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Rhodium-catalyzed asymmetric arylation of α,β-unsaturated imines with arylstannanes. Catalytic asymmetric synthesis of allylic amines

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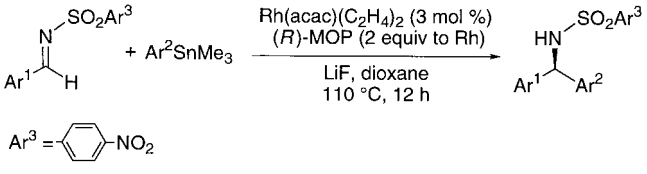
Abstract—Catalytic asymmetric arylation of *N*-alkylidenesulfonamides **1a**–**d**, which are prepared from α,β-unsaturated aldehydes and 4-nitrobenzenesulfonamide, with aryltrimethylstannanes **2m**–**p** proceeded in the presence of 3 mol% of a rhodium catalyst coordinated with (*R*)-MOP ligand in dioxane at 110°C to give sulfonamide of allylic amines (*R*)-**3** with high enantioselectivity (up to 96% ee) in high yields. Some of the allylic amines were converted in to the sulfonamide of (*S*)-phenylglycine without loss of enantiomeric purity by oxidative cleavage of the carbon–carbon double bond.

1. Introduction

Enantiomerically pure allylic amines are important molecules because of their synthetic utility as precursors to α-amino acids as well as their biological activity, and considerable efforts have been made to construct these molecules by means of asymmetric catalysis.[1] The stereogenic carbon center in the allylic amines is bonded to one hydrogen atom, two alkyl carbon substituents, and one amino group. Thus, the asymmetric synthesis of these amines can be accomplished by enantioselective formation of a new bond between either carbon–hydrogen, carbon–carbon, or carbon–nitrogen bond on the stereogenic carbon atom. The examples of the catalytic asymmetric reactions which correspond to the enantioselective bond formation described above are asymmetric reduction of imines derived from unsymmetrical ketones,[1–3] asymmetric addition of organometallic reagents to imines of aldehydes,[1,2] and asymmetric allylic amination,[1,4] respectively. Of these methods, the asymmetric addition to imines is most interesting because a new chiral carbon skeleton is created in a catalytic enantioselective fashion. Unfortunately, however, only a few examples have been reported where high enantioselectivity is achieved in this type of carbon–carbon bond forming reactions.[5] We have previously reported that a rhodium complex coordinated with chiral monodentate phosphine (MOP) catalyzes asymmetric arylation of imines, *N*-alkylidenesulfonamides, with arylstannanes to give sulfonamide of diarylmethylamines with high enantioselectivity (up to 96% ee) in high yields (Scheme 1).[6] This asymmetric reaction provides a new efficient route to optically active diarylmethylamines, some of which are biologically active compounds.[7] Here we wish to report that imines of α,β-unsaturated aldehydes also underwent the rhodium-catalyzed asymmetric arylation on the carbon–nitrogen double bond to give sulfonamides of allylic amines of high enantiomeric purity, which can be readily converted into arylglycines.

2. Results and discussion

Sulfonamides **1** were prepared by the reaction of α,β-unsaturated aldehydes with 4-nitrobenzenesulfonamide in the presence of tetraethoxysilane as a dehydrating reagent.[8] The sulfonamide containing 4-nitro group was used because the sulfonyl protecting group is readily removed from nitrogen by treatment with a thiophenoxide[9] and the imine of 4-nitrobenzenesulfonamide was found to be more reactive than other sulfonamides towards the rhodium-catalyzed arylation in our previous studies.[6] As R groups in α,β-unsaturated imines **1**, aryl groups were chosen because the imines containing alkyl groups could not be isolated pure. The phenylation of sulfonamide of (*E*)-3-phenyl-2-propenal



Scheme 1. Ar^1, Ar^2=Ph, 4-$CF_3C_6H_4$, 4-FC_6H_4, 4-ClC_6H_4, 4-$MeOCOC_6H_4$, 4-$MeOC_6H_4$.

Keywords: catalytic asymmetric synthesis; rhodium catalysis; asymmetric arylation; optically active allylamine; amino acid.

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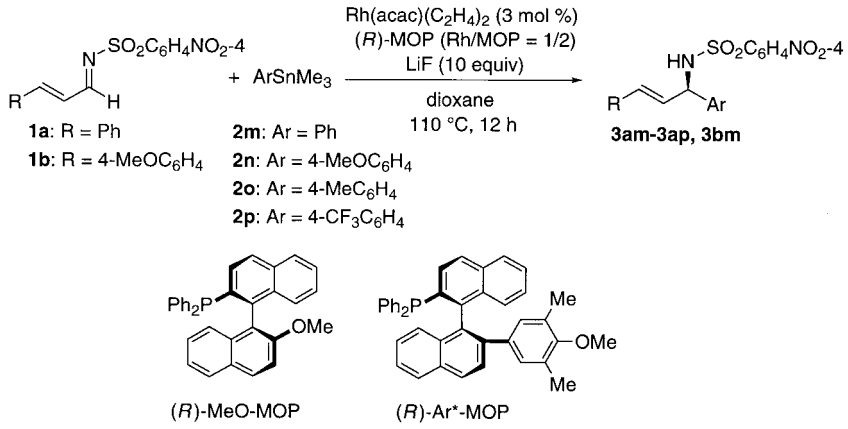


Scheme 2.

