiomeric excess: The ee values of most of the β-hydroxy sulfonates were determined by 500-MHz ^1H-NMR analysis of their (*R*)-MTPA esters. Preparation of these (*R*)-MTPA esters is exemplified by sodium 2-hydroxy-2-phenylethanesulfonate (**3**). To a 2 mL methanol solution of the alcohol (15 mg, 0.067 mmol) was added Dowex 50W-X8 (H^+) (200 mg). After the mixture was stirred at 25 °C for 10 min, the resin was removed by filtration. Pyridine (0.05 mL, 0.62 mmol) was added to the filtrate. The mixture was

concentrated in vacuo to give an oil, which was dissolved in CH_2Cl_2 (1 mL). To this was added (*S*)-MTPACl (39 mg, 0.15 mmol) and pyridine (0.05 mg, 0.62 mmol), and the solution was allowed to stand at 25 °C for 12 h. The mixture was partitioned between ethyl acetate (2 mL) and 1 M aqueous HCl (2 mL). The aqueous layer was extracted by two portions of ethyl acetate (2 mL). The combined organic layers were dried on Na_2SO_4, filtered, and concentrated to give an oil, which was subjected to the ^{1}H-NMR measurement. NMR chemical shifts of the (*R*)-MTPA ester used for area integration were: Sodium 2-hydroxy-2-phenylethanesulfonate, δ 6.60 and 6.64 (dd, 1, *J* = 3.0 Hz and 9.0 Hz, CH); sodium 2-hydroxy-2-(4-*n*-octylphenyl)ethanesulfonate, δ 6.47 and 6.54 (dd, 1, *J* = 2.8 Hz and 8.8 Hz, CH); sodium 2-hydroxypropanesulfonate, δ 1.34 (d, 3, *J* = 6.0 Hz, CH_3) and 1.47 (d, 3, *J* = 5.6 Hz, CH_3); sodium 2-hydroxyheptadecanesulfonate, δ 5.57 and 5.62 (m, 1, CH); sodium 2-hydroxy-3-methylbutanesulfonate, δ 0.74 and 0.78 (d, 6, *J* = 6.8 Hz, 2 CH_3) and 0.85 and 0.86 (d, 6, *J* = 6.8 Hz, 2 CH_3). Sodium 2-hydroxy-3,3-dimethylbutanesulfonate did not react with (*S*)-MTPACl under the conditions described above. The ee value was determined by 400-MHz ^{1}H-NMR analysis of the (*S*)-1-(1-naphthyl)ethylammonium salt prepared as follows. Dowex 50W-X8 (H^+) (100 mg) was added to the alcohol (8.0 mg, 0.039 mmol) that was dissolved in methanol (1 mL). The mixture was stirred at 25 °C for 10 min and passed through a column with a sintered glass. To the filtrate was added (*S*)-1-(1-naphthyl)ethylamine (6.7 mg, 0.039 mmol) at 25 °C. Concentration of the mixture afforded the corresponding ammonium salt of 2-hydroxy-3,3-dimethylbutanesulfonic acid as an oil, which was analyzed by NMR in a 1:1 $CDCl_3$–CCl_4 mixture at 27 °C. Integration of two signals at δ 0.63 (s, 9, $(CH_3)_3$) and 0.66 (s, 9, $(CH_3)_3$) determined the ee value to be 47%. This method was also used for the confirmation of the ee value of sodium (*R*)-2-hydroxy-2-phenylethanesulfonate ((*R*)-**3**) (96% ee). The ratio of two signals at δ 4.90 (dd, 1, *J* = 3.1 Hz and 9.0 Hz, C*H*OH) and δ 5.01 (dd, 1, *J* = 3.1 Hz and 9.2 Hz, C*H*OH) was 98:2.

Absolute configuration: The absolute configurations of sodium 2-hydroxy-2-phenylethanesulfonate (**3**) obtaind by (*R*)-BINAP/Ru-catalyzed hydrogenation (see below) were determined by X-ray crystallographic analysis of the corresponding camphanic ester. The synthetic procedure was the same as that described for the preparation of MTPA ester. The sulfonate **3** (103.5 mg, 0.46 mmol) was treated with Dowex 50W-X8 (H^+) (6 g) in methanol (10 mL). To the filtrate was added pyridine (0.1 mL, 1.24 mmol), and the solution was concentrated in vacuo to give the pyridinium salt as an oil. This was dissolved in CH_2Cl_2 (2 mL). To the solution was added (*S*)-camphanic chloride (98.5 mg, 0.46 mmol) and pyridine (0.2 mL, 2.79 mmol). After stirring at 25 °C for 12 h, the mixture was worked up. The resulting pyridinium sulfonate was dissolved in methanol (2 mL) containing Dowex 50W-X8 (H^+) (6 g). After 10-min stirring at 25 °C, the resin was removed and the filtrate was concentrated in vacuo, giving the corresponding sulfonic acid as an oil. This was immediately dissolved in triethyl orthoformate (1 mL), and the mixture was stirred at 25 °C for 17 h. Evaporation of all volatiles followed by silica-gel column chlomatography (10 g, 2:1 hexane–ethyl acetate mixture as eluent) afforded (*R*)-ethyl 2-(*S*)-camphanyloxy-2-phenylethanesulfonate (**11**) (50 mg) in 26% overall yield: ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.95 (s, 3, CH_3), 1.06 (s, 3, CH_3), 1.11 (s, 3, CH_3), 1.39 (t, 3, *J* = 7.5 Hz, OCH_2CH_3), 1.67 (m, 1, CH_2CHH), 1.91 (m, 1, CH_2CHH), 1.99 (m, 1, $CHHCH_2$), 2.41 (m, 1, $CHHCH_2$), 3.49 (dd, 1, *J* = 3.5 and 15.5 Hz, C*H*H), 3.81 (dd, 1, *J* = 9.5 and 15.5 Hz, CH*H*), 4.30 (m, 2, OCH_2CH_3), 6.38 (dd, 1, *J* = 3.5 and 9.5 Hz, CH), 7.35–7.39 (m, 1, aromatic), 7.39–7.42 (m, 4, aromatic); ^{13}C NMR (100 MHz, $CDCl_3$) δ 9.6, 15.1, 16.6, 16.8, 28.8, 30.8, 54.4, 54.9, 55.3, 67.0, 71.5,

90.8 126.4, 129.1, 129.4, 136.9, 166.2, 178.1. Recrystallization from methanol at 25 °C for 2 days gave colorless needle-like crystals of **11** suitable for X-ray crystallographic analysis: mp 125–127 °C. Anal. Calcd for $C_{20}H_{26}O_7S$: C, 58.52; H, 6.38. Found: C, 58.51; H, 6.40. The crystallographic data are listed in Table 3 and the molecular structures are shown in Figure 4. On the basis of the structure of camphanyl group, the stereogenic centers of **3** were determined to be *R*. Details of the analysis, including atomic parameters, anisotropic temperature factors, complete listings of bond angles and distances, and observed and calculated structure factors have been deposited with the Cambridge Crystallographic Data Centre.

Table 3. Crystallographic data for **11**.

compound	(*R*)-ethyl 2-(*S*)-camphanyloxy-2-phenylethanesulfonate (**11**)
mol formula	$C_{20}H_{26}O_7S$
mol wt	410.48
crystal color, habit	colorless, needle
crystal size, mm^3	0.20 x 0.20 x 0.50
crystal system	orthorhombic
lattice type	Primitive
no. of reflections used for unit cell determination	25 reflections (57.8–59.8°)
omega scan peak width at half-height	1.01°
space group	$P2_12_12_1$
cell determination	
a, Å	15.5(1)
b, Å	20.00(10)
c, Å	6.88(6)
α, deg	90
β, deg	90
γ, deg	90
vol, $Å^3$	2125(21)
Z	4
ρ calcd, g cm^{-3}	1.282
μ (Cu Kα), cm^{-1}	16.79
diffractometer	Rigaku automated four-circle diffractometer, AFC-7R
radiation	Cu Kα (l = 1.54178 Å)
monochrometer	graphite monochromated
scan type	ω-2θ
scan width	(1.68 + 0.30 tan θ)°
scan speed, deg min^{-1}	16.0°/min (in ω) – up to 5 scans
2θ scan limit, deg	120.7
total reflections scanned	total 1863
corrections	Lorentz-polarization Decay (2.06% decline)

—the continuation of Table 3—

structure solution	Patterson Methods
function minimized by refinement	$\Sigma\omega(\|F_0\|-\|F_c\|)^2$
no. of observations ($I > 3.00\sigma(I)$)	1485
R	0.060
R_w[a]	0.046