1a with phenyltrimethylstannane (**2m**) was carried out under the reaction conditions which were used for the reaction of sulfonamides of aromatic aldehydes.[6] Thus, a mixture of **1a**, **2m** (5 equiv. to **1a**), lithium fluoride (10 equiv.), and 3 mol% of the catalyst generated from $Rh(acac)(C_2H_4)_2$ and (*R*)-MeO–MOP in dioxane was heated in a sealed tube at 110°C for 12 h. Aqueous work-up followed by chromatography on a silica gel column with ethyl acetate as an eluent gave 75% yield of the sulfonamide of (*E*)-1,3-diphenyl-2-propenylamine **3am** (Scheme 2). Its enantiomeric purity was determined to be 88% ee by HPLC analysis with a chiral stationary phase column (entry 1 in Table 1), and the absolute configuration was determined to be (−)-(*R*) by correlation with (*S*)-phenylglycine (vide infra). Under the present reaction conditions, the addition proceeded in a 1,2-fashion exclusively, the 1,4-addition product being not detected at all. The addition of lithium fluoride to the reaction mixture is not essential for the phenylation reaction to proceed, but the reproducibility in the chemical yield of **3am** was higher in the presence of lithium fluoride than in its absence. A higher enantioselectivity (93% ee) was observed with (*R*)-Ar*–MOP which contains 3,5-dimethyl-4-methoxyphenyl group in place of methoxy at the 2′ position of the MOP ligand (entry 2). The (*R*)-Ar*–MOP was prepared in 58% yield by nickel-catalyzed cross-coupling of the 3,5-dimethyl-4-methoxyphenyl Grignard reagent with (*R*)-TfO–MOP[10] which was obtained from 2,2′-dihydroxy-1,1′-binaphthyl by a sequence of reactions including palladium-catalyzed monophosphinylation of binaphthyl ditriflate as a key step[11,12] (Scheme 3).

The asymmetric arylation of imine **1a** also proceeded with phenylstannanes substituted at the *para*-position with electron-donating or electron-withdrawing groups **2n**–**p**, though the enantioselectivity was a little lower than that in the reaction with unsubstituted phenylstannane **2m** (entries 3–8). In the reaction of imine **1a**, Ar*–MOP ligand always showed higher enantioselectivity than MeO–MOP ligand (entries 1–8).

N-Alkylidenesulfonamides **1c** and **1d**, which were prepared from α,β-unsaturated aldehydes containing two substituents at the β-position, were also subjected to the rhodium-catalyzed

Table 1. Catalytic asymmetric arylation of imines **1** with arylstannanes **2** catalyzed by rhodium/(*R*)-MOP complexes

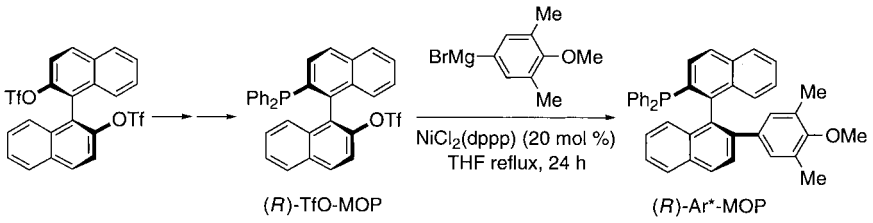
Entry	Imine **1**	Ar in $ArSnMe_3$ **2**	(*R*)-MOP	Yield (%)[a] of **3**	% ee[b] of **3**	$[\alpha]_D^{20}$ (*c* in $CHCl_3$)
1	**1a**	Ph (**2m**)	MeO–MOP	75 (**3am**)	88 (*R*)[c]	
2	**1a**	Ph (**2m**)	Ar*–MOP	77 (**3am**)	93 (*R*)[c]	−15.9 (0.50)
3	**1a**	4-$MeOC_6H_4$ (**2n**)	MeO–MOP	68 (**3an**)	52	
4	**1a**	4-$MeOC_6H_4$ (**2n**)	Ar*–MOP	70 (**3an**)	79	−4.0 (0.50)
5	**1a**	4-MeC_6H_4 (**2o**)	MeO–MOP	67 (**3ao**)	74	
6	**1a**	4-MeC_6H_4 (**2o**)	Ar*–MOP	67 (**3ao**)	80	−7.1 (0.50)
7	**1a**	4-$CF_3C_6H_4$ (**2p**)	MeO–MOP	46 (**3ap**)	68	
8	**1a**	4-$CF_3C_6H_4$ (**2p**)	Ar*–MOP	63 (**3ap**)	90	−17.3 (0.50)
9	**1b**	Ph (**2m**)	MeO–MOP	65 (**3bm**)	92	
10	**1b**	Ph (**2m**)	Ar*–MOP	74 (**3bm**)	89	−9.8 (0.50)
11	**1c**	Ph (**2m**)	MeO–MOP	80 (**3cm**)	95 (*R*)[c]	
12	**1c**	Ph (**2m**)	Ar*–MOP	92 (**3cm**)	96 (*R*)[c]	−123 (0.50)
13	**1c**	4-$MeOC_6H_4$ (**2n**)	MeO–MOP	79 (**3cn**)	90	
14	**1c**	4-$MeOC_6H_4$ (**2n**)	Ar*–MOP	95 (**3cn**)	96	−154 (0.50)
15	**1d**	Ph (**2m**)	MeO–MOP	82 (**3dm**)	95	
16	**1d**	Ph (**2m**)	Ar*–MOP	93 (**3dm**)	96	−65.8 (0.50)

The reaction was carried out in dioxane at 110°C for 12 h with 5 equiv. of **2** in the presence of LiF (10 equiv. to imine) and 3 mol% of the catalyst generated from $Rh(acac)(C_2H_4)_2$ and (*R*)-MOP.

[a] Isolated yields by column chromatography on silica gel (pretreated with methanol and dried) using ethyl acetate as an eluent.

[b] Determined by HPLC analysis with chiral stationary phase column, Daicel Chiralcel OD-H. Eluent: hexane/2-propanol=8/2 for **3am**, **3ao**, **3ap**, and **3bm** and hexane/2-propanol=9/1 for **3an**, **3cm**, **3cn**, and **3dm**.

[c] Determined by conversion into *N*-(4-nitrobenzenesulfonyl)phenylglycine methyl ester (**4**). See also text.



Scheme 3.

asymmetric arylation (Scheme 4). The chemical yields of the arylation products **3cm**, **cn** and **3dm** are generally very high and the enantioselectivity was over 90%, higher than that in the reaction of imines **1a** and **1b** (entries 11–16 in Table 1). The enantioselectivity of 96% was observed in the phenylation and 4-methoxyphenylation of **1c** and **1d** catalyzed by the rhodium complex coordinated with Ar*–MOP ligand (entries 12, 14, and 16).

The asymmetric phenylation products **3am** and **3cm** were converted into a phenylglycine derivative by oxidation of the carbon–carbon double bond. Thus, the oxidation of (−)-**3am** (88% ee), obtained by the phenylation catalyzed by rhodium/(*R*)-MeO–MOP (entry 1 in Table 1), with ruthenium chloride and sodium periodate[13] followed by esterification of the carboxylic acid with diazomethane gave methyl *N*-4-nitrobenzenesulfonylphenylglycinate (**4**) whose specific rotation is $[\alpha]^{20}_{D}=+72.2$ (*c* 1.0, chloroform). The authentic sample of (*S*)-**4** prepared from (*S*)-(+)-α-phenylglycine (100% ee) showed $[\alpha]^{20}_{D}=+77.6$ (*c* 1.0, chloroform), indicating that the absolute configuration of (−)-**3am** is (*R*) and the oxidation proceeded without significant loss of the enantiomeric purity (Scheme 5). The absolute configuration of (−)-**3cm** was also determined to be (*R*) by the conversion into (+)-(*S*)-**4** in a similar manner.

3. Conclusions

In summary, we have shown that the rhodium-catalyzed asymmetric addition of aryltin reagents can be successfully applied to sulfonamides of α,β-unsaturated aldehydes. The enantioselectivity was generally very high, over 90% ee in the addition of phenyltrimethylstannane. The sulfonamides of optically active allylic amines were readily converted in to an α-amino acid derivative without loss of enantiomeric purity by oxidative cleavage of the carbon–carbon double bond.

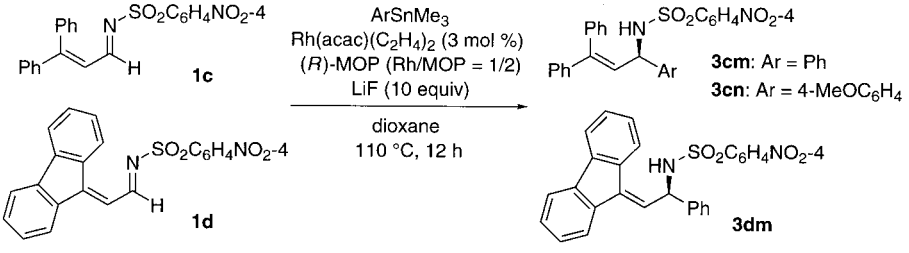
4. Experimental

4.1. General

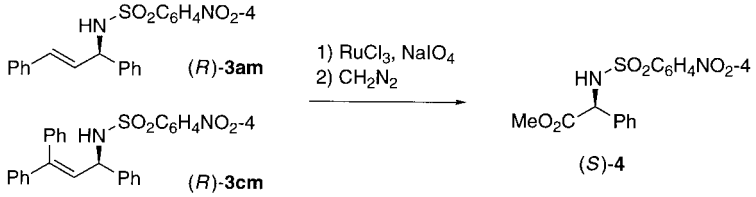
All moisture sensitive manipulations were carried out under a nitrogen atmosphere. Nitrogen gas was dried by passage through P_2O_5. Optical rotations were recorded with a JASCO DIP-370 polarimeter. NMR spectra were recorded on a JEOL JNM LA500 spectrometer (500 MHz for ^1H and 125 MHz for ^{13}C) in $CDCl_3$. Chemical shifts are reported in δ ppm referenced to an internal $SiMe_4$ standard for ^1H NMR. Residual chloroform (δ 77.0 for ^{13}C) was used as internal reference for ^{13}C NMR. HPLC analysis was performed on a Shimadzu LC-9A and JASCO PU-980 liquid chromatograph system with chiral stationary phase column, Daicel Chiralcel OD-H.

4.2. Materials

Tetrahydrofuran, 1,4-dioxane and diethyl ether were distilled from benzophenone-ketyl under nitrogen prior to



Scheme 4.



Scheme 5.

use. Dichloromethane, 1,2-dimethoxyethane and dimethylformamide were distilled from CaH_2 under nitrogen. Dess–Martin reagent,[14] $Rh(acac)(C_2H_4)_2$,[15] and (*R*)-MeO–MOP[12] were prepared according to the reported procedures.

4.3. Preparation of (*R*)-2-(diphenylphosphino)-2′-(3,5-dimethyl-4-methoxyphenyl)-1,1′-binaphthyl (Ar*–MOP)

A mixture of (*R*)-2-(diphenylphosphino)-2′-(trifluoromethanesulfonyloxy)-1,1′-binaphthyl (1.12 g, 1.91 mmol), dichloro-[1,3-bis(diphenylphosphino)propane]nickel (0.202 g, 0.38 mmol), and 3,5-dimethyl-4-methoxyphenylmagnesium bromide (1.5 M, 9 mL, in tetrahydrofuran) was refluxed for 24 h under nitrogen. After cooling to room temperature, the reaction mixture was quenched with saturated ammonium chloride (20 mL) on ice bath, and extracted with diethyl ether. The extract was dried over anhydrous $MgSO_4$ and concentrated in vacuo. The residue was chromatographed on silica gel (hexane/ethyl acetate=5/1) to give 0.634 g (58% yield) of (*R*)-2-(diphenylphosphino)-2′-(3,5-dimethyl-4-methoxyphenyl)-1,1′-binaphthyl (Ar*–MOP): $[\alpha]^{20}_D$=+183 (*c* 1.00, chloroform); ^{1}H NMR ($CDCl_3$) δ 1.83 (s, 6H), 3.61 (s, 3H), 6.61 (s, 2H), 6.65 (t, *J*=6.8 Hz, 2H), 6.83 (d, *J*=8.3 Hz, 1H), 6.90 (t, *J*=6.8 Hz, 2H), 7.00 (t, *J*=7.3 Hz, 1H), 7.04 (t, *J*=7.3 Hz, 2H), 7.09 (t, *J*=6.8 Hz, 2H), 7.12 (t, *J*=7.8 Hz, 1H), 7.17 (t, *J*=7.3 Hz, 1H), 7.22 (dd, *J*=8.8, 2.9 Hz, 1H), 7.35 (t, *J*=8.3 Hz, 1H), 7.36 (t, *J*=3.9 Hz, 1H), 7.45 (d, *J*=8.8 Hz, 1H), 7.50 (t, *J*=6.8 Hz, 1H), 7.63 (d, *J*=8.3 Hz, 1H), 7.74 (d, *J*=8.8 Hz, 1H), 7.86 (d, *J*=8.3 Hz, 1H), 7.91 (d, *J*=8.3 Hz, 1H), 8.03 (d, *J*=8.3 Hz, 1H); ^{31}P{^{1}H}NMR δ −19.54 (s). Anal. Calcd for $C_{41}H_{33}PO$: C, 85.99; H, 5.81. Found: C, 85.71; H, 5.91.