[a] $R_w = \{\Sigma\omega(\|F_0\|-\|F_c\|)^2/\Sigma\omega F_0^2\}^{1/2}$

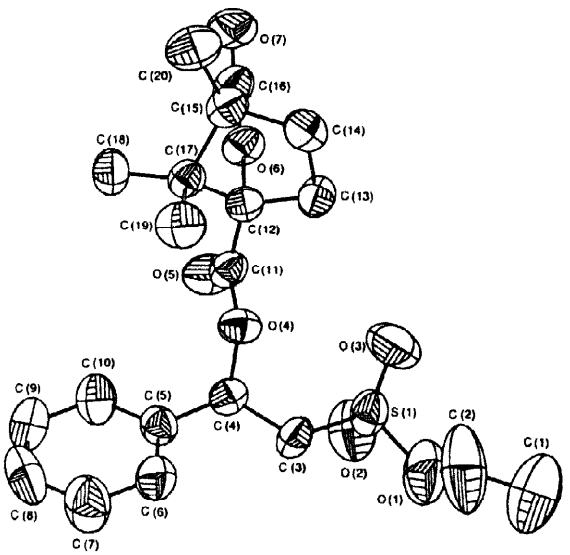


Figure 4. Molecular structure of **11** in the crystalline state.
All hydrogen atoms are omitted for clarity.

For determination of the absolute configurations of other β-hydroxy sulfonates, the modified Mosher NMR method was applied.[14] The ^{1}H $\Delta\delta$ values (Figure 2) were calculated on the basis of the following ^{1}H-NMR data of the (*R*)-MTPA esters of (±)-β-hydroxy sulfonates. The data are listed in the order of *R*,*R* and *R*,*S* isomers. Sodium 2-hydroxypropanesulfonate, δ 1.34 (d, 3, J = 6.0 Hz, CH_3), 1.47 (d, 3, J = 5.6 Hz, CH_3), 3.11 (m, 1, C*H*H), 3.10 (m, 1, C*H*H), 3.30 (m, 1, CH*H*), 3.28 (m, 1, CH*H*), 5.64 (m, 1, CH), 5.61 (m, 1, CH); sodium 2-hydroxyheptadecanesulfonate, δ 0.88 (t, 3, J = 6.8 Hz, CH_3), 0.88 (t, 3, J = 6.8 Hz, CH_3), 1.08 (m, 4, $(CH_2)_2$), 1.08 (m, 4, $(CH_2)_2$), 1.26 (br s, 22, $(CH_2)_{11}$), 1.26 (br s, 22, $(CH_2)_{11}$), 1.61 (m, 2, CH_2), 1.73 (m, 2, CH_2), 3.22 (dd, 1, J = 2.8 and 13.6 Hz, C*H*H), 3.21 (dd, 1, J = 2.8 and 13.6 Hz, C*H*H), 3.36 (dd, 1, J = 8.4 and 13.6 Hz, CH*H*), 3.34 (dd, 1, J = 8.4 and 13.6 Hz, CH*H*), 5.62 (m, 1, CH), 5.57 (m, 1, CH); sodium 2-hydroxy-3-methylbutanesulfonate, δ 0.74 (d, 3, J = 6.8 Hz, CH_3), 0.78 (d, 3, J = 6.8 Hz, CH_3), 0.85 (d, 3, J = 6.8 Hz, CH_3), 0.86 (d, 3, J = 6.8 Hz, CH_3), 1.90 (m, 1, CH), 2.00 (m, 1, CH), 3.17 (m, 2, CH_2), 3.17 (m, 2, CH_2), 5.53 (m, 1, CH), 5.52 (m, 1, CH). The absolute configurations at C(2) of these products obtained by use of (*R*)-BINAP/Ru catalyst were indicated to be *R*. ^{1}H-NMR

analysis of β-hydroxy sulfonates having aryl groups at C(2) was unsuccessful because the signals in the aromatic region overlapped.

Synthesis of β-Hydroxy Sulfonates

The synthetic procedure is represented with sodium (*R*)-2-hydroxy-2-phenylethanesulfonate ((*R*)-**3**). The conditions for hydrogenation of other substrates and the results are listed below for other β-hydroxy sulfonates, which could be obtained in high chemical and optical yields. All manipulations for the BINAP/Ru-catalyzed hydrogenation were performed using the usual Schlenk technique on a dual manifold vacuum/argon system. The operational process basically followed the reported one.[10,11] Hydrogenation proceeded quantitatively unless otherwise noted.