4.4. Preparation of 9-fluorenylideneacetaldehyde

According to Wadsworth's procedures,[16] 9-fluorenylideneacetaldehyde was prepared as follows: Triethyl phosphonoacetate (16.8 g, 75 mmol) was added dropwise at 20°C to a slurry of 60% sodium hydride (3.0 g, 75 mmol) in 1,2-dimethoxyethane (100 mL), and the mixture was stirred at room temperature for 1 h. 9-Fluorenone (13.5 g, 75 mmol) was added dropwise to the solution and the mixture was refluxed for 48 h. A large excess of water was added, and the solution was extracted with ethyl acetate. The extract was dried over magnesium sulfate and concentrated in vacuo. The residue was chromatographed on silica gel (hexane/ethyl acetate) to give 11.1 g (59% yield) of ethyl 9-fluorenylideneacetate: ^{1}H NMR ($CDCl_3$) δ 1.39 (t, *J*=7.4 Hz, 3H), 4.34 (q, *J*=7.4 Hz, 2H), 6.74 (s, 1H), 7.25 (t, *J*=7.4 Hz, 1H), 7.30 (t, *J*=7.4 Hz, 1H), 7.37 (t, *J*=7.4 Hz, 1H), 7.39 (t, *J*=7.4 Hz, 1H), 7.60 (d, *J*=7.8 Hz, 1H), 7.62 (d, *J*=8.3 Hz, 1H), 7.65 (d, *J*=7.8 Hz, 1H), 8.89 (d, *J*=8.3 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 14.36, 60.67, 113.92, 119.54, 119.74, 121.22, 127.44, 128.03, 129.20, 130.52, 130.85, 135.19, 138.84, 140.74, 142.49, 148.23, 166.29. To a solution of ethyl 9-fluorenylideneacetate (5.00 g, 20 mmol) in toluene was added 40 mL of DIBAH in toluene (1M solution) at −78°C. The mixture was stirred at −78°C for 4 h, and sodium sulfate decahydrate was added. It was diluted with *n*-hexane and sodium sulfate was added. The mixture was kept stirring at room temperature for 1 h. The salts were filtered off and washed with acetone. The filtrate was stripped of solvent. The precipitates formed were filtered off and washed with Et_2O. Removal of the solvent from the filtrate gave 3.07 g (75% yield) of 9-fluorenylidenemethanol: ^{1}H NMR ($CDCl_3$) δ 1.81 (t, *J*=5.9 Hz, 3H), 4.99 (t, *J*=5.9 Hz, 2H), 6.81 (t, *J*=5.9 Hz, 1H), 7.27–7.40 (m, 4H), 7.60 (d, *J*=7.9 Hz, 1H), 7.68 (t, *J*=8.3 Hz, 2H), 7.73 (d, *J*=7.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 60.57, 119.62, 119.97, 120.16, 125.19, 127.16, 127.17, 128.15, 128.41, 128.43, 136.05, 136.69, 138.75, 139.23, 141.08. To a solution of 9-fluorenylidenemethanol (1.46 g, 7 mmol) in CH_2Cl_2 was carefully added Dess–Martin reagent (3.57 g, 8.4 mmol) in small portions. After 24 h the solution was extracted with CH_2Cl_2 and the extract was washed with 1 M NaOH solution, water and brine, and dried over sodium sulfate. Evaporation of the solvent gave 1.35 g (93% yield) of 9-fluorenylideneacetaldehyde: ^{1}H NMR ($CDCl_3$) δ 6.82 (d, *J*=8.3 Hz, 1H), 7.29 (t, *J*=7.4 Hz, 1H), 7.30 (t, *J*=7.4 Hz, 1H), 7.42 (t, *J*=7.4 Hz, 1H), 7.45 (t, *J*=7.4 Hz, 1H), 7.62 (d, *J*=7.4 Hz, 1H), 7.66 (d, *J*=7.4 Hz, 2H), 8.01 (d, *J*=7.4 Hz, 1H), 10.84 (d, *J*=8.3 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 120.13, 120.48, 122.29, 122.94, 127.58, 127.95, 131.15, 131.39, 131.50, 135.51, 138.15, 141.09, 142.68, 151.22, 190.09.

4.5. Preparation of imines (1a–d)

Imines **1a–d** were prepared according to the procedures reported[8] for the synthesis of imines by use of tetraethoxysilane as a dehydrating agent: a sulfonamide, an aldehyde (1.0–1.1 equiv.), and tetraethoxysilane (1.1 equiv.) were combined in a flask equipped with a Dean–Stark, and the mixture was heated at 160°C under nitrogen for 6 h. After cooling to room temperature, the reaction mixture was dissolved in warm ethyl acetate, treated with *n*-hexane, and allowed to stand at room temperature. The crystals were collected by filtration, washed with *n*-hexane, and dried.

4.5.1. *N*-[(*E*)-2-Phenylethenyl]methylidene-4-nitrobenzenesulfonamide (1a). ^{1}H NMR ($CDCl_3$) δ 7.01 (dd, *J*=15.5, 9.3 Hz, 1H), 7.43–7.51 (m, 3H), 7.58–7.62 (m, 3H), 8.17 (d, *J*=8.8 Hz, 2H), 8.38 (d, *J*=8.8 Hz, 2H), 8.86 (d, *J*=9.3 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 124.32, 124.37, 128.96, 129.23, 129.33, 132.26, 133.89, 144.50, 150.54, 155.91, 172.97. Anal. Calcd for $C_{15}H_{12}O_4N_2S$: C, 56.95; H, 3.82. Found: C, 56.69; H, 3.85.

4.5.2. *N*-[(*E*)-2-(4-Methoxyphenyl)ethenyl]methylidene-4-nitrobenzenesulfonamide (1b). ^{1}H NMR ($CDCl_3$) δ 3.87 (s, 3H), 6.88 (dd, *J*=15.7, 9.8 Hz, 1H), 6.95 (d, *J*=8.8 Hz, 2H), 7.54 (d, *J*=15.7 Hz, 2H), 7.55 (d, *J*=8.8 Hz, 1H), 8.16 (d, *J*=9.3 Hz, 2H), 8.37 (d, *J*=9.3 Hz, 2H), 8.82 (d, *J*=9.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 55.59, 114.88, 121.95, 124.27, 126.82, 129.10, 131.13, 144.91, 150.44, 156.02, 163.19, 173.12. Anal. Calcd for $C_{16}H_{14}O_5N_2S$: C, 55.48; H, 4.07. Found: C, 55.35; H, 4.21.

4.5.3. *N*-(2,2-Diphenylethenyl)methylidene-4-nitrobenzenesulfonamide (1c). ^{1}H NMR ($CDCl_3$) δ 6.94 (d, *J*=9.8 Hz, 1H), 7.24 (d, *J*=7.9 Hz, 2H), 7.36 (d, *J*=7.9 Hz, 2H), 7.40 (t, *J*=7.9 Hz, 2H), 7.46 (t, *J*=7.9 Hz, 1H), 7.49 (t, *J*=7.9 Hz, 2H), 7.55 (t, *J*=7.9 Hz, 1H), 8.12 (d, *J*=

8.8 Hz, 2H), 8.37 (d, *J*=8.8 Hz, 2H), 8.65 (d, *J*=9.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 123.34, 124.22, 128.70, 128.75, 129.15, 129.18, 130.33, 130.65, 131.33, 136.54, 139.41, 144.53, 150.42, 166.77, 171.29. Anal. Calcd for $C_{21}H_{16}O_4N_2S$: C, 64.27; H, 4.11. Found: C, 64.01; H, 4.24.

4.5.4. *N*-(9-Fluorenylidenemethyl)methylidene-4-nitrobenzenesulfonamide (1d). ^{1}H NMR (CD_2Cl_2) δ 7.30 (d, *J*=10.8 Hz, 1H), 7.40 (t, *J*=7.8 Hz, 1H), 7.47 (t, *J*=7.8 Hz, 1H), 7.56 (t, *J*=7.4 Hz, 1H), 7.60 (t, *J*=7.4 Hz, 1H), 7.74 (d, *J*=7.4 Hz, 1H), 7.79 (d, *J*=7.8 Hz, 1H), 7.81 (d, *J*=7.8 Hz, 1H), 8.04 (d, *J*=7.4 Hz, 1H), 8.31 (d, *J*=8.8 Hz, 2H), 8.50 (d, *J*=8.8 Hz, 2H), 9.96 (d, *J*=10.8 Hz, 1H); ^{13}C NMR (CD_2Cl_2) δ 110.98, 119.86, 120.73, 121.20, 123.20, 124.77, 127.84, 128.60, 128.68, 129.72, 132.50, 132.69, 135.52, 138.19, 141.72, 143.44, 155.88, 168.34. Anal. Calcd for $C_{21}H_{14}O_4N_2S$: C, 64.61; H, 3.61. Found: C, 64.33; H, 3.33.

4.6. Preparation of arylstannanes (2m–p)

A typical procedure is given for the preparation of **phenyltrimethylstannane** (**2m**). A general procedure is shown below: to a solution of trimethyltin chloride (7.97 g, 40.0 mmol) in 20 mL of THF was added phenylmagnesium bromide (80 mL, 1.0 M THF solution, 80.0 mmol). The mixture was refluxed for 1 h. After cooling to room temperature, the reaction mixture was quenched with saturated ammonium chloride (20 mL) on ice bath and extracted with diethyl ether. The organic layer was washed with saturated $NaHCO_3$, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The residue was purified by bulb-to-bulb distillation under reduced pressure to give 9.62 g (quantitative yield) of phenyltrimethylstannane.

4.6.1. Phenyltrimethylstannane (2m). ^{1}H NMR ($CDCl_3$) δ 0.28 (s, 9H), 7.33 (t, *J*=6.9 Hz, 3H), 7.49 (d, *J*=5.9 Hz, 2H).

4.6.2. 4-Methoxyphenyltrimethylstannane (2n). ^{1}H NMR ($CDCl_3$) δ 0.26 (s, 9H), 3.80 (s, 3H), 6.92 (d, *J*=8.4 Hz, 2H), 7.40 (d, *J*=8.4 Hz, 2H).

4.6.3. 4-Tolyltrimethylstannane (2o). ^{1}H NMR ($CDCl_3$) δ 0.26 (s, 9H), 2.33 (s, 3H), 7.17 (d, *J*=7.4 Hz, 2H), 7.39 (d, *J*=7.4 Hz, 2H).

4.6.4. 4-Trifluoromethylphenyltrimethylstannane (2p). ^{1}H NMR ($CDCl_3$) δ 0.32 (s, 9H), 7.55 (d, *J*=7.3 Hz, 2H), 7.61 (d, *J*=7.3 Hz, 2H).