Sodium (R)-2-hydroxy-2-phenylethanesulfonate: Sodium sulfite (228.9 g, 1.81 mol), ethanol (1 L), and water (250 mL) were placed in a 2-L round-bottomed flask equipped with a dimroth condenser. To this was added phenacyl chloride (251.4 g, 1.62 mol), and the suspension was refluxed for 20 h. The resulting mixture was passed through a filter paper, and the filtrate was cooled to 0 °C. The resulting white solid was separated by filtration and dried at room temperature and 0.05 mmHg for 12 h. The solid was suspended in ethanol (10 L) and heated at reflux temperature for 30 min. Insoluble material was removed by filtration. The filtrate was left at 20 °C for 15 h to liberate the white solid. The solid was dried at room temperature and 0.05 mmHg to give analytically pure sodium 2-oxo-2-phenylethanesulfonate (**2**) (239 g, 66% yield). The compound **2** (100 g, 450 mmol) and $RuCl_2$[(*R*)-binap](dmf)$_n$ (1.79 g, 2.25 mmol) were placed in a dry 2 L Schlenk-type flask equipped with mechanical stirrer. To this was added degassed methanol (900 mL) containing 12 M HCl (9.38 mL, 113 mmol) under an argon stream. The whole mixture was again degassed, and then hydrogen gas regulated at the pressure of 1 atm was introduced. The yellow mixture was vigorously stirred for 72 h, under continuous pressure from the hydrogen cylinder. After closing the main valve of the cylinder, the suspension was filtered to give sodium (*R*)-2-hydroxy-2-phenylethanesulfonate ((*R*)-**3**) in 96% ee (83.5 g, 83% yield): mp 223 °C (dec.); $[\alpha]_D^{21}$ –21.0 (*c* 1.0, CH_3OH); ^1H NMR (400 MHz, DMSO-d_6) δ 2.70 (dd, 1, *J* = 10.2 and 13.7 Hz, C*H*H), 2.78 (dd, 1, *J* = 2.4 and 13.7 Hz, CH*H*), 4.95 (dd, 1, *J* = 2.4 and 10.2 Hz, CH), 7.20–7.25 (m, 1, aromatic), 7.29–7.36 (m, 4, aromatic); ^{13}C NMR (100 MHz, DMSO-d_6) δ 59.1, 69.5, 125.7, 127.0, 128.1, 143.9. Anal. Calcd for $C_8H_9O_4SNa$: C, 42.86; H, 4.05. Found: C, 43.09; H, 4.01. The filtrate was concentrated to 100 mL, giving a second crop of (*R*)-**3** in 96% ee (12.1 g, 13% yield). Total yield was 95.6 g (95%).

Sodium 2-hydroxy-2-(4-n-octylphenyl)ethanesulfonate: Hydrogenation conditions: **5** (1.0 g, 3.0 mmol); (*R*)-**1** (12 mg, 0.015 mmol); 12 M HCl (0.063 mL, 0.75 mmol); CH_3OH (30 mL); 1 atm of H_2; 50 °C; 12 h. *R* product in 95% ee: mp 266 °C (dec.); $[\alpha]_D^{21}$ –4.2 (*c* 1.0, CH_3OH); ^1H NMR (270 MHz, DMSO-d_6) δ 0.84 (t, 3, *J* = 6.9 Hz, CH_3), 1.25 (m, 10, $(CH_2)_5$), 1.54 (m, 2, CH_2), 2.59 (dd, 1, *J* = 10.2 and 13.5 Hz, C*H*H), 2.70 (dd, 1, *J* = 2.3 and 13.5 Hz, CH*H*), 4.87 (dd, 1, *J* = 2.3 and 10.2 Hz, CH), 7.11 (d, 2 *J* = 8.3 Hz, aromatic), 7.22 (d, 2 *J* = 8.3 Hz, aromatic); ^{13}C NMR (67.5 MHz, DMSO-d_6) δ 13.9, 22.0, 28.6, 28.7, 28.8, 30.9, 31.2, 34.8, 59.0, 69.3, 125.6, 128.0, 140.9, 141.1. Anal. Calcd for $C_{16}H_{25}O_4SNa$: C, 57.12; H, 7.49. Found: C, 56.81; H, 7.15.

Sodium 2-hydroxypropanesulfonate: Hydrogenation conditions: **6** (2.0 g, 12.5 mmol); (*R*)-**1** (49.7 mg, 0.063 mmol); CH_3OH (125 mL); 12 M HCl (0.263 mL, 3.15 mmol); 1 atm of H_2; 50 °C; 24 h. *R* product in 97% ee: mp 244–245 °C; $[\alpha]_D^{20}$ –8,5 (*c* 1.0, CH_3OH); ^1H NMR (400 MHz, DMSO-d_6) δ 1.05 (d, 3, *J* = 6.3 Hz, CH_3), 2.40 (dd, 1, *J* = 8.8 and 13.2 Hz, C*H*H), 2.53 (dd, 1, *J* = 3.4 and 13.2 Hz, CH*H*), 3.92 (ddq, 1, *J* = 3.4, 8.8 and 6.3 Hz, CH); ^{13}C NMR (100 MHz, DMSO-d_6) δ 22.7, 58.9, 63.3. Anal. Calcd for $C_3H_7O_4SNa$: C, 22.22; H, 4.35. Found: C, 22.38; H, 3.92.

Sodium 2-hydroxyheptadecanesulfonate: Hydrogenation conditions: **7** (140 mg, 0.426 mmol); (*R*)-**1** (1.7 mg, 0.0021 mmol); CH_3OH (4.3 mL); 12 M HCl (0.009 mL, 0.108 mmol); 1 atm of H_2; 50 °C; 24 h. *R* product in 96% ee: mp 174–176 °C; $[\alpha]_D^{30}$ –20.9 ± 1.6 (*c* 0.11, 1:1 CH_3OH–$CHCl_3$); ^1H NMR (270 MHz, DMSO-d_6) δ 0.85 (t, 3, *J* = 6.6 Hz, CH_3), 1.24 (br s, 26, $(CH_2)_{13}$), 1.33 (m, 2, CH_2), 2.36 (dd, 1, *J* = 9.2 and 13.5 Hz, C*H*H), 2.56 (dd, 1, *J* = 2.8 and 13.5 Hz, CH*H*), 3.77 (m, 1, CH); ^{13}C NMR (67.5 MHz, DMSO-d_6) δ 13.9, 22.0, 24.8, 28.6, 29.0, 31.2, 36.2, 57.2, 66.8. Anal. Calcd for $C_{17}H_{35}O_4SNa$: C, 56.95; H, 9.84. Found: C, 56.98; H, 9.62. Hydrogenation conditions: **8** (104 mg, 0.287 mmol); (*R*)-**1** (1.2 mg, 0.0015 mmol); CH_3OH (2.8 mL); 12 M HCl (0.006 mL, 0.072 mmol); 1 atm of H_2; 50 °C; 92 h. Under the conditions 2-hydroxyheptadecanesulfonic acid was obtained. The crude product (100 mg, 0.276 mmol) in CH_3OH (50 mL) was neutralized with 1 M NaOH (0.28 mL, 0.28 mmol) under 0 °C. The solution was evaporated, and recrystallization from CH_3OH (40 mL) gave 0.10 g of *R* sulfonate in 95% ee.

Sodium 2-hydroxy-3-methylbutanesulfonate: Hydrogenation conditions: **9** (3.0 g, 15.9 mmol); (*R*)-**1** (63.2 mg, 0.080 mmol); CH_3OH (159 mL); 12 M HCl (0.063 mL, 0.75 mmol); 1 atm of H_2; 50 °C; 24 h. *R* product in 97% ee: mp 214–215 °C; $[\alpha]_D^{21}$ –17.2 (*c* 1.0, CH_3OH); ^1H NMR (270 MHz, DMSO-d_6) δ 0.82 (d, 6, *J* = 6.5 Hz, 2 CH_3), 1.59 (dqq, 1, *J* = 5.3, 6.5 and 6.5 Hz, CH), 2.35 (dd, 1, *J* = 9.9 and 13.5 Hz, C*H*H), 2.57 (dd, 1, *J* = 2.0 and 13.5 Hz, CH*H*), 3.60 (ddd, 1, *J* = 2.0, 5.3 and 9.9 Hz, CH); ^{13}C NMR (67.5 MHz, DMSO-d_6) δ 17.4, 18.3, 32.4, 54.2, 71.3. Anal. Calcd for $C_5H_{11}O_4SNa$: C, 31.57; H, 5.83. Found: C, 31.76; H, 5.58.