4.7. Rhodium-catalyzed asymmetric arylation of imines with organostannanes (3am, 3an, 3ao, 3ap, 3bm, 3cm, 3cn, 3dm)

The reactions conditions and results are summarized in Table 1. A typical procedure is given for the preparation of *N*-[(*E*)-2-phenylethenyl)phenylmethyl]-4-nitrobenzenesulfonamide (**3am**) (entry 1, Table 1): Phenyltrimethylstannane (482 mg, 2.00 mmol) and 1,4-dioxane (0.6 mL) were added to a pressure bottle charged with lithium fluoride (104 mg, 4.00 mmol), Rh(acac)$(C_2H_4)_2$ (3.1 mg, 12 μmol), (*R*)-MeO–MOP (12.4 mg, 26 μmol), and *N*-[(*E*)-2-Phenylethenyl]methylidene-4-nitrobenzenesulfonamide (127 mg, 0.40 mmol; **1a**). The bottle was sealed under nitrogen. The mixture was stirred at 110°C for 12 h and concentrated in vacuo. The residue was dissolved in dichloromethane, washed with water, dried over anhydrous $MgSO_4$, and evaporated. The residue was chromatographed on a silica gel column (COSMOSIL 75SL-II-PREP, 18 mmϕ ×30 mm, pretreated with methanol and dried) with ethyl acetate as an eluent to give 119 mg (75% yield) of **3am**. Analytically pure sample was obtained by preparative thin-layer chromatography on silica gel (hexane/ethyl acetate=2/1). Chiral stationary phase columns and eluents used for the determination of enantiomeric purities of the arylation products are shown in Table 1.

4.7.1. *N*-[(*E*)-2-(Phenylethenyl)phenylmethyl]-4-nitrobenzenesulfonamide (3am). $[\alpha]^{20}_D$=−15.9 (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 5.18 (s, 1H), 5.25 (t, *J*=6.9 Hz, 1H), 6.09 (dd, *J*=15.5, 6.9 Hz, 1H), 6.41 (d, *J*=15.7 Hz, 1H), 7.16–7.21 (m, 4H), 7.22–7.29 (m, 6H), 7.85 (d, *J*=8.8 Hz, 2H), 8.11 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 60.28, 123.92, 126.46, 127.11, 127.29, 128.33, 128.44, 128.45, 128.68, 128.91, 133.08, 135.46, 138.67, 146.67, 149.67. Anal. Calcd for $C_{21}H_{18}O_4N_2S$: C, 63.94; H, 4.60. Found: C, 63.70; H, 4.65.

4.7.2. *N*-[(*E*)-2-(Phenylethenyl)(4-methoxyphenyl)methyl]-4-nitrobenzenesulfonamide (3an). $[\alpha]^{20}_D$=−4.0 (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 3.76 (s, 3H), 6.08 (dd, *J*=15.7, 6.9 Hz, 1H), 6.40 (d, *J*=15.7 Hz, 1H), 6.76 (d, *J*=8.8 Hz, 2H), 7.09 (d, *J*=8.8 Hz, 2H), 7.19 (d, *J*=7.9 Hz, 2H), 7.22–7.32 (m, 5H), 7.86 (d, *J*=8.8 Hz, 2H), 8.14 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 55.34, 59.78, 114.21, 123.90, 126.44, 127.51, 128.37, 128.39, 128.49, 128.67, 130.73, 132.77, 135.54, 146.76, 149.65, 159.57. Anal. Calcd for $C_{22}H_{20}O_5N_2S$: C, 62.25; H, 4.75. Found: C, 61.98; H, 4.59.

4.7.3. *N*-[(*E*)-2-(Phenylethenyl)(4-tolyl)methyl]-4-nitrobenzenesulfonamide (3ao). $[\alpha]^{20}_D$=−7.1 (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 2.29 (s, 3H), 5.04 (d, *J*=6.9 Hz, 1H), 5.20 (t, *J*=6.9 Hz, 1H), 6.08 (dd, *J*=16.1, 6.9 Hz, 1H), 6.41 (d, *J*=15.7 Hz, 1H), 7.04 (s, 4H), 7.17–7.30 (m, 5H), 7.85 (d, *J*=8.8 Hz, 2H), 8.12 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 20.96, 60.02, 123.82, 126.40, 126.99, 127.48, 128.29, 128.41, 128.59, 129.08, 129.43, 132.69, 135.53, 138.19, 146.65, 149.53. Anal. Calcd for $C_{22}H_{20}O_4N_2S$: C, 64.69; H, 4.94. Found: C, 64.40; H, 4.86.

4.7.4. *N*-[(*E*)-2-(Phenylethenyl)(4-trifluoromethylphenyl)-methyl]-4-nitrobenzenesulfonamide (3ap). $[\alpha]^{20}_D$=−17.3 (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 5.03 (d, *J*=6.9 Hz, 1H), 5.31 (t, *J*=6.9 Hz, 1H), 6.05 (dd, *J*=15.7, 7.3 Hz, 1H), 6.40 (d, *J*=15.7 Hz, 2H), 7.19 (d, *J*=7.8 Hz, 2H), 7.23–7.28 (m, 2H), 7.36 (d, *J*=7.8 Hz, 2H), 7.53 (d, *J*=7.8 Hz, 2H), 7.88 (d, *J*=8.8 Hz, 2H), 8.17 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 59.85, 123.62 (q, *J*=272 Hz), 124.41, 125.77 (q, *J*=3.6 Hz), 126.19, 126.50, 127.58, 128.40, 128.73, 128.75, 130.48 (q, *J*=33 Hz), 133.82, 135.09, 142.77, 146.30, 149.79. Anal. Calcd for $C_{22}H_{17}O_4N_2SF_3$: C, 57.14; H, 3.71. Found: C, 56.88; H, 3.65.