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REFERENCES AND NOTES

1. (a) Eckles, W. E.; Starinshak, T. W. U.S. Patent US-4134803, January 16, 1979. (b) Willis, W. J. U.S. Patent, US-4347108-A, August 31, 1982.
2. Dohi, N.; Obata, K. Jpn Kokai Tokkyo Koho JP-5314131, February 8, 1978.

3. (a) Suzuki, T.; Hasegawa, Y. Jpn Kokai Tokkyo Koho JP-55131195, October 11, 1980. (b) Suzuki, T.; Hasegawa, Y. Jpn Kokai Tokkyo Koho JP-55131196, October 11, 1980. (c) Suzuki, T.; Hasegawa, Y. Jpn Kokai Tokkyo Koho JP-55131197, October 11, 1980.
4. Cleary, J. W. U.S. Patent Office, US-3842044, October 15, 1974.
5. (a) Hasegawa, H.; Kametani, J. Jpn Kokai Tokkyo Koho JP-06340521, December 13, 1994. (b) Hasegawa, H.; Kametani, J. Jpn Kokai Tokkyo Koho JP-06340523, December 13, 1994. (c) Takeda, T.; Murakami, A.; Honda, K.; Nakamura, M.; Yamamura, S. *Kagaku To Kogyo (Osaka)* **1995**, *69*, 85–88. (d) Fujio, A.; Terasaki, H.; Tsuda, H. Jpn Kokai Tokkyo Koho JP-08199187, August 6, 1996.
6. (a) Olah, G. A.; Iyer, P. S.; Prakash, G. K. S. *Synthesis* **1986**, 513–531. (b) El-Kattan, Y.; McAtee, J. In *Encyclopedia of Reagents for Organic Synthesis*; Paquette, L. A., Ed.; John Wiley & Sons: Chichester, 1995; Vol. 6, 3677–3679.
7. (a) Ozegowski, J.-H.; Günther, E.; Reichardt, W. *Zbl. Bakt.* **1994**, *280*, 497–506. (b) Prager, R. H.; Schafer, K.; Hamon, D. P. G.; Massy-Westropp, R. A. *Tetrahedron* **1995**, *51*, 11465–11472.
8. For the synthesis of racemic β-hydroxy sulfonates, see: (a) Lauer, W. M.; Hill, A. *J. Am. Chem. Soc.* **1936**, *58*, 1873–1874. (b) Bordwell, F. G.; Suter, C. M.; Webber, A. J. *J. Am. Chem. Soc.* **1945**, *67*, 827–832. (c) Stewart, J. M.; Cordts, H. P. *J. Am. Chem. Soc.* **1952**, *74*, 5880–5884. (d) Weil, J. K.; Smith, F. D.; Stirton, A. J. *J. Org. Chem.* **1962**, *27*, 2950–2952. (e) Sheehan, J. C.; Zoller, U. *J. Org. Chem.* **1974**, *39*, 3415–3416. (f) Sugaya, H. Jpn Kokai Tokkyo Koho JP-59202219, November 16, 1984.
9. (a) Noyori, R.; Ohkuma, T.; Kitamura, M.; Takaya, H.; Sayo, N.; Kumobayashi, H.; Akutagawa, S. *J. Am. Chem. Soc.* **1987**, *109*, 5856–5858. (b) Kitamura, M.; Ohkuma, T.; Inoue, S.; Sayo, N.; Kumobayashi, H.; Akutagawa, S.; Ohta, T.; Takaya, H.; Noyori, R. *J. Am. Chem. Soc.* **1988**, *110*, 629–631.
10. Kitamura, M.; Tokunaga, M.; Noyori, R. *J. Am. Chem. Soc.* **1995**, *117*, 2931–2932.
11. Kitamura, M.; Tokunaga, M.; Ohkuma, T. Noyori, R. *Org. Synth.* **1992**, *71*, 1–13.
12. (a) Parkes, G. D.; Tinsley, S. G. *J. Chem. Soc.* **1934**, 1861–1864. (b) Fridovich, I. *J. Biol. Chem.* **1968**, *243*, 1043–1051.
13. (a) Taber, D. F.; Silverberg, L. J. *Tetrahedron Lett.* **1991**, *32*, 4227–4230. (b) King, S. A.; Thompson, A. S.; King, A. O.; Verhoeven, T. R. *J. Org. Chem.* **1992**, *57*, 6689–6691. (c) Genêt, J.-P.; Ratovelomanana-Vidal, V.; Caño de Andrade, M. C.; Pfister, X.; Guerreiro, P.; Lenoir, J. Y. *Tetrahedron Lett.* **1995**, *36*, 4801–4804. (d) Pye, P. J.; Rossen, K.; Reamer, R. A.; Volante, R. P.; Reider, P. J. *Tetrahedron Lett.* **1998**, *39*, 4441–4444.
14. (a) Kusumi, T.; Ohtani, I.; Inouye, Y.; Kakisawa, H. *Tetrahedron Lett.* **1988**, *29*, 4731–4734. (b) Ohtani, I.; Kusumi, T.; Ishitsuka, M. O.; Kakisawa, H. *Tetrahedron Lett.* **1989**, *30*, 3147–3150. (c) Kusumi, T.; Fujita, Y.; Ohtani, I.; Kakisawa, H. *Tetrahedron Lett.* **1991**, *32*, 2923–2926. (d) Ohtani, I.; Kusumi, T.; Kashman, Y.; Kakisawa, H. *J. Org. Chem.* **1991**, *56*, 1296–1298. (e) Ohtani, I.; Kusumi, T.; Kashman, Y.; Kakisawa, H. *J. Am. Chem. Soc.* **1991**, *113*, 4092–4096.
15. (a) Bennett, M. A.; Matheson, T. W. "Catalysis by Ruthenium Compounds", in *Comprehensive Organometallic Chemistry*; Wilkinson, G.; Stone, F. G. A.; Abel, E. W., Eds.; Pergamon Press: Oxford, 1982; Vol. 4, Chapter 32.9. (b) Jardine, F. H. *Prog. Inorg. Chem.* **1984**, *31*, 265–370.
16. (a) Ohta, T.; Takaya, H.; Noyori, R. *Tetrahedron Lett.* **1990**, *31*, 7189–7192. (b) Ashby, M. T.; Halpern, J. *J. Am. Chem. Soc.* **1991**, *113*, 589–594.
17. (a) Hallman, P. S.; McGarvey, B. R.; Wilkinson, G. *J. Chem. Soc. A* **1968**, 3143–3150. (b) James, B. R. *Inorg. Chim. Acta Rev.* **1970**, 73–95. (c) Mezzetti, A.; Costella, L.; Del Zotto, A.; Rigo, P.; Consiglio, G. *Gazz. Chim. Ital.* **1993**, *123*, 155–164.

18. Kitamura, M.; Yoshimura, M.; Tsukamoto, M.; Noyori, R. *Enantiomer* **1996**, *1*, 281–303.

19. Kitamura, M.; Tokunaga, M. Noyori, R. *J. Org. Chem.* **1992**, *57*, 4053–4054.

20. (a) Miyashita, A.; Yasuda, A.; Takaya, H.; Toriumi, K.; Ito, T.; Souchi, T.; Noyori, R. *J. Am. Chem. Soc.* **1980**, *102*, 7932–7934. (b) Miyashita, A.; Takaya, H.; Souchi, T.; Noyori, R. *Tetrahedron* **1984**, *40*, 1245–1253.

21. (a) Grot, W. G. *J. Org. Chem.* **1965**, *30*, 515–517. (b) Krespan, C. G.; Smart, B. E.; Howard, E. G. *J. Am. Chem. Soc.* **1977**, *99*, 1214–1217. (c) Hofmann, K.; Simchen, G. *Synthesis* **1979**, 699–700. (d) Krespan, C. G. *J. Org. Chem.* **1979**, *44*, 4924–4929. (e) Yoshino, N.; Abe, M. *Chemistry and Chemical Industry* **1995**, *48*, 524–526.

22. Henriques, R. G.; Widlanski, T. S.; Xu, T.; Lambeth, J. D. *J. Am. Chem. Soc.* **1992**, *114*, 7311–7313.

23. Padmapriya, A. A.; Just, G.; Lewis, N. G. *Synth. Commun.* **1985**, *15*, 1057–1062.