4.7.5. *N*-[(*E*)-2-(4-Methoxyphenylethenyl)phenylmethyl]-

4-nitrobenzenesulfonamide (3bm)$[\alpha]^{20}_D=-9.8$ (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 3.79 (s, 3H), 5.10 (d, *J*=6.9 Hz, 1H), 5.22 (t, *J*=6.9 Hz, 1H), 5.93 (dd, *J*=15.7, 6.9 Hz, 1H), 6.34 (d, *J*=15.7 Hz, 1H), 6.79 (d, *J*=8.8 Hz, 2H), 7.12 (d, *J*=8.8 Hz, 2H), 7.17 (d, *J*=6.9 Hz, 2H), 7.22–7.26 (m, 3H), 7.84 (d, *J*=8.8 Hz, 2H), 8.10 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 55.32, 60.44, 114.07, 123.88, 125.06, 127.09, 127.73, 128.17, 128.43, 128.65, 128.82, 132.56, 138.92, 146.70, 149.59, 159.79. Anal. Calcd for $C_{22}H_{20}O_5N_2S$: C, 62.25; H, 4.75. Found: C, 62.00; H, 4.53.

4.7.6. *N*-[(2,2-Diphenylethenyl)phenylmethyl]-4-nitrobenzenesulfonamide (3cm). $[\alpha]^{20}_D=-123$ (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 4.94 (d, *J*=5.4 Hz, 1H), 5.08 (dd, *J*=9.8, 5.4 Hz, 1H), 6.03 (d, *J*=9.8 Hz, 1H), 7.03 (t, *J*=9.3 Hz, 4H), 7.15–7.40 (m, 11H), 7.75 (d, *J*=8.8 Hz, 2H), 8.14 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 57.12, 123.94, 125.95, 127.09, 127.45, 128.07, 128.13, 128.18, 128.20, 128.36, 128.41, 128.94, 129.45, 138.11, 139.62, 140.85, 144.36, 146.22, 149.67. Anal. Calcd for $C_{27}H_{22}O_5N_2S$: C, 68.92; H, 4.71. Found: C, 68.95; H, 4.65.

4.7.7. *N*-[(2,2-Diphenylethenyl)(4-methoxyphenyl)methyl]-4-nitrobenzenesulfonamide (3cn). $[\alpha]^{20}_D=-154$ (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 3.77 (s, 3H), 5.00 (dd, *J*=9.3, 5.9 Hz, 1H), 5.22 (d, *J*=5.9 Hz, 1H), 6.01 (d, *J*=9.8 Hz, 1H), 6.78 (d, *J*=8.8 Hz, 2H), 6.98–7.04 (m, 4H), 7.09 (d, *J*=8.8 Hz, 2H), 7.20–7.25 (m, 3H), 7.33–7.38 (m, 3H), 7.75 (d, *J*=8.8 Hz, 2H), 8.14 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 55.32, 56.65, 114.32, 123.96, 126.26, 127.50, 128.08, 128.13, 128.23, 128.38, 128.41, 128.45, 129.52, 131.70, 138.21, 140.98, 144.08, 146.36, 149.74, 159.50. Anal. Calcd for $C_{28}H_{24}O_5N_2S$: C, 67.18; H, 4.83. Found: C, 67.06; H, 4.73.

4.7.8. *N*-[(9-Fluorenylidenemethyl)phenylmethyl]-4-nitrobenzenesulfonamide (3dm). $[\alpha]^{20}_D=-65.8$ (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$) δ 5.32 (d, *J*=7.3 Hz, 1H), 6.14 (d, *J*=9.6 Hz, 1H), 6.22 (dd, *J*=9.6, 7.3 Hz, 1H), 7.16 (t, *J*=7.4 Hz, 1H), 7.24 (d, *J*=7.8 Hz, 1H), 7.27–7.37 (m, 5H), 7.41 (t, *J*=7.4 Hz, 1H), 7.44 (d, *J*=7.8 Hz, 2H), 7.62 (d, *J*=7.8 Hz, 1H), 7.67 (d, *J*=8.8 Hz, 2H), 7.71 (d, *J*=7.4 Hz, 1H), 7.72 (d, *J*=7.8 Hz, 1H), 7.78 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 55.79, 100.58, 119.86, 120.24, 123.63, 124.69, 124.98, 127.01, 127.18, 127.63, 128.32, 128.64, 129.13, 129.17, 129.49, 135.59, 137.88, 138.03, 138.04, 139.03, 141.47. 145.96, 149.29. Anal. Calcd for $C_{27}H_{20}O_4N_2S$: C, 69.22; H, 4.30. Found: C, 69.34; H, 4.04.

4.8. Conversion of *N*-[(*E*)-2-(phenylethenyl)phenylmethyl]-4-nitrobenzenesulfonamide (3am) and *N*-[(2,2-diphenylethenyl)phenylmethyl]-4-nitrobenzenesulfonamide (3cm) into methyl *N*-4-nitrobenzenesulfonylphenylglycinate (4)

The oxidation was carried out according to the reported procedures:[13,17] to a solution of **3am** (118 mg, 0.30 mmol, 88% ee) in carbon tetrachloride (0.6 mL), acetonitrile (0.6 mL), and water (0.9 mL) was added sodium metaperiodate (263 mg, 1.23 mmol) and ruthenium trichloride hydrate (3.5 mg, 2.2 mol%). After the solution was stirred vigorously at 20°C for 18 h, the reaction mixture was diluted with Et_2O and extracted twice with saturated sodium bicarbonate solution. The basic extracts were acidified to pH 2 using 2 M HCl and extracted three times with Et_2O. The extracts were dried over anhydrous $MgSO_4$ and concentrated in vacuo. The residue was dissolved in Et_2O. Excess ethereal diazomethane was added and the mixture was stirred at room temperature for 1 h. Acetic acid was added to quench excess diazomethane and the solvent was evaporated. The residue was chromatographed by preparative TLC on silica gel (benzene/ethyl acetate=5/1) to give 41 mg (39% yield) of methyl *N*-4-nitrobenzenesulfonylphenylglycinate (**4**). Ester **4** was prepared from **3cm** (188 mg, 0.40 mmol, 96% ee) by a similar method to give 90 mg (26% yield): $[\alpha]^{20}_D=+72.2$ (*c* 1.00, chloroform) [A sample prepared from **3cm** gave $[\alpha]^{20}_D=+73.7$ (*c* 1.00, chloroform)]; ^{1}H NMR ($CDCl_3$) δ 3.66 (s, 3H), 5.18 (d, *J*=6.9 Hz, 1H), 5.89 (d, *J*=6.9 Hz, 1H), 7.15 (d, *J*=7.4 Hz, 2H), 7.20 (t, *J*=7.4 Hz, 2H), 7.25 (t, *J*=6.9 Hz, 1H), 7.78 (d, *J*=8.8 Hz, 2H), 8.14 (d, *J*=8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 53.37, 59.54, 123.90, 127.39, 128.23, 128.95, 129.02, 134.51, 146.09, 149.79, 170.11. Anal. Calcd for $C_{15}H_{14}O_6N_2S$: C, 51.42; H, 4.03. Found: C, 51.69; H, 4.21.

4.9. Preparation of methyl *N*-4-nitrobenzenesulfonylphenylglycinate (4) from (*S*)-(+)-α-phenylglycine

(*S*)-(+)-α-Phenylglycine (44 mg, 0.40 mmol) was suspended in 10 mL of dimethoxypropane, and to the suspension was added 1 mL of 36% aqueous hydrochloric acid. The mixture was stirred at 20°C for 18 h before the solvent was evaporated. Recrystallization of the residue from methanol–ether gave 193 mg (94% yield) of methyl phenylglycinate hydrochloride.[18] To a suspension of methyl phenylglycinate hydrochloride (81 mg, 0.4 mmol) in tetrahydrofuran (3.0 mL) were added 4-nitrobenzenesulfonyl chloride (106 mg, 0.48 mmol), triethylamine (97 mg, 0.96 mmol), and 4-dimethylaminopyridine (3.0 mg, 24 μmol), and the mixture was stirred at 20°C for 14 h. The mixture was quenched with saturated citric acid solution and extracted with ethyl acetate. Combined organic extracts were washed with saturated sodium bicarbonate solution, dried over magnesium sulfate, and concentrated under reduced pressure. The residue was chromatographed on silica gel (preparative thin-layer, benzene/ethyl acetate=5/1) to give 80 mg (57% yield) of methyl *N*-4-nitrobenzenesulfonylphenylglycinate (**4**): $[\alpha]^{20}_D=+77.6$ (*c* 1.00, chloroform).

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References

1. For reviews on asymmetric catalysis, (a) Ojima, I. *Catalytic Asymmetric Synthesis*; 2nd ed.; Wiley-VCH: New York, 2000. (b) Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; Wiley: New York, 1994. (c) Jacobsen, E. N.; Pfaltz, A.;

Yamamoto, H. *Comprehensive Asymmetric Catalysis*; Springer: Berlin, 1999.
2. Kobayashi, S.; Ishitani, H. *Chem. Rev.* **1999**, *99*, 1069.
3. Blaser, H.-U.; Spindler, F. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; Vol. 1, Chapter 6.2.
4. Pfaltz, A.; Lautens, M. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; Vol. 2, Chapter 24.
5. (a) Gittins (née Jones), C. A.; North, M *Tetrahedron: Asymmetry* **1997**, *8*, 3789. (b) Denmark, S. E.; Nakajima, N.; Nicaise, O. J.-C. *J. Am. Chem. Soc.* **1994**, *116*, 8797.
6. Hayashi, T.; Ishigedani, M. *J. Am. Chem. Soc.* **2000**, *122*, 976.
7. For examples: (a) Bishop, M. J.; McNutt, R. W. *Bioorg. Med. Chem. Lett.* **1995**, *5*, 1311. (b) Spencer, C. M.; Foulds, D.; Peters, D. H. *Drugs* **1993**, *46*, 1055. (c) Sakurai, S.; Ogawa, N.; Suzuki, T.; Kato, K; Ohashi, T.; Yasuda, S.; Kato, H.; Ito, Y. *Chem. Pharm. Bull.* **1996**, *44*, 765.
8. Love, B. E.; Raje, P. S.; Williams II, T. C. *Synlett* **1994**, 493.
9. Fukuyama, T.; Jow, C.-K.; Cheung, M. *Tetrahedron Lett.* **1995**, *36*, 6373.
10. (a) Cho, S.-Y.; Shibasaki, M. *Tetrahedron Lett.* **1998**, *39*, 1773. (b) Gladiali, S.; Pulacchini, S.; Fabbri, D.; Manassero, M.; Sansoni, M. *Tetrahedron: Asymmetry* **1998**, *9*, 391.
11. Kurz, L.; Lee, G.; Morgans, Jr., D.; Waldyke, M. J.; Wars, T. *Tetrahedron Lett.* **1990**, *31*, 6321.
12. (a) Uozumi, Y.; Hayashi, T. *J. Am. Chem. Soc.* **1991**, *113*, 9887. (b) Uozumi, Y.; Tanahashi, A.; Lee, S.-Y.; Hayashi, T. *J. Org. Chem.* **1993**, *58*, 1945. (c) Uozumi, Y.; Suzuki, N.; Ogiwara, A.; Hayashi, T. *Tetrahedron* **1994**, *50*, 4293.
13. Carlsen, H. J.; Katsuki, T.; Martin, V. S.; Sharpless, K. B. *J. Org. Chem.* **1981**, *46*, 3936.
14. (a) Dess, D. B.; Martin, J. C. *J. Am. Chem. Soc.* **1991**, *113*, 7277. (b) Ireland, R. E.; Liu, L. *J. Org. Chem.* **1993**, *58*, 2899.
15. Cramer, R. *Inorg. Synth.* **1974**, *15*, 16.
16. Wadsworth, W. S.; Emmons, W. D. *J. Am. Chem. Soc.* **1961**, *83*, 1733.
17. Hayashi, T.; Yamamoto, A.; Ito, Y.; Nishioka, E.; Miura, H.; Yanagi, K. *J. Am. Chem. Soc.* **1989**, *111*, 6301.
18. Rachele, J. R. *J. Org. Chem.* **1963**, *28*, 2898.